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CONCEPTUAL DESIGN REPORT

BASIC EXPERIMENTAL EQUIPMENT

April 13, 1990

(Revised)

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CEBAF BASIC EXPERIMENTAL EQUIPMENT

April 13, 1990

(Revised)

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CONCEPTUAL DESIGN REPORT
BASIC EXPERIMENTAL EQUIPMENT

HALL A

April 13, 1990
(Revised)

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1. INTRODUCTION

1.1 OVERVIEW

The Continuous Electron Beam Accelerator Facility (CEBAF) will be dedicated to basic research in Nuclear Physics using electrons and photons as projectiles.

Due to the intrinsic qualities of the electromagnetic probe – weak, known and kinematically flexible – precise quantitative information has been obtained on the structure of nuclei, mostly from inclusive (e,e') experiments. In principle, one can obtain much more detailed information on nuclear dynamics from experiments in which one (or more) of the final nuclear fragments are detected in coincidence with the scattered electron. However, the low-duty cycle of present medium-energy electron accelerators make such experiments difficult, being limited to narrow kinematical regions for which sufficient real-to-accidental coincidence ratios can be achieved.

In addition to the highest possible duty-cycle, a higher energy in the few GeV range is highly desirable. First, because it broadens the kinematical domain and brings the kinematical flexibility needed to disentangle the various reaction mechanisms. Second, it opens a completely new domain of coincidence studies at higher energy and momentum transfers. Probing the nucleus over small distances compared to the nucleon size and internucleon distance should reveal the role played by short range correlations between nucleons and by the quark substructure of hadrons and multihadron clusters in the nuclear dynamics.

The beam characteristics of CEBAF,

- maximum energy	4 GeV
- duty cycle	100%, CW
- emittance	$2 \times 10^{-9} \text{ m}$
- energy spread (4σ)	10^{-4}
- maximum intensity	$200 \mu\text{A}$,

have been chosen to fully support such studies.

In addition, the accelerator configuration allows three nearly continuous beams to be delivered simultaneously in three experimental halls, which will be equipped with complementary sets of instruments:

Hall A: two high resolution magnetic spectrometers.

Hall B: a large acceptance magnetic spectrometer.

Hall C: a high-momentum, moderate resolution, magnetic spectrometer and a variety of more dedicated instruments.

This report contains a short description of the initial complement of experimental equipment to be installed in Hall A, the core of which is a pair of High Resolution Spectrometers (HRS²).

Starting from preliminary designs performed during the Summer of 1985, the spectrometers evolved towards a "baseline solution" satisfying the requirements of the physics

program, with two identical *QQQDDQQ* 4 GeV/c spectrometers having superconducting magnets. This solution was presented to a Technical Advisory Panel (TAP) for review, in April 1988. Although the design was considered to be satisfying from the point of view of optics and performance, the Panel recommended looking for alternate solutions along similar lines, with less magnetic elements, possibly with warm coils and reduced field performance and accuracies to reduce the costs and the technological risks.

This lead to a new version of the spectrometer design with similar optical properties, but a much simplified *QQDQ* configuration. Basically, a new design of the dipole, with a non-uniform field and tilted pole ends has been used to eliminate two radially focussing quadrupoles. The field gradients and the apertures of the remaining quadrupoles are reduced, making them consistent with state-of-the-art technology. All magnets have superconducting coils, this choice being essentially dictated by operating cost considerations.

The superconducting *QQDQ* solution for the High Resolution Spectrometers was reviewed by the TAP in June 1989. The summary of the TAP report stated that, *"The design appears to fully address the needs of the CEBAF physics program and the most recent recommendations of the PAC".... "The panel endorses the use of identical spectrometers in the two arms of the spectrometer system. Such a choice minimizes the cost of design, engineering, procurement, and commissioning, and maximizes experimental flexibility....The proposed QQDQ design meets the physics requirements and is cost effective. The choice of a 45° non-uniform field dipole for radial focussing is probably the lowest cost approach"*. The panel also endorsed the choice of superconducting magnet elements over resistive ones.

A layout of the 4 GeV/c High Resolution Spectrometer is shown in Figure 1.1. Its main design characteristics are summarized in Table 1.1. The vertically bending design includes a pair of superconducting, $\cos 2\theta$ quadrupoles followed by a 6.6m long dipole magnet, shown in Figure 1.2, with focusing entrance and exit faces and including further focusing through the use of a field gradient. The main characteristics of the dipole are given in Table 1.2.

Beyond the dipole is another superconducting $\cos 2\theta$ quadrupole. The second and third quadrupole of each spectrometer have sufficiently similar field requirements that they can be of identical design and construction (see Figure 1.3). The main characteristics of the HRS quadrupoles are given in Table 1.3.

More detail about the spectrometer optical properties is given in Section 4. The magnetic and engineering design of the dipole and quadrupole elements are described in Section 5, and the support structure in Section 6. Section 7 gives the essential features of the detection systems equipping the electron and hadron spectrometer, the latest including a focal plane polarimeter. A sketch of the detector system for the hadron spectrometer inside its shielding hut is shown in Figure 1.4. These systems are being conceived, designed and will be built by user groups outside CEBAF, within the Hall A Collaboration.

4 GeV/c High Resolution Spectrometer

Figure 1.1

4/6/90

Table 1.1
Main Design Characteristics of the 4 GeV/c QQDQ Spectrometer

Configuration	vertical
Bending angle	45°
Optical length (m)	23.4
Momentum range (GeV/c)	0.3 to 4
Momentum acceptance (%)	10
Momentum dispersion (D, cm/%)	12.4
Momentum resolution*	10 ⁻⁴
Radial linear magnification (M)	-2.5
D/M (cm/%)	5.0
Angular range	12.5° to 165°
Angular acceptance : horiz. (mr)	±30
vert. (mr)	±65
Angular resolution* : horiz. (mr)	0.5
vert. (mr)	1.0
Solid angle (msr)	7.8
Transverse length acceptance (cm)	±5
Transverse position resolution (cm)*	0.1

*FWHM, including effects of finite beam spot size and detector resolutions (see expected performances section).

Figures 1.5 and 1.6 show Hall A in plan and elevation view. The 174' diameter wall, as well as the roof height are tightly fitted to the overall dimensions of the spectrometers and their detector shielding huts. The floor is 10' below beam line, which is the minimum acceptable value for a design of the spectrometer support structure allowing the required small angle positioning. Some provisions are made in the Hall A civil construction for making possible the future implementation of an out-of-plane beam line. By having the beam vertically deflected before impinging on the target would allow the realization of non-coplanar kinematics, an important feature in the planned physics programs for Hall A. A general description of the beam line and its instrumentation is given in Section 8.

Although the High Resolution Spectrometer Pair will constitute the core of the Hall A experimental facility, additional instruments are under investigation for future implementation in the Hall. They include:

- Neutron detectors and neutron polarimeters.
- Non-magnetic detectors for triple coincidence experiments, possibly in non-coplanar configurations.
- A short, high resolution spectrometer# with maximum momentum capability

Under study by an Italian group.

Dipole Assembly

Approx. Weight 920 Klbs.

4/19/90

Figure 1.2

Table 1.2
Dipole Design Parameters

Magnetic length	6.6	m
Central gap	0.25	m
Central bend radius	8.4	m
Central bend angle	45°	
Effective width	1.0	m
Entrance angle	-30°	
Exit angle	-30°	
Entrance curvature	0.274	m ⁻¹
Exit curvature	-0.140	m ⁻¹
Maximum central field	1.6	T
Minimum central field	0.16	T
Field index (<i>n</i>)	-1.25	
Field reproducibility	±10 ⁻⁴	
Gap dimensional tolerance	10 ⁻³	
Current density (overall)	3.57	kA/cm ²
Total Amp-turns	400	kA
Operating current	1800	A
Stored energy	3.5	MJ
Peak coil field	1.08	T
Maximum coil force	7.5	10 ³ kg/m

Table 1.3
Quadrupole Design Parameters

	Q1	Q2 / Q3	
Magnetic length	0.8	1.8	m
Useful bore radius (UBR)	0.15	0.30	m
Maximum field gradient	9.5	3.5	T/m
Max. field @ UBR	1.43	1.05	T
Gradient uniformity	10 ⁻³	10 ⁻³	
Multipole strengths:			
<i>Sextupole</i>	0	1.52	T/m ²
<i>Octupole</i>	0	3.11	T/m ³
Total Amp-turns	1.02	1.40	MA
Operating current	2.64	1.85	kA
Stored energy	130	600	kJ
Peak coil field	2.12	1.83	T
Maximum coil force	11.7	13.1	10 ³ kg/m

Dimensions are in cm.

Q2/Q3 Cosine 20 Quadrupole
Figure 1.3

4/12/90

Focal Plane Instrumentation

4/20/90

Figure 1.4

Sketch of the Detector Assembly for the Hadron Spectrometer

Hall "A" Elevation View

12/8/89
S. ESP

Figure 1.5

Hall "A" Plan View

12/6/89
S. ESP

Figure 1.6

around 1.5 GeV/c, which could be used for K^+ detection in hypernuclear physics experiments, or as a third arm in triple coincidence measurements. One can also envision moving this device out-of-plane, as an alternative to moving the beam.

In Section 9, the management plan for the procurement, construction, commissioning and implementation of HRS ² is outlined while cost and manpower aspects are summarized in Section 10.

The overall estimated cost to complete the equipment described in the present report, referred to as Phase I Equipment for Hall A is \$ 24.2M (FY89) out of which up to \$ 4M is expected to come from foreign contributions. This figure does not include contingency.

The corresponding manpower needs amount to 207 man.years, out of which 117 are expected to be CEBAF staff (engineers, technicians, physicists) and 90 are from outside user groups.

The remaining part of this section describes how the users are organized and how they are involved in the development of the physics program and experimental equipment in Hall A.

1.2 HALL A COLLABORATION

1.2.1 Overview of the Physics Program

Electron scattering has proven to be an extremely useful tool for understanding the structure of nucleons and nuclei. The high quality, intense CW electron beam afforded by CEBAF, together with a pair of high resolution spectrometers, represents a unique capability for performing precision nuclear physics studies. Electron-proton coincidence experiments have long been considered the benchmark of Hall A physics and *the program will encompass a broad spectrum of measurements including those on the nucleon and the few-body systems as well as other experiments requiring high resolution.* Clearly, a thorough understanding of the structure of free nucleons is required before one can devise reliable theories of nuclei based upon these constituents. Studies of few-body systems are a natural extension of such nucleonic measurements. The relative simplicity of these systems allows for detailed calculations to be performed and thus they provide the most direct connection with microscopic nuclear theories. The two-body system (deuterium) is of particular importance since, in addition to isolating the two-body NN interaction, most neutron form factor measurements will employ deuterium targets. Thus, effects arising from the interaction of this neutron with its neighboring proton must be understood if one is to extract information about free neutrons. Of course, understanding the nucleon-nucleon (N-N) interaction is also the starting point for theories of more complex nuclei. Interaction effects, including nucleon correlations as well as non-nucleonic degrees of freedom such as excited nucleonic states (isobar configurations - IC) and Meson Exchange Currents (MEC), are also phenomena of basic interest and their understanding may help provide a connection between conventional descriptions of nuclei and descriptions involving quarks and gluons.

Electrons interact rather weakly with the nuclear system and, since the electromagnetic interaction is well understood, one can deduce quantitative information about the electromagnetic structure of the nucleus under study. The nuclear structure so obtained provides important constraints to various interaction models. In deeply inelastic scattering of electrons from nuclei one would like to examine in detail the various reaction mechanisms which contribute to the inclusive nuclear response. By detecting particles emitted from the nucleus along with the scattered electron one can derive more detailed information of the reaction than in single-arm (e,e') measurements alone. In particular, the selectivity of the final nuclear state inherent in $(e,e'p)$ knockout reactions allows for a more thorough understanding of the various contributing processes. Further, measurement of the separated response functions in $(e,e'p)$ allows one to disentangle various aspects of the reaction.

Although the relative weakness of the electromagnetic interaction results in small cross sections and hence counting rates, *the high current afforded by the CEBAF beam will allow statistically precise measurements to be made with reasonable counting times.* In addition, since cross sections fall rapidly at high momenta, such high currents are of paramount importance in probing the *short distance structure of nuclei* where subnucleonic effects are expected to appear. This rapid variation of the cross section also implies the need to precisely determine the kinematics of each scattering event in order to control measurement

errors. This requirement is even more crucial in performing separations of the individual response functions since errors are typically magnified by large amounts in deducing these quantities from the measured cross sections. Thus, *high resolution spectrometers are required not only to separate closely spaced nuclear final states but, perhaps even more importantly, to control the systematic uncertainties.*

The Hall A facility will provide orders of magnitude of increased sensitivity for studying the $(e,e'p)$ reaction, allowing systematic studies to be undertaken for the first time. It will allow access to the long sought after *high momentum components* in nuclei, *subtle relativistic effects* (both in nuclear wavefunctions and in nucleon propagation through the nuclear medium) and the role of *non-nucleonic degrees of freedom*. It should be possible to obtain high precision results on the electromagnetic structure of both free protons and protons embedded in the nuclear medium.

In order to fully exploit the advantages of the electromagnetic probe in $(e,e'p)$ reactions, *polarization observables and out-of-plane capability* as well as separation of the unpolarized structure functions will be required. The qualities of CEBAF will open up a new window on fundamental spin physics measurements, making systematic studies of the spin degrees of freedom, both for the electron as well as ejected nucleons, possible. Such studies will provide stringent tests of nuclear wavefunctions and currents. These measurements will, in general, require both a *polarized electron beam* and a *focal plane polarimeter (FPP)* for protons. Calculations for deuterium and oxygen suggest that such polarization studies may yield greatly enhanced sensitivity to various nuclear interaction models.

There are several basic requirements that must exist if we are to fully exploit the physics potential of this reaction. *Resolution in scattering angle and momentum, and, for extended targets, transverse position are crucial. The ability to view extended targets is essential for the high-priority experiments on the few-body systems. Resolution in the vertical angles, although not as critical, is also important especially for out-of-plane experiments.* These basic resolutions define our ability to determine the kinematics $(Q^2, \omega, \dots)$ of the scattering event.

Although $(e,e'p)$ studies, both polarized and unpolarized, are expected to form the bulk of the Hall A physics program, the spectrometers will be employed for any experiments requiring high resolution. These include single-arm (e,e') measurements where high resolution allows precise definition of the virtual photon kinematics, real photon induced reactions such as ${}^3\text{He}(\gamma, pp)$, pion and perhaps kaon electroproduction, $(e,e'2N)$ measurements and cluster knockout reactions involving deuterons, ${}^3,{}^4\text{He}$, etc.

Studies of $(e,e'n)$ reactions are vital to our understanding of the nucleus, in particular as regards the spectroscopy of neutron hole states. Questions of proton-neutron symmetry can be fruitfully addressed, making $(e,e'n)$ an important complement to $(e,e'p)$ studies. The ability to adapt one of the spectrometers as a *recoil proton spectrometer* would be a way of carrying out such measurements with reasonable resolution. Measurements of the electric form factor of the neutron are also of fundamental importance and could be carried out with a set of specialized detectors designed for neutron polarimetry. *The neutron electric form factor* is one of the most wanted pieces of information in nuclear

physics today because of its pervasive effect on the interpretation of (e,e') cross sections in terms of nuclear models and as a fundamental test of quark models of the nucleon. The development of high-energy neutron detectors and polarimeters operating in the CEBAF environment is a necessary task for measurements on single-neutron knockout and for the neutrons in $2N$ and jet reactions. These detectors should be light enough to allow out-of-plane angular distributions to be measured easily in order to access interference form factors.

Many of the questions raised by recent measurements of single proton knockout may find their answers in *two- (or more) nucleon knockout reactions*. Such measurements will require a *third spectrometer*, although this is not part of the basic complement of equipment. Ejection of $A=2-4$ nuclei shows the extent to which groups of correlated nucleons participate in nuclear reactions. Questions about missing strength, initial- and final-state nucleon correlations, meson exchange currents, and medium modifications of fundamental processes may be answered when we understand the extent to which nucleons are ejected in high energy clusters from complex nuclei.

At the highest momentum transfers available at CEBAF one will begin to see the products of the *hadronization* of struck quarks into jets of nucleons and mesons. The systematics of this process and any differences seen between nucleon and nuclear targets will begin a fascinating new era of nuclear reaction studies. A particular aspect of such studies that can be addressed by $(e,e'p)$ is the so-called '*color transparency*' phenomenon predicted by perturbative QCD. This phenomenon is a weakening of the nucleon-nucleus interaction at high momentum transfers (i.e. short distance scales) resulting in an increased transparency of nuclei to high-energy hadrons. The possibility therefore exists for a sensitive test of quark models and QCD by performing $(e,e'p)$ experiments at Q^2 of several $(\text{GeV}/c)^2$, a situation CEBAF is uniquely qualified for.

The *pion charge form factor* can be measured with greater precision and over a wider range of momentum transfer than in previous experiments by making use of the superior properties of the CEBAF beam and the matched magnetic spectrometers in Hall A. This form factor is important for quark models of elementary particles and as an ingredient for the nuclear many body problem. The Hall A spectrometers are well suited for carrying out the necessary separations.

To summarize, the CEBAF Hall A physics program will encompass a broad range of nuclear physics experiments (the experiments and physics are discussed in more detail in section 2). Much of the program can be carried out with an initial complement of equipment comprised of two high resolution spectrometers with a focal plane polarimeter in the hadron arm coupled with a polarized beam and associated monitoring device. At a later date, a third spectrometer will be required for $(e,e'2N)$ and $(e,e'\pi p)$ measurements, etc. Neutron detectors will also be needed to carry out complementary $(e,e'n)$ experiments. Finally, an out-of-plane capability is crucial to accessing many of the response functions which cannot be gotten otherwise.

1.2.2 Formation of the Hall A Collaboration

1.2.2.1 History

Initially, the outside user involvement in Hall A was in the form of various working groups focussed on specific instrumentation issues. These working groups produced considerable high-quality efforts in defining the physics to be addressed, in the instruments required and in additional capabilities (polarimetry, neutron detection etc.) to augment the basic two spectrometer setup. These efforts have typically been undertaken by individual university groups which then convened a few times throughout the year with representatives from CEBAF. This somewhat loosely organized user group has gradually evolved into the more structured formal Hall A Collaboration.

There have been many forums for users to give their input regarding the physics and instruments. In addition to the CEBAF Summer Workshops where the bulk of the users met, there have been several meetings of those users most interested in, and committed to, the Hall A project. A brief chronology is given in Table 1.4. Furthermore, subsets of these individuals have formed working groups and then met to deal with specific issues.

Meeting	Location	Dates	Participants
Hall A Users	U. Maryland	Dec. 11-12, 1987	45
Data. Acq. Wrkshp.	CEBAF	Feb. 22-24, 1988	80
Hall A Users	CEBAF	Feb. 26-27, 1988	35
Users Group Meeting	APS, Baltimore	April 20, 1988	75
1988 Summer Workshop	CEBAF	June 20-24, 1988	157
Hall A Steering Comm.	NBS	Sept. 9, 1988	14
Hall A Users	UVa	Oct. 24-25, 1988	27
Hall A Users	CEBAF	Jan. 29-31, 1989	36
Hall A Users	MIT-Bates	April 10, 1989	24
Hall A Collab.	CEBAF	June 7-9, 1989	34
Hall A Collab.	UVa	Sept. 7-9, 1989	33
Hall A Steering Comm.	CEBAF	Nov. 20, 1989	12
Hall A Collab.	CEBAF	Nov. 20-21, 1989	29
Hall A Steering Comm.	CEBAF	Mar. 23, 1990	10
Hall A Collab.	CEBAF	Mar. 23-24, 1990	32

Table 1.4 Chronology of Hall A user activities.

In addition, a task force to study the options for out-of-plane experiments in Hall A was formed in the summer of 1987 and issued its report in October of that year; the task

force was comprised of 26 members, 14 of which were from institutions other than CEBAF. This group developed Monte Carlo codes to simulate out-of-plane reactions, studied the sensitivity to energy and angular resolutions and the kinematic coverage required to perform meaningful measurements. A chronology of the activities of the various working groups, prior to formation of the Collaboration, appears in Table 1.5.

Meeting	Location	Dates	Participants
FPP Working Group	CNC	June 1987	15
(e,e'N) Working Group	CNC	June 1987	33
(e,e'N) Physics Collab.	William and Mary	Sept. 1987	35
FPP Working Group	U. Maryland	Dec. 1987	4
(e,e'n) Working Group	U. Maryland	Dec. 1987	6
FPP Working Group	CEBAF	Feb. 88	26
FPP Working Group	CNC	June 1988	17
(e,e'n) Working Group	CNC	June 1988	12
Out-of-plane Task Force	CEBAF	Summer 1988	26
FPP Working Group	CEBAF	Sept. 1988	16

Table 1.5 Chronology of Hall A working group activities prior to 1989.

1.2.2.2 Present Status of the Collaboration

The joint requirements of defining and presenting the initial physics program to PAC4 along with the fact that Hall A is now entering the procurement/construction stage, necessitated a more formal organizational structure for the various user groups. This structure is the *Hall A Collaboration*. As currently configured, the membership essentially consists of those committed to a specific project for Hall A. This commitment is expressed either in an MOU document or, for foreign collaborators, in a written statement of intentions. The detailed structure and operation of the Collaboration will be governed by a written charter which is currently in the process of being devised. This document will address the following issues:

- Goals of the Collaboration.
- Governance of the Collaboration.
- Management of:
 - Physics issues and their consequences for Hall A instrumentation.
 - Membership, publication and Ph.D theses issues.
 - Allocation of resources within the collaboration.
 - Resolution of technical conflicts in construction and operation.
 - Monitoring progress in design and construction of Hall A instrumentation.

- Technical Working Groups.
- Elections.
- Meetings.
- Proposals for Beamtime.
- Access to Data.

A first draft of the charter has been produced and distributed to the members for discussion. Adoption of the final version is expected to occur at the June 1990 Collaboration meeting.

At the June, 1989 meeting, the Hall A users defined a list of highest priority experiments to be presented to PAC4. These experiments ranged from studies of the nucleon to $^{208}\text{Pb}(e,e'p)$ with each experiment having from 1 to 4 co-spokespersons from within the Collaboration. The Hall A physics program was quite favorably received by the PAC. The physics program and specific Collaboration experiments are discussed in more detail in section 2. The institutions and individuals involved in the preparation of these proposals are listed at the end of this section.

1.2.3 Working Groups and User Projects

Initially, working groups were formed to study design choices for various hardware and instrumentation and to devise simulation software both for the instruments and for specific physics experiments. These working groups are now producing final designs along with costs, schedules and personnel requirements. They will eventually construct, test and install their particular component in the Hall A environment. The specific areas for which user groups have responsibility are:

- 1) The focal plane instrumentation which includes drift chambers, Cherenkov, shower and scintillation counters.
- 2) The focal plane polarimeter.
- 3) Trigger electronics and the data acquisition system.
- 4) Electron beam polarimetry.
- 5) Development of high-power cryogenic targets.
- 6) Neutron detection and polarimetry.
- 7) Computer simulations.

Within the Hall A Collaboration, the operation of the working groups is currently coordinated by the *Hall A Steering Committee*. This committee ensures liaison between the management group/project team and the users in the Hall A collaboration. Its members are, apart from the two co-managers and the project engineer, the CEBAF and user physicists leading the user groups responsible for specific project tasks. The steering committee meets regularly (3 to 4 times a year) to review the status of the project and make technical and managerial decisions on its evolution. These decisions have to be approved by the CEBAF directorate. It is the role of the Hall A co-program managers to negotiate such approval. Table 1.6 indicates the current members of this committee and their areas of responsibility.

Hall A Steering Committee

•Management	
J. Mougey, CEBAF	CEBAF Program Manager
R. Lourie, UVa	User Co-Program Manager
J. Alcorn, CEBAF	Project Engineer/ Cost Account Manager
• W. Bertozzi, MIT	Coordination, focal plane instrumentation
• L. Weinstein, MIT	Wire chambers
• C.C. Chang, UMd	Shower detectors
• G. Lolos, U. Regina	Scintillation and Cerenkov counters
• C. Glashauser, Rutgers	Focal plane polarimeter
• M. Finn, W&M	Trigger electronics and data acquisition
• G. Petratos, U.Rochester	Spectrometer Calibration
• B. Flanders, Am.U	Simulation software
• M. Epstein, CSU	High power cyrotargets
• D. Day/J. McCarthy, UVa	Cryotargets and polarized targets
• R. Lindgren, UVa	Target chamber
• Z.E. Meziani, Stanford	Beam polarimeter
• R. Madey/J. Watson, KSU	Neutron detection and polarimetry

Table 1.6 *Hall A Steering Committee*

In addition to the U.S. institutions participating in the Collaboration, there are also several foreign collaborating groups, contributing in the following areas :

- Possible third high-resolution spectrometer: INFN Rome and Lecce, (Italy), S. Frulani coordinator.
- Gas Cherenkov counter(s): CEN-Saclay (France), B. Frois coordinator.
- Temporary installation of non-magnetic detector(s): NIKHEF (Holland), H. Blok

coordinator.

- I. Blomqvist, Univ.of Mainz (Germany), has been and continues to be involved in the optics and conceptual magnet design.

The CEBAF Hall A Collaboration

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+ 16 graduate students and 11 postdocs/research scientists

- (1) *American University*
- (2) *The California State University at Los Angeles*
- (3) *Chungnam National University*
- (4) *The College of William and Mary in Virginia*
- (5) *The Continuous Electron Beam Accelerator Facility*
- (6) *The Free University of Amsterdam*
- (7) *George Washington University*
- (8a) *INFN Sezione Sanita, Rome*
- (8b) *INFN Sezione Lecce*
- (9) *The Indiana University Cyclotron Facility*
- (10) *Kent State University*
- (11) *Massachusetts Institute of Technology*
- (12) *The National Institute for Standards and Technology*
- (13) *NIKHEF-K*
- (14) *Norfolk State University*
- (15) *Rutgers University*
- (16) *Saclay - CEN*
- (17) *Stanford University*
- (18) *The University of Georgia*
- (19) *The University of Mainz*
- (20) *The University of Maryland*
- (21) *The University of New Hampshire*
- (22) *The University of Regina*
- (23) *The University of Rochester*
- (24) *The University of Saskatchewan*
- (25) *The University of Virginia, Charlottesville*
- (26) *Western Kentucky University*

HALL A PHYSICS PROPOSALS – PAC 4

Proposal #	Title	Spokespersons	Beam Hours Requested
PR-89-003	Study of the Quasielastic (e,e'p) reaction in ^{16}O at high recoil momenta	R. Lourie (UVA) A. Saha (CEBAF) L. Weinstein (MIT) W. Bertozzi (MIT)	1528
PR-89-005	The Electric Form Factor of the Neutron from the $D(\bar{e},e'\bar{n})$ reaction	R. Madey (KSU)	910
PR-89-014	Electric Form Factor of the Proton by Recoil Polarization	C.F. Perdrisat (W&M) V. Punjabi (NSU)	1440
PR-89-016	The Trans. and Long. Response Functions for quasielastic electron scattering in the mom. regime $0.3 < Q^2 < 1.5 \text{ (GeV/c)}^2$	Z.E. Meziani (Stanford)	720
PR-89-018	An Experiment to measure the charge form factor of the Nucleon	D. Day (UVA)	1325
PR-89-019	Measurement of Proton Polarization in the $D(\gamma,p)n$ Reaction	R. Gilman (Rutgers) Z.E. Meziani (Stanford)	492
PR-89-021	Elastic electron $^3\text{He} - ^4\text{He}$ scattering at large momentum transfers	G.G.Petratos (Rochester)	1440
PR-89-026	In-plane separations and High momentum structure in $D(e,e'p)$	J.M. Finn (W&M) P.E. Ulmer (CEBAF)	554
PR-89-028	Polarization Transfer measurements in the $D(\bar{e},e'\bar{p})n$ reaction	J.M. Finn (W&M) P.E. Ulmer (CEBAF)	708
PR-89-029	Study of the (e,e'd) reaction on $^{3,4}\text{He}$	H.P. Blok (NIKHEF/VU)	200
PR-89-030	Two Nucleon Knockout reactions on $^{3,4}\text{He}$	R.A. Lindgren (UVA) M.B. Epstein (CSU) G. Lolos (Regina) Z.E. Meziani (Stanford)	3075
PR-89-033	Measurement of recoil polarization in the $^{16}\text{O}(e,e'p)$ reaction with 4 GeV Electrons	C.C. Chang (Maryland) C. Glashauser (Rutgers) S. Nanda (CEBAF) J.W. Van Orden (CEBAF)	456
PR-89-034	Medium Effects of the (e,e'p) Nucleon Knockout Reaction	P. Boberg (Maryland) C.C. Chang (Maryland)	100

Proposal #	Title	Spokespersons	Beam Hours Requested
PR-89-035	Measuring the Number of Pions in the Nucleus	C.C. Chang (Maryland) J.S. O'Connell (NIST) R. Gilman (Rutgers)	800
PR-89-044	Selected studies of the ^3He and ^4He nuclei through electrodisintegration at high momentum transfer	J. Mougey (CEBAF) A. Saha (CEBAF) M.B. Epstein (CSU) R. Lourie (UVA)	2000
PR-89-046	Study of Quasi-Particle orbits in closed shell nuclei with $(e,e'p)$	B. Frois (Saclay) C.N. Papanicolas (Ill) L. Lapikas (NIKHEF) J. Mougey (CEBAF)	420
PR-89-047	Deuteron Electrodisintegration at threshold at large momentum transfers	J. Jourdan (Basel) G.G.Petratos (Rochester) J. Mougey (CEBAF)	1000

2. PHYSICS MOTIVATION

2.1 COLLABORATION EXPERIMENTS

The Hall A Collaboration has presented a set of *high priority experiments* to the CEBAF Program Advisory Committee (PAC4). These experiments indicate the breadth of the Hall A physics program and encompass measurements of the electromagnetic structure of nucleons and few-body nuclei, studies of high-momentum components and spin observables in complex nuclei, high-resolution spectroscopic studies in ^{208}Pb and pion knockout from nucleon and nuclear targets. The Collaboration will also pursue single-arm (e,e') measurements which will extend to higher Q^2 our knowledge of the elastic form factors of the few-body systems, the threshold electrodisintegration of the deuteron and quasielastic scattering from complex systems. *High power cryogenic targets* are clearly a high priority item as they are necessary for the studies of the few-body systems. Also, a *focal plane polarimeter* in the hadron arm along with a *polarized electron beam* are necessary to carry out a broad program of measurements of spin observables.

2.1.1 The (e,e'p) Physics Program

Hall A at CEBAF will be the premier facility worldwide for studies of the (e,e'p) reaction. The combination of the high-quality CEBAF beam and two high resolution spectrometers will provide an unprecedented opportunity for electromagnetic coincidence experiments. The resolution of these instruments will allow *high precision coincidence experiments* to be performed. This precision results in large part from the high degree to which the kinematic quantities can be defined and this translates directly into reduced systematic effects. It will then be possible to obtain *precise separations of structure functions* which will provide our most stringent tests of theoretical models. In the following subsections, a description will be given of the proposed Hall A (e,e'p) physics program.

2.1.1.1 The Structure of Free Nucleons

The electromagnetic structure of both free and bound nucleons is a particularly important topic for study at CEBAF. Obviously, precise knowledge of the free nucleon form factors is necessary before one can meaningfully search for modifications of those form factors in the nuclear medium. The free nucleon form factors are basic ingredients in all calculations of electromagnetic processes which treat nucleon effective degrees of freedom. The uncertainty in our knowledge of these form factors can prove to be the limiting factor in extracting additional information from many nuclear reactions. In addition, theoretical descriptions of nucleon structure must ultimately be able to reproduce the electromagnetic form factors of the nucleons. The magnetic form factors are the best determined experimentally while the electric form factor of the proton is not well known for large four-momentum transfers and the electric form factor of the neutron is poorly determined at almost all four-momentum transfers due to its small size and the lack of a free neutron target. The electric and magnetic form factors of the proton (G_{Ep} and G_{Mp}) have been determined by a Rosenbluth separation of elastic electron-proton cross sections. The free proton electric form factor G_{Ep} , in particular, is quite poorly known

Figure 2.1 Data^[1] and theoretical models^[2] for the proton electric form factor G_{Ep} expressed as the ratio to the dipole form. Solid curve: Gari and Krümpelmann, long dashes: Höhler et al., short dashes: Iachello et al., dot-dashed: Radyushkin. The filled circles are the projected data points from the proposed CEBAF experiment.^[4]

above $Q^2 \sim 3 \text{ (GeV/c)}^2$ (see figure 2.1); the data^[1] cannot distinguish between various models^[2] of nucleon structure.

At high momentum transfers the cross section is mainly transverse and thus dominated by the proton magnetic form factor $G_{Mp} (\approx \mu_p G_{Ep})$. Standard Rosenbluth separation techniques are then unable to achieve high precision results at high Q^2 for the proton longitudinal structure function (proportional to G_{Ep}^2). A promising technique for determining G_{Ep} at high Q^2 is to measure the interference term that results when polarized electrons are incident on either a polarized proton target or when the recoil proton polarization is detected.^[3] In the recoil polarization method, $^1\text{H}(\vec{e}, e' \vec{p})$, the transverse and longitudinal components of the proton polarization vector are given by:

$$\begin{aligned} I_0 \Pi_t &= h \left(-2\sqrt{\tau(1+\tau)} G_{Mp} G_{Ep} \tan \frac{\theta}{2} \right) \\ I_0 \Pi_l &= h \left(2\tau \sqrt{(1+\tau)(1+\tau \sin^2 \frac{\theta}{2})} \sec \frac{\theta}{2} \tan \frac{\theta}{2} G_{Mp}^2 \right) \end{aligned} \quad (1)$$

where h is the longitudinal polarization of the electron beam and I_0 is the unpolarized cross section (except for σ_{Mott}):

$$I_0 = G_{Ep}^2 + \tau G_{Mp}^2 \left[1 + 2(1+\tau) \tan^2 \frac{\theta}{2} \right] \quad (2)$$

and $\tau = Q^2/4M^2$. In terms of the standard response functions:

$$\begin{aligned} R_L &= (1 + \tau)G_E^2(\tau) \quad , \\ R_T &= 2\tau G_M^2(\tau) \quad , \\ R_{LT'}^l &= -2\sqrt{\tau(1 + \tau)}G_M(\tau)G_E(\tau) \quad , \\ R_{TT'}^l &= 2\tau G_M^2(\tau) \quad . \end{aligned} \tag{3}$$

At large momentum transfers, the transverse and polarized transverse-transverse contributions, R_T and $R_{TT'}^l$, which are proportional to $G_{M_p}^2$ dominate, while the longitudinal contribution, which is proportional to $G_{E_p}^2$, is small. This clearly shows why it is difficult to use the Rosenbluth separation of longitudinal and transverse response functions to determine G_{E_p} . While the longitudinal contribution to the cross section is almost two orders of magnitude smaller than the transverse at $Q^2 = 4 \text{ (GeV/c)}^2$, the polarized longitudinal-transverse contribution, which is proportional to the product of G_E and G_M , i.e. is *linear* in G_{E_p} , is only one order of magnitude smaller. This technique of recoil polarization measurement will be used by Perdrisat *et al.* to obtain a few percent measurement of G_{E_p} up to $Q^2 = 4.5 \text{ (GeV/c)}^2$.^[4] The quality of the data expected from this experiment is indicated by the filled circles in figure 2.1.

The electric form factor G_{E_n} of the neutron is also a fundamental quantity needed for the understanding of both nucleon and nuclear structure. The dependence of G_{E_n} on Q^2 , the four-momentum transfer squared, is determined by the charge distribution of the neutron. Also the Q^2 -dependence of G_{E_n} tests the spatial symmetry of the neutron wave function under quark permutation. The electric form factor G_{E_n} is small and poorly known for all Q^2 except for the slope at $Q^2=0$, which was obtained to 2% accuracy by scattering neutrons from atomic electrons.^[5] Present models of the nucleon predict significantly different values of G_{E_n} at high momentum transfer; accordingly, good determinations of G_{E_n} will provide an important test of these models. Also the influence of G_{E_n} is not negligible in the interpretation of electron scattering from nuclei at high momentum transfer. For these reasons, it is of great importance to determine G_{E_n} with smaller uncertainties than before.

As in the case of G_{E_p} , G_{E_n} can be determined more accurately by measuring the polarization of the recoil neutron after quasielastic scattering of a longitudinally-polarized electron from an unpolarized neutron. The components of the polarization of the recoil neutron lie in the scattering plane of the electron and the recoil neutron. The polarization component normal to the scattering plane vanishes in the plane wave impulse approximation. The component of the neutron polarization parallel to the scattering plane, but normal to the momentum transfer, is proportional to G_{E_n} . Using a neutron polarimeter already constructed for the low momentum transfer G_{E_n} experiment at Bates, Madey *et al.* will determine G_{E_n} at CEBAF for momentum transfers up to 1.5 (GeV/c)^2 and with better than 20% error bars.^[6]

Another method to measure the charge form factor of the neutron is through the $^2\text{H}(\vec{e}, e'n)p$ reaction, using longitudinally polarized electrons on a (vector) polarized deuterium target. This technique has been proposed by Day *et al.* from UVA where polarized NH_3 and ND_3 targets are under development.^[7] This experiment is proposed in Hall C. The anticipated results of both the recoil polarization and polarized target experiments are shown in figure 2.2 along with various theoretical predictions.^{[2] [8]}

Figure 2.2 Theoretical models^[2,6] for the neutron electric form factor G_{En} . Solid curve: Gari and Krümpelmann, short dashes: Galster *et al.*, dot-dashed: dipole form. For comparison, the dipole form for G_{Ep} is shown by the long dashed curve. The filled circles are the projected data points, based on the Galster calculation, for the proposed CEBAF experiment employing a polarized ND_3 target.^[7] The open circles are the anticipated result, based on the dipole form, for the recoil polarization measurement.^[6]

2.1.1.2 Electromagnetic Structure of the Few-Body Systems

The importance of detailed experimental study of these systems is simply that they provide the most direct connection with microscopic theories. A complete set of the $(e,e'p)$ response functions will provide stringent constraints on models of the NN interaction, both for bound and scattering states, and on the currents connecting these states. These will require polarization observables, separation of the unpolarized structure functions and, ultimately, an out-of-plane capability. Of particular importance are measurements at large values of recoil momentum ($\vec{p}_r$) since they probe the short-distance character of the nuclear wavefunctions.

Proposals have been submitted for determining the separated longitudinal and transverse response functions in the deuteron, ^3He and ^4He at both low and high values of the internal momentum.^[9] On deuterium, there are plans to considerably extend the present knowledge of the basic $\text{D}(e,e'p)$ reaction by studying the momentum distribution at higher momentum transfers and by undertaking separations of the R_L , R_T and R_{LT} response functions. The Q^2 dependence of the reaction will be examined by performing longitudinal/transverse (L/T) separations for protons emitted along $\vec{q}$ at $Q^2 = 0.23, 0.81, 2.14$ and 3.41 $(\text{GeV}/c)^2$ at quasifree kinematics ($p_r = 0$). In addition, by detecting protons away from the direction of $\vec{q}$, the angular distribution of emerging protons will be measured for recoil momenta up to 500 MeV/c at a single 3-momentum transfer of 1.0 GeV/c . From in-plane measurements on either side of $\vec{q}$, plus a backward angle measurement, R_T , R_{LT} and $R_L + R_{TT}$ can be determined and will provide additional

tests of the microscopic models of this reaction.

In the Helium nuclei, both the two-body and many-body breakup channels will be explored. The (e,e'p) reaction on the few-body systems has the potential to disentangle nuclear structure and reaction mechanism effects from the question of the electromagnetic structure of bound nucleons since, in these systems, it is possible to perform reliable structure calculations. For the two- and three-body systems, 'exact' non-relativistic Faddeev or variational wavefunctions for the bound states are available while wavefunctions of similar quality are now becoming available for the scattering states and ^4He . To the extent that the nuclear structure and scattering states are known, the (e,e'p) reaction can directly probe the electromagnetic current of bound nucleons. By studying the many-body breakup channels, we learn about the two-body short-range correlations in the ground state.

At low values of the initial proton momentum, where detailed knowledge of the short-range character of the nuclear wavefunction is not required, the (e,e'p) cross section data are in good agreement with theory.^[10] Of course, the existing data were all taken at low Q^2 and thus do not allow the spatial extent of the currents responsible for nucleon ejection to be determined. Also, only a narrow range of ejected proton energies (around 100 MeV) have been examined where relativistic effects in the nucleon-nucleus dynamics should be considerably less important than at CEBAF energies. These studies can only be extended into the interesting high Q^2 regime at CEBAF. Initial measurements would be in parallel kinematics so as to eliminate the contributions from the interference response functions R_{LT} and R_{TT} . The remaining longitudinal and transverse response functions can then be separated by the standard Rosenbluth technique. The reaction will also be studied in the continuum region where the dominant process is the electroexcitation of correlated nucleon pairs. Typical kinematic conditions for separations at zero recoil momentum are shown in tables 2.1 and 2.2 (measurements are also planned at recoil momenta of ± 300 MeV/c). The full beam energy of 4 GeV is employed at the forward angles to 1) provide as large a longitudinal polarization (ϵ) as possible and 2) to maximize the count rate.

Q^2 (GeV/c) ²	E_0 (GeV)	E_f (GeV)	$ \vec{q} $ (GeV)	ω (GeV)	θ_e (deg.)	$\theta_q = \theta_p$ (deg.)	ϵ
0.81	4.00	3.56	1.0	0.44	13.7	57.4	0.97
2.37	4.00	2.72	2.0	1.28	27.0	38.2	0.84
4.11	4.00	1.79	3.0	2.21	44.5	24.7	0.58

Table 2.1 Kinematics for the forward electron angle part of a L/T separation on the few-body systems at three Q^2 values.

Additional tests of nuclear wavefunctions and currents are possible when the polarization degrees of freedom are studied. These observables, being generated by interference effects, are particularly sensitive to small amplitudes such as those resulting from nucleon isobar components in the nuclear wavefunction. Their determination will require both a

Q^2 (GeV/c) ²	E_0 (GeV)	E_f (GeV)	$ \vec{q} $ (GeV)	ω (GeV)	θ_e (deg.)	$\theta_q = \theta_p$ (deg.)	ϵ
0.81	0.84	0.40	1.0	0.44	101.8	23.1	0.21
2.37	1.71	0.43	2.0	1.28	126.8	10.0	0.07
4.11	2.77	0.55	3.0	2.21	110.0	10.0	0.10

Table 2.2 Kinematics for the backward electron angle part of a L/T separation on the few-body systems at three Q^2 values.

polarized electron beam and a focal plane polarimeter for protons. Measurements of the $(\vec{e}, e' \vec{p})$ reaction are planned on the deuteron where detailed *non-relativistic* calculations exist by Fabian and Arenhövel.^[11] They have found that meson exchange currents (MEC) and Δ isobar configurations (IC) can have large (50–100%) effects on response functions that are in-plane accessible with a polarized beam and a focal plane polarimeter. Effects of this size are also present in the out-of-plane transverse-transverse interference response function. Note that these effects are at the few percent level in the usual longitudinal and transverse responses. Figure 2.3 displays the three components of the proton polarization vector, two of which require a polarized electron beam for their determination. In parallel kinematics, the transverse, longitudinal and normal polarizations correspond to the R_{LT}^t, R_{TT}^l and R_{LT}^n response functions respectively. The polarization observables are shown as a function of the opening angle between the ejected proton and the three-momentum transfer in the two-nucleon center of mass system. Calculations are shown for the plane wave born approximation (PWBA), with final state interactions (FSI), and including meson exchange currents (MEC) and isobar currents (IC) along with the FSI. There is significant sensitivity to the non-nucleonic components of the reaction mechanism. Note that at large values of θ_{pn}^{cm} , the relative neutron-proton momentum can be a significant fraction of the nucleon mass, making the applicability of a non-relativistic treatment questionable. Therefore, relativistic calculations are highly desirable and are currently underway by Gross and Van Orden.^[12] A proposal^[9] has been submitted to measure the recoil proton polarizations in $d(\vec{e}, e' \vec{p})$ over a broad range of kinematics. These are given in table 2.3; note that the outgoing proton energy varies from 125 MeV to 1.7 GeV, providing a rigorous test of the description of the two-nucleon scattering state as well as the deuteron structure itself.

2.1.1.3 High-Momentum Components and Short-Range Correlations

A topic of particular interest in nuclear physics is the high momentum structure of nuclei. We know that whatever high momentum components exist arise from short-range aspects of the nucleon-nucleon interaction. These components are conspicuously absent in mean field wavefunctions based on potential models. Indeed, in one of the few cases where high recoil momenta have been probed, deuteron $(e, e' p)$ ^[13] at 500 MeV/c, significant contributions from non-nucleonic degrees of freedom (meson exchange currents and isobar configurations) are required to adequately describe the data. However, proton momentum distributions for single-particle and continuum states in light nuclei are only known for

Figure 2.3 Polarization observables for $d(\bar{e}, e' \bar{p})$ as calculated by Arenhövel for an incident electron energy of 899 MeV and electron scattering angle of 60° . The transverse, longitudinal and normal polarizations correspond, in parallel kinematics, to the R_{LT}^t , R_{TT}^l and R_{LT}^n response functions respectively.

Kin	E_0 GeV	$\vec{q}$ GeV/c	E_{np}^{cm} MeV	ω MeV	T_p MeV	θ_e deg	θ_p deg
1	1.600	0.5	62	127.1	124.9	18.12	-66.40
2	4.000	1.0	206	435.2	433.0	13.69	-57.55
3	4.000	1.5	378	833.2	831.0	20.19	-46.75
4	4.000	2.0	554	1273.1	1270.9	27.01	-38.26
5	4.000	2.5	727	1734.2	1732.0	34.80	-31.15

Table 2.3 Kinematics for a proposed $d(\bar{e}, e' \bar{p})$ experiment.

initial momenta $\vec{k} < 300$ MeV/c. Knowledge of the distributions out to much higher initial (+ = - recoil) momenta will provide stringent constraints on nuclear structure models and yield quantitative information on the part of the wavefunction not described by the

mean field. Furthermore, one hopes to test whether our conventional nucleon-meson framework continues to provide an adequate description when the relevant distance scale becomes considerably less than the nucleon radius.

One expects a definite relationship between high-momentum components and continuum strength; as indicated, for example, by the calculations of Ciofi degli Atti *et al.* [14] displayed in figure 2.4. The nucleon momentum distribution,

$$n(\vec{k}, E_{max}) = \int_0^{E_{max}} S(\vec{k}, E_m) dE_m, \quad (4)$$

in ^3He is shown for $E_{max} = \infty$ (the full distribution), 300, 50 and 12 MeV by the solid, dotted, dot-dashed and short-dashed curves respectively. The contribution from the two-body $p+d$ breakup channel is shown as the long-dashed curve. One sees that 1) the high-momentum strength is completely dominated by the correlations and 2) that the strength is spread over a large continuum in missing energy.

Figure 2.4 The proton momentum distribution in ^3He . The long-dashed curve (a) is the contribution of the two-body $p+d$ breakup channel while the short-dashed (b), dot-dashed (c) and dotted (d) curves result from integrating the continuum strength up to 12, 50 and 300 MeV respectively. The full $n(\vec{k})$, obtained by integrating over all separation energies, is indicated by the solid curve (e).

Recently, this relationship between high-momentum components and continuum strength has been observed in measurements of $^3\text{He}(e,e'p)$ and $^4\text{He}(e,e'p)$ at Saclay. [15] Their results on the momentum distributions for the two- and many-body breakup channels, along with the associated missing energy spectra are displayed in figure 2.5. The kinematics are beyond the quasielastic peak, in the dip region. At low E_m the narrow peak resulting from $1s_{1/2}$ proton knockout is present but the spectra are dominated by the broad peak populating the continuum out to $E_m > 100$ MeV. The broad structure observed in both nuclei has the kinematic signature expected for interaction with a two-nucleon pair; it moves to higher E_m as the initial momentum is increased. The arrows in the figure indicate the position expected from disintegration of a pair at rest. The width then reflects

Figure 2.5 Top: The experimental proton momentum distribution in ^3He (left) and ^4He (right) from Saclay.^[15] For ^3He , the 2- and 3-body breakup channels are shown separately. Note the dominance of the many-body breakup channels at large momenta. Bottom: The missing energy spectra obtained in the $^3,^4\text{He}(e,e'p)$ reactions. The many-body breakup modes are responsible for the continuum of missing energies.

the center-of-mass motion of the pair. One sees that the high $|\vec{k}|$ strength is indeed spread over a large continuum in missing energy and resides mostly in the many-body breakup channels. Of course, these data were, by necessity, obtained at a quite modest Q^2 and no separation into longitudinal and transverse components was possible. At CEBAF, it is proposed to vastly extend the range of these studies:^[9] Separation of three of the four unpolarized structure functions at $Q^2=1.0 (\text{GeV}/c)^2$ for recoil momenta up to $1 \text{ GeV}/c$. These measurements would be made on both ^3He and ^4He .

The basic relation between high momenta and large separation energies, resulting es-

Figure 2.6 Nucleon momentum distributions for nuclei from the deuteron to nuclear matter. For ^{16}O , the mean field theory result is shown along with a correlated distribution.

essentially from the interaction with a correlated nucleon pair, is expected to hold in heavier nuclei as well. Therefore, another initial goal of the Hall A program is to establish the high-momentum content of ^{16}O , both in the single-particle states and in the continuum.^[16] The initial measurements will be done at a four-momentum transfer of $0.58 (\text{GeV}/c)^2$ which, while fairly modest, is still significantly larger than can be achieved at present-day facilities. We note that conventional single-particle wavefunctions have little strength for $|\vec{k}| > 500 \text{ MeV}/c$ so a first measurement needs to be made simply to characterize the single-particle strength at these high momenta. It would be surprising indeed if the simple Woods-Saxon potential produced a correct description of the short-range structure of these wavefunctions.

The high-momentum content of complex nuclei is found to be dominated by two-nucleon correlations both in sophisticated microscopic (Brueckner-Hartree-Fock)^[17] treatments as well as in more phenomenological approaches.^[18] Figure 2.6 shows the nucleon momentum distribution for the few-body systems, ^{16}O and nuclear matter from Ciofi degli Atti.^[19] For ^{16}O both correlated and mean-field results are displayed. One sees that the correlated distributions completely dominate above $400 \text{ MeV}/c$ and that the similarity of all the correlated distributions derives from the underlying two-nucleon interaction. Clearly, experimental determination of the $(e,e'p)$ cross section for large internal momenta should provide detailed information on short-range nucleon-nucleon correlations.

The single-particle states, the $1p_{3/2}$ and $1p_{1/2}$, are of particular interest as they are spin-orbit partners and the nuclear spin-orbit force remains to be fully understood on a microscopic basis. This force certainly has its origins in the $\vec{L} \cdot \vec{S}$ part of the NN interaction. This in turn results, in boson exchange models, from ρ and σ exchange. Eventually, one would make large variations in Q^2 and this variation, along with separation of individual structure functions, should shed light on the contributions to the spin-orbit force. More generally, the structure of these single-particle states, probed at high Q^2 and initial momenta, will provide an exceptionally stringent test of any nuclear mean-field theory.

As discussed above, much of the high momentum strength is expected to lie in the continuum of the $A-1$ system and will therefore require exploration of a large range (~ 300 MeV) of missing energy for its determination. It should also be noted that for $^{12}\text{C}(e,e'p)$ data in the dip region^[20] there is a strong indication that reaction mechanisms involving only two nucleons, either as initial-state correlations or final-state scatterings, are inadequate to account for the observed yield in complex nuclei.^[21] The origin of the deep continuum strength in $(e,e'p)$ is presently unknown. However, since some processes, such as meson exchange currents, primarily affect the transverse response functions, our ability to characterize different components of the reaction process is greatly enhanced when we are able to separate response functions from the cross sections.

2.1.1.4 Nuclear Structure with the $(e,e'p)$ Reaction

The traditional use of the $(e,e'p)$ reaction is for nuclear structure studies performed under quasielastic kinematics. Here, the reaction is, in large part, due to incoherent scatterings from individual nucleons whose removal leaves the residual $A-1$ system in its ground (or a discrete excited) state. In the simplest version of this, the impulse approximation, the (unpolarized) $(e,e'p)$ cross section factors into an elementary (e,p) cross section, σ_{ep} , times a quantity depending only on nuclear structure:

$$\frac{d^4\sigma}{d\Omega_e d\Omega_p de' dE'} = K \sigma_{ep} S(\vec{k}, E_m) \quad , \quad (5)$$

where K is a kinematic factor and $S(\vec{k}, E_m)$, the nuclear spectral function, is the joint probability of finding a proton of momentum $\vec{k}$ within the nucleus and leaving the residual system excited by energy $E_m - E_m^0$ where E_m^0 is the separation energy of the least bound proton. In the Independent Particle Shell Model, $S(\vec{k}, E_m)$ takes a particularly revealing form:

$$S(\vec{k}, E_m) = \sum_{\alpha} |\phi_{\alpha}(\vec{k})|^2 \delta(E_m - E_{\alpha}) \quad , \quad (6)$$

where ϕ_{α} is the single-particle wave function of the bound state with quantum numbers $\alpha = \{n, \ell, j, \dots\}$ and E_{α} is its separation ($= -\text{binding}$) energy.

The early $(e,e'p)$ studies demonstrated the basic validity of the shell model, determined the energy distribution of low-lying single-particle states and mapped out the nucleon momentum distributions (single particle densities) of these states for internal momenta up to about 300 MeV/c.^[26] A significant advance in the use of $(e,e'p)$ for nuclear structure studies occurred with the development of the high-resolution $(e,e'p)$ facility at NIKHEF. They routinely achieve missing energy (E_m) resolutions of 200 keV. A beautiful example of the power of high-resolution in $(e,e'p)$ is shown in figure 2.7 for the $^{208}\text{Pb}(e,e'p)$ reaction^[22] where the several states in the region 0–3 MeV are revealed. The central issues with respect to mean field theories are: 1) the momentum distribution of these hole states 2) the fragmentation in excitation energy of single-particle strength and 3) the occupation of the single-particle orbits in the nuclear ground state. Orbits near the Fermi surface are expected to be depleted by ground state correlations;^[23] this phenomena is shown in figure 2.7 for ^{208}Pb where a definite binding energy dependence is observed.

Beam energy limitations at NIKHEF, however, prevent the structure of any of these discrete states to be studied for internal momenta much above 200 MeV/c. Although

Figure 2.7 Left: Missing energy spectrum for $^{208}\text{Pb}(e,e'p)$ obtained at NIKHEF. Right: Spectroscopic factor for different orbitals plotted as a function of distance from the Fermi surface.

the electron accelerators at MIT-Bates and Saclay can reach significantly higher energies (800–1000 MeV), their instruments have 5–10 times lower resolution, making the observation of weak discrete states difficult or impossible. The combination of high energy and high resolution at CEBAF will allow nuclear structure studies of unprecedented scope and quality.

In particular, the Collaboration intends to measure $^{208}\text{Pb}(e,e'p)$ for recoil momenta from 250–450 MeV/c.^[24] Longitudinal/transverse separations will be performed to help isolate nuclear structure information from reaction mechanism effects. A range of outgoing proton energies will be employed to constrain uncertainties in the treatment of final state interactions. The relatively large momentum acceptance of the Hall A spectrometers allows a missing energy ‘bite’ of 100 MeV to be sampled, permitting an angular-momentum decomposition to be performed as a function of missing energy. This allows us to study the energy distribution of spectroscopic strength for each ℓ value.

2.1.1.5 Nucleon-Nucleus Dynamics in Complex Nuclei

Experiments with many-nucleon nuclei have also raised many interesting questions concerning the dynamics of nuclear reactions. Quasielastic electron scattering experiments for both inclusive (e,e') and exclusive $(e,e'p)$ reactions have found several features which are difficult to account for in the context of traditional models of these reactions. For (e,e') ^[25] the longitudinal response has been found to be suppressed by as much as 50 percent in overall size and integrated strength relative to simple calculations. In addition, the size of the transverse response in the “dip” between the quasielastic and Δ -resonance peaks has not been reproduced in parameter free calculations. For $(e,e'p)$,^{[26] [27]} attempts to determine spectroscopic factors for simple situations where the state of the residual system can be modeled as a single hole in the original target nucleus have yielded values which are small compared to those expected from other reactions and to theoretical

predictions. Attempts to describe the cross section over a range of values for various kinematical variables within the context of the distorted wave impulse approximation have not been successful. Ratios of longitudinal to transverse response have also been difficult to model.^[28] Finally, a large amount of strength has been found at high missing energies^[20] which also defy explanation within simple models.^[21] The challenge, then, is to find observables which can distinguish among these dynamical models. One alternative is to examine the $(\vec{e}, e' \vec{p})$ reaction as a means of discriminating among the various models of quasielastic electron scattering.

In order to study the possible sensitivity of the $(\vec{e}, e' \vec{p})$ reaction to details of the reaction dynamics in many-body nuclei, a representative example is presented here. In this case, the cross section and polarizations are given for the knock out of a 500 MeV proton from the $1p_{1/2}$ shell of ^{16}O , the measurement of which has been proposed by Glashauser *et al.*^[29] The objective is to look for possible signatures of relativistic dynamics within the context of the distorted wave impulse approximation (DWIA). The new dynamical content of Dirac models is the presence of virtual negative energy solutions to the Dirac equation in the nuclear wave functions. The optical potentials^[30] are calculated in the impulse approximation, which is a good approximation at the proton energy used here.

Considering the restricted case of in-plane experiments, the unpolarized cross section contains contributions from R_L , R_T , R_{TT} and R_{LT} . The normal component of the polarization contains contributions from R_L^n , R_T^n , R_{TT}^n and R_{LT}^n ; the longitudinal from R_{LT}^l and R_{TT}^l ; and the transverse from R_{LT}^t and R_{TT}^t . In figure 2.8, the cross section and the three components of the polarization vector are shown as a function of $|\vec{p}_r|$ for the ejection of a 500 MeV proton from the $1p_{1/2}$ shell of ^{16}O in constant-q kinematics.^[31] The various line types correspond to: Dirac DWIA (solid line), nonrelativistic DWIA (dashed line), Dirac PWIA (dot-dashed line) and nonrelativistic PWIA (dotted line). The semilog plots of the cross section show that the DWIA calculations exhibit a qualitative variation in shape from the PWIA at recoil momenta above the peak in the cross section. This is not the case for the same calculations in parallel kinematics. Π^n , which again vanishes in PWIA, is on the order of 50 percent over most of the recoil momentum range and shows large differences between the two DWIA calculations for recoil momenta above $p_r = 250$ MeV/c. Both Π_l and Π_t also show considerable sensitivity to the choice of calculation for the larger recoil momenta. Due to the larger size of Π_n and the greater sensitivity to choice of calculation, it appears that the constant-q kinematics provides a promising means of discriminating among the various dynamical models of quasielastic electron scattering. The proposed measurement will determine all three components of the proton polarization vector over the recoil momentum range 50–300 MeV/c.

2.1.1.6 Hadronization

The first evidence for the existence of point-like constituents (partons) in nucleons was obtained in the late 1960's via deep inelastic electron-nucleon scattering.^[1] The observed energy and angular distributions of the inelastically scattered electrons were consistent with the assumption that each electron scatters from a charged parton that is essentially free. What happened to the struck parton after the collision was not an important factor in reaching this conclusion.

However, studying the properties of the hadronic system produced following the deep

Figure 2.8 Cross section and polarization vector for the ejection of a 500 MeV proton from the $1p_{1/2}$ shell of ^{16}O in constant- q in-plane kinematics. The incident electron energy is 2 GeV. Calculations^[31] are shown for Dirac DWIA (solid line), nonrelativistic DWIA (dashed line), Dirac PWIA (dot-dashed line) and nonrelativistic PWIA (dotted line).

inelastic scattering (the so-called hadronization process) is of great interest for the following reasons. The production of hadrons can give information on the mechanisms by which the nucleon's partons rearrange themselves into the observed hadrons after the primary scattering. These mechanisms must be related to the forces that bind partons into the original nucleon, and may give clues to the confinement mechanism.

Recently nuclear medium effects on the nucleon structure function have been demonstrated (the EMC effect);^[32] i.e., the structure function of a nucleon embedded in a nucleus is different from that of a free nucleon. One important question to ask is how does the nuclear medium affect the hadronization process. The use of nuclear targets is interesting because the kinematics of the reaction can be set up so that the distance over which the fragmentation takes place (the hadronization length) can be made to be comparable to the nuclear size. The information on this subject is rather limited. With CEBAF's high duty factor electron beam, it would be possible to study exclusive hadron production on nuclear targets. An eventual goal is to perform a longitudinal-transverse separation of the hadronization process. Calculations with the Lund model Monte-Carlo code^[33] indicate that characteristic features of hadronization, i.e. jet production, similar to those observed at high energies are present even at CEBAF energies.

2.1.2 (e,e'2N) Reactions

Experiments where two nucleons are detected in coincidence are capable of providing the

long-sought-after direct measurement of the two-nucleon correlation function and consequent determination of the high-momentum content of the nuclear wave function. The short distance (high internal momentum) structure of nuclei is expected to be dominated by short-range two-body correlations that result from violent NN collisions. At these momenta, corresponding to distances <0.5 fm., effects from heavier meson exchanges ($\rho, \omega \dots$) and the internal structure of the nucleon itself should be important. The possibility exists that one or both nucleons involved in such short-range collisions could be excited to the Δ resonance, producing $N\Delta$ and $\Delta\Delta$ components in nuclear wave functions. More speculatively, the concept of individual nucleons may even break down for internucleon distances smaller than the nucleon radius so that quark degrees of freedom become appropriate, with two interacting nucleons being replaced by a six-quark (6q) bag. For these reasons, studies of the $(e,e'2N)$ reaction are expected to be an important part of the Hall A physics program.

The combination of low (<1 GeV) energies and 1% duty factors at existing electron accelerators makes the $(e,e'2N)$ reaction exceedingly difficult to study. Triple coincidence rates are simply too low and the accidentals rates too high. At CEBAF, the higher beam energy, 100% duty factor and the ability to reach small forward angles will allow, for the first time, systematic studies of the $(e,e'2N)$ reaction. The Collaboration plans to pursue two types of $(e,e'2N)$ studies in Hall A. The first is true triple coincidence experiments involving the two Hall A spectrometers augmented with another instrument such as a neutron detector or non-magnetic proton detector. The second type of $(e,e'2N)$ measurements will be of the $(e,e'd)$ reaction (a special case of $(e,e'pn)$). The few-body systems have been selected by the Collaboration for our initial explorations. Measurements are planned for $(e,e'd)$, $(e,e'pp)$ and $(e,e'pn)$ on both ^3He and ^4He [34].

Existing data on $^3\text{He}(e,e'd)$ and $^4\text{He}(e,e'^3\text{H})$ at NIKHEF [35] have already shown the importance of coupling of the virtual photon to correlated proton-neutron pairs and three nucleon clusters respectively. A calculation [36] that ignored the coupling to n-p pairs in ^3He underestimated the low-initial-momentum data by a factor of 50. On the other hand, allowing absorption of the photon on both $T=0$ and $T=1$ pairs that emerge as deuterons produced much better agreement with the data. A similar result, i.e. that coupling to correlated clusters is required, was also found for ^4He .

There is even some indication from other NIKHEF $(e,e'd)$ studies that the nuclear medium affects the pair wavefunction. [37] This is inferred from the momentum transfer dependence of this reaction on ^4He and ^6Li . In Lithium, with its α -d structure, one would not expect the rather loosely bound "deuteron" to be significantly different than in free space. On the other hand, p-n pairs in the tightly bound ^4He nucleus could have a considerably smaller spatial extent. This indeed seems to be the case as figure 2.9 shows. We see that the $(e,e'd)$ cross section in ^4He falls off in momentum transfer much more slowly than does the free deuteron while $^6\text{Li}(e,e'd)$ behaves essentially the same as the free deuteron. These $(e,e'd)$ studies will be extended to the much higher Q^2 of $1.5 (\text{GeV}/c)^2$, and for a large range of recoil momenta, 0–300 MeV/c, at CEBAF on ^3He and ^4He targets.

In complex nuclei, this high resolution available in the $(e,e'd)$ reaction allows specific final states of the residual system to be resolved and, therefore, the quantum numbers of the initial state p-n pair to be controlled. This feature has already been exploited at NIKHEF in the $^{12}\text{C}(e,e'd)$ reaction. [38] Figure 2.10 shows the missing energy spectrum from that measurement along with Rosenbluth plots (longitudinal/transverse separations) for the three states at 0.0, 0.72 and 1.74 MeV. The first two states have $T=0$ while the

Figure 2.9 The momentum transfer dependence of the ${}^4\text{He}(e,e'd){}^2\text{H}$ and ${}^6\text{Li}(e,e'd){}^4\text{He}_{\text{g.s.}}$ reactions measured at NIKHEF.^[41]

third has $T=1$; note that the cross section for exciting the $T=1$ state is, unlike that for the $T=0$ ones, completely transverse. Since the detected deuteron has $T=0$, a likely interpretation is that they are observing the inverse of deuteron electrodisintegration, namely a transition from a 1S_0 to a 3S_1 p-n pair. This unique result indicates the tremendous, but largely untapped, potential of *high-resolution* $(e,e'd)$ experiments which use the nucleus as a spin-isospin filter. The Hall A apparatus will allow such experiments to be performed over a wide kinematic range so that, for example, the spatial structure of the correlated pairs can be determined with high precision to rather small distances.

2.1.3 Coincidence Reactions with Pions

A class of measurements involving charged pions is being planned for Hall A. This program stresses the quantum hadrodynamics (QHD) description of nuclear structure and reactions in terms of baryons and mesons. However, in the high four-momentum transfer sector one crosses the boundary into the quantum chromodynamic (QCD) region where quarks and gluons are the appropriate degrees of freedom with which to describe the basic processes.

2.1.3.1 Nuclear Spectroscopy with Pions

The reaction $A(e,e'\pi^\pm)A^*$ is a powerful tool for populating discrete states in A^* isobars ($Z\mp 1, N\pm 1$) of the target nucleus. In real photon reactions the quantum numbers (J^π, T) of the A and A^* nuclei select different aspects of the fundamental $\gamma N\pi$ coupling, e.g. resonance versus Born. The single-particle or collective nature of the A^* state determines the three-momentum transfer response. The pion optical potential modulates the detected

Figure 2.10 Missing energy spectrum for the $^{12}\text{C}(e,e'd)$ reaction (top) and results of a Rosenbluth separation for the first three states. Note that the $T=1$ state is purely transverse.

pion flux. These three aspects of the $A(\gamma, \pi)$ reaction are augmented in $A(e,e'\pi)A^*$ experiments by: the addition of longitudinal coupling, the higher missing three-momentum (p_m) available with virtual photons, and the higher missing-energy (E_m) resolution available using the two magnetic spectrometers in Hall A. Moving E_m into the region of the giant multipole resonances will open up a new area of nuclear spectroscopy.

2.1.3.2 Nucleon Resonances In Nuclei

The nuclear medium can modify the production, propagation, and decay of nucleon resonances. The effects on the $\Delta(1232)$ resonance have already been seen in inclusive electron scattering. Studying the exclusive coincidence cross section $A(e,e' N^*)$ will provide much greater insight into the reaction mechanisms responsible for the medium modifications. Only coincidence reactions, which can isolate the resonances by their angular decay patterns and invariant mass behavior, will be able to identify them above a background of nonresonant processes.

To make a kinematically complete measurement of $A(e, e' N^*)$ one ultimately will need a third spectrometer in Hall A to detect the pion or nucleon from $N^* \rightarrow N\pi$ decay. This third spectrometer could be a scintillator to detect protons, neutrons, or charged pions. The energy-momentum resolution of this detector need only be good enough to restrict the N^* invariant mass (W_{N^*}) to the range of interest

$$W_{N^*}^2 = (E_N + E_\pi)^2 - (\vec{p}_N + \vec{p}_\pi)^2 \quad , \quad (7)$$

and to specify the missing energy to within one major shell in the residual nucleus.

The physics issues to be addressed in these measurements are the A dependence of the reaction as it affects: the resonance yield, the longitudinal to transverse production ratio, the change in shape (width) and position of the resonance, its form factor, and the amount of energy left behind in the $A-1$ nucleus. Those aspects of free nucleon resonance electroproduction and subsequent decay that depend on the polarization of the incident electron can also be studied in nuclei via the $A(\vec{e}, e' N\pi)$ reaction. Quenching of polarization asymmetries are a signature of a coupling of the spin of the resonance to spin degrees of freedom of the nuclear medium. The longitudinal coupling of virtual photons can be used to uncover pre-existing isobar components in the nuclear ground state. For example, the $\Delta\Delta$ and N^* components in the deuteron can be measured in a $D(e, e' p\pi^-)p$ experiment.

2.1.3.3 Constituent Pions

Bound nucleons exchanging pions with their neighbors create a population of virtual pions inside the nucleus. The number of pions (in excess of those associated with free nucleons) is a theoretically calculable and an experimentally measurable quantity. Recent calculations of the pion density give one exchange pion present at any time for every eight nucleons. This pion excess can account for part of the EMC effect^[39] and some authors^[40] ascribe the suppression of the Coulomb Sum Rule in quasielastic scattering to the same cause, namely an enhancement of the nuclear pion field. Experimental determination of the pion number in nuclei is thus seen to be of fundamental importance for understanding both the EMC effect and the so-called "missing charge" problem.

The spectral function (per nucleon) of pions in nuclei is given by:

$$S_\pi(\vec{p}, E) = \frac{1}{A} \langle \Psi | a_\pi^\dagger a_\pi | \Psi \rangle \quad , \quad (8)$$

where Ψ is the nuclear ground state and $a_\pi^\dagger a_\pi$ is the number operator for a pion of momentum $\vec{p}$ and total energy E . The density due to exchange pions is obtained by subtracting the contribution of the pion cloud around a free nucleon ψ :

$$\rho_\pi(\vec{p}, E) = S_\pi(\vec{p}, E) - \langle \psi | a_\pi^\dagger a_\pi | \psi \rangle \quad . \quad (9)$$

The total number of exchange (or constituent nuclear pions) is:

$$N_\pi = \int \rho_\pi(\vec{p}, E) d^3p dE \quad . \quad (10)$$

Theoretical predictions have been made using the following, rather different, techniques:

- (1) a Hamiltonian for the πNN and $\pi N\Delta$ interaction in a variational calculation for ρ_π ,^[41]

- (2) a pion-nucleus optical potential to give S_π ,^[42]
- (3) a direct calculation of ρ_π from the one-pion exchange potential.^[42]

It is encouraging that all three approaches agree in their predictions. Figure 2.11 shows the pion spectral function while table 2.4 gives the number of excess pions per nucleon for a range of nuclear targets. The experimental approach proposed^[43] for determining $S_\pi(\vec{p}, E)$ is to choose the kinematics such that a knocked-out pion is detected near the direction of three-momentum transfer with a momentum and energy close to that transferred by the scattered electron. The energy transfer is chosen to be above the nucleon resonance region ($\omega=2$ GeV) to minimize the creation of pions from nucleons and at low four-momentum transfer ($Q^2=0.55$ (GeV/c)²) to avoid suppression of the $(e, e'\pi)$ cross section due to the pion form factor. One would vary the ratio of longitudinal to transverse virtual photon flux, ϵ , in order to make a Rosenbluth separation of the coincidence cross section. The knockout of constituent pions occurs mainly through the coupling of the virtual photon to the charge of the pions (the pole term) which is a longitudinal process whereas pion production from the nucleon is mainly a transverse process. Of course, corrections to this simple scheme will have to be made to account for pion-nucleus interactions in the final state. However, Glauber multiple scattering theory is reliable for computing this effect for 2 GeV pions.

Figure 2.11 The pion spectral function $(|\vec{p}|^2/2\pi^2 A) \int \rho_\pi(\vec{p}, E) dE$ from ref. [44] showing the momentum distribution of constituent pions for several nuclei.

2.1.4 Inclusive Experiments

2.1.4.1 Quasielastic Scattering

In the last two decades, inclusive electron scattering has significantly improved our understanding of nuclear systems but also has revealed several deficiencies in that understanding. A large effort has been devoted to performing longitudinal/transverse separations of the response functions in nuclei for different regions of excitation energy: the quasielastic peak, the Δ (1232) region, and the deep inelastic region. Important unresolved issues and

A	N_π
2	0.024
4	0.09
27	0.11
56	0.12
208	0.14

Table 2.4 Number of constituent pions per nucleon versus atomic weight.^[44]

questions include: What is responsible for the suppression of the longitudinal response function, and the corresponding Coulomb Sum Rule, by $\sim 50\%$ in complex nuclei? What is the source of the excess transverse strength in the quasielastic and dip regions? How important are many-body effects such as multiparticle-multihole correlations? Are the nucleon form factors modified in the nuclear medium? What are the characteristics of Δ resonance excitation and propagation in nuclei? With the advent of CEBAF, there is great interest in a new generation of *high precision* inclusive (e,e') experiments for addressing these questions. These experiments are impossible to perform at the existing electron facilities and will also be impossible at the upgraded version of these same facilities primarily because of their limited beam energies (≤ 1 GeV).

Recall that, assuming only one-photon exchange, the differential cross section in the laboratory frame can be written as follows:

$$\frac{d\sigma}{d\Omega d\omega} = \Gamma_v \left[\sigma_T(Q^2, \omega) + \epsilon \sigma_L(Q^2, \omega) \right] ,$$

where

$$\Gamma_v = \frac{\alpha}{4\pi^2} \frac{K}{Q^2} \frac{e'}{e} \left(\frac{2}{1 - \epsilon} \right) , \quad (11)$$

is the flux of virtual photons and

$$\epsilon = \left[1 + 2 \left(1 + \frac{\omega^2}{Q^2} \right) \tan^2 \frac{\theta}{2} \right]^{-1} ,$$

is their polarization. Measurements at two different angles, keeping (Q^2, ω) constant, allow one to extract σ_T and σ_L .

The great advantage that CEBAF and Hall A offer for response function separations is simply that the combination of a 4 GeV beam, the ability to reach small forward electron angles and the precise kinematic definition provided by the high resolution spectrometers allows a large lever arm $\Delta\epsilon$ and small systematic errors. The Collaboration therefore intends to pursue a systematic study of the quasielastic response in selected systems throughout the periodic table: ^2H , ^3He , ^4He , ^{12}C , ^{27}Al , ^{40}Ca , ^{56}Fe and ^{208}Pb . Measurements would be made at four electron scattering angles (15, 40, 90 and 140°) to minimize systematic effects and determine corrections to the Born approximation from Coulomb distortion effects in heavy nuclei. Momentum transfers from 0.3 to 1.5 (GeV/c)² will be measured. This overlaps with existing data (although we will obtain much more precise

results) and then extends the momentum transfer by about a factor of three.

2.1.4.2 $A=2,3,4$ Form Factors

For many years, the few-body systems ($A=2,3,4$) have played a special role in our understanding of the structure of nuclei. The elastic form factors of the few-body systems present a particularly fertile testing ground for microscopic nuclear theories because of the possibility of performing exact (non-relativistic) calculations and, potentially, for revealing the role played in nuclei by the quark substructure of the nuclear constituents. Of course, these nuclei have already provided some of the strongest evidence for mesonic currents. However, the role of relativistic effects, quark clusters, and three body forces is not clear. At larger momentum transfers, we cannot expect the nucleon-meson model to describe both the long and the short range interactions; we must understand the transition from the nucleon-meson description to the more fundamental one based on quarks and gluons.

Indeed, the critical challenge for nuclear physics in the CEBAF era will be "the study of the interface and synthesis of traditional nuclear systematics with the short-distance quark and gluon substructure of hadronic interactions and wavefunctions."^[1] To address this physics requires probing these nuclei on the smallest possible distance scale, i.e. at the highest obtainable momentum transfers. The 4 GeV CEBAF beam provides this capability. However, to ensure elastic scattering or, in the case of the deuteron, threshold breakup also requires high resolution in the scattered electron energy, making Hall A the natural location for such measurements.

2.1.4.3 Electrodisintegration of the Deuteron at Threshold

Deuteron electrodisintegration at threshold $d(e,e')np$ has been of great historical importance in that it provided some of the most dramatic evidence for mesonic degrees of freedom. The Saclay data,^[44] averaged over 3 MeV of excitation energy, extend to almost $1.2 (\text{GeV}/c)^2$ while the newer SLAC data^[45] reached a Q^2 of $2.8 (\text{GeV}/c)^2$ although the lower resolution at SLAC necessitated averaging over 10 MeV. The Saclay data are displayed in figure 2.12. Calculations including nucleons only, predict a diffraction minimum around $0.5 (\text{GeV}/c)^2$ which results from a destructive interference between the ${}^3S_1-{}^1S_0$ and the ${}^3D_1-{}^1S_0$ amplitudes. Inclusion of MEC are essential for the interpretation of the data as can be seen in figure 2.12. At large momentum transfer they account for almost 100% of the strength. The q -dependence of the MEC provides us with information on their spatial distribution. The role of quarks appears to be negligible in the present set of data.

The extension of these measurements to Q^2 of $3.5 (\text{GeV}/c)^2$ ($= 88 \text{ fm}^{-2}$) is proposed and can be done very early at CEBAF.^[46] A single arm measurement, requiring reasonably modest energy resolution, will take advantage of the intense beam and low backgrounds of the end station (the resolution in E_{np} will always be better than 1.15 MeV). Large solid angles, and long targets must be available with cross sections at the $10^{-40} \text{ cm}^2/\text{sr}$ level. It is hoped that the extension to considerably higher momentum transfer will reveal the role of quark degrees of freedom.

Figure 2.12 Cross section for threshold electrodisintegration of the deuteron. The impulse approximation (nucleons only) result is shown by the dotted curve, the dash-dot curve includes π exchange currents, the dashed curve has ρ meson exchange currents in addition. The solid curve results from π, ρ exchange plus the Δ isobar contribution.

2.1.4.4 The A=3 and A=4 Elastic Form Factors

Elastic scattering from ^3H and ^3He has been separated into the charge and magnetic form factors out to about $1 (\text{GeV}/c)^2$, largely due to the work at Saclay^[47] and MIT-Bates.^[48] Elastic scattering from these systems receives contributions from only two multipoles: the charge monopole in the longitudinal and the magnetic dipole in the transverse form factor. Consequently, an ordinary Rosenbluth separation yields the maximal amount of information. For ^4He , there is only a Coulomb monopole form factor; it has been measured for momentum transfers up to about 50 fm^{-2} at SLAC.^[49]

The A=3 systems are especially important because they unambiguously determine the isoscalar and isovector form factors which makes direct tests of meson exchange models possible. This is the only case in the periodic table of a ground state isospin multiplet. The separated isoscalar and isovector charge and magnetic form factors are shown in figure 2.13. Up to 20 fm^{-2} , the isoscalar form factor is well reproduced by theory, which suggests that we understand the one-body current up to that Q^2 . Beyond this, isoscalar exchange currents may contribute as in the deuteron $B(Q^2)$ structure function, another pure isoscalar transition. The isovector magnetic form factor is dominated by meson exchange currents because the nucleonic component is very small as is in the case of the deuteron electrodisintegration cross section discussed above.

Theory and experimental results for the charge form factor of ^3He have disagreed for years in the region of the second diffraction maximum. Separation of the charge form

Figure 2.13 Top: Isoscalar/isovector separation of the charge form factors in the $A=3$ system. Bottom: Isoscalar/isovector separation for the magnetic form factor. The shaded band is the error envelope of the experimental data.

factor into its isoscalar and isovector pieces have exposed this further. As seen in figure 2.13, neither the isoscalar nor the isovector components are reproduced by the Hannover group calculations^[50] even when two body exchange currents have been added. The isovector charge form factor shows a more serious deviation from the models.

In ${}^4\text{He}$, virtually all existing theories drastically underestimate the height of the second maximum in the charge monopole form factor, even when three body forces are included, as can be seen in figure 2.14. Some calculations predict a third maximum in the vicinity of 50 fm^{-2} but existing data are too sparse to have revealed it. At CEBAF, the form factor measurements of ${}^3\text{He}$ and ${}^4\text{He}$ will be extended to 56 fm^{-2} and 75 fm^{-2} respectively^[51] (because of the extreme difficulty in handling large amounts of ${}^3\text{H}$, no experiments on it are planned, at least initially). A significant extension of our knowledge of these form factors will be provided by CEBAF.

2.2 LONG-RANGE PERSPECTIVES

The two high-resolution spectrometers are the essential elements of the initial complement of equipment in Hall A; they can address a rather broad range of physics programs as described above. There are, however, limitations on what can be achieved with just the basic two spectrometer set-up. In the long term, maximum physics productivity would require that these instruments be augmented by additional capabilities. The foremost of these is a means to perform $(e,e'p)$ experiments where the proton is detected out of the (e,e') plane ("out-of-plane" experiments).

Figure 2.14 The ${}^4\text{He}$ charge form factor. The dotted line is the impulse approximation result and the solid line represents a hybrid meson-nucleon-quark model calculation. ^[52]

Of the eighteen response functions in the $(\vec{\epsilon}, \epsilon' \vec{p})$ cross section, six of them are identically zero in-plane and two others require at least one out-of-plane measurement for their determination. It is therefore essential that an out-of-plane capability exist as an important tool for a complete determination of all the amplitudes which describe the elementary process. The response functions which require this capability for their determination are R_{TT} , R_{TT}^n , R_{LT}^l , R_{LT}^t , R_{TT}^t , R_{TT}^n , R_{LT}^t , R_{LT}^n . Of these, only two (R_{TT} and R_{LT}^l) can be determined without measuring the polarization of the knocked-out hadron. It is also therefore essential that the out-of-plane capability be coherently linked with a proton polarimetry capability.

It has been known for a long time that some of these response functions, since they result from interferences between amplitudes, have exceptionally high sensitivity to small "exotic" components of the reaction mechanism. One example is the transverse-transverse interference response R_{TT} in the deuteron. Figure 2.15 shows the *non-relativistic* calculation of this response by Fabian and Arenhövel^[11]. Note that extra-nucleonic degrees of freedom, meson exchange currents (MEC) and Δ isobar configurations (IC) can have large (50–100%) effects on this response function and also that these effects are at the few percent level in the usual longitudinal and transverse responses.

An out-of-plane capability may be achieved in two ways: either by bending the incoming electron beam so that the (e, e') plane is no longer horizontal or by moving the hadron detector out of the horizontal plane. The advantages and disadvantages of both methods, kinematic coverage etc. have been studied in detail^[53] and either method is capable of providing a suitable solution. The second option may be more likely to be realized since an Italian group led by S. Frullani is designing, and would independently fund, a relatively small, high resolution 1.5 GeV/c spectrometer for Hall A: the Multi-Purpose Spectrometer: MPS. They are investigating the out-of-plane possibilities of this device.

Furthermore, the presence of three high resolution spectrometers in Hall A would al-

Figure 2.15 Calculation^[11] of the R_{TT} response function in deuterium. Short dashed curve: PWBA, long dashed: including FSI, dot-dashed: FSI+MEC, dotted: FSI+IC, solid: FSI+MEC+IC.

low high quality (e,e'pp) measurements. As discussed in conjunction with the NIKHEF (e,e'd) data discussed above, the ability to resolve final states in the A-2 system resulted in a selectivity for the quantum numbers of the initial state p-n pair. Now one could achieve the same selectivity for p-p pairs and study rather different aspects of two-nucleon correlations as charged meson exchanges and Δ isobar contributions are greatly suppressed for p-p pairs relative to p-n pairs.

A third spectrometer with a relatively short flight path also provides new opportunities for studying short-lived hadrons (pions, kaons) in coincidence with electrons. In particular, high-resolution kaon production experiments will usher in a new, and greatly improved, generation of hypernuclear studies.

Hypernuclei are interesting because they add another flavor (strangeness) to the traditional weak, electromagnetic and hadronic probes of the nuclear system. The hyperon, whose additional quantum number distinguishes it from the nucleons, is not Pauli excluded from filled nucleon orbitals, and can penetrate deep inside the nucleus. We can use hypernuclei to explore such problems as the origin of the nuclear spin-orbit force, short range correlations, relativistic aspects of many-body nuclear dynamics and their extension to hypernuclei. The role of flavor symmetry and the chiral limit, extended models of the strong interaction, weak interactions in the nuclear medium, or possible modifications of baryon properties in the nuclear environment may all be investigated with hypernuclei.

High resolution is especially important for such studies; a 100 keV energy resolution would open new horizons here. In addition, the electromagnetic production experiments require a relatively large acceptance spectrometer (because of the small cross sections)

and a short kaon flight path (because of the relatively short K^+ lifetime, 1.2×10^{-8} sec).

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3. PERFORMANCE REQUIREMENTS

In this chapter, we examine the performance requirements for the Hall A experimental equipment, namely the High Resolution Spectrometer pair (HRS2) including their detector systems and the beam monitoring and target systems. These requirements incorporate the needs of the physics proposals submitted to the last Program Advisory Committee (PAC4). Although the proposals do not exhaust the possibilities encompassed by HRS2, they are indicative of the general needs of the physics program currently envisioned for Hall A. Since one would like to have the capability to carry out the complete set of approved experiments, the parameters summarized below reflect the most stringent requirements imposed by the set of proposals. Some of the experiments are less demanding and these could conceivably be performed during the commissioning phases of the equipment.

The requirements will focus mainly on coincidence knock-out reactions, specifically (e,e'p). The large dynamical range, high duty factor and high currents afforded by CEBAF will allow highly precise, systematic studies of coincidence knockout reactions. Since several facilities (Bates, NIKHEF and Mainz) will also have nearly continuous electron beams in the next 2 to 4 years, most of the lower energy coincidence measurements will be performed there. CEBAF is unique in that it can extend the kinematical domain to unexplored regions in Q^2 and W where new physics may be evidenced. Before entering into detailed considerations of specific requirements some general comments can be made:

- The spectrometers should be easily movable over a *wide angular range*. This is especially true for L/T separation measurements where large virtual photon lever arms are required to minimize uncertainties. Large backward angles for the electron give rise to virtual photons in the forward direction and thus also imply the need for a small angle capability for the hadron arm. Further, a small angle capability for the electron arm is required in general to maximize counting rates. The spectrometers must also have a relatively *large dynamic range* (~ 10 or 20 to 1) in order to perform measurements over a broad kinematical domain.
- Since electron scattering cross sections fall rapidly with increasing Q^2 , *large acceptance* devices are necessary in order to maintain reasonable statistics over a large dynamical range.
- Rapid variations in the coincidence cross section imply that the spectrometers must precisely define the kinematics in order to control systematic errors, particularly in separation measurements where errors magnify in extracting the response functions from the measured cross sections. Thus, *good angular and momentum resolution* are essential not only for separating discrete levels but for controlling systematic errors as well. This also implies the need for beam monitors with excellent spatial resolution.

- Since many of the physics proposals deal with the few-body systems the spectrometers must be able to accommodate *extended targets*.
- Some of the proposals call for measurements at very high recoil momenta where trues-to-accidentals ratios tend to be low. In order to perform these measurements good accidentals rejection is required implying the need for *standalone particle identification, good timing, vertex and (for discrete states) missing mass resolution*.
- Longitudinal/transverse (L/T) separation experiments involve measurements at large electron scattering angles where pion backgrounds tend to dominate the electron rates. Thus, *large π^-/e rejection ratios* are required for both single arm measurements and for signal-to-noise limited coincidence measurements. Further, standalone particle identification is required to eliminate correlated backgrounds for coincidence measurements.
- Nearly half of the response functions in (e,e'p) require that the emerging hadrons be detected out of the electron scattering plane for their determination. Thus, this out-of-plane capability is needed to fully exploit the power of coincidence reactions. It is also vital that this capability be coherently linked with a focal plane polarimeter in the hadron arm, since many of the response functions (in-plane as well as out-of-plane) are polarization dependent. *Both out-of-plane and polarization observables are expected to play a major role* in the Hall A physics program because of their typically large sensitivities to ingredients of various reaction models.

The requirements which have been considered as design goals for the Hall A spectrometers are summarized in Table 3.1. Detailed formulation and discussion of these requirements are given in the following sections.

3.1 KINEMATICAL COVERAGE

3.1.1 Maximum momentum capability

One of the most important requirements for a spectrometer is its maximum momentum capability. In particular, L/T separation experiments involve a forward angle measurement which almost always calls for the highest incident energy. In many cases, the scattered electron energy will be very close to the beam energy. In addition, for measurements (with or without separations) at moderately large momentum transfers, one will often use the minimum electron angle coupled with the highest incident energy in order to maximize counting rates. Figure 3.1 summarizes the kinematical requirements of the electron spectrometer as demanded by the physics proposals submitted to PAC4.

Table 3.1

Requirements for Hall A Spectrometers	
Parameter	Requirement*
• Maximum momentum	4 GeV/c
• Momentum acceptance	$\sim 10\%$
• Solid angle vertical/horizontal aspect ratio	~ 10 msr ≥ 2
• Angular range	$\lesssim 10^\circ, 165^\circ$
• Angular position accuracy	~ 0.1 mr
• Angular resolution (scattering plane)	~ 0.25 mr
• Transverse position resolution	~ 1 mm
• Momentum resolution (point target)	$< 10^{-4}$
• Target length acceptance (at 90°)	$\sim \pm 5$ cm
• Momentum resolution (extended target)	$\leq 3 \cdot 10^{-4}$
• Luminosity	$\geq 10^{38} \text{ cm}^{-2}\text{sec}^{-1}$

* Requirements are very similar for electrons and hadrons.

The complete set of proposals require a maximum spectrometer momentum of 4 GeV/c. Further, elastic normalization data require scattered electron momenta very close to the beam energy. Therefore, the electron spectrometer should be capable of accepting the full beam momentum, i.e. the 4 GeV/c design value.

The maximum momentum required for the hadron spectrometer is determined by the highest 3-momentum transfer envisaged, in a kinematics where the residual nuclear system recoils in the direction opposite to that of the virtual photon. Kinematically, this can exceed the beam momentum by a substantial amount, as recoil momenta of ~ 0.5 GeV/c or above can be envisaged, combined with 3-momentum transfers above 4 GeV/c. However, as cross sections fall off rapidly with both Q^2 and p_m , such combinations will be exceptional, the most demanding experiment involving the measurement of the electromagnetic form factors of nucleons far away from the mass shell. Figure 3.2 shows the kinematical ranges of the hadron arm for the complete set of PAC4 proposals. The maximum momentum required is for the proton electric form factor proposal of Perdrisat *et al.* [1] which requires proton momenta up to 3.22 GeV/c corresponding to $Q^2 = 4.53 \text{ GeV}^2/\text{c}^2$. However, with a beam energy of 6.0 GeV this measurement could be extended to $Q^2 = 6.0 \text{ GeV}^2/\text{c}^2$ provided the hadron spectrometer could accommodate a momentum of 4.05 GeV/c. For the hadron arm (as for the electron arm) elastic normalization data will require maximum momenta near the beam energy. Thus, a maximum momentum of 4 GeV/c for the hadron arm is highly desirable.

Figure 3.1 Kinematical requirements (minimum angle, maximum angle and maximum momentum) for the electron arm. Numbers above the arrows refer to proposal numbers. The number of proposals which lie outside the range of the plot is indicated at the left or right of each axis.

3.1.2 Minimum momentum

The minimum momentum appears to be in the range 200 - 300 MeV/c, based also on L/T separations at modest Q^2 values. Nine of the proposals require minimum momenta of 0.4 GeV/c or below for the electron arm. For the hadron arm the minimum momentum is in the range 200 - 500 MeV/c. This means a dynamical range of up to 20 for the field in the spectrometer magnets. At the lowest fields, inhomogeneities in the magnetic properties of the iron will probably deteriorate the $\delta p/p$ resolution, but not necessarily the *relevant* absolute δE resolution.

3.1.3 Angular range

As mentioned above, many experiments require very forward electron angles to maximize counting rates and to maximize the virtual photon polarization lever arm in L/T

Figure 3.2 Kinematical requirements for the hadron arm. The notation is the same as in Figure 3.1.

separation measurements. Further, backward electron angles which maximize the contribution from the transverse response imply small angles for the virtual photon and hence for the hadron spectrometer. For experiments involving separations of the response functions via examination of the proton azimuthal distribution about $\vec{q}$, one may need to detect protons forward of $\vec{q}$, making the small angle capability of the hadron arm even more important. Angular ranges required by the PAC4 proposals are shown in Figures 3.1 and 3.2 for the electron arm and hadron arm respectively. The bulk of the proposed experiments could be carried out with a minimum electron angle of 12.5° . Two proposals to measure correlations in nuclei [2] [3] require smaller angles implying the need for a larger drift space (and smaller solid angle) tuning mode. The minimum angle requirement for the hadron arm is most stringent for the L/T separation measurements on $d(e,e'p)$ [4] and $^3,^4\text{He}(e,e'p)$ [5] as well as nucleon correlation measurements with $^3,^4\text{He}(e,e'2N)$ [2]. In all but one case, a minimum angle of 12.5° is sufficient.

For the maximum angle of the electron arm, 150° is adequate for all cases except the inclusive (e,e') proposals, electrodisintegration of ^2H at threshold [6] and elastic scattering

from $^3,^4\text{He}$ at large momentum transfers^[7], where $\sim 165^\circ$ is required. A maximum angle of 120° for the hadron arm would satisfy all of the experimental proposals except the $^2\text{H}(\gamma, \vec{p})n$ measurement^[8] where 135° is specified.

Summary

- The high resolution spectrometers must be capable of accepting the full beam energy, i.e. the 4 GeV/c design value.
- The angular range for the electron spectrometer should be as large as possible. A $12.5^\circ - 165^\circ$ range should be considered. Alternate tunes with a larger first drift space and somewhat reduced solid angle may be needed for some experiments.
- The hadron spectrometer should also be capable of reaching small forward angles ($\sim 12.5^\circ$). The maximum angle can be limited to $\sim 130^\circ$.

3.2 ANGULAR AND MOMENTUM ACCEPTANCE REQUIREMENTS

As discussed earlier, the 100% duty factor of CEBAF increases dramatically the possibilities for coincidence studies. However, the small size of the cross sections and the goal to fully exploit the power of exclusive experiments with high resolution and high precision devices necessitate angular and momentum acceptances be not smaller than those used at present lower energy electron facilities.

For the electron arm, the momentum acceptance has to be large enough to give a substantial excitation energy acceptance, in particular when measuring the backward angles for L/T separation experiments in the continuum. Typically, $\Delta p/p = 10\%$ would allow $\Delta E_x = 40$ MeV at 400 MeV scattered energy, and has been considered as an acceptable number. The momentum acceptance of the hadron spectrometer is important as well, and should not be smaller.

Solid angles of the order of 10 msr have been considered to get enough counting rates at high Q^2 and/or p_m values. One would like the solid angle of the electron arm to be distributed with a smaller acceptance in the scattering plane, where the cross section varies very rapidly, especially at forward angles. To match the solid angle of the hadron arm to that of the electron arm, two sets of studies were made which are shown schematically in Figure 3.3. For the L/T separation at $\vec{q} = 1$ GeV/c, the acceptance of the hadron arm should be much larger than for the electron arm in the forward direction, and conversely in the backward direction. At $\vec{q} = 3$ GeV/c, the solid angle of the hadron arm needs to be slightly smaller than that for the electron arm in both the forward and

backward directions. Having similar solid angles for the two arms is therefore a reasonable compromise.

Although these rather large acceptances would greatly benefit most of the experimental program, they introduce another degree of complexity, in particular to coincidence experiments. In analogy to traditional Rosenbluth separation techniques for single arm electron scattering, the determination of individual structure functions in $(e,e'p)$ reactions involves comparisons of experimental cross sections taken under different kinematical conditions. The kinematics are selected to keep constant the relevant *physical* variables on which the response functions depend. These variables are not the *experimental* ones (incoming and outgoing particle momenta and angles) upon which the apparatus defines simple limits. The determination and understanding of the phase space acceptances for the physical variables is crucial. It implies in general the use of Monte Carlo techniques as the experimental setup defines complicated boundaries in the new variable space. Several issues have to be addressed:

- 1) The influence of uncertainties in the *central values* of energies and angles – alignment tolerances, absolute calibrations, *etc.*
- 2) Uncertainties in the kinematical reconstruction of *each coincidence event*: trajectory reconstruction within each spectrometer, finite resolution effects, *etc.*
- 3) Finite acceptance and averaging effects.^[9]

The first two issues are made quantitative in a subsequent section; here, we discuss only the last one. Ideally, one would like to perform separations in a model-independent manner. This involves matching the space of physical variables for each of the cross section measurements which comprises the separation. In order to make comparisons to theory, one would then average the calculated response functions over the same restricted acceptances. However, in many cases (especially for L/T separations) a perfect matching requires severe cuts in the physical variable space for the various measurements implying a large reduction in statistics. As a compromise, one might perform crude acceptance cuts which give both a reasonable match and adequate statistics. The remaining difference can be corrected for (in the context of a model) by averaging a theoretical model over the same acceptances. For cases where this correction is large (*i.e.* where the difference between the model evaluated at the central kinematics and the acceptance-averaged value is large) a separation using this technique is meaningless and one must then directly compare the average cross section at each kinematics with a model averaged over the same acceptance.

Summary

- The momentum acceptance of the spectrometers should be relatively large ($\sim 10\%$ is considered acceptable) to accommodate a substantial range of excitation energies.
- Solid angles of $\gtrsim 10$ msr are considered acceptable. The rapid variation of the cross section with angle implies that the vertical-to-horizontal aspect ratio should be large.

Figure 3.3 Matching of angular acceptances in elastic electron-proton scattering. The solid box defines the nominal solid angle (ϕ is vertical and θ is horizontal) for the spectrometer. The two dashed boxes give the resulting solid angle population for $\vec{q}$ for forward and backward electron angles. Note the two figures have different scales.

Upper figure: $\vec{q} = 1$ GeV/c, $\theta_e = 13.6, 99.5^\circ$.

Lower figure: $\vec{q} = 3$ GeV/c, $\theta_e = 44.4, 97.5^\circ$.

3.3 RESOLUTION REQUIREMENTS

As mentioned above, the (e,e'p) program in general requires good resolution in both momentum and angle. The momentum resolution is needed not only for the separation of various levels of the A-1 system but also to control the systematic errors. In addition, good resolution is needed for single arm experiments where one also wishes to separate various levels. For the few-body systems, this also implies good angular resolution since one must correct for differential recoil energy loss within the angular acceptance. Finally, good timing and vertex resolution are required to minimize the contribution from accidental events in coincidence measurements.

3.3.1 Resolution and separation of discrete states

In order to separate closely spaced levels, *good missing mass resolution* is required. In single arm experiments, the missing mass is directly related to the energy transfer ω and thus the scattered electron energy. Therefore, the high resolution is needed only over a limited energy range of ~ 15 MeV, i.e. a small portion of the focal plane. In the case of (e,e'p), in general the entire momentum acceptance of either arm contributes for a given missing mass so that the momentum must be precisely known over the entire focal planes of both spectrometers. Additional contributions to the missing mass resolution come from the energy spread of the beam, straggling within the target material and target windows and, for light systems and/or large recoil momenta, the effect of angle on the energy of the recoiling system. In some cases, vertex resolution will be needed to reduce the contribution from straggling within the target.

For medium mass nuclei (^{12}C and ^{16}O for example) on the order of 200 KeV missing mass resolution or better is desired for beam energies below 2 GeV where most nuclear structure studies can be performed. Resolutions of ~ 100 KeV have been achieved at NIKHEF at lower (≤ 400 MeV) energies. As an overall missing mass resolution of 200 KeV implies a resolution of ~ 100 KeV for, say, the scattered electron energy, it would require a 2.5×10^{-5} spectrometer resolution to achieve it at 4 GeV/c, which seems unreasonable. A practical limit is likely to be around 5×10^{-5} (500 KeV missing mass resolution).

Design studies of CEBAF indicate that the energy spread of the beam is expected to be small with a 4σ width of $\sim 10^{-4}$, which is almost compatible with the above mentioned value. However, in early operations the beam stability may be significantly worse than this and one should therefore be prepared to use dispersion matching techniques or correct for energy changes by measuring the beam energy at a point of high dispersion in the beam line to reduce the energy spread and instabilities in the beam.

As far as separating discrete states, the most stringent requirements on momentum resolution are imposed by the proposal of B. Frois *et al.* [3] This experiment requires a missing mass resolution of ~ 125 KeV in order to separate various low-lying states. A momentum resolution of $\delta p/p \sim 1 \times 10^{-4}$ is needed at the lower energies with somewhat better resolution at higher energies.

Single arm measurements, in general, require precise determination of the electron scattering angle as well as the momentum, especially for light nuclei. In particular, since for a given nuclear excitation energy the spectrometer's angular acceptance gives rise to a range of possible outgoing electron energies, one must be able to correct for recoil if one is to separate closely spaced levels. For elastic scattering the final electron energy, e' , is given in terms of the incident energy, e , and scattering angle, θ , as:

$$e' = \frac{e}{1 + (2e/m_T) \sin^2 \theta/2}$$

where m_T is the target mass. Thus, the effect of recoil may be estimated to first order as:

$$\frac{\partial e'}{\partial \theta} = \frac{-e'^2 \sin \theta}{m_T}.$$

As a worst case estimate, we choose deuterium for the target nucleus. For elastic scattering at $\vec{q}=1$ GeV/c with $\theta = 15^\circ$ and $e = 3.8$ GeV ($e' = 3.6$ GeV) this gives 1.8 MeV/mr. The contribution to the resolution width from the assumed spectrometer momentum resolution is 360 KeV. Thus, with an angular resolution of 1.0 mr the effect of differential recoil dominates. (In fact, for the two effects to be comparable one needs an angular resolution of 0.2 mr.) In order to clearly separate the ground state and continuum in ^2H , 1 MeV resolution would be desirable. Thus, for deuterium a scattering angle resolution of 0.5 mr is required; for heavier nuclei angular resolution is not as critical.

3.3.2 Resolution and systematic uncertainties

Resolution is also required to reduce systematic uncertainties. In particular, separation measurements will put the most stringent demands on the spectrometers since uncertainties in the measured cross sections result in much larger uncertainties in the response functions. If the uncertainty in the forward angle cross section, σ_f , dominates then the fractional error in R_L is approximately

$$\frac{\delta R_L}{R_L} \approx \left[\frac{\epsilon_f + \eta/r}{\Delta \epsilon} \right] \frac{\delta \sigma_f}{\sigma_f}$$

where ϵ_f and ϵ_b are the virtual photon longitudinal polarizations at the forward and backward angles, $\Delta \epsilon = \epsilon_f - \epsilon_b$, $\eta = R_T/R_L$ and $r = 2q_\mu^2/\vec{q}^2$. When $\vec{q}$ is large, η and hence, the error in R_L , become big. To quantify this, the uncertainties in the longitudinal and transverse response functions for $d(e,e'p)n$ are shown in Figure 3.4 assuming *equal* uncertainties (of 1%) in the forward and backward angle cross sections. The kinematics are quasifree with protons emitted along $\vec{q}$. For $\vec{q} = 3$ GeV/c, a 22% uncertainty in R_L results from the assumed errors. Although the dynamic range of CEBAF is somewhat higher, this appears to be the practical limit for most L/T separation measurements.

Because of the large error magnification for the "small" response functions, one would like to limit errors in the individual cross sections to $\sim 1 - 2$ percent in order to allow separation studies over a broad dynamic range. This includes errors from all sources, statistical and systematic. Since there are several sources of systematic error

Relative Error

Figure 3.4 Uncertainties in R_L and R_T for 1% total uncertainty in forward and backward angle cross sections for $d(e,e'p)n$ at quasifree kinematics.

one must restrict the contribution of each to $\lesssim 1\%$. This requirement, coupled with rapidly varying cross sections, implies one must determine the reaction kinematics very accurately. As an example Figure 3.5 shows the fractional change in E_0 which would produce a 1% change in the $d(e,e'p)$ cross section (see the figure caption for details). The errors were calculated using the computer code SIGEEP^[10] which employs a factorized PWIA model for the coincidence cross section. Longitudinal/transverse separations would be performed by making measurements near either end of a given $\vec{q}$ curve. For a particular $\vec{q}$, the sensitivity to the incident energy grows as one goes to more forward electron angles (i.e. to higher energies). At very forward angles (where most measurements will be performed to maximize $\Delta\epsilon$ and the counting rates) one must determine E_0 to 10^{-4} or better for a one percent error in σ . Since cross sections at forward angles show stronger dependence with E_0 than at backward angles, most of the error comes from σ_f . It must be stressed that **absolute knowledge of the incident energy is required**. This can be easily demonstrated for the above case. Errors in E_0 affect primarily σ_f and thus knowledge of the difference in energies for the two kinematics comprising the separation is insufficient.

To illustrate the generality of the above remarks, three $(e,e'p)$ proposals designed to separate various response functions for ^{16}O ^[11], ^2H ^[4] and $^3,^4\text{He}$ ^[5] are examined. The derivatives of the coincidence cross section with respect to each kinematical variable are given in Table 3.2. The tabulated numbers represent maximum values computed by

Figure 3.5 Fractional change in E_0 which results in a 1% change in the $d(e,e'p)n$ cross section. The kinematics are quasielastic (i.e. $\omega = q_\mu^2/2M + 2.2$ MeV) with $p_r = 50$ MeV/c. The curves, one for each value of $\vec{q}$ from 0.5 to 3.0 GeV/c, are drawn through the calculated points to guide the eye. Corresponding electron scattering angles are shown on the axes at the top of the figure. Each value refers to the point directly below on the corresponding $\vec{q}$ curve.

SIGEEP.^[10] The incident energy and scattered electron momentum must be known at the 10^{-4} level in order to restrict the error to $\sim 1 - 2\%$. All angles (beam, scattered electron and proton) must be known at the 0.1 mr level. For in-plane experiments such as these, determination of the angle out of the scattering plane does not need to be as precise. (However, for non-coplanar kinematics, the out-of-plane angle must be determined precisely as well.) The error introduced by uncertainties in the proton momentum was not calculated since it was assumed that the missing mass is known. Again, since the total uncertainty has contributions from many sources (kinematics, beam current, target thickness, detector efficiencies, radiative corrections, ...) one would like the error coming from each of the above kinematical uncertainties to be less than 1%.

Table 3.2

Maximum Sensitivities					
Proposal #	% / mr or % / 10^{-4}				
	E_0	θ_b	θ_e	θ_p	p_e
PR-89-003	0.56	5.2	3.2	2.1	0.54
PR-89-026	1.7	13	6.2	4.4	1.3
PR-89-044	1.8	15	18	0.30	0.60

The requirements on the beam energy imply the need for position monitors with excellent spatial resolution. One possibility would be to place these monitors at a point of high dispersion in the beam line where they would define the entrance and exit trajectories of the beam at the energy defining dipole. This magnet must be precisely mapped if one is to be able to determine the energy at the 10^{-4} level. In general, as mentioned above, the energy of the beam (as well as the scattered electron) must be determined *absolutely* at this level since L/T separation experiments will involve measurements with widely disparate electron energies.

The angle requirements imply precise monitoring of the beam position as well as precise knowledge of the location of the central axis of each spectrometer. Absolute knowledge of the positions of the beam monitors will probably be the primary limitation on the definition of the beam angle. If the beam position monitors are placed 5m apart and their absolute positions are known to within 0.5mm one can determine the beam angle at the 0.1 mr level. Because of the relatively large acceptance of each spectrometer, simply determining the central axis is not sufficient, especially if one wishes to bin the data by subdividing the solid angle in software. One must then know how the spectrometer maps the solid angle onto its focal plane with similar accuracy.

3.3.3 Resolution and accidentals rejection

For many (e,e'p) experiments, signal-to-noise will be the primary limitation. This is especially true for measurements at very high recoil momenta, where coincidence cross sections are small. Since the coincidence counting rate is also minimal for these cases, simply reducing the luminosity would often lead to unreasonably long counting times. Thus, reducing the contribution of accidental events is of paramount importance. This implies the need for good coincidence time-of-flight resolution. In addition, for experiments involving extended targets, good vertex resolution can further reduce the accidental yields by requiring that both particles originate from the same point within the target. Finally, for discrete states, good missing mass resolution provides another accidentals filter by considering only those events within a certain ϵ_m interval. As an example, the proposal of R. Lourie *et al.*^[11] assumes a missing mass resolution of 1 MeV which leads to a signal-to-noise ratio of 0.45 for the worst case. The proposal of J.M. Finn *et al.*^[4] also assumes a 1 MeV missing mass resolution as well as a vertex resolution of ± 1 mm giving a signal-to-noise ratio of 0.63 for the worst case.

Summary

- In order to achieve absolute cross sections at the 1% level, particle momenta should be determined with an *absolute accuracy* of 10^{-4} for the (e,e'p) experiments considered. This implies the ability to determine the absolute value of the beam energy and the spectrometer optical properties to that level of accuracy and correct for any instability of these quantities.
- *Absolute determination of the angle in the scattering plane to 0.1 mr accuracy* is needed. The beam orientation, as well as the position of the optical axis of the spectrometers should be determined to that level of accuracy. However, somewhat relaxed uncertainties may be acceptable on an event by event basis, provided they come from sources of a random nature like finite beam spot size, detector resolution or multiple scattering effects. *Angular accuracy and resolution in the vertical direction* (perpendicular to the scattering plane) are not as critical and can be relaxed to *0.3 and 1 mr respectively*.
- Most of the experiments using targets extended along the beam direction will require a position resolution in the transverse plane of about 1 mm.

3.4 BACKGROUND RATES/PARTICLE ID

Luminosities are typically limited by the maximum instantaneous singles rates in the focal plane detectors of each spectrometer. In addition, for some cases, the accidental coincidence rate between the two spectrometers imposes a further constraint on the maximum luminosity. Table 3.3 shows the singles rates for the electron and hadron arms (denoted by R_e and R_h respectively), coincidence rates, signal-to-noise and maximum luminosities for the set of proposals presented to PAC4. Some values are left blank

Table 3.3

Maximum Rates							
Proposal #	R_e sec ⁻¹	R_h sec ⁻¹	R_t sec ⁻¹	(S/N) _{min}	$\mathcal{L}$ $\times 10^{38}$ sec ⁻¹ cm ⁻²	Target	Power Watts
PR-89-003	6.6×10^3	6.2×10^4	2.0×10^{-2}	0.45	0.16	H ₂ O	150
005	1.4×10^5	5.7×10^3	1.2	1.3	2.8	LD ₂	300
014	1.2×10^3	4.9×10^4	0.77	288	4.0	LH ₂	425
016					0.61	LH ₂ ...	70.0
018			4.3		3.0×10^{-4}	pol. ND ₃	
019					1.9	LD ₂	200
021	63				3.2	^{3,4} He gas	680
026	1.6×10^6	5.7×10^5	1.6×10^4	0.63	1.5	LD ₂	160
028	3.3×10^6	2.3×10^6	9.8×10^4	96	3.0	LD ₂	320
029	3.6×10^4	1.0×10^5	310		0.38	L ^{3,4} He	80
030	5.0×10^6	1.0×10^6	5.0		3.2	^{3,4} He gas	1200
033			110		0.24	¹⁶ O gas	200
034	6.0×10^4	5.0×10^4	53		0.063	¹² C, ⁶³ Cu	40
035	4.0×10^4	1.0×10^5	4.3×10^{-2}	13	1.5	LD ₂ ...	160
044	2.5×10^6	2.0×10^6	5.8×10^3	0.3	1.7	^{3,4} He gas	420
046			0.22		1.6×10^{-4}	²⁰⁸ Pb	1.0
047	0.13				4.5	LD ₂	480

either because of non-applicability or because the information was not provided in the proposals.

For many of the proposals the electron singles rates are between one and several megahertz. However, these large singles rates are often coupled with large coincidence rates. Thus, in most cases one could lower the beam current without affecting the total beam time appreciably. Singles rates in the hadron arm are ~ 2 MHz or less. This is not expected to be a problem. In fact, (e,e'p) experiments at Bates have been run with comparable instantaneous rates. The true coincidence rates are 16 KHz or less, but again one could tolerate longer counting times for those runs with the highest coincidence rates. In general, one would like to be able to run with rates of ~ 10 KHz, especially for recoil polarization experiments where only a fraction of the data has useful analyzing power. One might relax this requirement if a fast on-line rejection system for small angle second scatterings were implemented. One could also envision, however, measurements attempting to extract a weakly excited state riding on a large background. Since one cannot foresee all future experiments, one should plan to allow for acquisition at the highest rates which are feasible. Signal-to-noise ratios are always at least 0.3. In some cases, a combination of three accidentals background filters are required to achieve this:

good timing resolution (~ 2 ns full-width at base), vertex resolution for extended targets ($\sim \pm 1$ mm) and missing mass resolution for discrete states (~ 1 MeV).

Of those proposals which give background estimates, good particle identification is most critical for the L/T separation measurements^{[4][5]}. At backward angles the π^- yield will dominate over the electron yield. The predicted ratios of π^-/e are $\sim 10^3$. A 1% measurement therefore requires a rejection ratio of 10^5 . A combination of a gas Čerenkov counter and shower counter should be adequate. Even though coincidence time-of-flight background subtraction would eliminate this uncorrelated background, one still needs to have standalone particle identification so as not to degrade the signal-to-noise ratio. Furthermore, single arm measurements such as elastic scattering from $^3,^4\text{He}$ at large momentum transfers^[7] and deuteron threshold electrodisintegration at large momentum transfers^[6] will require excellent particle identification in the electron arm. From the proposed experiments, particle identification does not appear to be as stringent for the hadron arm. An aerogel and gas Čerenkov counter should be sufficient.

In general, correlated backgrounds, such as $(e, e'\pi^+)$ and (γ, π^-p) , need to be considered as well. For quasielastic $(e, e'p)$ experiments at low missing mass, (γ, π^-p) requires a photon energy near the endpoint. Thus, we do not expect this process to dominate the correlated yield. Furthermore, for quasielastic measurements, the $(e, e'\pi^+)$ process is not allowed kinematically. However standalone particle identification will be required in general (for non-quasifree or deep continuum measurements, for example) in order to remove the correlated backgrounds. In some cases coincidence time-of-flight coupled with standalone particle ID in the electron arm may adequately remove the correlated backgrounds. In Figure 3.6 the time-of-flight of various particles relative to that for electrons is shown for a 25 meter spectrometer flight path. Assuming one has particle identification in the electron arm, particle ID can be achieved in the proton arm via a time-of-flight measurement relative to the electron. This holds only for the correlated coincidence backgrounds. To allow independent operation of the spectrometers and for redundancy (as well as to maximize the signal-to-noise ratio), standalone particle identification in both arms is highly desirable.

In order to carry out the bulk of the measurements on the few-body systems, extended targets capable of handling ~ 100 μA of beam current will be required. This translates to several hundred watts of cooling power in some cases (see Table 3.3). Since the beam is expected to be of excellent quality (low emittance) one will need to have substantial flow rates or a rastered or dispersed beam or a combination of both. This is also an issue for solid targets, where one must avoid melting.

Figure 3.6 Time-of-flight relative to electrons for a spectrometer flight path of 25 meters.

Summary

- The high duty factor afforded by CEBAF will allow systematic measurements to be undertaken with modest amounts of beam time. For the experiments proposed at PAC4, singles rates are not expected to be a problem (they are similar to those at existing 1% duty factor facilities) and existing detector technology should be suitable.
- Real rates are, in some cases, quite large and demand both improved computational power and data storage capabilities.
- Very good particle identification and rejection will be required for both arms. Aerogel and gas Čerenkov counters should be adequate for the hadron arm whereas a gas Čerenkov detector and shower counters will be needed in the electron arm. Rejection ratios of $\sim 10^5$ will be required for the cases studied.

3.5 EXTENDED TARGET REQUIREMENTS

A large portion of the physics program for Hall A consists of experiments involving few-nucleon ($A \leq 4$) systems. Such experiments will require liquid or gas targets extending along the beam. In order to determine the requirement for the target length acceptance of the Hall A spectrometers, a careful optimization between physics issues such as radiative losses in the target, background problems and practical design considerations such as dipole gap size, counting rates, target heating problems etc. must be done.

As already pointed out, precise definition of the target vertex allows, in a coincidence experiment, requiring that both particles come from the same target section in an extended target, improving the real/accidental coincidence ratio.

For typical experiments in Hall A, luminosities of the order of $10^{38} \text{cm}^{-2} \text{s}^{-1}$ will be required. This is primarily dictated by singles data handling rates of about 1MHz. In order to achieve such high luminosities extended targets will be required.

A 10 cm transverse acceptance (i.e. target length acceptance with the spectrometer at 90°) for both spectrometers will produce luminosities of the order of $10^{38} \text{cm}^{-2} \text{s}^{-1}$ at the full beam current of $200 \mu\text{A}$ for liquid targets as well as high pressure cryogenic gas targets. In most of the spectrometer designs considered for Hall A, larger target length acceptance leads to large apertures in the magnetic elements, in particular the gap of the dipole. Increasing magnet apertures becomes prohibitively expensive at some point imposing a practical limit on the acceptance.

From the above considerations, a 10 cm transverse target length acceptance is a reasonable compromise for the Hall A spectrometers.

Summary

- A target length acceptance of 10 cm appears to be a reasonable compromise. The ability to determine the beam-target interaction vertex is important both for correcting for energy loss in the target and as an accidentals filter for coincidence measurements.

3.6 OUT-OF-PLANE CAPABILITIES

Nearly half of the response functions (8 out of 18) given in the general form of the $(e, e'p)$ cross section require that the hadron be detected out of the electron scattering plane. It is therefore essential that an out-of-plane capability exist as an important tool for a complete determination of all the amplitudes which describe the elementary process. It is also essential that the out-of-plane capability be coherently linked with a focal plane polarimeter for the hadron arm.

There are essentially two methods to achieve this out-of-plane capability. One is to detect hadrons out of the horizontal (scattering) plane and the other is to tilt the scattering plane by bending the beam vertically. The first method could involve moving a relatively light spectrometer vertically or making simultaneous measurements with a multidetector system. Making simultaneous measurements is less prone to systematic errors since any time dependent effects, such as instability in the beam or changes in target density, affect all measurements equally. There are advantages and disadvantages to either method, and one has to determine which is better able to carry out the out-of-plane physics program. During the Summer of 1987 an out-of-plane Task Force chaired by Franz Gross^[12] addressed this issue in much detail and we present here only a few pertinent results from this report.

The maximum opening angle between $\vec{q}$ and the emerging proton puts constraints on the largest transverse momentum that one can probe for the recoiling system. An approximate relation for this angle for quasielastic scattering from a heavy nucleus in perpendicular kinematics is

$$\sin \theta_x \approx \frac{p_m}{|\vec{q}|}.$$

Thus, if one restricts oneself to $\vec{q} \geq 0.7$ GeV/c (since momenta below this range will be in the domain of other lower energy electronuclear facilities such as Mainz, NIKHEF and Bates), most of the region of interest lies in a narrow cone around the q vector. Recoil momenta up to 0.5 GeV/c could then be probed with opening angles $\theta_x \leq 40^\circ$ (45° for the deuteron). This is near the lower end of the $\vec{q}$ range for CEBAF since below this other kinematical constraints become important making an effective deconvolution of the response functions difficult. At $\vec{q} = 1.5$ GeV/c the same p_m range could be covered with opening angles less than 20° .

Another limit for the opening angle is given by the so-called symmetric kinematics. This occurs when two equal mass particles occur in the final state (e.g. for deuteron breakup) whose momenta are equal in magnitude and at symmetric angles on opposite sides of $\vec{q}$ ($\theta_{cm} = 90^\circ$). Here, θ_x is fixed by Q^2 and x . For $Q^2 \geq 0.5$ (GeV/c)² and all possible x , θ_x is $\leq 60^\circ$. For quasielastic kinematics this angle is less than 45° . We can therefore conclude that nearly all of the CEBAF out-of-plane physics program can be satisfied with opening angles which can vary continuously from 0 to $\sim 40^\circ$. In fact, opening angles of up to 30° would cover a major portion of the program for all nuclei, except maybe the specialized case of the deuteron symmetric kinematics for $x \ll 1$.

If one were to move the hadron spectrometer to achieve this out-of-plane capability, it would need to go 30° vertically out of the scattering plane. On the other hand, by bending the beam through a modest angle, relatively large out-of-plane angles can be achieved. The vertical beam deflection angle, ϕ_b , is related to the opening angle (for an azimuthal out-of-plane angle $\phi_x = 90^\circ$) by

$$\sin \theta_x \simeq \sin \phi_q = - \left(\frac{E}{|\vec{q}|} \right) \sin \phi_b.$$

For forward electron angles, the magnification factor, $E/|\vec{q}|$, can be quite large. For example for a 4 GeV beam, and $\vec{q} = 1.5$ (GeV/c), a beam deflection angle of only

10° gives rise to an opening angle of nearly 28°. (If one were to have discrete beam deflection angles, then care has to be taken that the acceptance of the two spectrometers is large enough to make a continuous variation in the opening angle.) However, the beam deflection technique is likely to be more prone to systematic errors since changing the azimuthal angle, ϕ_x , requires in general moving both spectrometers as well as changing the beam orientation.

Summary

- A substantial part of the out-of-plane program could be carried out with maximum opening angles of $\sim 30\text{--}40^\circ$. For small scattering angles the beam swinger technique would allow one to reach relatively large opening angles with only a modest bend angle. However, this method is more prone to systematic errors than the raised spectrometer method since changing ϕ_x requires moving both spectrometers as well as changing the beam orientation.

3.7 POLARIZATION EXPERIMENTS

The measurement of polarization observables will undoubtedly play an important role in the physics program in Hall A as they are expected to provide sensitive tests of the various ingredients in reaction models. Further, polarization measurements are of fundamental importance in that they promise to be an important tool in the extraction of nucleon form factors. In general, both target and recoil polarization measurements (in addition to a polarized beam) are required to determine the complete set of helicity amplitudes. In some cases, however, target and recoil polarization measurements give redundant information and one must then examine in detail the relative merit of either technique. A discussion of the relevant issues follows. A summary of the polarization experiments for Hall A submitted to PAC4 is given in Table 3.4.

Table 3.4

Proposed Polarization Experiments				
Proposal #	Short Title	Pol. Beam?	Recoil Pol.?	Target Pol.?
PR-89-005	G_E^n via $d(\vec{e}, e' \vec{n})p$	Yes	Yes	No
014	G_E^p via $p(\vec{e}, e' \vec{p})$	Yes	Yes	No
018	G_E^n via $\vec{d}(\vec{e}, e' n)$	Yes	No	Yes
019	$d(\gamma, \vec{p})n$	No	Yes	No
028	$d(\vec{e}, e' \vec{p})n$	Yes	Yes	No
033	$^{16}\text{O}(\vec{e}, e' \vec{p})$	Yes	Yes	No

3.7.1 Recoil polarization

Examination of the polarization of recoiling nucleons in $(e,e'N)$ is more generally applicable than measurements with polarized targets. Recoil polarization techniques can accommodate any target whereas only non-spin zero targets can be polarized. Further, one can examine the polarization of any constituent nucleon whereas target polarization arises from the spin of the valence nucleons only. There are also practical considerations which tend to favor recoil polarimetry. It is not hindered by the luminosity limitations imposed by polarized targets. Also, the large holding fields required for polarized targets impact significantly on the trajectories of any charged particles involved in the reaction (i.e. incident and scattered electron as well as the proton in $(e,e'p)$).

The recoil polarimetry proposals are summarized in Table 3.4. All but one, $d(\gamma, \vec{p})n^{[8]}$, requires a polarized beam (and beam polarimeter). The other proposals involve form factor measurements of the neutron^[13] and proton^[1] as well as reaction studies on $d(\vec{e}, e' \vec{p})n^{[14]}$ and $^{16}O(\vec{e}, e' \vec{p})^{[15]}$.

3.7.2 Target polarization

Although polarized targets can tolerate only very small beam currents, this luminosity limitation is partly compensated by the increased efficiency for nucleon detection relative to measurement of polarization of recoil nucleons. The lack of efficiency for the latter is due primarily to the relatively small fraction of nucleons which scatter usefully (i.e. with reasonably large analyzing power) in the polarimeter analyzer. Further, polarized targets require only one calibration, whereas a recoil polarimeter must be calibrated for all nucleon energies of interest. As mentioned above the polarized target holding field can alter the trajectories of charged particles significantly. Thus, compensation must be made either in the spectrometer optics or by using additional magnets near the target. Also, for cases where the beam deflection is significant provision must be made for steering the beam back to the dump.

So far, only one polarized target proposal was submitted for Hall A, the neutron electric form factor measurement of D. Day *et al.*^[16] (the proposal actually specifies either Hall A or Hall C). This proposal, along with the G_E^n proposal of Madey *et al.* mentioned above, provide a basis for comparison of the two techniques. A 10 nA beam current on a 1.5 cm ND₃ target is assumed for the polarized target experiment resulting in a luminosity of $5.6 \times 10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$. By contrast the recoil polarization experiment can use beam currents of 25–100 μA on a 5 cm LD₂ target yielding luminosities $\gtrsim 10^4$ times greater ($0.4\text{--}1.6 \times 10^{38} \text{ cm}^{-2} \text{ sec}^{-1}$). The efficiencies and solid angles assumed are respectively $\geq 30\%$ and $\geq 48 \text{ msr}$ for the neutron detector and $\sim 0.27\%$ and $\sim 4 \text{ msr}$ for the neutron polarimeter. Thus, the product of solid angle and efficiency is $\gtrsim 10^3$ times greater for the neutron detector than for the neutron polarimeter which partially compensates for the difference in luminosities. In fact, the predicted uncertainties in G_E^n from either method are roughly comparable ($\sim 20\text{--}30\%$) for similar data acquisition

times. Of course these numbers are only meant as a rough guide and the relative merits of either technique must be evaluated on a case-by-case basis.

Summary

- The measurement of polarization observables will constitute an important part of the Hall A physics program. In general, one needs a polarized beam, target and recoil polarimeter to obtain complete information on the reaction. In some cases, recoil and target polarization techniques give redundant information. Although polarized targets are limited in the maximum luminosity they can handle this is partially compensated by the increased efficiency for particle detection relative to recoil polarization measurements. The merits of either technique must be examined on a case-by-case basis.

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4. HALL A HIGH RESOLUTION SPECTROMETERS

4.1 GENERAL FEATURES

The core of the Hall A equipment is a pair of identical 4 GeV/c spectrometers. The basic layout of the 4 GeV spectrometer is shown in figure 4.1. The vertically bending design includes a pair of superconducting, $\cos 2\theta$ quadrupoles followed by a 6.6 m long dipole magnet with focusing entrance and exit faces and including further focusing through the use of a field gradient in the dipole. Subsequent to the dipole is another superconducting $\cos 2\theta$ quadrupole. The second and third quadrupole of each spectrometer have sufficiently similar field requirements that they can be of identical design and construction. The hadron arm will be equipped with a focal plane polarimeter to allow experiments involving spin observables.

The main design characteristics for the 4 GeV spectrometer are shown in table 4.1.

Table 4.1
Main Characteristics of the 4 GeV/c QQDQ Design

Configuration	vertical
Bending angle	45°
Optical length (m)	23.4
Momentum range (GeV/c)	0.3 to 4
Momentum acceptance (%)	10
Momentum dispersion (D, cm/%)	12.4
Momentum resolution*	10^{-4}
Radial linear magnification (M)	-2.5
D/M (cm/%)	5.0
Angular range	12.5° to 165°
Angular acceptance : horiz. (mr)	±30
vert. (mr)	±65
Angular resolution* : horiz. (mr)	0.5
vert. (mr)	1.0
Solid angle (msr)	7.8
Transverse length acceptance (cm)	±5
Transverse position resolution (cm)*	0.1

*FWHM, including effects of finite beam spot size and detector resolutions (see expected performances section).

4.0 GeV/c High Resolution Spectrometer

3/16/90
GAVALYA

Figure 4.1 General layout of the QQDQ 4 GeV/c spectrometer.

4.2 MAJOR DESIGN CHOICES

As it appears clearly from section 3, the highly demanding physics program for Hall A, the extremely good quality of the CEBAF beam, matched by the detector systems, lead to a set of quite extreme, certainly unprecedented requirements, for the spectrometers. Although a large variety of designs have been successfully used for high resolution spectrometers above ~ 0.5 GeV/c, none has really addressed such a combination of a maximum momentum capability of several GeV/c, large angular and momentum acceptances and very high resolution. The high resolution spectrometer designs in the 0.5 - 1 GeV/c range (see Table 4.2) are based on large bending angles ($\sim 90^\circ$) which become impractical at high energy. Above 2 GeV/c, the existing spectrometers (SLAC, Saclay, DESY, Bonn..) have more modest performances in angular acceptance and/or resolution.

In selecting this approach to high resolution spectrometers for CEBAF a certain number of design choices have been made, leading to the definition of a "class of spectrometers" capable of achieving the design goals. The most important ones are listed below.

a) Focussing, mainly "hardware-type" spectrometers

A focussing spectrometer is obviously the only practical way of achieving resolutions in the 10^{-4} range. In the CEBAF case this also allows one to make full use of the small dimensions of the beam. Moreover, the overall detector sizes are decreased, making them easier to shield against background, and allowing higher beam intensities. Thus, the choice was made to start with a good "hardware" design, corrected for the most important geometrical and chromatic aberrations by introducing higher order multipolar fields. Supplemental software corrections will be used to achieve the desired performance.

b) Moderate bending angle and efficient use of the dipole aperture

This choice is driven by the combined requirements of high resolution and low cost. High resolution demands high quality fields in the dispersive element of the system (i.e. the dipole). To achieve the desired field quality requires the use of iron-dominated magnets implying an ~ 1.7 Tesla limit on the maximum field in the useful aperture. Getting the desired resolution with such a modest field implies either a very long magnet or very efficient use of the dipole aperture. Efficient use of the dipole aperture to get high momentum resolution is accomplished by having the envelope of possible particle trajectories spread maximally and uniformly (a parallel beam is the best) in the dispersive plane while in the dipole field region. The large drift space

Table 4.2
Some High Resolution Spectrometers
for Intermediate Energy Nuclear Physics

	Type	P_{max} central ray (GeV/c)	Total bend	P_{max} P_{min}	Resol. (10^{-4})	$\Delta\Omega$ (msr)	θ_r θ_t	Resol. $\delta\theta_s$ (mr)
NIKHEF	QDD	0.6	150°	1.10	~ 2	5.6	1/1	2-4
	QDQ	0.75	90°	1.10	~ 5	16.	1/1	2-4
SACLAY								
600	D	0.6	153°	1.40	~ 4	6.5	6/1	2-4
900	D	0.9	169.7°	1.10	1.5	4.8	4/1	2-4
BATES ELSSY	DD	1	90°	1.06	0.4-0.5	5.4	6/1	$\lesssim 1$
SLAC								
8 GeV	QQDDQ	8	29.6°	1.08	5	0.75	4/1	~0.3
1.6 GeV	D	1.6	90°	1.10	5	2	2/1	~0.3
LAMPF HRS	QDMQ	1.52-2	150°	1.05	0.4	2.6	1/1	0.8
SATURNE								
SPES I	QSD	1.9	97°	1.04	0.5	3.8	2/1	
SPES IV	QQDSDQ+	4	0°	1.01	3	2.4	3/1	
	QDDSQQ		Reimaging	1.09	10	0.4	14/1	
MAMI B								
electron	QQDD	0.81	110°	1.15	<1	5.6	3.5/1	1-3
hadron	QDD	0.67	110°	1.20	<1	28.0	0.7/1	1-3
CEBAF 4 GeV	QQDnQ	4	45°	1.10	0.5	8	2.2/1	<0.5

Notations: θ_t = angle in the transverse plane

θ_r = angle in the radial plane

θ_s = scattering angle

between Q2 and the dipole helps bring about the transition from a circular aperture in the quadrupole to the rectangular one of the dipole, while trying to maintain a nearly parallel beam. In the present design focussing has been added to the function of the dipole in the form of entrance and exit shim angles and a first order field index. These features result in slightly less than optimum momentum resolution for the bend angle which is more than compensated by the elimination of the need for two additional quadrupoles in the design.

c) Vertical bending plane

The advantages of a vertically bending configuration can be summarized as follows:

- Momentum and scattering angle measurements are decoupled to first order
- Target position along the beam direction can be obtained without any extra detector
- Parallel-to-point tuning in the scattering plane is made possible, leading to better resolution of the scattering angle
- The double dispersion matching technique can be used when resolution better than the natural beam energy spread is needed
- Floor occupancy and radial extension are slightly reduced, although the support structure may be more complicated.

However, a vertical bend results in some loss of solid angle and/or resolving power for given dimensions of the dipole aperture, if one wants the angular acceptance to be smaller in the horizontal plane (scattering plane) than in the vertical plane. Also, with both spectrometers vertical, no information is available on the vertical position at the target. Usually this can be accepted as one expects beam displacement or spreading to be very small in the vertical direction. It is only when out-of-plane kinematics are obtained by moving the beam that a significant vertical extent is realized. Then one has to rely on horizontal position measurements to determine the vertical position of the reaction point. Good position resolution in the transverse plane is needed, especially when the spectrometer is at a small angle.

d) Superconducting coils in the magnet elements

The essential motivation for this choice is a strong reduction in operating costs. However, in the case of the quadrupoles, a current dominated $\cos 2\theta$ design has the added advantage that tuneable higher order multipole components can be added to the field configuration through the addition of auxiliary multipole windings in the coil pack. These extra windings are very simply incorporated in the magnet design. They can be used to perform "hardware" corrections of geometrical and chromatic aberrations. They can also serve to correct for unwanted higher order contributions coming from either possible deformations of the field map, particularly in the fringe field region, as compared to the expected one, or known misalignments.

e) Two identical 4 GeV/c spectrometers

The physics program in Hall A calls for a hadron spectrometer with characteristics that do not differ substantially from those of the electron arm. Required resolutions are similar. Although in most cases the maximum momentum of the hadron arm can be limited to 2.5–3.0 GeV/c, some very important experiments (like the measurement of G_{Ep}) would require higher values, up to 4 GeV/c.

Ideally, one would like to take advantage of a reduced momentum capability in the hadron arm to increase its angular and momentum acceptances. First, one observes that there is no unique way of “matching” the acceptance of the hadron arm to that of the electron arm, as the matching requirements, even for two-body reactions, vary widely with kinematics. Studies indicate that there are very different matching conditions at a given momentum transfer (q), between forward and backward electron angle kinematics (one needs a forward and backward angle measurement to make a transverse/longitudinal response function separation). These conditions also change widely when varying q . Having the acceptance of the hadron and electron arms be the same does not appear to be a bad compromise. Moreover, studies of possible designs for a lower momentum hadron spectrometer indicate that it is very difficult to go beyond about 10 msr solid angle at 2.5–3 GeV/c without running into serious cost problems. Only momentum acceptance can be increased (about doubled) without a major detrimental impact on cost, and that at the cost of some loss in momentum and/or transverse position resolution.

Two identical spectrometers has obvious advantages in terms of the manpower required for conception, design, tooling, fabrication, and testing, not only for the magnets themselves, but also for the detector systems as well.

f) Indexed Dipole

The possibility of achieving the same optical objective as that obtained using the indexed dipole through the use of two uniform field dipoles has been considered. In the two-dipole solution the extra focussing provided by the n -value is replaced by two additional field boundaries with shim angles. In this way essentially identical first order optical properties could be achieved without the complication of building an indexed magnet.

With the two-dipole solution one has two extra fringe regions to deal with which can be sources of problems. In trying to optimize the two-dipole system against

higher order aberrations, with its overall size constrained by the size of Hall A, it was impossible to make the two dipoles identical leading to more different magnetic elements in the package. The rotation of the focal plane to a reasonable angle was more difficult in the two-dipole design leading to more severe curvatures of the dipole field boundaries and stronger sextupole components in the quadrupoles. Two smaller dipoles would require at least as much and possibly more iron as well as two separate coil packages making the two-dipole solution costlier. Finally, it was concluded that the indexed dipole was a better choice.

4.3 OPTICS DESIGN

High resolution coincidence experiments, particularly those using few body systems for targets, present a very difficult set of requirements on the transverse optics of the spectrometer systems involved. That is the requirement of simultaneous position and angular measurement. This makes a defocussing quadrupole following the naturally focussing dipole magnet a necessity. In all the designs without a final quadrupole studied, it was impossible to simultaneously deliver adequate resolution for both transverse position and angle. The QQDQ design presented meets this requirement.

The evolution of the first order matrix elements is illustrated in figure 4.2. The front quadrupole, Q1, is convergent in the dispersive (vertical) plane (the angular acceptance is largest in the dispersive plane). Transverse focussing is provided in a nearly symmetrical way by the quadrupoles Q2 and Q3. Using the beam transport notation of K. Brown¹, the $\langle y|\phi_0 \rangle$ term goes through a shallow minimum inside the dipole, while the $\langle y|y_0 \rangle$ term goes to zero. Both features ensure an optimal use of the 25 cm gap for horizontal angular acceptance and horizontal target length acceptance. The fact that the $\langle y|y_0 \rangle$ term remains small (< 2.5) all the way through the spectrometer makes the use of extended targets ($\leq 10\text{cm}$ at 90°) possible, with no substantial loss in solid angle.

In the dispersive plane, the $\langle x|\theta_0 \rangle$ term is kept large inside the dipole to make efficient use of the dipole width to build resolving power, in spite of the rather modest bending angle. Radial focussing is given by a -30° tilt angle of the entrance and exit pole faces and by the introduction of a negative first order field index, $n = -1.25$.

Practical considerations led to certain constraints on the development of the present optical design. Some of the more important of those constraints were:

- Constraints have been put on the beam envelope not to exceed 0.25m(1m) in the dipole gap (width), and 0.3m(0.6m) diameter for the useful aperture for Q₁(Q₂Q₃).

4 GeV QQDQ

Figure 4.2 First order coupling coefficients in the dispersive (x) and transverse (y) planes for the QQDQ 4 GeV/c spectrometer. Units are meters×radians.

These size constraints help keep the cost of the magnets under control.

- The bend angle has been kept at 45° , a value selected at an early stage of the designs as a reasonable compromise for a high energy, high resolution device. The following expression based on first order optics principles²:

$$\frac{D_x}{M_x} \Delta\theta_0 = -2\omega \tan \frac{\alpha}{2}$$

relates resolving power ($\propto \frac{D}{M}$) and angular acceptance in the radial plane ($\Delta\theta$) to bend angle (α) and dipole half-width (ω). For a 10msr solid angle and $\Delta\theta/\Delta\phi = 2$ $\Delta\theta \sim \pm 70\text{mr}$. Then for $\omega = 50\text{cm}$ (100cm total width) and $D/M=5$ the above expression gives $\alpha = 39^\circ$, close to the chosen value of 45° . The expression assumes a parallel beam in a uniform field dipole. The radial focussing provided by the indexed dipole results in the need for a slightly larger bend angle.

- The pole face rotation angles have been fixed at -30° as a practical acceptable limit, the rest of the radial focussing being provided by Q_1 and the field index. An excessively large rotation angle of $\sim 43^\circ$ would be needed in the absence of the field index.
- The overall optical length was constrained not to exceed 24m in order that the device fit in the hall.

The first order transport matrix at the focal plane is the following:

$$\begin{pmatrix} x \\ \theta \\ y \\ \phi \\ \delta \end{pmatrix} = \begin{pmatrix} -2.48 & 0.0 & 0.0 & 0.0 & 12.4 \\ -1.54 & -0.40 & 0.0 & 0.0 & 20.4 \\ 0.0 & 0.0 & -0.40 & -0.13 & 0.0 \\ 0.0 & 0.0 & 5.39 & -0.78 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 1.0 \end{pmatrix} \begin{pmatrix} x_0 \\ \theta_0 \\ y_0 \\ \phi_0 \\ \delta_0 \end{pmatrix}$$

The beam envelope, calculated to second order in TRANSPORT³, for full solid angle, momentum acceptance, and target length is shown in figure 4.3.

Higher order aberrations were studied using the program RAYTRACE⁴ and hardware corrections were determined. These corrections were applied in the second quadrupole, in the curvature of the effective field boundary at the entrance and exit of the dipole, and in the third quadrupole. The focal surface, figure 4.4, has been determined using standard RAYTRACE 14-ray bundles

Figure 4.3 Second order TRANSPORT beam envelope for the dispersive and transverse planes in the QQDQ 4 GeV/c spectrometer assuming $\Delta\theta_0 = 65mr$, $\Delta\phi_0 = 30mr$, $\Delta y_0 = \pm 5cm$ and $\Delta\delta = \pm 5\%$ (full line) or $\Delta\delta = 0$ (dashed line).

4 GeV QQDQ

Figure 4.4 RAYTRACE⁴ generated focal plane representation for the QQDQ design. Ray bundles are the standard RAYTRACE 14-ray bundles from a point source spanning $\sim 75\%$ of the full solid angle. Each bundle represents a distinct momentum ranging from 3.795 GeV/c to 4.191 GeV/c. The dashed line connects the intersections of the axial and paraxial rays at each momentum. The dotted line connects the waists of each ray bundle. The solid line is a straight line fit to the waists.

from a point source at 5 different momenta ranging from $\delta = -5.125\%$ to $\delta = 4.775\%$. It has been approximated by a plane, at an angle of 44° with respect to the central trajectory. The full width of those ray bundles, spanning a solid angle of $\sim 5\text{msr}$ ($\sim 60\%$ of the full acceptance of the spectrometer), at the focal plane ranges from 0.036% at $\delta = 0$ to 0.075% at $\delta = 4.775\%$.

Table 4.3
Apertures and Fields of the 4 GeV/c QQDQ Design

Dipole				
Field at 4 GeV/c		1.6 T		
central gap		.25 m		
useful width		1.0 m		
Magnetic length		6.597 m		
Field index		-1.25		
Entrance Boundary:	angle	-30°		
Higher order corrections:	S_{02}	2.68 ($R_c=1.57\text{m}$)		
	S_{03}	-14.1		
	S_{04}	50.		
	S_{05}	-100.		
Exit Boundary:	angle	-30°		
Higher order corrections:	S_{12}	-1.5 ($R_c=-2.8\text{m}$)		
	S_{13}	20.26		
	S_{14}	-200.		
Quadrupoles		Q_1	Q_2	Q_3
Useful aperture (hor. x vert.) cm		11×14	25×18	15×30
Magnetic length (m)		0.8	1.8	1.8
Quadrupole gradient T/m		9.1	-3.2	-3.0
Sextupole strength (T/m^2)		0	0.16	1.0
Octupole strength (T/m^3)		0	1.8	0.8
Dodecapole strength (T/m^5)		0	0	2.9

The presently anticipated aperture and field characteristics of the QQDQ spectrometer magnets are given in table 4.3. Higher order corrections on the pole ends of the dipole are given in terms of the RAYTRACE⁴ expansion coefficients of the effective field boundary

$$\frac{\Delta z'}{\rho} = -[S_{02}(\frac{x'}{\rho})^2 + S_{03}(\frac{x'}{\rho})^3 + \dots]$$

where $\rho = 8.4\text{m}$ is the bending radius of the central ray and (x', z') are measured in a coordinate system which is rotated 30° , so that the x' axis is along the pole end. The

radius of curvature corresponding to the second order coefficient is also given. Naturally, with further study and refinement the magnet parameters given in table 4.3 may change slightly over time.

4.4 TUNING CAPABILITIES

This design, in spite of the built in untuneable focussing properties of the dipole, has some versatility that can be exploited to meet special experimental needs. Q1 and Q2 can be moved together as a pair both closer to and farther from the target, while leaving the other magnets at a fixed distance from the target. Moving the pair 0.8 m closer to the target results in an increase of the solid angle acceptance, a loss of momentum resolution, reduction of the maximum momentum, and an increase in the minimum possible scattering angle. If the pair is moved 1 m further away from the target the minimum achievable scattering angle is decreased at a cost of some loss in solid angle acceptance.

These alternate tunes have been studied in a very preliminary fashion using TRANSPORT³ and in the case of the large solid angle tune RAYTRACE⁴. The results of those studies are as follows. (Throughout performance estimates are based on the assumption of position resolution $\sigma_z = \sigma_y = 100\mu m$ and angular resolution $\sigma_\theta = \sigma_\phi = 0.5mr$ in the detectors)

Large Solid Angle: move Q₁-Q₂ as a pair 80 cm closer to the target. This will increase the minimum scattering angle to $\sim 22^\circ$. Then try to achieve maximum solid angle at the cost of momentum and scattering angle (ϕ) resolution.

from TRANSPORT³

$$\theta_0 = \pm 108mr$$

$$\phi_0 = \pm 36mr$$

$$P_{\max} = 2.4 \text{ GeV}/c \text{ (Q1 gradient limited)}$$

$$y_0 = \pm 5cm$$

$$\frac{\Delta p}{p} = \pm 4\%$$

$$\sigma_{\phi_0} = 0.5mr$$

$$\sigma_{\theta_0} = 2.6mr$$

$$\sigma_\delta = 3 \times 10^{-4}$$

from RAYTRACE⁴

$$\pm 98mr$$

$$\pm 36mr$$

(based on f.o. TRANSPORT³)

(based on f.o. TRANSPORT³)

(based on RAYTRACE⁴ through third order for a point source)

Reduced Minimum Scattering Angle: Move Q_1 - Q_2 back 1m further from the target emphasizing angular resolution ($\langle y|y_0 \rangle = 0$) at the cost of solid angle. This decreases the minimum scattering angle to $\sim 10^\circ$. One gets two possible tunes:

High Momentum Resolution	Reduced Momentum resolution
$\frac{D}{M} = -7.$	-3.4
$(\frac{D}{M} = -5. \text{ in the baseline tune})$	
$\theta_0 = \pm 45\text{mr}$	$\pm 49\text{mr}$
$\phi_0 = \pm 9\text{mr}$	$\pm 25\text{mr}$
$\frac{\Delta P}{P} = \pm 5.3\%$	$\pm 4.4\%$
$\sigma_{\phi_0} \leq 0.1\text{mr}(\langle y y_0 \rangle = 0)$	$\leq 0.1\text{mr}(\langle y y_0 \rangle = 0)$
$\sigma_{\theta_0} = 0.8\text{mr} \text{ (f.o. TRANSPORT}^3\text{)}$	$2.1\text{mr} \text{ (f.o. TRANSPORT}^3\text{)}$
$P_{\text{max}} \sim 4 \text{ GeV/c}$	$\sim 4 \text{ GeV/c}$

(nb: The above studies of possible alternate tunes are based primarily on first order TRANSPORT³ calculations and should be viewed as general indicators of the sorts of things that *might* be possible. There are unaddressed difficulties as regards higher order aberrations. Having the multipolar configuration of the dipole tuned to our baseline configuration leaves very few knobs to turn when attempting to minimize higher order aberrations in an alternate tune. As a consequence the actual performance in one of these tunes may be less than that implied by the first order matrix.)

4.5 FIELD AND ALIGNMENT TOLERANCES

The optical properties of the spectrometer are based on the realization of a well defined magnetic field configuration or field map, supposedly known with infinite accuracy. Once the particle coordinates in the focal plane area have been measured, this configuration serves as input in the reconstruction of particle momentum and angles from trajectory integration through the spectrometer. The purpose of this section is to show how much the field map which will enter into the calculation may differ from the desired theoretical one before the performances become degraded to an unacceptable level. This will define tolerances which fall into two broad categories:

- 1) Tolerances on an imperfect knowlege of the physically realized map itself. This imperfect knowlege results from field measurement uncertainties, instabilities of the field map, due for example to uncontrolled instabilities of the power supply, hysteresis effects, eddy currents, alignment uncertainties , etc....
- 2) Tolerances on deviations from the desired field map which are known (measurable) and reproducible. Such deviations result from mechanical imperfections and inaccuracies in predicting the field configurations. Unwanted multipole components can introduce aberrations to the optical properties that can compromise the performance of the device.

4.5.1 Type 1 Field Tolerances

Expressing the first order field properties of the various magnets in terms of their multipole strengths given by:

$$S_0 = hL \quad (\text{Dipole}) \quad (1)$$

$$S_1 = \frac{\lambda L}{B\rho} \quad (\text{Quadrupole}) \quad (2)$$

$$S_1 = -h \tan \beta \quad (\text{Dipole entrance or exit}) \quad (3)$$

$$S_1 = -nh^2 L \quad (\text{Dipole with field index}) \quad (4)$$

where λ = the quadrupole field gradient, $B\rho = \frac{P}{e}$ or the magnetic rigidity of the particle, β = the angle of rotation of the entrance or exit face of the dipole, and $h = (\text{bend radius})^{-1}$, one can evaluate the maximum allowed variation in the magnetic multipole strengths using first order transport formalism⁵.

First, consider the S_0 aspect of the dipole. In this case the momentum determination is the limiting factor. The momentum measurement comes into play in two different ways,

absolute calibration and resolution. For absolute calibration one is concerned with long term stability and reproducibility of the dipolar field. In this case we use the criteria that $\Delta\delta \leq 10^{-4}$ which gives

$$\delta S_0 \leq 8 \times 10^{-5}$$

leading to

$$\frac{\delta S_0}{S_0} \leq 10^{-4}$$

This gives the degree to which the product of the dipole field times its length must be known and maintained in order to get an absolute energy calibration of $\Delta\delta \leq 10^{-4}$. For resolution one is concerned with the short term stability of the dipolar field, changes that could occur during the course of taking a data point. This sets a tolerance on things like power supply stability. In this case we use the criteria that $\Delta\delta \leq 3 \times 10^{-5}$ which gives

$$\delta S_0 \leq 4 \times 10^{-5}$$

leading to

$$\frac{\delta S_0}{S_0} \leq 3 \times 10^{-5}$$

(restrictions on S_0 imposed by θ_0 resolution are about an order of magnitude greater than those imposed by momentum resolution.)

Table 4.4 shows the maximum allowed field error, as limited by the various performance constraints, for each quadrupolar element. The field errors are expressed in terms of the integrated multipole strength factors over the whole magnet. Also shown are the design values of the S_1 's, the minimum δS_1 , and the allowed relative error.

In constructing a table such as table 4.4 one needs to know what the acceptable variations of δ_0 , θ_0 , ϕ_0 , and y_0 are. In the present case these are driven by the design goals of the spectrometer. The values chosen were one half the FWHM's determined in the simulation studies of the spectrometer performance (see section 4.6):

$$\Delta\delta_0 \leq 3 \times 10^{-5}$$

$$\Delta\theta_0 \leq 1.0 \text{ } m\text{r}$$

$$\Delta y_0 \leq 0.06 \text{ } cm$$

$$\Delta\phi_0 \leq 0.3 \text{ } m\text{r}$$

Table 4.4

 δS_1 (cm^{-1})

	δ_o limited	θ_o limited	y_o limited	ϕ_o limited
Q_1	5.8×10^{-6}	8.1×10^{-5}	3.4×10^{-5}	3.5×10^{-5}
Q_2	5.1×10^{-6}	2.4×10^{-4}	3.3×10^{-6}	5.1×10^{-6}
Dipole entrance	5.4×10^{-7}	6.5×10^{-6}	1.1×10^{-5}	3.9×10^{-5}
Dipole center	5.1×10^{-7}	5.4×10^{-6}	2.3×10^{-5}	6.5×10^{-5}
Dipole exit	9.8×10^{-7}	9.0×10^{-6}	3.3×10^{-5}	2.2×10^{-5}
Q_3	3.4×10^{-6}	2.3×10^{-5}	3.1×10^{-5}	1.2×10^{-5}
	S_1	δS_1 (min.)	$\frac{\delta S_1}{S_1}$	
Q_1	5.5×10^{-3}	5.8×10^{-6}	$\pm 1.1 \times 10^{-3}$	
Q_2	4.3×10^{-3}	3.3×10^{-6}	$\pm 7.7 \times 10^{-4}$	
Dipole entrance	6.9×10^{-4}	5.4×10^{-7}	$\pm 7.8 \times 10^{-4}$	
Dipole center	1.2×10^{-3}	5.1×10^{-7}	$\pm 4.3 \times 10^{-4}$	
Dipole exit	6.9×10^{-4}	9.8×10^{-7}	$\pm 1.4 \times 10^{-3}$	
Q_3	4.1×10^{-3}	3.4×10^{-6}	$\pm 8.3 \times 10^{-4}$	

The tolerances presented in table 4.4 should be thought of as tolerances on performance of the magnets (category 1). That is to say they specify how reproducible the magnetic fields for the magnets should be as well as how well those fields will need to be mapped in order to understand the system well enough to achieve the desired resolutions.

To fully appreciate table 4.4 one needs to recall what S_1 and hence δS_1 mean in terms of each of the magnets. For a Quadrupole the case is simple. S_1 as given by equation 2 is just the field gradient times the length divided by a term proportional to the momentum of the particle (the "magnetic rigidity" of the particle). Table 4.4 then tells how well the product of field gradient times effective length must be maintained in each quadrupole.

In the middle of the dipole S_1 is given by the n -value through equation 4. From this one can evaluate a tolerance on n

$$\delta S_1 = -h^2 L \delta n \quad (5)$$

which gives

$$\delta n \leq 5.5 \times 10^{-4}$$

This is the maximum allowed variation in n averaged over the length of the magnet. Local variations may be larger. For example, if the variation in n occurred over only 10 cm along

the particle trajectory then

$$\delta n \leq 0.04$$

Similarly, the effective length of the dipole must be maintained, assuming n is constant and correct, to within 0.3 cm.

Recall that these are not actual mechanical requirements on the magnet. If n in the finally assembled magnet is not exactly that specified there is some range of adjustability in the design whereby the incorrect value of n can be compensated for by making adjustments in the quadrupole field gradients (see section 4.5.3). What these numbers tell is how stable and reproducible the n value and effective length of the magnet must be in normal operation.

For the entrance and exit of the dipole the situation is somewhat more complicated. For an entrance or exit face S_1 is given by equation 3. With this expression and the limits on δS_1 expressed in table 4.4 one can evaluate how well the angle β must be maintained, which is to say how well the slope of the effective field boundary must be maintained. With curved entrance and exit faces being used to minimize higher order aberrations the slope of the effective field boundary is not constant but varies along the boundary

$$\delta\beta \leq \frac{\delta S_1}{h \sec^2 \beta} \quad (6)$$

The variation of $\delta\beta$ with displacement from the central ray for the entrance and exit of the dipole is given in figure 4.5. On average the requirements are $\delta\beta \leq 0.25 \text{ } mr$ at the dipole entrance and $\delta\beta \leq 0.65 \text{ } mr$ at the dipole exit.

4.5.2 Type 2 Field Tolerances

Using transport optics formalism⁵ one can evaluate coupling strengths between second and higher order aberrations and their associated higher order multipoles in the various magnets. Couplings have been evaluated between selected higher order matrix elements and multipole field components in each of the magnets. The results are shown in table 4.5. The aberrations selected were in general aberrations that would have an effect on the x-position at the focal plane. This choice was driven by the observation that in table 4.4 it is almost always the momentum, and hence x measurement that defines the tolerance in the first order properties.

Having evaluated the couplings in table 4.5 one must then define how large a change in a given aberration can be tolerated. That allowed change in the aberration can then be

Figure 4.5 Maximum allowable deviation from its ideal value of the angle (β) between the optical axis and the effective field boundary of the dipole. Dipole entrance and exit are shown separately.

Table 4.5

	$\frac{\partial(x \theta\delta)}{\partial S_2}$	$\frac{\partial(x \theta^2)}{\partial S_2}$	$\frac{\partial(x \phi^2)}{\partial S_2}$	$\frac{\partial(y \phi\delta)}{\partial S_2}$	$\frac{\partial(y y\delta)}{\partial S_2}$
Q ₁	0.	-19.7	23.8	0.	0.
Q ₂	0.	-23.8	266.	0.	0.
D entrance	0.	-690.	245.	0.	0.
D center	-142.	-762.	126.	5.90	-1.03
D exit	-251.	-256.	52.9	28.7	-21.7
Q ₃	-69.8	-18.4	199.	61.8	-78.7
	$\frac{\partial(x \theta^3)}{\partial S_3}$	$\frac{\partial(x \theta^2\phi^2)}{\partial S_3}$	$\frac{\partial(x \theta^2\delta)}{\partial S_3}$	$\frac{\partial(x \theta\delta^2)}{\partial S_3}$	
Q ₁	-39.3	143.	0.0	0.0	
Q ₂	-50.5	1700.	0.0	0.0	
D entrance	-4.51×10^3	4.79×10^3	0.0	0.0	
D center	-5.14×10^3	2.55×10^3	-1.44×10^3	-134.	
D exit	-1.20×10^3	745.	-1.77×10^3	-869.	
Q ₃	-36.0	117.	-204.	-387.	
	$\frac{\partial(x \theta^4)}{\partial S_4}$	$\frac{\partial(x \theta^3\phi^2)}{\partial S_4}$	$\frac{\partial(x \phi^4)}{\partial S_4}$	$\frac{\partial(x \theta^3\delta)}{\partial S_4}$	
Q ₁	-78.5	570.	-115.	0.0	
Q ₂	-107.	7.21×10^3	-1.34×10^4	0.0	
D entrance	-2.94×10^4	6.26×10^4	-3.70×10^3	0.0	
D center	-3.47×10^4	3.44×10^4	-945.	-1.29×10^4	
D exit	-5.64×10^3	6.99×10^3	-241.	-1.11×10^4	
Q ₃	-70.2	456.	-82.2	-532.	
	$\frac{\partial(x \theta^5)}{\partial S_5}$	$\frac{\partial(x \theta^4\phi^2)}{\partial S_5}$	$\frac{\partial(x \theta\phi^4)}{\partial S_5}$	$\frac{\partial(x \theta^4\delta)}{\partial S_5}$	
Q ₁	-157.	1.90×10^3	-1.15×10^3	0.0	
Q ₂	-228.	2.55×10^4	-1.43×10^5	0.0	
D entrance	-1.92×10^5	6.81×10^5	-1.21×10^5	0.0	
D center	-2.34×10^5	3.87×10^5	-3.19×10^4	-1.09×10^5	
D exit	-2.65×10^4	5.47×10^4	-5.65×10^3	-6.50×10^4	
Q ₃	-137.	1.48×10^3	-803.	-1.30×10^3	

translated through the couplings into a change in a multipole component of each of the magnets.

Table 4.5 is useful for evaluating specific classes of field errors that can be simply characterized by a multipolar description of the field in a given magnet. However, to attempt to use the couplings in Table 4.5 to describe in a general way tolerances on all the possible field errors one is likely to encounter in the finally manufactured magnets is essentially

Table 4.5 continued

	$\frac{\partial(x \theta^6)}{\partial S_R}$	$\frac{\partial(x \theta^4\phi^2)}{\partial S_R}$	$\frac{\partial(x \theta^2\phi^4)}{\partial S_R}$	$\frac{\partial(x \phi^6)}{\partial S_R}$	
Q ₁	-313.	$5.68 \times 10^{+3}$	$-6.87 \times 10^{+3}$	554.	
Q ₂	-485.	$8.14 \times 10^{+4}$	$-9.10 \times 10^{+5}$	$6.79 \times 10^{+5}$	
D entrance	$-1.26 \times 10^{+6}$	$6.68 \times 10^{+6}$	$-2.37 \times 10^{+6}$	$5.59 \times 10^{+4}$	
D center	$-1.58 \times 10^{+6}$	$3.91 \times 10^{+6}$	$-6.46 \times 10^{+5}$	$7.11 \times 10^{+3}$	
D exit	$-1.24 \times 10^{+5}$	$3.85 \times 10^{+5}$	$-7.96 \times 10^{+4}$	$1.10 \times 10^{+3}$	
Q ₃	-267.	$4.34 \times 10^{+3}$	$-4.70 \times 10^{+3}$	339.	
	$\frac{\partial(x \theta^7)}{\partial S_7}$	$\frac{\partial(x \theta^5\phi^2)}{\partial S_7}$	$\frac{\partial(x \theta^3\phi^4)}{\partial S_7}$	$\frac{\partial(x \theta\phi^6)}{\partial S_7}$	
Q ₁	-625.	$1.59 \times 10^{+4}$	$-3.20 \times 10^{+4}$	$7.75 \times 10^{+3}$	
Q ₂	$-1.03 \times 10^{+3}$	$2.42 \times 10^{+5}$	$-4.52 \times 10^{+6}$	$1.01 \times 10^{+7}$	
D entrance	$-8.20 \times 10^{+6}$	$6.10 \times 10^{+7}$	$-3.60 \times 10^{+7}$	$2.55 \times 10^{+6}$	
D center	$-1.07 \times 10^{+7}$	$3.70 \times 10^{+7}$	$-1.02 \times 10^{+7}$	$3.36 \times 10^{+5}$	
D exit	$-5.83 \times 10^{+5}$	$2.53 \times 10^{+6}$	$-8.72 \times 10^{+5}$	$3.60 \times 10^{+4}$	
Q ₃	-522.	$1.19 \times 10^{+4}$	$-2.14 \times 10^{+4}$	$4.64 \times 10^{+3}$	
	$\frac{\partial(x \theta^8)}{\partial S_R}$	$\frac{\partial(x \theta^6\phi^2)}{\partial S_R}$	$\frac{\partial(x \theta^4\phi^4)}{\partial S_R}$	$\frac{\partial(x \theta^2\phi^6)}{\partial S_R}$	$\frac{\partial(x \phi^8)}{\partial S_R}$
Q ₁	-1.25×10^3	4.23×10^4	-1.92×10^5	6.19×10^4	-2.67×10^3
Q ₂	-2.19×10^3	6.86×10^5	-2.88×10^7	8.59×10^7	-3.43×10^7
D entrance	-5.36×10^7	5.32×10^8	-7.06×10^8	6.67×10^7	-8.45×10^5
D center	-7.20×10^7	3.33×10^8	-2.06×10^8	9.07×10^6	-5.35×10^4
D exit	-2.73×10^6	1.58×10^7	-1.23×10^7	6.76×10^5	-5.00×10^3
Q ₃	-1.02×10^3	3.09×10^4	-1.25×10^5	3.62×10^4	-1.40×10^3

impossible. As a general rule of thumb the type 2 tolerances on the magnets can be specified in essentially the same way as the type 1 tolerances except in this case the limiting criteria is the designed hardware rather than software resolution of the spectrometer. As the spectrometer has been optimized for hardware resolution in momentum only, hardware momentum resolution is the relevant quantity to maintain. One would like to maintain hardware momentum resolution at roughly 5 times that achieved in the software which leads to tolerances on the measureable deviations of the field map from its ideal value at 5 times those implied by table 4.4 column 1. These are tabulated in table 4.6.

Table 4.6 gives the maximum allowed deviation of the field gradient from its ideal value in each of the quadrupole magnets. Tolerances of this type in the dipole are given in the following section.

Table 4.6

Type 2 Tolerance on Field in Focussing Elements

	ΔS_1 (cm^{-1})	S_1	$\frac{\Delta S_1}{S_1}$
Q ₁	2.9×10^{-5}	5.5×10^{-3}	$\pm 5.3 \times 10^{-3}$
Q ₂	2.6×10^{-5}	4.3×10^{-3}	$\pm 6.1 \times 10^{-3}$
Q ₃	1.7×10^{-5}	4.1×10^{-3}	$\pm 4.2 \times 10^{-3}$

4.5.3 Retunability

Using the program TRANSPORT³ and considering only first order effects a study has been made of the possibility of retuning the quadrupole elements either by changing their field gradients slightly or moving them a few centimeters in order to compensate for errors in the finally achieved first order focussing properties of the dipole magnet. These would be errors in the form of known, measured deviations from the desired field map. In the study the shim angles, β 's, and the field index, n , were each varied separately in order to produce a 5% change in the value of S_1 , (see eqs. 3 and 4). Then the spacings and field gradients of the quadrupoles were adjusted in order to restore the first order focussing properties of the system. The results were studied with an eye toward loss of solid angle, unacceptable movement of a quadrupole, and unacceptable change in some first order optical properties. In general, it was possible to absorb the 5% changes in the dipole S_1 's without serious impact on the solid angle or optical properties of the spectrometer. However, the required changes in the field gradients and positions of the magnets did occasionally become critical. In conclusion, it is safe to say that changes on the order of 3% in the S_1 's resulting from the shim angles and field index of the dipole can be corrected for to first order by making adjustments in the quadrupole elements. This corresponds to

$$\Delta\beta = 13mr$$

$$\Delta n = 0.03$$

4.5.4 Alignment Tolerances

The principal effect of a misalignment of a magnet perpendicular to the optic axis on the overall performance of a spectrometer is the introduction of systematic errors in the absolute calibration of the instrument. Indeed, raytracing simulations have indicated that misalignments on the order of 1 mm linear displacement and 1 mr angular rotation produce no appreciable effect on the resolution capabilities of the device. That is to say

that one's ability to discern differences in momentum or scattering angle or transverse target position between various rays is unaffected by the misalignment. The absolute values of measurements are, however, affected. Assuming that one can make an absolute calibration of the spectrometer after it is assembled, the alignment tolerances discussed here represent the amount that a given magnet can be allowed to move, during an angle change for example, after it is positioned on the support structure.

Changes in the focal plane coordinates of rays, Δf 's, resulting from misalignments were determined using the magnet alignment tolerance feature of TRANSPORT³ (Type code 8.0). The effects at the focal plane on the centroid of a monochromatic ($\delta = 0$) beam, spanning the full solid angle of the spectrometer ($\theta = \pm 65$, $\phi = \pm 30$ mr), were evaluated for a full set of misalignments for each magnet element.

Misalignments of six specific types have been evaluated. Three orthogonal linear translations (Δx , Δy , & Δz) and rotations about each of the translation axes ($\Delta \Theta_x$, $\Delta \Theta_y$, & $\Delta \Theta_z$). Shifts at the focal plane (Δf) of the centroid of a monochromatic beam spanning the full solid angle of the spectrometer ($\theta = \pm 65$, $\phi = \pm 30$ mr) resulting from each type of misalignment for each magnet are evaluated using TRANSPORT³. Those Δf 's were translated through the first order transport matrix into changes in the trajectory coordinates at the target ($\Delta \tau$). These changes could then be related to maximum allowable misalignments.

Table 4.7 shows the amount of misalignment for each magnet needed to produce $\Delta \delta = 1 \times 10^{-4}$, $\Delta \phi_0 = 0.5$ mr, $\Delta \theta_0 = 1$ mr, and $\Delta y_0 = 0.1$ cm. The quoted maximum allowable misalignment in each category is the minimum in each row. In situations where the standard translations or rotations (1cm or 1mr) used in TRANSPORT³ produced negligibly small effects the tolerances are undoubtedly greater.

It should be noted that the described procedure for evaluating misalignment tolerances is based completely on the first order optics characteristics of the spectrometer. While it is reasonably safe to assume that first order effects will dominate, one would feel more confident if higher order effects could be included in the analysis. A raytracing based procedure can be envisioned that would address the desire to include higher order effects in the alignment tolerance analysis. Such an analysis was performed using an earlier design which showed the same sensitivities as those determined by the first order analysis.

In addition to the calibration errors discussed above misalignments involving translations along the optical axis of the spectrometer and rotations about the optical axis

Table 4.7

Misalignment of Magnet Elements Needed
to Produce the Listed Changes in
 $\Delta\delta_o$, $\Delta\theta_o$, Δy_o ,
and $\Delta\phi_o$

Misalignment of Q1	$\Delta\delta_o = 1 \times 10^{-4}$	$\Delta\theta_o = 1.0$	$\Delta y_o = 0.1$	$\Delta\phi_o = 0.5$
x (cm)	4.7×10^{-2}	0.49		
Θ_z (mr)			-1.9	2.1
y (cm)			8.2×10^{-2}	-8.5×10^{-2}
Θ_y (mr)	1.1	14.		
Misalignment of Q2				
x (cm)	-5.3×10^{-2}	0.25		
Θ_z (mr)			0.37	-0.58
y (cm)			-3.4×10^{-2}	5.3×10^{-2}
Θ_y (mr)	-0.6	2.3		
Misalignment of D				
x (cm)	2.9×10^{-2}	-6.2×10^{-2}		
Θ_z (mr)			-0.4	-0.4
y (cm)			-0.1	0.37
Θ_y (mr)	9.1×10^{-2}	-0.2		
z (cm)	5.7×10^{-2}	-0.14		
Θ_z (mr)			0.7	-5.6
Misalignment of Q ₃				
x (cm)	-6.0×10^{-2}	9.3×10^{-2}		
Θ_z (mr)			1.5	0.5
y (cm)			-0.12	-4.8×10^{-2}
Θ_y (mr)	-0.8	1.1		

introduce errors in the focussing properties of the device. These too can be evaluated using a first order TRANSPORT³ analysis. Using a point, monochromatic source spanning the full solid angle of the spectrometer the misalignments are varied until the half width of the beam matrix ($\sqrt{\sigma(1,1)}$), which for a point, monochromatic source spanning the full solid angle equals zero in first order, becomes 0.064 cm corresponding to an uncertainty in δ of $\pm 5 \times 10^{-5}$. Tolerances resulting from these focussing errors are shown in table 4.8.

Table 4.8

Focussing Error Misalignment Tolerances
 Misalignments given are those needed to
 generate a spot at the focal plane with
 $\sqrt{\sigma(1,1)} = 0.062\text{cm}$ corresponding to
 $\Delta\delta = \pm 5 \times 10^{-5}$

Magnet	Δz (cm)	$\Delta\Theta_z$ (mr)
Q_1	0.38	1.72
Q_2	0.49	0.63
Q_3	0.28	2.46
Q_1-Q_2	1.56	0.06
Dipole		0.75
QQDQ	0.38	

4.5.5 Summary of Tolerances

The tolerances developed here can be summarized as follows:

1) Tolerances on the knowledge of the physically realized field map itself:

Dipole Field:

$$\text{bending} \quad \frac{\Delta S_0}{S_0} = \frac{\Delta(B_0 L)}{(B_0 L)} = 6 \times 10^{-5} \text{ (FWHM)}$$

$$\text{focussing} \quad \frac{\Delta S_1}{S_1} \text{ (FWHM)}$$

$$D_{entr.} \quad 2 \times 10^{-3} \rightarrow \Delta\beta = 0.5 \text{ } mr$$

$$D_{center} \quad 8 \times 10^{-4} \rightarrow \Delta n = 6 \times 10^{-4} \text{ (avg. over 6.6 m)}$$

$$D_{exit} \quad 3 \times 10^{-3} \rightarrow \Delta\beta = 1.2 \text{ } mr$$

$$\text{Quadrupoles} \quad \frac{\Delta S_1}{S_1} \text{ (FWHM)} (= \frac{\Delta G_0 L}{G_0 L})$$

$$Q_1 \quad 2 \times 10^{-3}$$

$$Q_2 \quad 2 \times 10^{-3}$$

$$Q_3 \quad 2 \times 10^{-3}$$

2) Tolerances on known (measurable) deviations:

$$\text{Quadrupoles} \quad \frac{\Delta S_1}{S_1} \text{ (FWHM)} (= \frac{\Delta G_0 L}{G_0 L})$$

$$Q_1 \quad 1 \times 10^{-2}$$

$$Q_2 \quad 1 \times 10^{-2}$$

$$Q_3 \quad 1 \times 10^{-2}$$

Dipole Magnet (Retunability limited)

$$\Delta\beta = \pm 13 \text{ } mr$$

$$\Delta n = \pm 0.03$$

3) Tolerances on position uncertainties

(to achieve $\pm 10^{-4}$ absolute momentum calibration, $\pm 1mm.$ transverse position calibration, $\pm 0.5mr$ ϕ calibration, and $\pm 1mr$ θ calibration)

Quadrupoles

$$\Delta x = \pm 0.5 \text{ } mm$$

$$\Delta\Theta_x = \pm 0.4 \text{ } mr$$

$$\Delta y = \pm 0.4 \text{ } mm$$

$$\Delta\Theta_y = \pm 0.6 \text{ } mr$$

Dipole

$$\Delta x = \pm 0.3 \text{ mm}$$

$$\Delta \Theta_z = \pm 0.4 \text{ mr}$$

$$\Delta y = \pm 1 \text{ mm}$$

$$\Delta \Theta_y = \pm 0.1 \text{ mr}$$

$$\Delta z = \pm 0.6 \text{ mm}$$

$$\Delta \Theta_z = \pm 0.7 \text{ mr}$$

(to maintain $\pm 5 \times 10^{-5}$ momentum resolution)

Q_1	$\Delta z = \pm 0.4 \text{ cm}$	$\Delta \Theta_z = \pm 1.7 \text{ mr}$
Q_2	$\Delta z = \pm 0.5 \text{ cm}$	$\Delta \Theta_z = \pm 0.6 \text{ mr}$
Q_3	$\Delta z = \pm 0.3 \text{ cm}$	$\Delta \Theta_z = \pm 2.5 \text{ mr}$
Q_1 - Q_2	$\Delta z = \pm 1.6 \text{ cm}$	$\Delta \Theta_z = \pm 1.0 \text{ mr}$
Dipole		$\Delta \Theta_z = \pm 0.8 \text{ mr}$
QQDQ	$\Delta z = \pm 0.4 \text{ cm}$	

4.6 EXPECTED PERFORMANCES

4.6.1 Momentum, Angle and Position Resolution

In an effort to evaluate the potential usefulness of software corrections and their sensitivities to measurement errors the following *ad hoc* procedure was developed. Although a similar procedure will be used to interpret focal plane data, the one presented here has not been optimized towards that purpose. This procedure is intended more as a diagnostic tool for evaluating potential spectrometer performance.

A large number of randomly generated rays are traced through the spectrometer using RAYTRACE⁴. The target ray coordinates $(x_0, \theta_0, y_0, \phi_0, \delta)$ and the focal plane ray coordinates $(x_f, \theta_f, y_f, \phi_f)$ are used as input to the program MUDIFI⁶ which is used to determine a best fit polynomial that will give the target coordinates as a function of the four focal plane coordinates. Once a polynomial for each of the target coordinates has been determined one is in a position to make various tests of the spectrometer resolution capabilities.

For example, for the QQDQ spectrometer a set of ~ 2000 rays spanning the full acceptance was used (θ_0 and ϕ_0 were constrained such that the combination of θ and ϕ fell within the ellipse described by θ_{max} and ϕ_{max}). The "focal plane" used was a straight flat surface chosen at an angle of 44° relative to the optic axis (see figure 4.4)

Table 4.9 shows a summary of the achieved fits. Fits giving resolutions equal to or better than the desired spectrometer performance were achieved.

Having determined the four resolution functions $(\delta(x_f, \theta_f, y_f, \phi_f), \theta(x_f, \theta_f, y_f, \phi_f), y(x_f, \theta_f, y_f, \phi_f), \phi(x_f, \theta_f, y_f, \phi_f))$ one is in a position to evaluate the sensitivity of a δ , θ_0 , y_0 , or ϕ_0 determination to measurement errors. This was done using a different set of test rays and a gaussian random number generator. In the test set of rays the value of x_0 was varied between ± 0.01 cm to account for the finite beam spot size. Focal plane coordinates were randomly altered within certain σ 's, simulating an error in the measurements of the focal plane coordinates. The resolution function values with the altered focal plane coordinates were compared to the actual values of the target coordinates. The spreading of a histogram of the difference between the "measured" and actual value of the target coordinates as a result of this inclusion of measurement errors gives an indication of the sensitivity to those measurement errors.

We have considered an average measurement uncertainty in the linear coordinates of

Table 4.9
QQDQ
Resolution From Fitted Functions Alone

σ_δ (%)	0.0024
σ_{θ_o} (mr)	0.29
σ_{y_o} (cm)	0.057
σ_{ϕ_o} (mr)	0.17

$\sigma = 0.01$ cm and in the angular coordinates of $\sigma = 0.5$ mr. This could be achieved, in principle, using two sets of (x,y) drift chambers, the first one located in the focal plane at an angle of 44° to the optic axis, the second 50cm behind (see section 7). The quoted angular resolution is a typical value at 1 GeV/c for e^- , taking into account multiple scattering in the windows and chambers with He gas between the chambers. Table 4.10 shows how σ for the various histograms changed with the inclusion of measurement errors over the full acceptance described above. Figure 4.6 shows the momentum dependence of the different resolutions for the stated measurement errors.

Table 4.10
QQDQ
Resolutions With Measurement Errors Added

σ_{zf} (cm)	0.01	0	0	0	0.01
$\sigma_{\theta f}$ (mr)	0	0.5	0	0	0.5
σ_{yf} (cm)	0	0	0.1	0	0.01
$\sigma_{\phi f}$ (mr)	0	0	0	0.5	0.5
σ_δ (%)	0.0025	0.0028	0.0024	0.0027	0.0037
σ_{θ_o} (mr)	0.29	0.87	0.29	0.29	0.87
σ_{y_o} (cm)	0.057	0.058	0.057	0.069	0.071
σ_{ϕ_o} (mr)	0.17	0.21	0.17	0.28	0.34

It is of some interest to note that the target coordinate resolution sensitivity to measurement error is essentially what one would expect from the first order transport matrix, indicating good spectrometer performance and minimal contribution from higher order aberrations.

Procedures modeled after that described above can be used to evaluate many different aspects of spectrometer performance. Sample rays can be traced through deliberately misaligned or mistuned magnets and the effects of the misalignments or mistunings on

Figure 4.6 Results of multi-ray simulation of QQDQ spectrometer operation folding in the effects of typical experimental errors. a) indicates how δ and ϕ_0 resolution vary with momentum across the focal plane. Resolutions are given in terms of full width at half maximum. b) is the same as a) except now θ_0 and y_0 resolutions are shown.

resolution can be ascertained. Similarly, one can evaluate various experimental scenarios involving particular target configurations.

4.6.2 Beam Envelopes

An approximate representation of the expected beam envelope through the spectrometer has already been presented in figure 4.3. However, for the purposes of designing detector packages, magnetic elements, collimators, baffling, and vacuum systems, as well as to acquire a better understanding of the acceptance features of the device in terms of all of the above a more rigorous raytracing based representation of the beam envelope is more useful. The accompanying figures 4.7–4.10 generated with the raytracing program SNAKE⁷ and analytic magnetic field calculations are typical of what will be used to determine the beam envelope at various locations in the spectrometer. In the future realistic field maps from 3-D calculations can be used, in particular in the fringe field regions and at the limits of the useful apertures.

4.6.3 Geometric Acceptances

The geometric acceptance as limited by the physical apertures of the magnets has been studied using RAYTRACE⁴. Circular collimators were placed at the exit of each of the quadrupoles and rectangular collimators at the entrance and exit of the dipole. A set of 500 randomly generated rays spanning a solid angle of 14.4 msr, more than the expected acceptance, were traced through the spectrometer. Rays that exceeded the collimator dimensions were eliminated, and the fraction of rays leftover gave the solid angle acceptance, which has been studied as a function of momentum (δ_0) and target position along the beam (y_0). The results are shown in figure 4.11.

4.6.4 Special Issues

Here we briefly address two particular modes of operation

- the use of a momentum dispersed beam and dispersion matching to improve resolution.
- a possible scenario for out-of-plane experiments by moving the beam.

By having both spectrometers bend vertically, the missing energy resolution δE in a coincidence experiment can be improved over the beam energy spread by using a dispersion matching mode of operation analagous to the energy-loss mode used in single-arm experiments.

Figure 4.7 SNAKE⁷ generated envelope of rays traced through the spectrometer. Rays shown are for electrons at three discrete momenta (3.795, 3.993, and 4.191 GeV/c) with $\theta_0 = -65, -32.5, 0, 32.5,$ and 65mr , $\phi_0 = -30, -15, 0, 15,$ and 30mr . The top picture shows the entire spectrometer. The bottom picture gives an expanded view of the detector area. In both pictures (0,0) corresponds to the focus of the central momentum (4 GeV/c). Distances are in mm.

Figure 4.8 SNAKE⁷ generated envelope of rays traced through the spectrometer. Shown are 100 randomly generated rays within the limits $3.795 \leq P \leq 4.191$ GeV/c, $-65 \leq \theta_0 \leq 65$ mr, $-30 \leq \phi_0 \leq 30$ mr, and $-5 \leq y_0 \leq 5$ cm. The top picture shows the dispersive (vertical) plane for the entire spectrometer. The bottom picture shows an expanded view of the transverse plane in the detector region. The arrow in the top picture shows the direction along which one is viewing the transverse envelope in the bottom picture. In both pictures (0,0) corresponds to the focus of the central momentum (4 GeV/c). Distances are in mm.

Figure 4.9 SNAKE⁷ generated envelope of rays traced through the spectrometer. Shown are the same 100 randomly generated rays as in figure 4.10. The top picture shows the dispersive (vertical) plane for the entire spectrometer. The bottom picture shows an expanded view of the transverse plane in the detector region as viewed edge on to the focal plane. The arrow in the top picture shows the direction along which one is viewing the transverse envelope in the bottom picture. In both pictures (0,0) corresponds to the focus of the central momentum (4 GeV/c). Distances are in mm.

Figure 4.10a SNAKE⁷ generated envelope of rays in the detector area traced through the spectrometer for fixed energies with all possible combinations of $\phi_0 = -30, -15, 0, 15, 30$ mr and $y_0 = -3, -1.5, 0, 1.5, 3$ cm. Noteworthy is the very sharp transverse focus, corresponding to $\langle y|y_0 \rangle = 0$. Shown are the transverse envelope in the detector area for $p=3.8$ and 4.0 GeV/c .

Figure 4.10b SNAKE⁷ generated envelope of rays as in figure 4.10a. Shown are the transverse envelope in the detector area for $p=4.2 \text{ GeV/c}$ and the locations in the dispersive plane of the transverse foci.

Figure 4.11 Solid angle acceptances as a function of momentum (a) and target position along the beam (b) obtained from trajectory calculations through the QQDQ spectrometer.

The incident beam is vertically dispersed on the target with dispersion D_B , related to the dispersion D_e (D_p) and magnification M_e (M_p) of the electron (hadron) spectrometers through the relation⁸ (neglecting recoil of the residual system, but relativistically correct)

$$D_B = -p_o \left[p_e \frac{M_e}{D_e} + \frac{p_p^2}{E_p} \frac{M_p}{D_p} \right]^{-1}$$

where $p_o(p_e, p_p)$ is the beam (scattered electron, hadron) momentum, and E_p is the final hadron energy. In our case, $M_e = M_p = M$, and $D_e = D_p = D$ and the above expression simplifies to

$$D_B = -p_o \frac{D}{M} \left[p_e + \frac{p_p^2}{E_p} \right]^{-1}$$

This leads to a dispersion, D_B , for the beam which is always smaller than 10 m.

Such dispersion is achieved in the horizontal plane by an appropriate tuning of the beam transport line. Then, the beam is rotated by 90° through a five quadrupole system. The “beam rotator” can be made such that the equivalent first order matrix, in both planes is equivalent to a free drift space of the same length, or to a unit matrix. An example of such a five quadrupole rotator is shown section 8, figure 8.5.

The basic method envisaged to provide the capability to make coincidence measurements with non-coplanar kinematics is to bend the incident beam upwards and then downwards into the target thereby taking the electron beam out of the plane described by the two spectrometers. This is seen as a high priority capability to be implemented early in the second phase of development of Hall A. In order to ensure that such a capability remains a real possibility certain provisions have been made in the civil construction design of the hall. Most notably, the vertical size of the entrance of the beam dump tunnel has been increased to allow for an out-of-plane beam line entry to the dump. The out-of-plane beam line is shown schematically in figure 1.5 of section 1.

Section 4 References

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5. MAGNETIC ELEMENTS

5.1 DIPOLE

5.1.1 Overview

A single focusing dipole with a negative field gradient as well as rotated and curved pole faces will be the primary element of the Hall A high resolution spectrometers. The field in the useful volume for the dipole is iron-dominated and the field gradient is achieved with conical shaped pole pieces, i.e. the gap between the pole pieces varies linearly with the radius and is independent of bend angle. The main design parameters for the dipole are given in Table 5.1.

Table 5.1
Dipole Field Specifications

Magnetic length	6.6	m
Central gap	0.25	m
Central Bend radius	8.4	m
Central Bend angle	45°	
Effective width	1.0	m
Entrance Angle	-30°	
Exit Angle	-30°	
Entrance Curvature	0.274	m ⁻¹
Exit Curvature	-0.140	m ⁻¹
Maximum Central Field	1.59	T
Minimum Central Field	0.20	T
Field index (<i>n</i>)	-1.25	
Max. field deviation	$\pm 2 \times 10^{-4}$	

Shown in Figure 5.1 is a schematic representation of the field boundaries in the radial (dispersive) plane. Also shown in the figure are the curvatures of the entry and exit faces. At full excitation the central field value (along the optic axis of the dipole) is 1.59T which corresponds to 4 GeV/c particles. With a field index of -1.25, the field at the useful aperture will be 1.708T(1.472T) at the inside(outside) boundary. The pole surfaces are tilted by 2.13° with respect to each other.

5.1.1.1 Basic Choice

Exhaustive studies of various dipole geometries have been carried out¹ with field requirements very similar to the specifications of Table 5.1. These include both H-frame and window-frame yoke and pole configurations with saddle or racetrack coil packages. Room temperature as well as superconducting coils have been considered in these studies. After careful studies, the H-frame, separate pole and yoke geometry was determined to be

Figure 5.1 Schematic field boundaries of the HRS dipole. The entry and exit face field boundaries are shown in their local coordinate system.

the most efficient design for dipoles of such large apertures. Furthermore, it was decided that all of the spectrometer magnetic elements be equipped with superconducting coils following detail evaluation of operation costs and capital equipment costs.

Saddle coil geometries tend to produce wider useful field area for the same total pole width as racetrack coils. Hence, the total yoke volume is relatively smaller with saddle coils. However, saddle ends for such large superconducting coils are much more complex to fabricate, particularly for superconducting coils. The fabrication simplicity and structural stability of planar coils is likely to more than outweigh the cost saving in reduced iron weight in case of the technically more difficult saddle coils.

The pole surfaces need to be machined to very high tolerances. In view of the fact that the maximum bend radius of the pole pieces is in excess of 9.2 m and the surface area is relatively large, some considerations were given to the technical feasibility of machining such pole surfaces. The size precludes the use of vertical lathes which would otherwise be ideally suited for machining conical surfaces. Computer controlled horizontal boring mills capable of handling such large pieces are available. Based on discussions with potential vendors we feel encouraged that purely conical surfaces can be machined to desired tolerance.

Thus, the basic choice for the dipole geometry is: *H-frame, separate pole and yoke, conical pole surfaces, and superconducting racetrack (planar) coils.*

5.1.2 Magnetostatics

In a two dimensional cut transverse to the mid-plane of the dipole with conical pole surfaces, the gap as a function of the radial distance r , is given by:

$$g(r) = g_o \left(1 + n \frac{\Delta r}{\rho} \right)$$

where g_o is the gap at the central bend radius ρ (optic axis), Δr is $r - \rho$, and n is a constant.

For infinitely permeable iron, the magnetic field as a function of radial distance $B(r)$, is then inversely proportional to the gap:

$$\begin{aligned} B(r) &= \frac{B_o}{\left(1 + n \frac{\Delta r}{\rho} \right)} \\ &= B_o \left(1 - n \frac{\Delta r}{\rho} + n^2 \left(\frac{\Delta r}{\rho} \right)^2 - n^3 \left(\frac{\Delta r}{\rho} \right)^3 \dots \right) \end{aligned}$$

where B_o is the field at the optic axis ρ . The first order coefficient n is referred to as the field index. A negative field index implies increasing field with radial distance which provides the focusing in the radial plane.

5.1.2.1 Field Optimizations

The magnetostatics design for the dipole were carried out with the computer programs POISSON² and TOSCA.³ In optimizing the pole, yoke, and coil geometries, the following design considerations have been taken into account:

- The deviation of the computed field from an ideal conical pole field.
- The stability of the effective field boundaries and field quality over the entire dynamic range of the dipole (0.2 to 1.6 Tesla).
- Efficient magnetic circuit for the yoke in order to minimize iron volume.
- Magnetostatics forces on the coils and support structure.
- Harmonic contents, particularly in the fringing field regions.

The dipole clearly renders itself to a true 3-dimensional magnetostatics study due to its large width-to-length ratio, conical poles, tilted and curved entry and exit faces. The interior geometry of the transverse cut of the dipole was arrived at by optimizations with POISSON in 2D. An uniform mesh and standard low carbon steel B-H curves were used in the calculations. The same geometry with boundary conditions to simulate an infinitely long straight magnet (2D) was computed with TOSCA in order to test for consistency between the two programs. The two programs were in agreement about an order of magnitude better than our field quality requirements.

The optimal 2D geometry was then used as the starting parameters for full 3D studies with TOSCA. Details of the yoke volume geometry, entry and exit face curvatures, and the

coil package were optimized in 3D with TOSCA. The 3D TOSCA mesh was constructed with SCARPIA. Since the dipole has no other symmetries other than the two-fold mid-plane symmetry, one-half of the dipole space is needed to describe the case completely. The mid-plane geometry was used as the base plane in SCARPIA. The entry and exit pole faces were described with second order curves suitably adjusted to match the respective magnetic field boundaries required in the optics design performed with RAYTRACE. The volume of the dipole was constructed by extrusion of this base plane. The conical pole surfaces as well as the pole edge profiles were achieved with displacements of nodal points from the extruded planes. Shown in Figure 5.2 is the full 3D mesh used in the TOSCA

calculations. Since the problem space is rather large, careful attention was paid to the distribution of the density of nodal points to describe complex regions of the geometry, such as the entry and exit areas, accurately. Furthermore, the mesh size was also kept small in the gap so as to obtain accurate fields in the gap. Quadratic brick elements were used in the gap, fringes, and the pole volumes.

5.1.2.2 The Pole

Illustrated in Figure 5.3 is the geometry of the transverse and longitudinal cuts of the dipole. The details of the pole geometry and coil location are shown in Figure 5.4. The pole profile and coil placement shown have been optimized so as to obtain a stable field quality of about 2×10^{-4} over an excitation range of 0.2 to 1.6 T. There are four distinct features of the pole cross section:

- 1) Tilt of the inside faces forming the conical surface.
- 2) Rogowski type pole profiles at the corners.
- 3) Asymmetric tapering (shims) in the outer surface.
- 4) Thin air gap ("Purcell filter") between the pole and the yoke.

The pole surfaces themselves form part of the vacuum wall for the spectrometer. The central gap is 25 cm and the central pole thickness is 13.5 cm. In the useful region of the gap the poles are tilted at angle corresponding to the field index (2.13° with respect to each other). On either side of the pole there are flat sections which facilitate mechanical assembly of the pole pieces. The pole edges were profiled with two straight line cuts at 30° and 70° at the corners in order to reduce saturation effects. Although, such a profile does not usually create a stable field boundary as a function of field excitation, it maximizes the useful width for a given pole width. Note that stability of the field boundary is not important in the radial direction, as long as field quality is maintained in the useful width.

The entry and exit faces of the pole are contoured in accordance with the polynomials for the effective field boundaries specified by the optics requirements. Stability of the entry/exit face field boundary is much more desirable to maintain reproducibility of the $\int B dl$ seen by the particles. The pole profiles at the entry/exit faces are three-point approximations to a hyperbolic cosine profile. This profile was determined to be optimal in terms of stability of the field boundary over the dynamic range of the dipole.

Figure 5.2 The full 3D iron mesh used in the TOSCA calculations.

Figure 5.3 HRS dipole geometry.

Figure 5.4 Detail pole geometry.

The Purcell air filter gap and the tapering of the pole surface in this region plays a key role in maximizing the width of the useful field region. With racetrack coils positioned far off the mid-plane, the field falls off monotonically away from the central region. This leads to only a small fraction of the pole width as useful field region. The pole taperings extend the useful field region by boosting the amp-turns in the gap at the pole edges which introduces a slight increase of the field before falling off. We have also investigated the incorporation of these taperings on the inner surface of the pole. Although, this achieves the same result, the field stability and quality were found to be extremely sensitive to the inside taperings. Furthermore, the taperings will be incorporated via shims made out of thin sheets of iron. Additions of such shims on the outer pole surface will be much easier. They also allow for small corrections that might be necessary due to manufacturing defects. The total pole width is 1.75 m and the useful field region is 1 m; this implies that, on either side of the pole, $1.5 \times \text{gap}$ is wasted.

5.1.2.3 The Yoke

The field gradient along the gap as well as the curved shape of the magnet requires an asymmetric return yoke in order to ensure uniform saturation of the yoke. This is desirable to minimize the effect of field inhomogeneity caused by unequal saturation of the yoke at higher fields. The cross section area of the yoke in the mid-plane was determined so as to provide the area required for a split of the flux lines along the optic axis. The surface integrals of the field at the inside and outside halves of the pole about the optic axis were computed using TOSCA with a central field of 1.6T. The return leg yoke areas were then determined allowing for the yoke to run at an average field of 1.9T and keeping the same inside radius as obtained in 2D. Several iterations were necessary before arriving at the final yoke geometry. The results are shown in Table 5.2.

Table 5.2
Yoke Dimensions

Region	Area (m ²)	$\int B dA$ (T.m ²)	R _{in} (m)	R _{out} (m)	Width (m)
Pole	11.482	19.021	7.525	9.275	1.75
Yoke(Inner)	3.784	7.190	7.210	6.340	0.87
Yoke(Outer)	6.227	11.831	9.59	10.370	0.78
Pole weight	24	10 ³ kg	(26.4 Ton)		
Yoke weight	367	10 ³ kg	(404.6 Ton)		

The widths of the return legs of the yoke was determined to be 87 cm for the inside and 78 cm for the outside. The side plate thickness of the yoke was chosen so as to provide enough cross sectional area for the flux to return to either half. This thickness was found to be 78cm. A simple rectangular geometry for the yoke with 78 cm side plate proves to

be too wasteful in iron volume. It is assumed that the yoke will be fabricated with cast iron using shaped molds. With an irregular shaped yoke, the saving in iron volume will be reflected in the total cost of the iron. Hence, the yoke is shaped at the corners so as to provide enough iron such that the available cross section anywhere in the return path is about the same as those of the respective return legs. The entry and exit face yoke contours were made simple straight edges so as to conform with the pole contour.

5.1.2.4 The Coil

As pointed out earlier the dipole coil package is superconducting with a racetrack planar geometry. The overall coil cross section is $14 \times 4 \text{ cm}^2$ operating at a current density of 3.6 kA/cm^2 at full excitation. The coil package is embedded in the yoke cavity in a rectangular cryostat with approximately 9 cm thick walls. The space requirements on the cryostat impose constraints on the location of the coil with respect to the pole and the mid-plane of the dipole. Furthermore, at the end regions, the cryostat must not interfere with the acceptance phase space of the spectrometer. The required transverse clearance is about 30 cm at the entry face of the dipole. Thus, the coil is located 10 cm from the pole edges with a separation of 48 cm between the two coils. The coil is contoured to follow the pole contours exactly. This leads to negative curvatures for the coil in some regions. The minimum radius of curvature of the coil is about 26 cm.

5.1.2.5 Field Properties

TOSCA calculations were performed with the above configurations for various current densities in the coil. Field maps at full excitation for the midplane and the transverse planes for the entire dipole are shown in Figure 5.5.

At the nominal central field of 1.6T, the average field in the yoke is about 1.9 T; however small regions of the yoke such as corners around the coils run somewhat higher ($\approx 2\text{T}$). The inside and the outside yoke return paths have the same average field. Excitation functions were studied for six different ampere-turns for the dipole corresponding to 0.2 T up to 1.6 T central field. Summarized in Table 5.3 are the parameters for the dipole as a function of excitation. The fractional amp-turns and field index excitation curves are shown in Figure 5.6.

Figure 5.7 illustrates the field quality along the width of the dipole in the mid-plane. Plotted in this figure is the relative field deviation from a ideal conical field with $B_0=0.435\text{T}$ (dashed-dotted), 1.394T (dashed), and 1.601T (solid). The solid straight line at zero deviation corresponds to a field index of -1.25. The vertical and horizontal dashed lines represent the useful width and tolerance on the field deviations, respectively. It is clear that the field quality is consistent with the requirements of $\pm 2 \times 10^{-4}$ over 1m of width and over the required dynamic range. As mentioned earlier, the tapered shims were adjusted to maximize the effective width of the pole. In the low field region, the field in the larger radius side of the yoke is boosted by these shims. With increasing field the larger radius side of the pole approaches saturation more rapidly than the smaller radius side, and the field deviation reverse direction from the low field situation.

Figure 5.5 a) Contour map of the field; b) Transverse plane; b) Mid-plane.

HRS DIPOLE EXCITATION

Figure 5.6 HRS dipole excitation function. a) Fractional amp-turns spent in the gap as a function of current in each coil. The numbers in the curves are the corresponding central field values. b) Variation of the field index (n) as a function of current.

HRS DIPOLE (TOSCA)

Figure 5.7 HRS dipole field quality as a function of excitation. The curves are the deviation of the computed field from the ideal field required by the optical specifications. The vertical and horizontal dashed lines represent the useful width and tolerance on the field deviations, respectively.

Table 5.3
Full Field Characteristics

Current density (overall)	3.61	kA/cm ²
Total Amp-turns	400	kA
Operating current	1.8	kA
Stored Energy	3.5	MJ
Peak coil field	1.08	T
Maximum coil force	7.5	10 ³ kg/m

Excitation Parameters

Amp-Turn(NI)	B ₀	<i>n</i>	$(\int H dl)_{gap}$	$(\int H dl)_{gap}/NI$	$\langle \mu \rangle$
kA (T.m)	Telsa		T.m		
50 (0.0628)	0.2177	-1.2509	0.0546	0.8701	6400
100 (0.1257)	0.4350	-1.2504	0.1092	0.8685	6400
200 (0.2513)	0.8699	-1.2501	0.2174	0.8651	4482
336 (0.4222)	1.3939	-1.2490	0.3484	0.8252	279
370 (0.4650)	1.4954	-1.2476	0.3736	0.8035	170
400 (0.5027)	1.6017	-1.2449	0.3938	0.7834	107

5.1.2.6 Effective Field Boundaries

Fringing fields were evaluated for the entry and exit areas of the dipole in the mid-plane. The field distributions for the two faces of the magnet are shown in Figure 5.8. Effective field boundaries were computed from these distributions by integrating the field along constant radius. The calculated EFB's were then compared with those required in the specification. There are illustrated in Figure 5.8. The solid lines is the calculated EFB and the dashed line is the specification. Note that in the curves, the EFB is normalized to the central ray. The pole profiles used in the calculation is approximately hyperbolic cosine shapes normalized to take into account the variation of the local gap across the entry and exit pole faces.

The computed EFB's are well within the tolerance when compared with the specification in the useful field region. Note that the deviations sharply rise toward the fringes. In addition, the stability of the EFB's with central field variations is also within tolerances. However, in order to correct manufacturing defects, some tunable features are required in the entry and exit pole faces. This could be in the form of a tunable field clamp or a removable piece in the pole face itself that can be machined. With the confidence level demonstrated in these calculations, it will be relatively easy to compute necessary corrections to these removable pole pieces in order to achieve the required EFB after magnetic measurements have been done.

Figure 5.8 Mid-plane field maps for the entry face fringe field a); and exit face fringe field b).

5.1.2.7 Electromagnetic Forces

Electromagnetic forces on the coil and pole surfaces were evaluated with TOSCA. The coil was divided into 32 sections and the mesh space around the coil was carefully chosen to give accurate fields in the coil interior. Conductor body forces were then evaluated with OPERA using both the $\vec{j} \times \vec{B}$ method and integration of Maxwell's stress tensor over the coil surface. The coil field and force distributions for the central transverse section of the coil are shown in Figure 5.9. The vector array shows the force distribution whereas the contour map is for the coil field. The peak coil field is about 1.08T occurring at the inside edge close to the mid-plane. The coil forces in the body of the magnet are slowly varying with a magnitude of approximately 7 Ton/m and directed outward at about 45° from the mid-plane. At the end sections forces are slightly stronger around the corners. The force density distribution along the length of the coil are shown in Figure 5.9.

5.1.2.8 Coil Support Slots

The coil package will be self supporting by means of two support links (cold-to-cold) that connect the inside arc with the outside one radially. These support members are essential for the minimization of coil deformations under electromagnetic forces. The support links are embedded in the yoke just above the pole. Thus, there will be two radial slots, about 12×9 cm² is cross section, cut into the yoke. The effects of these slots on the field in the useful region was studied with TOSCA. For this study only the magnet was approximated to a rectangular geometry (figure 5.9). The perturbations on the midplane field is negligible for central fields of up to 1T. However, the effect is about 0.5% at full excitation. The deviation of the field due to the presence of these slot are shown in Figure 5.10. Note that this effect is predictable and can be accounted for in the spectrometer optics with no loss of resolution. Nevertheless, at higher fields, the dipole has very little "2D" region. Studies are under way to reduce this perturbation or devise alternate coil support schemes.

5.1.2.9 Conclusion

Detail magnetostatics studies for an H-frame, separate pole and yoke dipole with conical pole surfaces and superconducting planar coils have been carried out to an advanced level. Several refinements may be made to this basic design. In particular, we will investigate the possibility to reduce the total pole width further and hence, the total weight of the dipole. In addition, the yoke exterior geometry needs to be fine tuned to achieve a magnetic circuit so as to reduce the variation of the field index in the higher field regions. As the engineering designs evolve further and perturbations to the magnetic circuit due to structural elements are better known, the 3D magnetostatics designs can be refined to take these into account. In summary, we have presented a magnetostatics design for the dipole that meets the basic design goals.

Figure 5.9 Conductor body forces evaluated with OPERA: a) Force (vectors) and field (contours) distributions across the coil cross section in the central section of the dipole. b) Force distribution along the length of the coil in the plane of coil. c) Out-of-plane forces for the coil. The force numbers are in metric Ton/m.

Figure 5.10 Effect of the slots in the yoke for coil support links. a) The simplified rectangular model used for these calculations. b) Deviation of the field in the midplane from those without such slot in the yoke for a central field of 1.6T.

5.1.3 Dipole Engineering

5.1.3.1 Introduction

The dominant feature of each HRS arm is a large dipole, whose pole elements provide focussing in the dispersive plane, by virtue of entrance and exit ends which are rotated by to $+ 30^\circ$, and by a pole face index of -1.25. 4 GeV/c particles are deflected through 45° at an 8.4 m central radius of curvature. Along this 6.6 m (effective) length path, the field is 1.6 T across a 25 cm gap. Effective width of the "trapezoidal conical section" pole gap is 100 cm.

The "curved racetrack" coils are superconducting: the CEBAF developed Reference Conceptual Design features 1.8 KA flattened cable conductor, helium bath cooled at 4.5 K. Primary support against all magnetic loads is provided by the stainless steel helium vessel.

Overall weight of each dipole is 460 tons. Its stored energy is 3.5 MJ, at a rated ampere-turn level of 400 KAT.

The dipole is mounted upon a support cradle, which in turn rides upon the Hall A floor plates through a series of wheeled bogies. Dipole vertical position (elevation, pitch, roll) is adjustable over a limited range by the action of three hydraulic/mechanical jack sets, interposed between the dipole brackets and the cradle proper.

Following acceptance testing of the dipole, a structural steel box beam will be rigidly mounted upon it: this beam will bear the other active HRS elements (quads and detector package). Thus, once the active HRS elements have been optically aligned, their relative positions will not be affected by azimuthal relocation of the spectrometer arm about the Hall A central pivot.

5.1.3.2 Technical Specification

A draft version of this document, which will constitute the technical portion of our request for proposal, is included herein. As noted, several drawings which will be incorporated in the draft RFP edition are still in preparation. In considerable measure, this reflects the fact that the interpole gap has recently been reduced from 30 to 25 cm (nominal), with consequent reduction in iron weight from 500 to 430 tons – cost saving being the primary motive.

Also, prior to issuance in the draft RFP, the Technical Specification will be reviewed by our procurement department, to ensure compliance with the contractual aspects of the overall document.

12 April 1990

Dipoles for Hall A HRS

Technical Specification

1. Statement of Work

The Continuous Electron Beam Accelerator Facility (CEBAF) requires two large superconducting dipole magnets, one for each arm of the 4 GeV/c High Resolution Spectrometer (HRS) to be installed within experimental Hall A. One HRS arm is shown in Figure D.1.

This specification includes detail design, fabrication, installation within CEBAF's Hall A, and acceptance testing of two dipole magnet systems complete, in conformance to the requirements of this specification.

The superconducting dipole is a large 45°, H-frame bending magnet, which provides dispersive plane focussing by virtue of contoured entrance/exit pole ends and a pole face index.

The Technical Requirement includes configuration, tolerances and material specification for the iron yoke and pole elements, and yoke/pole assembly; plus configuration/performance aspects of the coil/cryostat. Based upon extensive magnetics analysis, CEBAF anticipates that conformance to the Technical Requirement (Section 2 below) will result in a magnet having acceptable field characteristics.

A Reference Conceptual Design (RCD) for the coil/cryostat is provided. This represents one approach which CEBAF considers feasible for meeting the configuration/performance requirements for this element, when fully developed by the contractor. The contractor is free to propose an alternative coil/cryostat design, or elements thereof, or to develop the Reference Conceptual Design. In either case, full responsibility for meeting the requirements of this specification will rest with the contractor.

The dipole RCD general arrangement is shown in Figure D.2: its basic parameters are given in Table D.1. The "curved racetrack" coils are pancake wound using 1.8 KA flattened "Rutherford" cable, which is cryogenically stabilized within a stainless steel helium vessel.

A5-21

4 GeV/c High Resolution Spectrometer

Figure D.1

4/6/90

Dipole Assembly

Approx. Weight 920 Klbs.

Figure D.2

4/6/90

Table D.1
HRS Dipole

Basic Characteristics

<u>Features</u>	
Iron:	"H" - Frame Curved in vertical "dispersive" plane Yoke modular for fabrication, shipping "Floating" pole pair Conical pole face geometry Dispersive plane focussing: Pole end contours Pole face index Pole faces exposed to beam vacuum
Coil/cryostat:	Superconducting Bath cooling, cryogenic stabilization "Curved racetrack" geometry Ends contoured to match poles Helium vessel support of primary magnetic loads

Parameters

Central bend angle	45°
Central field, maximum	1.6 T @ 4 GeV/c
Dynamic field range	10:1
Field uniformity over dynamic field range:	
magnetic analysis, integral B·dl	2×10^{-4}
manufacturing tolerance, surface to surface	1×10^{-3}
as measured, integral B·dl	1×10^{-4}
Central bend radius (CBR)	8.4m
Interpole gap @ CBR	25 cm
Effective field length @ CBR	6.6 m
Useful field width	100 cm
First order focussing index	-1.25
First order end focussing:	
entrance and exit	-30°
Ampere turns @ full excitation	400 KAT
Iron weight	430 tons

2. Technical Requirement

The Technical Requirement of this specification is defined by this Section, including Table II and the figures/tables identified therein.

For the baseline requirement, the vendor shall provide two dipole magnet systems complete, including detail design, fabrication, installation within CEBAF's Hall A, and acceptance testing. Alternatively, separate vendors may provide the coil/cryostat unit and the iron assembly to their respective requirements, with CEBAF performing system integration, installation and acceptance testing.

The Technical Requirement includes configuration, tolerance and material specifications for the iron yoke, poles and assembly; plus configuration/performance aspects of the coil/cryostat unit. These requirements have been established by CEBAF, based upon extensive 3-D TOSCA magnetics analysis to achieve the requisite optics characteristics over a decade excitation range. Therefore, the resulting dipole field quality, including measurement after system acceptance, will be CEBAF's responsibility.

Section 4: Yoke/Pole Iron is a narrative discussion of these elements, whose purpose is clarification of the requirement.

Design, fabrication and acceptance testing of these magnets must be performed in accordance with standards generally considered acceptable by recognized experts in the field of applied superconductivity, to result in a product which fully meets the performance/configuration requirements of this specification.

Table D.II
Dipole Technical Requirements

Iron Yoke/Poles

Material Specification: Per Table D.III
Iron Assembly Geometry/Dimensions (REF): Per Figure D.3
Pole Piece Configuration/Tolerances: Per Figure D.4
Pole Assembly Dimensions/Tolerances: Per Figure D.5
Yoke Configuration/Tolerances: Per Figure D.6
CEBAF Interface: Support brackets, Box beam: Figure D.7
Beam Vacuum: See text
Bolting/dowelling/registration features: to be established by contractor.

Coil

Configuration Envelope: Per Figure D.8
Operating Current: 1.8 KA @ 4.5 K
Ampere-Turns @ Operating Current: 400 KAT
Critical Current: 3.0 KA @ 4.5 K

Cryostat

Envelope Constraints: Per Figure D.9
Heat Load @ 4.5K: 25 Watts Maximum
Helium Vessel:

- Material: 300 series stainless steel
- Design internal pressure: 4ATM absolute (60 psia)
- Relief valve setting: 5psig
- Rupture disc pressure: 30psig
- Cold-to-Warm support: dynamic load criteria against support design stress:
 - vertical : 3g
 - horizontal, longitudinal: 2.5g
 - horizontal, transverse: 2.0g

Heat Shield: 1N₂ cooled shield required

Vactank:

- Matl: 300 series stainless steel
- Design internal pressure: 2atm absolute (30psia)

CEBAF Interface: Figure D.10

Power Supply/Protection System: Defined by schematic diagram, Figure D.11.

Instrumentation/Controls: Defined by schematic diagram, Figure D.12.

Table D.II
Dipole Technical Requirements
(continued)

Deliverables:

- Baseline: Two magnet systems complete, including:
 - Dipole assembly
 - Power supply/protection system
 - Controls/instrumentation
- Option A: Two Iron Assemblies complete
- Option B: Two coil/cryostat units complete
- Documentation:
 - Design analyses
 - Fabrication drawings, specifications
 - Manufacturing and final acceptance test results
 - QA/QC data
 - Monthly progress reports
 - Project schedule, including major milestones (provided with proposal)

Acceptance Testing:

- Location: Dipole permanently installed upon its support cradle, within CEBAF's Hall A.
- Acceptance test current: $1.1 \times I_{op} = 2.0 \text{ KA} = I_{atc}$
- Verification of steady-state heat load
- Charge, discharge, and steady-state operation at I_{atc} , shall occur without evidence of cryogenic instability

- Dimensions are in cm.
- Total weight = 430 net tons.
(2000 lbs/ton)

A5-27

Iron Assembly General Arrangement

Figure D.3

4/6/90

A5-28

-
- REMOVABLE POLE PIECE
(REF) BOTH ENDS
(See note #3)
- TYPICAL BOTH ENDS
- 13.986
- 5.000
- View B
- POSITIVE Y
- ORIGIN
- POSITIVE X
- 21.948°
- 95.176°
- 13.744°
- 37.232°
- R 1
- R 2
- R 3
- R 4
- R 5
- R 6
- R 7
- R 8
- R 9
- R 10
- R 11
- A
- B
ARC	RADIUS	CENTER	
		X	Y
R1	220.066	-64.361	-467.620
R2	95.325	-177.424	-410.348
R3	97.671	-232.865	-415.210
R4	934.501	-253.947	-481.372
R5	26.716	398.542	-149.764
R6	529.035	473.510	400.909
R7	159.332	379.091	43.467
R8	71.649	341.669	-35.829
R9	44.161	260.112	-118.052
R10	745.502	-253.947	-481.372
R11	88.880	-130.757	-343.864

TO BE REVISED

Pole Contour Specifications

Figure D.4

Pole Assembly
 Figure D.5

4/5/90

Yoke Assembly

Figure D.6

4/16/90

Table D.III
Dipole
Iron Material Specification

Yoke:

- Material: A1S1 1006, composition certified
- Forged per ASTM A 711-87
- Annealed for minimum induction of 0.18T @ 1.0 oersted
- Ultrasonically inspected per ASTM A 388-67;
- To ensure compliance with CEBAF specified limits for voids, inclusions and lamina (U.T. quality level 2, or equivalent)

Poles:

- Material: A1S1 1006, composition certified
- Forged per ASTM A 711-87
- Annealed for minimum induction of 0.18T @ 1.0 oersted
- Ultrasonically inspected per ASTM A 388-67;
- To ensure compliance with CEBAF specified limits for voids, inclusions and lamina (U.T. quality level 1, or equivalent)

Figure D.7
Dipole: CEBAF Iron Interface
(To be provided in RFP edition)

Longitudinal View

Basic Cross-Section

Coil Envelope Geometry

Figure D.8

Figure D.9
Cryostat Envelope Constraints
(In preparation for RFP edition)

Figure D. 10
CEBAF Cryostat Interface
(To be provided in RFP edition)

HRS DIPOLE POWER SUPPLY/PROTECTION CIRCUIT

POWER SUPPLY CABINET

PS - POWER SUPPLY, 10V, 20A
D1 - POWER SUPPLY PROTECTION DIODE (PAIR)
D2 - DUMP RESISTOR PROTECTION DIODES
D3 - PRIMARY CIRCUIT PROTECTION DIODES
SM1 - CHARGE/DISCHARGE SWITCHING

BOOTSTRAP SCR/OVERVOLTAGE PROTECTION CIRCUIT

R2, R3 - VOLTAGE DIVIDER RESISTORS
R4 - BYPASS RESISTOR
Z1 - ZENER DIODE
SCR1 - SILICON CONTROLLED RECTIFIER
SN - SNUBER CIRCUIT

CRYOSTAT

L1 - GAS COOLED CURRENT LEADS
L2 - MAIN COIL, 1.6 H, 9.3 MJ

10/23/89

Figure D.11

Figure D. 12
Instrumentation/Controls
(In preparation for RFP edition)

3. CEBAF Interface

This section describes documentation, equipment, services and labor which will, or can be provided by CEBAF in support of dipole design, manufacture, installation and testing by the contractor.

3.1 Documentation: CEBAF is prepared to make the following information available to the contractor following contract award:

- *Design Drawings:* Development by CEBAF of the dipole design will continue during the procurement process. In particular, details of the iron pole geometry will undergo detail refinement during the course of an ongoing effort to ensure optimal field quality through 3-D TOSCA analysis. CEBAF does not anticipate that such changes will increase machining complexity, tolerances or gross component dimensions. Work will also continue to develop a dipole installation scenario, as an aid to the contractor. Electrical and cryogenic interfaces will be further defined.
- *Magnetics Analyses:* Field and force data from the 3-D TOSCA analysis, which has formed the basis of our Technical Requirement will be provided upon request. CEBAF is prepared to perform additional magnetics analyses which may later prove necessary or appropriate for further requirement definition.
- *Structural, Cryogenic, Electrical Analyses:* All such analysis which have been performed to develop our Reference Conceptual Design will be available.
- *Pole Geometry:* The pole geometry has been indicated in Figures D.4 and D.5, which form a part of the Technical Requirement. However, due to the complex, three dimensional nature of these elements, more complete point-to-point or continuous data is required for manufacture. Therefore, a 3-D solid model computer file (tape) will be provided as a basis for generating CNC tool paths.
- *Hall A Civil Construction Drawings:* As reference for dipole installation.
- *HRS Support Structure Drawings:* Preliminary design drawings, as reference for dipole installation. These include the cradle upon which the dipole rests; the dipole mounting brackets; and the box beam, which mounts atop the dipole following acceptance testing.

3.2 Cryogenic Services:

During normal operation, the dipole will be connected to CEBAF's End Station Refrigerator (ESR), receiving supercritical helium at 3 atm and 5.15 K. Gas is to be returned to the compressors at 1.2 atm. Thus, gas separated liquid at 1.2 atm and 4.4 K should discharge into the helium vessel reservoir through a J-T valve. We anticipate a steady state liquid helium requirement of 1g/s or less.

For cooldown, 20 g/s of 300 K gas will be supplied at 4 atm, which can be brought to 80 K through a CEBAF supplied liquid nitrogen precooler. Below 100 K, 7.5 g/s of liquid helium will be available from the ESR, plus an additional 8 g/s if a transfer line from the central Refrigeration System is provided.

Liquid nitrogen will be supplied to Hall A from the ESR at 1.6 atm (~ 81 K). Boiloff will be vented to the atmosphere. A preliminary schematic diagram of cryogenic services to Hall A is shown in Figure D.13.

3.3 Electrical Services

- Input Power to Magnet Power Supplies (output from Hall A transformers): 480 VAC $\pm 10\%$, 3 phase, 4-wire, 60 Hz: 5% maximum unbalance, 0.5 Hz variation.
- Hall A General Service Outlets:
 - 440V, 3 phase, 60 amp, 60 Hz
 - 220V
 - 110V, single phase, 60Hz

The location of these outlets is indicated on a civil construction drawing which will be supplied to the contractor.

3.4 Cooling Water

Cooling water will be available within Hall A on an as-required basis. The contractor shall state his requirements.

3.5 Service Crane

A 20 ton capacity, half-polar crane, with a hook height of 50ft., will be available in Hall A.

Figure D.13
CEBAF Provided Cryogenic Services To Hall A
(To be included in RFP edition)

4. YOKE/POLE IRON

Magnetic performance of the dipole is determined primarily by the pole elements and return path yoke—the coils simply providing the magneto-motive energy. Therefore, CEBAF has fully defined the iron configuration, tolerances and material characteristics (permeability, hysteresis and impurity/imperfection limits) based upon 2-D and 3-D magnetics analysis. General arrangement views of the 430 ton iron assembly are given in Figure D.3 above.

Pole Elements: Precision machined, full length, “floating” pole elements provide good field quality across the 100 cm effective gap width, over an excitation range from 0.16 T to 1.6 T. The poles are biased to $+30^\circ$ at their exit and entrance ends to provide in-plane focussing; superimposed contouring serves to minimize higher order aberrations. This end bias focussing is augmented by a transverse (radial) pole tip (field gradient) index of -1.25. These features permit elimination of one upstream and one downstream quadrupole.

Figure D.4 above shows one pole element. Cross-section contours on the yoke (“Purcell gap”) side serve to counteract iron saturation effects near the gap edges, and resulting from the indexed gap surface. These back side contours can be applied with laminations, if appropriate, from manufacturing considerations. Note that the entrance and exit regions are removable: this allows the possibility of future replacement with slightly recontoured ends, should this prove advantageous following magnetic measurement. Also, this capability may facilitate initial end machining.

Pole Assembly: The pole assembly, shown in Figure D.5, provides the constant conical section gap required by the beam optics. This trapezoidal shaped region is defined by the pole element faces and by the precision machined stainless steel spacers to which they are bolted. The vacuum features are indicated.

Return Path Iron: Figure D.6 shows the 404 ton flux return path iron assembly. The lintel sectors are provided with recessed features to accommodate the transverse coil/cryostat support bars. The indicated segmentation, bolting and dowelling features are conceptual only. Their specific design is to be established by the contractor.

Fabrication Considerations: The indicated tolerances for pole machining and assembly reflect guidance from several potential suppliers of finished magnet iron. Though certainly aggressive—some would say optimistic, the 10 mil (1/4 mm) interpole true position value appears to be achievable by shops with appropriate large precision machine tool capability.

An inherent challenge is presented by the constant section, trapezoidal interpole gap—a conical “void of revolution”. Generating the appropriate “mirror image” pole faces would not be difficult for a rotating bed machine which could accommodate 31 foot radii. In lieu of such a (presumably) mythical device, one option is to machine each pole face on a numerically controlled horizontal boring mill having a tool column traverse of 35 feet. In this case, the pole blank would be stationary, with its long axis parallel to the machine bed and its face nearly vertical. While it may be possible to machine each pole face to

within 5 mils, true mirror image machining of its counterpart is not possible. In other words, any systematic machine errors will perforce be additive, resulting in a nominal face to face tolerance of 0.026 cm (10 mils).

It should be possible to machine (grind) the parallel edges of the short, stainless steel interpole spacer elements to within ± 1 mil (± 0.001 ") of each other. Therefore, the bolted and dowelled pole assembly should have an interface accuracy of around 10 mils, or 1×10^{-3} relative to the 25 cm gap. This tolerance condition is illustrated in Figure D.5 above.

The pole blanks should be made from composition certified AISI 1006 steel, forged per ASTM A 711-87 and annealed to produce a field of 0.18 T minimum at a magnetizing force of 1.0 Oersted. They should be ultrasonically inspected per ASTM A 388-67, to ensure compliance with CEBAF specified limits for voids, inclusions and internal defects. (U.T. Quality Level One, or equivalent.)

The yoke assembly consists of ten 45.5 ton (max) AISI 1006 elements, forged per ASTM A711-87 and annealed to yield a minimum induction of 0.18 Tesla at a magnetizing force of 1.0 Oersted. They should be ultrasonically inspected per ASTM 388-67, to ensure compliance with CEBAF specified limits for voids, inclusions and internal defects (U.T. Quality Level Two, or equivalent.)

Iron material specifications are summarized in Table D.III above.

Assembly Considerations: See Section 7 below.

Beam Vacuum: The dipole requirement includes a means for containing the beam vacuum. In the interest of minimizing interpole gap and thereby yoke size, the pole faces must serve as part of the vacuum barrier. While details of such a design must be jointly developed by CEBAF and the contractor, a conceptual approach is indicated. Along the "straight" region, the sides of the barrier are provided by a thin stainless steel "membrane", welded to the pole elements and bearing against the interpole spacers (Figure D.5). At the ends, the barrier can be provided by a flexible metallic seal which spans the gap between the poles and the cryostat, as also indicated in Figure D.5. Details of the transition from ends to "straight" region must be developed later: in any case, much of the fit must be "custom crafted" at installation.

5. Reference Conceptual Design of Coil/Cryostat

General: The Reference Conceptual Design applies to the coil/cryostat for the dipole, the iron primary components having been defined by the Technical Requirement.

The performance requirements for the coil/cryostat were defined in Table D.I above. Basically, they include the operational ampere-turns, operating current and cryostat heat load limits, plus various factors affecting coil stability/reliability.

The geometric requirements/constraints for the coil and cryostat indicated in the requirement Figures above. They are necessary in order to fit within the iron and to supplement it in shaping of the magnetic field.

5.1 COIL

Geometry: Two basic options are possible for the coil overall geometry; saddle and racetrack.

A saddle coil configuration offers a potential saving in iron yoke weight relative to the racetrack option. However, a saddle coil of this size and complexity represents a formidable manufacturing challenge. The net cost differential of iron saving less coil winding and cryostat fabrication increase may favor the saddle approach, although a comprehensive comparison has not been made. Certainly, in view of the much larger forces experienced by saddle coils, the racetrack option is perceived as more reliable. It has been selected primarily for this reason.

The dipole reference design does not feature iron "clamps" to tailor the magnetic fringe field at the entrance and exit ends. Instead, we have elected to shape the coils to follow the pole contours. By this expedient, aberrations to end focussing and $\int B \cdot dl$ are minimized, though at some cost in coil/cryostat complexity. Figure D.8 shows the required geometry of the active coil region; that is, of the winding pack (conductor, plus interlayer/interturn elements).

Coil Type: Our Reference Conceptual Design features bath cooled, cryogenically stable coils, wound from bare, flattened "Rutherford" cable type conductor. A cross-section of the coil and its conductor are shown in Figure D.14, while Table D.IV summarizes its characteristics.

Each coil is wound as one double pancake. Ten mil thick stainless steel strip, flanked by 5 mil thick mylar strips, is co-wound with the conductor to provide mechanical stability and interturn insulation. Interlayer, and ground plane spacing is provided by $\frac{1}{16}$ " thick, perforated G-10 sheet, in the "Livermore" pattern. This material, in conjunction with diagonal interwire passages in the cable, allows helium inventory and migration throughout the coil matrix.

Coil Detail: For the dipole racetrack geometry, in-plane (hoop) loads must be reacted by the stainless steel helium vessel. Therefore, in order to minimize radial coil motion as

HRS DIPOLE

COIL/CONDUCTOR CROSS-SECTION

MODULE: 0.251
CABLE: 0.200

DIMENSIONS ARE IN CM.

CABLE: UNFILLED, COMPACTED:

WIRE SIZE: 1.016 MM (40 MIL) DIA.
NO. OF WIRES: 36
-12 COMPOSITE
-24 COPPER, CDA 102
COMPOSITE WIRE:
Cu/NbTi RATIO: 7/1
J_{op} = 150 KA/CM²
(0.6 J_c @ 3T, 4.5K)
I_{op} = 150A
TWIST PITCH : 16° - 17°
COMPACTED PACKING FACTOR: 0.87
LENGTH PER COIL: 2,500 M

INTERTURN STRIP:

MAT'L: AISI 304 OR 316
THICKNESS: 0.254 MM (10 MIL)

INTERTURN INSULATION:

TWO STRIPS, FLANKING
STAINLESS STEEL STRIP
MAT'L: MYLAR
THICKNESS: 0.127 MM (5 MIL)

CABLE CORE STRIP:

MAT'L: BRASS
THICKNESS: 0.076 MM (3 MIL)
WIDTH: MFR'S CHOICE

1.80 KA CONDUCTOR MODULE

4/16/90

Figure D.14

Table D.IV

**HRS Dipole: Specifications of
Coil Reference Conceptual Design**

Electrical Characteristics:

Amp Turns @ 1.6 T, total for both coils	400 KA Turns
Maximum Operating Current (MOC)	1.80 KA
Stored Energy	3.5 MJ

Coil Detail:

Type	Superconducting, Cryogenically Stable
Geometry	Curved Racetrack
Conductor	Flattened cable, unsoldered
Cooling	Helium Bath
No. Turns	112 per coil
Turn Length	18.2 m
Matrix	2 layers $\times$ 56 turns
Coil Pack Cross-section	3.96 cm $\times$ 14.00 cm
Coil Cavity Cross-section	5.00 cm $\times$ 16.00 cm
Average Metallic Current Density	6.2 KA/cm ²
Coil Pack Current Density	3.61 KA/cm ²
Coil Cavity Current Density	2.5 KA/cm ²

Magnetic Load Support:

In Plane (hoop) and coil-to-coil	Stainless Steel Helium Vessel
Transverse, coil internal	Co-wound Stainless Steel Strip

the magnetic loads develop, it is prudent to wind the coils against the outer peripheral vessel walls. To assure that the coil fits snugly against the vessel wall, it must be well clamped over its entire length during winding. Also, provision must be made to maintain the coil under radial pressure of around 5 atm when installed within the helium vessel - at 4 K. This can be accomplished by inclusion of work hardened stainless steel strips with a wavy pattern placed between the coil I.D. and the inner periphery wall of the helium vessel.

Conductor: The 1.8 KA helium bath cooled conductor is a 36 wire, flattened "Rutherford" cable, as shown in Figure D.14 above. As indicated, each 40 mil (1mm) diameter composite (NbTi/cu) wire is flanked by two copper wires of the same size, for a total of 12 composite and 24 copper wires.

The selection basis for the 150 amp composite wires is given in Table D.V.

Cryogenic Stability: The coil cavity is flooded with liquid helium, at nominal surface conditions of 4.5K and 1.3atm, which fills the interstices of the cabled conductor, interlayer spacers and ground insulation channels.

The reference conductor/coil design is based upon "limited" rather than "full" cryogenic stability. In the latter "quasi steady-static" condition, local heat transfer to the helium bath is greater than ohmic heat generation from a fully resistive zone of unspecified origin, duration and length, usually expressed by the STEKLY criterion, to wit: $\alpha < 1.0 = \rho i^2 / h PA (T_c - T_b)$. Thus, when the external thermal disturbance is removed, the resistive zone will decay.

Our design is based upon limited stability, in which magnitude, duration and linear extent of the transient thermo-mechanical disturbance are considered. A "maximum credible" disturbance is then postulated, from which the conductor must be shown to recover.

In our design analysis, the offending event is taken as slip/stop inelastic relative motion within the coil pack, induced by in-plane magnetic forces acting over a region of conductor which is not in contact with the adjacent "down-load" element (conductor turn coil structure) by some gap and over some length. (Further detail to be provided in RFP edition. Analysis is now undergoing independent review.)

Quench Characteristics: Tuzel has performed a series of calculations for this coil using the Martin Wilson developed code QUENCH.

Due to the presence of interturn stainless steel strip, flanked by mylar, the ratio of longitudinal to transverse heat propagation is around ten to one; G-10 interlayer insulation (with resident lHe) reduces the layer-to-layer heat transfer to essentially zero. Thus, the quench analysis is two dimensional.

Four cases were investigated, as regards helium cooling of the heat affected (propagating) zone:

- If the lHe surrounding the heated cable was continually replenished (at 4.5K), the quench velocity would be relatively slow (7 cm/sec), resulting in a "hot spot" temperature of around 270K.

Table D.V
HRS Dipole
1.8 KA Conductor

Composite Superconducting Wire:

Typical NbTi critical current density

$$J_c = 275 \text{ KA/cm}^2 @ 3 \text{ T, } 4.2 \text{ K}$$

$$\text{Adjustment for } 4.5 \text{ K: } @ 3 \text{ T, } \Delta J_c / \Delta t \approx 80 \text{ KA/cm}^2 / \text{K}$$

$$\text{Reduction from } 4.2 \text{ K to } 4.5 \text{ K} \approx 25 \text{ KA/cm}^2$$

$$J_c = 250 \text{ KA/cm}^2 @ 3 \text{ T, } 4.5 \text{ K}$$

Selected NbTi operating current density (see Fig. 13)

$$J_{op} = 0.6 J_c = 150 \text{ KA/cm}^2 @ 3 \text{ T, } 4.5 \text{ K}$$

Select wire Cu: SC ratio = 7:1

Select wire operational current = 150A

Corresponding number of wires in 1.8 KA cable = 12

Wire Size:

$$\text{Area} = 150 \text{ A} \times 8 / 150 \times 10^{-3} \text{ A/cm}^2 = 8.00 \times 10^{-3} \text{ cm}^2$$

$$\text{Diameter} = (4 \text{ A}/\pi)^{1/2} = 0.1009 \text{ cm (0.0397 in)}$$

But, select 40 mil wire (0.1016 cm)

$$\text{Area} = 8.107 \times 10^{-3} \text{ cm}^2$$

$$\text{C.D. avg} = 18.5 \text{ KA/cm}^2; \text{C.D. (NbTi)} = 148 \text{ KA/cm}^2 \text{ O.K.}$$

Flattened (Rutherford) Cable:

Total number of wires = 36 (selected)

Assume 87% compaction

$$\text{Envelope area} = 8.11 \times 10^{-3} \times 36 / 0.87 = 335.6 \times 10^{-3} \text{ cm}^2$$

If compacted height = 0.192 cm (less core strip)

$$\text{Width} = 1.75 \text{ cm} / \cos 16^\circ = 1.83 \text{ cm}$$

- However, since resident interstitial helium within the heat affected zone will quickly be expelled, with no chance of liquid replenishment, the cable channels will soon be exposed to rapidly flowing helium gas. Under this hypothesis, using a Reynolds Number of 10^5 , Tuzel calculated a hot spot temperature of 170K, corresponding to a quench velocity of a 25 cm/sec. This probably represents a case close to reality for an extensive propagating resistive zone, leading to a full coil quench.
- Another extreme is the adiabatic case, in which the coil is uncooled except by metallic conduction (i.e. if it were epoxy filled). This would produce the maximum quench velocity (70 cm/sec) and minimum hot spot temperature (120K). (Of course, it also represents the condition of minimum stability against thermomechanical disturbances.)
- In service, the dipole electrical circuit will include a 0.3 ohm external dump resistor. Under these conditions, the hot spot coil temperature will be around 50K, achieved within one minute of quench initiation.

5.2 HELIUM VESSEL

Requirement: The helium vessel design shall conform to the requirements listed in Table D.II above:

Reference Conceptual Design: The helium vessel serves the dual role of cryogen containment and support of the coil magnetic loads, both in-plane (hoop) and out-of-plane (coil to coil).

In order to support the in-plane running loads of around 5 tonnes/meter along the "straight" sections without excessive deflection in bending (or, excessive cold mass bulk), the helium vessel structure is provided with two pairs of cold links at locations shown in Figure D.15. With the "straight" section spreading loads thus reacted by cold stainless steel links, no differential thermal contraction deflections, or cold mass heat loads are incurred.

The out of plane "repulsive" loads are reacted by the structure which connects one coil housing to the other. A coil/helium vessel cross-section at a link location is shown in Figure D.16.

At each end, the coil in-plane and out-of-plane magnetic loads are borne by the surrounding helium vessel structure, strengthened locally as required. A detail views of the end structure a is shown in Figure D.17.

Structural Analysis: the TOSCA generated in-plane magnetic "running" loads, in metric tons (tonnes) per meter along the coil, are shown in Figure D.18; the corresponding out of plane loads are given in Figure D.19. Figure D.20 is a finite element model of the reference design coil/helium vessel, showing deflections induced by the magnetic loads. The cold-to-cold links and cold-to-warm support loads are indicated, as well as peak deflections. The corresponding peak stresses within the helium vessel are well below the ASTM based limit of $\times 17$ Kpsi for 300 series stainless steel (based upon $2/3 \times$ yield stress @ RT)

- Material: Stn Stl 316L
- Weight $\cong$ 7 tons

Helium Vessel Assembly Longitudinal View

Figure D.15

4/16/90

Coil/Helium Vessel Cross-Section @ Link

Figure D.16

Coil Case Assembly End View Section

Figure D.17

4/6/90

$B_0 = 1.6$ Tesla

Forces are in metric tons/meter.

HRS Dipole: In-Plane Magnetic Load

Figure D.18

Coil/Helium Vessel: Deflections Due To Magnetic Loads

Figure D.20

5.3 Cryostat

This section covers the cryostat elements of the Reference Conceptual Design (RCD) other than the helium vessel (described in Section 5.2 above).

Overall Aspects: The cryostat envelope constraints are shown in Figure D.9 above. Figure D.2 above shows the coil/cryostat installed within the magnet iron: note that the cold-to-cold tension links of the helium vessel, and their vactank extension shrouds, embrace the pole assembly. Therefore, these elements must of course be demountable for magnet assembly.

Figure D.21 is a longitudinal section view of the coil/cryostat assembly; Figure D.22 shows a typical cross-section; Figure D.23 is taken at a cold-to-cold link location; Figure D.24 is a longitudinal section at one end. Overall weight of this assembly is 10 tonnes.

Vacuum Vessel: This welded vessel is made from 316L series stainless steel, designed for internal as well as external pressure of 1 atm. A relief valve is provided, sized and set to prevent the internal pressure from rising above 5 psig even under a worst case failure scenario (rupture to air, with cryocondensation on 4K surfaces).

While not required to be a coded vessel, it shall be designed in general conformance with the ASME Pressure Vessel Code, Section VIII.

Heat Shields: The LN_2 heat shield is built up from copper or aluminum sheet, secured to a support frame, as required for dimensional control. Electrical breaks are provided in the sheet pattern to minimize the development of eddy current induced forces during a quench condition. The shield is cooled by LN_2 passing through trace tubing by thermal siphon effect. 80 K intercepts are provided to the cold-to-warm helium vessel supports.

The heat shield is covered with 20 layers of aluminized mylar "super insulation" (NORTON NRC-2 or equivalent). If properly applied, this should result in a net heat flux to the LN_2 shield of around 1 w/m^2 .

Also, the helium vessel is covered with 5 layers of the same material, carefully applied so as to minimize "shine" from the 80 K shield surface, especially in the area of cold-to-warm supports and cryogenic lines. This should result in an average heat flux of around 100 mw/m^2 to the 4 K surface.

Cold-to-Warm supports: These elements are indicated in Figures D.15 and D.21 above. Their locations, attachments, orientations and effective spring moduli are chosen to eliminate cold mass to vactank relative motion during cooldown; while supporting the cold mass against gravity and any anticipated net magnetic force unbalance. Also, these supports must be designed for dynamic ("g") loads, as the coil/cryostat unit is transported to CEBAF. Even for an air cushion tractor-trailer rig, the dynamic design load should be at least 3g, at least in the vertical direction (presumably, the unit will be shipped in the horizontal position). Alternatively, the contractor may prefer to provide temporary cold mass restraint for shipment.

Figure D.21
Coil/Cryostat Assembly
Longitudinal Section View
(In preparation for RFP edition)

Coil/Cryostat: Typical Cross-Section

Figure D.22

Coil/Cryostat: Cross-Section Through Link

Figure D.23

Dimensions are in cm.

4/16/90

Coil/Cryostat: Typical End Cut

Figure D.24

Figure D.25 is a conceptual representation of one typical cold-to-warm support, designed for both tension and compressive loading, at a peak rating of 100 Klb. The re-entrant geometry confers a longer heat path, and a relatively low effective spring modulus - around 3×10^6 psi. This is necessary in order to limit support loads reacting the relatively large cold mass and distortions under magnetic loading.

Cryogenic Aspects: During normal operation, the dipole will be connected to CEBAF's End Station Refrigerator (ESR), receiving supercritical helium at 3 atm and 5.15 K. Gas is to be returned to the compressors at 1.2 atm. Thus, gas separated liquid at 1.2 atm and 4.4 K should discharge into the dipole helium vessel reservoir through a J-T valve.

We estimate the 4K heat load to the dipole as follows:

Radiation:	
Helium Vessel	3
Cold-To-Cold Links	1
Conduction:	
Supports: 8@ 1 w each	8
LN ₂ shield support	<u>3</u>
	15 W
Uncertainty allowances	<u>5</u>
Nominal	20W

In addition, the pair of 2KA current leads require $2 \times 2 \times 1.5 = 6$ watts of cooling, which can be provided by boiloff gas from the other cryostat heat sources.

The dipole cryogenic system schematic diagram is shown in Figure D.26. The corresponding features (valves, piping, headers, controls, etc.) are indicated in Figure D.27.

6. Electrical System

The electrical system for the HRS dipole consists of the power supply, dump circuit, charge/discharge switch, the busbars connecting to the coil parallel with a bootstrap SCR, and the cryostat internal components. Figure D.12 above is a schematic diagram of the circuit.

The cryostat internal components include the magnet coil itself (L), and a flux loop (FL) for sensing field changes. Also included are monitors, flow meters, and valves for the gas-cooled current leads.

The bootstrap SCR components provide backup protection to the coil in the event that the external (power supply, dump resistor/switch) circuit should become disabled or disconnected. These elements should be located near the coil terminals.

The external circuit components include the power supply, dump resistor/switch, busbars, monitors, and controls. The dump switch is normally closed and will be rated for opening during full current at full dump voltage (75 V). The water-cooled dump resistor will have sufficient thermal capacity to absorb the full coil stored energy (3.5 MJ).

Figure D.25
Cold-to-Warm Support Concept: Reentrant
(To be provided in RFP edition)

Figure D.26
Cryogenics Schematic Diagram
(To be provided in RFP edition)

Figure D.27
Cryostat Cryogenic Features
(To be provided in RFP edition)

The power supply and dump circuit consist of the power supply, three sets of redundant diodes, a dump resistor, and a refersing switch, as shown in Figure D.30.

The power supply is rated at 2000 A, 10 V, and 50 mV rms voltage ripple.

7. Installation

The basic requirement includes installation of the dipole within CEBAF's experimental Hall A.

As indicated in Figure D.1 above, the dipole sits "on edge" atop the cradle of the HRS support structure, adjustably mounted upon three sets of vertically oriented hydraulic/mechanical jacks. Jack hard points are provided by fabricated steel brackets which are bolted and dowelled to the dipole yoke, as shown in Figure D.10 above. These brackets will be provided by CEBAF.

The quadrupole magnets and detector package are borne by a box beam, which will later be installed atop the dipole.

It is assumed that the entire dipole has previously been assembled at the vendor's facility, in order to verify component fits and to perform the various match drilling operations for receipt of assembly dowels. Thus, the dipole arrives at CEBAF as a marked and pre-fitted "kit".

The large dipole elements: yoke pieces, pole pair, coil/cryostat unit - are probably best handled by a portable "A" frame gantry. This equipment could be provided by a contract rigging company, although CEBAF may elect to acquire one for end station use. A 20 Ton capacity half polar crane will be installed within Hall A, having a hook height 51'6" above the floor. This will be available to assist in dipole assembly.

It is anticipated that the vendor will bring a core group of foremen, engineers and senior technicians to supervise dipole installation, trades personnel being hired locally.

In addition to the 20 ton crane, electrical power (440, 220 + 110 V) will be available within Hall A. The location and capacity of these outlets is indicated in a civil construction drawing which will be supplied to the vendor under separate cover.

Cryogenic services (1 He, 1N₂) will be available as described in the section CRYOGENICS above.

Assembly Considerations: While erection procedure has not been addressed in detail, we envision the curved bottom rail of the iron yoke being employed as the "keel" to which the side elements are subsequently attached. This keel would be tilted with outrigger brackets for three-point mounting upon the cradle, through hydraulic jacks (with mechanical backup jacks for each). The return path sectors are on one side would then be installed, by dowelling and bolting to the keel. Temporary cribbing would be required to stabilize the structure prior to later installation of the opposite return path sectors. Contract rigging services will be required for dipole assembly/installation.

The coil/cryostat assembly (with one cold link subassembly installed) is set in place, shimmed against the installed yoke sectors and keel. The poles, delivered as a 26 ton assembly from the vendor's plant, are then rigged into place and temporarily held against the installed yoke sectors. Alignment of the pole assembly relative to the yoke is achieved by the "shoulder dowels" (Figure D.5), which also bear the pole loads (primarily gravitational,

in shear). At this point, the other coil cold support link assembly is installed. The remaining yoke sectors, and top rail, are rigged into place and installed with the indicated dowels, dowel plugs and through bolts.

Figures D.28, D.29 and D.30 show basic conceptual steps in erection of the dipole major elements upon the HRS cradle.

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Figures D.28, D.29 and D.30
Dipole Installation Sequence
(Initial drawings to be available for CDR presentation)

5.2 QUADRUPOLES

5.2.1 Overview

The HRS pair will require a total of six quadrupoles. Each spectrometer consists of a front-end quadrupole Q1, and two regular quadrupoles Q2 and Q3. The magnetic field requirements for these quadrupoles are given in Table 5.4.

Table 5.4
Magnetic Field Requirements

	Q1	Q2	Q3	
Magnetic Length	0.8	1.8	1.8	m
Useful Aperture	0.22×0.30	0.50×0.36	0.33×0.55	m×m
Field@Useful Aperture	1.3641	-0.8909	-0.8195	T
Multipole strengths:				
<i>Quadrupole</i>	9.0940	-3.1820	-3.0243	T/m
<i>Sextupole</i>	0	0.2233	1.1111	T/m ²
<i>Octupole</i>	0	1.6148	-0.4519	T/m ³
Gradient Uniformity	10^{-3}	10^{-3}	10^{-3}	

Furthermore, each spectrometer must be capable of achieving central scattering angles as low as 12.5°. This imposes special constraints on the overall sizes of the front end quadrupoles.

5.2.1.1 Basic Choice

Several quadrupole configurations were considered during the CEBAF magnet design and technology workshop. The useful aperture field (about 1T) for the quadrupoles are consistent with room temperature coil and iron pole piece design. However, the cos2θ superconducting design was chosen for all three quadrupoles primarily due to the following:

- The ease of incorporating auxiliary multipolar fields in a cylindrical geometry.
- Prohibitively high power consumption for the conventional designs.

Cos2θ superconducting quadrupoles have been successfully implemented in several laboratories such as CERN and FNAL. This is a well proven technology. However, the magnetic and structural design of the Hall A quadrupoles are still challenging because of: a) the large aperture-to-length aspect ratio which makes the magnetostatics design a true 3-dimensional problem and b) large sizes which leads to relatively higher magnetic forces and stored energies.

The quadrupolar field is realized by means of appropriate current distributions, hence, these quadrupoles are current dominated. However, in view of the high resolution requirements, an iron shield (yoke) is used to isolate the field of the quadrupole from the environment. In addition, the yoke iron contributes about 25% to the field in the useful bore. The

yoke is at room temperature outside the superconducting coil package and the associated cryogenic support structure. The choice of a room temperature yoke is twofold: a) the cold mass is significantly reduced; b) it also facilitates shaping of the yoke to accommodate the vacuum pipe for the direct beam in order to reach small spectrometer angles.

In addition to the main quadrupolar coils, auxiliary multipolar windings for optics requirements as well as correction of undesirable harmonics will be incorporated in the same cryo-assembly concentrically.

Figure 5.11 The $\cos 2\theta$ current distribution and some practical approximations. (Figure is taken from Ref. 4)

5.2.2 Magnetostatics

In two-dimensions, the ideal current dominated quadrupolar field is generated by two orthogonal and intersecting elliptic current distributions. This leads to the $\cos 2\theta$ current distribution, where θ is the azimuthal angle in a cylindrical geometry. In practice, the $\cos 2\theta$ current distribution is approximated with either stacks of conductor layers or a number of sectors of constant thickness conductor blocks, or a combinations of both (see Figure 5.10). We have chosen constant thickness multisector design because of its ease of fabrication. This choice was based on the experience of the CERN/ISR quadrupoles.⁴

In a quadrupolar symmetry, the tangential component of the field in a plane normal to the axis may be expanded in terms of multipoles as

$$B_\theta(r, \theta) = \sum_n C_n r^{n-1} \cos n\theta, \quad n = 2, 4, 6, 10 \dots$$

where C_n is the strength of the n^{th} multipole. Note that $n = 2$ is the quadrupole term. The degree of approximation to the ideal $\cos 2\theta$ current distribution depends on the desired gradient uniformity; or equivalently, the higher order harmonic contents that can be tolerated. In the present quadrupole about 75% of the bore is required to have 10^{-3} gradient uniformity. Detail studies^{1,2} have shown that the first five harmonics need to be minimized in order to achieve such gradient uniformity. With m sector blocks one has $2m - 1$ degrees of freedom. hence, three sector blocks are needed to eliminate the first five harmonics, $n=6,10,14,18,22$.

5.2.2.1 Design Parameters

The front quadrupole Q1 is approximately half the size of Q2 and Q3, whereas Q2 and Q3 are essentially identical. Therefore, we consider the quadrupoles to be of two modular types. Allowing for some margin to provide tunability to the optics design we have selected slightly higher gradients for the design parameters. The main design parameters for the quadrupole modules are given in Table 5.5.

Table 5.5
Design Parameters

	Q1	Q2/Q3	
Field Gradient	9.5	3.5	T/m
Magnetic Length	0.8	1.8	m
Useful Aperture	0.3	0.6	m
Gradient Uniformity	10^{-3}	10^{-3}	

5.2.2.2 Field Optimization

The magnetostatics design for the quadrupoles were carried out with the computer programs TOSCA³ and CEM.⁵

With coils wound on a cylindrical mandrel, the coil ends take the natural shape which forms the so called "constant perimeter" end. Although, in principle, one can force the conductor to deviate from this shape, the winding process becomes more complicated. In addition, with thin ribbon like conductors, this leads to stresses under which the conductor may buckle. However, the ideal constant perimeter end shape, which describes a circle on the cylinder, tends to occupy too much space, particularly for large bore cylindrical magnets. In the present design, we have used an approximation to the ideal end shape, in which the base curve on the cylinder is an ellipse, leading to a more compact coil package.

It is expected that each quadrant will be fabricated separately; the quadrants will then be assembled together to form the complete quadrupole. For mechanical tolerance reasons it was found necessary to keep a small gap between quadrants. Although, the discrete conductor have rectangular cross sections, we expect to introduce wedge type shims inside the sector blocks so as to achieve sector faces oriented radially.

The large aperture to length ratio of these magnets make the field calculation a true three dimensional problem. The initial coil geometry was determined with the program CEM. The program computes magnetic fields due to multipolar sector block windings with constant perimeter end shapes in 3-dimensions. In addition, it performs minimization search for geometry parameters so as to eliminate high order harmonics. The effect of an infinitely permeable iron shield is included in the calculations. The coil geometry was determined by varying the widths (b) and central azimuthal angles (α) of the three sector blocks with the constraint that the angular gap between quadrant be fixed at 0.52° . The minimization criterion was to reduce the contribution of $n = 6, 10, 14, 22, 26$ multipole strengths, at the useful bore, integrated along the axis of the quadrupole.

Transverse and longitudinal cuts of the optimal coil geometries for Q1 and Q2/Q3 are shown in Figures 5.12 and 5.13, respectively. At the end sections, the distance between the blocks was adjusted to allow for spacer blocks for coil support. The parameter of the overall coil and iron geometries for Q1 and Q2/Q3 are given in Table 5.6. Details of the three-sector quadrant geometry are given in Table 5.7.

The thickness of the room temperature iron yoke was determined using the program TOSCA. The inside radius of the yoke was taken to be 57.5 cm. The thickness of the yoke is 17.5 cm; this minimizes the contribution of the dodecapole strength arising for the yoke as well as maintains an average field of about 1.4T in the yoke which is well below saturation value for iron.

As mentioned earlier the iron-contribution to the field is about 25% in these quadrupoles. However, due to the axial symmetry of the iron and the low average field, it truly acts as a shield. It does not shape the field distribution in the useful bore in any significant manner.

Table 5.6
Overall Geometry

	Q1	Q2/Q3	
<i>Coil:</i>			
Overall Length	108.4	230.2	cm
Straight Length	56.0	131.5	cm
Coil Radius	20	40	cm
Thickness	3	3	cm
Layers	2	2	cm
Turns	388	756	
<i>Iron:</i>			
Inside Radius	32	57.5	cm
Thickness	15	17.5	cm
Length	80	180	cm
Weight	2.3	12.8	Ton
Average Field	1.5	1.4	T
Average Permeability	2300	3100	

Hence, the quadrupoles exhibit excellent linearity as a function of current as expected of a truly current dominated magnet. It is therefore adequate to study the field properties at only the highest excitation. The operating parameters at the highest field for both quadrupoles are listed in Table 5.8. Field maps over the entire volume with the above described geometry were computed with TOSCA for both the quadrupoles. For Q2/Q3, three different gradient excitations, $G_0=1.7, 3.1$, and 3.5 T/m were studied. For Q1, only the high field characteristics ($G_0 = 9.1$ T/m) was evaluated.

Table 5.7
Coil Quadrant Geometry

	Q1			Q2/Q3			
Sector→	1	2	3	1	2	3	
α	11.30	22.87	36.97	11.30	22.87	36.97	°
β	8.88	71.46	60.83	8.88	71.46	60.83	°
b	1.458	2.867	5.413	2.953	6.048	10.826	cm
h	28.0	28.0	28.0	65.75	65.75	65.75	cm
r	20.0	20.0	20.0	40.0	40.0	40.0	cm

The integral gradient uniformity in the mid-plane as function of the radius are plotted in Figure 5.14. The gradient uniformity is consistent with the requirements for both the quadrupoles. The gradient quality does not change appreciably with excitation as shown

Figure 5.12 Schematic views of the Q1 geometry. a) Perspective view of full coil package; b) transverse cut of central section first quadrant; c) Longitudinal view. Dimensions are in cm and degrees.

Figure 5.13 Schematic views of the Q2/Q3 geometry. a) Perspective view of full coil package; b) transverse cut of central section first quadrant; c) Longitudinal view. Dimensions are in cm and degrees.

Table 5.8
Operating characteristics

	Q1	Q2/Q3	
Current density (overall)	9.00	5.63	kA/cm ²
Total Amp-turns	1.02	1.4	MA
Operating current	2638	1852	A
Stored Energy	130	592	kJ
Peak coil field	2.12	1.83	T
Max. radial force	7.5	7.8	Ton/m
Max. tangential force	11.0	11.6	Ton/m
Max. axial force	11.7	13.1	Ton/m

in the figure for Q2. Past the useful radius, the gradient quality deteriorates rapidly due to very high order multipole contributions. Shown in Figure 5.15 is a contour map of the deviation of the field from the ideal quadrupolar field ($\Delta B/B_q$) in the central section of Q2. In the useful bore, $\Delta B/B_q$ is a few parts in 10^{-4} which is considerably better than the gradient uniformity.

The field distribution along the axial direction at the maximum useful bore in the mid-plane are shown in Figure 5.16a. The fringe fields die out reasonably in less than two gaps from the effective field boundaries. Since Q1 and Q2 are close to each other we have investigated the possibility of interference due to fringing fields in this region. Illustrated in Figure 5.16b is a contour map of the fringing field of Q2 up to the iron region of Q1. The field of Q2 at the iron boundary of Q1 (2.15 m from the center of Q2) is about 1 gauss. Thus, interference effects should be minimal and field clamps will not be required for these two quadrupoles. However, interference due to other magnetic structural elements have not been studied.

5.2.2.3 Harmonic Analysis

The coefficients C_n 's were evaluated by Fourier analysis of the TOSCA field maps evaluated at the useful bores in different transverse planes along the axis of the quadrupoles. Shown in Figure 5.17 are the harmonic contents for Q2 at full excitation. The multipole fields at the useful radius (30 cm) are shown in the bargraph (Figure 5.17a) normalized relative to the quadrupole strength (B_n/B_2); the open bars are for the harmonics in the central straight section of Q2 while the shaded bars are for the integrated strengths for the entire length of the quadrupole. In addition, the distribution of the first few multipoles along the axis of the quadrupole are shown in Figure 5.17b.

Q2 Gradient Uniformity

Figure 5.14 Integral gradient error as a function of bore radius. for Q2 at $G_0=1.7$, 3.1, 3.5 T/m.

Figure 5.15 Relative deviation contour map ($\Delta B/B_{quad}$) for the central transverse plane for Q2.

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Figure 5.16 a) Q2 axial field distribution at different bore radii. The dashed curve is the effective field boundary. b) Contour map of Q2 fringing field in the mid-plane.

Figure 5.17 Q2 Harmonic contents at $r=30$ cm at full excitation. a) Multipole fields normalized relative to the quadrupole strength (B_n/B_2); the open bars are for the harmonics in the central straight section of Q2 while the shaded bars are for the integrated strengths for the entire length of the quadrupole. b) Axial distribution along the axis (z) of the quadrupole.

5.2.2.4 Energy and Forces

The field distribution on the inner surface of the coil was calculated with TOSCA. The peak field on the conductor was determined to be 1.83 T which occurs at the coil ends. The peak coil field in the straight section of Q2 is 1.5 T. These values are quite conservative for a cryomagnet. Stored energy and magnetic body forces along the coil were also evaluated with TOSCA. The magnetic forces in the transverse plane at the straight section of Q2 are shown in Figure 5.18a and forces at the end sections are plotted in Figure 5.18b. The forces in these figures are in metric Tons/m.

5.2.2.5 Conductor Placement Tolerances

Simulation of conductor misplacement errors with TOSCA was found to be prohibitively time consuming. We have simulated conductor placement errors with the program CEM in two dimension. A few of these calculations were checked with TOSCA and were found to be in good agreement. The possible errors can be divided into two classes: symmetric and asymmetric misplacements of coil sectors. In the first case coil blocks are misplaced within each quadrant, however the four-fold symmetry between quadrants is maintained. In such symmetric cases, only the allowed harmonics $n = 6, 10, 14, \dots$ are generated. The higher multipolarity of these harmonics implies they only affect the fringes of the useful bore and may not create a significant problem. The second type of misplacement allows for misalignment of the quadrants with respect to each other. This was simulated by moving all sector blocks randomly. Shown in Figure 5.18 is the gradient error due to asymmetric misalignments. Without any means of correcting the higher order harmonics, the conductor placement tolerances need to be about ± 0.15 mm.

Harmonic analysis of the field due to asymmetric misalignments reveals that the non-allowed harmonics contribute significantly. In particular, lower multipoles from dipole to dodecapoles, rise significantly above 10^{-3} level. This is illustrated in Figure 5.20c. Furthermore, these unwanted multipoles may have very different phase angles from the main field. With normal-skewed pair auxiliary coils, such harmonics can be corrected for leading to a considerably relaxed tolerance on conductor placement. If we allow for correctional multipoles $n=1, 3, 5, 6$ up to 10% of the main coil amp-turns, the conductor placement tolerance needs to be only ± 0.5 mm.

5.2.2.6 Multipole Elements

A schematic view of the multipole current sectors are shown in Figure 5.20. The design is similar to the one in Ref.1 and consists of a grooved bore tube with multipole current filaments placed just inside of the main coil. The filament conductor is about 1 mm in diameter. Each multipole layer is completely contained in a radial thickness of 1.5 mm. The total radial thickness of all the multipoles will be about 1 cm. The optics requires sextupole and octupole fields for Q2 and Q3 (see Table 5.4). The amp-turns for the multipolar fields are driven by the sextupole in Q2 and the octupole in Q1. The multipolar fields will be incorporated in the same cryostat and support structure assembly

Figure 5.18 Magnetic forces on the coil of Q2: a) in the transverse plane at the straight section; b) at the end sections. The forces in these figures are in metric Tons/m.

Q3 Sextupole Forces (Ton/m)

Q3 Octupole Forces (Ton/m)

Figure 5.19 Magnetic forces on the Sextupole (a), and Octupole (b) elements of Q3. The force vectors represent both magnitude (metric Ton/m) and direction.

Figure 5.20 a) Schematic view of multipole windings. b) Blow up of the multipole layers; c) Harmonic strengths relative to the quadrupole term allowing for a random misalignment of ± 0.5 mm. The solid(open) bars are with(without) correctional multipoles. Note that $n=3,4$ are required by optics.

as the main quadrupole coil. The sextupole and the octupole will carry 13% and 8% of the amp-turns of the main coil, respectively. The parameters of these required multipoles are given in Table 5.9. As discussed in the previous section we will also need Correctional normal and skewed dipole, skewed quadrupole, skewed sextupole, decapole, and dodecapole elements. The geometrical arrangements and the amp-turns are given in Table 5.9.

Table 5.9
Q2/Q3 Multipole Elements

n	B_n/B_2 (%)	Amp-turns (kA)	Radius (cm)	Type	Phase (deg)
1	1	6	39.80	NORM	0
	1	6	39.65	SKEWED	90
2	1	13	39.50	SKEWED	45
3*	13	183	39.35	NORM	0
	1	14	39.20	SKEWED	30
4*	8	109	39.05	NORM	0
5	1	36	38.90	NORM	0
6	1	57	38.75	NORM	0

5.2.2.7 Small Angle Capability

The smallest angle feasible with these quadrupoles is illustrated in Figure 5.21. We have assumed a 3° conical beam pipe for this estimation. In order to achieve this small angle, the yoke of Q1 will require notches (see figure) to allow room for the beam pipe. The effect of the notches on the quadrupole field quality as well as the effect of the leakage field on the beam are minimal. It appears the quad pair can reach about 12.5°. Note that the yoke of Q2/Q3 remains in tact.

5.2.2.8 Conclusion

We have presented a reference design for the $\cos 2\theta$ quadrupoles for the high resolution spectrometers for Hall A. The present design meets the field quality requirements as well as the small angle capability required. In addition, a conceptual design is presented for the sextupole and octupole fields required by the optics design. The conductor placement tolerances, which is often the critical factor for high quality current dominated design, have been considerably relaxed through the inclusion of correctional multipole elements.

Figure 5.21 Small angle capability with Q1 yoke cut in the horizontal mid plane. The rays shown correspond to 4 GeV electrons. The curve is leakage field seen by the beam in gauss. The $\int Bdl$ corresponds to 0.25 mr of beam deflection.

References

1. CEBAF Magnet Design Workshop; HRS TAP1/TAP2 reviews; Preliminary Conceptual Design Report, CEBAF 1988.
2. POISSON group of magnetostatics computer programs, Los Alamos.
3. TOSCA, 3D Non-linear Magnetostatics computer program, SCARPIA Pre-processor and OPERA post-processor, Vector Fields, Oxford, England.
4. R. Perin, T. Tortschanoff and R. Wolf, CERN Report
5. CEM, 2D/3D Linear Magnetostatics computer program, S. Nanda.

5.2.3 Quadrupole Engineering

5.2.3.1 Introduction

As described in Section 5.2 above, two identical superconducting quadrupoles (Q2, Q3) are required for the HRS to provide focussing in the dispersive (horizontal) plane. In-plane focussing is provided by pole face index and end biasing features of the dipole, and by the smaller front quad (Q1).

As a result of magnet workshop recommendations and of our own studies, a cosine 2θ configuration has been selected as the most efficacious solution for the HRS quadrupole requirement. This conclusion is based primarily upon the following considerations:

- required $\int \beta \cdot dl$ field quality of 1×10^{-3} ;
- maintenance of this fixed quality over a decade excitation range. The cos 2θ option exhibits a linear B vs I characteristic, since the field geometry is defined by the coils, the iron serving primarily as a flux return path/shield;
- accomodation of tunable, superconducting multiple field coils within the (cold) bore of the main coil;
- technical maturity of the cosine 2θ quadrupole option:

The Technical Requirement has been established through extensive TOSCA 3-D modelling of the coil (and iron) geometry and tolerances, to meet the HRS optics criteria over a decade excitation range.

The CEBAF Reference Conceptual Design is based generically upon the ISR and LEP quads developed for CERN.

Our Technical Requirement and Reference Conceptual Design for Q2/Q3 have been reviewed and approved by our Technical Advisory Panel (TAP). These elements have been incorporated into a Specification, which will serve as the technical content of our forthcoming procurement.

5.2.3.2 Technical Specification

The included draft Technical Specification defines the Scope of Work, Technical Requirements and Reference Conceptual Design for the Q2/Q3 quadrupoles. An addendum covering the smaller front quad, Q1, is in preparation.

5.2.3.3 Analytical Basis for the Reference Conceptual Design

The superconducting cosine 2θ quadrupole design has been supported by engineering analysis throughout its multi-year development. The following analysis have been performed for the Q2/Q3 Reference Conceptual Design. They are available as an HRS Technical Note. Magnetics analyses are discussed in Section 5.1 above.

- Conductor Calculations (summarized in Table Q.IV the Technical Specification);
- Quench Analysis (Tuzel)
- Cold Mass Stress/Strain (Tuzel)
- Cryostat Heat Load (Tuzel)
- Cold-To-Warm Supports (Tuzel)

Cosine 2θ Quadrupoles Q2/Q3 for Hall A HRS

Technical Specification

Four identical 60 cm bore $\times$ 3.5 T/m superconducting cosine 2θ quadrupoles are required for the two 4 GeV/c High Resolution Spectrometer Arms of CEBAF's Experimental Hall A. This specification is defined in five sections: Statement of Work; Technical Requirement; Reference Conceptual Design; Design, Analysis and Testing; Deliverables.

1. Statement of Work

The Continuous Electron Beam Accelerator Facility (CEBAF) requires four identical superconducting quadrupole magnets of a cosine 2θ coil configuration. Principal characteristics include: 60 cm clear bore; 1.8 m effective length; 3.5 T/m field gradient; 1×10^{-3} field gradient quality; room temperature cylindrical iron return path. Geometry, tolerances and forces for a three-sector, two layer coil quadrant are specified, based upon 3-D magnetic analysis performed by CEBAF. A reference conceptual design is provided, which represents one approach which CEBAF considers feasible (when fully developed) for meeting this requirement. The respondent is free to propose alternative structural/cryogenic designs or to follow the reference approach. In either case, full responsibility for meeting this specification will rest with the vendor, who must test each unit at full excitation before delivery. These magnets are to be part of two identical high resolution 4 GeV/c spectrometers required for CEBAF's Experimental Hall A, (Figure Q.1), designated Q2 and Q3.

2. Technical Requirement

The technical requirement for these devices is defined by Table Q.I and by the accompanying figures.

Main Coils: The main coil configuration has been defined by 3-D TOSCA computer analysis, performed by Nanda of CEBAF to achieve a quadrupole field gradient uniformity of 1×10^{-3} within the active field region, over a decade excitation range. Thus, the specification requirements are coil configuration/tolerances as shown, the resulting field gradient quality being the responsibility of CEBAF.

Also part of the main coil requirement are the total ampere-turns, operating current and other conductor characteristics, as given in Table Q.I, as well as the return iron geometry and composition.

Auxiliary Multipole Coils: The HRS optics requires sextupole and octupole fields, with some excitation control for various experimental tunes. Also, to correct for inevitable hardware errors, as well as inherent fringe field dodecapole aberrations, various correction coils must be provided. The specifications for these coils are given in the appropriate figure.

Cryostat: Requirements specified in Table Q .I include heat load at 4.5K, criterion for the main coil cold support structure, cold mass dynamic support interior, clear bore, overall length and external envelope constraints.

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4 GeV/c High Resolution Spectrometer

Figure Q.1

4/6/90

Table Q.I
Cosine 2θ Quadrupoles
Requirements

Number of identical quadrupoles: 4

Magnet Type: Quadrupole; superconducting; bore field defined primarily by cosine 2θ coil geometry; iron flux return path.

Main Coil:

Total ampere turns: 1.40 MAT

Coil Quadrant Dimensions, Geometry, Tolerances: As defined in Figures Q.2, Q.3 and Q.4. The indicated dimensions and tolerances apply at room temperature, after the coil assembly has been preloaded by its support structure, which has been designed to meet the criterion stated below.

Conductor Characteristics:

- Operating current: 1.85KA @ 4.5K
- Minimum critical current: 3KA @ 4.5K and 5T
- Average current density in copper at operating current, max.: 7.5 KA/cm²

Cryostat:

Clear Bore: 60 cm

Magnet Heat Load @ 4.K, Max: 15 watts

Flux Return Path:

- Geometry: cylindrical, surrounding cryostat: 180 cm long $\times$ 114.9 cm I.D. $\times$ 132.4 cm O.D. Longitudinal seams and connections as required for installation.
- Material: Iron, AISI 1006

Cold Mass Dynamic Support Criterion: 5g omnidirectionally

External Envelope Constraints: Per Figure Q.5.

Coil Structure Criterion: Coil must remain under radial compression at full excitation, with no possibility of thermally destabilizing inelastic motion. The magnetic forces generated within the coil at full excitation are shown in Figure Q.6.

Aside from the 60 cm clear bore, the magnets must allow positioning of both HRS arms within $12\frac{1}{2}^\circ$ of the 0° forward angle beam line.

Table Q.I
Cosine 2θ Quadrupoles

Requirements
(continued)

Auxiliary Multipole Coils:

- **Type:** superconducting
- **Location:** inside helium vessel, within bore of main coils.
- **Support:** cylindrical tube, which may be helium vessel bore.
- **Multipole locations, ampere-turn requirements:** Figure Q.7.
- **Magnetic forces, in cross-section:** Figure Q.8.

Acceptance Testing: Each completed quadrupole is to be energized to 1.05 times operating current within 15 minutes, with no evidence of cryogenic instability (quenching). Conformance to the heat load requirement shall be verified, following 4 hours operation at 1.85 KA.

Standards: Design, fabrication and acceptance testing of these magnets must be performed in accordance with standards generally considered acceptable by recognized experts in the field of applied superconductivity, to result in a product which meets the performance/spatial requirements with a high level of operational reliability.

NOTES:

- Dimensions are in cm.
- All dimensions are 'BASIC' unless a tolerance is otherwise specified.
- All dimensions are for the assembled coil at room temperature, preloaded by its support structure in accordance with the specification requirements.

Coil Quadrant Sectors Position/Tolerance

Figure Q.2

All dimensions in cm.

Longitudinal Section

Figure Q.3

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Cross-Section Alignment

Longitudinal Alignment

Detail A: Quadrant Mating Edges

Coil Quadrant Assembly Tolerances

Figure Q.4

4/6/90

- Dimensions are in cm.
- Removable Iron pieces may be used to achieve the required clearance as long as azimuthal symmetry is conserved.
- Notches in the Cryostat must be symmetrical about a vertical plane thru the magnet axis to allow positioning of the magnet on either side of the beam line.

**Magnet Envelope Constraints
(Plan view)**

Figure Q.5

4/6/90

These forces must be reacted in such a manner that the cylindricity of the coil assembly is maintained within 0.25 mm (0.010") on the diameter.

Forces are in metric tons/meter

**Cosine 2θ Quadrupoles: Field and Force Data
for the Coil Quadrant Cross Section**

Figure Q.6

4/6/90

Figure Q.7
Auxiliary Multipole Coils

Q3 Octupole Forces (Ton/m)

Q3 Sextupole Forces (Ton/m)

Figure Q.8
Auxiliary Multipole Coils
Magnetic Forces in Cross-Section

3. Reference Conceptual Design

General

As noted in the **Statement of Work**, this Reference Conceptual Design is provided in order to represent one approach which CEBAF considers feasible, when fully developed by the vendor, for meeting this technical requirement. The vendor is free to propose alternative structural/cryogenic designs or to generally follow this reference approach. In either case, full responsibility for meeting the Technical Requirement rests with the vendor, who must test each unit prior to delivery in accordance with the requirements.

Basic parameters of the 60 cm bore, 1.8 m long, 3.5 T/m magnets are given in Table Q.II; their key features are summarized in Table Q.III. The overall magnet assembly is illustrated in Figure Q.9, which indicates its cylindrical geometry, iron flux return path, and cold-to-warm support horns. Figure Q.10 is a longitudinal elevation section of the magnet, whose cross section is given in Figure Q.11.

The concentric shell, shrink ring/stave support, 3 sector coil quadrant configuration is based generically upon the 13 cm bore cosine 2θ quads built for the CERN LEP.

Table Q.II
 Superconducting Cosine 2θ Quadrupole
Basic Parameters of
Reference Conceptual Design

Clear Bore	60 cm
Magnetic Length	180 cm
Field Gradient	3.5 T/m
Gradient Uniformity	1×10^{-3}
Total Ampere Turns	1.40 MAT
Operating Current	1.85 KA
Stored Energy	592 KJ
Coil Peak Field	1.83 T
Total Magnet Weight	16×10^3 KG
Overall Magnet Length	295 cm

Table Q.III
Superconducting Cosine 2θ Quadrupole
Primary Features of
Reference Conceptual Design

Main Coil:

- Intrinsically stable, epoxy impregnated.
- Three sector, two layer quadrants.
- Coil geometry established by Tosca 3-D analysis.
- Elliptical, constant perimeter ends.
- Coil remains under radial compression at full excitation.
- Conductor: "Built-up" monolith; 1.85 KA @ ~ 7 KA/cm² avg. C.D.

Main Coil Support: Concentric Shell Design

- Aluminum shrink rings provide coil precompression, magnetic hoop and bending load support.
- Stainless steel quadrant staves provide longitudinal stiffness, assist in coil protection from shrink ring heat.
- Coil banded with B-stage epoxy-glass, machined after cure. Provides ℓ He passages, electrical and (shrink ring) heat insulation.

Cold-To-Warm Support:

- Eight horn design, oriented to accommodate differential thermal contraction and two arm 25° forward included angle HRS position, while supporting all magnetic (eccentricity), gravity and dynamic loads.

Iron Return Path Cylinder: 1.80m long $\times$ 115cm I.D. $\times$ 17.5cm thick.

Auxiliary Multipole Coils:

- Superconducting, installed upon stainless steel support tube located between main coil and helium bore tube.
- Coil wire: 1 mm (40 mil) diameter, 7:1 Cu/NbTi ratio. 150 AMP operating current.
- Current Control: separate circuit for each multipole coil set.

Coil

Each quadrant employs a three sector, two layer, epoxy impregnated "cylindrical surface racetrack" coil, whose geometry, tolerances and forces have been defined by 3-D Tosca analysis to achieve the requisite cosine 2θ field to 1×10^{-3} quality. This coil geometry, given in Figures Q.2, Q.3, and Q.4 above, constitutes part of the technical requirement of this specification.

Cosine 20 Quadrupole: Overall View

Figure Q.9

Dimensions are in cm.

4/6/90

Cosine 2θ Quadrupole: Longitudinal Section

Figure Q.10

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Cosine 2θ Quadrupole: Assembly Cross-Section

Figure Q.11

4/6/90

Intrinsic Stability: For this design, the helium cooled coil must be sufficiently restrained to preclude the spontaneous occurrence of inelastic slip/stop transient thermo-mechanical disturbances of sufficient magnitude to generate a propagating resistive (“normal”) zone, without the presence of direct conductor to coolant heat transfer from the affected zone. In other words, the coil is cooled globally, but not locally.

To achieve this goal, the coil must be tightly wound, epoxy impregnated under radial and azimuthal load, and maintained under radial (and azimuthal) pressure under full magnetic loading, to ensure that no significant inelastic relative motion between conductors can occur.

As regards “intrinsic stability”, 7 KA/cm^2 represents an empirically selected value which we consider safe for a well constrained coil of this geometry and stored energy density. While the SSC beam line magnets employ conductor with average current densities in the 50 KA/cm^2 range, their coils are “fully constrained” and their design has evolved through an extensive development program. 10 KA/cm^2 represents the lower end of typical current density values for industrially supplied whole-body magnetic resonance imaging (MRI) solenoids, while 5 KA/cm^2 may be optimal for larger, less well constrained intrinsically stabilized coils.

Coil Geometry: The quadrupole field is determined entirely by the coil assembly geometry, wherein its three sectors closely approximate the cosine 2θ ideal, achieved (in cross-section) by two intersecting ellipses of appropriate major and minor axes.

For the 2-D field (as generated by POISSON, or equivalent), the key parameters are number of sectors (3); azimuthal location (11.305° ; 22.865° ; and 36.975° , relative to the quadrant midline); number of turns (28, 55 and 106 respectively) and cross-section geometry, as shown in Figure Q.12. Note that the edges of the each sector are oriented radially, wedge-shaped spacers having been inserted within the sector, as appropriate.

Geometry of the coil quadrant ends is important from the standpoints of magnetic field quality (minimization of harmonic content), effective magnetic length ($\int B dl$), cryostat length, forces, peak field at the conductor, and practical fabrication technique. The 3-D code Tosca (or its equivalent) is required to adequately describe the field resulting from a given end geometry. We have selected elliptical ends, with the conductors assuming their natural “constant perimeter” shapes, leading to sectors which are parallelogram shaped in longitudinal end section. See Figure Q.13. The coil ends must be supported against substantial axial (in-plane), and moderate radial (outward and inward) magnetic loads. Figure Q.14 is a longitudinal view of one quadrant, showing the three sectors, end geometry, cross overs and current leads.

Coil Tolerances: The coil quadrant tolerances given in Figures Q.2 and Q.3 are met through precision machined components (quadrant core, intersector spacers), conductor size, winding measurement/shimming, and maintenance of the coil under radial and azimuthal compression throughout the wind/cure process.

The coil dimensions and tolerances given in Figures Q.2, Q.3 and Q.4 above match the magnetic field analyses and thus apply, in principle, when the magnet is cold and fully

Coil Quadrant Cross-Section
Figure Q.12

4/6/90

06 FEB 90
Gavalya

Coil Quadrant Longitudinal-Section

Figure Q.13

Coil Quadrant Longitudinal View

Figure Q.14

4/6/90

energized. As a practical matter however, the vendor should regard these specifications as applying to the coil at room temperature, following application of the aluminum shrink rings.

The central core for each quadrant is accurately machined from stainless steel 304LN. The intersector spacers (both straight and end elements) are to be made from easily machinable copper alloy, in order to closely match the coils' modulus and thermal contraction, and to promote conductive cooling (and heat propagation during a quench).

The rectangular conductor can be obtained with metallic cross-section tolerances specified as nominal to 1 mil ($25\ \mu\text{m}$) undersize. The 4 mil (0.1 mm) nominal insulation thickness could vary by $\pm 1/2$ mil ($\pm 12\ \mu\text{m}$): but, when the coil is squeezed azimuthally, it will probably never exceed its nominal value. Sector measurement and shimming is discussed under "Coil Winding" below.

Assembly of the quadrants into a complete coil must conform to the tolerances given in Figure Q.4 above. In order to achieve the interquadrant azimuthal position of $90^\circ \pm$, the edge of each quadrant can be trimmed as appropriate. Although a proper edge could be obtained in a number of ways, it may be convenient to epoxy a copper strip in place so that after machine trimming its nominal thickness is around $1/32$ ".

Conductor: The 1.85 KA conductor of the reference conceptual design is a "two component monolith" wherein a flattened ("Rutherford") cable is soldered into the longitudinal groove of a rectangular copper substrate (annealed CDA102). Figure Q.15 depicts the conductor and its insulation: Table Q.IV provides specifications for the cable and its constituent composite wire. Figure Q.16 shows the "load line" for the NbTi @ 4.5K, and 5 Tesla. This field value is arbitrarily selected to provide a considerable safety margin for the conductor.

Table Q.IV
Cosine 2 θ Quadrupoles
2 KA Conductor

Composite Superconducting Wire:

Typical NbTi critical density

$$J_c = 250 \text{ KA/cm}^2 @ 5 \text{ T, } 4.2 \text{ K}$$

$$\text{Adjustment for } 4.5 \text{ K: } @ 5 \text{ T, } \Delta J_c / \Delta t \approx 80 \text{ KA/cm}^2/\text{K}$$

$$\text{Reduction from } 4.2 \text{ K to } 4.5 \text{ K} \approx 25 \text{ KA/cm}^2$$

$$\therefore J_c = 225 \text{ KA/cm}^2 @ 5 \text{ T, } 4.5 \text{ K}$$

Selected NbTi operating current density (see Fig. Q.16)

$$J_{op} = 0.6 J_c = 135 \text{ KA/cm}^2 @ 5 \text{ T, } 4.5 \text{ K}$$

Select wire Cu:SC ratio = 2:1

Select wire operational current = 92.5 A

Corresponding number of wires in 1.85 KA cable = 20

Wire Size:

$$\text{Area} = 92.5 \text{ A} \times 3/135 \times 10^3 \text{ A/cm}^2 = 2.06 \times 10^{-3} \text{ cm}^2$$

$$\text{Diameter} = (4 \text{ A}/\pi)^{1/2} = 0.0512 \text{ cm (0.0201 in)}$$

But, select 20 mil wire (0.0508 cm)

$$\text{Area} = 2.027 \times 10^{-3} \text{ cm}^2$$

$$\text{C.D. avg} = 45.6 \text{ KA/cm}^2; \text{ C.D. (NbTi)} = 137 \text{ KA/cm}^2 \text{ O.K.}$$

Flattened (Rutherford) Cable Insert:

Assume 85% compaction

$$\text{Envelope area} = 2.027 \times 10^{-3} \times 20/0.85$$

$$= 47.69 \times 10^{-3} \text{ cm}^2$$

If compacted height = 0.0900 cm

$$\text{width} = 0.530 \text{ cm}$$

Copper Substrate:

$$\text{Area} = 1.49 \times 0.184 - 0.048 + (2/3 \times 20 \times 2.027 \times 10^{-3} = 0.027) = 0.253 \text{ cm}^2 \text{ (See Fig. Q.15)}$$

$$\text{Average substrate current density} = 7.31 \text{ KA/cm}^2$$

Notes:

- Dimensions are in cm

Conductor:

- Maximum operating current 1.85 KA
- Average current density 6.75 KA/cm² @ 1.85 KA

NbTi:

- $J_c = 250 \text{ KA/cm}^2$ @ 5 T , 4.2 K
- $J_{op} = 138 \text{ KA/cm}^2$ @ 5 T , 4.5 K

Composite wire insert:

- Configuration: flattened (Rutherford) cable
- Number of wires: 20
- Wire diameter: 20 mil (0.508 mm)
- Cu:NbTi: ratio = 2:1

Copper Substrate:

- Area = 2.53 cm²
- Average Current Density = 7.3 KA/cm²

1.85 KA Conductor of Reference Design

Figure Q.15

5/2/90

J vs B & t for NbTi

Figure Q.16

4/6/90

Coil Winding: Two options are possible for 3 sector, 2 layer quadrant winding. One complete layer could be wound, with intersector spacers and intrasector shims inserted as appropriate. For the second layer, the intersector spacers must be match drilled/dowelled to those below.

While it requires more handling of conductor supply spools, it is probably better to wind both layers of each sector before proceeding to the next. Installation of intersector spacers is much simplified, since each element can be full height. In either case, no conductor splices are allowed within a coil quadrant.

Winding tooling must be devised to maintain the completed coil portion under azimuthal and radial pressure of around 10 atmospheres at all times and locations – except of course in the region of the oncoming conductor. While such clamping could be performed manually, an automated scheme may result in a net cost saving to the vendor. Also, the oncoming conductor must be maintained under 1000 psi or so tension.

Each sector must be maintained within the angular tolerances indicated in Figure Q.2. Furthermore, the edges of each sector are to be radial, as indicated. In principle, these results could be achieved with trapezoidal conductor having the exact nominal dimensions. In practice, it is advisable to employ rectangular conductor, toleranced downward from nominal. Thus, within each sector, one or more sets of wedge-shaped, G-10 shims are inserted, specifically: Sector 1-1; Sector 2-2; Sector 3-3 (see Figure Q.12). After winding the requisite number of turns within a sector up to a “shim station”, the compressed azimuthal “build” is measured from the scribed centerline of the quadrant core, and compared to nominal. The trapezoidal shim pieces are custom machined accordingly.

As with any magnet, care must be exercised to prevent interturn, interlayer or coil to ground shorts—achieved through careful, experience-based design and manufacture. Particular attention must be given to ensure “short-proof” interlayer crossovers.

Epoxy Filling: The reference design specifies epoxy impregnation of each coil quadrant, in or order to facilitate assembly handling and to provide a dimensionally stable monolith, free of any significant motion threatening interturn voids. Epoxy filling can be achieved either by wet layup process or by vacuum impregnation. The conductor itself must be insulated in a manner which assures complete bonding throughout the coil matrix. Alternatives include adhesive backed Kapton wrap, B-stage epoxy-fiberglass wrap, dry epoxy-fiberglass tape wrap—or a combination thereof.

In the reference design, the shrink rings will impart a radial pressure of around 150 psi (15 atm) to the coil. Recalling $S=pr/t$, this translates to an azimuthal stress of 2000 psi (130 atm). This raises the issue: should the coils be measured for intrasector shimming (see above), and epoxy cured under an azimuthal pressure approaching 130 atm, or at 10-15 atm? This, of course, must be resolved during or before final design.

Coil Assembly: After curing, the quadrant edges must be trimmed (machined) to meet the assembly tolerances given in Figure Q.4. Recall that these apply at room temperature, following application of the aluminum shrink rings. Appropriate allowance must therefore be made for winding mandrel O.D. and for I.D. of the assembled coil before application of the shrink rings.

After edge trimming, the quadrants are assembled upon a collapsible mandrel, so that their mating edges are in firm contact. One inch wide prepreg epoxy fiberglass tape is then applied to yield a pattern of circumferential bands separated by 1/2" inch wide gaps (later to serve as liquid helium passages). Considerable tension must be maintained on the prepreg tape, to ensure a monolithic, high density band when cured. Also, clamp rings should be placed at intervals along the length, to preload the coil assembly.

After curing, the band surfaces are machined (ground), by rotating the coil assembly on the collapsible mandrel.

Cold Support Structure

The role of the cold support structure is to accurately constrain the coil quadrants within their cylindrical shell geometry, preloaded so that they remain under radial compression at full excitation. The elements comprising this structure, plus the coil, are shown in Figures Q.17 and Q.18. The structure components and their functions are described within the context of the assembly sequence.

Staves: The stainless steel quadrant staves serve the dual role of providing rigid longitudinal support for the entire cold mass, and of shielding the coil and its epoxy-glass banding from direct shrink ring heat.

The staves are cut longitudinally from a tube of appropriate size, which has had circumferential grooves machined at several axial locations, for later banding. The staves are dimensioned so that a slight longitudinal gap exists between them, even after application of the shrink rings. The staves are placed over the coil/bore tube assembly, and tightly clamped in place by stainless steel banding applied in the several circumferential grooves. See Figure Q.18.

Aluminum Shrink Rings: These ten sequentially applied elements serve the triple function of providing coil precompression, hoop load support, and restraint against transverse bending (out of round distortion by magnetic quadrupole forces). As noted above, interference fit precompression must be such as to ensure that the coil remains under radial compression at full current (field) excitation. This condition, achieved through proper sizing and tolerancing of several participating elements, must be confirmed by careful analysis, especially regards the effects of differential thermal contraction and transverse magnetic loading.

Our preliminary reference design analysis indicates that the 5 cm (2") thick 2024T6 aluminum shrink rings must deliver a room temperature pressure of 210 psi (14 atm) to the coil shell. This is equivalent to a 0.46 mm (18 mil) diametral interference fit between the cooled shrink rings and the staves. At a ring temperature of 300°F, the slip-on diametral clearance is 0.164 in (4.2 mm) between it and the stave surface. The preliminary component dimensions, pressures, etc. at various stages of shrink ring assembly are shown in Figure Q.19.

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Cold Structure Longitudinal Section

Figure Q.17

4/11/90

Coil Assembly/Support

Figure Q.18

4/6/90

1) As machined

2) Shrink Ring heated

**3) Shrink Rings installed:
room temperature**

4) 4.2 K

Cosine 20 Quadrupoles Shrink Ring Installation/Support

Figure Q.19

4/8/90

Shrink Ring Installation: Clearly, the procedure by which the ten aluminum shrink rings are applied over the coil/stave assembly is critical, in order to ensure correct positioning and protection of the coil from excessive heating. While such a procedure has not been developed in detail by CEBAF, shrink ring assembly was successfully accomplished for the CERN ISR and LEP magnets. Also, several potential US manufacturers have expressed confidence in their ability to perform this operation (for our previous 80 cm bore design).

Key aspects of shrink ring assembly will be development of and adherence to a good procedure (probably through mockup testing) and provision of appropriate hot ring handling devices and positioning fixtures. Presumably, the coil/stave assembly will be oriented with its axis vertical, and a collar fixture placed around it to position the first, mid length shrink ring. Once this central ring has been properly installed, it should only be necessary to ensure that subsequent rings come to rest freely upon the one below. After all of the rings to one side of the central ring have been applied, the assembly is inverted to receive the remainder. It is doubtless appropriate to blow air through the coil helium channels to promote cooling as the rings are applied.

It is necessary to analytically verify that the local "choking" pressure of the initially applied rings does not distort the coil to the point of fracturing the epoxy matrix. (inter-laminar shear stresses should not exceed 1000 psi.) If this condition appears threatening, it may be appropriate to consider a flexibilized epoxy formulation.

Each completed coil/stave/ring assembly should be "open dewar" tested to full 2 KA current, in order to verify its functional integrity. At this time, it should also be quenched (by temporary installation of a heating device), in order to confirm its ability to survive such a fault condition.

Cryostat: The coil/cryostat assembly is shown in Figures Q.20, Q.21 and Q.22.

Helium Vessel: The helium vessel consists essentially of a cylindrical stainless steel can enclosing the coil/stave/ring assembly, which incorporates end features for the cold-to-warm supports and cryogenics/electrical services.

In accordance with accepted practice for these elements, it should be designed for four atmospheres internal pressure, with an appropriate relief device located in the vent line. Fault/failure modes defining the pressure requirement are discussed below under Cryogenic Features/Operation. Its manufacturer/design shall be in accordance with ASME Pressure Vessel Code, Section VIII.

During cryostat assembly, the helium vessel should be covered with at least five layers of aluminized mylar "superinsulation", in accordance with accepted cryogenic practice.

Heat Shield: A liquid nitrogen cooled shield surrounds the "cold mass", to intercept radiant heat from the vacuum vessel walls and conductive heat from the cold-to-warm supports (by conductive attachment at appropriate points).

A typical heat shield consists of 1/16" thick copper or aluminum sheet, stiffened by rings, supported from the cold-to-warm supports and segmented as appropriate to limit force inducing eddy current flow during fast discharge.

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Dimensions are in cm.

Coil/Cryostat Assembly Longitudinal Views

Figure Q.20

4/6/90

Coil/Cryostat Assembly
Longitudinal View

Figure Q.21

Dimensions are in cm.

+1/6/90

**Coil/Cryostat Assembly
End Section**

Figure Q.22

4/6/90

Aluminum or copper trace tubing is attached to the sheet (brazed, soldered or welded as appropriate) in a pattern which will permit convective nitrogen flow in response to heat influx. Intertube spacing, as determined from simple hand calculation, should be one foot or more over the sheet face: attachment need not be continuous.

During cryostat assembly, the heat shield must be covered with at least 20 layers of aluminized mylar "superinsulation", in accordance with accepted cryogenic practice.

Vacuum Vessel: The vacuum vessel consists essentially of a cylindrical stainless steel can enclosing the "cold mass" (coil/stave/ring/helium vessel assembly) and its surrounding liquid nitrogen heat shield. Its features include the cold-to-warm support horns, cryogenic service box and attachment/locating points to the return path iron. It is illustrated in Figures Q.7, Q.8, and Q.9 above. It must be equipped with a relief valve located on its cryogenic service box, which limits its fault/failure mode internal pressure to 5 psig, or less. Thus, it is not a "pressure vessel" in ASME terminology. Nevertheless, it should be designed to withstand 1 atm internal pressure, and it should conform to ASME practice.

Cold-to-Warm Supports: The cold mass is supported within the vacuum tank by eight "horns", oriented so as to constrain it omnidirectionally, while partially accommodating differential thermal contraction during cooldown.

An important constraint for the upbeam cosine 2θ quadrupoles (as well as Q1) is minimal interference with forward angle HRS position, as regards both the 3° beam pipe and the opposite spectrometer. This situation is illustrated in Figure Q.5, where a 21° included angle is achievable with the reference design. (or $12\frac{1}{2}^\circ$ for a single HRS arm, relative to the beam pipe). This constraint forces the inward orientation of the front pairs of cold-to-warm support horns.

Figure Q.23 depicts a cold-to-warm support featuring cold adjustment and a nitronic 40 tension link with a 78 K heat intercept. Figures Q.24 and Q.25 depict the supports relative to other magnet components.

Various cold-to-warm support methods could be used: however, CEBAF favors a metallic link in order to maximize long term positional stability. An alternative to cold adjustment is to provide for some repositioning of the cryostat within the iron, after the magnetic centerline of the coil has been determined.

Cold to Warm Support Concept

Figure Q.23

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Coil Suspension in Vacuum Vessel

Figure Q.24

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Front view
Figure Q.25

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Cryogenic Aspects

Cold Mass Cooling: The inner vessel is flooded with liquid helium, whose level is controlled within its service box reservoir. Bottom and top fill lines are provided, in addition to the vent line. A schematic cryogenic flow diagram is shown in Figure Q.26.

The intrinsically stable coil quadrants are cooled directly from helium in the interband grooves. Other helium passages are provided by circumferential gaps between the aluminum rings, by the longitudinal grooves in the stainless steel staves, and by annular regions between the helium vessel and the coil/support structure assembly.

Heat Load: The heat loads to the cold mass are estimated to be as follows:

Radiation	1
Cold to-Warm Supports	8
Cryogenic Lines	<u>1</u>
	10 W

The two 2 KA current leads contribute a further 6 watts, which is at least partially absorbed by sensible heat from the boiloff helium from other heat sources.

Therefore, the total rated heat load for the magnet is estimated at 12 W.

Quench Characteristics: The quench behavior of this concept has been analyzed using the 3-D, time dependent code QUENCH, developed by Martin Wilson. Even if the entire 592 KW of magnetic stored energy is absorbed by the coils, their peak temperature will not exceed 100 K.

In service, the magnet is not expected to suffer loss of cryogenic stability from spontaneous inelastic slip/stop relative motion within the coil matrix. However, other factors could trigger a quench including low liquid helium level.

Fault/Failure Modes: As the coil must withstand a quench without damage, so must the cryostat elements, in conjunction with their relief features, be able to survive various credible failure modes without suffering further damage or presenting a safety hazard. Failure modes for which the cryostat must be designed include vacuum and helium vessel rupture.

Sudden loss of vacuum could result from severing of a service line, perhaps by impact from a vehicle or crane load. Not only would the intruding air destroy the insulating vacuum: it would immediately begin to cryocondense on all 4 K surfaces (at least some of the superinsulation would be blown off by the intruder.) This, of course, would result in rapid helium boiloff, through coil quench and subsequent conduction through the helium vessel walls. This is the failure mode for which the helium vessel walls and relief valve/line must be designed.

4. Design, Analysis, and Testing

Design: CEBAF vendor evaluation will be based in part upon the offerer's technical proposal. While this will perforce be only a concept, it must address all of the basic aspects of an approach which would, through further development, lead to a design meeting the subject requirements: an assessment to be made by CEBAF personnel, plus a panel of recognized superconducting experts.

Once a contract has been awarded, the vendor is to fully develop the agreed upon concept. This will be reviewed at least twice by the CEBAF staff, whose role will, in effect, be passive: They will not dictate design details, but will request clarification and make suggestions whose intent will be in both CEBAF and the vendor's best interests.

Analysis: The vendor will be expected to perform such analyses as are appropriate for verification that the selected design will indeed meet its performance requirements. These will include the following:

- Structural calculations to ascertain that the coil will remain under radial compression at full excitation; will not deform out of round beyond the specified dimensional tolerances; and will not suffer destabilizing inelastic slip/stop relative motion through gross failure of epoxy within the coil matrix.

- Structural analysis of the cold mass support scheme to verify its ability to withstand the dynamic load criterion, accommodate differential thermal contraction, and maintain the coil in a dimensionally stable adjusted position relative to the return path iron, while meeting the heat load constraints.

- Structural analysis of the cryostat vessels to assure compliance with the appropriate pressure criteria.

- Cryostat heat load analysis, to demonstrate compliance with the specified total 4 K load.

- Independent verification of CEBAF's quench analysis, to assure that the coil will not be damaged thereby.

- Independent assessment of the coil's intrinsic stability, given its configuration, magnetic loading, current density and helium cooling.

- Dynamic analyses of the fault/failure modes resulting from rupture of the helium or vacuum vessels, demonstrating that the selected venting schemes will not allow overpressure of either.

- Independent analysis of the structural/dimensional/tolerance/thermal expansion/contraction aspects of the CEBAF reference concept for coil support, if selected by the vendor.

- Any other structural, dimensional or cryogenic analyses which would constitute good engineering practice to assure proper function of the selected design.

As noted elsewhere, CEBAF has performed all of the 3-D magnetic analyses appertaining to this requirement, and will provide the resulting coil force data. CEBAF will provide the magnetics analysis data upon request and will provide all other calculations made in support of its reference conceptual design.

Testing: The following tests are to be performed by the vendor at his plant and the results provided to CEBAF:

- A prototype coil quadrant shall be wound using production tooling and methods, to demonstrate compliance with the configuration/tolerance requirements. Production conductor shall be used, since its stiffness and tolerances are relevant factors.
- Each production coil/stave assembly shall be measured for harmonic field content, using a rotating coil device, with the series connected cosine 2θ quadrants carrying 10 amperes at room temperature. As an adjunct to QA/QC measurements, this test will verify that the coils have been wound and assembled properly.
- Following installation of the aluminum shrink rings, the rotating coil measurement of harmonic field content shall again be performed, at room temperature. The corresponding harmonic content limits will be keyed to the positional tolerances given in Figures 2, and 3 above.
- Each production coil/cold structure shall be "open dewar" tested to full current; followed by a heat induced quench and return to 1.05 x full current, in order to verify its proper function.
- After completion, each magnet shall be energized to full current, to verify electro-magnetic/cryogenic performance, including compliance with the heat load requirement.

The vendor is not required to perform full magnetic field measurements, nor is such data part of CEBAF's acceptance criteria. If the coil sectors have been positioned correctly, magnetic performance will inevitably follow.

5. Deliverables

In fulfillment of the contract, the vendor shall deliver the following items to CEBAF:

Magnet Systems: Four cosine 2θ quadrupoles complete, including integral instrumentation; current loads; and cryostat pressure relief apparatus.

Drawings: Four complete sets of magnet fabrication drawings, including instrumentation, control, power supply/protection circuit schematics.

Specifications: A complete listing of magnet performance/configuration specifications. A multi-view general arrangement drawing of the magnet shall be included, clearly depicting significant operating features.

Analyses: Copies of all formal analyses supporting the design, including those cited in section Analysis above.

Test Results: Results of all tests cited in section Tests above.

QA/QC: All formal QA/QC reports, including a clearly understood, vendor certified of measurements confirming that each coil quadrant meets its dimensional/tolerance requirement; and that each quadrant is properly located within the coil assembly.

6. SUPPORT STRUCTURE AND POSITIONING

6.1 GENERAL DESCRIPTION AND REQUIREMENTS

The HRS support/positioning system consists of two functional component groups:

Support Structure :

- Includes all system elements which bear the weight of the various spectrometer components and preserve their spatial relationships as required for 45° vertical bending optics.

Alignment and Positioning System :

- Includes all system elements that position the spectrometer within the hall and which measure and adjust the spatial relationships of the various spectrometer components.

Table 6-1 summarizes the requirements of, and constraints upon, the HRS support and positioning systems. Included are weights and center of gravity locations of the major support/supported elements, floor plate reactions, and the tolerances for the alignment and positioning of the HRS. Figures 6.1a through 6.1d show one HRS support/positioning assembly with identification of the major system elements.

6.1.1 Support Requirements

The support components for each HRS arm must meet the following requirements:

- Provide rigid support for the magnet and detector elements in their correct relative positions.
- Permit limited adjustment of the active HRS elements relative to each other. This is necessary for achieving correct initial alignment, and so that subsequent fine adjustments may be made.
- Be constructed so as to allow axial relocation of the Q1 and Q2 quadrupole pair as required for optical tuning. The limits of motion with respect to the nominal position are 0.8 m in the direction of the target and 1.0 m in the direction of the dipole.
- The support structure, and the quadrupoles mounted upon it, must be constructed so as to allow both HRS arms to be simultaneously positioned within 12.5° of the 0° beam line. When the Q1/Q2 quadrupole pair is moved towards the dipole, one should be able to position one of the two spectrometer at an angle not greater than 10.° from the 0° beam line.
- The total weight of each HRS arm including detector shielding must be borne entirely by the three concentric floor plates of Hall A through a series of wheeled bogies rated at 250 tons dead weight each.

- The structure should mechanically constrain the HRS to revolve about the Hall A vertical centerline at a fixed radius.

6.1.2 Alignment/Positioning Requirements

The HRS alignment/positioning components must meet the following requirements:

- Provide a frame of reference for Hall A which can be used by all alignment and positioning systems.
- Provide azimuthal positioning of the two HRS arms about the Hall A vertical centerline.
- Provide capability for realignment of the "HRS proper" (magnets, detector package, and associated rigid structure) in elevation, roll, pitch, and yaw at each azimuthal location.
- Provide capability for measuring the azimuth, elevation, roll, pitch, and yaw to a higher precision than that of the positional requirements.

The minimum and maximum azimuthal angles, as well as the tolerances on absolute positioning and position measurements are given in Table 1.

6.2 SUPPORT STRUCTURE

The support structure consists of the primary fabricated steel components which support the magnets, detector, shield house, and associated equipment. It is composed of the following subgroups, all of which are indicated in Figure 6.1:

- The BOX BEAM, which supports the active HRS elements (quadrupoles, detector) in fixed (but adjustable) relative positions atop the dipole, and features a detector service platform.
- The DIPOLE SUPPORT BRACKETS, through which the dipole rests upon the vertical jacks.
- The CRADLE, upon which the "HRS proper" (dipole plus box beam plus box beam mounted components) rests, through the vertical positioning system (hydraulic and mechanical jacks). The cradle also bears a portion of the shield house load, through the inboard legs of the gantry. It rests upon the two inner Hall A floor plates, through its wheeled bogie suspension.
- The GANTRY, which supports the 1.5 MLB detector shield house. Its outer legs rest upon the outer Hall A floor plate, through its wheeled bogie suspension.
- The BOGIES, which support the cradle-gantry assemblies, ride on the floor plates, and provide the driving power to move the arms.

6.2.1 Box Beam

Figure 6.2 shows the Box Beam, which is mounted atop the dipole to support the quadrupoles and detector. By this means, the relative locations of the active HRS elements

HALL A HRS SUPPORT/POSITIONING ASSEMBLY PARAMETERS

BEAM HEIGHT ABOVE FLOOR	10' (3.05 m)
INNER WALL MINIMUM RADIUS FROM HALL A VERTICAL CENTERLINE	86' (26.21 m)
CRANE HOOK HEIGHT ABOVE FLOOR	50' (15.24 m)
CRANE RAIL HEIGHT ABOVE FLOOR	55' (16.76 m)

HRS LOAD DISTRIBUTION

CG IS LOCATED HORIZONTALLY FROM THE CENTER LINE OF THE
TARGET AND VERTICALLY FROM THE CENTERLINE OF THE BEAM

ID	COMPONENT	WEIGHT		CG RADIUS		CG HEIGHT	
		KLB	×10 ³ KG	FT-IN	M	FT-IN	M
A	Q1	15	6.8	7'3"	2.21	0	0
B	Q2	40	18.1	15'7"	4.75	0	0
C	DIPOLE	900	408	43'7"	13.28	2'6"	0.76
D	Q3	40	18.1	57'9"	17.60	13'8"	4.17
E	DETECTOR	4	1.8	74'1"	22.81	31'2"	9.5
F	WHEEL ASSEMBLIES	132	59.9	63'7"	19.38	-7'8"	-2.34
G	TRANSPORTER CRADLE	131	59.4	43'7"	13.28	-4'7"	-1.4
H	LEVELING DEVICES	11	5.0	44'0"	13.41	-3'0"	-0.91
I	YOKE SUPPORT	62	28.1	45'2"	13.77	-1'0"	-0.03
J	BOX BEAM	165	74.8	46'2"	14.07	15'5"	4.70
K	LINE OF SIGHT SHIELDING	49	22.2	38'2"	11.63	15'1"	4.83
L	DETECTOR FLOOR	147	66.7	65'2"	19.86	20'7"	6.27
M	ELEVATOR PLATFORM & LADDERS	25	11.3	65'0"	19.81	15'0"	4.57
N	POWER SUPPLIES	20	9.1	75'6"	23.01	1'6"	0.46
O	DUMP RESISTORS	6	2.7	70'0"	21.34	13'0"	3.96
P	PIPES AND CABLES	30	13.6	43'0"	13.11	20'0"	6.10
Q	GANTRY	300	136.1	73'5"	22.38	12'1"	3.68
R	SHIELD HOUSE	1,150	521.6	72'1"	21.97	28'5"	8.66
FLOOR PLATE REACTIONS							
	INNER RADIUS PLATE	637	288.9	28'0"	8.53	10'0"	-3.05
	MIDDLE RADIUS PLATE	1,657	751.6	58'0"	17.68	10'0"	-3.05
	OUTER RADIUS PLATE	933	423.2	82'0"	24.99	10'0"	-3.05

Table 6-1a

Table 6-1a

Table 6-1b

HRS Alignment Requirements/Tolerances

Azimuthal position.....	± 2 mr
Azimuthal pointing.....	± 0.1 mr
Azimuthal position measurement.....	± 0.1 mr
Azimuthal traversing rate	3°/min
Azimuthal traversing range:	
Electron Arm	12.5°-165°
Hadron Arm	225°-347.5°
Azimuthal minimum angle:	
Between beam and HRS.....	12.5°
Between arms.....	25°
Vertical pointing.....	± 0.1 mr
Vertical elevation.....	± 0.06"
Radial position.....	± 0.2" (5mm)

Table 6-1b

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SECTION 1-5A

HRS Support/Positioning Assembly

Figure 6-1a

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PLAN VIEW 2-5B
AT TOP OF BOX BEAM

SECTION 2-7A

SECTION 2-5A

Figure 6.1b

HRS Support/Positioning Assembly

Figure 6-1b

A6-7

PLAN VIEW 3-5B
AT TOP OF CRADLE

HRS Support/Positioning Assembly
Figure 6-1c

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Figure 6.1d

SECTION 4-7A

SECTION 4-4A

SECTION 4-2B

HRS Support/Positioning Assembly

Figure 6-1d

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remain fixed, regardless of azimuthal and vertical alignment of the spectrometer. Elastic distortion is minimized, since the box beam does not bear the 450 ton dipole weight.

Stiffness of the deep section box beam structure is further enhanced by the indicated pillars between the dipole support brackets and the beam portion over Q3.

In order to facilitate transport, Hall A tunnel access, and installation, the prefabricated box beam must be delivered in three segments split along the bolted joints indicated in Figure 6.2. The center section, which is mounted directly atop the dipole, will be designed to accommodate $\sim$ two meters of line-of-sight concrete shielding, weighing around 30 tons.

A fourth, wedge-shaped (in elevation) element will be added after the three section box beam proper is installed. This serves primarily as a base for the service platform, which receives the rail mounted detector package, once the shield house doors have been opened. A catwalk extension to the platform will be provided, to intercept the fixed, elevated walkway from the counting house access tunnel.

Our present intention is to locate the magnet water bath dump resistors within the box beam.

6.2.2 Dipole Support Brackets

The dipole is equipped with structural steel brackets, as required for attachment of the box beam, and for support from the cradle-mounted hydraulic jacks (3) and their mechanical screw jacks (4). In all cases, six inches of 300 series stainless steel "shimming" is placed between the magnet yoke and the brackets, in order to minimize magnetic field distortions. Figure 6.3 shows the dipole brackets in isolation.

6.2.3 Cradle

The cradle, depicted in Figure 6.4, is the "chassis" upon which the HRS proper rests, through the intermediary of the vertical support jacks. The cradle transmits the 1147 ton "sprung weight" to the two inner radius Hall A floor plates through a series of wheeled bogies.

As indicated in Figure 6.1, the inner leg of the shield house gantry rests upon the outer radius edge of the cradle. The gantry and cradle are also pinned together at this location, constraining them to track in azimuth (and radius), while providing compliance with elevation variations among the three floor plates.

6.2.4 Gantry

The gantry for each HRS arm supports the 1.5 MLB detector shield house, while permitting it to track azimuthally with the spectrometer. The inboard portion of the gantry rests upon, and tracks with the HRS cradle, which transmits the combined 1.5 MLB load to the 58-ft.-radius floor plate through four bogies. The outboard portion of the gantry is fitted with four bogies, which track along the 82-ft.-radius floor plate.

Figure 6.5 shows the 300 KLB gantry structure in isolation. We have elected to place the four magnet power supplies within the gantry legs; one inboard and three outboard, as indicated. At this location, the power supplies benefit from dipole shielding from target radiation, as well as distance.

HRS Box Beam Assembly

Figure 6-2

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Figure 6.2

HRS Yoke Support Bracket Assembly

Figure 6-3

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FAH

Figure 6.3

HRS Cradle Assembly

Figure 6-4

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FAH

Figure 6.4

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FAH

HRS Gantry Assembly

Figure 6-5

Figure 6.5

6.2.5 Bogies

The cradle-gantry mounted HRS rests upon the Hall A floor plates through a series of four-wheel bogies, each with a design load of 250 KLB. One such bogie is illustrated in Figure 6.6.

The front (upstream) end of the cradle rests upon the inner radius floor plate through two bogie units, shown in Figure 6.1b, rated for 250 tons each.

6.3 ALIGNMENT AND POSITIONING - MECHANICAL

The alignment/positioning group consists of the following subsystems:

- The VERTICAL POSITIONING system, consisting primarily of the cradle mounted hydraulic and mechanical jacks which support and vertically position the HRS proper.
- The FLOOR DRIVE system, which provides azimuthal positioning of the HRS.
- The QUADRUPOLE SUSPENSION, which is the equipment attached to the box beam that aligns and positions Q1, Q2, and Q3.
- The CENTRAL PIVOT AND LINK assembly, which provides the basis for the Hall A alignment/positioning reference frame.

6.3.1 Vertical Positioning System

These elements position and support the HRS proper (dipole, plus box beam mounted elements) atop the cradle. Elevation, pitch and roll adjustments are provided by three hydraulic jacks. Once the hydraulic jacks have positioned the HRS to within tolerances, a set of four mechanical jacks are brought snug against it and the hydraulic jacks are backed off. This assures positional stability and safety.

- *Hydraulic Jack System:* This includes three identical 500 ton capacity hydraulic jacks, located as indicated in Figure 6.1, and their associated pumps and controls. Each unit is a double acting solid ram cylinder hydraulic jack with a stroke of 3" and a "push" force of 500 tons at a pressure of 7500 p.s.i. (rated capacity=664 tons @ 10,000 p.s.i.) - SIMPLEX Model R500 or equivalent. A servo control system will drive the jacks in coordinated response to elevation, pitch and roll error signals as the HRS transverses in azimuth.
- *Mechanical Holding Jacks:* These are a set of four mechanical screw jacks, which are servo-actuated in response to load cell signals from the hydraulic jacks. Each unit is a machine screw (acme thread) actuator of 150 ton rated "push" capacity (DUFF-NORTON Model 18150, or equivalent). The static holding capacity of each such jack is in excess of 250 tons, according to the manufacturer.

6.3.2 Floor Drives

Azimuthal drive is accomplished by a set of six electronically synchronized, servo controlled, gear reduced drive mechanisms, each of which powers a pair of bogie wheels. Two pairs of driven wheels are at each of the three floor plate locations. By this means, the

HALL A SPECTROMETER BOGIE

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Figure 6-6

Figure 6.6

drive traction can be balanced about the HRS center of gravity, thus minimizing transporter twist and reaction force at the central bearing and link. The azimuthal traversing rate is limited to 3° /min.

While the bogie wheels will be tapered and their axes oriented to roll about the Hall A centerline, some tracking error is inevitable. Azimuthal pointing errors will be corrected by driving the bogie wheels so as to alternately introduce and remove transporter twist in a manner similar to parallel parking an automobile.

6.3.3 Quadrupole Suspension

The Q1/Q2 pair will be interconnected at a fixed center-to-center spacing of 2.55 m. As indicated in Figure 6.1, this pair will be mounted on (HRS) axial rails, to permit optical tuning; 0.8 m towards the target, or 1 m toward the dipole, from their nominal baseline position. These adjustments need not be automated.

Q3 will have but one basic location. Capability will be provided for slim adjustment of all three quadrupoles, as dictated by alignment requirements.

6.3.4 Central Pivot and Link

Figure 6.7 shows the six foot (nominal) diameter central bearing assembly. The two HRS arm bearings are of a self-aligning spherical roller bearing type.

As the figure illustrates, the central pivot/bearing assembly is rigidly attached to the support column mounted directly upon the Hall A survey monument. It is therefore a suitable base for the core components of the Hall A alignment and positioning system, since it can be used as the origin of a reference frame.

6.4 ALIGNMENT AND POSITIONING - OPTICAL AND ELECTRONIC

The positioning system for each arm must be capable of placing its associated spectrometer at a precise azimuthal location relative to a reference line with which the central axis of the incident beam will be made to coincide. As depicted in Figure 6.8, this line is the Z axis of the Hall A reference coordinate system, and will be defined by two high precision Beam Position Monitors (BPM). The azimuthal position is described by the angle θ , which is the angular deviation from the Z axis in the XZ plane. The direction of positive θ is counterclockwise when viewing the experimental hall from above as shown in Figure 6.9. This figure also depicts some of the constraints related to the azimuthal motion of the spectrometer.

Figures 6.10 through 6.12 illustrate several specific types of tilt or pointing errors which may result from intrinsic structural and environmental imprecision, or simply from the act of moving the spectrometer. Table 6-2 lists factors contributing to these errors.

6.4.1 Azimuthal Position

The azimuthal angle is regulated by the system shown in Figure 6.13. A rotating laser is mounted at or near the center of the hall and is oriented so that as the path of the laser changes it sweeps out a vertical reference plane. Specially designed photosensors are attached in pairs at diametrically opposite positions on the top and bottom of the HRS

proper so as to intercept the beam and intersect the vertical plane. The laser is mounted on a precision rotary table capable of an angular positioning resolution of 1 arc sec or 0.005 milliradians. The function of the rotary table is to cause the vertical reference plane generated by the rotating laser to revolve about the Hall A vertical centerline.

The rotary tables for the two spectrometer arms and their associated laser devices are collectively referred to as the "Umphalos". This is a greek term which was used to describe a rounded stone monument at Delphi denoting the center of the world during classical times.* Our umphalos is located beneath the target, with its components being supported by a series of platforms rigidly attached to the Hall A survey monument.

To initiate an azimuthal relocation of a spectrometer arm, the rotary table is set in motion toward the desired position. As it begins to revolve, the photosensors detect changes in the path of the laser beam across their surfaces and generate error signals which are sent to the control electronics. The control electronics then send position correction signals to the drive mechanisms. The result is that the spectrometer tracks the motion of the rotary table and the azimuthal position changes.

While travelling azimuthally, the level and orientation of the spectrometer will be maintained within a reasonable margin, but not within the tolerances required for the physics. The control loop oscillations generated by the motion of the spectrometer are believed to preclude this accuracy if the requirement for traversing rate is to be met. Once the azimuthal position has stabilized, the other parameters will be adjusted to within tolerances.

Further referencing will be provided to the primary azimuthal positioning system by a number of photosensors on the walls of Hall A. The photosensors will be placed at precise, surveyed, angular positions so that as the spectrometer centerline travels past each one a reference signal will be generated. The signal itself will be generated by a gated coincidence check with the wall photosensors and a photosensor located on the spectrometer centerline.

6.4.2 Azimuthal Pointing (Yaw)

Azimuthal pointing error is measured by comparison of the error signals generated by different sets of the azimuthal photosensor pairs. If an azimuthal pointing error exists, the signals from a pair of photosensors located at a small radius from the Hall A vertical axis will generate a different magnitude and/or polarity signal than a pair located at a large radius.

Yaw may also be independently checked by the laser rangefinder equipment used for radial position measurements.

6.4.3 Elevation

This parameter is regulated by a laser/photosensor system which is virtually identical to the system used to measure azimuthal position. The primary difference is that the laser is oriented so that the beam sweeps out a horizontal reference plane rather than a vertical

* The monument is still in Delphi, but the center of the world is now located in a shopping mall parking lot near Anaheim, California.

SECTION 2-7B

SECTION 2-3B

SECTION 2-6A

HRS Central Bearing & Link Assembly

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Figure 6-7

Figure 6.7

#

HRS AZIMUTHAL POSITIONING

SPECTROMETER MUST BE POSITIONED
TO WITHIN ± 2 mr OF DESIRED
AZIMUTHAL POSITION.

Figure 6-9

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Figure 6.9

Figure 6-10

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Figure 6.10

HRS POINTING ERROR INDUCED BY TRANSPORTER TILT

HALL A - ELEVATION VIEW

X_e = CONTRIBUTION OF TRANSPORTER/WHEEL SET TO AZIMUTHAL POSITION/POINTING ERROR.
 Y_e = CONTRIBUTION OF TRANSPORTER WHEEL SET TO VERTICAL POSITION/POINTING ERROR.

- VERTICAL POSITION TOLERANCE IS $\pm 0.06"$.
- VERTICAL POINTING TOLERANCE IS ± 0.1 mr.

TOTAL POINTING ERROR INCLUDES CONTRIBUTIONS BY AT LEAST THE INNER 2 WHEEL SETS.

Figure 6-11

R. Johnson - 2/28/90

Figure 6.11

R. Johnson - 2/28/90

Figure 6-12

Figure 6.12

LASER ALIGNMENT SYSTEM - AZIMUTHAL

Figure 6-13

R. Johnson - 2/28/90

Figure 6.13

one as is shown in Figure 6.14. The photosensors are then, of course, located on the sides of the HRS proper in order to intersect this plane. The accuracy and stability of this plane, as with the vertical plane, is expected to be ± 15 arc seconds or ± 0.075 milliradians.

As with the azimuthal positioning system, the photosensors generate errors signals which are processed through the control electronics into correction signals which are sent to the hydraulic jacks.

One notable difference between this system and the azimuthal positioning system is that in this case, it is not necessary for the rotating laser to be located near the center of the Hall. While a central location is preferable because it allows a single laser to generate the horizontal reference plane, two or more lasers placed at strategic locations on the walls of the hall could accomplish this task equally well.

6.4.4 Roll

Roll (rotation about the spectrometer optical axis) is measured by comparing the polarity and magnitude of the signals from the photosensors associated with both the vertical and azimuthal positioning systems. Any deviation is translated into vertical and azimuthal errors and corrected by the systems which regulate those parameters.

6.4.5 Vertical Pointing (Pitch)

Figure 6.15 schematically indicates the inclinometer sensor/control function for correction of vertical pointing error in the beam line (dispersive) plane. These signals are sent only to the two rear vertical hydraulic jacks. The correction acts in conjunction with elevation control to achieve in-plane leveling of the HRS proper.

As was the case with yaw, this parameter may also be independently checked by the laser rangefinder equipment used for radial position measurements.

6.4.6 Radial position measurement

Radial position will be determined from measurements taken by a set of three laser interferometers as depicted in Figure 6.16. These devices are arranged at right angles so as to define the coordinate system for Hall A. Distances are measured from each interferometer to a retroreflector located on the spectrometer. Together, these measurements provide enough information to calculate the coordinates of the retroreflector in the reference frame defined by the interferometers. The coordinate calculations are based on the law of cosines from basic trigonometry.

An additional means of obtaining coarse radial position will be provided by a series of sliding potentiometers mounted on each side of the link near the gap between the link and the spectrometer. The handles of the potentiometers will be rigidly attached to the spectrometer structure so that a change in radial position will be reflected by a change in the resistance of the potentiometer. A similar setup may be used to monitor the movement of the gantry relative to the main structure.

R. Johnson - 2/28/90

Figure 6-14

Figure 6.14

SPECTROMETER PITCH

VERTICAL POINTING IS REGULATED BY FEEDBACK FROM INCLINOMETERS WITH RESOLUTION OF LESS THAN 0.0006° (0.0105 mRAD).

Figure 6-15

R. JOHNSON
2/28/90

Figure 6.15

A6-27

LASER ALIGNMENT SYSTEM - RADIAL

Figure 6-16

R. Johnson - 3/27/90

Figure 6.16

7. DETECTOR SYSTEMS/DATA ACQUISITION

7.1 OVERVIEW OF ELECTRONICS REQUIREMENTS

The initial complement of equipment for Hall A includes the focal plane instrumentation required for the two high resolution spectrometers.¹ These spectrometers must be able to carry out a broad spectrum of coincidence and single arm experiments with emphasis on studies of the few body systems and other experiments requiring good resolution. They are intended to make full use of the capabilities of the CEBAF accelerator with its broad dynamical range, high luminosity beams, exceptional phase space and energy resolution, and high duty factor for coincidence measurements.

The most important capability of a focusing spectrometer is its ability to reconstruct particle trajectories, measuring precisely the momenta and entrance orientations of the tracks. In the case of the CEBAF spectrometers momentum resolutions of 10^{-4} are obtainable, consistent with the resolution of the incident beam. Such resolutions are important for studies of the few body systems at high momenta and are essential for detailed studies of nuclear structure. At CEBAF energies angular resolution has also been shown to play a significant role in energy determination and it is important to resolve scattering angles at the order of a milliradian and to control the angular systematics to a tenth of a milliradian. Vertex reconstruction is important as well for background rejection and to correct for higher order aberrations. Much of the program at CEBAF will attempt to explore the spin degrees of freedom associated with coincidence measurements (i.e., photon interference amplitudes, beam, target, and recoil particle polarization measurements)². Since these amplitudes are small, very high precision and control of systematic errors will have to be realized. These requirements put very strong demands on the focal plane detector package.¹

A summary of the requirements follows:¹

- Momentum Resolution

Momentum resolution of 10^{-4} is required and can be achieved with vertical drift chambers having a sigma of 100 microns position resolution. To minimize multiple scattering contributions the chambers should ideally lie along the focal plane.

- Angular Resolution

Angular resolution in the focal plane on the order of 0.5 milliradian for momentum greater than 0.5 GeV/c and systematic control of the angular uncertainty at the 0.1 milliradian level are required. This implies the use of thin windows and interchamber Helium gas to minimize multiple scattering and in fact without further development we appear to be about a factor of two from achieving this goal. However most of the demand for high angular resolution appears to be at high momentum where multiple scattering effects are smaller.

• Rate Requirements

Based on an analysis of rates for a broad spectrum of kinematics³ anticipated maximum single arm rates are on the order of a MHz for real events traversing the spectrometers. The maximum anticipated double arm coincidence rate is ~ 10 KHz. The instantaneous single arm rates are no more than experienced at existing laboratories and make no special demands on the front end electronics. However, readout of data at an estimated rate of 4-10 Mbytes/sec will make significant demands on the data buses and the storage and analysis capabilities of the computers. At the other extreme some studies in the few body regime are aimed at examining single arm cross sections as small as 10^{-40} cm²/sr. These cross sections are limited by cosmic ray background yields and the high duty factor is actually a disadvantage in this case. For these measurements the premium is on good vertex resolution, stringent timing requirements, and particle identification for background rejection.

• Accuracy Requirements

Relative cross section measurements on the order of 1% accuracy will be required to carry out separations and other measurements of spin dependent amplitudes. In the case of longitudinal/transverse separations this is because the longitudinal response is small at high momentum transfers and the lever arm effect causes an amplification of the uncertainties in carrying out the separations. This is demonstrated in Figure 7.1 where the relative errors in R_L and R_T are shown as a function of momentum transfer for the case of D(e,e'p) assuming 1% uncertainties in the cross sections. In general spin amplitudes tend to be a small part of the total cross section and require careful attention to systematic sources of error. Because the coincidence cross sections can vary rapidly with the kinematics over the focal plane this implies the need for a very uniform and highly efficient detector package, as well as a detailed understanding of rate-dependent effects. This is especially true for small electron scattering angles where most measurements are expected to be performed to maximize both counting rates and, in the case of L/T separation measurements, the virtual photon polarization lever arm. To illustrate this rapid variation, the fractional derivatives of the D(e,e'p) cross section with respect to the momentum and angle of the scattered electron are shown in Figure 7.2 for $\vec{q} = 1$ GeV/c, $p_r = 0$ and an electron scattering angle of 15° .

• Particle Identification

Particle identification can be achieved by a variety of means.⁴ For coincidence measurements relative time-of-flight is an important and effective filter for separating particles of different velocities as can be seen by Figure 7.3, showing relative time-of-flight in a 25 meter path. Assuming 1 ns or better full-width-at-base timing resolution can be obtained after track reconstruction, the primary uncertainty will be between distinguishing energetic pions from electrons above 1 GeV/c momenta. Standalone particle rejection and identification is necessary in each arm to supplement time-of-flight information. A goal of 10^{-5} rejection for pions will be required in some cases particularly at backward angles where the pion yield can dominate the electron yield by a factor of as much as

Figure 7.1 Relative error in R_L and R_T for 1% uncertainties in the measured cross sections.

a thousand. At CEBAF energies N_2 or CO_2 gas Čerenkov counters are effective in distinguishing pions from electrons (Figure 7.4). Shower counters provide additional pion to electron discrimination capability. To distinguish protons from pions either a silica aerogel or lucite Čerenkov can be used depending on the momentum of the pions. At low momentum we can use scintillator dE/dx for particle identification.

• Background Rejection

Rejection of accidentals is enhanced by use of high duty factor together with good time-of-flight resolution. For extended targets consistency of the reconstructed vertices can be used to further reduce accidental backgrounds. Time-of-flight spreads due to differential flight paths through the spectrometer should be a few nanoseconds and can be corrected to a fraction of a nanosecond. The time substructure of the beam is 2 nanoseconds between pulses. If we can resolve this structure we can further reduce the time uncertainty for TOF measurements. Timing resolution on the order of 1 nanosecond full width is needed to achieve this goal.

Figure 7.2 Fractional derivatives of the $D(e,e'p)$ cross section with respect to momentum and angle of the scattered electron for $\vec{q} = 1$ GeV/c, $p_r = 0$ and $\theta_e = 15^\circ$.

7.2 EXPECTED EVENT RATES

Various people involved in the $(e,e'p)$ program have performed calculations of expected rates, the results of which have been utilized to guide our preliminary design study. While the $(e,e'p)$ reaction provides a good means of characterizing general coincidence rates, a more comprehensive look still needs to be done examining a broad spectrum of the program. A detailed analysis of the $D(e,e'p)$ reaction has been performed³ and may be taken as typical of the $(e,e'p)$ reaction since the basic rates scale as A , although for more complicated nuclei the yield is fragmented over a number of states. Further, the high recoil component of the nuclear momentum distribution tends to track with that of the deuteron.

For the purposes of rate estimation we assume a luminosity of roughly $1 \times 10^{38} \text{ cm}^{-2} \text{ s}^{-1}$. This corresponds to 50 μAmp on a 1 gm/cm² target requiring 100W of cooling power. In the region of $\vec{q}$ from 0.5 to 3.0 GeV/c, the singles rates are always less than one MHz in either arm, with a maximum coincidence yield of approximately 10 KHz at the lowest momentum for forward angle scattering.

Higher power targets are envisioned for such low cross section experiments as the threshold electro-disintegration of the deuteron where luminosities of $1 \times 10^{39} \text{ cm}^{-2} \text{ s}^{-1}$

Time-of-Flight

Figure 7.3 Relative time-of-flight for a 25 meter path for various particles.

may be realized. This would correspond to liquid targets requiring a kilowatt of cooling power. However, kinematics employed in these experiments give event rates much smaller than expected at the quasielastic peak.

Therefore for coincidence experiments we can work at a comfortable rate (10 kHz) if we first make a coincidence decision before committing our front-end electronics. Because of the difference in particle velocities and cable delays making the coincidence decision requires holding an event for somewhere between 400-1000 ns. Assuming about 250 4-byte words per event, the bus will have to handle a maximum rate of about 10 Mb/s. Maximum data rates on existing buses are 40 Mb/s for Fastbus and 10 Mb/s for VME and ECL bus electronics. Because of overhead involved in the handshaking protocols sustained throughputs are somewhat less than maximum ratings. Therefore, it will be necessary to use buffered electronics and to segment the databus into 10 Mb/s links. Use of FIFO buffers can allow us to work at up to 100 KHz but only at a substantial increase in cost to the entire front end electronics.

Figure 7.4 Velocity of particles (plotted as $1 - \beta$) versus momentum and the indices of refraction (at STP), plotted as $n - 1$, of several materials commonly used in Čerenkov counters.

7.3 DETAILS OF THE FOCAL PLANE PACKAGE

The focal plane detector package will have to be responsive to a general program of studies. In addition to the well analyzed benchmark case of (e,e'p) reactions, the program includes a variety of anticipated experiments ranging from single arm studies of few body form factors, to some gamma induced reactions such as $^3\text{He}(\gamma,2p)$, to triple coincidence measurements using a future third spectrometer, and even possibly, (e,e'n) experiments detecting recoil protons. The focal plane detector package should therefore be adaptable to a changing experimental environment. The conceptual design for the hadron arm focal plane is shown in Figure 7.5. The electron arm detector package looks similar except the focal plane polarimeter is replaced by a shower counter and the CO_2 Čerenkov is 0.5 m longer. The focal plane detectors for the high resolution spectrometers will include 2 wire chambers near the focal plane (probably VDC's) each consisting of two orthogonal wire planes, Čerenkov counters (CO_2 and aerogel) and a scintillator stack to define the crude trigger. In addition, the nominal "electron" arm will be equipped with a shower counter and the "proton" arm with a focal plane polarimeter.

It is envisioned that each package will be mounted on a rigid carriage along with its associated electronics and that the carriages can be easily removed for servicing. Reproducible positioning of the package relative to the spectrometer is essential. The detector hut will have to be heavily shielded to prevent radiation damage from target and dump related sources.

Some details of the various detector elements follow.

7.3.1 VDC's

The spacing between the two sets of front end chambers is dictated by the desired angular definition (~ 0.1 mr at the target). For 100μ position accuracy in each of two orthogonal wire planes with wires oriented at 45° with respect to vertical, the position accuracy along x and y (Transport notation) is also 100μ . This assumes the wire planes are normal to the central ray. For chambers along the focal plane, neglecting multiple scattering, the accuracy in y is unchanged. Thus, assuming a spacing of 50 cm, we have

$$\delta\phi_f = \frac{100\mu}{50\text{cm}} \times \sqrt{2} = 0.3\text{mr}$$

for the accuracy of the focal plane angle. Here, the factor of $\sqrt{2}$ arises from the quadrature sum of the individual position resolutions of each chamber pair. In terms of the coordinates at the focal plane, one has to first order

$$\phi_t = \langle\phi|y\rangle_{ft} y_f + \langle\phi|\phi\rangle_{ft} \phi_f$$

where the subscripts ft indicate the matrix elements for the focal plane to target map. With $\langle\phi|y\rangle_{ft} = -5.4$ mr/cm and $\langle\phi|\phi\rangle_{ft} = -0.40$ and assuming the above accuracies for position and angle, we have $\delta\phi_t = 0.13$ mr, where the position and angular uncertainties have been added in quadrature. This is reasonably close to the desired 0.1 mr accuracy.

Dimensions are in meters

4/7/90

HRS Detector Hut

Figure 7.5 *Conceptual design for the detector package for the hadron arm.*

Figure 7.6 Typical track in a drift cell of a VDC along with the field configuration of the cell.

Current VDCX's used at Bates⁵ have a sense wire spacing of 4.2 mm and a drift cell length of 12.7 mm. A single chamber consists of two orthogonal wire planes rotated at 45° with respect to the frame. Between the sense wires there are two guard wires to reduce cross talk. At Bates with a chamber rotation angle of 42° a typical track intercepts 3–6 cells. A typical track through a drift cell of a VDC along with the field configuration of the cell are shown in Figure 7.6. Taking the full acceptance of the beam as given by Raytrace for a 10 cm extended target leads to dimensions for the active area of the chambers of 2.10 m by 0.20 m requiring approximately 1500 wires for all four planes. It will cost 400 k\$ to instrument two spectrometers with 1472 wires each in FASTBUS using LeCroy TDCs and Amplifier/Discriminator Cards with minimal spares. The MIT group estimates chamber fabrication costs at 150 k\$ per spectrometer.

7.3.2 Scintillators

Scintillators will form the primary single arm trigger, perhaps supplemented by Čerenkov particle ID tests. A minimal package consists of two scintillators before the focal plane polarimeter or shower counter followed by a final scintillator at the end of the detector stack. Initially, we plan to use minimal segmentation to minimize the cost. The three scintillators in the electron arm are unsegmented as are the first two scintillators in

the hadron arm. The last scintillator in the hadron arm is further from the focal plane and covers a greater area due to the angular acceptance requirements of the polarimeter. This scintillator is divided along the dispersive plane into seven segments with minimal overlap to equalize background rates among all scintillators. Each scintillator will be viewed by a phototube at either end with mean timing used to reduce the time spread. We have estimated costs for the scintillator stack assuming 5" phototubes and a nominal scintillator size of 60 cm by 2 m. 5" tubes will view scintillators as much as 2 cm thick by 60 cm wide, although the front scintillators will be much thinner. If the front scintillators are 1/8" thick, 2" phototubes could be used instead at some cost savings. Presently, we have assumed the use of Constant Fraction Discriminators and mean-timed logic for all segments.

Several methods of monitoring gain stability are being investigated by the Regina group. A common laser with fiber optic strands to each PMT is one option. Another alternative is GaAs laser diodes embedded in each plastic scintillator. A third, and perhaps most attractive alternative, is a common box with a Xe flash source at ~10Hz rate coupled with fiber optic strands to each PMT. A scintillator with an alpha-source embedded in it plus the fiber optic cable can provide an absolute measure of gain with respect to the Xe source output. This method can also be used to time the electronics at the beginning of each experiment.

7.3.3 CO₂ Čerenkov

In order to separate π^+ and e^+ (or π^- and e^-) a gas Čerenkov will be needed. CO₂ will suffice over the entire momentum range of the spectrometers. The number of photons emitted is

$$N = 2\pi\alpha L \int_{\lambda_1}^{\lambda_2} \frac{d\lambda}{\lambda^2} \sin^2 \theta$$

where α is the fine structure constant, L is the length of the detector, λ is the wavelength of light and θ is the emission angle. Further,

$$\cos \theta = \frac{1}{n\beta}$$

where n is the index of refraction and β is the particle velocity in units of c . For CO₂ at STP, $n - 1 = 4.3 \times 10^{-4}$ giving a threshold momentum of 4.8 GeV/c for pions and 17 MeV/c for electrons. For $\lambda_1=200$ nm, $\lambda_2=500$ nm as well as a light collection efficiency of 0.50 and a quantum efficiency at the photocathode of 0.20 this gives $N = 12$ photons/meter. Thus, a 1 meter counter (85 cm effective length, accounting for the curvature of the mirror) gives 10 photoelectrons. With a threshold of 3 photons this gives ~ 99.7% efficiency for e^+/e^- detection. A schematic of the CO₂ Čerenkov is shown in Figure 7.7. The Čerenkov shown is viewed by five 5" phototubes. The light is collected using five mirrors whose surfaces are parabolas of revolution satisfying the equation

$$z = \frac{r^2}{4z_0}$$

where $z_0 \sim 60$ cm. A bi-alkalide or multi-alkalide photocathode should be used for high quantum efficiency and the phototube should have quartz windows to optimize the UV response and should be selected for low noise operation. Because of the more severe requirements on particle ID in the electron arm, a 1.5 meter gas Čerenkov will be needed in conjunction with a shower counter for π/e discrimination. We estimate the cost of a gas Čerenkov at 50 k\$.¹ B. Frois of Saclay has offered to build at least one of the gas Čerenkovs.

7.3.4 Aerogel Čerenkov

For π -p discrimination an aerogel Čerenkov counter will be required as well. A schematic diagram of this detector is also shown in Figure 7.7. With an index $n = 1.025$ the threshold momentum is 4.2 GeV/c for protons and 0.62 GeV/c for pions. Assuming a light collection efficiency of 0.25 and a quantum efficiency of 0.20, 7 cm of silica aerogel will enable the measurement of 880 MeV/c pions with $> 99\%$ efficiency. If one wishes to detect lower momentum pions, acrylic plastic with an index $n = 1.48$ can be substituted for the aerogel; the threshold for protons is then 860 MeV/c. Because of the larger angular divergence of light in the aerogel compared to the CO₂ Čerenkov, the focal surface is divided into two parabolic mirrors with

$$y = \frac{x^2}{4y_0}$$

where $y_0 = 12$ cm. In the z direction the phototubes are tightly packed. 26 five inch phototubes (13 on each side) are required; the specifications of these tubes are the same as for the CO₂ Čerenkov.

The Čerenkov container can be made of injection formed plastics for light weight, minimal scattering and air (as well as light) tightness. One alternative we are investigating is the use of carbon-epoxy fiber material; it is lightweight, very strong and rigid. A small scale prototype would be the best way to proceed. Using CAD/CAM software, the parabolic surfaces can be designed under the desired geometry and optical parameters and a CNC three-axes milling machine will mill out the molds for the plastic parabolic mirrors. The Regina group has been in contact with the SRC labs which have significant experience with injection molded plastics and have used their techniques in defense and NASA contracts. Furthermore, Aerogel Čerenkov detectors have been recently tested at TRIUMF, so they have access to the latest performance characteristics and manufacturer specifications.

Figure 7.7 Schematic diagrams of a) CO₂ and b) aerogel Čerenkov counters.

7.3.5 Shower Counters

In the electron arm rejection requirements for either pions or electrons can reach 10^5 depending upon the kinematics of the experiment. Because of knock-on electrons pion rejection of much better than 10^{-3} is difficult to achieve in a single Čerenkov detector. In this case the Čerenkov detector will have to be supplemented by a shower counter. Over 150 lead glass blocks with phototubes from the UA2 experiment of dimensions $15 \times 15 \times 35$ cm³ have been obtained by CEBAF at a nominal cost. 128 of these are sufficient to cover the focal plane if they are stacked 4 deep by 16 high by 2 across. We estimate incremental cost for electronics and mechanical structure at about 50 k\$. This includes high voltage for every channel, and 32 channels of ADCs and discriminators if we sum the analog outputs in groups of four. We assume these modules can be put into existing crates. Figure 7.8 shows a Monte Carlo simulation with GEANT of electron and pion induced showers in these counters.¹ Since the dominant interactions responsible for the cascade process in the shower material are considerably different between the electromagnetic and the hadronic showers, the longitudinal extent of the electromagnetic showers is much smaller than that of the hadronic showers. Figure 7.9 indicates there is a clean separation in energy deposition between the hadronic and electromagnetic showers in these counters. The University of Maryland shower counter simulations indicate a factor of 500 suppression of π^- relative to electrons. When used in conjunction with a CO₂ Čerenkov, an overall rejection ratio of 2×10^{-6} can be achieved.

Alternate designs of the shower counter are being examined. For example, a counter based on the use of scintillating fibers is estimated to cost ~ 225 k\$.

7.3.6 Focal Plane Polarimeter

Methods for measurement of polarizations in the focal planes of magnetic spectrometers have been developed at proton accelerators over the past decade. Focal plane polarimeters (FPP) have been used at energies up to 800 MeV at LAMPF⁶; recent experiments at Saturne have proved feasibility to 1.2 GeV, and higher energy tests are planned for this summer. Polarimeters have been used at lower energies at IUCF and TRIUMF⁷. An FPP is an integral part of the detector package for the hadron arm in Hall A, and its design is similar in principle to the polarimeters mentioned above. At intermediate proton energies, ¹²C has been used as the analyzer due to its large analyzing power. In this energy range, the useful analyzing power for ¹²C lies in the range of $\theta=5^\circ$ to 20° .

Shown in Figure 7.5 is the detector arrangement for the proposed polarimeter for the hadron HRS for Hall A. The polarimeter uses a segmented carbon analyzer up to 60 cm in thickness, to allow a variable thickness of carbon so that operation over a wide range of proton energies will be possible. A pair of front and a pair of rear wire chambers determine the incident and scattered angles, respectively. In addition, Čerenkov counters are provided in the front end for pion rejection. Finally, a scintillation counter at the rear end provides the trigger for the polarimeter. The dimensions of the polarimeter detectors were determined so as to accept a 20° cone of protons scattered in the carbon. With this

Development of electromagnetic shower for an incoming 4 GeV/c electron.

Development of hadronic shower for an incoming 4 GeV/c π^- .

Figure 7.8 Monte Carlo simulation of electron and pion induced showers in a shower counter.

Figure 7.9 Energy deposition of electron and pion induced showers.

geometry, all values of ϕ for this cone are accepted by the polarimeter. The very forward angles are dominated by coulomb scattering and yield very little analyzing power.

Since the inclusive analyzing power and the cross section for the $\bar{p} + {}^{12}\text{C}$ reaction are both slowly varying functions of the angles, the requirements on angular resolution of each track are modest. The angular resolution of the whole system is dominated by the multiple scattering in the thick analyzer. However, the centroid of the cone needs to be determined very precisely in order to minimize instrumental asymmetry. Better than 1% systematic error in polarization can be achieved with angular resolution of about 0.1° .

Extensive carbon analyzing power data exist for proton energies of up to 1.2 GeV in the angular range of 5° to 20° . Additional measurements at higher energies are planned at Saturne. However, it is also essential to calibrate the analyzing power of the FPP on-site; this will remove false asymmetries of the FPP that are specific to the detector geometry. In addition to the measurement of false asymmetries with the scattering of unpolarized protons, it should be possible to directly measure the wire chamber efficiencies and chamber offsets by the tracking of protons with the carbon analyzer removed. Finally, elastic scattering from hydrogen will allow an absolute calibration of the polarimeter.

The azimuthal asymmetry of the scattered protons is then used in determining the polarization of the incident proton. The azimuthal distribution of the $\bar{p} + \text{analyzer}$ scattering in the polarimeter is given by

$$I(\theta, \phi) = I_0(\theta)[1 + P_n A_y(\theta) \cos \phi + P_t A_y(\theta) \sin \phi] F(\theta, \phi)$$

where θ and ϕ are the polar and azimuthal scattering angles in the analyzer, $I_o(\theta)$ is the unpolarized cross section, $A_y(\theta)$ is the analyzing power of the analyzer and $F(\theta, \phi)$ is the acceptance function of the FPP. Fourier transformation of the complete azimuthal distribution thus determines the transverse components of the vector polarization. The statistical uncertainties in the measured polarizations are

$$\Delta P_n = \Delta P_t \approx \frac{\pi}{2} \sqrt{\frac{1}{N_0 \overline{A_y}^2 f}}.$$

where f is the fraction of scattered protons accepted by the FPP, N_0 is the total number of protons incident on the FPP and $\overline{A_y}$ is the angle-averaged analyzing power of carbon.

In general, by utilizing the differing helicity dependence of the various amplitudes and spin precession in the spectrometer, one can separate all three spin components simultaneously in the focal plane polarimeter for favorable kinematics. Because of the large spectrometer acceptance, we need to develop software algorithms that include spin transport through the spectrometer.

Several support systems are necessary in addition to the basic components, the carbon block and wire chambers. These systems include gas supply systems for the wire chambers, high voltage supplies, readout electronics and a second level trigger, mechanical support systems, and software for data analysis, control and testing. The difficulty of moving the heavy carbon slabs and the time overhead involved in entering the experimental area will require a remotely controllable mechanical system. All FPP components will be mounted on an FPP subframe for installation and removal as a unit.

The baseline design calls for four wire chambers mounted in X and Y orientations, with 8 mm spacing between adjacent anode wires. The total number of anode wires in the system needed to cover the active areas of the four chambers is about 1600. We plan to use individual wire readout for the anode wires, plus a left - right determination from induced pulses on the cathode wires. Since only a small fraction of the particles scatter with a useful analyzing power, we plan to make a hardware angular determination of the second scattering angle. This requires fast readout of the wire addresses which can then be decoded using memory lookup units and arithmetic logic units.

Polarimeter costs have been estimated based on a design using HDC's. Design alternatives are also being investigated, including the use of delay line drift chambers to lower readout costs. In addition, C. Perdrisat of William & Mary is investigating the use of scintillating fiber technology as an alternative to wire chambers. The cost of the focal plane polarimeter has been estimated by R. Gilman from Rutgers University and these costs are included in Table 7.1.

7.3.7 Vacuum Windows

One of the largest sources of uncertainty in the angle measurement of a particle track is multiple scattering in the spectrometer vacuum window.¹ At the MIT-Bates laboratory about 20 mg/cm² of kevlar sailcloth and mylar vacuum seal has been shown to provide a safe vacuum window at one atmosphere. The aperture of the Bates window is about 30 cm by 220 cm which is slightly larger than our application. This gives about 1 mr of scattering for electrons at 500 MeV/c. Perhaps a more judicious choice of materials and design or reduced pressure operation of the track detectors could reduce this. This would require some research and development work. However, as mentioned earlier, the greatest demands on angular resolution appear to be at higher momentum where multiple scattering effects are less important.

7.4 TRIGGER ELECTRONICS¹

In designing a general trigger for the Hall A spectrometers a modular approach to the electronics must be taken to allow flexibility. Each spectrometer should be capable of operating as a fully independent arm, with multiple triggers allowing prescaling of various combinations of events for normalization and other reasons. We plan to scale all branches of the logic tree. Most importantly the trigger must be capable of dealing with expected high counting rates. Logic decisions will be made locally at the detector hut and the information encoded and sent by optical links to the experimental control room.

We envision a three- or four-stage trigger comprised of:

- i) a fast single-arm trigger consisting of scintillator coincidences with optional Čerenkov and shower counter input,
- ii) a fast coincidence between 2 or more arms as appropriate (this will involve introduction of delays of up to 400 ns),
- iii) a secondary decision involving hardware readout of the wire chambers using memory look-up units (MLUs) to further select data of interest (such decisions are in common use in focal plane polarimeters where only a small fraction of the events scatter usefully but the technique can be applied to many other circumstances),
- iv) further optional data reduction at the software level.

Because the decisions are being made locally at the back of the spectrometers it is important that the experimenters have remote control of the circuitry. This can be accomplished for example by the use of commercially available programmable logic units, programmable delays, and remotely settable voltages and thresholds. For example the LeCroy ECL line presents a method of achieving these goals in a CAMAC environment. Figure 7.10 shows a schematic of the main trigger logic implemented using ECL logic. Not shown are the details of how the single-arm trigger is formed nor how this circuit

interfaces with the polarimeter. The secondary outputs on the programmable delays are routed to TDCs and scalers.

Figure 7.11 shows how the predicted position test can be implemented in hardware using a combination of Arithmetic Logic Units (ALUs) and Memory Look-up Units (MLUs). This test is used to determine whether a second scattering event in the polarimeter exceeds a predefined minimum angle of scattering.

Software simulations of the trigger electronics have been started by the William & Mary group using the Verilog simulation package.

7.5 DATA ACQUISITION MODEL¹

Our design viewpoint is that the information should be digitized locally at each spectrometer in Fastbus or VME crates and sent over an optical link to a central crate where the data from various spectrometers can be combined and reformatted for further processing. This minimizes the number of cable connections to and from the experimental control room but does require a remote control and calibration capability. In order to be able to analyze every event on line we envision a CPU farm consisting of approximately 5 RISC type nodes residing in the VME crate. Nodes running at 20–100 MIPS are expected to be available within two years for about 10 k\$ per node. The data acquisition will be coordinated by a central host, most likely a μ VAX III (if it were to be bought today). Data control will be through a series of graphic work stations running under UNIX. Entry level workstations presently cost 10–20 k\$ each and the price/performance ratio is rapidly improving. The system will be tied together by an Ethernet link which will be used to control and change the experimental environment. Figure 7.12 shows a conceptual design for the data acquisition as developed by the CEBAF Data Acquisition Group.⁸ This particular implementation shows the use of Fastbus or VME crates for the front-end data acquisition with a CPU farm for data processing. If 10^4 events/s were all to be stored on tape it would fill one high density (6250 bpi) tape every three minutes. Therefore mass storage is a potential problem, which can be partially addressed by further data reduction at the analysis stage.

To avoid data bottlenecks the data will be buffered and segmented into 10 Mb/s data paths. This data is then switched to the first available CPU via a switching network as illustrated in Figure 7.13. Each CPU has sufficient local memory to build histograms which can then be sampled and summed as the user requires. CEBAF personnel are collaborating with Fermilab and other high energy laboratories in developing the switching network. We estimate the cost of this interface will be about 10 k\$.

Because of the variety of experimental situations envisioned a standard data acquisition system will be developed and maintained by the CEBAF staff which will minimally include a histogramming and plotting package, a logic test package and data management tools. Physics programming will be in a higher level language such as FORTRAN. Portability of the DAQ to other institutions is a high priority and a minimal hardware

Figure 7.10 Schematic of main trigger logic using ECL logic.

Example of level 2 trigger use
in polarimeter angle test $\delta\theta_S > \theta_{\min}$

Predicted Position Test

Figure 7.11 Predicted position test to determine whether a particle in the polarimeter exceeds a predefined minimum second scattering angle.

Reference Data Acquisition System

Figure 7.12 Schematic of generic CEBAF data acquisition system.

Figure 7.13 Schematic drawing of a data switching network showing 10 Mbyte/s data source fragments linked to CPU farm with dual ported memory.

configuration standard should be specified. As much as possible the system will involve the use of widespread industrial standards for both hardware and software. For example a typical hardware replay configuration might use UNIX based work stations and a VME farm. Graphic interface standards might include use of X-windows, and finally a standard Ethernet protocol like TCP/IP will be used.

7.6 COSTS, MANPOWER AND SCHEDULES

Based on the above conceptual design, we have made some preliminary cost estimates for the electron and hadron arms as shown in Table 7.1. These costs do not include manpower, R&D or contingency. These costs draw heavily from user and laboratory estimates. A similar estimate for the data acquisition package based on conversations with the CEBAF Data Acquisition Group is shown in Table 7.2. In costing the electronics, we have made some arbitrary decisions on how the costs should be divided. For example, the scintillator cost includes the cost of scintillator, phototubes, and analog electronics (Linear Fanouts, Discriminators, and ADCs). High voltage for the scintillators, Čerenkovs and wire chambers is included in a separate line item. Digital electronics except for wire chamber readouts is included in the trigger electronics.

W. Bertozzi and J.M. Finn have estimated the manpower requirements to construct the detector instrumentation as shown in Table 7.3. These numbers are consistent with the promised manpower as specified in the various Hall A Memoranda of Understanding. A total of 76 Manyears are estimated to build the detector hardware and write the data acquisition and analysis software. Figure 7.14 shows a time chart for construction. This

Table 7.1: Focal Plane Instrumentation Costs in k\$

	"H"	"e"
1 Detectors-Mechanical		
1.1 Focal plane VDC's 2 <i>XY</i> planes	150	150
1.2 Support structure	75	75
1.3 Gas supply system	25	25
1.4 Vacuum windows	15	15
SUBTOTAL	265	265
2 Detectors-Electrical		
2.1 Focal plane detector readout	200	200
2.2 Focal plane signal delays	40	40
2.3 3-plane scintillator stack	98	33
2.4 CO ₂ Čerenkov	50	50
2.5 Silica aerogel Čerenkov	100	100
2.6 Trigger electronics	120	120
2.7 Shower counters		50
2.8 H.V. distribution	30	30
2.9 Cables and connectors	25	25
2.10 System calibration laser	10	10
SUBTOTAL	673	658
3 Focal Plane Polarimeter		
3.1 Carbon analyzer & frame	46	
3.2 Wire chambers 4 <i>XY</i> planes	135	
3.3 Wire chamber electronics	161	
3.4 2 nd level trigger logic	80	
3.5 Miscellaneous (H.V., gas system, etc.)	28	
3.6 Tests	10	
SUBTOTAL	460	
TOTAL	2321	

time chart is consistent with the Hall A project milestones, the Hall A commissioning scenario and available manpower provided adequate and timely funding of the project.

We have experienced research groups working on all major system components. The MIT group (W. Bertozzi spokesman) will coordinate the focal plane instrumentation, and will provide the focal plane wire chambers, wire chamber readout, and associated hardware (gas handling system, vacuum window, etc). A timeline of their efforts is shown in Figure 7.15. The University of Maryland group (C.C. Chang spokesman) will provide the shower counter. A timeline of their efforts is shown in Figure 7.16a. The University of Regina group (G. Lolos spokesman) will provide the scintillators and the aerogel Čerenkov detectors. A timeline of their efforts is shown in Figure 7.16b. The Saclay group (B. Frois spokesman) will provide the gas Čerenkov counters. The William

Hall A Detector and DAQ Development

Figure 7.14 Timeline for Hall A detector and DAQ packages.

and Mary group (J.M. Finn spokesman) will provide the electronic trigger system and DAQ. Their timeline has been incorporated into Figure 7.14. The Rutgers group (C. Glashausser spokesman) will coordinate several institutions (CEBAF, the University of Georgia, the University of Maryland, Norfolk State University, Rutgers University, the University of Virginia and the College of William and Mary) providing the focal plane polarimeter. A timeline for the polarimeter is shown in Figure 7.17.

All detectors and electronics planned for the initial focal planes use proven technology. Electronics modules are readily available commercial units. Other than the wire chambers there are no large, technically complicated components which need to be manufactured. The wire chambers themselves are straightforward adaptations of existing chambers. However, they are much larger than existing wire chambers and require much more precision in construction and machining. Therefore, except for this precision, we feel we can assign minimal risk to the construction of the instrumentation described above.

We note that additional operating funds are required by the MIT group in order to augment their research group commensurately with the task involved. These requirements (excerpted from their MOU) are outlined in Table 7.4 below. In addition, the MIT group needs funds for wire chamber electronics research and development amounting to 50k\$ and for upgrading their wire chamber laboratory amounting to 100k\$. These monies will be required in a timely fashion as noted in the task timeline shown in Figure 7.15.

Although neutron detection is not part of the initial complement of equipment for Hall A, and thus has not been included in the above cost estimates for the detector systems, this capability is very important both for neutron form factor measurements and as a complement to other single and multiple nucleon emission studies. A brief description of the plans of the Kent State group to design, construct, test and commission a high resolution neutron time-of-flight system and a neutron polarimeter can be found in the appendix at the end of this chapter.

Table 7.2: Hall A DAQ Costs in k\$ (estimated)

Host Computer and Mass Storage	100
Graphic Workstations (3)	50
CPU Farm (5 high speed nodes)	50
Crates, Intelligent Controllers, Switching Circuits, Cables, etc.	50
Software Licenses	50
TOTAL	300

Figure 7.15 Work schedule and manpower levels for the MIT group to provide the focal plane wire chamber and associated instrumentation.

Figure 7.16 a) Work schedule for the University of Maryland group to provide the shower counter and associated instrumentation, b) work schedule for the University of Regina group to provide the scintillators and aerogel Čerenkov detectors and associated instrumentation.

Figure 7.17 *Focal plane polarimeter timeline.*

Table 7.3
Manpower (Manyears)

Item	R/D	Constr., Assemb. and Testing
FPI Coordination	0.5	1
Upgrade WC Laboratory	0.5	1
Wire Chambers	3	5
WC Readout	3	3
WC Software	1	1
Vacuum Window	1	0.5
Gas Systems	0.5	1
Scint. and Electr.	0.5	2.5
CO ₂ Čerenkov (2)	1	2
Aerogel Čerenkov (2)	2	3
Shower Counter	0	3
Support Structure	1	2
FPP and Software	3	13
Trigger Electronics	2	2
Data Acquisition	4	13
TOTAL	23	53

Table 7.4
MIT Manpower

NAME	CALENDAR YEAR				
	1990 %	1991 %	1992 %	1993 %	1994 %
Prof. W. Bertozzi	10	20	30	40	50
Dr. L.B. Weinstein	10	20	30	40	50
Dr. W.U. Boeglin	10	20	30	40	50
2 grad students	10/10	20/20	20/20	60/60	100/100
2 grad students*	0/0	0/0	20/20	60/60	100/100
3 physicists*	0/25/50	75/75/75	75/75/75	75/75/75	50/75/100
0.5 engineer*	0	100	100	100	100
1 technician*	25	100	100	100	100

NOTE: Personnel for which additional operating funds at MIT will be required are identified with an asterisk.

References

- [1] *CEBAF Hall A Technical Advisory Panel*, June 28-30, 1989; *CEBAF Hall A Preliminary Conceptual Design Report*, 1989.
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- [4] M. Holtrop and L. Weinstein, *Particle Identification in Hall A, A First Approximation*, to be published.
- [5] W. Bertozzi et al., Nucl. Inst. Meth. **141**, 457 (1977).
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- [8] C. Watson, private communication.

APPENDIX: NEUTRON DETECTION AND POLARIMETRY

The Kent State group plans to provide a neutron detection capability for CEBAF consisting of two major components: a high resolution detector system (J. Watson, coordinator) and a neutron polarimeter (R. Madey, coordinator).

• Neutron Detection

Assuming funding assistance from other agencies, including CEBAF, the KSU Users group plans to develop and test a high resolution system consisting of a highly-segmented neutron time-of-flight detector package. In addition, they plan to extend procedures for determining neutron detector efficiencies to a few GeV, the range relevant for work at CEBAF. Their R&D efforts will include testing a recoil-proton system used in combination with the CEBAF spectrometers for neutron detection as well as evaluating exotic scintillator materials for neutron time-of-flight detectors.

At the conclusion of their three year research and development project, the Kent State group will provide an assessment report to CEBAF of the performance of various prototype high-resolution neutron detection systems, and their suitability to the research program at CEBAF. As appropriate, the Kent State Group will then generate proposals for submission to CEBAF and/or federal funding agencies for the construction and commissioning of the optimum high-resolution neutron detection systems for CEBAF.

• Neutron Polarimetry

Another project which the Kent State group plans to undertake involves designing and constructing a neutron polarimeter for use at CEBAF, including the associated electronics and data acquisition code. This device is being considered primarily for performing neutron electric form factor measurements but could also be used for a more general program of polarized neutron emission studies.

Together with collaborators, KSU will calibrate the neutron polarimeter at appropriate accelerator facilities such as IUCF, LAMPF and Saturne. The polarimeter will include an adjustable mounting stand so that the mean angle for the secondary scattering can be varied to optimize the polarimeter's figure-of-merit for any neutron energy. In addition, KSU will provide consultation services to CEBAF in designing and procuring an appropriate shielding enclosure, collimator and movable platform (e.g. air pads) for the polarimeter.

Associated tasks headed by the KSU group include evaluating the advantages of a short duration timing signal from the beam microstructure, operating the beam line equipment (particularly the beam polarimeter) and specifying an appropriate target cell for the electric form factor experiment.

8. HALL A GENERAL EQUIPMENT

8.1 HALL A CIVIL CONSTRUCTION

While not within the formal scope of this equipment conceptual design report, Hall A Civil Construction is directly relevant: therefore, this summary description is included for reference.

8.1.1 Contract Awards

An \$11.8M fixed price contract for Package A: Underground Construction of the CE-BAF End Station/Beam Switchyard Area was awarded to Robert F. Gay Construction Company of Jacksonville, Florida on 19 March 1990, following a 9 February RFQ bid opening. Notice to proceed was given on 27 March 1990: the underground package, basically the concrete structures, is to be completed within 18 months of this date. Beneficial occupancy by CEBAF is to occur within 30 months of Notice to Proceed (by 27 August 1992). Package B: Aboveground Construction (all remaining aspects of civil construction) is scheduled to commence on or about 1 March 1991.

8.1.2 Hall A General Description

Figure 8.1 is a general plan view of the research area, showing the beam switchyard and halls A, B and C. Figures 8.2 and 8.3 show Hall A in plan and elevation views respectively, while its basic parameters are summarized in Table 8.1.

The 174 foot nominal wall inside diameter (86' minimum radius from the Hall A center monument), the 53' 6" roof spring line above the hall floor, and the 10 foot beam height above the floor, were all minimum possible values for accommodation of the two 4 GeV/c spectrometer arms: established in the interest of cost saving during civil construction. While a forward angle trench was eliminated for the same reason, some provision has been retained for future accommodation of an out-of-plane beam line. (Vertically arching the beam line before impinging upon the target would allow realization of non-coplanar kinematics, an important aspect of future Hall A physics programs).

The cantilever, domed concrete roof is designed to support a thickness of earth shielding consistent with the radiation safety requirement for 40 watts within the hall-public limits off-site.

Crane: A 20 ton capacity, half polar crane, with a hook height of 50' from the floor, is provided in the aboveground civil construction package.

Hall Floor: A 2 1/2' thick reinforced concrete floor is provided in the civil underground package. The floor will be laid upon the Yorktown formation, a semi-consolidated sedimentary material capable of bearing a pressure load of 6 KIPS/ft². Following installation of the three concentric floor plates, an additional 4" of concrete will be set atop the foundation floor: plates, installation and this concrete will be provided as Hall A equipment.

Beam Dump Cavity: A 7' x 7' x 30' long beam dump tunnel is provided in the forward beam direction. 18' of sand shielding is provided in all directions around the beam dump cavity.

Heavy Equipment Access: Each CEBAF experimental hall is provided with a ramp/tunnel for heavy equipment access. Ramp grade is 10%; The effective useful tunnel size is 13' H x 12' W. In fact, however, the tunnel is oval shaped, with one side isolated from the roadbed for personnel access.

Personnel Access: In addition to the walkway in the heavy equipment access tunnel, a cable/personnel access tunnel is provided to the upstream end of Hall A from the counting house.

Table 8.1 General Specifications for Hall A Civil Construction

Inside diameter of hall - 174 ft (nominal)
Inside radius of hall - 86 ft minimum, from center bench mark
Floor elevation: 3'-6' above mean sea level
Beam height - 10'-0' above the floor
Hook height - 50'-0' above the floor
Building height - at spring line - 53'-6' above the floor
Floor thickness - 2'-6' concrete (nominal)
Floor preparation - for HRS steel tracks
4" concrete added, flush with plate surfaces
- Hall A equipment item
Wall thickness - 2'-6' concrete (minimum for radiation shielding)
Dome concrete thickness - TBD
Earth shielding thickness
- Walls: 15'-0' at spring line iwth 1.5/1 slope of berm to grade
- Roof: 3'-3' overall
Dome rise, from spring line - 21'-9'
Forward-angle shielding thickness - see Hall A drawings
Beam dump tunnel
- 7' x 7' x 70' interior envelope
- 18' thickness surrounding concrete enclosure (material to be determined)
Air conditioning
- 74°F
- 50% relative humidity
Crane - 20 ton half polar
Access requirements
- Truck: 12'W x 13'H x 380' L tunnel
- Personnel and light equipment: from counting rooms via service elevator and/or staircase
- Cable/personnel: 7'W x 8' H cable way labyrinth
- Auxiliary emergency exits: across end station from normal access and/or through beam switchyard
Magnet and end station power - (36) 5" diameter "PVC" conduits encased in 4' x 4' concrete
Dewatering: - Permanent underdrain pumping
Ventilation
- Target gases: 4000 CFM exhaust
- Smoke removal rate: 6 air changes per hour
Fire protection - Sprinkler density: 0.15 GPM per ft ²

END STATION SITE PLAN

CEBAF

Figure 8.1 General Plan View of Experimental Area

Hall "A" Plan View

12/6/89
S ESP

Figure 8.2 Hall A - Plan view

Hall "A" Elevation View

12/8/89
S ES

Figure 8.3 Hall A - Elevation view

8.2 BEAMLINE EQUIPMENT

8.2.1 Introduction

The control and measurement equipment to be used in the Hall A beam line after the last magnetic element will consist of beam current, position and profile monitors, most of which are being developed and tested here at CEBAF and will be used in the circulation arcs and the beam switchyard of the accelerator.

The resolution and accuracy requirements in Hall A are such that special attention should be paid to the following issues:

- Determination of the incident beam energy
- Control of beam position, emittance and energy stability
- Determination of the beam current, total charge and luminosity

Figure 8.4 gives the layout of the beam as it enters Hall A. It shows the position of the last eight dipoles which bend the beam 37.5° from the beam switchyard into the hall. Each dipole has a quadrupole and a pair of steering magnets associated with it. After the last dipole, there are two more quads followed by space for a 5 quad rotator (a conceptual design is shown in figure 8.5). A set of 5 quads focus the beam on target. Each of these quads comes with a beam position, current and profile monitor and a pair of steering coils. Each such unit is shown in figure 8.6. The last quad element is still about 20 meters from the target position. A sectional view of the beam line is shown in figure 8.7 and an enlarged view near the target position is shown in figure 8.8. Figure 8.9 gives a transport output of the beam envelope from the beam switchyard to the target position.

8.2.2 Determination of Incident Beam Energy

Measurement of the beam energy is important not only for reducing absolute errors in the experimental data analysis (see Chapter 3) but also for the associated feedback system of the accelerator which in turn helps stabilize the energy of the beam. This improves the effective emittance by reducing the dispersion in the optics. Elimination of beam energy variations will thus simplify the accelerator tuning. One way to measure the beam energy would be to have good knowledge of the field maps of the eight dipoles which bend the beam 37.5° into the hall. This would enable us to measure the beam energy to 1 part in 10^{-4} provided an accurate knowledge of the bend angle is also known.

An alternate method of determining the beam energy absolutely to high accuracy is to use the angular and energy dependences of the synchrotron radiation (SR) intensity distribution in the direction vertical to the orbit plane^[1]. The absolute measurement of the beam energy for colliders or storage rings with a resolution as good as 10^{-7} has been achieved at the Yerevan synchrotron^[2]. Measurement of the energy spread in the extracted beam with resolution 10^{-6} was also performed. Using feedback, the energy of the accelerator has been stabilized to better than 10^{-5} . The evaluation of such methods for CEBAF must take into account the great differences between the beam in a storage ring and the CEBAF beam.

Figure 8.4 Hall A Beam line

The principle of the method described by Karabekov *etal*^[2], permitting measurement of the mean beam energy with a precision of 10^{-4} , is to measure the variation in the angular distribution of the synchrotron radiation (SR) in the vertical plane when the energy changes. This distribution depends only upon $\gamma (= E_0/mc^2)$. If one can measure and compare the SR beam intensity at two angles, $\psi = 0$ and $\psi = \psi_1$, the energy can be determined absolutely, since the relation between the fluxes at the two angles can be calculated accurately for the given γ .

One considers two horizontal slits of equal width, d , but different lengths l_1, l_2 , so that the number of photons per unit time through the slits are equal:

$$\Delta\theta_1 N_K(\psi = 0) = \Delta\theta_2 N_K(\psi = \psi_1)$$

where N_K is the flux density of the radiation in the bandwidth $\Delta\lambda/\lambda = K$. The aperture angles are $\Delta\theta_1 = l_1/L$, $\Delta\theta_2 = l_2/L$, where L is the distance between the slits and the point on the trajectory where the SR beam originates. The mean energy E_0 of the beam is determined absolutely when the two photon fluxes are equal, which is measured as the zero difference. A crystal is used for beam monochromatization. Since the SR is in two beams with slightly different angles, the crystal must be bent so that it reflects the beam at ψ_1 the same way it reflects the beam at $\psi = 0$. Ionization chambers made of aluminium tubing with a central electrode supported by ceramic insulators can be used for

90° Five Quadrupole Rotator

Equivalent to 10m drift length
45° rotation of the quadrupole
line around beam axis

Figure 8.5 Hall A Five Quad Rotator System

the detector. The realizability of this method with respect to CEBAF conditions is being investigated^[1].

8.2.3 Determination of Beam Position, Current and Profile

To determine the beam position, current and angle of approach of the beam on the target, we place a set of position and current monitors 4 meters and 0.5 meters upstream of the target position shown in locations A and B respectively in figure 8.8. In position A we have a set of steering coils, a beam profile monitor and a beam current and position monitor. Just outside the scattering chamber, in position B, we have a beam position and current monitor also. At the target position, within the scattering chamber, we plan to have a profile monitor. At present, no elements have been planned to be placed downstream of the target, but one can conceive of placing a current and a profile monitor to ensure that the beam is properly channeled into the beam dump. We present now a brief description of the instrumentation used.

8.2.3.1 Beam Position Monitors

Several different types of beam position monitors are being considered for use along various sections of the accelerator. The object of the monitors is to obtain an absolute beam centroid position determination to within 100 microns which is slightly better than the dimensions of the beam (140 microns). One would also prefer to make this determination in an as continuous and non-intrusive method as possible. Moreover, since several hundred of these will be required in the arc sections of the accelerator as well as near the injector and beam switchyard, the cost of each individual monitor also becomes a factor. Unless the demands of the beam position determination in Hall A become incompatible with those required for the accelerator, we plan to use the same monitors as those for the accelerator. A few different types of these monitors are being developed here at CEBAF to meet the special needs of the machine. The dynamic range of most of these monitors is between 10^{-10} A.m and 10^{-6} A.m. It is therefore clear that for currents below $1 \mu\text{A}$, one needs to

Figure 8.6 Hall A - Each unit of the beam focussing system

Figure 8.7 *Hall A Beam line - sectional view*

Figure 8.8 *Hall A Beam line - sectional view enlarged*

Figure 8.9 *Hall A Beam line Transport*

devise some other means to monitor the beam position.

1. Inductive loop beam position monitors

The inductive loop monitors determine the position by amplitude modulating the beam at a relatively low frequency (in this case 100 MHz)^[3]. Because of the relaxed mechanical tolerances on 100 MHz pickup compared to microwave pickup and the availability of low cost electronic components in this frequency range, these monitors are expected to be significantly cheaper (~\$ 630 + electronics and installation ~\$ 3500). The expected beam position determination is 100 microns at 1 μ A and gets better at higher beam currents. The monitor is being developed at CEBAF so as to be able to detect separately the position of each of the five different beams residing simultaneously within the CEBAF linacs. One obtains this by pulsing the amplitude modulation for a period of less than one circulation time in the machine (4.2 μ sec). In addition, the time interval between pulses of modulation should be greater than five circulations (21 μ sec) to allow one pulse to exit the machine before the next one is introduced. These monitors will be used in the linac section of the accelerator.

2. RF pickup monitors

Plans are underway to develop an RF pickup monitor for the determination of the beam position and current without modulating the beam and with position and current determination accuracies comparable to those obtained with the loop monitors. These are planned to be used in the arc sections of the accelerator. No details of these monitors are available at present.

8.2.3.2 Current Monitors

Since the beam at CEBAF is going to be continuous, the usual method of using toroids to measure the current as is done in low-duty factor machines is not possible. Several other devices are being looked into, some of which are being designed here at CEBAF for our specific needs.

1. Inductive loop monitors

The inductive loop monitors as described above can also be used as very accurate relative current monitors if one adds the the inductive loop pickups from both pairs which are transverse to each other. The resolution is rated to be also of the order of 1%. One can then calibrate these against an absolute current monitor system.

2. Parametric DC current transformer (Unser monitor)^[4]

A parametric dc current transformer measures the total number of circulating charged particles without requiring any timing information for proper operation. It makes use of high permeability alloys with amorphous structure and provides a precise, absolute calibration without any ambiguity ($0.2 \mu\text{A}$ over its full range of up to $250 \mu\text{A}$). Its operation is similar to the ZFCT (zero flux current transformer), which consists of a toroidal current transformer and an operational amplifier, connected together in a closed feedback loop. The current to be measured (e.g. the beam) passes through the center of the toroid and is the single turn primary winding. The operational amplifier maintains the dynamic balance between primary and secondary current over a wide frequency range (down to the mHz region). An auxiliary circuit with a magnetic modulator/demodulator, using a pair of toroidal modulator cores, senses the dc error between primary current and feedback current and corrects this error in the feedback loop. This maintains the main toroid at zero flux (static and dynamic) and extends the frequency range to dc. The feedback current is measured with a precision resistor. The parametric current transformer (PCT) differs from the ZFCT in the electronic circuit and a parametric amplification scheme reduces the effect of amplifier noise. These monitors are expensive ($\sim \$13000$), and present plans are to use only a few of these in the accelerator beam line and calibrate the rest of the relative current monitors with respect to these.

3. RF pickup monitors

These are the same as described above to determine the beam centroid position. They are still in the process of development here at CEBAF and can also be used as relative current monitors.

4. Faraday Cups

For low beam intensities of the order of $1 \mu\text{A}$ or less, one could think of using high powered Faraday cups before the beam dumps to make an absolute determination of the charge collected during an experimental run. At 4 GeV, the power deposited by a $1 \mu\text{A}$ beam is 4 kW and extensive cooling of this device would be necessary. At present two Faraday cups of 1 kW power are being planned to be used in the accelerator section for the front end test. The cost of these Faraday cups is $\sim \$4000$ plus $\sim \$940$ for electronics and installation. Faraday cups with 8 kW power dissipation is being employed at the SLC at SLAC^[5].

8.2.3.3 Profile Monitors

There are basically two types of profile monitors which give a profile of the beam as they interact with it.

1. Foils

Plans are to use Aluminium oxide (chromium doped) foils to intercept the beam to determine its position. Used in conjunction with CCD pickup TV monitors, one could obtain a resolution of approximately $100\text{ }\mu\text{m}$ though a resolution of $25\text{ }\mu\text{m}$ is conceivable. A 4"x4" foil is about \$ 1000 and the mechanical assembly of the plunger is about \$1000. A CCD camera is about \$1200 whereas a simple TV monitor is about \$200.

2. Wire scanners

These wire scanners are constructed in the shape of a harp with two wires strung perpendicular to each other and at an angle of 45 degrees to the beam. These scanners intercept the beam horizontally and is able to achieve a resolution of 10 microns in both the x and y position. The mechanical hardware costs about \$3500 and the electronics is about \$2000.

8.2.4 Additional Equipment

Various other pieces of equipment will be used in the beamline to monitor several other characteristics of the beam:

1. Beam Polarimeter

The range of energy and current needed in the experiments to be performed in Hall A using a longitudinally polarized electron beam, varies from 0.5 GeV to 4 GeV and from $0.5\text{ }\mu\text{A}$ to $100\text{ }\mu\text{A}$ respectively. The longitudinal polarization of the beam must be known with an accuracy that varies from 1 % to 5 %. The most common requirements in these experiments are in one case a *high energy* and *high current*, in the other case a *low energy* and *low current*. Given these requirements, it is mandatory to consider two methods for the determination of the electron beam polarization.

- The first method is the elastic back-scattering of photons from a continuous laser beam off the electron beam. The measurement of the electron beam polarization is performed by measuring the asymmetry resulting from scattering with parallel or antiparallel spin orientation of the two beams. The size of the asymmetry at high electron beam energies and the currents available make this method suitable for a high accuracy measurement of the electron beam polarization. In principle one can achieve a 1% accuracy in this measurement.
- The second method is the Möller scattering of the electron beam off electrons from a thin magnetized iron target. The asymmetry measured in this process is large enough at low energy that the intrinsic precision around (3%) of this method can in principle be achieved.

The Compton Polarimeter

Figure 8.10 Longitudinal asymmetry for three different incident energies of the electron beam respectively $E = 4 \text{ GeV}$, $E = 1.3 \text{ GeV}$ and $E = 0.5 \text{ GeV}$. We assume the photon beam to be 100% polarized and the electron beam to be 50% polarized. The energy of the incident photon beam is $k = 2.41 \text{ eV}$

We will denote E , E' , k and k' respectively as the incident electron energy, scattered electron energy, incident photon energy and scattered photon energy. All angles are defined with respect to the direction of the incident beam such that the scattered photon emission angle is defined as $\theta_k = \pi - \theta_0$ where θ_0 is the emission angle defined as usual with respect to the direction of the incident photon. The emission angle θ_k and the energy of the scattered photon k' are related in this elastic process by the following expression:

$$k' = k'_{max} \left[1 + \eta \left(\frac{E\theta_k}{m} \right)^2 \right]^{-1}$$

the parameter η is defined as

$$\eta = \left(1 + \frac{4Ek}{m^2} \right)$$

k'_{max} is the maximum energy of the back scattered photon and can be expressed in terms of the parameter η as

$$k'_{max} = E(1 - \eta)$$

We also define the parameter $\xi = k'/k'_{max}$ which is the fraction of maximal energy carried by the back scattered photon. This parameter varies from zero at large emission angles to unity at zero emission angle. For a continuous photon beam from an Argon Laser operating in the green wavelength ($\lambda = 514.5 \text{ nm}$) $k = 2.41 \text{ eV}$ and interacting with an electron beam of $E = 4 \text{ GeV}$ incident energy, the maximum energy of the back-scattered photon is $k'_{max} = 514.6 \text{ MeV}$. The angular range where the energy would drop by a factor of two ($\xi = 0.5$) is given by $\theta_k = m/E\sqrt{\eta}$. In our example this angle is

$\theta_k = 1.36810^{-4} \text{radians}$. The scattered beam is mainly in a very narrow cone allowing an easy integration over the azimuthal angle of the cross section with a small size photon detector. Regardless of other constraints (for example a small asymmetry) if one set a limit for the detectable back scattered photon with the same detector of $k' = 50 \text{ MeV}$ with a 20 MeV energy bin this method can be used down to an incident electron beam of $E = 1.3 \text{ GeV}$. The longitudinal asymmetry in Compton scattering is defined as the following quantity:

$$A_l = P_e \cdot P_\gamma r_0^2 [1 - \xi(1 + \eta)] \left\{ 1 - \frac{1}{[1 - \xi(1 - \eta)]^2} \right\} \cdot \left(\frac{d^2\sigma}{d\xi d\phi} \right)^{-1}$$

P_e and P_γ are respectively the longitudinal polarization of the electron beam and the polarization of the photon beam and where $\frac{d^2\sigma}{d\xi d\phi}$ is the unpolarized differential Compton cross section per radians and unit ξ given by the following expression:

$$\frac{d^2\sigma}{d\xi d\phi} = r_0^2 \eta \left\{ \frac{\xi^2(1 - \eta)^2}{1 - \xi(1 - \eta)} + 1 + \left[\frac{1 - \xi(1 + \eta)}{1 - \xi(1 - \eta)} \right]^2 \right\}$$

r_0 is the classical electron radius $r_0 = 2.810^{-13} \text{ cm}$

In Fig. 8.10 we show the value of the asymmetry A_l for the case where the incident energy of the beam is 4 GeV , 1.3 GeV , and 0.5 GeV . We have assumed a 50% longitudinal polarization of the electron beam and a 100% circular polarization of the photon beam these parameters are realistic with our expectations of the polarized beam at CEBAF. If we average the energy region between $\xi = 0.8$ and $\xi = 1$ which corresponds to a bin of 20% in photon energy the cross section weighted asymmetry obtained is 6% at $E = 4 \text{ GeV}$, 2% at $E = 1.3 \text{ GeV}$ and 0.8% at $E = 0.5 \text{ GeV}$.

Because of the forward peaked angular distribution of photons a small sized detector allows to 2π azimuthal angle ϕ . Figure 8.11 shows the unpolarized cross section integrated over the azimuthal angle ϕ as a function of ξ for several incident electron beam energies. We still consider only the range of x between 0.8 and 1. where the cross section is almost maximum for the detection of the scattered photons.

In order to evaluate the time required to perform the measurement of the longitudinal polarization of the beam. It is first useful to evaluate the total number of counts necessary to obtain a given uncertainty in the measurement of the asymmetry. The relative uncertainty of the asymmetry A_l is given by the following expression:

$$\frac{\Delta A_l}{A_l} = \sqrt{\frac{(1 - A_l^2)}{N_t}}$$

where N_t is the total number (parallel and antiparallel orientations of spins) of counts to be detected. We can now evaluate the total number of counts needed for the energies listed before. For example the longitudinal asymmetry of the beam at $E = 4 \text{ GeV}$ is 6% therefore the total number of counts needed to achieve $\frac{\Delta A_l}{A_l} = 1\%$ is obtained directly from the above formula and is equal to $N_t = 2767777$.

Figure 8.11 The unpolarized cross section plotted for the same three different incident energies of the electron beam as for Fig. 8.10. Notice that the cross section does not change rapidly with the incident beam but it changes by almost a factor of 2 in the range $x = 0.8$ to $x = 1$.

We want to evaluate the time to reach a precision between 1% and 5% for different conditions of the beam parameters. The rate of back scattered photons is given by the formula

$$N_{\gamma'} = \frac{N_e N_{\gamma} \sigma l}{S c}$$

where N_e is the number of incident electrons per second, N_{γ} is the number of incident photons per second, σ the cross section integrated over the energy region $\xi = 0.8$ to $\xi = 1$, l is the length of the interaction region, c the speed of light and S the area of the largest beam (in this case it is the photon beam). The relevant parameters in the evaluation of the rate are therefore the beam percentage of longitudinal polarization, the average current needed for the nuclear physics experiment being performed at the time of the measurement, the duty cycle of the machine, the length of interaction for the Compton scattering and the area of the largest beam between the photon beam and the electron beam.

As we said before the range of the incident electron beam parameters vary over a wide range, however one can optimize the surface of the largest beam and set up the largest possible interaction region to enhance the rate. As an example, we assume 2 m for the interaction region length, 2 mm² for the area of the photon beam, 10 μA for the average electron beam current with a 50% polarization and a 10 Watt laser beam power, the resulting rate is 80 Hz. It will take in this specific case almost 10 hrs for the measurement at the 1% level. Nevertheless a relative uncertainty of 3% can be reached in 1 hr. This example is realistic and does not assume a very large current and 100% polarization beam. In table 8.2 we give the time for different configurations of the beam. It is clear that this polarimeter is best for very high current and high energies where the Möller polarimeter is

less adequate since the target for Möller polarimetry can not stand a beam of high average electron beam current.

Table 8.2						
Incident energy (GeV)	average current (μA)	polarization of the beam (%)	Average Asymmetry (%)	Maximum beam Energy (MeV)	Scattered photons Rate (Hz)	Time needed (hrs)
2.	50.	50.	3.2	137.5	431.	6.3
4.	50.	50.	6.0	514.6	403.	1.9
2.	100.	80.	5.7	137.5	863.	1.0
4.	100.	80.	9.9	514.5	807.	0.95

In Table 8.2, the energy of the incident photon beam corresponds to a 10 W Argon laser with a wavelength $\lambda = 514.5 \text{ nm}$ (green) and an area of 2 mm^2 . The asymmetry A_I is cross section weight-averaged between $\xi = 0.8$ and $\xi = 1$. The time is computed for a determination of the polarization at the 1% relative uncertainty level.

We plan to set up the interaction region after the eight dipoles that guide the beam into Hall A in the straight section before the entrance of the hall. It is crucial that this interaction region be as long as possible. Four dipoles are needed to perform this task. The interaction region will be parallel to the beam line after the electron beam has been bent up and back horizontally. Two identical dipoles will return the beam along its initial direction.

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8.3 TARGETS AND SCATTERING CHAMBER

The Hall A physics program calls for the use of a large variety of targets, from *solid slabs of various thicknesses to extended liquid or high pressure gas targets, mostly cryogenic*, for experiments on few nucleon systems and possibly *solid polarized targets*. The target assembly will be installed in vacuum inside a *scattering chamber*.

The scattering chamber, a target holder for solid targets, and a cryotarget system have been considered as part of the initial complement of equipment for Hall A. Polarized target systems will have to be borrowed from the equipment planned in the other Halls. Dedicated polarized targets can be envisaged later.

The solid target holder will allow one to remotely select the target to be exposed to the beam, as well as to orient the angle of the (vertical) target plane with respect to the beam, for example to minimize the fluctuation in overall energy losses of incoming and outgoing particles. The cryogenic target system, is designed to have interchangeable target cells which will contain low temperature (10 - 20 K), high pressure (up to 70 atm.) liquid or gas.

The most important issue in designing Hall A target systems is the very localized and very high energy deposition when the experiment is performed at luminosity values $\geq 10^{38} \text{ cm}^{-2} \text{ sec}^{-1}$. Moreover, the accuracy requirements of most Hall A experiments dictate that the effective target thickness should be very well controlled. We consider here only briefly the problem of target heating for thin solid targets and the design of a high power target system. Some general features of the Hall A scattering chamber are given at the end.

8.3.1 Target heating for thin solid targets

For the purpose of the study a thin molybdenum target of $2 \times 2 \text{ cm}^2$ was considered. The target thickness along the beam direction was taken to be 0.2 mm, which corresponds to about 0.15% radiation lengths (0.204 g/cm^2) for Mo. A beam current of $200 \mu\text{A}$ was used and the target periphery was kept fixed at 20 K as was the initial target temperature. The beam spot size was taken to be 0.2 mm diameter.

The target temperature increase when exposed to the CEBAF beam was simulated for two situations: (a) the beam spot remained fixed at a given position and (b) the beam scanned the target with a sinusoidal motion in both the horizontal and vertical axis.

The results of the study can be summarized as follows:

1. With the beam spot fixed at the center of the target, the steady state beam spot temperature reached about 2500 K.
2. Heat loss through radiation was not appreciable. Most of the power dissipated through conduction to the fixed temperature boundary at the target periphery and therefore this boundary must be made as efficient as possible for heat transfer.
3. Defocussing the beam horizontally by a factor 10 decreases the temperature by the same factor, if one assume a uniform distribution of the energy deposition over the beam spot area. As the beam can be defocussed far from the target ($\geq 20 \text{ m}$), the induced uncertainty on the beam direction would be negligible.

4. If the beam is not defocussed, the beam spot must scan the target with relatively large frequencies which appear to preclude any mechanical means of physically moving the target. Calculations were made assuming that the beam spot scan the target with a sinusoidal motion having frequency/amplitude of 100Hz/9.6 mm (97Hz/4.8 mm) in the horizontal (vertical) direction. The steady state temperature was about 350K over most of the target area except the four extreme points of the motion.

8.3.2 High power cryogenic targets

Various experiments described in the current Hall A Experimental proposals submitted to PAC4 require luminosities up to $10^{38} \text{cm}^{-2} \text{s}^{-1}$. Taking into account the characteristics of the electron beam and the thermodynamic properties of the few-nucleon targets this is a reasonable limit of achievable luminosities. The use of extended cryogenic targets is mandated by such luminosity requirements. Moreover, the track reconstruction capabilities of the Hall A spectrometers will allow a significant reduction in the background contributions to coincidence spectra through the use of extended targets, as true coincidence events originate from the same point in the target while background coincidences come from the entire target.

8.3.2.1 Physical Parameters of the Cryotarget

The CEBAF accelerator's 4 GeV beam with currents as high as 200 μA and spot size of as little as $0.1 \times 0.1 \text{ mm}^2$ will produce up to a kilowatt of power deposition on a target with high power densities (up to a MW/cm^3). These beam characteristics produce density effects in the target resulting from local beam heating and, in the case of liquid targets, bubble formation in the region of the target traversed by the beam. Both these effects make the counting rates beam current dependent.

The bulk power dissipation in the target (of the order of 1 kW) is a technical problem that can be addressed by the use of a suitable refrigerator and heat exchanger. Such refrigerators exist, though they are costly. For example, in the case of a liquid hydrogen target 15 cm long operating at 20 K with a 200 μA beam the power dissipation is 1 kW. For a ^4He gas target of similar configuration operating at 10 K and a pressure of 70 atm the power dissipation is 1.2 kW. A suitable refrigerator must remove this heat.

To minimize density variations due to local beam heating and bubble formation effects, flowing the target material past the beam perpendicular to it has been considered. Calculations indicate that substantial though achievable flow velocities (10 to 30 m/s) are required. These flow velocities can be reduced substantially by rastering the beam as in the case of thin targets discussed above. With a beam defocussed to 2 mm in the horizontal direction, flow velocities of under 5 m/s are needed to maintain 5% density variations. Experience at other laboratories e.g. SLAC, indicates that speeds of 1 to 10 m/s are feasible.

Bubble formation in a liquid target is a complex process and can only be described semiquantitatively. Macrobubble formation is suppressed empirically through pressurization of the target cells using pressures equivalent to the vapor pressure of the liquid at the local temperature and flowing the liquid as mentioned previously. At the same time, the target liquid will be circulated past the beam as mentioned previously.

Table 8.3 summarizes the parameters of cryogenic targets for few nucleon systems to be used in the CEBAF conditions discussed. Liquid targets have been chosen for Hydrogen and Deuterium to operate at a nominal 20 K and pressures suitable for suppression of macro bubble formation. Gas targets have been chosen for ^3He and ^4He to operate at nominal 10 K under pressure of 70 atm. In all cases the target cells have a physical length of 15 cm and a beam current of 100 μA and 0.1 mm spot size has been assumed.

TABLE 8.3				
	LH_2	LD_2	$^3\text{He}(\text{gas})$	$^4\text{He}(\text{gas})$
Operating T (k)	20	20	10	10
Operating p (atm)	17	17	70	70
ρ (gm/cm ³)	0.07	0.17	0.11	0.17
L (cm ⁻² s ⁻¹)	2.7×10^{38}	3.2×10^{38}	1.7×10^{38}	1.6×10^{38}
P(W)	500	600	500	600
$v_f(\text{m/s})$ with $\Delta\rho/\rho=0.05$	1	0.5	2	1.5

The design specifications will allow initial operation of the target at moderate levels of power dissipation (200-500 W) with reduced luminosity. As increased refrigeration capability becomes available, the target will be able to operate at its full design specification of 1 kW.

8.3.2.2 Target Loop

Preliminary designs are underway to construct and test a target loop that, with the exception of the target cell itself, will be identical for all four target materials. The target cell will be replaceable and will be designed to match the needs of specific experiments.

The target loop consists of the following elements:

1. cells (interchangeable)
2. fans and motors
3. heat exchanger
4. temperature, pressure, and flow velocity monitors
5. pressure relief valves, vents, and dump tanks

A drawing of the loop is presented in Figure 8.12

(1) Cells

Cells are being designed for the different targets being considered. Cells for H and D will be built for liquids with operating pressures of about 17 atmospheres. This overpressure is needed to suppress bubble formation in the beam path. Minimum cell wall thicknesses in this case are about .003" for a 7075-T6 aluminum cylinder of 1 cm diameter with hemispherical end caps. Initially, standard lengths of 15 cm will be built. Additional cells will also be designed to satisfy experiment specific requirements. Figure 8.13 shows three

Figure 8.12 Target Loop

Figure 8.13 *Target Cell Designs*

general cell shapes currently being considered. The advantage of the design in Figure 8.13b over Figure 8.13a is that the beam entrance and exit points are cooled directly by the target fluid and are not in quieter pockets of the flow. The design in Figure 8.13c is easier to fabricate and lends itself to forming of the cell. Cells for gaseous targets of ^3He and ^4He will have the same geometry, but will be of more robust construction since these targets will operate at 70 atmospheres at 10 K. Minimum wall thicknesses in this case will be about .010" for the same materials.

The cells will be interchangeable since the requirements of the rest of the loop are largely target independent. Cells will include entrance and exit ports for the vertically flowing target material and flanges to enable attachment into the loop. Figure 8.14 shows the general configuration of the interchangeable cell.

(2) Fans and Motors

Target fluids will be propelled by fans submerged in the fluid. Motors to drive the fans are to be placed outside the target fluid. Experience at SLAC indicates that the design criterion of 10 m/s is achievable.

(3) Heat Exchanger

The heat exchanger will be similar to the one currently being designed at SLAC for a high power cryotarget to be used at MIT Bates. The design basically consists of a counter flow arrangement of the target material inside of a steel bellows with the coolant flowing about the outside of the bellows in a circulating motion caused by the appropriate positioning of baffles in the coolant stream.

(4) Temperature, Pressure, Flow Velocity Monitoring

Figure 8.14 *Interchangeable Target Cell*

The temperature, pressure, and flow velocity are macroscopic target parameters which need to be monitored, mainly for reasons of safety. Carbon-glass resistors can be used at the temperature ranges envisioned for the target. Pressure transducers capable of operating at low temperatures will be necessary. The flow velocity can be indirectly monitored by measuring the rotation rate of the driving fans and/or motors. The flow velocity can be calibrated against these indirect parameters at room temperature using commercially available flow meters. This is a standard technique developed for the high power cryogenic targets currently in existence. Measurement of flow velocity for cryogenic fluids has not been so successful, but it appears that the indirect determination has been adequate. We may investigate possible means of directly measuring cryogenic flow.

Users of the high power target should be aware that the availability of the macroscopic thermodynamic parameters is insufficient for an accurate determination of target thickness during an experiment. Subsidiary measurements using cross section ratios must be used to obtain reliable target densities in the beam.

(5) Heater

Part of the safety system for the target must include a provision to ensure continued stable operation of the loop in the event of a loss of beam. A heater will be installed in the loop to simulate the total beam power dissipation. When the electron beam is interrupted the heater should come on to prevent the refrigeration system from overcooling the target.

(6) Pressure Relief Valves, Vents, and Dump Tanks

The design of the target scattering chamber should incorporate the possibility of a rupture of the cell. This means that the scattering chamber volume should be large enough to safely contain the warming gas as it is being vented. The hydrogen isotopes and ^4He

Figure 8.15 Scattering Chamber at NIKHEF⁽¹⁾

can be vented to the outside of the experimental hall into the atmosphere. ^3He will be vented to dump tanks for subsequent recovery. The weakest part of the loop is the cell. It is unlikely that the heat exchanger will break and vent refrigerant into the scattering chamber. The contents of the loop are thus the most probable to escape into the scattering chamber. The loop volume is presently envisioned to be 20 liters. For liquid hydrogen this means about 840 moles of target material. Since this mass cannot instantly come up to room temperature, a large enough diameter venting tube can safely siphon the gas out of the scattering chamber.

8.3.3 Target chamber

A general layout for the target chamber is being designed to incorporate many diverse features required by the experimental conditions. It is planned to have a sliding seal on both spectrometer arms as well as to incorporate the full angular range possible for both arms. A reasonable inner diameter for the chamber would be 1 m. This allows both the spectrometers to reach a minimum angle of 8° with the sliding seals, leaving a margin of 4 cm between the exit beam tube and the spectrometer opening in their most forward position. Figure 8.15 shows the scattering chamber designed for NIKHEF^[1] with sliding seals on both spectrometer arms. Since the spectrometer solid angle subtends $\pm 108\text{ mr}$ in the vertical and $\pm 36\text{ mr}$ in the horizontal directions when the front quadrupole pair is in the most forward position, the sliding seal has to have a vertical dimension of at least 11 cm. This would then require an internal support mechanism for the sliding seals, as the maximum width of an unsupported seal is approximately 8 cm. A rough sketch of the scattering chamber layout is shown in Figure 8.16.

Figure 8.16 Scattering Chamber Layout

If the high power cryogenic targets must also fit within the scattering chamber, as well as several thin solid targets, a design of these targets will have to be incorporated in the design of the scattering chamber. According to John Mark (SLAC), who has provided a rough sketch of these targets, it seems that they can fit within the 1 m scattering chamber. If extra space is required, then it is possible to extend the scattering chamber on the hadron arm side between 140° and 170° without impinging on any other limitations of the experimental setup (see figure 8.16). In the vertical direction the scattering chamber could have two separate lids, one incorporating only solid targets, and another which would provide space for both cryogenic as well as solid targets. The return paths for the sliding seals could be either above or below the scattering plane leaving space in the other half for portholes for both viewing and/or for extra openings to the scattering chamber.

As we see from the above considerations, which are at a preliminary stage, a general purpose scattering chamber can be quite easily designed which will meet all the requirements for the various experiments proposed for Hall A.

References

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8.4 INSTRUMENTATION AND CONTROLS

8.4.1 Operational Requirements

At a primary level, the *Hall A Control System* must provide a means to read and set parameters and values for a number of devices in the hall. Also, it provides a way to link the Hall A instrumentation and operations to the Machine Control Center. Finally, it can be a major element of the interface between the user groups and the hall A instrumentation.

Although the definition of the Hall A control system is still in a very preliminary stage, one can enumerate the main operational requirements in each of these three categories.

8.4.1.1 Monitoring and Control of Hall A Equipment

The major instruments are the spectrometer lines. The ultimate goal is to be able to setup each spectrometer at a given polarity, momentum and angle in a completely computer-controlled way, and to monitor the stability of the settings within the required tolerances as well. This implies control/monitoring of the following subsystems:

- *Cryogenic Systems* : Monitoring of the liquid helium cooling and distribution systems, quench detection and protection, etc.
- *Power Supplies* : Setting the current in each magnet coil system to the desired value, based on the particle momentum value and calibration curves. Predefined cycling procedures to minimize hysteresis effects and ensure reproducibility will be used. For the dipole, the reference will be the signal of an NMR probe with a feedback loop on the magnet excitation.
- *Positioning systems* : Bringing the spectrometer to the desired azimuthal position, aligning the spectrometer line within tolerances, registering and monitoring the actual position.
- *Detector systems* : Setting-up and monitoring gas flow in wire chambers, temperatures, high-voltages, thresholds, trigger configurations, etc... A large fraction of these controls are included in the Detector Electronics and Data Acquisition System described in section 7.
- *Miscellaneous systems* : Positioning the proper acceptance defining slit. Checking and monitoring the ready-to-take-data status of all vacuum, water cooling, safety, etc... systems attached to the spectrometer lines.

Another important area is the *target system*. For solid targets, target selection and positioning at the desired angle will be computer controlled, as well as any hydrogen-flow cooling or target motion if needed (and implemented!). High power cryotargets will be much more demanding in instrumentation and controls.

8.4.1.2 Beamline Controls. Link with the Accelerator

Information from the Machine Control Center concerning beam status, energy, intensity, beam switchyard setups, etc... will be registered together with all nondestructive on-line measurements performed in the hall. For some periodic checks, the data taking may have to be interrupted. Information from the Hall A Control System will be sent

to the machine, to define a "ready-to-take-the-beam" status and also to provide feedback signals on beam performance stability.

Other systems include the various safety systems (hall and equipment interlocks, fire protection and explosive gas systems, ventilation systems, radiation safety monitors, beam dump status, etc...). Operating conditions, alarm signals and shutdown procedures will have to be defined.

8.4.1.3 Experimenter interface and data bases

Experiments will be run by physics groups including outside personnel not necessarily familiar with operating complex engineering systems. For that reason, control access protections and possibly restrictions, as well as proper documentation are very important to define. The control system has to be flexible enough to incorporate easily the control and monitoring of special user provided instruments. Finally, the control system can provide access by users to useful information concerning the instrumentation characteristics and configuration (like spectrometer transport coefficients, beam monitor calibrations, targets performance, etc...)

8.4.2 Control System Hardware and Software

The architecture of the Hall A control system is expected to be developed similarly to that of the main accelerator as a hierarchical, distributed computer network.

Decisions concerning the choice of the hardware/software to be used have not been finalized yet. One possibility would be to use the same components as those used for control and monitoring of the accelerator itself. This may present some advantages in terms of initial operation and maintenance costs.

A possibly more efficient solution, in which the central computer system is the Apple MacIntoshTM and its peripherals is being evaluated. This equipment is already used extensively at CEBAF and throughout the physics community. Its reliability and flexibility for control applications is well established, and there is extensive vendor and user support for it. It has the major advantage over the HP system designed for the machine of being fully compatible with the data acquisition system defined in section 7. A brief description of this system is given below.

Each station on the system is designed to function as a multiple usage unit. Using established communication links, each will be able to interface to any of the various CEBAF systems (VAX, HP, etc...), in addition to providing an environment for control and monitoring, hardware testing, and custom software development.

In the proposed architecture, control functions are divided into two levels, known as supervisor and local. The function of the local level is to provide monitoring and control for individual systems, such as those described previously under operational requirements, with a single machine handling each major subsystem. This level also provides the necessary interface between the supervisory computers and the operational equipment.

The supervisory computers provide overall system control, platforms for running user applications, access to operational documentation, and general operator interfaces.

At least one other machine will be available to serve as a gateway to other CEBAF computer systems, or as a spare should one of the other machines fail.

The interface to the local level computers from operating hardware will be via CAMAC with the interface from CAMAC to the local computer provided by Small Computer Systems Interface (SCSI), and/or a specialized direct memory access interface and crate controller combination developed at CERN known as MICRON (MacVee Interface Card Resident on NuBus) and Mac-CC respectively.

The majority of the software for operating the MacIntosh based control system can be obtained commercially. The main software package would be the KmaxTM package from Sparrow Inc. Additionally, the choice of the MacIntoshTM allows us to utilize most of the major software packages (INGRES, X-WINDOWS, etc...) currently in use at CEBAF, and provides close compatability with the data acquisition system.

Although the MacIntosh-based system looks more promising, we based our cost estimate for the Hall A Control System on the HP system used for the accelerator itself.

8.5 VACUUM SYSTEMS

8.5.1 Magnet Cryostat Vacuum

Each magnet cryostat is independent, and is not actively pumped during normal operation. However, each vacuum chamber includes a standardized 6" diameter, horizontal axis pumping port, with gate valve. A portable vacuum pumping station will be provided for Hall A, which includes a roughing pump, diffusion pump, cold trap and associated valves, flanges and controls. This will be used to pump down each magnet vacuum separately, prior to cooldown. Thereafter, the vacuum should remain at 1×10^{-7} torr or better by cryocondensation on the 4 K surfaces.

Provision is also made in the service tower region of each magnet for vacuum pump down of the helium vessel.

Also, a mass spectrometer type helium leak detector will be available in Hall A for diagnostic use.

8.5.2 Beam Line Vacuum System

Figure 8.17 is a schematic diagram of the Hall A beam line vacuum system; from the switchyard interface, through the target, to the beam dump.

8.5.3 Spectrometer Vacuum System

Figure 8.18 is a schematic diagram of the beam vacuum system associated with each HRS arm.

Figure 8.17 Hall A beam line vacuum system

Figure 8.18 Beam vacuum system for each HRS arm

HRS Vacuum System

J. Miller
8/30/89

8.6 HALL A FLOOR PLATES

The three sets of concentric floor plates upon which the spectrometers ride are shown in Figure 8.19. The plates, their installation and the final 4" of concrete which brings the Hall A floor level to 10 below the beam, and nominally to the top surfaces of the plates, is provided as Hall A equipment (WBS 6.5).

CEBAF has acquired a quantity of 2 1/2" thick mild steel (AISI 1018 or similar) plate, surplus from the Norfolk naval shipyard. We are hopeful of obtaining more: perhaps enough surplus for all of our floor plate requirement. We originally had planned to use AISI 1040 (or similar) plate, which could be flame surface hardened due to its relatively high carbon content.

We have determined that, from an allowable bearing stress standpoint, the mild steel surface is acceptable. AISC specifications permit an allowable load of 135×10^3 lb on mild steel plate (30 Kpsi yield stress) from a 24" diameter $\times$ 7 1/2" wide steel wheel. Four such wheels are to be used on one HRS bogie, whose total rated load is 500×10^3 lb. Comparable formula from Roark and Timoshenko yield allowable values of around 125×10^3 pounds per 24" dia. $\times$ 7 1/2" wide wheel. In fact, the nominal maximum load on any one bogie of our support design is around 400×10^3 lb, or 100×10^3 lb/wheel. However, Rosenblatt personnel caution that some localized spalling is probably inevitable, due in part to uneven load distribution. They state that this will only develop after considerable use, and can be repaired by adding weld material and grinding.

NOTES:

1. CENTRAL BEARING PLATE PARAMETERS:
 - A. THICKNESS - 3.5 IN.
 - B. DIAMETER - 13 FT 10 IN.
 - C. MATERIAL - HIGH STRENGTH STEEL
 - D. SPEC - ASTM A 572, GR 50
 - E. YIELD - 50,000 PSI
2. FLOOR PLATE PARAMETERS:
 - A. THICKNESS - 2.25 IN.
 - B. WIDTH - 3 FT 4 IN.
 - C. MATERIAL - HIGH STRENGTH STEEL
 - D. SPEC - ASTM A 572, GR 50
 - E. YIELD - 50,000 PSI

PLAN VIEW

HRS Floor Plates

4/10/00
FAH

Figure 8.19 Floor Plates in Hall A for the HRS

9. CONSTRUCTION, CALIBRATION AND COMMISSIONING

9.1 PROCUREMENT OF HRS MAIN COMPONENTS

In the following subsections, we outline our present intentions for procurement of the primary HRS components, including the magnets, support/positioning system, detector package, beam line and general equipment.

9.1.1 Quadrupoles

We are presently negotiating an agreement with CEN-Saclay whereby the six $\cos 2\theta$ quadrupoles $2 \times (Q1, Q2, Q3)$ will be designed, constructed and tested by the DPhPE/STIPE superconducting magnet group, under the direction of Dr. Henri Desportes.

CEBAF has defined the coil geometry/tolerance requirements for these magnets, based upon 3-D TOSCA analysis performed by Sirish Nanda. A Reference Conceptual Design for the Q2/Q3 elements has been prepared, based generically upon the three sector coil/concentric shell support approach developed for the CERN LEP quadrupoles.

9.1.2 Dipoles

Schedule: We intend to solicit proposals from prospective, qualified superconducting magnet vendors according to the bid cycle schedule indicated:

Issue Draft RFP	30 May 90
Vendor Response Meeting	15 June 90
Issue RFP	29 June 90
Proposals Due	28 September 90
Call for BAFOs	29 October 90
Contract Award	20 December 90

Approach: Our solicitation will be in the form of a Request For Proposal (RFP) for a fixed price contract to provide complete magnet systems, including the following:

- Engineering design
- Fabrication
- Acceptance testing
- Delivery

Our baseline RFP will include installation within CEBAF's Hall A, upon the HRS support cradle provided. Acceptance testing will be performed after installation.

While some single vendor responses are anticipated, teaming is acceptable, as long as one member is designated as having primary responsibility for the contract. Subcontracting of major components is, of course, allowed.

We intend to solicit RFP responses either for the entire job as noted above, for the coil/cryostat only, or for the iron (yoke/poles) only. It is felt that this will yield a wider spectrum of responses from which to make our selection evaluation. Thus, we have the option of purchasing the coil/cryostat from one vendor, the iron from another, and of

performing the role of system integration/installation ourselves, should this combination appear to offer major cost savings relative to the single vendor "turnkey" approach. In this case a greater burden of performance responsibility would be borne by us.

Technical Specification: The CEBAF Request For Proposal (RFP) will include a Technical Requirement and a Reference Conceptual Design, the latter representing one approach which CEBAF believes will meet the Technical Requirement when fully developed by the vendor. Except where components are fully defined in the Technical Requirement, the vendor is free to propose alternative designs, subject to review and approval by CEBAF. In any case, full responsibility for meeting the Technical Requirement shall rest with the vendor.

The Technical Specification for the dipole systems is included in Section 5.1.3 above.

CEBAF lacks sufficient engineering staff to fully define the magnets, including production of "build-to-print" manufacturing drawings. In any event, we prefer to permit vendors considerable design freedom, for the following reasons:

- to encourage innovation and to benefit from vendor experience, leading to the most efficacious design in terms of function and cost.
- most vendors prefer to prepare manufacturing drawings tailored to their own shop practices.
- to ensure that design/fabrication responsibility rests with the vendor (i.e., to avoid the ". . . but your drawings showed it this way" syndrome).

However, magnetic field characteristics must be defined in detail by the CEBAF staff, based upon an in-depth understanding of the physics optics requirements. For this reason, we have chosen to specify the geometry of the field generating magnet elements, rather than to provide the vendor with a mass of 3-D field data, or require him to develop this information from a list of field requirements. To this end, the dipole pole, yoke and coil geometries are fully defined. Thus, while the vendor bears full and clear responsibility for meeting the configuration/dimensional/tolerance requirements for these elements, CEBAF assumes the burden of their resulting field characteristics.

Proposal Evaluation Criteria: In accordance with established CEBAF policy for procurement of expensive, complex devices such as these, proposal evaluation will be based upon three separate factors:

- Technical approach;
- Corporate fiduciary responsibility;
- Price

The technical proposal will be reviewed by a Source Evaluation Board (SEB), consisting of several qualified people selected by us from among our technical and administrative staff.

A preliminary list of technical evaluation factors and percentage weighing of each is given in Table 9.1.

The SEB will score each Technical Proposal according to the factors and weight percentages shown in Table 9-1. This will be done without prior knowledge of the price proposals, so as not to prejudice their judgment.

The Government Auditing Office (GAO) guideline for evaluation of large proposals is 50/50 for technical content/price. However, any proposal can be rejected irrespective of the rating weight factors, if any aspect is non-responsive to the solicitation –or if any aspect is judged to be so weak as to be prejudicial to fulfillment of the contract. For example, if the offerer has no record of successful completion of large, complex superconducting magnet systems, this may be cause for rejection.

If the price difference between one offerer and another is 10% or greater, then the technical evaluation of the higher priced offer must be significantly higher (30% or more) to justify award to him.

Corporate fiduciary responsibility is not a weighted rating factor. However, if a corporation has a record of contract default, cost overruns, poor credit rating or inadequate/insecure financial backing, its proposal may be rejected.

Expenditure Profile: Upon placement of an order, CEBAF and DOE incur an obligation to the vendor for the full contract price (subject of course to fulfillment of the requirements). However, disbursement to the vendor is made incrementally, usually according to an agreed upon progress milestone basis. This translates to a (fiscal) yearly expenditure profile for the contract.

An important point here is that, while a milestone disbursement to the vendor is not anticipated until early in a given fiscal year (say, first quarter of FY91), funds to cover the work in progress up to that point must be committed by the laboratory and DOE during the prior fiscal year, in order that the vendor not be performing "at risk." This is necessary since funds for a given fiscal year are not actually released by Congress until some months into that period.

Table 9-1

Vendor Proposals for HRS Magnets

Technical Proposal Evaluation Factors

- I. Experience and Qualifications of Key Personnel-20%
 - A. Engineering
 - B. Manufacturing
 - C. Project Management
- II. Technical Approach-40%
 - A. Appropriateness for the requirement
 - Performance/geometric constraints/reliability aspects
 - B. Justification of key selected features/aspects
 - Precedent/criteria/explanation
 - C. Thoroughness and clarity of proposal
 - D. Fabrication approach
- III. Relevant Capabilities-30%
 - A. Delivered Superconducting Magnet Systems
 - Number/generic relevance/success
 - B. Completed magnet system design studies
 - C. Engineering Design Staff/facilities
 - Mix of relevant skills available/CAD, analytical tools
 - D. Manufacturing, testing capabilities
 - Floor space, equipment,staff
- IV. Project Management-10%
 - A. Management Plan
 - B. Project schedule/milestones
 - C. Fabrication plan (subcontractors)
 - D. Teaming arrangements (as appropriate)
 - E. Willingness to interact with CEBAF staff
 - F. Documentation and change order control
 - G. QA/QC plan

9.1.3 HRS Support/Positioning System

CEBAF has enlisted the services of a local ship design firm, ROSENBLATT, to develop a Preliminary Design for the HRS support/positioning system, working under the overall direction of our engineering staff. The present status of this design is presented in Section 6 above.

We anticipate that the Preliminary Design package for the support structure, undercarriage, central pivot and azimuthal drive elements will be complete by August 1990. Therefore, we plan to tender a fixed price RFP for final design (manufacturing drawings) and construction of this package, awarding a contract by March 1991. Our overall schedule calls for the HRS electron arm components to be delivered by October 1992, except for the box beam, which is not required until one year later. The hadron arm components, excepting the box beam, are required by March 1993.

Incidentally, CEBAF has acquired ~ 30 tons of mild steel plate (varying in thickness from $3/4"$ to $1\ 1/2"$), surplus from the US Navy. This material will be available for the HRS support structure.

9.2 SPECTROMETER CALIBRATION

9.2.1 Choice of a Calibration Scheme

The spectrometers and their associated detector systems are designed to provide an accurate determination of the individual particle trajectories—momentum, position and angles—at the reaction point. Basically, the requirements are that momenta should be known to $\sim 10^{-4}$ accuracy, horizontal (vertical) angles to $0.1(0.3)\text{mr}$, and the position along the beam direction to $\sim 1\text{mm}$. A plan based on field measurements and operational techniques, using the electron beam, is being developed to ensure that the spectrometers can be tuned and calibrated for experiments according to these requirements. In that “calibration scheme” the following issues are being addressed :

- Determination of the spectrometer optical properties.
- Absolute angular and energy calibrations.
- Operating procedure to set up the magnetic fields and tune the spectrometer to a given energy.
- Online controls of stability and reproducibility of the spectrometer tunings.

The trajectory coordinates at the target are obtained from those measured in the field-free focal plane region using functional expressions (polynomials) representing the transformation accomplished by the spectrometer. In fact, only four target coordinates can be determined that way, namely θ_o, y_o, ϕ_o and δ . The determination of the vertical position x_o would require an additional detector inside the spectrometer line. In practice, the vertical dimension of the beam can be kept small enough ($0.1 - 0.3 \text{ mm}$) that this determination is not necessary.

Two methods can be used to determine the spectrometer transformation functions:

- a) One can determine the *actual magnetic field configuration of the entire spectrometer* by performing field measurements on the various elements, and positioning them precisely on the spectrometer line. Then, trajectories can be computed, and polynomials can be fitted using the procedure described in Section 4.
- b) One can use *empirical methods to define input trajectories* and measure their coordinates in the focal plane region. They include floating wire techniques ^[1], use of the primary beam with the spectrometer at 0° and the use of “sieve slits” ^[2] or “jail bars” ^[3] at the spectrometer entrance to specify scattered electron trajectories.

Our plan includes a combination of both :

- A complete field mapping of the magnetic elements at different excitation values. This is the way to obtain the most detailed information on the spectrometer optical properties. Once the overall field map is known at various mean field values with adequate accuracy, any acceptance, resolution or calibration problem can be studied by computer simulation, including problems involving particle decay inside the spectrometer, scattering on pole pieces or vacuum chamber walls, etc...
- The use of scattered electrons and sieve slit arrangements to improve the calibration of the whole spectrometer and check that the optical properties remain stable.

The floating wire technique ^[4,5] has been used extensively to simulate charge particle trajectories in a magnetic field. Basically, if a thin, flexible, wire of negligible

mass carrying a current i is suspended under a tension T in a magnetic field, it will take a shape corresponding to the trajectory of an electron having momentum such that $p(\text{MeV}/c) = 2.939 \times T(\text{g})/i(\text{Amp})$. Using this technique, magnetic field versus particle momentum calibrations were derived with 2×10^{-4} accuracy (EPICS, LAMPF^[4]; 8 GeV, SLAC^[5]). The results are better at the higher field values, as the wire tension should be large enough (>50 g). Considering the large aperture and length of our devices and the accuracy required ($\sim 10^{-4}$), we think that the floating wire technique may not be the best approach to the determination of the transport coefficients.

The low emittance (2.0×10^{-9} m) and excellent energy definition 10^{-4} of the CEBAF beam makes it appealing to use the direct beam to calibrate the spectrometer, the latter being positioned at 0° . Several problems need to be overcome :

- The minimum beam current that can be reasonably monitored (10 nA) is too large to operate with the standard detector package, so an alternate device has to be designed and cross-calibrated with the focal plane detectors. One can also consider operating with a pulsed beam, but it appears that the minimum burst length which can be achieved ($\sim 100 \mu\text{sec}$) would probably be too large to prevent damage in the chambers.
- To map out the spectrometer acceptance would require some sort of a steering device at the target position. A Helmholtz coil similar to those typically used with polarized targets, producing a 5 Tesla field over 20 cm, may be adequate for this purpose.
- The deflected beam ($\sim 40\text{W}$) has to be dumped.

These problems, while not insurmountable, lead us to consider using the direct beam more as a one time operation rather than the routine way of checking the spectrometer calibration.

More details are given below on our plans concerning field measurements and the use of the sieve-slit method.

9.2.2 Magnetic field measurements

Our plan is to perform detailed magnetic measurements over the whole useful field volume of each of the magnets, for the following reasons:

- Our spectrometers are multi-element systems. One needs to know the actual magnetic properties of each of them to tune the spectrometer in an optimized way.
- Field measurements on the magnets would allow us, if needed, to apply corrections before the spectrometer line is assembled.
- The position and geometry of the baffles along the spectrometer line can be revised.
- Finally, the use of actual field maps as input data for computer simulation of trajectories give a good first approximation, if not the best determination, of the optical properties of the spectrometer.

One has first to select the appropriate measuring technique. In our case, one has to measure large field volumes ($\sim 0.3 \text{ m} \times 1.0 \text{ m} \times 9.0 \text{ m}$ for the dipole, $\sim 0.6 \text{ m diam} \times 4.0 \text{ m}$ for the large quadrupoles) with $\sim 10^{-4}$ accuracy. Similar problems are being encountered in field measurements of the large detectors for high energy physics, and devices using Hall probes in 3D arrangements to measure the three components of the field have been used

successfully. Recent examples include the field measurements of the TOPAZ magnet at the TRISTAN e^+e^- collider of KEK [6] and of the large magnetic detectors for LEP [7] (Figure 9.1). A combination of NMR and 3D Hall probes (Siemens FC33 or SBV579) have been used to map out the useful field volume using a device moving in cylindrical coordinates, all measurements along a diameter being done in parallel. Typical positioning accuracies were ~ 0.2 mm along z , 0.3 mrad in ϕ . An overall accuracy of 10^{-4} in the measurement of $B_\perp/B_z$ has been achieved. For the ALEPH detector magnet, the effective time needed for a full map (~ 900 steps, 75000 measurements) was about 10 hours.

Search coils can also be used to measure the field in 3D, as it was done in the Fermilab ZIPTRACK field mapping device [8], and for the recent measurement of the magnetic field of the CDF magnet [9], in combination with Hall probes and NMR probes.

9.2.2.1 Dipoles

A device similar to the ones described above can be used for measuring our dipoles. A series of 3D hall probes plus a few NMR probes can be mounted on an arm allowing simultaneous measurements along a radius, over the 100 cm useful width. This arm will move on curved rails to measure the field at various positions along the central ray, with large angular intervals in the central region where the field configuration is essentially 2-dimensional. A device allowing measurements in cartesian coordinates XYZ on a finer mesh will be used for the fringe field region. Measurements in the mid-plane, plus 2 or 4 other planes (± 5 cm, ± 10 cm for example) should be sufficient to determine the field over the entire useful volume [10] at several excitation values. Typically, a complete field map (5 planes) at a given excitation may include $\approx 30,000$ measurement points. Five to ten values of the central field should suffice to determine the field configuration at any given excitation.

In addition, a measurement of the integrated dipole strength, at least in the entrance and exit regions, and possibly over the full length of the magnet will be performed at various field excitations using a long rotating coil.

9.2.2.2 Quadrupoles

For our $\cos 2\theta$ quadrupoles, one can also think of using similar devices operating in cylindrical coordinates. Indeed, in July 1988, we made some field measurements on one of the LEP $\cos 2\theta$ quadrupoles using an XYZ field mapping system to move 3 Hall probes in a 3D arrangement [11]. Although the measured volume was small compared to Hall A quadrupoles, the field gradient (22 T/m) was much higher, increasing the sensitivity to positioning errors. Nevertheless, the overall accuracy in the determination on each of the 3 components was ≈ 2.5 gauss. The field configuration is better determined when the measurements are done at the outer radius where the field is the largest.

More global information on the field configuration of the quadrupoles can be obtained through harmonic analysis of the signal generated by rotating wire loops around the quadrupole axis. This method is the most widely used in superconducting, current-dominated accelerator magnets. A large variety of coil geometries for harmonic measurements have been used [12,13] (see figure 9.2). In this class of SC magnets, the typical requirements for field measurement accuracies are 10^{-4} (5×10^{-4}) for dipole (quadrupole) integrated strength, ≤ 0.5 mrad midplane angular definition, and 0.1 mm accuracy in the

determination of the quadrupole axis^[12] and these requirements can be met by rotating coil techniques. The fringe field regions, which are small compared to the central one in the above examples, are treated separately.

However, several important differences make a rotating coil approach less appropriate in our case. First, the apertures of our quads are very large, and trajectories deviate substantially from the paraxial approximation. Second, fringe field regions contribute about as much to the integrated quadrupole strength as the 2-dimensional central region. Our plans include the use of a rotating coil to determine the overall effective length of the various multipole components and to perform a detailed field harmonics analysis in the central region. It will be used also to define the optical axis (≤ 0.1 mm should be achievable^[14]). Discrete point measurements will be performed over the whole useful volume in cylindrical coordinates for use in raytracing computer codes. Making measurements along a diameter at once using a multiprobe system (15-20 3D probes) would allow us to measure a complete 30,000 points map with 1500-2000 steps. The operation will be repeated at several (≈ 5) field values to control the effect of the iron shield.

Additional measurements may have to be performed in regions where fringe fields from two neighbouring magnets overlap, like between Q1 and Q2, or the dipole and Q3. Field calculations using TOSCA will be used to define the best strategy to approach this problem.

9.2.3 On-line controls

9.2.3.1 Sieve slit technique

A convenient method for calibrating and optimizing the transport coefficients of a spectrometer is to use a specially designed solid angle defining slit arrangement, often called a "sieve slit". It consists of an array of small holes which define pencil beams over the acceptance of the spectrometer. By considering elastically scattered electrons from a monoenergetic beam hitting a thin target, one has a way of limiting the phase space extension in all target coordinates for each individual pencil beam. Its centroid can be considered as a single trajectory. This method has been successfully utilized in the QDD and QDQ spectrometers at NIKHEF-K^[2].

A conceptual design of the sieve slit to be used in the HRS is shown in figure 9.3a. It is made up of 3 cm thick stainless steel plate with an array of solid angle defining circular holes of 5 mm diameter. Scattered electrons hitting the plate will lose approximately 36 MeV and will therefore be well separated from those elastically scattered through the holes in the energy range we are considering (0.5 GeV to 4 GeV). The sieve slit arrangement is placed 1m from the target, in front of the first spectrometer quadrupole. The array of holes covers slightly more than the defined solid angle of the aperture of the spectrometer ($\Delta\phi = 60$ mr, $\Delta\theta = 130$ mr). The latter is indicated by the dotted lines in the figure. Each hole subtends 0.02 msr solid angle. The holes have to be drilled with an oblique axis aligned with the target. Their width of 5mr results from a compromise between sufficient counting rate in an elastic peak and the resolution goal of <0.5 mr in defining the centroid. A conceptual layout of the sieve slit arrangement with respect to the beam and the spectrometer is shown in figure 9.3b.

Figure 9.1a Field mapping device for ALEPH and DELPHI magnets.

Figure 9.1b Hall probe module for the ALEPH/DELPHI mapping system.

Quadrupole Search Coil Configurations

(a)

(b)

SEXTUPOLE COIL

(c)

Figure 9.2 Various loop geometries for rotating coil measurements.

- (a) quadrupole search-coil array (Green et al., ref. 10)
- (b) rotating coil for LEP quadrupoles
- (c) Morgan-type sextupole coil (ref. 10)

Figure 9.3a Sieve-like solid angle defining slit.

Figure 9.3b Schematic layout of the sieve slit arrangement.

Table 9-2 shows the expected count rates through a selected single hole of the slit if one uses a 100 mg ^{12}C target with a 50 μA beam on it, the spectrometer being placed at 13 degrees. The acceptance of the slit subtends nearly 5 degrees. We see that at some energies the rates vary by about a factor of 10 in going from 10.5 degrees to 15.5 degrees. Above 2.5 GeV, the rates become too low to be practical. We could then use hydrogen instead of carbon as a target. Table 9-3 shows the rates one obtains with a 5 μA beam on a 50 mg CH_2 target at the higher energies.

Additional angular positions of the holes can be obtained by sliding the slit both horizontally and vertically. In so doing, high order terms in the polynomial expansions of the trajectory coordinates can be fitted. Moving the slit ± 7.5 mm horizontally (± 10 mm vertically) does not introduce significant parallax errors.

A complete simulation of the use of a sieve slit to determine the spectrometer optical properties is underway [15].

The sieve slit will be located inside the spectrometer vacuum chamber with a mechanism to remotely control its positioning. The same mechanism will be used to insert solid angle defining collimators.

The sieve slit measurements described above are performed with thin targets. Other devices have to be designed – including various target geometries – to measure the y -dependent terms. For example, one can imagine a target consisting of vertical wires, ~ 0.5 mm diameter thick, spanning 10–15 cm along the beam to study the reconstruction of the y_0 coordinate, and the variation of solid angle and momentum acceptance when the reaction point is moved along the beam.

9.2.3.2 Absolute calibrations

The procedure to determine the angular position of the spectrometer with respect to the beam to $\approx 0.1\text{mrad}$ accuracy is described in Section 6.2.

The absolute energy calibration is more difficult to achieve. In principle, from field measurements performed with $\approx 10^{-4}$ accuracy and a probe positioning error not greater than ≈ 0.3 mm, one could achieve $2\text{--}3 \times 10^{-4}$ accuracy in the determination of $\int B \cdot dl$ and thus the absolute momentum. By sending the direct beam through the dipole, or using electrons scattered at small angle from a thin target of a heavy element through a small aperture collimator, one should be able to determine the beam energy to about 3×10^{-4} accuracy. To achieve this, the position of the dipole needs to be known to $\approx 0.3\text{mm}$. A 1mm vertical displacement of the dipole would result in a 4.4×10^{-4} error coming from the slanted pole faces (2.9×10^{-4}) and from the index (1.5×10^{-4}).

Several methods are being examined in order to achieve 10^{-4} accuracy. They include the use of a small gap, uniform field, $\approx 20^\circ$ bending dipole (which can be one element of the out-of-plane beam line discussed in section 3.4) or a measurement inside the beam handling line to the End Station. As discussed in section 8.2, the use of the angular and energy dependence of the synchrotron radiation intensity distribution in the direction perpendicular to the orbit plane is being considered as a possible way of achieving $\sim 10^{-4}$ accuracy.

Table 9-2
Rates for ^{12}C Elastic Scattering

e_0 GeV	e_f GeV	θ_e deg	Rate sec^{-1}	Time for 100 counts hours
0.5	0.500	10.5	0.20×10^6	1.4×10^{-7}
	0.499	13.0	0.70×10^5	4.0×10^{-7}
	0.499	15.5	0.21×10^5	1.3×10^{-6}
1.0	0.999	10.5	0.11×10^5	2.5×10^{-6}
	0.998	13.0	0.18×10^4	1.5×10^{-5}
	0.997	15.5	0.35×10^3	7.9×10^{-5}
1.5	1.497	10.5	0.48×10^3	5.8×10^{-5}
	1.495	13.0	0.31×10^1	9.0×10^{-3}
	1.493	15.5	0.23×10^1	1.2×10^{-2}
2.0	1.994	10.5	0.21×10^1	1.3×10^{-2}
	1.991	13.0	0.26×10^1	1.1×10^{-2}
	1.987	15.5	0.26	1.1×10^{-1}
2.5	2.491	10.5	0.40×10^1	6.9×10^{-3}
	2.486	13.0	0.17	1.6×10^{-1}
	2.480	15.5	0.22×10^{-2}	13

Table 9-3
Rates for ^1H Elastic Scattering

e_0 GeV	e_f GeV	θ_e deg	Rate sec^{-1}	Time for 100 counts hours
2.667	2.546	10.5	12	2.3×10^{-3}
	2.486	13.0	3.5	7.9×10^{-3}
	2.417	15.5	1.2	2.3×10^{-2}
3.244	3.066	10.5	5.9	4.7×10^{-3}
	2.980	13.0	1.6	1.7×10^{-2}
	2.882	15.5	0.51	5.4×10^{-2}
4.000	3.733	10.5	2.5	1.1×10^{-2}
	3.606	13.0	0.62	4.5×10^{-2}
	3.463	15.5	0.17	1.6×10^{-1}

9.2.3.3 Field setting procedures and on-line controls

When using iron-dominated magnets, one has to worry about the reproducibility of the field configuration when the excitation is varied. Hysteresis in the core material causes the magnet to remember where it has been in excitation. Procedures have to be defined to ensure repeatability of the field configuration. The most commonly used procedures imply driving the magnet to full saturation. We expect this problem to be much less important for the quadrupoles which are mainly current-dominated.

We plan to install a few NMR probes equipped with gradient-correcting quadrupoles at various locations within the dipole to control the reproducibility of the field configuration. One of them will be used as a reference to stabilize the field. The field setting procedures will be determined at the time the field measurements will be performed. The long coil integral measurements can be used for quick reproducibility checks.

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9.3 HALL A EQUIPMENT COMMISSIONING SCENARIO

This is a first attempt to develop a scenario for the commissioning of the Hall A experimental equipment. This document is preliminary in that we expect it to evolve depending on delivery dates for equipment and beam availability as well as changing physics priorities. However, the need for such a plan at this time is clearly evident. At the end of this commissioning phase the equipment will be fully operational. Facility development will be interleaved with the start of the experimental program. We plan to take an incremental approach to developing system capability and achieving the desired resolution and accuracy goals. This phase will end when the entire initial complement of equipment has been installed and is fully operational and we are able to perform all the collaboration experiments approved by PAC4.

Any commissioning scheme depends on the achievement of certain project milestones (hall completion, etc.) and on assumptions on delivery of experimental equipment and available beam time. We have made the following assumptions in developing this scenario:

- 1) Beam available in Hall A by $\sim$ Spring 1994.
- 2) Completion of HRS1 and equipment package by $\sim$ Fall 1994.
- 3) Cryogenic target available by early 1995.
- 4) Completion of HRS2 and equipment package by $\sim$ Spring 1995.
- 5) Commencement of polarization physics studies by $\sim$ Fall 1995.
(Requires operational recoil polarimeter, polarized beam and beam polarimeter.)
- 6) High power refrigerator available by $\sim$ Spring 1996.

These assumptions imply that certain functionality will exist at specified times. We will attempt to amplify these needs in the following discussion. The goals of the commissioning phase are to instrument and calibrate the initial equipment and to produce publishable results and Ph.D. theses. The Hall A collaboration will be responsible for commissioning the hall and for performing the initial round of experiments. The commissioning phase is divided into four intervals, designated as Phases 1-4. Our commissioning approach is incremental in the sense that greater accuracy and functionality is assumed for successive phases. The commissioning period will require approximately 2 years to complete and will be followed by the completion of the first set of approved experiments which may take an additional one to two years to complete.

Below is a description of the goals and assumed functionality for each phase. We also indicate some suggested experiments which could be performed given the assumed functionality. Estimates of the beam time needed to complete each phase are given in

the Table 9-4. This time estimate is primarily for facility development especially in the early phases and includes some time for running initial experiments. A time-line for the commissioning phase is shown in Figure 9.4.

9.3.1 Phase 1

Phase 1 consists of the period of time between beam availability and completion of the first spectrometer. Completion means that all the magnetic elements have been field mapped, installed and aligned and that the initial detector package is in place. In addition, we assume the data acquisition system has been tested off-line and is reliable. During this phase we can use limited beam time for beam-line studies. We assume that the beam dump has been installed and is operational and that the beam can be satisfactorily steered through the hall and that the necessary beam-line monitors have been installed. We are primarily interested in studying the beam profile, current and initial energy calibration (*i.e.* the absolute value and time dependence of the beam energy) during this time. The requirements on the beam energy imply the need for position monitors with excellent spatial resolution. One possibility would be to place these monitors at a point of high dispersion in the beam line where they would define the entrance and exit trajectories of the beam at an energy defining dipole. This magnet must be precisely mapped if one is to be able to determine the energy at the 10^{-4} level as required by the general experimental program. The dipoles for both spectrometers should be mounted on their carriages at this time and with some minimal instrumentation could be used to verify the calibration of the beam energy. Our initial goal is to determine the instantaneous beam centroid to approximately $2-3 \times 10^{-4}$. This will be particularly important in the early stage of beam operation where beam stability may be questionable. To accomplish this a number of short evening or weekend runs will be necessary and will be scheduled to have minimal impact on ongoing construction in the hall.

9.3.2 Phase 2

Phase 2 will involve measurements with a single instrumented spectrometer with an initial goal of performing single arm measurements to 3% accuracy and achieving a momentum resolution of $\sim 2-3 \times 10^{-4}$ or at the beam resolution limit. Our plans for the detector package is to assemble it in its final configuration and to thoroughly test it with cosmic rays prior to installation. The first step will be to perform initial optics studies using solid targets. This should not take much time since the field mapping of the spectrometer should give the matrix elements at this level. In addition to the optics study, detector response will be examined and relative efficiency maps will be undertaken. We expect to achieve absolute efficiencies at the 3% level by measuring elastic scattering. Given a relatively mature data acquisition code this phase should not take more than 1-2 weeks. Once the basic performance of the spectrometer has been established, extended target optics studies will be undertaken. We also plan to make a number of measurements using solid targets including single-arm scattering to discrete states as well as quasielastic measurements. Finally, we plan to undertake background studies of (e,x) yields as a function of energy and angle. These latter measurements will serve as input for estimating accidentals for coincidence measurements and may be

publishable. If sufficient accuracy can be achieved, a longitudinal/transverse separation of quasielastic (e, e') data could be undertaken on several targets.

9.3.3 Phase 3

Phase 3 involves commissioning of the second spectrometer and the beginning of coincidence data taking. Since the two spectrometers are identical we believe the commissioning of the second spectrometer will proceed relatively quickly and the main effort will consist of determining the coincidence efficiency of the spectrometer pair. Again the initial goal for coincidence measurements will be to reach a modest initial accuracy of 3-5% in the cross section. This will be sufficient for cross section and angular distribution measurements not involving separations. Initial measurements will be made with solid targets. A rotating CH_2 target will be used for normalization purposes. During this time we also plan to begin coincidence measurements with extended targets. The target cells are being designed to withstand ~ 1 KWatt power dissipation but will initially be used with a refrigerator of moderate cooling capacity ($\sim 100 - 300$ W). Angular distribution measurements will be undertaken on $\text{D}(e, e'p)$. Since it takes so little time to acquire data at the top of the quasielastic peak, test runs will also be undertaken to determine the accuracy of coincidence Rosenbluth separations. This will be done primarily with CH_2 and hydrogen gas targets for calibration purposes. We may also include a few initial measurements on higher mass targets. Low resolution ($\delta\epsilon_m \sim 2$ MeV) survey measurements of the $(e, e'p)$ continuum response in the dip, Δ and negative y regions may also begin at this time. During this period the neutron detector for the G_E^n experiment will be installed in the hall and parasitic studies using the FPP will be undertaken.

9.3.4 Phase 4

Phase 4 involves the commissioning of the FPP and the beginning of polarized beam measurements. This phase ends when the high power refrigerator becomes available thus completing the initial complement of equipment. The FPP will be calibrated using the $\text{H}(\vec{e}, e'\vec{p})$ reaction. Initial measurements with the FPP will involve spin-orbit reaction studies on ^{16}O . Measurements of nucleon form factors will also be undertaken using the $\text{H}(\vec{e}, e'\vec{p})$ and the $\text{D}(\vec{e}, e'\vec{n})p$ reactions. Completion of these measurements will require the high power refrigerator. During this period we will attempt to improve our understanding of systematic errors and beam optics. By the end of this period we should be able to undertake measurements at the less than 2% level and achieve momentum resolution at the 10^{-4} level.

9.3.5 Initial Collaboration Experiments

The end of the commissioning phase will be followed by running the approved Hall A collaboration experiments. It is premature to prioritize these experiments at this time. As noted earlier, these experiments will have already been started during the commissioning phase and may lead to Ph.D. theses and publications. Some of the experiments proposed for Hall A require high resolution and/or accuracy and studies undertaken in the commissioning phase will greatly facilitate the performance of those experiments.

Table 9-4
Beam Time Estimates

Phase	Time (hours)
1	200
2	750
3	1000
4	1500
Total	3450

Figure 9.4

Figure 9.4 Timeline for Hall A Commissioning Phase

10. COSTS, MANPOWER AND SCHEDULE

10.1 COSTS

The overall cost estimate for the Hall A equipment (WBS 6.5) is shown in Table 10-1. As indicated, the cost elements are grouped into six WBS categories:

- 6.5.1 Electron HRS Arm
- 6.5.2 Hadron HRS Arm } Combined in Summary Table
- 6.5.3 Beam Line Equipment
- 6.5.4 Hall A General Equipment
- 6.5.5 Counting House Equipment
- 6.5.6 Magnetic Measurement

Notice that each element total includes equipment and installation costs. Backup data is included below for most WBS Level 5 element equipment costs. This cost data has come from many sources, including CEBAF internal, manufacturer budgetary quotes and Hall A user/collaboration input. In most cases, the cost source is indicated on the data sheet.

Quadrupoles: Our internal cost estimate (Table 10.1, Item B) for industrial fixed price procurement of the four large quadrupoles ($2 \times Q2/Q3$) is \$4.0M. Under contract to CEBAF, Interatom recently performed a budgetary fixed price cost estimate totalling \$4.25M for the four large quads, while a second estimate of \$6.8M was obtained from IGC. Hence, \$4.25M is shown in Table 10-1 as the baseline estimate for industrial fixed price procurement of the four large quads. We extrapolated the Interatom plus our internal cost data to include the two smaller Q1's, for a total fixed price industrial cost of \$6.0M, to cover $2 \times (Q1+Q2+Q3)$.

As noted elsewhere, our intention is to negotiate a collaborative agreement with SACLAY for these magnets.

Dipoles: CEBAF intends to let a fixed price contract for industrial procurement of the two dipoles for Hall A. Three options will be allowed in the Request for Proposal:

- A. the entire job, wherein a single prime contractor provides design, fabrication, installation within Hall A, and acceptance testing using our cryogenic facilities;
- B. the coil/cryostat only;
- C. the iron only (machined yoke and pole pairs, pre-assembled at the vendor's plant).

Depending upon the price difference between the RFP responses for option A and the sum of B + C, CEBAF may elect to perform the role of system integration, including installation and testing within Hall A.

The \$7.3M dipole equipment cost shown in Table 10-1 reflects the B + C + CEBAF option. The separate B + C industrial procurement price estimates are summarized on page A10-4. The CEBAF estimate for option A, single vendor "turnkey" procurement is \$8.3M, as shown on page A10-5. The indicated iron yoke/pole material/machining costs are based upon budgetary guidance provided by several manufacturers, including Westinghouse, Japan Steel, Nippon Steel and Thyssen.

Other Cost Elements: Backup data for major cost elements D through Y is given in the accompanying tables.

Table 10.1							
Cost Estimate - Summary							
WBS 6.5: Hall A Equipment							
Two 4 GeV/c Superconducting HRS (without CEBAF contingency)							
WBS 6.5.			Item		Equip.	Instl.	Σ
Item	Elect.	Had.	No.	Two HRS Arms	\$K	\$K	\$K
A	1.2	2.2	2	Quad Q1: Cosine 2θ	1750	20	1770
B	1.3	2.3	4	Quad Q2-Q3: Cosine 2θ	4250	70	4320
C	1.1	2.1	2	Dipole, 45° , Focussing	7300	160	7460
D	1.4	2.4	2	Support/Positioning	3400	150	3550
E	1.5	2.5		Vacuum System	270	20	290
F	1.6	2.6		Cryogenics	203	50	253
G	1.7	2.7		Power Supplies	486	25	511
H	1.8	2.8	2	Detector Shielding	560	-	560
	1.9	2.9		Detector:			
I	1.9.1	2.9.1	2	Mechanical	530	50	580
J	1.9.2	2.9.2	2	Electronic	1330	-	1330
K		2.9.3	1	Focal Plane Polarim.	460	-	460
				HRS Total	20,539	545	21,084
	6.5.3.-		Beam Line Equipment				
L		.1		Vacuum System	37	15	52
M		.2		Beam Dump	80	20	100
N		.3		Target Chamber	230	-	270
O		.4		High Power Cryotarget - Phase I	250	-	250
P		.5		Instrumentation (WBS 2)	-	-	-
Q		.6		Beam Polarimeter	130	-	130
				Total	727	35	762
	6.5.4 -		Hall A General Equipment				
R		.1		Floor Plates	465	-	465
S		.2		Central Pivot	110	25	135
T		.3		Electrical Equipment	200	-	200
U		.4		Platforms	40	25	65
V		.5		Utility Cables	188	50	238
W		.6		Detector Cables	200	30	230
X		.7		Instrumentation & Controls	295	-	295
				Total	1498	130	1628
Y	6.5.5		Counting House Equipment		450	-	450
Z	6.5.6		Magnetic Measurement		270	-	270
				Hall A Basic	23,484	710	24,194
Less Anticipated Foreign Contribution							4000
Total							20,194

Hall A Equipment Cost							
Item B							
Quadrupoles Q2/Q3							
Fixed Price Industrial Procurement For Four							
Item	Activity	Rate \$/hr.	Each		Four		
			Man-hrs.	\$K	Duration (months)	Man-hrs.	\$K
A	Labor:	85			42	1646	140
B	•Project Mgmt.	65			12	4308	280
C	•Eng. Design	50			4	1280	64
D	•Facility Prep.	55	1414	79			
E	•Coil Wind	58	1213	70			
F	•Assembly	60	262	16			
G	•QA/QC	65	440	29			
	•Test		3329	194		13,316	776
	Subcontract:					20,550	1260
H	•Conductor			30			
I	•Bore tube/helium vessel			15			
J	•Stainless Steel Staves			62			
K	•Aluminum Shrink Rings (incl. instl.)			28			
L	•Heat Shield			16			
M	•Vacuum Vessel			24			
N	•Cold-to-Warm Supports, 8			36			
O	•Multipole Coil Fabrication (320 man-hrs.)			20			
P	•Iron: 23 KLB @ \$1.20/lb.			28			
				259			1036
	Materials & Services:						
Q	•Coil Insulation, Spacer Blocks			40			
R	•Cryogenic Components			5			
S	•Current Leads; Misc.			15			
T	•Correction Coil: Tube, Cond.			15			
U	•Instrumentation			25			
V	•Shipping			10			
				110			440
			Recurring Cost:	(563)			
W	•Tooling for Winding, Assembly						200
X	•Travel						20
	Base Cost for Four Magnets:						2956
Y	•Contingency: Labour; \$1,260 @ 30%						378
	Subcontract, M&S; \$1696 @ 20 %						339
Z	•Profit @ 10%						367
	Internal Estimate for Four:						4040
Budgetary Fixed Price Industrial Cost Estimate For							
Four Q2/Q3 Type Quads, Per Iteratom: \$4,250 K							

Hall A Equipment Cost Focussing Dipole

Separate fixed price industrial procurement of iron and coil/cryostat:
CEBAF performs system integration, including installation and acceptance testing.

Iron

	<u>One (\$ K)</u>	<u>Two (\$ K)</u>	
Project Management, Admin		100	
Design, Manufacturing Eng'g		150	
Yoke: 800 KLB	1200		
-Composite MFR Estimate			
Pole Pair: 30KLB	275		
-Conical Faces, Contoured Ends			
-Industrial Estimate			
Misc (Bolts, Dowels, Spacers)	50		
Contractor Preassembly			
-3 Mo x 5 FTE @ \$ 50/hr + \$18K M & S	150		
Shipping	<u>25</u>		
	1700	<u>3400</u>	
		3650	
Manufacturer's Contingency @ 15%		550	
Profit @ 10%		<u>420</u>	
		4620	
		USE	\$4600

Coil/Cryostat

	<u>One (\$ K)</u>	<u>Two (\$ K)</u>	
Project Management, Admin		195	
Design, Manufacturing Engineering		300	
Tooling/Facility preparation		65	
Conductor	53		
Coil Winding	104		
Cryostat Components	332		
Coil/Cryostat Assembly	165		
Contractor Cold Tests	50		
Shipping	<u>20</u>		
	724	<u>1448</u>	
		2008	
Manufacturers Contingency @ 20%		402	
Profit @ 10%		<u>240</u>	
		2650	
		USE	<u>\$2700</u>
Industrial Procurement Total			<u>\$7300</u>

**Hall A Equipment Cost
Item C
Focussing Dipole
Single Vendor Procurement**

Item	Activity	One \$K	Two \$K
A	Project Management		405
B	Engineering Design		450
C	Conductor	53	106
D	Tooling/Facility Prep.		65
E	Coil Winding	104	208
F	Helium Vessel	150	300
G	Vacuum Vessel	80	160
H	Cryostat Components	102	204
I	Coil/Cryostat Assembly, Test	216	432
J	Iron	1,675	3,350
K	Power Supply, Controls (included separately)		
L	Vacuum Pumping System (included separately)		
M	Beam Vacuum Chamber (included separately)		
N	Shipping	65	130
O	Installation at CEBAF	188	376
P	Acceptance Tests	66	132
Q	Engineering Estimate		6318
	Contingency @20%		1264
R	Profit @10%		758
			\$8,340K
CEBAF estimate for fixed price industrial procurement of two complete dipole systems, installed and acceptance tested within Hall A by contractor			\$8.30M

Hall A Equipment Cost
Item D
HRS Support/Positioning System

WBS 6.5.1.4/2.4

Structure (Steel Fabrication)	Unit Cost \$/LB	One KLB	One \$K	Two \$K
• Box Beam	1.15*	100	115	
• Dipole Support Brackets	2.15	60	129	
• Cradle, Link	1.65	130	215	
• Gantry	1.15*	<u>140</u>	<u>161</u>	
* Rosenblatt Guidance 4-90: Material available surplus to CEBAF		430	620	1240
Suspension/Positioning (Rosenblatt Input)			One \$K	
• Bogies, four wheeled, 250 ton rating; est. per NEPCO, std wheels: \$50K each. CEBAF est, custom tapered wheels: \$60K each × 10 bogies			600	
• Azimuthal Drive: six units: (\$10K each) American Bearing & Power Transmission Quote To Rosenblatt for 3225/14 cyclo reducer + 5hp motor			60	
• Hydraulic Jacks - 3 × 500T cap'y each, simplex double acting 3 @ \$20K each			60	
- Power unit, 20 hp, 5 Kpsi, 156 pm			3	
• Mechanical Jacks: Duff-Norton, 250 ton Cap'Y, 2" travel: four @ #36.5K			146	
- Drive system, est			25	
• Central bearing: six foot inside diameter; Roller bearing, torrington: Rosenblatt est.			76	
• Quadrupole mounting features: six @ \$2K (CEBAF est)			12	
• Quadrupole carriage			30	
• Detector mounting features			<u>5</u>	
			1017	2034
Alignment System (per Rick Johnson, 4/4/90)				
• Lasers, sensors, receivers		30		
• Rotary tables, platform		34		
• Inclometers, rangefinders, interferometer		36		
• Control electronics		25		
				<u>125</u>
				<u>\$3400</u>

**Hall A Equipment Cost
Item E
HRS Vacuum System
WBS 6.5.1.5 and 6.5.2.5**

Cost Estimate Originator: Steve Lassiter
Ref. Dwg. (Accompanying Schematic)

	One	Two
<u>Beam line system per HRS:</u>		
Turbo pumping station, with backing pump		
Two @ \$28.5K each*	57.0	
Stainless steel tube, flanges	1.0	
Stainless steel bellows	5.8	
10" gate valve	4.6	
Vacuum box (75"x24"x95")	5.0	
Vacuum housing:Q3 to window	5.0	
Gauges, monitors	3.0	
Miscl. hardware & accessories	<u>10.0</u>	
	95	190
<u>Magnet Vacuum Station:</u>		80
Common for all HRS magnets		—
		\$270K

*Backup Cost Sheets Available

Hall A Equipment Cost
Item F
WBS 6.5.1.6/2.6
Hall A Cryodistribution Materials

Box #1

Item	Name	Unit Cost \$K	Qty.	Cost \$K
1	Bayonet	0.75	9	6.8
2	Valve	3.00	9	27.0
3	Pipe	0.01	100	1.3
4	Steel	1.00	6.5	6.5
5	Misc.	8.69	1	8.7
				48.3

Box #2

Item	Name	Unit Cost \$K	Qty.	Cost \$K
1	Bayonet	0.75	6	4.5
2	Pipe	0.01	50	0.6
3	Steel	1.00	4.5	4.5
4	Misc.	0.96	1	1.0
				10.6

Box #3

Item	Name	Unit Cost \$K	Qty.	Cost \$K
1	Bayonet	0.75	6	4.5
2	Pipe	0.01	30	0.4
3	Steel	1.00	4.5	4.5
4	Misc.	0.94	1	0.9
				10.3

Hall A Cryo-System

Item	Name	Unit Cost \$K	Qty.	Cost \$K
1	Box #1	48.25	1	48.3
2	Box #2	10.59	2	21.2
3	Box #3	10.31	2	20.6
4	ESR-B1	1.50	0.2	0.3
5	B2-B3	1.50	0.2	0.3
6	20-FLEX	5.00	6	30.00
7	6-FLEX	3.00	24	72.0
8	MISC.	10.23	1	10.2
			Total	202.9

**Hall A Equipment Cost
Item G
Power Supplies
WBS 6.5.1.7/2.7**

Description	Qty.	Unit \$	Total \$
Power Supplies*		.	
10VDC, 2000A or 2500A, .001%	8	45,000	360,000
AC Cable (480V)	#8 AWG 5000ft.	.35/ft.	1,750
Panelboard**	1	2,250	2,250
Cable Tray	156 ft.	150/12 ft.	1,950
Misc. (supports, nut & bolts, etc...)			2,000
DC Bus Duct			
2500A	400 ft.	255/ft.	102,000
Duct Fittings	8 sets	792/set	6,336
Labor***	300 hrs.	29.40/hr.	8,820
		Total	\$485,106

*Price estimate based on average of budgetary quotes from several vendors which included:

Power Energy Industries
Alpha Scientific
Dynapower Corporation
Inverpower Controls Ltd.
GMW Associates

**(400A w/main breaker 480V 3P3W 36 cir.)

***Current CEBAF contract labor rates.

Hall A Equipment Cost
Item H
Detector Shield House
WBS 6.5.1.8/2.8

	Rate \$/lb.	KLB	One \$K	Two \$K
<u>Steel Housing:</u>				
• Material: Mild STL Plate*	0.50	200	(100)	
• Fabrication:	0.30		60	
• Installation:	0.10		20	
<u>Concrete:</u>	0.05	820	40	
• Density: 150 LB/FT ³ (4 KBL/YD ³)				
• Unit cost: \$200/YD ³ installed				
- Per Matherny via Tilles (1/4 × cost/lb. of FeO mortar)				
<u>Lead Lining:</u>	0.25	400	110	
<u>Boron Lining:</u>		30	30	
<u>Door Mechanism:</u>			20	
		<u>1,450</u>	<u>280</u>	<u>560</u>

*Steel plate available as government surplus (NAS Norfolk)

Hall A Equipment Cost Detectors

Cost Source: Mike Finn (Wm & Mary), W. Bertozzi (MIT/Bates)

	Hadron WBS 6.5.1.9	Electron WBS 6.5.2.9	Total
DETECTORS - MECHANICAL: ITEM I	WBS 6.5.1.9.1	WBS 6.5.2.9.1	
Focal plane VDC's 2 XY planes	150	150	
Support structure	75	75	
Gas supply system	25	25	
Vacuum windows	<u>15</u>	<u>15</u>	
SUBTOTAL	265	265	530
DETECTORS - ELECTRICAL: ITEM J	WBS 6.5.1.9.2	WBS 6.5.2.9.2	
Focal plane detector readout	240	240	
3-plane scintillator stack	98	33	
CO ₂ Cerenkov	50	50	
Silica aerogel Cerenkov	100	100	
Trigger electronics	120	120	
Shower counters		50	
H.V. distribution	30	30	
Cables and connectors	25	25	
System calibration laser	<u>10</u>	<u>10</u>	
SUBTOTAL	673	658	1331
FOCAL PLANE POLARIMETER: ITEM K	WBS 6.5.1.9.3		
Carbon analyzer	46		
Wire chambers 4 XY planes	135		
Wire chamber electronics	161		
2 nd level trigger logic	80		
Miscellaneous (H.V., gas system, etc.)	<u>38</u>		
SUBTOTAL	460		<u>460</u>
			2,320

Hall A Equipment Cost
Item L
 Beam Line Vacuum System
WBS 6.5.3.1

Cost Estimate Per Steve Lassiter
 Ref. Dwg. (Accompanying Schematic)

Purchased Items:	
•Incoming beam line:*	
-2" gate valve, bellows, flanges, pipes, turbo pumping station	21
•Turbo pumping station for target chamber*	13
•Helium gas bag for beam dump line	3
	<hr/>
	\$37K

* Backup cost sheets available

Hall A Equipment Cost
Item N
Target Chamber
WBS 6.5.3.3

Budgetary Cost Data Provided By Erich Feldl, 8-21-89

Engineering (costed separately)	(\$50K)
<u>Vacuum Chamber</u>	180
-30"-40" diameter, aluminum	
-Double sliding seal:	
elastomer	
<u>Pumping, Gauging</u>	(30)
- costed under Item L:	
beam line vacuum	
<u>Target Mechanism/Air Lock</u>	35
<u>Base</u>	5
<u>AFI</u>	<u>10</u>
	<u>\$230K</u>

Hall A Equipment Cost
Item O
High Power Cryotarget
WBS 6.5.3.4

Cost Source: John Mark (SLAC), via Dimitri Margaziotis (Cal State - LA)

Target design/fab/test	127
Control systems	80
Detection/warning/position devices	96
Vacuum tank/scattering chamber	68
Fans	46
Vacuum/gas piping	40
Transfer lines/shields	37
Schematics	33
Heat exchanger	21
Assembly	30
AFI	22
	\$600K

Phase I (\$250K) includes overall design and construction of the target loop and heat exchanger and procurement of some long lead items.

**Hall A Equipment Cost
Item R
Floor Plates, Installation
WBS 6.5.4.1**

Estimate Source: Rosenblatt (Swink, Hellier)

CEBAF Drawing Reference

Plate Material Data:

Track No.	<u>1</u>	<u>2</u>	<u>3</u>	Σ
Radius (FT)	28	58	82	
Circumference (FT)	176	365	515	1056'
Plate: ASTM A-572, 6R 50 (50 Kpsi yield)				
2 1/4" thick $\times$ 20" wide				
weight (KLB)	53.8	111.6	157.4	322.8 KLB
Purchase weight: finished weight $\times$ 1.56				504.3 KLB
55 $\times$ 20' LG $\times$ 5' W $\times$ 2.25" thick				

Cost Data: **\$K**

Plate: 504.3 KLB @ \$280/KLB	141
Vendor quote 4/2/90, via Rosenblatt	
Flame cut plate (vendor plant)	50
Plate installation hardware	30
Plate paint	10
Leveling jacks on 24" centers	15
Plate shipment	28
323 KLB $\times$ 250 miles @ \$85/KLB	
per Rosenblatt, 4/3/90	
Installation:	
Install plate: 4 men plus crane for 5 wks.:	60
\$300/hr. $\times$ 5 $\times$ 40 hrs.	
Plate leveling: 6 men for 3 wks.	36
Grout	35
Concrete: 4" over entire hall, 24K FT ²	<u>60</u>
8 KFT ³ /27 $\simeq$ 300 yd ³ @ \$200/yd ³	\$465K

**Hall A Equipment Cost
Item V
Instrumentation and Control Cables
WBS 6.5.4.5**

Item Description	Qty.	Unit Cost	Total
Cabling (500 ft. per run)			
Coax (20 runs)	10000	\$2.15	\$21,500
Control (20 runs)	10000	\$8.00	\$80,000
Twisted Pair (60 runs)	30000	\$1.00	\$30,000
Tray (2 trays)	2400	\$15.00	\$36,000
(2 complete runs from counting house plus runs internal to the hall.)			
Flexible cable track	1	\$15,000	\$15,000
(For spectrometer pivot area)			
Cable connectors			<u>\$5,000</u>
		Total	\$187,000

**Hall A Equipment Cost
Item X
Instrumentation & Controls**

WBS 6.5.4.7

Item Description	Qty.	Unit \$		Total
Control Computers				\$118,250
(All equipment is Hewlett Packard for compatability with accelerator controls.)				
Hardware				
Local Computer	2	\$12,500	\$25,000	
Disc Drive	2	\$7,500	\$15,000	
Misc. Peripherals*			\$7,000	
*(i/o cards, printers, mice, etc...)				
(Located within the hall, these computers provide direct monitoring and control of hardware. One computer is used for safety systems, the other for everything else.)				
Supervisor Computer	1	\$30,000	\$30,000	
Disc Drive	1	\$7,500	\$7,500	
Misc. Peripherals			\$5,000	
(Located in the counting house, this computer provides overall system control, a platform for running user applications, and access to operational documentation.)				
I& C Gateway Computer	1/3	\$30,000	\$10,000	
Disc Drive	1/3	\$7,500	\$2,500	
Misc. Peripherals			\$1,250	
(A network server shared by all three end stations which serves primarily to pass data from the end stations to other CEBAF systems including the main control room computers.)				
Software				
Application Code and Licensing (purchased from vendors)			\$15,000	
Camac Hardware				\$104,000
Crates	4	\$2,500	\$10,000	
Crate Controller	4	\$1,000	\$4,000	
Camac Modules	60	\$1,500	\$90,000	
(CAMAC will be used for monitoring and control of power supplies, cryogenics, vacuum, water and air cooling, drainage, beam instrumentation, carriage positioning, target positioning, and field mapping equipment. Some level of safety system monitoring will also be handled by CAMAC, although no safety system function will be dependent upon CAMAC.)				
Relay Rack Assembly	6	\$3,000		\$18,000
(Rack, cross-connect blocks, tie strips, etc., for control cabling.)				
Safety Systems				\$55,000
Oxygen Deficiency Sensor	6	\$500	\$3,000	
Interlock Rack	1	\$5,000	\$5,000	
(Rack and electronics for monitoring and controlling interlocks.)				
Run/Safe Box	5	\$1,000	\$5,000	
Radiation Monitors	3	\$4,000	\$12,000	
Fast Beam Shutoff System	1	\$5,000	\$5,000	
Dual Gate Access Control	2	\$5,000	\$10,000	
Quench Protection System	1	\$15,000	\$15,000	
				\$295,250

**Hall A Equipment Cost
Item Y
Counting House Electronics
WBS 6.5.5**

REF: Attached DAQ General Schematic
Cost Data via Chip Watson & Mike Finn

<u>Data Acquisition System</u>	
•Host computer + mass storage	100K
•Graphic workstations (3)	50
•CPU Farm:	50
- 5 High speed VME boards @ 8K ea.	
+ 2 Tape drives @ 5K ea.	
•Two FASTBUS crates, intelligent controllers, switching circuits, cables, etc.	50
•Software licenses	<u>50</u>
DAQ Total	\$300K
<u>Miscellaneous Items</u>	
•Test & calibration equipment	-
•Cabling for miscellaneous equip.	-
•Spares	-
•AFI	<u>-</u>
	\$150K
Item Y Total	\$450K

[cdr.halla4-90]section10-1.tex

10.2 MANPOWER

10.2.1 Manpower needs

The institutional manpower needs for Hall A Experimental Equipment for the years 1990 to 1994 can be summarized as follows:

CEBAF 117 man.years (Eng/Techn: 40; Physicists: 57; Contract labor: 20)

Users 90 man.years

The "Physicists" category includes physicists and postdocs in the Hall A group as well as personnels in the CEBAF Detector Development Group and Data Acquisition Group which are involved in Hall A instrumentation.

The "Engineers/technicians" category includes engineers, technicians, designers and craftsmen working on Hall A equipment.

Also, contract labor, including rigging services, is required for major equipment installation, primarily the magnets and support structures. The corresponding costs are given in Section 10.1 above.

The anticipated breakdown (man.years) is the following :

	CEBAF (Eng.)	CEBAF (Phys.)	USERS	Contract labor
Spectrometers, magnetic measurements	30.5	20	5	18
Detector systems	3	8	50	
Data acquisition		7	10	
Targets, beamline instrumentation, ..	6.5	8	15	2
Experiment planning and simulations		14	10	
	40	57	90	20

A more detailed breakdown of the CEBAF engineering staff manpower needed for Hall A is given in the following table.

HALL A: ENGINEERING STAFF LEVELS					ALCORN	April 11, 1990
Fiscal Year:	90	91	92	93	94	Totals
	WKS	WKS	WKS	WKS	WKS	WKS
QUADRUPOLES:						
• Hall A Engr.	15	10	10	15	18	68
• Mech. Engr.	7	4	6	8	15	40
• Designer	12	10	12	16	12	62
• Tech.			8	73	70	151
TOTAL (WKS)	34	24	36	112	115	321
DIPOLES:						
• Hall A Engr.	15	13	16	10	20	74
• Mech. Engr.	20	8	12	8	15	63
• Designer	30	12	14	8	12	76
• Tech.				48	54	102
TOTAL (WKS)	65	33	42	74	101	315
STRUCTURE:						
• Hall A Engr.	7	8	8	8		31
• Mech. Engr.	8	8	6	6	4	32
• Designer	10	4	14	8	3	39
• Tech.	2	8	24	34	8	76
• Elect. Engr.	18	24	30	24	24	120
TOTAL (WKS)	45	52	82	80	39	298
HRS SYSTEM:						
• Hall A Engr.	4	10	5	6	5	30
• Mech. Engr.	10	14	12	12	6	54
• Elect. Engr.	2	12	18	15	5	52
• Designer	15	20	28	19	40	122
• Tech.	2	24	70	47	70	213
TOTAL (WKS)	33	80	133	99	126	471
BEAM LINE EQUIPMENT:						
• Hall A Engr.	3	3	4	3		13
• Mech. Engr.		2	2	2	5	11
• Elect. Engr.	1	2	3	2	1	9
• Designer	4	7	10	6	2	29
• Tech.		16	19	18	10	63
• Target Design	16	18	8			42
TOTAL (WKS)	24	48	46	31	18	167
SUPPORT EQUIPMENT:						
• Hall A Engr.	3	3	4	5	4	19
• Mech. Engr.	2	9	7	11	2	31
• Elect. Engr.	6	9	6	6	17	44
• Designer	6	12	16	18	3	55
• Tech.	4	26	39	34	55	158
TOTAL (WKS)	21	59	72	74	81	307
TOTALS:						
• Hall A Engr.	47	47	47	47	47	235
• Mech. Engr.	47	45	45	47	47	231
• Elect. Engr.	27	47	57	47	47	225
• Hall A Design	47	33	47	47	47	221
• Design, Other	46	50	55	28	25	204
• Tech. (Instl. Coord.)	0	47	47	47	47	188
• Technicians	8	27	113	207	220	575
TOTAL (WKS)	222	296	411	470	480	1879
TOTAL (MY)	4.72	6.30	8.74	10.0	10.2	40.0

Detailed information on manpower needs for the detector and data acquisition systems which constitutes the second important subsystem after the spectrometers (magnets+supports) is given in section 7.

The manpower plan for Hall A would then be:

years	1990	1991	1992	1993	1994	Total
<hr/>						
CEBAF						
Physicists/postdocs	8	10	12	13	14	57
Engineers/Technicians	5	6.5	8.5	10	10	40
Designers						
<hr/>						
Non-CEBAF Users	10	15	20	20	25	90
Contract labor				10	10	20
<hr/>						
Total	23	31.5	40.5	53	59	207

The CEBAF positions are consistent with the CEBAF Institutional Plan.

10.2.2 User participation

As explained in Section 1, the outside users have expressed their commitment to the Hall A project by signing either a Memorandum of Understanding (MOU) document or a written statement of intentions.

The total manpower commitment reflected in these documents, given in equivalent man.years for the period 1990-1994 is summarized in tables 10.2 and 10.3. One sees that the numbers are consistent with the needs for the equivalent period. About 25% of them correspond to personnel to be hired if additional funding is provided.

Table 10.2
User involvement (per institution)

Institution	Spokesman	man.years
American U.	B. Flanders	1.2
Cal. State U.	M. Epstein	4.3
U. Georgia	T. Baker	2.2
Kent State U.	R. Madey	4.4
Kent State U.	J. Watson	12.2
U. Maryland	C. C. Chang	6.2
MIT	W. Bertozzi	29.6
U. New Hampshire	J. Calarco	0.7
Norfolk State U.	V. Punjabi	2.5
U. Regina	G. Lolos	6.2
U. Rochester	G. Petratos	1.5
Rutgers	C. Glashausser	11.3
U. Saskatchewan	C. Rangacharyulu	0.7
Stanford	Z.E. Meziani	6.3
U. Virginia	R. Lourie	12.4
William & Mary	J. M. Finn	7.4
William & Mary	C. Perdrisat	5.8
	TOTAL	114.9

Table 10.3
User involvement (per activity)

Activity	man.years	Institutions involved
Spectrometer design and calibration	2.0	MIT, U.Roch., UNH
Detector systems	40.5	MIT, W&M, UVa, UMd, Am.U, NSU, U.Reg., U.Sask., UNH
Focal Plane Polarimeter	17.5	Rutgers, MIT, W&M, UVa, NSU, U.Georg.
Data Acquisition	12.5	W&M, UVa, Rutgers, Am.U, NSU, UNH
Targets, beam instrumentation...	19.6	CSU, UVa, Stanford
Computer simulations	6.1	W&M, UMd, Am.U, U.Georg., U.Roch., UNH
Neutron detection	16.6	KSU, UVa

10.3 PROJECT MANAGEMENT

As discussed above, the Hall A project is based on a strong involvement of the future users of the facility. The performance characteristics and essential features of the spectrometer designs have been matched to the needs of the user physics program and thoroughly reviewed in the various Hall A user meetings. User groups are now taking the lead in designing and building parts of the instruments. A project management organization, outlined below, is being set up, following the recommendation of the TAP reviewers, to coordinate the effort of CEBAF and user engineers and physicists towards realization of the Hall A equipment and its commissioning, testing and tuning-up for experiments.

The basis of the Hall A project organization is the *Hall A Collaboration* whose goal is to develop a high quality physics program centered around the High Resolution Spectrometer pair, and to fully exploit the outstanding characteristics of the CEBAF beam. The Collaboration has selected ten major experiments which were presented by chosen spokesmen at the last PAC meeting. These experiments will serve as a basis to complete the design of the Hall A equipment and to focus the activities of the various scientific groups on construction and operation of the specific tools required to achieve their program.

An organizational structure has been defined to ensure technical success, quality control and construction within cost and schedule in a CEBAF/user integrated effort. It is based on three management structures:

- a management group,
- a steering committee,
- a project team.

10.3.1 Management Group

It is composed of *two physicists* plus a CEBAF *senior engineer*. One physicist is from the CEBAF senior scientific staff and the other from the national nuclear physics community. At present, this physicist has been appointed by CEBAF following the recommendation of the CEBAF User's Group. It is anticipated that, once the Hall A Collaboration will be formally organized, this role may be taken by the Chairman of the Collaboration Coordinating Committee.

The CEBAF Program Manager has the overall responsibility for the realization and commissioning of Hall A experimental equipment.

The two physicists ensure coordination of the various scientific groups in the Hall A collaboration, and the definition and presentation to the CEBAF management and funding agencies of the Hall A scientific program and corresponding equipment.

They ensure proper assignation and coordination of the various project tasks to be performed by CEBAF staff and users, and ensure adequate circulation of information within the collaboration. The senior engineer has primary responsibility for supervision and coordination of the project engineering activities. He ensures proper liaison and coordination with CEBAF civil engineers, CEBAF procurement staff, and vendors. He has the primary

responsibility for engineering design, quality control, procurement and commissioning procedures. As cost account manager, he ensure adequate and timely allocation of funds to the various activities in accordance with the budget and funding profile established for Hall A Equipment, and control the proper use of the funds.

The management group directs a *project team* which includes physicists and engineers responsible for the various parts of the project.

Finally, the management group, with the help of the Hall A collaboration , defends to CEBAF and the funding agencies the case for a proper allocation of resources to Hall A scientific programs.

10.3.2 Steering Committee

A steering committee ensures liaison between the management group/ project team and the users in the Hall A collaboration.

Its members are, apart from the three members of the management group, the CEBAF and user physicists leading the user groups responsible for specific project tasks (hardware or not). The steering committee meets regularly (at least 4 times a year) to review the status of the project and make technical and managerial decisions on its evolution.

The present membership of the Steering Committee is given in Table 10.4. In addition, it may include, as advisors, two or three outside experts in managing projects of a similar nature.

10.3.3 Project Team

A project of this scale necessitates frequent working meetings to bring together the people in charge of the various aspects of the project. As geographical considerations exclude the possibility for the steering committee to play this role, the management group directs a project team, which meets at CEBAF regularly, once a week. Everyone reports on progress/cost/schedule in the activity he (or his team) is in charge of, or for which he acts as a CEBAF liaison when a user group is responsible for it. Actions are defined and minutes are produced.

The present membership list is given in Table 10.5. In addition, L. Keller ensures liaison with the civil engineering group (end station/counting house).

Each physicist in the project team has been designated to be the CEBAF liaison for one or several of the user group coordinators. As such, he will report at the weekly meeting on the activities of the group. In most cases, he is himself a member of that group. He visits the user group institution as required to straighten out difficulties, ensure proper interface with the rest of the project. When necessary, the visit is made by one or some of the members of the management group. The liaison assignments of the project team members are listed in Table 10.6.

Table 10.4
HALL A STEERING COMMITTEE

•Management	
J. Mougey, CEBAF	CEBAF Program Manager
R. Lourie, UVa	User Co-Program Manager
J. Alcorn, CEBAF	Project Engineer/ Cost Account Manager
• W. Bertozzi, MIT	Coordination, focal plane instrumentation
• L. Weinstein, MIT	Wire chambers
• C.C. Chang, UMd	Shower detectors
• G. Lolos, U. Regina	Scintillation and Cerenkov counters
• C. Glashauser, Rutgers	Focal plane polarimeter
• M. Finn, W&M	Trigger electronics and data acquisition
• G. Petratos, U.Rochester	Spectrometer Calibration
• B. Flanders, Am.U	Simulation software
• M. Epstein, CSU	High power cyrotargets
• D. Day/J. McCarthy, UVa	Cryotargets and polarized targets
• R. Lindgren, UVa	Target chamber
• Z.E. Meziani, Stanford	Beam polarimeter
• R. Madey/J. Watson, KSU	Neutron detection and polarimetry

Table 10.5
HALL A CEBAF TEAM

J. Mougey	CEBAF Program Manager
R. Lourie (UVa)	User Co-Program Manager
J. Alcorn	Project engineer/ Cost Account Manager
J. LeRose	Spectrometer design
S. Nanda	Magnetic studies; focal plane polarimeter
W. Tuzel	Cryomagnet engineering
A. Gavalya	Mechanical design (magnet and support structure)
R. Johnson	Electrical engineering and controls
A. Saha	Beam line equipment; targets; liaison with Accelerator Division
M. Finn (W&M), P. Ulmer	Detectors and data acquisition

Table 10.6
HALL A CEBAF TEAM/USER GROUP LIAISON

Activity	User coordinator	CEBAF liaison
Focal plane instrumentation	W. Bertozzi, MIT	J.M. Finn
Wire chambers	L. Weinstein, MIT	P. Ulmer
Shower detectors	C.C. Chang, UMd	J.M. Finn
Scintillators, Cerenkovs	G. Lolos, U.Regina	P. Ulmer
Focal plane polarimeter	C. Glashausser, Rutgers	S. Nanda
Simulations	B. Flanders, Am.U.	P. Ulmer
High power cryotargets	M. Epstein, CSU	A. Saha
Polarized targets	J. McCarthy, UVa	A. Saha
Target Chamber	R. Lindgren, UVa	A. Saha
Beam polarimeter	Z.E. Meziani, Stanford	A. Saha
Spectrometer calibrations	G. Petratos, U.Rochester	J. LeRose
Neutron detectors	R. Madey/J. Watson, KSU	J. Mougey

At present, the management group members ensure liaison with the foreign collaboration groups on non-magnetic detectors, Cerenkov counters and the 3rd arm spectrometer.

10.4 SCHEDULE

10.4.1 Overall

Figure 10.1 shows the overall schedule for procurement, installation, testing, magnetic measurement and commissioning of the HRS pair and associated equipment for Hall A.

Note that Beneficial Occupancy of Hall A is scheduled for August 1992 (BOD). Floor plates, an equipment item, will have been installed by that time. Installation of the HRS support structure commences immediately following BOD.

Both the dipoles and quadrupoles are critical path items for achieving the indicated completion dates of 1 November 1994 and 2 April 1995 for the HRS Electron and Hadron arms respectively.

10.4.2 Dipoles

Figure 10.2 shows the single vendor procurement schedule for the dipole systems. As indicated, acceptance testing of the first dipole is completed 34 months after receipt of order (ARO), the second dipole following three months later. Note that the conductor and helium vessel are pacing items, both delivered 18 months ARO to the contractors plant for subsequent coil winding (we anticipate the coils being wound directly into the helium vessel cavities.) We believe that a 12 month delivery subcontract for the conductor can be placed 6 months ARO. However, the 9 month helium vessel subcontract (or, in-house fabrication) cannot logically be initiated until completion of the 9 month magnet design phase.

Subcontract procurement of the iron, including machining, does not appear to be a critical path item - so long as this activity is begun soon (~ 3 mos) after contract award.

Factory preassembly of the major magnet elements - yoke, pole pair and coil/cryostat unit - is essential to ensure proper component fits. (Match drilling for iron doweling is done at this time). Vendor's say that this activity will require three months. Thereafter, the magnet is disassembled and the components shipped to CEBAF for reassembly within Hall A, atop the HRS cradle. We have allowed three months for this activity also, followed by two months for cooldown and acceptance testing. Magnetic measurement by CEBAF will follow thereafter.

10.4.3 Quadrupoles

Figure 10.3 is a CEBAF prepared schedule for industrial procurement of the six cosine 2θ quadrupoles required for the two HRS arm.

The 42 month ARO completion date is consistent with guidance received from several potential manufacturers.

10.4. Detector and data acquisition systems

Figure 10.4 shows the schedule for completion and testing of the two detector packages and data acquisition software. This schedule was prepared by the user groups in charge of the focal plane instrumentation and data acquisition, in coordination with the CEBAF Data Acquisition Group. More detail on subsystem schedules are given in Section 7.

HALL A EQUIPMENT SCHEDULE

CEBAF

4/16/90

Figure 10.1

A10-30

HRS Dipole: Single Vendor Schedule

Figure 10.2
A10-31

HRS Quadrupoles: Schedule For Industrial Procurement

Figure 10.3

Hall A Detector and DAQ Development

Figure 10.4

CONCEPTUAL DESIGN REPORT
BASIC EXPERIMENTAL EQUIPMENT

HALL B

April 13, 1990
(Revised)

CEBAF HALL B

CONCEPTUAL DESIGN REPORT

April 1990

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A Introduction

CEBAF is a single-purpose facility for basic research in nuclear physics. Its central instrument will be a superconducting electron accelerator with a maximum energy of 4 GeV, 100% duty-cycle, and a maximum current of 200 μ A. The accelerator will deliver independent beams for simultaneous use in three experimental stations. To carry out a broad physics program, the three endstations will be instrumented with complementary experimental equipment:

Hall A: two high-resolution magnetic spectrometers

Hall B: a large acceptance magnetic spectrometer

Hall C: a high-momentum magnetic spectrometer and
a short orbit hadron spectrometer

This following Conceptual Design Report will describe the physics motivation and the proposed instrumentation for Hall B.

Hall B is devoted to two types of experiments that each require a large acceptance detector:

- o the detection of several uncorrelated particles in the hadronic final state
- o measurements for which the luminosity is limited by beam, target or accidental background.

The main instrument proposed for Hall B is the toroidal multi-gap spectrometer CLAS (CEBAF Large Acceptance Spectrometer). The magnetic field is generated by six iron-free superconducting coils. The particle detection system consists of drift chambers to determine the trajectories of charged particles, Cerenkov counters for the identification of electrons, scintillation counters for the trigger and for time-of-flight measurements, and an electromagnetic shower calorimeter to identify electrons and to detect photons. The six segments are instrumented individually to form six independent spectrometers. This is a good basis for high-luminosity operation and high count-rate capability. The field-free region in the center of the spectrometer allows the installation of a polarized target; the open structure of the magnet makes it possible to add equipment at the outside, e.g. for improved particle identification or for neutron time-of-flight measurements.

B Physics Motivation

The main theme of CEBAF's scientific program is the precision study of the structure and the motion of the nuclear constituents. Presently, our knowledge is essentially limited to the electromagnetic structure of the ground states and the excited states of nuclei (explored in (e,e') experiments) and to selected aspects of the nuclear single-particle structure (explored in (e,e'p) experiments). In contrast to this precise information, surprisingly little is known about the many-body aspects of the nucleus, e.g.:

- o the modification of the properties of bound nucleons,
- o the nature of short-range nucleon-nucleon correlations,
- o the importance of three-body forces in nuclei,
- o the production and propagation of nucleon resonances in the nuclear medium.

This lack of knowledge is largely due to the technical features of present electron accelerators and detection equipment:

- a) The low duty-cycle of present electron accelerators makes coincidence experiments difficult; in practice, they are limited to relatively narrow kinematical regions for which a sufficient ratio of real-to-accidental coincidences can be obtained. The low duty-cycle also limits the useful count rate that can be achieved in a large acceptance device. (Note that in a large acceptance detector, the maximum instantaneous rate is limited by background).
- b) The standard experimental equipment at electron accelerators consists of focussing magnetic spectrometers that cover small solid angles (typically 10^{-3} of 4π) and small momentum bites ($\Delta p/p \approx 10\%$). The main advantage of this type of spectrometer is the high resolution (that relies on the use of carefully arranged magnetic fields) and the low sensitivity of the particle detector system to background (the detectors are located in a well-shielded enclosure far away from both target and beam). The disadvantage, however, is the small acceptance in both solid angle and momentum which limits the experiments in practice to the coincident detection of two (perhaps, in selected cases, three) particles. To get sufficient counting rate in spite of the small acceptances, one has to operate at high luminosity. Accidental coincidences then prevent the

experimenter from exploring rare events from that part of the phase space where the detected particles are essentially uncorrelated. In addition, measurements at limited luminosity (target density • beam intensity) are practically ruled out. The limitation can be due to

- o the target (e.g.: a polarized solid state target that can tolerate only very low electron currents), or
- o the beam (e.g. a tagged bremsstrahlung beam which is limited by the tagging method to a flux of less than 10^8 photons/sec).

The ideal solution for these problems is a spectrometer capable of covering the complete solid angle and momentum range for all outgoing charged and neutral particles while maintaining as much of the high resolution and count rate capability of focussing spectrometers as possible. In the past, there were two main obstacles for the use of such a device:

- o the useful hadronic production rate that could be achieved was low because of low electron accelerator duty-cycle,
- o large acceptance spectrometers were technically too complex for the small groups typical for the medium energy nuclear physics community.

The quality and reliability of large acceptance spectrometers have improved substantially, mainly due to the effort of the high-energy physics community in the last two decades. Because of this development, the operation of a large acceptance spectrometer has now become feasible for a collaboration of small-size groups in intermediate-energy nuclear physics.

A high-quality electron beam (halo-free, 100% duty-cycle) will be necessary to operate a large acceptance spectrometer at high luminosity. In addition, a high-intensity beam will be required for experiments that use very thin targets. The continuous, high-quality beam of the CEBAF accelerator will be ideally suited for the operation of a large acceptance spectrometer.

In 1989, CEBAF's Scientific Director asked for proposals for the first round of experiments. A large fraction (21) of the 47 proposals received proposed to carry out experimental programs using the large acceptance magnetic spectrometer in Hall B. The proposals are listed in Table B1.

Table B1: Proposals Submitted to PAC4 for Hall B

Proposal #	Title	Contact person
001	Nuclear Mass Dependence of Vector Meson Interactions Using the Photoproduction of Lepton Pairs	B. Freedom
002	Shadowing of Real Photons in Nuclei: Measurement of the Total Hadronic Cross Section	D. Sober
004	Electromagnetic Production of Hyperons	R. Schumacher
007	Experiments with a Polarized ^3He Target and the CLAS	R. McKeown
015	Study of Coincidence Reactions in the Dip and Delta-Resonance Regions	H. Baghaei
017	Electroexcitation of the Delta(1232) in Nuclei	R. Sealock
020	Deuteron Disintegration	D. Jenkins
024	Radiative Decays of the Low-Lying Hyperons	G. Mutchler
025	Vector-Meson Decay of High-Lying Nucleon Resonances	J. Comfort
027	Coincidence Reaction Studies with the LAS	L. Weinstein
031	Study of Multi-Nucleon Knockout with the CLAS	R. Miskimen
032	Study of the Local Properties of Nuclear Matter in Electron-Nucleus and Photon-Nucleus Interactions with Backward Particle Production Using the CLAS Detector	G. Laksin
036	Study of Short-Range Properties of Nuclear Matter in Electron-Nucleus and Photon-Nucleus Interactions with Backward Particle Production Using the CLAS Detector	K. Egiyan

Table B1: Proposals Submitted to PAC4 for Hall B (continued)

Proposal #	Title	Contact person
037	Electroproduction of the $P_{33}(1232)$ Resonance	V. Burkert
038	Measurement of $p(e,e'\pi^+)n$, $p(e,e'p)\pi^0$, and $n(e,e'\pi^-)p$ in the Second and Third Resonance Regions	R. Minehart
039	Amplitudes for the $S_{11}(1535)$ and $P_{11}(1710)$ Resonances from an $p(e,e'p)\eta$ Experiment	S. Dytman
040	The Study of Excited Baryons at High Momentum Transfer with the CLAS	P. Stoler
041	A Longitudinal-Transverse Separation of the Amplitudes for the $S_{11}(1535)$ Resonance	K. Giovanetti
042	Measurement of the Electron Asymmetry in $p(e,e'p)\pi^0$ and $(p(e,e'\pi^+)n)$ Reaction in the Mass Region of the $P_{33}(1232)$ for $Q^2 < 2 \text{ (GeV/c)}^2$	V. Burkert
043	Measurements of the Electroproduction of Λ , $\Lambda(1520)$, and $f_0(975)$ via the K^+K^-p and the $K^+\pi^-$ Final States	L. Dennis
045	Study of Kaon Photoproduction on Deuterium	B. Mecking

C Design Goals for a Large Acceptance Spectrometer

The main experimental features of the physics program proposed by members of the CLAS collaboration and recommended by the PAC are summarized in Table C1. The importance of specific detector features for the program is indicated by stars (*). While many features are common to most large acceptance spectrometers, the strong emphasis on good momentum resolution and the possibility to operate polarized targets is unusual. Good momentum resolution is valuable for all experiments in order to determine kinematical quantities, e.g. the determination of the virtual photon four-momentum in electron scattering or the missing mass of particles that are difficult to detect like π^0 , η , or ω . Good resolution becomes crucial in nuclear experiments because the final nucleus is generally undetectable; its excitation energy can only be determined from an accurate measurement of the other reaction partners.

To carry out the broad physics program outlined before, the following properties are desirable for a general purpose large acceptance spectrometer:

1. Homogeneous coverage of a large angular and momentum range for charged particles, photons, and neutrons:

angular range for particle detection	$5^\circ \leq \theta \leq 150^\circ$
momentum range for charged particles	$p = (0.1 - 4.0) \text{ GeV}/c$
energy range for photons	$E \geq 50 \text{ MeV}$

2. Good momentum and angular resolution:

momentum resolution (small θ , high p)	$\delta p/p \simeq 0.5 \% \text{ (Fwhm)}$
momentum resolution (large θ , low p)	$\delta p/p \simeq 1.0 \% \text{ (Fwhm)}$
angular resolution	$\delta\theta \simeq 1.0 \text{ mrad}$

Due to the Lorentz-boost, the average particle momentum increases with decreasing emission angle. In order to keep the absolute momentum resolution constant, the relative $\delta p/p$ has to improve in the forward direction.

3. Good particle identification: separation of electrons, pions, kaons, protons, and deuterons in the momentum range of interest as well as the separation of photons and neutrons.

4. High luminosity and count rate capability. The spectrometer should be able to operate in the difficult background environment encountered in electron scattering experiments. Design goals are:

electron beam luminosity	$L \simeq 10^{34} \text{cm}^{-2} \text{sec}^{-1}$
tagged photon beam intensity	$N \simeq 10^8 / \text{sec}$

Fast detector elements and a high level of segmentation are required. The magnetic field configuration should cope with the large flux of particles from electromagnetic processes, especially

- a) deflect low-momentum charged particles emitted at large angles (like e^- from Møller scattering) and keep them away from the chambers,
- b) not deflect forward-going charged particles (like e^- from bremsstrahlung or e^+e^- -pairs) into the detector. Transverse magnetic field at the beam axis should be avoided.

The requirements 1-4 listed above are indispensable for practically all experimental programs. The following properties are vital for subsets of the CEBAF program:

- 5. The spectrometer should allow operation of polarized targets (solid state or gaseous) requiring their own magnetic guiding field or other complicated equipment in the target region (e.g. track sensitive targets, vertex detectors etc.). Therefore, sufficient space ($\simeq 1$ meter diameter) in the target region is required. The magnetic field should vanish in the target region to avoid interference with the polarized target field.
- 6. Open geometry for the installation of detectors with a long flight path for neutron energy measurement.

The operation of the spectrometer (e.g. triggering) and the data analysis (e.g. pattern recognition and the determination of the track parameters) will be facilitated by the following properties:

- 7. Symmetry around the beam axis
- 8. Homogeneous magnetic field.

Table C1: Typical Physics Programs Proposed for CLAS

Physics Program	emphasis good resolution	on polarized target	typical multipli- city	luminosity limitation due to
Nucleon Resonances				
$\gamma_{\nu} N \rightarrow N^* \rightarrow \pi N$	*	*	2	detector
$\rightarrow \eta N$	*	*	2	
$\rightarrow \pi\pi N$	*		3-4	
Hyperon Production				
$\gamma_{(\nu)} N \rightarrow K \Lambda (\Sigma)$	*	*	1-2	tagged γ
$\rightarrow \pi N$	*	*	2-3	
$\gamma_{(\nu)} d \rightarrow K (\Lambda N)$	**		1-4	
Nuclear Processes				
$e A \rightarrow e' NN A'$	**		3	detector
$\rightarrow e' \pi N A'$				
$\gamma A \rightarrow K A(\Lambda, \Sigma)$	***		1	tagged γ
$\rightarrow \pi N X$	***		2-3	
$\rightarrow NN X$	***		3	
Polarized Targets				
$e d \rightarrow e' n(p) \quad G_{\sigma}^n$	*	***	2	target
$e {}^3\text{He} \rightarrow e' n(pp) \quad G_{\sigma}^n$	*	***	2-3	target
$\rightarrow e' \Delta(NN) \quad N \rightarrow \Delta$	*	***	2-3	or detector

D Design Options

The consequences of the requirements outlined above for the choice of the magnetic field configuration have been studied. Solenoids with longitudinal field, dipoles with transverse field, and toroidal magnets with the axis along the beam line have been considered. In all cases, the target has been assumed to be inside the magnetic field volume. The configurations will be discussed in more detail.

D.1 Solenoid

Solenoids have become the standard magnet configuration for large acceptance spectrometers at e^+e^- and $\bar{p}p$ -colliders. Solenoids offer large solid angle coverage, high tolerance to backgrounds and efficient pattern recognition and trajectory reconstruction. Momentum resolution at large angles with respect to the solenoid axis can be very good. At small angles, however, the outgoing particles move essentially in the direction of the magnetic field and experience only a small deflection. This results in poor momentum resolution at small angles. (For e^+e^- -collider applications, the loss in momentum resolution at small angles can be tolerated since the laboratory system coincides with the center-of-mass system.)

D.2 Dipole

Dipole magnets have been used or proposed for electroproduction experiments, especially at high energies (≥ 10 GeV). In the forward direction, they can achieve good ϕ -angle coverage and high momentum resolution. Disadvantages are the limited ϕ -coverage at large scattering angles and the sensitivity to electromagnetic background which is spread out by the transverse field.

Note that solid state polarized targets are very difficult to accommodate in both solenoid and dipole spectrometers because of their large size and their high magnetic fields. (For experiments that require coverage of the forward part of the solid angle only the problem could be solved by putting the target upstream of the detector.)

D.3 Toroid

Toroidal magnet spectrometers offer a field-free region around the target and a magnetic field that is always transverse to the particle momentum (important for high momentum resolution). Since the ϕ -pattern of the event is preserved, the determination of ϕ is decoupled from the measurement of polar angle θ and momentum p . These properties of toroidal spectrometers have often captured the imagination of physicists, especially in the planning stage for a new accelerator. The main disadvantages of toroidal spectrometers are the lack of complete ϕ -coverage due to the coils and the inhomogeneous magnetic field which makes trajectory reconstruction more complicated than in a uniform field. Table D1 lists advantages and drawbacks of toroidal spectrometers.

D.4 Comparison

None of the magnetic field configurations can satisfy all requirements; advantages and disadvantages are designated in Table D2 by + and - signs. The best configuration for the CEBAF physics program is the one that has the widest overlap with the physics requirements. The comparison of the spectrometer features with the importance for the physics program shows that the toroidal configuration is the best choice.

Table D1: Advantages and Drawbacks of Spectrometers with Toroidal Magnetic Field

Feature	Advantage	Drawback
Magnetic field always transverse to the particle track	efficient use of the installed field, particle tracks at different ϕ don't mix	need independent detection system for each segment + large number of detector elements
Coil can be be shaped to give desired $\int B \cdot dl$ as a function of θ	better $\delta p/p$ for high p, forward going particles (can account for Lorentz-boost)	inhomogeneous field, complicated track reconstruction, limited ϕ -coverage due to coils
Efficient coverage of large field volume	good momentum resolution, good particle identification due to long flight path	expensive calorimetry due to large surface area
Large field-free region around the target	space for polarized target, no interference with polarized target magnetic field	low momentum background can travel large distances before being bent back by the magnetic field + first detector far from the target, + limited accuracy for vertex and V-reconstruction
Open mechanical structure	can add detectors at the outside, long time-of-flight path possible (e.g. for neutron detection)	

Table D2: Comparison of Spectrometer Concepts

	solenoid	dipole	toroid
θ -range	+	+	++
ϕ -range	+++	- -	-
Momentum range	++	++	++
Momentum resolution			
small θ , high p	- -	++	++
large θ , low p	++	++	++
Particle identification	+	++	++
Maximum luminosity	++	-	++
Polarized target operation (B=0 at target location)	- -	-	++
Open structure for neutron ToF	- -	+	++
Simple trajectory reconstruction	++	-	-

E Hall B Overview

The design solution that has been proposed for the CEBAF Large Acceptance Spectrometer (CLAS) is a magnetic toroidal multi-gap spectrometer. The design features that drive the size and the configuration of the system are listed in Table E1.

The magnetic field is generated by six superconducting coils arranged around the beam line to produce a magnetic field which is primarily in the ϕ -direction. The size (about 5 meter long and 2.5 meter wide) and the shape of the coil were determined on the basis of the physics requirements. A perspective view of the magnet is shown in Figure E1.

A side view of the particle detection system is given in Figure E2, a view in the direction of the beam (cut in the target region) in Figure E3. The system consists of drift chambers to determine the track of charged particles, gas Cerenkov counters for electron identification, scintillation counters for the trigger and for measuring time-of-flight, and an electromagnetic calorimeter to detect showering particles like electrons and photons. The segments are individually instrumented to form six independent magnetic spectrometers. This will facilitate pattern recognition and track reconstruction at high luminosity.

Charged particles are tracked by drift chambers whose wires are arranged in 3 regions: Region 1 close to the target, Region 2 between the coils, and Region 3 outside of the coils. Each drift chamber region defines a track segment independent of the other regions. The distribution of energy loss in the drift cells gas is recorded and provides additional information useful for particle identification. For electron scattering experiments, a small normal-conducting toroid surrounding the target will be used to keep low momentum charged background from reaching the Region 1 drift chamber.

The threshold gas Cerenkov counters are sensitive to particles with $\beta \geq 0.998$. In combination with the electromagnetic calorimeter they give good electron identification, sufficient even at large electron scattering angles where the π/e ratio becomes large. The location of the Cerenkov counters in front of the scintillation counters minimizes photon conversion and knock-on electrons.

The scintillation counters serve the double purpose of contributing to the first level trigger and providing time-of-flight information. Each counter is viewed by phototubes at both ends for improved timing and position resolution. A single counter covers the full ϕ -range corresponding to one segment, but a θ -range of only $\approx 3^\circ$. This will facilitate the selection of kinematical quantities, e.g. the electron scattering angle, in the trigger.

The electromagnetic calorimeter is used for the identification of electrons and the detection of photons from the decay of hadrons like π^0 , η , η' , Λ^* etc. The resolution requirements are $\sigma/E \leq 0.10/\sqrt{E(\text{GeV})}$ for the energy resolution and ≤ 10 mrad for the angular resolution.

Ideally, the solid angle covered by Cerenkov counters and electromagnetic calorimeters should be complete. Initially, it is proposed to provide electron detection up to 45° in 5 segments and up to 90° in one segment.

The CLAS will be located in Hall B; a perspective view is shown in Figure E4. The hall is a circular building (98 feet diameter) with a domed roof and a polar crane. For large size detector components access to the hall is provided by a truck ramp. A bremsstrahlung tagging spectrometer is located in an enlarged tunnel section at the entrance of the hall. For tagged photon experiments, the primary electron beam will be deflected vertically into a low-power beam dump. Monitoring equipment for the tagged photon beam, e.g. a pair spectrometer, will again be located in an enlarged downstream tunnel section. The hall and the beam dump are fully shielded to allow for experiments that use a high-intensity beam on a thin target.

In the following sections, the CLAS components will be described in detail.

Table E1: Toroidal Spectrometer Design Features**Momentum resolution:**

- magnetic field: $\int B \cdot dl \geq 2.0 \text{ Tesla} \cdot \text{meter at } 20^\circ$
- $\int B \cdot dl \geq 0.5 \text{ Tesla} \cdot \text{meter at } 90^\circ$
- tracking device: individual super-layers of drift chambers (separated by helium bags to reduce multiple scattering)
- position resolution $\approx 200 \mu\text{m}$ per sense wire layer
- long baseline ($\geq 3 \text{ meter}$)

Particle identification:

- long time-of-flight basis for $\beta < 1$ particles
- Cerenkov and shower counters for electron identification (separation from pions)

High luminosity:

- highly segmented particle detectors
- wire chambers protected by magnetic field
- redundant tracking information

Polarized target operation:

- large diameter space ($d \geq 1 \text{ m}$) around target
- no magnetic field at target position
- easy access to the target region

CLAS Magnet and Support Structure

Figure E1: Perspective view of the toroidal magnet and the space frame. The catwalks provide access to the drift chamber readout electronics.

Figure E2: Midplane slice of the CLAS detection system (viewed from the top). The dotted lines show the projection of the coil contours on the midplane. The Cerenkov counters and the electromagnetic calorimeter extend to 45° . The trajectory of a 1 GeV/c particle is shown.

Figure E3: Cut through the CLAS detection system transverse to the beam at the target location.

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CEBAF

Figure E4: Perspective view of Hall B, showing the bremsstrahlung tagging system, the CLAS detector, and the electron beam dump.

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F Toroidal Magnet

F.1 Magnet Design

The magnetic field is generated by six superconducting toroidal coils with a total current of 5×10^6 Ampere-turns. The coil shape, shown in Figure F1, consists of two circular sections joined by straight sections. The circular inner section minimizes transverse motion of out-going particles. The toroid design must meet the following requirements:

- Generate the required toroidal field
- Occupy no more of the total solid angle than is permitted by the physics requirements
- Provide reliable operation
- Stay within heat load requirements

We have prepared a "reference design" (see Table F1) of the toroidal magnet. This design incorporates a cable in conduit conductor (CICC). This conductor has about 30% of its cross section occupied by liquid helium; thus offering a high tolerance for heat impulses. In comparison to intrinsically stable conductor, the CICC can tolerate a volumetric (Joules/cc) heat impulse that is at least an order of magnitude greater. Yet this conductor does not require a massive liquid helium vessel to contain pressures in the event of a quench, as would be the case with a bath cooled coil.

The use of a forced flow cooling scheme is chosen to insure effective heat removal. The orientation of the coils is such that vapor pockets could form, ruling out a pool boiling scheme. Thermal siphon cooling is also excluded since it would require excessively large cooling passages.

F.1.1 Structure

Loads The distribution of electromagnetic forces that are applied to the coil are shown in Figures F3 and F4. Figure F3 shows the forces in the plane of the coil. Figure F4 shows out-of-plane forces that would exist if one coil is off and the remaining five at full current.

Coil In-Plane Forces Electromagnetic forces, acting on the windings of each coil, are such that they tend to increase the coil perimeter. These in-plane forces are as large as 6400 lb/in (2.3 MN/m) and are borne by the bobbin plate. Cutouts, for lightening the plate and for vacuum vessel standoff posts, etc. can be accommodated. See Figure F5.

Table F1: Parameters of the CEBAF large acceptance spectrometer toroid.

Selected Features	Number of Coils Superconducting Cable	6 CICC
Overall Parameters	Total Stored Energy Total Ampere Turns Inductance	18 MJ 5.0 MA-turns 0.36 H
Conductor	Operating Current Cross-section, Bare Average Current Density Cu:SC ratio Peak Field at Conductor Conductor Insulation Operating Temperature	10.42 kA 10×10 mm ² 100 A/mm ² 7.5:1 3.5 Tesla 0.1 mm 4.5 K
Coil	Number of Turns/coil Number of Layers/coil	80 4
Quench Analysis	External resistor Maximum external voltage Maximum internal voltage Maximum internal temperature	0.1 Ω 1000 V 20 V 60 K

Centering Loads These are reacted by a large ring in the aft location and a number of rings forward. By inclusion of appropriate grooves and bolt patterns, (such as indicated in Figure F6), these rings also provide assembly and out-of-plane support for the coil inner legs. These rings were sized using the finite element program I-DEAS.

Out-of-Plane Loads These arise from three sources for the CLAS toroid: gravity, intercoil misalignment and fault mode current imbalance. Since the toroidal axis is horizontal, the coils will experience varying degree of out-of-plane gravity loading up to the full 2400 lb (1090 kg) weight of a coil.

Out-of-Plane Support The maximum load that the coil will experience due to one degree out-of-plane misalignment is 1500 lbs on the most heavily loaded support. This cold-to-warm support is designed to accommodate this load at a spring rate which is an order of magnitude greater than the magnetic "spring rate". The magnetic spring rate is 4000 lbs/in of misalignment. Thus the higher mechanical spring rate prevents any run-away condition (see Figure F7).

The most stringent requirement would result if five coils were at full current and the sixth coil had zero current. Under this highly improbable condition we would experience a load of 3400 lbs/in (0.5 MN/m) at the coil. The out-of-plane support system will survive such a load.

F.1.2 Coil Design

Quench Analysis In case of a quench the coil is protected by the external resistor of 0.1Ω which limits hot spot temperatures to about 60K. We are currently studying the effect of current sharing and quench back inducing large currents within the bobbin plate. This current sharing and quench back are both beneficial for reducing temperature rises and induced voltages. Figure F2 shows a coil cross-section. Each coil has 80 turns of superconductor operating at 10,420 A.

Cooling Considerations A schematic of the proposed cooling scheme is shown in Figure F8. The coil is indirectly cooled with a forced flow of 2.8 atm supercritical helium. The helium flows through a subcooler bath and then through all six coils in series. The flow is re-cooled after each pass through a coil.

The total heat load to helium is calculated to be less than 100 watts. We will circulate the supercritical helium at a rate of 30 grams/sec. This flow rate provides an ample margin to maintain the required coil operating temperatures.

F.1.3 Procurement Plan

CEBAF intends to procure this magnet by means of a firm fixed price contract. The vendor will have responsibility for completing the engineering design as well as fabrication. The vendor will also erect the magnet in Hall B and demonstrate that it operates according to specifications.

F.2 Magnetic Field

The magnetic field can be calculated by approximating the coil by straight conductor elements and summing up the contributions from all conductor elements. Lines of constant magnetic field strength are shown in Figure F9 which show a strong magnetic field (2 Tesla) in the forward direction, and dropping by a factor of five at large angles. The dependence of the magnetic field on the distance from the target position is given in Figure F10 for different θ . In a cylinder of 50 cm diameter around the axis, the magnetic field is ≤ 10 Gauss. The field map in the plane of the target is shown in Figure F11. Figure F12 gives the integral over the ϕ -component of the field as a function of the particle emission angle θ . The integral reaches 2.8 Tesla-meter in the forward direction; it drops to $\simeq 0.7$ Tesla-meter at 90° .

The dependence of the magnetic field on the position of the coils has been studied to derive the accuracy requirements for the conductor placement. If a coil is moved by 1 mm, the field in the center of the neighboring sector changes by less than 0.1%.

F.3 Toroidal Shield

In electron scattering experiments the dominant background component is due to electrons from Møller scattering with a strict correlation between emission angle and electron momentum. In the CLAS detector we use this kinematical correlation to provide very efficient shielding of the drift chambers in Region 1 against charged background. The detectors located in Region 2 and 3 are shielded sufficiently by the magnetic field produced by the main toroidal magnet.

The magnetic field to shield background is generated by a small toroidal coil arrangement inserted into the cavity of the large superconducting magnet. The toroidal shield is made of normal conducting coils. These coils occupy only space inside the geometrical shadow of the large CLAS magnet coil and create no additional obstruction of the geometrical acceptance. The geometry of one of the six magnet coils is shown in Figure F13. The six coils rest on support rings in the front and in the rear. The windings are water cooled.

To generate sufficient $\int B dl$ the magnet is energized to 180 kA-turns. The magnetic field generated by the toroidal shield is small compared to the field generated

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by the main coil. The field of the combined system is shown in Figure F14. Note that there is little overlap between the main field and the field generated by the toroidal shield.

The polarity of the magnetic shield is such that electrons are bent towards the beam axis. Electrons emitted at small angles deposit their energy in a shielding tube made of high Z material which surrounds the downstream beam pipe. Very low energy electrons emitted at large angles lose their energy either by hitting the coil of the toroidal shield or the beam pipe. The background rejection power of the toroidal shield is quite dramatic; nearly a factor of 100 in background rejection is gained in Region 1 (see Figure N8).

Figure F1: Cross sectional view of one of six coils of the toroid. Each coil is approximately $4.7\text{m} \times 2.7\text{m}$.

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Figure F2: Cross section of a coil, showing the Cable in Conduit Conductor (CICC) option.

Figure F3: In-plane electromagnetic forces in the coil in units of metric tons/meter.

Figure F4: Transverse (out-of-plane) electromagnetic forces with five coils at full current and one coil turned off. Forces are given in metric tons/meter.

Figure F5: Coil bobbin plate.

Figure F6: Isometric view of the toroid which shows the location of rings to support the electromagnetic centering forces.

Figure F7: Out-of-plane warm-to-cold supports.

Figure F8: Schematic of the proposed cooling scheme.

Figure F9: Lines of constant magnetic field strength in the mid-plane between the coil. The magnetic field reaches 2 Tesla in the forward direction, and drops by a factor of five at large angles. Most of the detectors reside far from the coil. For example the TOF scintillators are in a region of less than 200 gauss.

Figure F10: Magnetic field strength is plotted as a function of distance to the target along a variety of scattering angles θ .

Figure F11: The magnetic field map in a plane perpendicular to the beam passing through the target. The length of each line is proportional to the field strength at that point. The cross sections of the coils are displayed as rectangles.

Figure F12: $\int Bdl$ as a function of scattering angle θ .

Figure F13: Geometry of one of the six coils of the toroidal shield.

Figure F14: Magnetic field distribution generated by the combined coil system (main coil and toroidal shield).

G Drift Chambers

G.1 Design Overview

We present a design for the tracking chambers of the CEBAF Large Acceptance Spectrometer (CLAS). To reconstruct particle trajectories, we propose a system of eighteen multiwire drift chambers[1], three in each of the six sectors of the toroidal magnet. The three chambers in a sector are located in and denoted as Region 1, 2 and 3 respectively as one goes radially outward. Region 1 is a low magnetic field region just outside the toroidal shielding magnet. Region 2 is a high field region situated within the large toroid, while Region 3 is located beyond the outer coil of the large toroid. Figure E1 illustrates the layout of the magnet and support structure.

Each chamber is wedge-shaped and resembles an orange section. The plane which is midway between any two coils which define a sector is called the mid-plane. Half of the wires are strung normal to the mid-plane and are called "normal" wires. They are approximately parallel to the magnetic field direction and thus perpendicular to the bend plane of the particle trajectories. The track's position along these wires will be measured by "stereo" wires which are canted by 6° with respect to the normal wires. Figure E2 shows the target area, large toroid and counter assemblies in a side-view at the mid-plane of a sector. Figure E3 is an end-view of the detector cut at $\theta = 90^\circ$ which shows the three drift chamber regions in each of the six sectors.

Within each drift chamber, the wires are grouped into two separate superlayers, one normal and one stereo. Each superlayer consists of six layers of sense wires surrounded by field wires in an hexagonal arrangement. Each sense wire layer will be comprised of 128 wires in Region 1, and of 192 wires in Regions 2 and 3. This will lead to maximum drift distances of 0.7, 1. and 2. cm respectively in the three regions. For the six sectors, there will be a total of 136,104 wires in the detector of which 36,864 will be instrumented sense wires.

We plan to use a gas mixture of 50/50 argon-ethane and small ($20\mu m$ dia.) sense wires run at approximately 2500 V, resulting in a gas gain of $5 \cdot 10^4$. This design should yield spatial resolutions in the bend plane of better than $200\mu m$ and dE/dx resolutions of about 9% for particle identification. With the expected spatial resolution of $200\mu m$ per wire and the 6° stereo angle we expect a local resolution per region of about $3mm$ in the coordinate along the wire.

The use of small wire diameters and low wire tension makes possible the design of thin end-plates which maximizes solid angle coverage. The use of thin foil entrance windows minimizes multiple scattering. The amount of material ranges from 0.1% radiation length (r.l.) for Region 1 to 0.4% r.l. for Region 3. The combination of

low multiple scattering and the expected spatial resolution will enable us to achieve momentum resolution of 0.5%(FWHM) at a momentum of 4 GeV/c and a scattering angle of 20° .

G.2 Chamber Layout - Cell Geometry and Construction

The cell type which we have chosen is an hexagonal arrangement; that is, each sense wire is centered in a field cage consisting of six field wires arranged in a hexagon around it. Figure G1 shows the hole pattern on the end-plate from such a layout, for Region 2. Note that the superlayer begins with and ends with a layer of guard wires whose potential is adjusted to reproduce the electric field configuration given by an infinite grid of hexagonal cells.

We have chosen the hexagonal configuration because tracks will be traversing the chambers at widely varying angles. Hexagonal cells offer a good approximation of the ideal circular cell in which the drift-time relation is independent of entrance angle. In addition, the 'brick-wall' pattern of the layout affords easy resolution of the left-right ambiguity, gives a high degree of segmentation and is quite effective at discriminating against out-of-time tracks.

We plan to construct the drift chamber end-plates out of a light and strong composite material; for example, thin sheets of aluminum or stainless steel filled with an hexagonal-cell core. The wires will be affixed to insulating feed-throughs which penetrate the end-plates, using metal crimp pins which fit into the rear of the injection-molded plastic feed-throughs. In order to hold constant tension on the wires, we will pre-tension the end-plates before stringing them. We are investigating various tooling methods to automate the various labor-intensive tasks of the stringing operation. The construction is being planned with mechanical tolerance and survey techniques in mind.

G.3 Cell Design: Gas, Wire, Cell Size

The physics requirements of low multiple scattering, ability to handle high data rates, good spatial resolution and modest dE/dx capability greatly restrict the choices of gas, wire diameter and cell size. We have chosen a small drift distance (0.7 cm in Regions 1, 1 cm in Region 2, and 2 cm in Region 3) and a fast gas ($50\mu m/ns$) in order to handle high rates. Our choice of gas is a 50/50 argon-ethane mixture, bubbled through alcohol. This gas mixture is well studied; it has a saturated drift velocity of $\approx 50\mu m/ns$, gas gains up to $\approx 10^5$, a diffusion level of $100\mu m$ per cm of drift, good quenching characteristics and no aging problems if bubbled through a low ionization potential, non-polymerizing vapor, such as an alcohol.

The dual requirements that the wire tension be minimized and that the gas gain be a few times 10^4 require that we use a small ($\approx 20\mu m$) sense wire and an operating voltage of about 2.5 kV. In addition, we must ensure that the electric field at the surface of the field wires remains below 20 kV/cm to minimize conditions causing cathode deposits. This requires that the diameter of the field wires be about seven times the diameter of the sense wire; in this case, about $140\mu m$ diameter.

We have chosen gold-plated tungsten and gold-plated aluminum for the sense and field wires, respectively. Gold-plating gives good electrical conductivity and chemical inertness. We have chosen tungsten because of its durability which is necessary for the small diameter choice ($20\mu m$). Aluminum was chosen for the field wires because it has the longest radiation length of any practical wire material and thus minimizes multiple scattering. In addition, its low density means that it can be strung at lower tension than a more dense wire and still keep the same gravitational sag. This minimizes the forces on the end-plates. We plan to tension the aluminum wires at about 50% of their yield point, so breakage and creep problems will be minimized.

G.4 Timing, Signal Sizes and Electronics

We have modelled the electrostatic and drift time properties of the various cell designs. To accomplish this, we have extensively used the drift chamber simulation program, GARFIELD[2]. Figure G2 shows the isochrone contours ($100ns$ intervals) for representative cells in Region 2 for a typical magnetic field strength of 1 Tesla. Note that the contours are circular close to the wire but become hexagonal near the outer boundaries of the cell.

The intrinsic spatial resolution of a drift chamber is due to two contributions: the discreteness of the location of the ion clusters, and diffusion in the drift of the ions through the gas. In argon-ethane at atmospheric pressure the primary ionization clusters are spaced about $300\mu m$ apart; for a track very close to the sense wire this will give an inherent spread of about $75\mu m$. The diffusion term is about $100\mu m/\sqrt{cm}$ of drift for argon-ethane. In addition, the effect of time slewing in the electronics is expected to be of order $1ns$, or about $50\mu m$ for this gas. We conclude that resolutions of about $200\mu m$ should be readily achievable; in the next section we will discuss various systematic factors which must be accounted for to make this a reality.

We also plan to use the pulse heights from the chambers for specific ionization measurements. A track which strikes the scintillators will traverse 36 drift chamber layers and a total of about 80 cm of gas. We estimate that the dE/dx resolution for such a track is 9%. In Figure G3 we have plotted the most probable energy

loss per layer as a function of momentum. Note the five bands (plotted with $\pm 9\%$ spread) corresponding to electrons, pions, kaons, protons and deuterons. From this graph one can read off the expected particle separation as a function of momentum. These specific ionization measurements will augment the particle identification capabilities of the Cerenkov, shower and time-of-flight counters, and will provide the only particle identification information for tracks which do not reach the outer part of the detector.

The electronics will serve two purposes: one, to measure the time of arrival of the drifting ions to determine track position and two, to measure the total ionization within the cell which will enable us to do particle identification. We plan to use fast, linear amplifiers on each wire. The analog signals will be split, with one half being discriminated to provide the input for a TDC and the other half going into an ADC. The discriminator output also starts the gate to the ADC.

The amplifiers must have a risetime of $\leq 5ns$, have a high gain (150 or more), and the system should have inherent noise much less than about $5 \cdot 10^4$ electrons. With such an amplifier gain, we will need ADC's which are sensitive to integrated charges ranging between 10 and 250 pC's. Our requirement on the accuracy of the ADC's is based on their use in particle identification. For dE/dx measurements, the inherent Landau fluctuations in individual measurements means that we only need about 10% resolution in the individual charge measurements. The TDC's should have a range of $750ns$ and a resolution of $1ns$.

G.5 Performance - Systematic Factors and Prototypes

In order to achieve the design values for momentum and angular resolution, the drift chamber must measure track positions with an accuracy of $200\mu m$. Our goal is to keep individual systematic variations in time or distance below $1ns$ or $50\mu m$, respectively. These factors include the following: variation of the drift-time relation with incident track angle, variations in voltage and wire radius, variations in the B field, variations in the gas mixture and alcohol fraction and uncertainties in the wire position due to electrostatic deflections or initial misplacements. We have studied these systematic variations[3] in the position determination and quantify them here.

One example of a systematic factor is that the drift isochrones are not perfect circles. They are circular close to the sense wire but become hexagonal in shape near the periphery of the cell. This means that, for example, at a distance of 8 mm from the wire, the sensitivity to a change in the entering angle of the track is $1ns$ per degree. Therefore, we must know the entering angle to an accuracy of 1° .

The limits on the change in other quantities required to keep the change of time below $1ns$ include the following: 16 volts in the chamber high voltage value, $2\mu m$

in sense wire diameter, 0.4% in the value of the B field, 2% in the argon fraction and $0.2^\circ C$ in alcohol temperature. The sensitivity on B field can be turned into a sensitivity on the position along the wire (since the B field varies with this change). The value for B varies by as much as 0.25 T from the center to the end of the wires at 90° in Region 2 (the worst case). To keep the error in drift time caused by this variation in B to less than $1ns$, we must know ϕ to better than 1° or to about 2 cm in Region 2.

Various aspects of chamber construction and operation, and choice of materials were tested in a prototype chamber. The test chamber is one meter long and has 44 sense wires with a maximum drift distance of 1 cm. Timing and pulse height measurements are done with commercial TDC and ADC modules which are read out by a CAMAC interface. Using a cosmic-ray trigger provided by a scintillator telescope, we have established the operating point of the chamber by determination of the high voltage plateaus and the discriminator threshold curves. We have written a program to find and fit straight line tracks to cosmic ray events in order to measure the efficiency and resolution of the device. Figure G4 shows the average residual for a layer which was excluded from the fit. The lower portion of the figure breaks the distribution into regions of different distance from the wire: 0-2 mm, 2-4 mm, 4-6 mm, 6-8 mm and 8-10 mm as one goes upward. The root-mean-squared deviation of the distribution is $165\mu m$. Figure G5 shows the resolution and the efficiency of the test chamber as a function of discriminator threshold and chamber voltage, respectively. We are continuing to use the small prototype as the test-bed to study various amplifier configurations, including mounting and grounding schemes.

We are currently constructing a large-scale prototype which will approximate a section of the actual chamber design for Region 3. It will have full-length wires, canted end-plates of composite construction, realistic placement of amplifiers, high and low voltage power and signal readouts. It should test most aspects of construction and operation, with the exception of overall end-plate strength and deflections.

References

- [1] F. Sauli, "Principles of Operation of Multiwire Proportional and Drift Chambers," CERN 77-09 (1977).
- [2] GARFIELD has been developed at the University of Mainz by R. Veenhof and revised by M. Guckes and K. Peters. See HELIOS note 154 (1986).
- [3] For more details on the design studies, see "Preconceptual Design Report; CEBAF End Station B", CLAS Collaboration (1988).

Figure G1: Location of wire positions on the end-plate for a portion of superlayer 1 in Region 3. Guard, sense and field wire locations are shown. The horizontal distance between sense wires is about 4 cm.

Figure G2: Drift time isochrones for six representative cells in superlayer 1 of Region 2. Shown are typical drift paths as well as 100 ns time contours. The magnetic field strength is 1 Tesla.

Figure G3: Most probable energy loss in 1.5 cm of argon-ethane for various particle types plotted as a function of particle momentum. The dashed lines are situated at plus or minus 9% from the mean to indicate the expected resolution.

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Figure G4: Residual distribution from track-fitting in the CLAS 44-wire prototype. The lower sub-graphs correspond to different distances of closest approach of the track to the wire; 0-2mm, 2-4mm, 4-6mm, 6-8mm and 8-10mm, respectively.

Figure G5: Resolution and efficiency results from the CLAS 44-wire prototype.

H Cerenkov Counters

H.1 Overview

The Cerenkov counters will be used for identifying electrons and separating them from other charged particles, mostly pions. In electron scattering experiments the primary charged particle background is due to negative pions. In performing experiments at the percent level of accuracy it is necessary to separate electrons from pions with high efficiency. For example, for inclusive cross section measurements the ratio of the number of pions misidentified as electrons to the number of electrons should be less than 0.01. The pion rejection power of gas Cerenkov counters is typically of the order of 100:1, which is insufficient if $\pi^-/e^- \geq 1$.

To achieve sufficient pion rejection in the CLAS detector requires a combination of techniques. At forward scattering angles, momenta are usually rather large, and the electromagnetic calorimeter provides sufficient additional pion rejection. Above pion threshold (e.g. 2.5 GeV/c for 1 atm freon gas as radiator) the full pion rejection has to be provided by the calorimeter. At large angles, where momenta are usually rather low, the efficiency of the calorimeter to separate pions from electrons becomes rather poor, and additional rejection power will be needed. Here drift chamber dE/dx information becomes useful. Only the combination of all 3 techniques will give sufficient pion rejection over a large angular and momentum range.

H.2 Threshold Gas Cerenkov Counters for CLAS

The gas Cerenkov counter planned for the CLAS detector employs mirrors to funnel the light toward specially positioned photomultiplier tubes. This type of design is most useful when there is a significant degree of correlation between the direction of the detected particles and their position in the detector. Due to the symmetry of the CLAS toroid, the azimuthal angle of the scattered particles remains almost unchanged when they pass through the magnetic field. This allows a mirror system to be built which focusses the light from particles with different azimuthal angles (and fixed scattering angle) to a point near the coil. The focii for particles from different polar angles will then be a line extending over the full polar angular range. The focal area will be equipped with an array of photomultiplier with sensitivity to single photoelectrons.

A Monte Carlo computer code has been implemented to aid in optimizing the overall detector design within the allocated space, which is 60cm of radiator. In order to maximize the number of Cerenkov photons generated, Freon 114 will be used as the radiating material ($n-1 = 14 \times 10^{-4}$, where n is the index of refraction), yielding about 1.08 photons per cm of trajectory. The high n causes a larger

Cerenkov angle, statistically reducing the correlation of the photon direction with the particle direction. The use of Freon 114 limits the pion-electron discrimination to a maximum momentum of about 2.5 GeV.

Pions may be misidentified when they produce knockon electrons with velocity greater than the Cerenkov threshold. These are primarily produced in the radiator gas, with other important sources being the Cerenkov entrance window and the material in the last layer of drift chambers. We have calculated the number of such electrons produced per incident pion as a function of pion momentum to vary from 1×10^{-3} up to 2×10^{-3} as the pion momentum varies from 1 to 2.5 GeV/c. The results are displayed in Figure H1. The efficiency for detecting these electrons is lower than that for primary particles since a large fraction will be produced at unfavorable angles.

Monte Carlo simulations were run for a number of possible mirror configurations, and our best design has been implemented in a test prototype (see below). In order to maximize the active surface area, the photomultiplier tube assemblies will be placed in rows within the shadow areas of the coils. Simulations indicate that under ideal operating conditions the average number of photoelectrons collected is about seven, giving a theoretical minimum inefficiency of about 1×10^{-3} .

Our simulations indicate that we will achieve our design goal of an electron efficiency of greater than 99%, combined with a pion rejection of greater than 100.

The detectors will be modular, with each unit subtending $1/2$ sector in the ϕ plane ($\Delta\phi \sim 25^\circ$) and subtending an angle in the θ direction of $\Delta\theta \sim 15^\circ$. Thus, there will be 12 modules around the ϕ direction for each interval of θ . In the initial stage of operation there will be three such rings for full ϕ coverage through $\theta \sim 45^\circ$. One sector will be instrumented for θ between 45° and 90° , for a total of 42 modules.

H.3 Prototyping

We have constructed a prototype of this design. Figure H2 shows a vertical cut perpendicular to the bend plane — the particles enter from below, and increasing ϕ is toward the right. Light rays originating at different angles ϕ are shown. Cerenkov radiation will be emitted in cones of half angle 3° at points along the particle trajectories, and focussed toward the Winston cones at the right. There are three Burle 8854 5 inch, bi-alkali, high gain photomultiplier tubes in the module.

The flat reflecting mirrors are made of aluminized mylar. We have measured a reflectivity of 0.85 over a range of wavelengths from about 350 nm through 600 nm. This compares favorably to the $\sim 90\%$ expected from a fluoride coated aluminum surface which would be vacuum evaporated to a thin glass substrate. For the curved

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mirror we plan to try several options.

We are testing this unit at the Brookhaven AGS test beam in April 1990. It is expected that valuable information regarding design improvements will be obtained from these tests. In particular, important information on the necessary active length of the detector will be obtained.

Figure H1: Knockon electrons with energies greater than the threshold energy for Cerenkov radiation (9.2 MeV).

Figure H2: Diagram of the optical configuration of the test Cerenkov module with idealized light rays.

I Scintillation Counters

For the purpose of triggering and particle identification by Time-of-Flight (TOF), a layer of scintillator counters will enclose the magnet and drift chambers. The primary design goal is to build a system with very good timing resolution ($\sigma \sim 150$ ps). The highest momentum particles go forward, so the system stresses the best timing resolution at small angles. This method of particle identification combines the momentum obtained from magnetic analysis with the velocity measured using the particle flight time from the target to the scintillation counters.

Bands of different particles can be separated on a plot of the flight time vs particle momentum, for which we show typical examples at forward and backward angles in Fig. 11. For example, in the forward direction π/K separation can be achieved at the 3σ level up to 2 GeV/c. Separation of kaons from protons can be made at the same level of significance up to 3.2 GeV/c.

The scintillators are positioned outside the drift chambers and Cerenkov counters to reduce multiple scattering and the production of knockon electrons. Each scintillator is placed perpendicular to the beam direction such that the width of the counter subtends about 3° of the scattering angle θ (see Figure E2). The counters are parallel to the normal drift chamber wires and thus span the azimuthal angular range of one sector. Each of the six sectors has 48 counters (20cm wide and 5cm thick) with a photomultiplier tube (PMT) at each end. The lengths of the counters vary continuously from backward to forward angles, ranging from 400 cm down to 30 cm. The total area covered by the scintillators is 176m^2 .

The first level trigger requires a hit in any of a contiguous number of scintillators to select particles scattered into the angular range defined by those counters. The maximum counting rate occurs in the forward direction. At a luminosity of $10^{34}\text{cm}^{-2}\text{s}^{-1}$ the hadronic rate per scintillator is 5kHz ($\theta=10^\circ$). This rate drops by an order-of-magnitude at $\theta=90^\circ$. Better timing resolution is achieved naturally at small angles due to the shorter counter length. The solid angle subtended is also reduced due to the longer distance from the target to the scintillator array.

Several systems have been built which are similar to the one we are proposing and have achieved comparable timing resolution [1, 2, 3, 4, 5, 6, 7]. The main problems we face in our design are those imposed by geometry which will require careful construction techniques. In order to understand the timing characteristics of the TOF counters, we have modeled the light production in the scintillator and collection to the PMT using a program based on one developed for the MARK II detector.¹ We have used this program successfully to model the performance of the counters used by the CLEO detector [3]. Although slightly optimistic, the simulation seems to be

¹This program was kindly provided to us by Ryszard Stroynowski from CalTech.

quite satisfactory. In Fig. 12 we show the expected timing resolution of counters 18cm wide (5cm thick) vs $\xi = \sqrt{L(cm)/N_e}$, where L is the length of the counter. N_e is the average number of photoelectrons (~ 280) collected per minimum ionizing track. This relation is expected to be linear [8] for $\sigma \geq 100ps$. In the simulation we have assumed that the light guides are straight and the characteristics of the Amperex XP2262 photomultiplier, a good compromise between cost effectiveness and the best time response. The Monte Carlo simulation predicts the resolution of the counters to vary between 70ps in the forward direction to 95ps at 90° . We will achieve our design goals allowing for a factor of 1.5-2 worse resolution of the TOF system than predicted.

The performance of the system, in particular the timing resolution, is crucial to the success of the CLAS so we are considering commercial electronics to instrument the counters. Both time and pulse height information will be obtained for each PMT, allowing time-walk corrections to be made in software. The pulse height also measures the energy loss in the counter which is independently useful for particle identification. Monitoring and calibration will be accomplished with pulses from a nitrogen laser and distributed with optical fibers.

It is interesting to note, that the flight time provides a better measurement of the particle energy than magnetic analysis for slow particles when the resolution is dominated by multiple scattering. For example, the momentum resolution for protons and deuterons with momentum less than 500 MeV/c is better than 1%. If neutrons interact in the counters (efficiency $\sim 5\%$), their energies may also be determined this manner.

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Figure I1: Flight time (relative to $\beta=1$ particles) vs. the momentum for various particles. The dotted lines indicate $\pm 1\sigma$ error bands for both flight time and momentum. We show typical plots for forward and backward angles.

MC Predictions for the Resolution of the TOF Counters

Figure I2: Predicted resolution for the CLAS TOF counters compared to the performance of existing systems. The solid line shows an empirical representation of previous experience with TOF counters [8].

J Electromagnetic Shower Calorimeter

J.1 Overview

The forward regions of the six CLAS detector sections, corresponding to scattering angles between 8° and 45° , will each be equipped with an electromagnetic shower calorimeter (ESC). For one sector the coverage is extended to include scattering angles up to 90° .

The calorimeters are an integral part of the the total CLAS detector system. They are particularly important in identifying both charged and neutral particles. For instance:

- In electron scattering experiments, the ESC's are used together with the threshold Cerenkov counters for electron and pion identification over an energy range of 0.5 to 4.0 GeV. By properly tagging pions, one can greatly reduce background due to misidentified electron triggers. ESC based background suppression is available both at the data acquisition trigger level and later at the more refined analysis level.
- The ESC will be used in the reconstruction of π^0 and η via detection and identification of their 2γ decays, and in the detection of radiative photons.
- The ESC will also be used for the detection of neutrons and the discrimination between photons and neutrons.

The calorimeter is designed to operate in a high electromagnetic background environment at luminosities of $10^{34} \text{ cm}^{-2}\text{sec}^{-1}$. In such an environment, the average number of background photons emerging from a hydrogen target in the angular range of 8° to 45° is $\approx 10^8\text{sec}^{-1}$ in the energy range of 1 KeV to 1 MeV. High energy photons ($E_\gamma \geq 1 \text{ MeV}$) are generated at a rate of 10^7sec^{-1} .

In Section J.2 we state the technical parameters for the calorimeter determined by the physics requirements. In Section J.3 we describe a detailed design of a lead/scintillator sandwich calorimeter that meets these requirements. A second option, namely a lead/scintillating fiber calorimeter is also under consideration. Prototypes of both designs are being tested at BNL before a final decision is made.

J.2 Requirements

J.2.1 Electron Identification

Among the major purposes of the ESC is the identification of electrons in the momentum range of 0.5 GeV/c to 4.0 GeV/c. By identifying scattered electrons and

measuring their scattering angles and momenta, one determines kinematic quantities Q^2 , W , and ϵ . In many experiments it is advantageous to determine these quantities approximately at the trigger level. Determination of Q^2 and W at the trigger level sets resolution requirements for scattering angle and momentum which can be satisfied with the use of the ESC's together with other CLAS detector elements. An angular resolution of approximately $\delta\theta \approx 3^\circ$ is achieved using the scintillation trigger counters. An energy resolution of

$$\frac{\sigma_E}{E} \leq \frac{0.1}{\sqrt{E(\text{GeV})}} \quad (\text{J1})$$

is available using the ESC. The combination provides the necessary trigger input for a first pass filter on the kinematic nature of an event.

Measurements of absolute cross sections to an accuracy of a few percent is facilitated by electron detection efficiencies greater than 98%, independent of energy, incident angle, and impact position on the ESC.

J.2.2 Pion Rejection

The ESC should help to distinguish between pions and electrons. The requirements for electron selectivity and pion rejection strongly depend on the π/e ratio at a given angle and momentum. For example, at small scattering angles and high particle momenta, the ratio π/e is much less than one, while at large scattering angles and low particle momenta, the ratio π/e is much greater than one. To be able to measure absolute cross sections to an accuracy of a few percent, the ratio of pions misidentified as electrons to the number of electrons at the same angle and momentum should not exceed a few times 10^{-2} . The threshold Cerenkov counters go a long way toward the proper identification of electrons and pions. However, pion rejection factors thus obtained are insufficient for absolute cross section measurements. For momenta greater than 2.8 GeV/c, identification of pions and electrons relies entirely on the information provided by the ESC. The pion rejection provided by the ESC should therefore increase with increasing particle momenta.

J.2.3 Reconstruction of π^0 and η decays

The ESC will be used to reconstruct π^0 and η with momenta up to 3.5 GeV/c. A mass resolution of $\delta m/m \leq 0.15$ is sufficient to provide adequate separation between π^0 and η and to reject multiple pion background. The particle mass resolution is limited by the uncertainties in the energy of decay photons and the determination of the decay opening angle of these photons. Figure J1 displays the relative importance

of these two components for π^0 and η as a function of particle momentum. If one assumes a photon energy resolution given by Equation J1 then an angular resolution of $\delta\theta \approx 10$ mrad is necessary to reconstruct π^0 events with the required mass resolution up to the highest momenta. For η particle the mass resolution is totally dominated by uncertainties in the energy of the decay photons.

J.2.4 Neutron Detection

In addition to the measurement of electromagnetic energy, the ESC should also have good photon/neutron discrimination capabilities. Good neutron detection efficiency will also be important for a number of experiments. Due to their large hadronic interaction length, neutron detection efficiencies exceeding 50% can be achieved, without increasing the total radiation length beyond what is needed for the total absorption of electromagnetic showers. A distinction between photons and neutrons for momenta up to 3 GeV/c is required to cover nearly the full phase space. The only practical way to achieve this is to use time-of-flight techniques. A time resolution of ≈ 1 nsec is required to achieve this goal.

J.3 The Lead/Scintillator Sandwich Design

J.3.1 Small Angle Calorimeter Geometry

Each of the six CLAS sectors will be equipped with an independent electromagnetic shower calorimeter having an approximate triangular shape (Figure J2). An ESC consists of 13 identical submodules (SM), each submodule having 3 layers of 2 mm thick lead plates interleaved with 10 mm thick, 10 cm wide scintillators. Each SM is thus 1.14 radiation lengths thick. The scintillator strips in one layer are rotated by 120° relative to the previous plane such that they are parallel to the 3 sides of the triangle (U-, V-, and W-strips). This provides the possibility of a stereo readout, which is necessary to resolve multiple particles in the ESC. The scintillation light is converted into green light by wavelength shifter bars attached to one end of the strips. Five of the SM's constitute the radially inward portion of the ESC nearest to the target. The remaining eight SM's form the outer portion of the ESC. The inner and outer portions of the ESC are read out independently, thus providing longitudinal sampling of the showers.

J.3.2 Large Angle Calorimeter Geometry

In one of the six CLAS sectors the coverage of the calorimeter is extended to 90° . This region is covered by a rectangular calorimeter having an area of $3.6 \times 3.9 \text{ m}^2$.

The energies of particles scattered into this calorimeter is limited by kinematics to 1.8 GeV (for proton targets), assuming a 4 GeV beam. The total thickness of the large angle calorimeter is therefore reduced to 12 radiation lengths. Alternate layers of scintillator strips are perpendicular to each other. Ambiguities in the reconstruction of shower positions are minimized by reading out both ends of the scintillator strips. Waveshifter bars are used for readout in a manner identical to that used for the triangular calorimeters.

J.3.3 Expected Performance

Uniformity of Response. The largest scintillator strips in the triangular ESC's are about 3.5 m long. Due to light attenuation the light output will depend upon the position where the light was generated. To minimize degradation of the calorimeter performance due to attenuation, we use high quality scintillator with a long attenuation length. The response of the triangular ESC is then largely independent of position. Figure J3 illustrates the expected pulse height deviation for the U, V, W sums relative to the sums of the central strips. As input, one assumed an equal energy deposition in the scintillator strips running in the U, V, and W orientations, and an effective light attenuation of 2.8m. The deviations are always less than 15 percent. This effect is sufficiently small, such that one can make use of the calorimeter energy information in the data acquisition trigger. After reconstruction of the shower position the measured calorimeter response can be corrected for light attenuation.

Energy Resolution for Electromagnetic Showers. The uncertainty in the calorimetry of electromagnetic showers is determined by various sources. The most important ones are:

- sampling fluctuations (σ_{sp})
- leakage fluctuations (σ_{lk})
- photo-electron statistics (σ_{ph})
- and light attenuation fluctuations (σ_{at}).

The combined effects of sampling fluctuation and energy leakage have been studied using the GEANT3 [1] detector simulation package for electrons normally incident on the ESC. An energy cutoff of $E_c = 0.1$ MeV was used in the simulation. In Figures J4 and J5 the peak position and the relative Gaussian width of the energy

distribution are shown as a function of the particle energy. For $E \leq 4$ GeV the widths are well reproduced by the parametrization:

$$\frac{\sigma_{sp+lk}}{E} = \frac{0.06 \pm 0.005}{\sqrt{E(GeV)}} \quad (J2)$$

Up to 4 GeV the response is also linear. It is only at the highest energies that leakage in the rear of the calorimeter causes slight deviations from the linear response.

The energy deposited in the active material is approximately 330 MeV for a 1 GeV incident electron or photon. From test measurements [2] conducted using NE110 scintillator material, and wavelength shifter bars made of NE172 [3], 10 - 15 photoelectrons per MeV deposited energy were obtained using a standard PMT, with a photon conversion efficiency of 20%. Given an average attenuation length of 2.8 m, one obtains 6.6 and 10.0 photoelectrons per MeV. This contributes additional uncertainties of approximately

$$\frac{\sigma_{ph}}{E} = \frac{0.022}{\sqrt{E(GeV)}} \quad (J3)$$

This contribution is largely independent of the sampling fluctuations and thus

$$\sigma_{sp+lk+ph} = \sqrt{\sigma_{sp}^2 + \sigma_{lk}^2 + \sigma_{ph}^2} \approx \frac{0.066}{\sqrt{E(GeV)}} \quad (J4)$$

Contributions to the resolution due to light transmission irregularities are more difficult to estimate. At least two sources for such fluctuations can be identified: (1) fluctuations in the light transmission properties in the scintillator strips (material inhomogeneities, fluctuations in the surface properties, etc.), and (2) light attenuation in the wavelength shifter bars. The latter can be corrected for by controlling the light transmission from the scintillator strips to the wavelength shifter bars to match the known attenuation properties of the wavelength shifter. The size of contribution (1) has to be obtained by measuring the relevant properties of the scintillators used. One anticipates that fluctuations in the light transmission do not contribute more than $\frac{0.05}{\sqrt{E}}$. Therefore one expects the total uncertainty to be

$$\frac{\sigma_{Etotal}}{E} \leq \frac{0.085}{\sqrt{E(GeV)}} \quad (J5)$$

Pion Rejection. Using the GHEISHA package in GEANT3 the response of the ESC to negative pions was simulated, and compared to the response to electrons. As

an example, Figure J6 displays the total energy loss in the active part (scintillator) of an ESC for 1.5 GeV/c pions and electrons. The peak is due to pions which do not interact in the calorimeter but suffer only dE/dx losses. Since the momenta of the incident particles are measured with the CLAS drift chamber one can place momentum dependent cuts on the energy measured in the calorimeter. In addition, one can make use of the longitudinal and transverse sampling in the calorimeter. The different longitudinal shower development for electrons and pions is illustrated in Figures J7 and J8. Moreover, the transverse shower development is quite different for electromagnetic and hadronic showers. Hadronic showers tend to spread out over a more extended area than electromagnetic showers. By making use for these different distributions, one can significantly improve pion rejection. Figure J9 illustrates the pion rejection factor

$$P_r = \frac{\text{number of rejected } \pi^-}{\text{number of missidentified } \pi^-} \quad (\text{J6})$$

as a function of energy, for different electron detection efficiencies. For pion momenta greater than 1 GeV/c, rejection factors $\geq 10^2$ can be achieved.

Reconstruction of π^0 and η Decays. π^0 and η particle can be identified by reconstructing their two photon decays. Due to the high granularity of the ESC, photons from π^0 decays can be reconstructed for momenta up to ≈ 3.5 GeV/c. Figure J10 shows as an example the calorimeter response to a 3 GeV/c π^0 . The two photons are well isolated and their respective energies and angles can be reconstructed. Figure J11 shows the reconstructed two photon mass distribution for 1.5 GeV/c π^0 emitted at an angle $\theta = 25^\circ$. The 2γ mass resolution is well below the specified requirements. Note that this simulation includes fluctuations due to sampling and leakage.

Neutron Detection. The total hadronic absorption length of the ESC is $l_{abs} \approx 1$ which permits the detection of neutrons with high efficiency. With an energy threshold of 20 MeV, efficiencies in excess of 50% are achieved for neutron momenta above 600 MeV/c (see Figure J12). It should be noted that not all nuclear reactions are included in the GHEISHA simulation package, in particular at lower energies. Therefore, one cannot expect that fine details of the efficiency curve at lower energies are correctly predicted. At higher energies the gross features are well determined and agree with estimates employing global material properties such as hadronic interaction lengths.

Time Resolution. The time resolution of a scintillator sandwich calorimeter is intrinsically very good. The present design is intended to achieve a resolution of 1 nsec (FWHM). This uncertainty is dominated by longitudinal position knowledge of the shower. To achieve a time resolution better than 1 nsec, finer longitudinal sampling is required. The current design resolution is such that one can separate neutrons and photons for momenta up to 3 GeV/c.

J.4 Calibration and Monitoring

Calibration and monitoring of the ESC's will have the following goals:

- Establish a relation between the detected response and the energy of the incident particle.
- Monitor variations in the detector response. In the proposed design, groups of scintillators are read out through one wavelength shifter bar and phototube combination. To monitor individual scintillators the calibration system would be required to pulse scintillators sharing the same readout channel independently.
- Detect component failures.
- Provide a method to tune the response (eg. match gains for a threshold trigger)
- Aid in the electronic setup and testing.

The ESC will initially be calibrated either with electrons, muons and pions from a test beam or with cosmic ray muons. Monitoring the energy calibration can be accomplished by evaluating the detector response to electrons, charged pions and a distributed UV pulsed laser. The comparison of electron response to minimum ionizing particle (using the minimum dE/dx loss peak) response can be used to establish the fraction of the shower energy deposited in the scintillator material. The comparison of the electron energy and the pion energy with the laser system could be used to establish the absolute energy reference scale for the laser system.

J.4.1 The Calibration System

The calibration system will inject light into each individual scintillator using a N_2 laser and a fiber optic system. Fibers for the present design are fed through holes drilled in the support structure and mounted on the ends of each of the scintillators. The laser intensity is monitored with a photo-diode and a radioactive source. One would like to be sensitive to the response of individual scintillators. This can be accomplished in several ways:

- use of independent lasers.
- a fiber positioning system with several bundles that can be alternately illuminated.
- beam splitters and shutters.

The laser system would test the transmission of light through the detector. It would easily isolate individual component problems. It could also be used to set up the electronic timing and phototube gains.

Various options are being explored. For example, one may use 100 micron graded index fused silica fibers encased in a protective coating. The total fiber length required for such a system is 15,000 meters. The method used to distribute light to all fibers should not generate a large loss and should be uniform. The minimal configuration would be to position a bundle of fibers within the emittance cone of a single fiber.

J.5 Triggering

The granularity of the CLAS ESC provides the possibility of a rather sophisticated and selective trigger scheme. Initially, a relatively simple trigger scheme based on the total energy deposition in one of the six ESC sectors would be employed. When combined with information from the trigger scintillation counters and the gas Cerenkov counters this will generate an efficient electron trigger with reasonable angular and energy definition. If necessary, a more selective cluster finding trigger may be implemented later. Such a trigger would be used to distinguish between single and multiple energy clusters to allow for the selection of single electrons, photons, as well as π^0 and η particles.

J.6 Alternative Solutions and Prototyping

As mentioned in section J.1, an alternative design solution for the ESC is under consideration. This design makes use of recent advances in the development of scintillating fibers of comparable attenuation length to plastic scintillator bars. Use of scintillating fibers allows the design of electromagnetic calorimeters with much finer sampling granularity, which is expected to lead to improved energy resolution for electromagnetic showers.

Small towers made of scintillating fibers embedded in lead have been manufactured at the University of Illinois for an experiment at LEAR. These towers were tested with electrons hitting the towers at a small angle w.r.t the fiber orientation. An energy resolution of approximately 6% at 1 GeV has been achieved ⁴.

We expect that in an arrangement where the fibers are oriented perpendicular to the direction of the incident particles, the finer shower sampling will yield further improvement in the energy resolution. An arrangement under consideration for CLAS is shown in Figure J13. A left/right readout is used to determine the impact position of the particles. Like in the lead/scintillator sandwich design the longitudinal shower profile would be sampled twice. The position resolution and multiple hit resolution, however, are not as good as in the design described above.

Prototypes of the two versions have been constructed:

- A reduced version of the sandwich calorimeter with 11 scintillator stacks in each view (instead of 33), but with the full depth of 15 radiation lengths. Two-fold longitudinal readout has also been implemented.
- Two modules of a lead/scintillating fiber arrangement, with left/right readout and two-fold longitudinal segmentation. The complete arrangement has dimensions of $120 \cdot 18 \cdot 24 \text{ cm}^3$.

Both prototypes are being tested at BNL with electrons, pions, and muons for energies up to 6 GeV. We expect valuable information on the performance of the ESC as a result of these beam tests.

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Figure J1: Mass resolution for π^0 and η via 2γ mass reconstruction. An energy resolution of $\sigma_E/E = 0.1/\sqrt{E(\text{GeV})}$ and an angular resolution $\delta\theta=10$ mrad have been used.

Lead/Scintillator Sandwich Calorimeter with Wavelength Shifter Readout.

Figure J2: One sector of the CLAS Forward Calorimeter. The scintillator light is read out via wavelength shifters.

Figure J3: Deviations in percent of pulse height sums over the U, V, W strips relative to the sums in the center. Equal energy deposition in all three views is assumed.

Figure J4: Peak position of the energy deposited in the scintillators for incident electrons (GEANT simulation).

Figure J5: Energy resolution of the ESC multiplied by $\sqrt{E}$ (GEANT simulation).

Figure J6: Energy deposited in the scintillator strips for 1.5 GeV/c pions and electrons (GEANT simulation).

Figure J7: Energy deposited in the front part and rear part for 1.5 GeV/c electrons. The dashed line indicates a window with 95% electron detection efficiency (GEANT simulation).

Figure J8: Same as in Figure 7, but for 1.5 GeV/c π^- 's.

Figure J9: π^- rejection factor versus pion momentum for $\geq 95\%$ (open squares) and $\geq 98\%$ (full squares) electron detection efficiency (GEANT simulation).

Figure J10: Energy distribution in the U, V, W strips of a calorimeter segment, generated by a 3 GeV/c incident π^0 with symmetric 2γ decay.

Figure J11: Reconstructed 2γ mass distribution for 1.5 GeV/c π^0 .

Figure J12: Neutron detection efficiency for 20 MeV energy threshold in the scintillator strips (GEANT-GHEISHA simulation).

Figure J13: Possible arrangement of a lead/scintillating fiber ESC. The fibers are oriented perpendicular to the front face of the ESC. The scintillator light is read out at both ends

K Detector Simulation

K.1 GEANT simulation of CLAS

For a system with the complexity of the CLAS detector, detailed Monte Carlo simulation studies are essential:

- to design and optimize the detector components,
- to develop and test the reconstruction and analysis programs, and
- to interpret the experimental data.

The GEANT software package [1] developed at CERN is used for the CLAS detector simulation. The main applications of GEANT are:

- tracking of particles through an experimental setup to study detector response and acceptance,
- the graphical representation of experimental setup, particle trajectories, and detector response.

Both features are combined interactively, making GEANT a very powerful tool, especially in the design phase of a detector.

GEANT simulates the experimental setup in an efficient and simple way using geometric volumes. Particles (generated by a Monte Carlo method) are transported through the various regions of the detector, taking into account the detector geometry and all physical effects, such as electromagnetic and hadronic interactions, deflection in electromagnetic fields, and decays. All particle trajectories and the responses of the sensitive detector elements are recorded and can also be visualized interactively.

The present implementation of the CLAS into GEANT allows us to study particle tracking, energy deposition, hit pattern in the sensitive detector elements, and particle time-of-flight. Figure K1 shows a view of the CLAS detector at $y = 0$ (zx -plane) together with a typical Monte Carlo generated event from the reaction $e + p \rightarrow e' + p + \eta$ as seen in the CLAS.

K.2 Physics Monte Carlo

Simulation of physics to be observed with the CLAS detector is predominately undertaken using the program CELEG [2] developed at CEBAF. CELEG is a general

purpose Monte Carlo event generator for the simulation of lepton - nucleon interactions. CELEG generated events encompass elastic scattering, baryon resonance production, and non-resonant deep inelastic processes. CELEG may also be used to generate lepton - nucleus quasi-elastic scattering events. CELEG is structured such that the addition of more general lepton - nucleus scattering models to CELEG is straight forward. In particular, lepton - nucleus models can readily incorporate already coded lepton - nucleon processes.

CELEG is currently used for detector studies and trigger testing as well as development of the CLAS physics program. CELEG is distributed to and used widely by the CLAS collaboration.

K.3 FAST Detector Simulation

The FAST Monte Carlo program [3] has been developed for the purpose of estimating the acceptance and expected resolution of the CLAS detector in a quick manner. This implementation has been quite useful in preparing proposals and generating expected experimental distributions. The FAST Monte Carlo, as GEANT, reads events generated by CELEG, and models the effect of resolution and acceptance of the CLAS detector on the distributions of interest.

This application program has been written so that specific analysis routines may easily be incorporated into the overall structure. It can therefore be used to design an experiment to be run with the CLAS detector. The resolution and acceptance parameterization which are input to FAST are determined *a priori* as a function of the momenta of particles at the target. This procedure allows rapid computation of experimental quantities. For example, 100k events may be processed in one hour of VAX8700 CPU time.

K.4 Background Simulation in CLAS

In the experimental environment of an intense high-energy electron beam, a high flux of electromagnetic particles is emitted from the target. This flux often determines the maximum luminosity that an experiment can tolerate. This is particularly true for a detector such as CLAS which has a completely open structure, where all detector elements have direct sight of the production target.

There is only limited experience with the operation of large-aperture spectrometers in fixed target electron scattering experiments [4, 5]. An experiment that may be compared to the CLAS is the LAME [5] detector which was operated at the Cornell 12 GeV electron synchrotron. This detector was able to operate at instantaneous luminosity up to $3 \cdot 10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$. At higher luminosities, spurious hits made

event reconstruction impossible.

In contrast to the LAME detector, background charged particles emitted in the very forward direction are not swept into the active detector region. This is due to the field-free region around the beam line. In addition, the small, normal-conducting toroidal magnet placed around the target area will provide effective shielding against charged electromagnetic background emerging from the target at larger angles. Therefore, the CLAS detector should be able to handle considerably higher luminosity than did the LAME detector.

In order to obtain a more quantitative estimate of the luminosity limitations, the GEANT3 package was used to simulate the detector response to electromagnetic background. Energy and angular distributions of photons, e^+ , and e^- emerging from the target were generated for specific target materials and geometries using the EGS4 code [6]. Examples of electron and photon spectra generated this way are shown in Figure K2 and Figure K3. The EGS4 spectra served as input to the GEANT3 event generator. In addition we have implemented sources of electromagnetic background which are presently not implemented in EGS4 like wide angle bremsstrahlung, and the emission of X-rays after electron knock-out from atoms.

All particles generated during the sensitive time of the drift chambers were traced through the magnetic field and the detector system. The total number of particles traced through the detector volume depends on the specific target material, target thickness, and incident electron beam energy. For example, using a 3 GeV electron beam at a luminosity of $10^{34} \text{ cm}^{-2} \text{ sec}^{-1}$, approximately 2500 electrons and positrons, with energies greater than 100 keV and 50 photons with energies greater than 1 keV emerge from a 7.5 cm long liquid hydrogen target, in an angular range between 2° and 180° within 200 nsec. From a 20 μm thick lead target, about 1000 electrons or positrons and nearly 20,000 photons, are emitted at the same luminosity and time period.

References

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- [5] L.A. Ahrens *et al.*, Nucl. Instr. and Meth., **173**, 537 (1980).
- [6] W.R. Nelson *et al.*, SLAC Report 265 (1985).

Figure K1: View of CLAS detection system as implemented in GEANT at $y = 0$ (zx-plane) together with a typical Monte Carlo generated event from the reaction $e + p \rightarrow e' + p + \eta$. Only the sensitive detector elements are shown; structural elements are left out.

Figure K2: Energy spectrum of background electrons emitted from a liquid hydrogen target at a scattering angle of 30° . The integrated luminosity is $10^{33} \text{cm}^{-2} \text{s}^{-1}$.

Figure K3: Energy spectrum of background photons emitted from a liquid hydrogen target at a scattering angle of 10° . The integrated luminosity is $10^{33} \text{cm}^{-2} \text{s}^{-1}$.

L Triggering and Data Acquisition

L.1 Triggering

The CLAS detector is designed to run at a luminosity of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. This corresponds to a hadronic interaction rate of approximately 10^6 s^{-1} . We describe a four level hierarchical electronic triggering system for data acquisition in such an environment. This system is designed to select events of interest and reject background processes. Table L1 provides an overview of the trigger levels and figure L1 illustrates the relationship between the triggering and data acquisition systems.

As shown in table L1, the LEVEL 1 trigger establishes the time bases for digitization. The LEVEL 1 trigger decision is made using the pattern of hits in the scintillator and Cerenkov layers, and the energy deposited in the electromagnetic calorimeter. Analog signals from the electromagnetic calorimeter are summed together within sub-regions; each of these sums is then compared against a programmable threshold. The LEVEL 1 trigger is programmed by specifying which hits and sums over threshold from each sector must be in coincidence. The trigger decision for LEVEL 1 is expected to be made within 200 ns after the event.

The LEVEL 2 trigger performs crude track finding using hits in the drift chamber to determine if the hits in the scintillator, Cerenkov, and electromagnetic calorimeter layers are due to a charged particle or to a neutral conversion. Each hit in the LEVEL 1 trigger may be required to be confirmed as being consistent with a track, required not to be consistent with a track (as in a neutral trigger), or passed without checking. The LEVEL 2 trigger is programmed by specifying which bits from each sector (after track confirmation) must be in coincidence. If an event passes the LEVEL 2 trigger, event digitization and local readout begins, otherwise the front end electronics are reset. This decision is made within $2 \mu\text{s}$ after the event.

The LEVEL 3 trigger forms track segments from the hits in the drift chambers, then links those segments into tracks with an estimated momentum and production angle. These tracks may optionally be matched up with hits in the scintillator, Cerenkov, and electromagnetic calorimeter layers. The LEVEL 3 trigger may specify up to eight tracks in each event. Each track is defined in terms of momentum, angle, and sign, as well as the presence or absence of hits in the scintillator, Cerenkov, and electromagnetic calorimeter layers. The LEVEL 3 trigger is expected to have a momentum resolution of about 25% and a polar angular resolution of about 5 degrees. Events passing the LEVEL 3 trigger are completely read out, those which fail are rejected. This occurs within 10-20 μs of the event.

The event readout is handled by the data acquisition system, which assembles fragments from different detector subsystems into complete events and pushes them

LEVEL	Technique	Action Initiated	Time to decision
1	Hits in scintillator and Cerenkov detectors, energy sums in electromagnetic calorimeter	LEVEL 2 Trigger PMT start Drift chamber stop	200 ns
2	Crude point-to-vertex road finding in drift chambers	LEVEL 3 Trigger Event digitization Local readout	2 μ s
3	Track finding in drift chambers	LEVEL 4 Trigger Event readout	10 μ s
4	Event reconstruction	Event recording	1-10 MIP-s

Table L1: Overview of the trigger levels.

into the LEVEL 4 trigger microprocessor farm. This consists of a large number of microprocessors in the 40-100 MIP range which use the full event information to reconstruct the event. Each event is sent to one processor where it is processed to determine if it meets the software criteria. An accepted event is stored permanently and, with or without further analysis, made available to the online experiment control computer. The processor is then free to receive the next event. Rejected events are discarded after providing some statistical information. The number of nodes will depend on the amount of processing required in LEVEL 4, which can go from simple event reformatting with a few processors in an initial phase, to a sophisticated on line filtering and analysis stage with 100 or more nodes.

L.2 Data Acquisition

The estimated average event size for the CLAS is 5 Kbytes. Initially CLAS experiments will often use inclusive electron or hadron triggers, producing an expected event rate of up to 1.5 kHz. During this period little actual filtering will be done by the microprocessor farm — its job will be mainly event reformatting — so the event rate written to tape will also be about 1.5 kHz. The data acquisition system is therefore being designed to handle a sustained throughput greater than 10 Mbytes/s into the microprocessor farm and onto tape in the initial configuration, with minimal impact on the dead-time of the detector. Additional data links and tape drives may be easily added to handle future increases in event size or rate.

Figure L2 shows the overall architecture of the proposed data acquisition system. Readout controllers in each crate of front end electronics transfer the data at high speed (10 Mbytes/s) into a switching network. This network merges the event

CLAS Trigger Hierarchy

Figure L1: Overview of the trigger system.

fragments from different parts of the detector into complete events which are transferred into the microprocessor farm. Multiple paths through this network ensure that there will be no bottlenecks in the system. Output from the microprocessor farm is written to 8 mm tape. The use of 8 mm tape allows 2 Gbytes of data to be stored on a cassette no larger than a conventional audio cassette.

A local area network links the host, the farm, several scientific workstations, and the front end readout controllers. This network is used for downloading control and data information as well as for event monitoring and analysis. This configuration allows monitoring the data at any stage of the readout pipeline, to check on the microprocessor farm for example, as well as complete analysis of some fraction of the events written to tape.

CEBAF Reference Data Acquisition System

Figure L2: The proposed data acquisition readout and control architecture.

M Pattern Recognition & Track Reconstruction

The information from the wire chambers is used to reconstruct the momenta and angles of charged particles at the interaction point. In this section we describe track finding and fitting procedure.

M.1 GEANT Simulation of the CLAS Drift Chambers

The CLAS tracking detector is organized in 3 separate packages (Region 1-3) each consisting of a normal and a stereo superlayer (see Figure K1). A superlayer consists of 6 layers of sense wires; each layer consists of 192 sense wires which are parallel to the y axis, perpendicular to the middle plane in a given sector. The wires in stereo superlayers are canted at 6° with respect to the normal wires. The cells are oriented such that subsequent layers are shifted by one-half of a cell in order to resolve the left-right ambiguity. Realistic particle trajectories traversing the CLAS magnetic field are simulated. The coordinates (x_i, y_i, z_i) of hits generated by a charged particle passing through a cell are digitized. The digitization returns the wire number and the minimum drift time. The drift time is smeared according to the expected spatial resolution of the measurement, $200 \mu m$. Small-angle stereo wires give y -coordinate resolution of about $3 mm$.

M.2 Pattern Recognition

The CLAS drift chambers are grouped into superlayers, rather than being distributed uniformly along particle trajectories. Such a distribution allows one to reconstruct local vectors from each cluster of wires and improves the pattern recognition capabilities of the tracking detector. For example, this helps to resolve the left-right ambiguity in a non-uniform magnetic field. Our code is designed for rapid event reconstruction. We have implemented global pattern recognition using bit manipulation rather than doing local point-to-point searches or global trial-and-error fits.

The first stage of pattern recognition utilizes cell hit information without the use of drift times. This technique, guided by the superlayer geometry of the CLAS detector, identifies tracks passing through a specific drift cell or group of cells. A dictionary is generated by a program which performs tracing of particles through the CLAS detector. It contains cell hit patterns which correspond to real tracks. The first part of the dictionary helps to recognize a track segment within a superlayer. The second, much larger part of the dictionary, is used to link the track segments to form track candidates.

Thus pattern recognition is performed in two steps:

1. For each superlayer, the cell hits in individual layers are locally linked (using the first part of the dictionary) to form track segments. From the wire positions and drift distances the track segment parameters are calculated. All possible left-right combinations are tried, and the combination with the best χ^2 is chosen.
2. Track segments from different superlayers are linked (using the second part of the dictionary) to form track candidates.

Finally, the set of track candidate hits, with crude track parameters, are fed to a track fitting program (described below) which determines final track parameters ($1/p, \theta, \varphi, y, z$) at the target position and the associated error matrix.

M.3 Momentum Analysis

An ever-returning problem in the analysis of experimental data is the determination of the momentum of a particle moving in a known magnetic field. The problem is not only to compute the momentum accurately but also as fast as possible. We have investigated three methods which differ in accuracy but also in computer time required.

M.3.1 Tabulated Functions

The fastest way to determine the momentum from the measured track coordinates is to use explicit expressions for the momentum as a function of the measured coordinates. The accuracy in momentum determination is estimated to be of the order 1.3% (σ). The method is very fast; it can be used for event preselection, both in the trigger and in the off-line analysis.

M.3.2 Spline Method

A spline method [1] has been developed to determine the momentum from the observed track coordinates. The CERN routine SPLIN3 was used for the calculation of the third-order spline approximation between the observed points. The spline fit returns functions and 1st and 2nd order derivatives, which are used for integration of the equation of motion in the magnetic field. This method is slower than using tabulated functions but still much faster than step-by-step track tracing through the magnetic field. The process is iterated to get an improved value of the momentum; then, only the local slope of the track (rather the momentum itself) is varied. The method is independent of the coordinate system and is particularly suited for experiments involving particles spread out over a wide angular range. The spline

method was tested over the full range of momenta and angles and was found to work reliably. As an example, the spline fit method gives a momentum resolution (σ) of $\delta p/p = [0.30 - 0.45]\%$ for $p = 1\text{GeV}$, $\theta = 40^\circ$ and $\varphi = 0^\circ - 20^\circ$; the error includes both position resolution and multiple scattering contribution as well as uncertainties due to the spline approximations.

M.3.3 Reference Trajectory Method

A maximum amount of information can be extracted from the measured coordinates by performing a variational calculation that can ultimately generate a trajectory that connects all measured coordinates with the smallest deviations possible. This can be achieved by generating a reference trajectory close to the measured hits and then evaluating the deviations between the coordinates of the hits and the reference trajectory. We have used the CERN package [2] which allows one to calculate the average trajectories of particles and to calculate the transport matrix as well as the propagated error covariance matrix. Each trajectory is characterized by five independent variables as a function of one parameter (e.g. the path length). The most common representation of these five parameters are: $1/p, \theta, \varphi, y, z$, where θ and φ are the polar and azimuthal angles related to the momentum components, and y and z are the coordinates of the trajectory in a local orthonormal reference frame with the x axis along the particle direction. This method relies on initial values for these five parameters defined at least on one space point, for example at the target position. The method can be applied in the most general case: in an inhomogeneous magnetic field and in the presence of multiple scattering.

To reconstruct the particle trajectory parameters x_0 (5 variables described above) at the plane 0 (target position) one can use the measured coordinates x_i^m at N different detector planes. First, a trial trajectory x_i^t is calculated (by tracing through the detector), starting with a value x_0^t at the target position (obtained with the spline method). Actual trajectory parameters are obtained by:

$$x_0 = x_0^t + \Delta x_0 \quad (\text{M1})$$

where

$$\Delta x_0 = \sigma_{x_0} \sum_{i=1}^N T^T(i, 0) (\sigma_i^m)^{-1} (x_i^m - x_i^t) \quad (\text{M2})$$

and the covariance matrix of x_0 given by:

$$\sigma_{x_0} = \left\{ \sum_{i=1}^N T^T(i, 0) (\sigma_i^m)^{-1} T(i, 0) \right\}^{-1} \quad (\text{M3})$$

Here $T(i, 0)$ is the 5×2 transport matrix between plane 0 and plane i , and σ_i^m is the 2×2 covariance matrix of the measurement on plane i . If the first estimate of x_0 is unacceptable (χ^2 test) the second tracing, with new starting values $x_0^t = x_0$, is performed. It was found that for tracks near coils ($\varphi > 15^\circ$) 2 or 3 iterations are needed.

This method has been implemented and tested with the Monte Carlo generated events (GEANT). The following are typical resolutions (σ), obtained with the reference trajectory method, for $p = 1\text{GeV}$, $\theta = 40^\circ$ and $\varphi = 0^\circ - 20^\circ$ (unknown vertex at the target position):

$$\begin{aligned} \delta p/p &= [0.15 - 0.30] \% \\ \delta\theta &= [0.50 - 1.00] \text{ mrad} \\ \delta\varphi &= [1.00 - 2.00] \text{ mrad} \\ \delta y &= [0.10 - 0.20] \text{ cm} \\ \delta z &= [0.05 - 0.10] \text{ cm} \end{aligned} \tag{M4}$$

The errors include the contributions from position resolution and multiple scattering.

The only disadvantage of this method is the large computer time required to reconstruct one track. In order to reduce the computer time we plan to use prefabricated reference trajectories ($T(i, 0)$ and x_i^t) with matrix coefficients calculated up to 2^{nd} order.

References

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- [2] V. Innocente *et al.*, L3 Report No. 572 (1988).

N Expected Performance

The expected performance of the CLAS has been investigated using the GEANT code[1] and a variety of other computer programs [2, 3]. The main features are summarized in Table N1.

N.1 Track Resolution

The track resolution has been calculated taking into account the magnetic field distribution, the position resolution of the chambers and multiple scattering. The momentum resolution is due to two terms: one that depends on multiple scattering and one that depends on the position resolution of the drift chamber.

$$\left(\frac{\sigma_p}{p}\right)^2 = \left(p^2 \left(\frac{\sigma_p}{p}\right)_{pos}^2 + \frac{1}{\beta^2} \left(\frac{\sigma_p}{p}\right)_{ms}^2\right) \quad (1)$$

Figure N1 shows the relative contributions of multiple scattering and position uncertainty as a function of scattering angle for particles of 1.0 GeV/c momentum. The solid curves are for the case when the event vertex is known and the dashed curves are for long targets.

For known vertex position, the overall momentum resolution for 1 GeV/c particles is about 0.4% (FWHM) in the forward direction, $\theta = 25^\circ$. At larger angles of about 75° , it increases to 0.8% (FWHM) due to the decreasing $\int B \cdot dl$. The resolution $\delta\theta$ for the production angle θ for 1.0 GeV/c particles is 1-2 mrad. For unknown vertex, the momentum resolution is 0.6% in the forward direction; in the central part, it is about 1.2%, while θ can be determined with an uncertainty $\delta\theta$ of 2-3 mrad. Vertex resolution in the bend plane is typically 3 mm.

An important feature of the CLAS detector is its ability to reconstruct the entire event, even if one particle remains undetected. This capability arises from the good momentum and angular resolution which allow good missing mass resolution. This is illustrated in Figure N2 which shows well-defined π^0 and η peaks in simulated $p(e,e'p)X$ reactions.

N.2 Acceptance

Generally, the ϕ -acceptance is a function of particle momentum, emission angle and charge. However, for high momentum particles the ϕ -acceptance is particularly simple. It reaches 85% of 2π at $\theta=90^\circ$; and it drops to about 50% at $\theta=15^\circ$ (see Figure N3). The total integrated solid angle is 77% of 4π . The acceptance for charged particles reaching the TOF scintillator counters is shown in Figure N4. For

Table N1: Expected Performance of the CLAS detector.

θ -range	8°– 140°	
ϕ -acceptance		
$\theta = 15^\circ$	50%	of 2π
$\theta = 20^\circ$	65%	of 2π
$\theta = 90^\circ$	85%	of 2π
Momentum Resolution		
σ_p	0.4% (FWHM)	at 1 GeV/c, 20°
	0.8% (FWHM)	at 1 GeV/c, 90°
Momentum range		
$\theta = 20^\circ$ (outbending tracks)	≥ 0.2	GeV/c
$\theta = 20^\circ$ (inbending tracks)	≥ 1.5	GeV/c
$\theta = 90^\circ$	≥ 0.1	GeV/c
Particle Identification (TOF and dE/dx, 3σ separation)		
π /K separation up to	2.0	GeV/c
π /p separation up to	3.0	GeV/c
K/p separation up to	3.5	GeV/c
neutron detection efficiency	5%	scintillators
	60%	electromagnetic calorimeters

a rather complete analysis of the acceptance and resolution of the CLAS, see Ref. [3]. The acceptance as a function of the physical variables Q^2 and ν is shown in Figure N5.

N.3 Particle Identification

The identification of charged particles will play an important role in both online and off-line analysis. Pions, kaons, protons and deuterons will be identified by measuring the flight time (TOF) between the target and the scintillator counters and the energy loss in the drift chambers and scintillators. Electron identification will be mainly achieved with the Cerenkov counters and electromagnetic calorimeters; however, by using the energy loss in the drift chambers as additional information, the π/e separation can be improved. The scintillator counters are expected to give an r.m.s. resolution of 120 ps in the forward direction with a typical flight path of 400 cm. In the forward direction, separation by TOF of e/π , π/K , and K/p at the 3σ level is possible up to 0.6 GeV/c, 2.0 GeV/c and 3.2 GeV/c, respectively (see Figure N6).

Neutrons can be detected over the same solid angle as charged particles via their interactions in the TOF counters, however with an average efficiency of 5%. For angles less than 45 degrees, neutrons will be detected in the electromagnetic calorimeter with an efficiency of 50-60%.

N.4 Polarized Target Operation

The physics program requires use of polarized solid state targets, NH_3 and ND_3 , for polarized protons and deuterons (neutrons). To operate these targets one must maintain a homogeneous magnetic field of 3.5 to 5.0 Tesla at the target which will deflect both the primary electron beam and the scattered charged particles. Figure N7 illustrates how the polarized target assembly might fit within the field free region of the CLAS toroid.

The effect of a realistic polarized target magnetic field distribution on the particle trajectories has been studied. It was found that the main effect of the target field is a momentum-dependent change of the projected azimuthal and polar angle of the scattered particles. The overall acceptance is practically unaffected. The incident electron beam is vertically deflected by an angle α_p which depends on the incident beam momentum, and the orientation of the target field. This deflection is compensated by the introduction of two dipole magnets in the beam line. The incident beam is transported to the target in such a way that the incident beam angle is $-\alpha_p$. After the target the beam is thus directed towards the beam dump.

N.5 Background and Maximum Luminosity

We briefly discuss the limitations due to background of the CLAS detector for various experimental conditions. For operating the CLAS detector in a tagged photon beam with an incident photon rate of 10^7 to 10^8 s^{-1} we do not expect any problems with background either from hadronic production processes or from electromagnetic interactions.

We expect the ultimate limitation in the performance of the CLAS to come from operating the drift chamber in a high background environment of an intense electron beam. As there is virtually no limit to the instantaneous luminosity that can be achieved with the CEBAF accelerator, measurements will be made at the highest luminosity which the detector can tolerate.

The photon and electron background yields will depend upon the type of target used in a given experiment. The situation was studied for low Z (H_2), and high Z (Cu, Pb) targets, and for polarized solid state targets (NH_3). For operation with unpolarized targets the toroidal shield (see section F.3) was assumed to be in place providing efficient shielding for low energy electrons. Passive shielding was accomplished with a beam pipe which consisted of 0.5mm of Be and $10\mu\text{m}$ of Pb and a copper cone in the rear of the detector.

As a measure of the background load, we used the total energy deposited in the drift chambers within a time window of 200 ns. Table N2 summarizes the luminosity limitations of the CLAS detector for various target configurations. Figure N8 displays the background rate from a H_2 target as a function of the current in the toroidal shield. Effective shielding against charged particles is obtained with 150 kA - turns of current in the magnet. We do not expect chamber performance or pattern recognition to limit experiments for luminosities below $10^{34}\text{cm}^{-2}\text{s}^{-1}$.

For a high Z nuclear target, the main source of background is the flux of X-rays generated by electron knock-out from inner shells. For this case we expect the chamber to operate safely at luminosities of $10^{33}\text{cm}^{-2}\text{s}^{-1}$. When a polarized target is used, the toroidal shield is replaced by the field of the target and experimental conditions depend on the axis of polarization. If the polarization is along the beam, the luminosity will be limited by the target. For other polarization directions, the shielding must be optimized to the chosen experiment.

Table N2: Luminosity limitations of the CLAS operation with electron beams. The study assumes the detector is shielded with 0.5mm Be beam pipe with $10\mu\text{m}$ of lead and a 3 cm thick Cu cone in the rear of the detector.

<i>Target</i>	<i>Max Luminosity</i> <i>($\text{cm}^{-2}\text{s}^{-1}$)</i>	<i>Limitation</i>
Low Z	10^{34}	Bremsstrahlung photons and low-energy electrons
High Z	10^{33}	K-,L- shell X-rays
Polarized Solid State Target – Along beam – At angle to beam	10^{34} $10^{33}\text{--}10^{34}$	Target Requires optimized shielding

References

- [1] R. Brun *et al.*, GEANT3, CERN DD/EE/84-1 (1987).
- [2] D. Joyce, “CELEG 1.0, CEBAF Large Acceptance Spectrometer Event Generator User’s Manual,” CLAS-NOTE-89-004, 1988.
- [3] E.S. Smith, “Fast Monte Carlo Program for the CLAS detector,” CLAS-NOTE-90-003, 1990.

Figure N1: Fractional momentum resolution (FWHM) is shown for the case when the vertex is specified (solid) and for long targets (dashes). The contribution due to multiple scattering and position resolution are shown separately.

Figure N2: Missing mass squared distribution for the reactions $p(e,e'p)X$ as generated by CELEG and FASTMC. Note that the $p\pi^0$ channels are well separated from the two-pion production threshold.

Figure N3: Azimuthal acceptance as a function of scattering angle for infinite momentum tracks.

CLAS Acceptance for Scintillators

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Figure N4: Particle momentum versus scattering angle, showing the accepted region of phase space for particles reaching the TOF counters. The solid curve is for inbending tracks, the dashed for outbenders.

ep Kinematics ($E_{\text{beam}}=4\text{GeV}$)

Hall B CDR

Figure N5: Kinematically available phase space for a 4 GeV electron beam. The region for which inbending electrons are accepted is shown by the solid curve. Lines of constant scattering angle and W are shown as dotted lines.

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Figure N6: Flight time versus momentum for pions, kaons and protons at $\theta=20^\circ$ and $\theta=90^\circ$.

Figure N7: Layout of the polarized target magnet, target cryostat and support structure within the CLAS toroid.

Figure N8: Background rates in the drift chambers as a function of current in the toroidal shield. The various symbols refer to rates in Regions 1, 2 and 3. The lines are to guide the eye. Background rates are substantially reduced for currents above 150 kA - turns.

O Fabrication and Installation

The CLAS detector components will be fabricated both at CEBAF and at the home institutions of the CLAS collaborators. We expect that scintillation and Cerenkov counters as well as the detectors for the photon tagging system will be fabricated off-site. Major parts of other systems, like the electromagnetic calorimeter and the Region 1 drift chamber, may also be fabricated outside of CEBAF.

The stringing of the Region 2 and Region 3 wire chambers will be done in a class 10,000 clean room located in CEBAF's Experimental Equipment Laboratory (EEL). After wire stringing, the chamber gas manifolds, preamplifiers, and high voltage connections will be installed, and the chamber will be tested using cosmic rays and radioactive sources. Completed chambers will be stored in the EEL building. At installation time, a cart with low pressure tires will transport the chambers from the EEL building through the truck ramp into Hall B.

Immediately after the beneficial occupancy date of Hall B (see also the installation schedule, Table S2), the space frame including catwalks, platforms, and staircases will be erected. During this time the tagging magnet will be transported into its final resting place in the upstream alcove, and the tagging counter hodoscope will be installed. Once the space frame is completed utilities can be installed, and the crates for the drift chamber readout electronics can be mounted on the frame. The main part of this activity should be completed by the time the toroidal coils arrive in Hall B.

The CLAS toroidal coils will be fabricated by a vendor. Due to the size of the completed toroid, final assembly must take place in Hall B. We presently expect the vendor to assemble the six coils with the axis of symmetry vertical, presumably outside of the space frame. The cryostat vacuum system will be completed, and the assembly will be mounted in the space frame. The magnet will be connected to CEBAF's End Station Refrigerator, and commissioning and acceptance testing will be performed. Measurements of the magnetic field will be performed; however, the measurements will be restricted to a determination of coil positions and magnet axis.

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The Region 2 drift chambers must be installed first since they require access to their mounting fixtures from both inside and outside. The Region 3 drift chambers will be installed next. The drift chambers will be hooked up to the supply lines and the readout electronics already mounted on the space frame. Following the drift chambers, the Cerenkov and scintillation counters will be installed. It should be noted that the detector installation is done by sectors. This will permit work on several sectors to proceed simultaneously.

The Region 1 drift chamber and the toroidal shield are independent structures and may be installed any time after the Region 2 drift chamber. The front electromagnetic shower calorimeter will be mounted on a separate support structure and may be assembled immediately after beneficial occupancy.

Installation of major components in Hall B will be coordinated by an Installation Manager reporting to the Project Engineer. Appropriate tradesmen will be used for such tasks as electrical power distribution and the rigging of heavy objects. Mounting of light-weight detector components as well as installation and cabling of electronics will be done by the physicists responsible for a particular subsystem.

P Alignment Tolerances

To achieve high momentum resolution, a precise knowledge of the magnetic field configuration and the drift chamber positions is necessary.

P.1 Magnetic Field

Since the toroidal magnet is iron-free, the magnetic field can be calculated with very high accuracy once the position of the conductor is known. The main goal of the magnetic field measuring program is therefore to determine the location of the coils within the cryostat. Presently, we are planning to measure the ϕ - and r-components of the field on both sides of the coil right outside the cryostat. Close to a coil, the influence of the other five coils is negligible. The radial position of the coil can be determined by observing the steep rise of ϕ -component as a function of the radius. A measurement of the r-component on both sides of the cryostat determines the transverse position of the coil. A field measurement with an accuracy of 1% is sufficient to determine the coil position to 1 mm.

P.2 Drift Chamber Position

The position of the sense wires within a detector segment will be determined by precision holes in the end plates of the wire chambers. The remaining problem is to know the position of the Region 1 to Region 3 chambers relative to each other and relative to the magnet. The sensitivity of the momentum determination to changes in the position of the complete drift chamber package has been investigated using the methods described previously. The largest effects are found for a shift of the chambers in the x-direction (transverse to the toroid axis). For 1 GeV/c particles, this causes a systematic momentum deviation of 0.14% per 1-mm displacement at $\theta=20^\circ$, decreasing to 0.09%/mm at $\theta=90^\circ$.

If only one region is misaligned the effects are largest for Region 2, leading to systematic momentum deviations of up to 0.5% and angular deviations up to 0.8 mrad per 1-mm displacement.

P.3 Calibration Reactions

There are several monitor reactions with high data rates that can be used to check the momentum calibration.

(a) For electron beams:

Elastic e-p scattering will check the overall energy resolution, especially in the critical forward part of the CLAS. At a luminosity of $10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$, the rate of scattered electrons in the angular range $15^\circ \leq \theta \leq 20^\circ$ is 100/sec ($E_0 = 2 \text{ GeV}$, hydrogen target, 60% ϕ -acceptance). The coincident recoiling proton will test the relative alignment of the opposite detector segment and the momentum resolution at large angles.

Electroproduction processes like

$$\begin{aligned} e + p &\rightarrow e' + p + (\pi^0, \eta) & \text{or} \\ e + p &\rightarrow e' + \pi^+ + n \end{aligned}$$

will check the capability of the system to reconstruct the mass of the unobserved neutral system. This tests both momentum and angular reconstruction.

(b) For photon beams:

Two-body reactions like $\gamma p \rightarrow \pi^+ n$ or $\gamma d \rightarrow p n$ can be used to check the missing-mass resolution and to determine the response of the detector to neutrons.

Q Bremsstrahlung Tagging System

Tagged photons will be available for experiments using the CLAS detector with energies between 20% and 95% of the electron beam energy E_o . Photons can be tagged at a rate in excess of $10^7 s^{-1}$ with the fractional energy resolution of the photon $\delta E_\gamma/E_\gamma=0.3\%$. The uncollimated photon beam spot size at the target (diameter of circle containing 70% of the photons) will be $4.7 \text{ cm}/E_o(\text{GeV})$. Polarized photons can be selected either by measuring angular correlations between the bremsstrahlung photon and scattered electron or by coherent bremsstrahlung from oriented crystals. The layout of the system is shown in Figure Q1.

The tagging spectrometer uses a single uniform-field dipole magnet (see Figure Q2), whose exit field boundary is a straight line. The bremsstrahlung radiator is placed outside the field. Full-energy electrons are deflected downward into the beam dump, while the bremsstrahlung recoil electrons are deflected such that they can be detected along a nearly flat image surface outside the field. The bremsstrahlung photons are nearly collinear with the incident electron beam, and pass through a hole in the magnet return yoke.

The tagging spectrometer is slightly defocusing in the transverse direction, so a point target is imaged to a line in the image plane. This defocusing property is useful in selecting polarization by the angular correlation technique, as transverse position at the detector plane is proportional to the transverse angle at the radiator. Spatial limitations in Hall B prescribe the bend angle to be at least 25° . An angle of 30° was chosen as a compromise between the cost of higher resolution and magnet size and adequate clearance. The radius of curvature for full-energy electrons ($E_o = 4\text{GeV}$) was chosen to be 11.8 m, corresponding to a field of 11.3kG. The exit edge for the full-energy electrons is inclined so as to make the outgoing beam more nearly parallel. A magnet gap of 6 cm is required in order to obtain high tagging efficiency for photons up to $0.8E_o$ at $E_o \leq 1\text{GeV}$. The first- and second-order optics of the spectrometer allow an energy resolution of $10^{-3}E_o$ to be easily achieved for a nominal radiator position and thickness (10^{-4} radiation lengths).

The focal plane will be instrumented with two sets of overlapping counters, each composed of 128 scintillators. The scintillator arrays may be separated away from the midplane of the magnet to tag polarized photons. This, however, degrades the photon energy resolution by a factor of two. The scintillators, approximately 2 cm wide, oriented normal to the electron trajectories and spaced about 10 cm apart, would provide the design resolution by identification of 2-, 3- and 4-fold coincidences. Each channel will be read out via a high-resolution TDC. With a time resolution of less than $\sigma=300\text{ps}$, the correct RF bucket of the event can be determined and used as a start time for the time-of-flight particle identification system.

Hall B CDR

REVISED OCT 17 1989

Figure Q1: Side view of Hall B, including the tagged photon beam system.

Figure Q2: Tagging spectrometer. The full-energy electron beam is deflected by 30° into the beam dump.

R CLAS Collaboration

Members of the the CEBAF users community were involved in all stages of the design of the Hall B instrumentation. The large number of letters-of-intent and proposals clearly document that the interest in a detector with a large acceptance extends far beyond the traditional electromagnetic nuclear physics community. The physics programs outlined in the letters-of-intent and the proposals were used to set the requirements for CLAS. Following the letter-of-intent phase, working groups were formed to study the Hall B subsystems in detail.

A formal organization, the CLAS Collaboration, is presently being established. At the January 13, 1990 meeting, a collaboration charter was unanimously approved. According to the charter, the goal of the CLAS collaboration is the design, construction, and commissioning of the instrumentation for CEBAF Hall B, in particular the CEBAF Large Acceptance Spectrometer CLAS, and the completion of the initial round of experiments.

Initial membership will come from institutions which have entered into an agreement with CEBAF (Memorandum-of-Understanding or MOU) for the development of CLAS and the associated instrumentation (hardware or software). Physicists named explicitly in the MOU's will be members of the collaboration. CEBAF staff physicists who have responsibility for Hall B instrumentation will also be members of the collaboration.

The consequences of physics issues for Hall B instrumentation will be discussed and compromises will be worked out in the following Physics Working Groups:

- Structure of the nucleon,
- Multi-hadron emission in $A(e,e')$, and
- Real photon experiments

Subsystems of Hall B instrumentation will be designed and their construction and commissioning be coordinated by the following Technical Working Groups:

Drift Chambers
Scintillation Counters
Electron, Gamma, and Neutron Detection
Software (simulation and analysis)
Trigger/Data Acquisition System
Photon Tagging System
Beam Line Instrumentation

The collaboration will be managed by a Coordinating Committee consisting of the Chairman, the Hall B Program Manager, and one representative of each of the Physics Working Groups. With the exception of the Program Manager, the members of the Coordinating Committee will be elected by the collaboration. The coordinating committee will make decisions regarding major collaboration issues, in particular: allocation of resources within the collaboration, and resolution of conflicts in construction and operation caused by different physics requirements. The committee will also monitor the progress in design and construction of Hall B instrumentation.

The Hall B Program Manager will be appointed by the CEBAF management. He/she will have responsibility for the overall organization and management of the construction and operation of the Hall B instrumentation.

Technical matters will be handled by a Technical Committee consisting of the Hall B Program Manager, the Hall B Engineer, and two representatives of each of the Technical Working Groups.

Table R1 lists the home institutions of the members of the CLAS collaboration. Table R2 gives the current division of responsibility for subsystems of Hall B instrumentation and estimates for the manpower (converted to Full Time Equivalent units) available from outside collaborators.

Table R1: Home Institutions of CLAS Collaborators

Arizona State University
Catholic University of America
California Institute of Technology
Carnegie Mellon University
CEBAF
Christopher Newport College
College of William and Mary
Duke University
Florida State University
George Washington University
Institute of Theoretical and Experimental Physics, Moscow, USSR
James Madison University
Kharkov Physics Institute, USSR
Leningrad Physics Institute, USSR
Massachusetts Institute of Technology
National Institute of Science and Technology
Rice University
Rensselaer Polytechnic Institute
University of Massachusetts
University of New Hampshire
University of Pittsburgh
University of Richmond
University of South Carolina
University of Virginia
Virginia State University
Virginia Polytechnic Institute and State University
Yale University
Yerevan Physics Institute, USSR

Table R2: Responsibilities for Hall B Subsystems

Hall B subsystem	Group	Contact person	FTE years
<hr/>			
Drift chamber	CMU	R. Schumacher	9.5
	UMass	R. Miskimen	5.8
	U. Pittsburgh	S. Dytman	8.6
	U. Richmond	M. Vineyard	3.5
	VPI&SU	D. Jenkins	9.2
Cerenkov counters	RPI	P. Stoler	15.5
Scintillation counters	UNH	W. Hersman	9.0
	VSU	C. Stronach	9.0
	W&M	R. Welsh	4.0
Sci/fi start counters	Yale	M. Gai	1.5
Electromagnetic shower calorimeter	Duke U.	H. Weller	7.8
	JMU	K. Giovanetti	>1.5
	Rice	G. Mutchler	3.0
	UVa	R. Minehart	14.0
	W&M	H. Funsten	10.5
	W&M	J. Kane	>9.5
			<hr/>
			121.9

Table R2: Responsibilities for Hall B Subsystems (continued)

Hall B subsystem	Group	Contact person	FTE years
Photon tagging system	Catholic U.	D. Sober	11.3
	GWU	W. Briscoe	21.0
	UVa	S. Thornton	3.1
	S. Carolina	G. Blanpied	3.0
	ASU	B. Ritchie	12.3
Trigger and data acquisition	CNC	D. Doughty	9.0
	FSU	L. Dennis	31.0
	George Mason U.	J. Lieb	1.2
	S. Carolina	B. Freedom	3.0
Charge monitoring and target for e^- -scattering	MIT	W. Bertozzi	2.0
General detector development		K.Sh. Egiyan	15.0
	Yerevan		
	Kharkov		
	ITEP		
	Leningrad		-----
			111.9
from previous page			121.9
Total			----- 233.8

S Schedule, Cost, and Manpower

S.1 Schedule

The present status of the CLAS components is given in Table S1. The Hall B schedule is shown in Table S2. The fabrication of the toroidal magnet is on the critical path. Important constraints for the fabrication and installation of detector components are the beneficial occupancy dates for the Experimental Equipment Laboratory and Hall B.

S.2 Cost

The cost estimate for Hall B instrumentation is based on CEBAF engineering experience, on contacts with experts in the area of large acceptance detector instrumentation, and on contacts or quotes from industrial vendors. The estimated costs of the subsystems are listed in Table S3. At the present stage of the project, a contingency of approximately 25% seems to be appropriate.

S.3 Manpower

The manpower required to design, fabricate, and commission Hall B instrumentation is presented in Table S4 for the various elements of the work breakdown structure. Table S5 gives a breakdown of the manpower available from CEBAF staff and outside collaborators. The CEBAF positions are consistent with the CEBAF manpower plan; in addition to the Hall B group, they include also those employees in the Data Acquisition Group and the Detector Development Group who are directly involved in Hall B instrumentation. The contributions from outside collaborators are consistent with the Memoranda-of-Understanding.

Table S1: Hall B Component Status

Component	Group responsible	Status
Toroidal magnet	CEBAF	internal design complete RFP package out (4/1994)
Drift chamber	CEBAF CEBAF, UMass, U. Richmond CMU, Pittsburgh	small prototype chamber tested large prototype under construction Region 1 drift chamber design started
Cerenkov counter	RPI	prototype design complete prototype test at BNL (4/1990)
Scintillation counter	CEBAF, UNH, VPI&SU W&M	small prototype tested at CEBAF and UNH bent light guide developed
Electromagnetic shower calorimeter	UVa, W&M CEBAF UVa Illinois W&M CEBAF, Duke, GMU, ITEP, JMU, UVa, W&M, Yale, Yerevan Yerevan, Kharkov (USSR)	component tests at W&M and UVa design of sandwich prototype fabrication of sandwich prototype fabrication of scintillating fiber prototype fabrication of lightguide for Sci/Fi prototype Cerenkov and calorimeter tests at BNL (4/1990) scintillation material fabrication
Tagging system	CUA, GWU, UVa, ASU, USC	optics design complete preliminary design for tagging magnet preliminary design of detector system

Table S2: HALL B SCHEDULE

CLAS Magnet

FY CY Month	1989 1989 FMAMJJASOND	1990 1990 FMAMJJASOND	1991 1991 FMAMJJASOND	1992 1992 FMAMJJASOND	1993 1993 FMAMJJASOND	1994 1994 FMAMJJASOND	1995 1995 FMAMJJASO
design (CEBAF)	-----	12/89					
prepare RFP		-----	2/90				
bid cycle		8 mo -----	10/90				
pre-bid conference			x 4/2/90				
initial proposals received			x 6/90				
contract award			x 10/90				
engineering (by vendor)		12 mo -----	10/91				
order superconductor			x 4/91				
fabricate magnet			28 mo =====			2/94	
install and test in Hall B						6 mo -----	8/94
magnetic field measurements						2 mo --	9/94

Wire Chambers

Cerenkov and Scintillation Counters, Electromagnetic Shower Calorimeter

FY CY Month	1989 1989 FMAMJJASOND	1990 1990 FMAMJJASOND	1991 1991 FMAMJJASOND	1992 1992 FMAMJJASOND	1993 1993 FMAMJJASOND	1994 1994 FMAMJJASOND	1995 1995 FMAMJJASOND
<hr/>							
CERENKOV COUNTERS							
design		-----9/90					
prototype			-----1/91				
fabricate and test			24 mo	=====6/93			
install							-----5/95
SCINTILLATION COUNTERS							
design			-----1/91				
prototype				-----6/91			
fabricate and test				24 mo	=====11/93		
install							-----6/95
ELECTROMAGNETIC SHOWER CALORIMETER							
design			-----1/91				
prototype				-----7/91			
fabricate and test				29 mo	=====1/94		
install small angle calorimeter						-----5/94	
install large angle calorimeter							-----6/95
<hr/>							

Trigger electronics, Tagging system

FY CY Month	1989 1989 FMAMJJASOND	1990 1990 FMAMJJASOND	1991 1991 FMAMJJASOND	1992 1992 FMAMJJASOND	1993 1993 FMAMJJASOND	1994 1994 FMAMJJASOND	1995 1995 FMAMJJASO

READOUT AND TRIGGER ELECTRONICS							
design trigger system				-----3/91			
prototype trigger system						-----12/92	
fabricate and test trigger				28 mo	=====	12/93	
TAGGING SYSTEM							
design tagging system				-----12/90			
fabricate magnet				19 mo	=====	12/92	
install tagging magnet						---3/93	
design tagging counters				-----1/91			
prototype and test				-----7/91			
fabricate tagging counters				20 mo	=====	8/93	
install tagging counters						---12/93	
test tagging system with beam							--4/94

Installation Schedule

FY CY Month	1990 1990 FMAMJJASOND	1991 1991 FMAMJJASOND	1992 1992 FMAMJJASOND	1993 1993 FMAMJJASOND	1994 1994 FMAMJJASOND	1995 1995 FMAMJJASOND
B counting house beneficial occupancy				x 10/92 ?		
Hall B beneficial occupancy				x 10/92		
Cryogens from ESR available				x 4/93		
erect space frame			4 mo ----1/93			
install electrical power, chamber gas, crates					-----2/94	
assemble and test magnet					6 mo -----8/94	
magnetic field measurements					2 mo --9/94	
install drift chambers						-----4/95
install Cerenkov counters						-----5/95
install scintillation counters						-----6/95
install small angle calorimeter					-----5/94	
install large angle calorimeter						-----6/95
install electronics						-----6/95
install tagging magnet and dump				---3/93		
install tagging counters					---11/93	
test tagging system with beam					--4/94	
test electromagnetic shower calorimeter with tagged photons					---6/94	
install electron beam line					--	--6/95
first beam from accelerator					x 2/94	

Table S3: **Cost Estimate for Hall B Instrumentation**

(in FY89 \$)

6.6.1. TOROIDAL MAGNET

	k\$
6.6.1.1 Engineering by vendor	805
6.6.1.2 Components	
Cold structure	260
Superconductor	1,070
Nitrogen shield	60
Support system (warm/cold)	180
Vacuum tank	750
Service header	313
6.6.1.3 Tooling	560
6.6.1.4 Coil winding	138
6.6.1.5 Power supply and controls	375
6.6.1.6 Installation	250
6.6.1.7 Checkout	190
6.6.1.8 Project coordination and management	850

	5,801

6.6.2. DRIFT CHAMBER SYSTEM

	k\$
6.6.2.1 Mechanical Structure	1,454
6.6.2.2 Wire Stringing Apparatus, Transporter	100
6.6.2.3 Wires, Pins, Feedthroughs	472
6.6.2.4 Wire Stringing	400
6.6.2.5 High Voltage System + Distribution	184
6.6.2.6 Drift Chamber Electronics	2,296
6.6.2.7 Electronics Test and Installation	200
6.6.2.8 Gas System	237
6.6.2.9 EDIA	140
	<hr/> 5,483

6.6.3. SCINTILLATION COUNTERS

based on 288 (6 segments @ 48 counters)	
	k\$
6.6.3.1 Scintillation Material (176 m ²)	460
6.6.3.2 Mechanical Parts and Assembly	308
lightguides	
tube bases	
assembly	
support structure	
6.6.3.3 Photomultipliers	187
XP2262	
6.6.3.4 Electronics	510
discriminator, ADC, TDC	
scaler, HV, cables	
crates	
6.6.3.5 Calibration System (laser + light fibers)	20
6.6.3.6 EDIA	100
	<hr/> 1,585

6.6.4. CERENKOV COUNTERS

coverage: $\theta \leq 45^\circ$ in 5 sectors, $\theta \leq 90^\circ$ in 1 sector

	k\$
6.6.4.1 Materials	140
6.6.4.2 Photomultipliers (Burle 8854, 5")	196
6.6.4.3 Tube bases	126
6.6.4.4 Fabrication and testing	110
6.6.4.5 Electronics	46
6.6.4.6 EDIA	90
	<hr/>
	708

6.6.5. ELECTROMAGNETIC SHOWER CALORIMETER

coverage: $\theta \leq 45^\circ$ in 5 sectors, $\theta \leq 90^\circ$ in 1 sector

	k\$
6.6.5.1 Scintillation material (1660 m ²)	1,577
6.6.5.2 Light guides	100
6.6.5.3 Lead sheets	250
6.6.5.4 Photomultipliers (2") + bases (1400 channels)	615
6.6.5.5 Electronics (trigger and readout)	1,203
6.6.5.6 Laser calibration	100
6.6.5.7 Cables	130
6.6.5.8 Mechanical structure and assembly	340
6.6.5.9 EDIA	170
	<hr/>
	4,485

6.6.6. PHOTON TAGGING SYSTEM

	k\$
6.6.6.1 Magnet	270
6.6.6.2 Power Supply	50
6.6.6.3 Vacuum Chamber	110
6.6.6.4 Detector System	420
6.6.6.5 Photon Beam Monitoring	80
6.6.6.6 EDIA	165
	<hr/>
	1,095

6.6.7. COUNTING HOUSE EQUIPMENT

	k\$
6.6.7.1 Trigger System	295
6.6.7.2 Host Computer (30 Mips, 2 Gbyte disc)	135
6.6.7.3 Graphics workstations	65
6.6.7.4 Readout controllers, switches, links	165
6.6.7.5 Microprocessor farm (incl. tape drives)	130
6.6.7.6 Racks	30
	<hr/>
	820

6.6.8. BEAM LINE AND MISCELLANEOUS EQUIPMENT

	k\$
6.6.8.1 Vacuum system	50
6.6.8.2 Beam dump	50
6.6.8.3 Møller polarimeter	100
6.6.8.4 Beam line instrumentation	60
6.6.8.5 Target system	100
6.6.8.6 Magnetic field measurement	50
6.6.8.7 Mini-toroid	100
6.6.8.8 Space frame and utility distribution	350
6.6.8.9 Handling devices	40
6.6.8.10 Cable trays	20
6.6.8.11 EDIA	210
	<hr/>
	1,130

6.6 COST ESTIMATE SUMMARY

	10 ⁶ \$
6.6.1 Toroidal Magnet	5.801
6.6.2 Drift Chamber System	5.483
6.6.3 Scintillation Counters	1.585
6.6.4 Cerenkov Counters	0.708
6.6.5 Electromagnetic Shower Calorimeter	4.485
6.6.6 Photon Tagging System	1.095
6.6.7 Counting House Equipment	0.820
6.6.8 Beam Line Equipment	1.130
	<hr/>
6.6 Total	21.107
- contribution from Soviet collaborators (scintillation material)	-1.000
	<hr/>
	20.107
	<hr/> <hr/>

Table S4: Manpower Required for Hall B Instrumentation

(man-years)

WBS	Engineers designers technicians	Physicists
6.6.1 Toroidal magnet	8	3
6.6.2 Drift chamber	46 *	25
6.6.3 Scintillation counter system	3	11
6.6.4 Cerenkov counter system	3	10
6.6.5 Electromagnetic shower calorimeter	15	22
6.6.6 Photon tagging system	3	16
6.6.7 Electronic and counting house equipment	10	14
6.6.8 Beam line and miscellaneous equipment	9	6
Detector development/simulation		40
Data acquisition		30 **
Data analysis		31
Project management and review	4	10
Total	101	218

* includes 20 man-years for wire stringing

** 20 man-years shared with other halls

Table S5: Manpower Plan for Hall B

	1990	1991	1992	1993	1994	FTE•years
CEBAF staff						
Physicists	9	10	11	13	14	57
Engineers/designers/ technicians	7	8	9	10	10	44
Engineers/designers technicians (temporary)	2	5	5	5	2	19
Temporary help (wire stringing, testing)		3	8	8	8	27
Collaboration						
Physicists	18	24	34	40	42	158
Engineers/designers/ technicians	1	2	2	3	4	12
Total	37	52	69	79	80	317

CONCEPTUAL DESIGN REPORT
BASIC EXPERIMENTAL EQUIPMENT

HALL C

April 13, 1990
(Revised)

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A End Station C Executive Summary

A.1 Overview: Physics Program and Hall Layout

The role of Hall C at CEBAF will be to support a broad and varied program of scientific initiatives that fall outside the programmatic capabilities of the Hall A and B facilities. The experiments planned include: high- q^2 inclusive electron scattering, photodisintegration, and $(e,e'p)$ reactions; electroweak physics; hypernuclear physics; and high-luminosity out-of-plane $(e,e'p)$ measurements. To mount such a varied program will require a highly flexible set of instruments. The complement of instruments planned for Hall C begins with a High Momentum Spectrometer (HMS) that will serve as a hadron spectrometer for high- q^2 physics and as an electron spectrometer for inclusive scattering experiments and for a series of coincidence experiments utilizing "second-arm" spectrometers. To provide the necessary flexibility, the HMS has the capability of analyzing high-momentum particles (up to 6 GeV/c), a large solid angle and momentum acceptance, and excellent trajectory reconstruction capability to the target; its momentum resolution will be somewhat better than 10^{-3} . These capabilities provide an excellent match to the planned research program that includes the extensive use of cryogenic and polarized targets.

The "second arm" spectrometers for Hall C, each of which has been optimized for a different physics program, will be constructed by user-managed consortia. The first of these "second-arm" spectrometers to come into operation will be the Short Orbit Spectrometer (SOS). It will be used in conjunction with the HMS for studies of the electroproduction of pions and kaons, and also for a variety of $(e,e'p)$ coincidence experiments aimed at the investigation of the energy and mass dependence of nucleon propagation in nuclei. The SOS may also be used as a "stand-alone" instrument for studies of proton polarization in the $d(\gamma, \vec{p})n$ reaction. Finally, it will be used in conjunction with a virtual photon tagging system for a first-generation hypernuclear spectroscopy system (HNSS). Later, the HNSS could be upgraded through the construction of a kaon spectrometer having substantially higher resolution than the SOS, but with a lower maximum momentum capability and range.

Another major instrument under study for Hall C is the Symmetric Toroidal Array (STAR) spectrometer. The STAR will be used for a number of programs, including: out-of-plane coincident electron scattering on the nucleon and nuclei; the study of two-body correlations through the $(e,e'2N)$ reaction; and the electroproduction of pions and kaons. It can also be used as a recoil polarimeter and as a stand-alone, large solid angle electron spectrometer, and will be a key element in the programs of parity violation studies of the electro-weak interaction and of nucleon structure that are planned for Hall C. The design of the STAR has not yet advanced to the stage where it has passed internal CEBAF scientific and technical reviews and become a formal instrument proposal. Since it is anticipated that the STAR will be built primarily with NSF and/or foreign funds, it is not included in the detailed budgets presented in this report. It is presented here to document its impact on the design of the HMS and the hall.

Table 1: Relationship of Physics Programs to Instrumentation in Hall C.

Physics Program	Instrument				
	HMS	SOS	STAR [†]	HNSS	PAVEX [†]
Color Transparency	•	•			
Baryon Resonances	•	•	•		
Exclusive Photoproduction	•	•			
Scaling at $x > 1$	•				
Nucleon Form Factors	•		•		
$(e, e'\pi)$, $(e, e'K)$	•	•	•		
Out-of-Plane Spectrometry	•		•		
$(e, e'2N)$	•		•		
Hypernuclear Spectroscopy		•		•	
Parity Violation			•		•

HMS High Momentum Spectrometer
 SOS Short-Orbit-Spectrometer
 STAR Symmetric Toroidal Array Spectrometer
 HNSS Hypernuclear Spectrometers
 PAVEX Parity Violation Experiments
[†] Not included in initial funding

Parity violation experiments will be an important part of the Hall C program. Before these demanding measurements can be undertaken it will be necessary to have a complete understanding of the quality of the polarized beam that is deliverable on a target in the end station at CEBAF. We include in the budget for the hall the instrumentation that will be necessary to characterize the polarized beam in the end station for all of the experiments that require this beam.

The proposed complement of Hall C equipment is listed in Table 1 cross referenced with the scientific programs. Each of these instruments is summarized briefly below, and presented in detail in the body of this report. All of these instruments will enhance the ability of Hall C to support a broad research program for many years to come.

In order to convey a feeling for the scale of the Hall C instruments, Figure 1 shows an artist's sketch of the hall with the HMS and SOS spectrometers configured for an experiment. The primary entrance to the end station is via a 400 foot long, 10° slope tunnel. Figure 2 shows a plan view of the proposed spectrometers and their relative dimensions, excluding the Hypernuclear Spectrometer System which has a separate pivot.

A maximum of two of the "user" arms could be mounted simultaneously around the primary pivot. Other "user" arms would be stored off to one side within the end station.

Figure 1: Artist's conception of Hall C with the HMS and SOS spectrometers in place.

Figure 2: Plan view of Hall C with the HMS and SOS spectrometers.

With the relatively small cross sections that are typical of the high q^2 electron scattering studies planned for Hall C, luminosity is one of the critical issues. Several other specific experiments anticipated for Hall C (such as parity violation and color transparency) also require large luminosities. To meet the needs of the program, Hall C will be shielded sufficiently to permit experiments to run with the full CEBAF beam intensity and realistic targets without compromising radiation safety.

A number of experiments such as parity violation, out-of-plane spectroscopy, and nucleon form factor measurements will require polarized electron beams. In order to monitor the polarization of the beam at the target position, Hall C will be equipped with a back-scattering laser polarimeter. In addition, a group from the University of Illinois is collaborating with CEBAF in R&D aimed toward the development of a polarized source with the highest possible figure of merit; a prototype source is now operational at Illinois.

A.2 The High Momentum Spectrometer (HMS)

The High Momentum Spectrometer is unanimously considered by the Hall C steering committee to be the highest priority instrument. The CEBAF PAC, in its review of experimental equipment, has supported the HMS as the keystone of Hall C activities. Many of the experiments that users are anxious to perform center on physics at high q^2 and other short-distance phenomena accessible through either $(e,e'p)$ or photodisintegration. Some of these experiments require the detection with reasonable resolution of protons with momenta in excess of 4 GeV/c, even though the CEBAF electron beam will be limited to energies of ≤ 4 GeV in its initial stages. If future machine upgrades result in higher beam energies, it will also be necessary to analyze electrons with momenta above 4 GeV. For these reasons, the High Momentum Spectrometer (HMS), which will be capable of analyzing momenta up to 6 GeV/c, is the "core" device for Hall C. In general, the HMS will serve as the "electron" arm for coincidence experiments that will use a second instrument for hadron detection, and will serve as the "hadron" arm in specific experiments where the hadron momentum exceeds the capability of the other Hall C spectrometers. All of these experiments will utilize the 4 GeV electron beam, and many of them can fruitfully be extended to higher energies when the accelerator performance increases.

The specifications of the HMS design have been chosen to meet the requirements of most of the proposed experiments. A collaboration between the Argonne National Laboratory, Caltech, the University of Illinois, MIT, the University of Virginia, and CEBAF has set design goals and studied options to realize this spectrometer. A schematic view of the HMS design that emerged from these studies is shown in Figure 3; the characteristics of the HMS are summarized in Table 2.

Included in the HMS budget are the funds for the construction of a polarized target based on the dynamic nuclear polarization technique. This target will be useful for a broad variety of physics programs at CEBAF, but its initial use will be in an experiment aimed at determining G_E^n , the electric form factor of the neutron, via a measurement of the

Figure 3: Schematic of the HMS.

Table 2: Characteristics of the HMS Spectrometer for Different Tuning Modes.

Transverse focussing mode	$\delta p/p$ (%)	Solid Angle (msr)	Vertex Reconstruction (mm)		Scattering Angle Error (mr)
			@10 deg	@90 deg	
parallel $\rightarrow$ point	0.057	6.4	19.4	3.4	0.4
point $\rightarrow$ point	0.058	6.4	3.7	0.64	0.8

Note: Resolutions include the effects of a 10 cm long target as well as the estimated 0.17 mm spatial resolution and 0.25 mr angular uncertainty in the trajectory measurement in the HMS detector. Eight reconstruction terms are used for momentum and six each for vertex position and in-plane scattering angle.

asymmetry in the quasielastic scattering of longitudinally polarized electrons from polarized deuterium nuclei in deuterated ammonia. Also included are low and intermediate-power cryogenic targets for studies of the proton and few- body systems.

A.3 The Short Orbit Spectrometer (SOS)

Electroproduction of low energy pions or kaons from few-nucleon systems provides a wealth of information on their pion and strange quark content. Experiments that study these phenomena must deal with the fact that these pions and kaons are likely to decay before reaching the detector stack. In order to carry out such experiments, a group at Argonne National Laboratory is proposing to build the Short Orbit Spectrometer (SOS), a device with moderate resolution and acceptance but a very short flight path. The HMS would serve as the electron detection arm for these experiments. For typical experiments of this type, the pions and kaons are limited to momenta no higher than 2 GeV/c. A review of spectrometer designs appropriate for these experiments suggests that the optical characteristics of the MRS spectrometer, recently brought into operation at Los Alamos, are close to ideal. This spectrometer has adequate resolution and a large momentum bite, and it can be shielded heavily enough to permit it to operate in coincidence with the HMS at the highest luminosities allowed at CEBAF. A schematic view of the SOS is shown in Figure 4, and the characteristics of this spectrometer design are summarized in Table 3.

A.4 The Hypernuclear Spectrometer System (HNSS)

The high energy and exceptional beam quality of CEBAF will make possible the study of the splitting of individual levels in hypernuclei via high resolution ($e,e'K$) coincidence measurements on complex nuclear targets. Kinematics dictate that the electron and kaon both be detected at very small angles relative to the beam line, although the maximum momentum of both particles is modest. A collaboration led by the University of Houston has designed a Hypernuclear Spectrometer System (HNSS) for this program. The HNSS will initially consist of a dipole for separating the forward-going residual electron and kaon from the beam, a virtual photon tagger for measuring the residual electron energy, and the SOS (with a special detector package) to measure the kaon momentum. The virtual photon tagger will be based on a refurbished split pole spectrograph. Based on the experience gained with this initial system, the collaboration plans to eventually construct an improved HNSS in which the SOS is replaced by a higher resolution kaon spectrometer. A schematic of the HNSS is shown in Figure 5. This improved system, which is not included in the initial HNSS costing, would permit the experiments to resolve the spin splitting of hypernuclear levels. The kaon spectrometer resolution in this ultimate system has been estimated to be of the order of 150 keV FWHM. For a 0.01 gm/cm² target the net resolution has been estimated and is given in Table 4. This resolution may be improved somewhat by reducing target thickness and increasing the beam current to keep the luminosity constant. However, the dominant resolution contribution comes from the

Figure 4: Schematic of the SOS.

Table 3: Short Orbit Spectrometer (SOS) Characteristics.

Configuration	QDD
Horizontal Opening Angle	120 mr
Vertical Opening Angle	80 mr
Solid Angle	9 msr
Momentum at B_{nom}	1.5 GeV
Momentum Acceptance	40%
Dispersion	0.94 cm/%
Optical Length	7.4 m
Resolving Power	2200
Angular Range	> 11 deg
Total Weight	110 tons
Distance, Target-Q1	1.5 m

energy spread in the primary beam, and a dispersed beam will be required to reduce this value significantly. The high quality of these instruments makes them also useful for other low q^2 electroproduction experiments that require similar kinematics.

A.5 The Symmetric Toroidal Array Spectrometer (STAR)¹

Our extensive experience with single-arm electron scattering has demonstrated the value of isolating the two electromagnetic response functions (longitudinal and transverse) that are accessible in conventional (e,e') measurements. In coincident electron scattering from unpolarized targets three additional responses involving the interference of transverse and longitudinal polarization states can be accessed. The measurement of all five responses permits the complete reconstruction of the charge and current distributions of the system under study. The superb quality, high intensity, cw beam of CEBAF provides an excellent opportunity to use this approach to explore the structure of fundamental systems such as the nucleon, ^2H , ^3H , ^3He , and ^4He with unprecedented precision. Out-of-plane detection capability is required to isolate the five response functions.

The symmetric toroidal array spectrometer (STAR) has been designed to support a program of this physics at CEBAF. A schematic of the STAR is shown in Figure 6, and its characteristics are summarized in Table 5. It will provide for the simultaneous detection of hadrons, in coincidence with electrons detected with the HMS, at eight azimuthal angles located symmetrically around the momentum transfer vector. Systematic errors in the measurement of the small azimuthal asymmetries that permit the extraction of the response functions are minimized by this approach.

STAR is also well-suited for other programs of high interest to the CEBAF community. Its large solid angle and multi-hadron detection capability will permit the exploration of short range correlations in nuclear systems through the $(e,e'2p)$ reaction. Its symmetry will facilitate recoil polarimetry experiments; for example the charge form factor of the neutron can be measured by using the $d(\vec{e},e'\vec{n})$ reaction and detecting the polarization of the neutron by a second scattering, $H(n,p)$, with STAR serving as the proton detector.

STAR can also serve as a large solid angle electron spectrometer at forward or backward scattering angles by orienting the device along (parallel or anti-parallel to) the beam direction. At large backward scattering angles transverse form factors of nuclear systems (eg., $F_M(Q^2)$ for ^3He) can be studied at very large momentum transfers. At either forward or backward scattering angles STAR can be used for measuring parity violation in polarized electron scattering; its azimuthal symmetry is essential for limiting systematic errors in experiments of this type.

The STAR collaboration is planning to seek funding for this spectrometer primarily through the National Science Foundation and/or foreign contributions. As a consequence,

¹Not included in initial equipment funding

Figure 5: Schematic of the HNSS.

Table 4: Hypernuclear Spectrometer System (HNSS) Design Goals.

Primary Beam	$(\delta p/p \simeq 10^{-4} \text{ at } 1.8 \text{ GeV/c})$	180 keV
Inelastic Electron	$(\delta p/p \simeq 3 \times 10^{-4} \text{ at } 0.3 \text{ GeV/c})$	90 keV
Kaon Spectrometer	$(\delta p/p \simeq 10^{-4} \text{ at } 1.2 \text{ GeV/c})$	120 keV
Kaon Energy loss	$(1.7 \text{ MeV/gm/cm}^2) \times 10 \text{ mg/cm}^2$	17 keV
Overall Resolution		235 keV

Figure 6: Schematic of the STAR spectrometer.

Table 5: Characteristics of the Symmetric Toroidal Array Spectrometer (STAR).

- Range of opening angles about $\vec{q}$ to span $0^\circ < \theta_p \leq 50^\circ$
- Nominal maximum momentum (for all θ_p) $p_{max} \geq 1.5 \text{ GeV}/c$
- Momenta as high as $4 \text{ GeV}/c$ for small θ_p
- Momentum resolution $\leq 10^{-3}$
- θ_p angular resolution $\leq 0.1^\circ$
- ϕ_p angular resolution $\leq 0.1^\circ$
- Large solid angle
- The ability to accommodate extended and/or polarized targets, and
- The ability to accommodate a focal plane polarimeter

this report does not include detailed budget information for the STAR. It is presented here to document its impact on the scientific program planned for Hall C, and on the design of the HMS and the hall itself. The STAR will be subjected to TAP and PAC review at CEBAF prior to the submission of a formal proposal for its funding and construction.

A.6 Parity Violation Experiments (PAVEX)²

In the "Standard Model" of electroweak interactions essentially one free parameter, the weak mixing angle $\sin^2\theta_W$, predicts the structure of the weak neutral current in terms of the familiar electromagnetic current. Measurements of a wide variety of weak neutral current processes show exceptionally good agreement with this simple model. We can measure the weak neutral current form factors directly by measuring parity violation in elastic $\vec{e}p$ scattering. If we assume the standard model is correct and we write the currents in terms of u, d , and s quarks, we derive simple relationships between the unknown weak form factors and the well known electromagnetic proton and neutron form factors, as well as form factors for the "strange quark current." Since CEBAF will provide intense, highly polarized electron beams with very low emittance soon after it begins operation, it will be an ideal laboratory for studying such processes.

A collaboration lead by CEBAF and William and Mary plans to undertake a concerted effort to measure the parity violating asymmetry in elastic $\vec{e}p$ scattering. Experiments of this type are difficult since they require statistical and systematic errors of order 10^{-7} , and therefore require specialized apparatus and significant amounts of beam time. The initial phase of the parity violation program at CEBAF will center on a careful study of the characteristics of the beam, in order to understand the level of asymmetry that will be detectable in an experiment. The CDR includes the funds for the beam instrumentation necessary to characterize the polarized beam for all of the experiments that will need polarized electrons, but no funds for a specific parity violation experiment. A first-generation detector prototype will be developed by the collaboration using ongoing operations funds, and a detailed proposal for an experiment will be forthcoming between now and the turn-on of CEBAF. The second-generation parity violation program at CEBAF will exploit the higher resolution that should be achievable with the STAR.

A.7 User Involvement and Manpower Commitment

An important feature of the Hall C program is the degree to which the equipment has been conceived and designed by users. Many of the instruments will be constructed by users with support from CEBAF to insure uniform quality control and integration into the experimental area. To provide the oversight and guidance necessary for this process, the management of the end station has been undertaken jointly by an internal and an

²Not included in initial equipment funding

Table 6: Hall C Steering Committee Composition.

<u>R. Carlini</u> *	L. Harwood, J. Napolitano, C. Sinclair	CEBAF
<u>L. Cardman</u> *	R. Laszewski, C. Papanicolas	Illinois
D. Day, J. Lichtenstadt		UVa
B. Filippone		Caltech
R. Siegel		Wm & Mary
E. Hungerford		Houston
H. Jackson, B. Zeidman		ANL
J. Lightbody		NSF
J. Martoff		Temple
R. Milner		MIT
J. Reidy		Mississippi

*Hall C Co-Program Managers

external co-program manager; they are supported by a steering committee that includes the spokesmen of the various hardware and scientific collaborations. One of the principal functions of the steering committee has been to encourage the evolution of user-proposed designs into instruments of maximum flexibility and utility. Indeed, as discussed briefly above, these efforts have enjoyed real success, and there are several different experimental programs that will utilize each of the proposed instruments.

The management structure outlined in section J of this report has been established to oversee and coordinate user effort to realize the instrumentation presented in this document and to use it for scientific research. The organization of the scientific effort in Hall C is centered around the Hall C "Instrumentation Collaboration" whose purpose is to exploit efficiently the scientific potential of CEBAF End Station C. The term "Instrumentation Collaboration" refers to a federation of "Scientific Collaborations," each having commitments to specific programs of research and to the design, construction, and operation of the specific instrument(s) required to conduct that research. Each scientific collaboration is led by internally-chosen spokesmen. The collaborations interact with the CEBAF management through the Hall C co-program managers, who receive advice from and disseminate information through the Hall C steering committee. This committee, whose present membership is listed in Table 6, provides a forum for discussion of issues of common interest to all users of Hall C and its facilities.

The Hall C instrumentation breaks down into two components: the common, moderate resolution High Momentum Spectrometer; and a number of user-constructed second arms. In order to proceed with the development and construction of the instrumentation required

for the Hall C research programs in the most cost-effective and scientifically productive manner, we have defined the following "split" of responsibilities. For the HMS "core" spectrometer: the optics has been designed jointly by CEBAF and users; CEBAF will engineer the spectrometer and supervise its construction; the detector package will be designed and built by the users; and the data acquisition hardware will be provided by CEBAF & coded by users. On the other hand, the "second arm" spectrometers and other user-driven initiatives will be designed primarily by users with CEBAF engineering assistance, and constructed by the users with funds provided through CEBAF and/or their ongoing research contracts. CEBAF will build/assemble only those items which are inappropriate or impossible for users. The detector packages will be built by the users, and the data acquisition hardware for these devices will be provided by CEBAF & coded by users.

Table 7 summarizes projected USER and CEBAF manpower available to design, engineer, construct, and commission the instrumentation proposed for Hall C under the assumption that funds are available for all projects. Asymptotic CEBAF staffing levels for the Hall C group are assumed.

A.8 Cost Estimates

The cost estimates for each of the devices proposed for Hall C is given in Table 8. These cost estimates have been developed by the CEBAF engineering staff, and were reviewed by DOE at the September, 1989 semi-annual review. They include all CEBAF labor necessary for the equipment listed. This includes the complete fabrication and testing of the HMS spectrometer itself, but only parts and materials costs for the HMS detector package. The SOS cost estimates were developed based on LANL costs for a similar instrument, with corrections for the changes necessary to adapt the spectrometer to the more hostile environment of an electron scattering hall. The costs for instruments that are partially or totally constructed at user institutions make the presumption that the necessary labor will be obtained from the ongoing grants of those user institutions. The man-years of software development required to make each device operational is also assumed to be borne by the user community, with CEBAF staff providing the data acquisition hardware system and the basic software.

Magnet designs are based upon POISSON and TOSCA models with the exception of the SOS dipoles, where the design of the MRS from Los Alamos has been adopted. The cost of the SOS magnets is the same as LAMPF procurement costs after correction for inflation. For all resistive magnets, previous National Laboratory experience was used in making cost estimates. For superconducting magnets, previous vendor and National Laboratory experience was used. Cost estimates include vendor design and construction labor, materials, procurement, testing, shipping, etc. EDIA costs include non- CEBAF labor for design, procurement, installation, and testing of the magnets, carriages, vacuum systems, detector packages, and shielding.

Table 7: Status of the Manpower Available for Major Hall C Instruments.

Instruments Institutions	Types of Individuals				FTE's per year	duty factor
	Faculty & Staff	Post Docs.	Graduate Students	Technical		
HMS						
<u>Detectors</u>						
Cal Tech	1.0	1.0	1.0	1.0	0.5	0.13
Hampton	2.0	1.0	1.0	1.0	2.0	0.50
MIT	2.0	1.0	1.0	1.0	0.5	0.13
UVa/ANL	2.0	1.0	1.0	1.0	2.0	0.40
<u>Magnet & Optics</u>						
CEBAF	4.0	1.0	0.0	3.0	<u>8.0</u>	1.00
Sub Total					13.0	
<u>Polarized Target</u>						
UVa	4.0	3.0	1.0	1.0	3.9	0.43
SOS/HNSS						
ANL	6.0	4.0	*	2.0	3.2	0.27
BNL	4.0	1.0	*	1.0	1.0	0.17
FSU	2.0	1.0	1.0	1.0	0.5	0.10
Houston	2.0	2.0	2.0	1.0	3.2	0.45
Mississippi	1.0	1.0	1.0	1.0	<u>0.5</u>	0.13
Sub Total					8.4	
PAVEX†						
Harvard	1.0	*	1.0	1.0	0.1	0.03
MIT/Bates	3.0	1.0	1.0	0.4	1.0	0.19
Mississippi	3.0	1.0	1.0	1.0	1.5	0.25
Syracuse	1.0	0.0	1.0	0.2	0.2	0.09
Temple	2.0	1.0	1.0	0.2	0.5	0.12
W & M	2.0	1.0	2.0	1.0	<u>1.0</u>	0.17
Sub Total					4.3	
STAR†						
Arizona	2.0	1.0	1.0	1.0	2.5	0.63
Illinois	6.0	2.0	5.0	2.5	6.0	0.39
MIT/Bates	1.0	1.0	1.0	1.0	0.5	0.13
Saclay	*	*	*	*	*	
Stanford	1.0	*	*	*	*	
Sub Total					<u>9.0</u>	
User Support & Beam Line						
CEBAF	4.0	2.0	*	4.2	10.2	1.00

Total Estimated Manpower

$48.8 \times 5 = 244$ man- years

* Not known at this time.

† Not included in the initial equipment complement

Table 8: Hall C Equipment Cost Estimate (in FY89 \$K).

Hall C Project	CDR Costs (FY89 \$k)
High Momentum Spectrometer	
Magnets, Carriage, Power Supplies, Cryo. & Vac. Systems, etc.	6,422
Detector System	731
Sub Total	7,153
Short-Orbit Spectrometer	
Magnets, Carriage, Power Supplies, Cryo. & Vac. Systems, etc.	1,515
Detector System	373
Sub Total	1,888
Hypernuclear Spectrometer System (Phase 1)	
Split Pole Transport and Refurbish; & Sep. Dipole	250
Beam Separator Dipole	140
Sub Total	390
Cryogenic Targets	
Polarized NH ₃ Target (CEBAF Contribution)	250
LH2/LD2 Targets	250
Sub Total	500
End Station Support Systems	
Beam Line Hardware	385
Counting House Electronics and Computers	470
Beam Line Diagnostics (includes polarimetry)	200
Misc. Hardware (Cables, Field Mapping, Installation, etc.)	460
Sub Total	1,515
TOTAL	11,446

Note: A detailed breakdown of the costs summarized in this table is provided in the appendix to this report. STAR and PAVEX funding is not included in the initial complement of equipment for Hall C.

A.9 Instrumentation Construction Schedule

Figure 7 summarizes the schedule of Hall C activities during the construction period.

A.10 Conclusion

In conclusion, we note that there are many scientists eager to develop and use a variety of instruments in Hall C at CEBAF. The initial complement of major instruments planned will support a rich and varied program of nuclear and particle physics that addresses a wide range of inter-related and exciting physics topics. Additional, smaller-scale, developmental efforts will permit exploratory measurements in new and complementary areas of research. The instrumentation proposed for Hall C, while sometimes novel, does not push technology limits in spectrometer design or detector packages; as a result, it can be specified and built with confidence. The conservative design of this equipment makes it straightforward to have the HMS and SOS ready for operation when CEBAF turns on. We are confident that Hall C will do exciting work at CEBAF from the start and well into the future of the facility.

Hall C Construction Schedule Summary (Calendar Year)

Figure 7: Hall C Construction Schedule.

B Hall C Overview

This overview gives a brief description of the Hall C civil design, beam line components, and utilities systems. This is followed by a discussion of the design philosophy for the support systems for the spectrometers.

B.1 General Layout of Hall C

Figure 8 shows a layout of the three end stations planned for CEBAF and the beam switchyard. The End Station Refrigerator (ESR) cryogen supply, counting house and cooling tower are shown as well. Entrance to Hall C will be by 10% grade tunnel (for equipment), and there will be a second entry tunnel from the counting house. A third entrance/exit will be provided via the switchyard. A plan view of Hall C is shown in Figure 9. The hall is 150 feet in diameter, with the central pivot displaced from the hall center by 4.7 meters in each direction. This offset allows room for the HMS (whose length exceeds the hall radius) to swing from 0° to 90° , and for a (shorter) second arm to have 360° movement. "Second arms" planned for use in conjunction with the HMS include the STAR and a Short Orbit Spectrometer (SOS) that will also serve as part of the Hyper-Nuclear Spectrometer System (HNSS). The separating magnet and virtual photon tagger for the HNSS will be located downstream of the HMS pivot for operation, and stored to the side in the hall when not in use. The parity violation experiment (PAVEX) will also be located in this area when appropriate.

Figure 10 shows the hall and HMS in elevation. The beam centerline is 13 feet above the floor. This height was chosen to accommodate the STAR. The spectrometer is shown in the 90° position which illustrates clearance from the wall to the shield house. Various other dimensions are also indicated. Figure 11 shows a floor plan of the Hall C beam transport, scattering chamber, beam dump, HMS, and the Short Orbit Spectrometer. Notice also the location of the cooling water, AC power, dc power supplies, and the cryogenics supply/return. Power supplies for the HMS magnets will be mounted on the HMS carriage and will "ride" with the magnets. Thus AC power will be brought to the HMS along the beam line and then to each power supply. We are assuming at this point that the SOS and HNSS will use conventional, water-cooled copper coils. Power will be floor mounted and then DC cabled to the magnets. The STAR will be superconducting and power for it will "ride" on its carriage. All cryogens will be supplied through flexible couplings. Cooling water will be supplied through flexible hoses to each cooled device.

B.2 Spectrometer Support, Alignment, and Movement

Each spectrometer will be supported on its own carriage. The preliminary design for the HMS carriage, done by Rosenblat Engineering, is visible in Figure 10. The design of this

Figure 8: The layout of the three halls and beam switchyard.

Figure 9: Plan view of CEBAF Hall C.

HALL C ELEVATION

CEBAF

Figure 10: Elevation view of CEBAF Hall C and the HMS.

Figure 11: The floor plan of CEBAF Hall C. The locations of the beam transport magnets, scattering chamber, beam dumps and spectrometers are indicated.

carriage is typical of the approach that will be used for all of the Hall C spectrometers. All of the HMS magnetic elements will be supported on a common carriage. The design philosophy is to use a carriage rotating around a central bearing which is rigidly mounted to the floor. Due to the nature of the site and end station construction we do not have the option of using thick concrete beams under the carriage tracks. The floor thickness is specified only to be adequate to retain its integrity under expected loadings. Therefore, the floor deflections will be relatively large and will require the use of a leveling system that adjusts the spectrometer after each angle change. This will be accomplished by leveling jacks attached to the end of the spectrometer. Thus, in any position, the front bearing and leveling jacks will support the load of the spectrometer. The shield weight for the HMS is approximately 500 tons.

Each spectrometer will be supported on carriages which rotate around the target center line. A central bearing system, concentric with the target center line, will be used as the pivoting member. Each carriage will rest on tracks secured to the floor. These tracks will be aligned precisely with respect to concentricity of target center line and rotational flatness. The carriage will then be attached to the central bearing and motor driven around the target center line. A suitable angular position sensing system will be installed.

There will be a common bed-plate attached to a three-point, mechanically adjustable suspension system. In this way, the spectrometer can be aligned with respect to a central ray emanating from the target center. Allowance will also be made for left-right and radial mechanical alignment of the bed-plate.

Each magnetic component of the spectrometer will be mounted to the bed-plate using individual three point mechanical adjustment with allowance made for left-right and radial alignment. Thus we can align each magnetic center line to the central ray accounting for pitch, roll, left-right, and radial positions. Prior to installation, the magnets will have to be magnetically and mechanically "mapped" and magnetic center lines determined.

The shielding and detector package will be mounted to a common carriage which will be rigidly attached to the spectrometer carriage in the radial direction. The detector package will be mounted on an X-Y-Z servo operated support system. The detector center line can then be aligned to the spectrometer central ray. In this way it is hoped that high positioning accuracy of the detector package can be achieved.

The above description applies mostly to the HMS. Other support systems can be expected to incorporate additional features as appropriate for their operation. For example, the STAR will have movement along the radial direction as well as rotational movement; its carriage system will be more complex for that reason. Some detector packages may not require precision movement. It should also be noted that the HMS shield house must be split and open/close for detector work. A similar approach will probably be adopted for all of the Hall C spectrometers.

C The High Momentum Spectrometer (HMS)

C.1 Physics Program Overview

The broad design goals for the High Momentum Spectrometer (HMS) evolved from the consensus that developed among the users at the 1987 CEBAF Summer Workshop that a high momentum, moderate resolution spectrometer would be needed for most experiments envisioned for Hall C. An experimental device must be justified by the research program(s) it will serve.

The research program planned for the HMS is broad and varied. It includes single-arm (inclusive) electron scattering experiments such as the measurements of the deep inelastic structure functions outlined or the proton electric form factor outlined in sections C.1.a and C.1.b below. The use of the HMS in conjunction with a polarized target to measure the neutron electric form factor is described in section C.1.c; the polarized target is presented in section C.8. The HMS can also be used in a "stand-alone" mode as a hadron detector, as is the case for the study of the photodisintegration of the deuteron at high Q^2 , outlined in section C.1.d.

Many more experiments are planned using the HMS in coincidence with one of the user-constructed "second arm" spectrometers, the SOS and the STAR. Among the initial experiments planned for the HMS/SOS pair are studies of the energy and mass dependence of nucleon propagation in nuclei as measured in the $(e,e'p)$ reaction; longitudinal charged pion electroproduction in ^2D , ^3He , and ^4He ; electroproduction of kaons and hypernuclei; and proton polarization in the $d(\gamma,p)n$ reaction. These experiments are outlined in sections D.2.a through D.2.d, as part of the discussion of the scientific motivation for the SOS.

Experiments involving the use of the HMS in coincidence with the STAR spectrometer, such as the measurement of nuclear and nucleon response functions using out-of-plane coincidence techniques, $(e,e'2N)$ experiments, and $(e,e'\vec{p})$ investigations are discussed in section F.1 of this document, where the scientific motivation for the STAR spectrometer is outlined. The design goals for the high momentum spectrometer for Hall C were set on the basis of a careful review of all of these proposed studies.

A careful review of the requirements for all of these experiments formed the basis for the specifications for the performance requirements for the HMS.

C.1.a Inclusive Scattering from Nuclei at Large x and Q^2

The most direct probe of the quark degrees of freedom in the nucleus is via the deep inelastic structure functions $F_2 = \nu W_2$ and $F_1 = MW_1$ in the scaling limit. The EMC collaboration [Au83] provided the first detailed investigation of the influence of the nuclear

medium on the nucleon structure functions with initially surprising results. These investigations (and subsequent data from SLAC [Bo83,Ar84]) concentrated on the region of Bjorken $x(=Q^2/2M\nu)$ less than one. The behavior of the structure functions in a nucleus for $x > 1$ (kinematically forbidden for the free nucleon) is unknown and the predictions vary considerably. Frankfurt and Strikman [Fr81,Ak86,Fr88] have stressed the importance of studying this region as a probe of very high momentum components in the nuclear wavefunction. This region should be sensitive to nucleon–nucleon correlations and to possible non-nucleonic degrees of freedom [Ba85] in the nucleus. Inclusive scattering in this kinematic region will also be crucial to unraveling the nuclear response at high Q^2 in semi-exclusive experiments – $(e, e'p)$ and $(e, e'\pi)$ – which are discussed in other sections of this document. The region $x > 1$ is also the kinematic domain where y -scaling [We75,Si80] of the quasielastic response can be investigated. By following the Q^2 evolution of the nuclear response, the transition from the y -scaling of quasielastic scattering to the x -scaling of deep inelastic scattering can be probed directly.

To understand the kinematic range that can be explored at CEBAF, consider the Q^2 vs. ν plot shown in Figure 12. For a 4 GeV beam (ie. $\nu < 4$ GeV) only a tiny corner of the conventional deep inelastic region ($Q^2 > 1$ GeV² and $W > 2$ GeV) can be explored. However, a fairly large area of the $x > 1$ region can be studied; for $Q^2 \gtrsim 3$ GeV² this region is largely unexplored. With a 6 GeV beam a significantly larger area in the (Q^2, ν) plane can be probed, especially when actual rate estimates are considered. For purposes of estimating running times we will assume a beam energy of 6 GeV.

In order to estimate counting rates and running times we need a model for the cross section. We will take the previous data from SLAC [Da87] at lower Q^2 as a guide and attempt extrapolation. A recent analysis [Fipr] of that data has shown an intriguing scaling of the structure function when analyzed with the Nachtmann scaling variable $\xi = 2x/[1 + (1 + 4M^2x^2/Q^2)^{1/2}]$. This has been shown [Ge76] to be the correct variable for the study of scaling violations of the deep inelastic response at finite Q^2 ; it accounts for the finite target mass M_N . The approach to this “scaling” is shown in Figure 13 for Fe. We will take the highest Q^2 results and assume convergence (ie. no further dependence on Q^2) and extrapolate to the Q^2 of interest. We further assume 100 μ A of beam current, a 6% Fe target, a spectrometer solid angle of 5 msr, a $\delta p/p$ bite of 10%, and a fixed x bin of 0.05.

Time estimates are shown in Table 9, for two extreme kinematic points, one at a forward angle and one at a large angle. The measurements would actually be run at several angles to cover the full kinematic range. For the forward angle measurements, which reach the largest values of x , a spectrometer with maximum momentum > 4 GeV/c is required. As can be seen from the running times, $Q^2 \gtrsim 11$ GeV² and $x \rightarrow 2 - 3$ can be achieved. Backgrounds can be controlled with an adequate detector package. Parameterizations of previous π photo- and electro-production indicate that π/e ratios may reach ~ 200 , but a threshold Čerenkov detector and electromagnetic shower counter can provide sufficient particle identification to reduce the uncertainties due to π subtraction to $< 2-3\%$.

Figure 12: The kinematic range in Q^2 and ν are shown for several values of the Bjorken x variable. Also shown in the regime of conventional deep inelastic scattering (Missing Mass $W > 2 \text{ GeV}$).

Table 9: Running Times and Kinematics for Two Extreme Kinematic Points.

$E = 6 \text{ GeV}$, $\theta=15^\circ$, $Q^2(x=1) = 2.0 \text{ (GeV/c)}^2$
Desired Error = $\pm 5\%$

E' (GeV)	x	Q^2 (GeV ²)	σ_{tot} (nb/sr/MeV)	Rate (counts/hr)	Time Req. (hr)
4.020	0.44	1.6	3.0×10^0	7.2×10^7	3.5×10^{-7}
4.221	0.52	1.7	2.2×10^0	5.7×10^7	5.8×10^{-7}
4.432	0.62	1.8	1.6×10^0	4.3×10^7	1.0×10^{-6}
4.654	0.75	1.9	1.1×10^0	3.1×10^7	2.0×10^{-6}
4.887	0.96	2.0	6.1×10^{-1}	1.8×10^7	5.4×10^{-6}
5.131	1.29	2.1	2.0×10^{-1}	6.2×10^6	2.7×10^{-5}
5.388	1.92	2.2	1.7×10^{-2}	5.5×10^5	6.4×10^{-4}
5.657	3.59	2.3	6.1×10^{-4}	2.1×10^4	4.6×10^{-2}
5.940	21.48	2.4	2.4×10^{-5}	8.8×10^2	4.6×10^1

$E=6 \text{ GeV}$, $\theta=70^\circ$, $Q^2(x=1) = 9.1 \text{ (GeV/c)}^2$
Desired Error = $\pm 25\%$

E' (GeV)	x	Q^2 (GeV ²)	σ_{tot} (nb/sr/MeV)	Rate (counts/hr)	Time Req. (hr)
1.000	0.84	7.9	7.5×10^{-4}	4.5×10^3	4.2×10^{-3}
1.050	0.89	8.2	4.8×10^{-4}	3.0×10^3	6.8×10^{-3}
1.102	0.95	8.7	2.8×10^{-4}	1.8×10^3	1.1×10^{-2}
1.158	1.01	9.1	1.5×10^{-4}	1.0×10^3	2.2×10^{-2}
1.216	1.07	9.6	6.8×10^{-5}	5.0×10^2	5.1×10^{-2}
1.276	1.14	10.0	2.4×10^{-5}	1.9×10^2	1.4×10^{-1}
1.340	1.21	10.5	9.1×10^{-6}	7.4×10^1	4.0×10^{-1}
1.407	1.29	11.1	3.1×10^{-6}	2.7×10^1	1.1×10^0
1.477	1.37	11.6	1.0×10^{-6}	9.2×10^0	3.7×10^0
1.551	1.47	12.2	3.1×10^{-7}	2.9×10^0	1.2×10^1
1.629	1.57	12.8	8.9×10^{-8}	8.7×10^{-1}	4.7×10^1
1.710	1.68	13.5	2.3×10^{-8}	2.4×10^{-1}	1.8×10^2

Figure 13: The measured structure function for Fe [Fipr].

Thus, an inclusive scattering experiment exploring the deep inelastic and quasielastic response of nuclei at large x and large Q^2 appears to be easily within reach. Clearly this experiment can be run shortly after turn-on (initially with a 4 GeV beam) and can provide important physics results early as well as set the stage for further studies of this kinematic range in coincidence experiments (such as color transparency studies at $x \gtrsim 1$).

C.1.c Measurement of the Electric Form Factor of the Neutron

The form factors of the proton and neutron are fundamental properties of the nucleon, and a critical testing ground for models based on QCD. A detailed knowledge of these form factors is essential to our understanding of the electromagnetic response functions of nuclei. Our present knowledge of the neutron electric form factor is inadequate. The slope of $G_{E_n}(Q^2)$ at $q^2 = 0$ is known accurately from neutron-electron scattering, but at higher Q^2 , where G_{E_n} has been extracted from elastic $e-d$ scattering, or inclusive quasielastic $e-d$ scattering, the systematic errors are very large. For both of these measurements removal of the proton contribution to the data requires information about the deuteron structure, and large uncertainties are introduced from uncertainties in the theoretical description of the deuteron (mostly from final state interactions and meson exchange current contributions). As a result, G_{E_n} is known with a systematic error of about $\pm 100\%$.

An alternative way of extracting G_{E_n} by measuring the spin-dependent part of the elastic $e-n$ cross section has been proposed [Da89] by a Virginia/Basel/Tel Aviv collaboration. A measurement of the asymmetry in the quasielastic scattering of longitudinally polarized electrons from polarized deuterium nuclei in deuterated ammonia (ND_3) will determine the ratio G_{E_n}/G_{M_n} . Dombey [Do69] was the first to point out that the scattering of longitudinally polarized leptons on polarized nucleon targets could be used to determine the form factors of the nucleons. The idea is to measure the part of the $e-N$ elastic cross section that corresponds to the interference between the Coulomb and the transverse components of the nucleon current. The measurement is carried out by observing the asymmetry in the cross section that results when either the beam or the target polarization is reversed.

Following Donnelly and Raskin [Do86a, Do89] we can express the inclusive $e-N$ cross section as a sum of an unpolarized part, Σ , that corresponds to the elastic cross section $d\sigma/d\Omega_e$, and a polarized part, Δ , that is different from zero only when the beam is longitudinally polarized (helicity h):

$$\sigma(h) = \Sigma + h\Delta; \quad h = \pm P_{beam}. \quad (1)$$

The asymmetry is then

$$A_n = \frac{\sigma(+)-\sigma(-)}{\sigma(+)+\sigma(-)} = \frac{\Delta}{\Sigma}. \quad (2)$$

In this expression Σ is just the elastic unpolarized free $e-N$ cross section; for neutrons it is given by:

$$\Sigma = \sigma_{Mott} \frac{E'}{E_0} \left(\frac{G_{E_n}^2 + \tau G_{M_n}^2}{(1+\tau)} + 2\tau G_{M_n}^2 \tan^2(\theta_e/2) \right) \quad (3)$$

where $E_0(E')$ are the initial (final) electron energy, $\tau = Q^2/4m_n^2$, m_n is the neutron mass, $-Q^2 = q_\mu^2$ is the square of the four-momentum transfer, and G_{E_n, M_n} are the neutron Coulomb and magnetic form factors. The polarized part, Δ , contains two terms associated with the possible directions of the target polarization. The full expression for the asymmetry for the special case where the target is longitudinally polarized perpendicular to $\vec{q}$

Table 10: Kinematic Quantities for the Proposed G_{E_n} Measurement

Q^2 (GeV/c) ²	E_0 (GeV)	ν_{qe} (GeV)	$ \vec{q} $ (GeV/c)	θ_e (deg)	θ_q (deg)	θ_B (deg)	T'_n (MeV)
0.5	2.849	0.273	0.758	15	61.6	28.4	268
1.0	3.880	0.553	1.143	16	53.3	36.7	540
1.5	3.973	0.843	1.487	20	46.0	44.0	819
2.0	4.020	1.142	1.818	25	40.1	49.9	1107

is given by:

$$A_n = \frac{\Delta}{\Sigma} = \frac{-2\sqrt{\tau(1+\tau)} \tan(\theta_e/2) G_{E_n} G_{M_n}}{G_{E_n}^2 + \tau[1 + 2(1+\tau) \tan^2(\theta_e/2)] G_{M_n}^2}. \quad (4)$$

To determine the region of Q^2 where the proposed technique will be most effective, it is customary to evaluate a figure of merit (FOM) for the experiment. For the present measurement the FOM is related to the time required to accumulate the number of counts needed to determine the asymmetry to a given precision. This number is proportional to the product of the square of the asymmetry times the cross section:

$$FOM = A_n^2 \frac{d\sigma}{d\Omega_e}. \quad (5)$$

The FOM sets a practical limit on the upper value of the attainable momentum transfer, independent of other technical complications that arise from the high kinetic energy of the recoil neutrons and the opening of the inelastic ($e, e'\pi$) and ($n, p\pi$) channels. It is proposed to extract G_{E_n} at four values of Q^2 , starting at about 0.5 (GeV/c)², up to 2.0 (GeV/c)².

Table 10 summarizes the kinematics for the proposed experiment. The symbols in this table have been defined earlier, with the exception of: ν_{qe} which is the electron energy loss at the quasielastic peak, including the average separation energy of the nucleon; θ_B which is the direction of the target magnetic field relative to the beam in the laboratory reference frame (main coordinate system), and is perpendicular to $\vec{q}$; and T'_n , which is the kinetic energy of the recoil neutrons in parallel kinematics (i.e. zero initial momentum).

Tables 11 lists the experimental uncertainties in the target asymmetry, $\delta A_{ed}/A_{ed}$, and in the experimental asymmetry, $\delta\epsilon/\epsilon$, the total counts, N , and the counting rates, counting times, and FOM for the experiment for the kinematics listed in Table 10. The uncertainties in the values of G_{E_n} extracted from the target asymmetries depend [Da89] on the theory that is used to interpret the results; they vary from 9 to 17% for a Q^2 of 0.5 (GeV/c)² and from 18 to 36% for a Q^2 of 2.0 (GeV/c)².

The HMS has the necessary combination of momentum acceptance, resolution, and solid angle for this experiment. Only modest energy resolution on the electron side is

Table 11: Counts, Uncertainties, and the Figure of Merit for the G_{En} Experiment

Q^2 (GeV/c) ²	$\delta\epsilon/\epsilon$ (%)	$\delta A_{ed}/A_{ed}$ (%)	N	R (Hz)	t (hours)	$\frac{FOM(Q^2)}{FOM(0.5)}$
0.5	8.2	9.3	1.43×10^6	4.30	92.5	1
1.0	12.1	12.9	5.53×10^5	1.55	99.0	0.23
1.5	10.8	11.6	3.06×10^5	0.36	235.2	0.06
2.0	11.5	12.3	1.50×10^5	0.10	400.0	0.02

necessary as the neutron arm dominates the overall determination of the missing energy. The large vertical acceptance of the HMS is an advantage when considering the deflection of the electrons in the target field. Quasi-elastic scattering events from the neutron will be identified by detecting the recoil neutron in coincidence with the scattered electron. The neutron detector will consist of an array of scintillators which will form a continuous wall with the approximate dimensions of $1.5 \times 3.0 \times 0.3$ meters.

C.1.d Two-Body Photodisintegration of the Deuteron

One of the central issues in nuclear physics concerns the existence of clear signatures for the presence of quarks in nuclei. Constituent counting rules, appropriate at high momentum transfer, provide a means for studying the simplest nucleus, the deuteron, but the rapid decrease in cross section with increasing momentum transfer has heretofore prevented investigations of dimensional scaling in the elastic scattering of electrons by deuterons. This problem can be circumvented by study of the exclusive photo-disintegration of the deuteron where the momentum transferred to the nucleon is higher than can be achieved in elastic e-d scattering. In a recent experiment at SLAC by an ANL-Caltech collaboration, it was found that at the highest energies studied, the cross section dependence was s^{-11} , in accord with the dimensional scaling rules. Extension of these measurements to higher energies is essential to either verify scaling behavior or indicate modifications of the simple constituent counting rules.

The basic experiment consists of producing bremsstrahlung photons slightly upstream of the deuteron target and detecting protons from the $D(\gamma, p)n$ reaction. In order to ensure exclusivity in the reaction, only protons with energies above the pion threshold are analyzed. At forward angles, the kinematics of the reaction result in protons with momenta larger than that of the primary electron beam. The experiment requires a spectrometer to detect protons with momenta up to 6 GeV/c, a resolution $\delta p/p < 10^{-3}$, as large a solid angle as possible (5 msr would suffice), and a momentum bite $> 10\%$. With a 5 msr spectrometer, the anticipated count rate would be 0.3 counts/minute for a 4 GeV beam of 30 μ A average intensity.

Table 12: Design Goals for the HMS.

Maximum central momentum	6 GeV/c
Momentum bite $[(p_{max}-p_{min})/p_0]$	20%
Momentum resolution $[\delta p/p]$	0.1%
Solid angle	10 msr
Minimum scattering angle	<10 degrees
Angle measurement precision	
in scattering plane	0.1 mr
out-of-plane	1.0 mr
Target length	20 cm
Vertex reconstruction accuracy	~ 1 mm

C.2 The Ion Optical Design of the HMS

The detailed evaluation of the experiments outlined above, together with the discussions at the 1987 Summer Workshop and at a series of meetings of the Hall C Steering Committee, lead to the ideal performance goals given in Table 12 for the HMS. In the subsections that follow we review existing spectrometer designs for high momentum spectrometers, consider possible choices for the optical elements of the spectrometer, and then present an overview of the design for the HMS that emerged from these studies. Later subsections present details on the detector package and on the engineering studies that have been carried out on the realization of the HMS design.

C.2.a A Brief Review of Existing Spectrometers

User group discussions of how to meet the above goals addressed the two basic options of focussing and non-focussing spectrometers. A majority favored a focussing spectrometer so as to minimize the volume of the detector package and shielding, reduce overall count rates, and provide a hardware defined "tag" for the virtual photons.

The design goals, coupled with the kinematic constraints envisioned in a wide variety of experiments, suggest a general approach to the optical design. Extremely good momentum resolution is NOT required, although excellent angular precision is required. This is not the first system which needed good angular resolution, moderate-to-good momentum resolution, and extended targets or insensitivity to kinematics changes. Some existing solutions to this combination of requirements are summarized in Table 13; none of these designs meets all the goals set for the HMS.

Table 13: Selected High Momentum Spectrometer Designs.

	Type	p_{max} (GeV/c)	Total bend	$\frac{p_{max}}{p_{min}}$	Resol. (10^{-4})	$\Delta\Omega$ (msr)	$\frac{\theta_r}{\theta_t}$	Resol. $\delta\theta_s$ (mr)
NIKHEF	QDD	0.6	150°	1.10	~2	5.6	1	2-4
SACLAY 600	D	0.6	153°	1.40	~4	6.5	6	2-4
900	D	0.9	169.7°	1.10	1.5	4.8	4	2-4
MAMI B hadron	QDD	0.67	110°	1.20	<1	28.0	0.7	1-3
NIKHEF	QDQ	0.75	90°	1.10	~5	16.	1	2-4
MAMI B electron	QQDD	0.81	110°	1.15	<1	5.6	3.5	1-3
BATES ELSSY	DD	1	90°	1.06	0.4-0.5	5.4	6	
NSCL S800	QQDD	1.2	150°	1.1	1	20	1.5	1
LAMPF HRS	QDMQ	1.52-2	150°	1.05	0.4	2.6	1	0.8
SLAC 1.6 GeV	D	1.6	90°	1.10	8	4.1	4	0.37
SATURNE SPES I	QSD	1.9	97°	1.04	0.5	3.8	2	
SPES IV	QQDSDQ+	4	0°	1.01	3	2.4	3	
	QDDSQQ		Re-imaging	1.09	10	0.4	14	
CEBAF 4 GeV	QQDQ	4	45°	1.10	0.5	8	2.2	<0.5
SLAC 8 GeV	QQDDQ	8	29.6°	1.05	5	0.75	4	~0.3

Notation: θ_t = angle in the transverse plane
 θ_r = angle in the radial plane
 θ_s = scattering angle

Within this basic approach many optical choices can be made, both in number and type of elements. Part of the choice in configurations is driven by fabrication and aberration correction considerations. Some use many adjustable "knobs"; others do not. For this design, it was decided to use an approach which minimizes reliance on mechanics and "knobs" and substitutes a reliance on measurement of the actual performance of the system. Such an approach lead to a mechanically simple, relatively inexpensive 20 msr spectrometer design at NSCL. Another characteristic of the approach at NSCL was the choice to not utilize any aberration- correcting hardware, eg. sextupoles, octupoles, or curved pole edges.

C.2.b Possible Choices for the Magnetic Optics

There are still options within the design approach outlined above, such as the number of quadrupoles, their locations, and their strengths (or similarly for the dipoles). The first-order optics of a variety of systems were studied with TRANSPORT; these included the QQDD, QQD, QQQD, QQDQ, and QQQDQ configurations. Entrance- and exit-edge angle focussing as well as a first-order field index in the dipole were investigated for each option. The solid angle (5 msr), momentum bite (18 %) and target length (10 cm) were not varied during the initial study in order to fairly compare the options. After an initial analysis of the options, the solid angle was increased to 6.4 msr for the final studies (the momentum bite primarily affected the focal plane length.). The pros and cons of each configuration are summarized below:

- QQD: This configuration had a very small resolving power as defined by the ratio of dispersion to magnification, D/M .
- QQDD: Optically similar to the QQQD discussed below, but more expensive since the QQDD design trades a D for a Q.
- QQDQ: This option received extensive study as it has been selected for the HRS² spectrometer pair in CEBAF Hall A. A crucial feature of the tune used in Hall A is the index in the dipole field. A second important feature is the 45 degree bend. Both of these work to bring the quadrupole gradients to manageable levels. A 45 degree dipole for 6 GeV/c would be an engineering tour de force and quite expensive. It was decided to keep the bend angle at or below 30 degrees. This led to a field index of between 1.5 and 4.5; such an index would make the system critically sensitive to dipole alignment errors. Furthermore, the requisite quadrupoles become quite ambitious. A gradient of 15 T/m on a magnet with a 0.15 m radius for particles and a 0.2 m radius at the coil location ("pole" field of 3.0 T) was required even if the magnet were longer than that used in Hall A. The other two quadrupoles required a 5 T/m gradient on a 0.30 m radius aperture (0.40 m radius at the coils or a "pole" field of 2.0 T). The dipole would have been as long as the Hall A dipole, have a slightly larger gap, and be about the same width. The resolving power of this solution was 50% larger than the others; and the solid angle was 20% larger. It was felt that these advantages were offset by the increased technical risk of the quadrupoles and

the sensitivity to dipole alignment. The latter was a point of concern expressed by the Hall A TAP2. Further, as the last quadrupole is "up in the air", its alignment and stability could be problematic.

- QQQD: This solution provided sufficient resolving power to meet the momentum resolution requirements and the first-order optics were sufficient to meet the other resolution requirements when detector effect were folded in. No dipole field index was required. A large, 3.2:1, out- of-plane/in-plane angular acceptance ratio could be accommodated for a 6.4 msr solid angle with quadrupoles with pole fields below 1.5 T. This configuration seemed the most promising and was chosen for further detailed study.
- QQQDQ: A priori, this configuration was expected to have better characteristics than the QQQD. It did, indeed, have a slightly reduced envelope in the non-dispersive plane. However, the additional quadrupole after the dipole with its associated acquisition cost, alignment sensitivity, and limitation to extended momentum acceptance offset the modest gains in cost to the other components in the system.

C.3 The Proposed (QQQD) Design

C.3.a Mechanical and Magnetic Design

Figure 14 shows elevation and plan views of the proposed QQQD design for the HMS spectrometer. All of the magnets are superconducting. The physical characteristics of the dipole and the quadrupoles are listed in Table 14. The magnetic/physical properties of the dipole are listed as well. Drift lengths between elements are shown. The HMS is designed to have a minimum closing angle of 12.5° with respect to the 0° beam line. The limiting element that defines this minimum scattering angle is Q1.

Figure 15 is a three dimensional drawing of Q1. It is a superconducting cold-iron quadrupole. Magnetic effective length for the "quad" is 1.8 meters. The pole tip field is approximately 1.5 Tesla, a gradient of 605 gauss/cm with pole tip radius of 25 cm. The warm bore for Q1 is 22 cm radius.

Figure 16 shows a cross section of Q1. The inner tube is the beam vacuum surface, then moving outwards is the 70 K surface followed by the helium dewar. The coils are made from about 100 turns/pole of Fermi cable. The pole surfaces are hyperbolic in shape. This is a narrow quad-necessary to make the 12.5° closing angle. The thin width coils are canted at an angle of 5° which best fits a hyperbolic coil design. Figure 17 displays the calculated magnetic fields for Q1. All magnetics calculations were done with POISSON and TOSCA. More detail will be presented below.

Figure 18 shows a cross section of the Q2 and Q3 quadrupoles, which are identical in design. Both have a pole tip radius of 35 cm and are 2.1 m long. The design field for this

Figure 14: Elevation and plan views of the HMS QQQD spectrometer.

Figure 15: A three dimensional sketch of HMS quadrupole Q1.

Table 14: Basic HMS Magnet Parameters.

Quadrupoles

	Warm Radius (cm)	Pole Radius (cm)	Length (m)	Pole Field (T)
Q1	22	25	1.89	1.5
Q2	30	35	2.10	1.56
Q3	30	35	2.10	0.68

Dipole

Gap	42 cm
Good Field width	± 30 cm
B(at $p_0=6$ GeV/c)	1.66 T
Length	5.26 m
Pole face rotations	$-6^\circ, -6^\circ$

Figure 16: A cross section sketch of HMS quadrupole Q1.

Figure 17: POISSON calculation of the field for Q1.

Figure 18: Schematic of HMS quadrupoles Q2 and Q3.

Figure 19: The HMS dipole with cryostat coils installed.

magnet is 1.56 tesla, which is necessary for 6 GeV/c operation of the HMS. The magnetic characteristics of this design is being refined through TOSCA and POISSON calculations

Figure 19 shows the dipole with cryostat coils installed. This magnet will weigh about 450 tons. The basic design was shown in Figure 14, and the characteristics of the dipole were listed in Table 14. The magnet is driven by a main superconducting coil. The field specification for the dipole states that the desired component be highly uniform: $((B_y(x, y) - B_y(0, 0))/B_y(0)) \leq 10^{-3}$, and that the transverse field be very small: $B_x(x, y)/B_y(0, 0) < 4 \times 10^{-3}$ for parallel-to-point optics, and $< 1 \times 10^{-3}$ for point-to-point optics; these criteria apply throughout the elliptical region traversed by particles of interest. This is accomplished by a combination of variable Purcell gap, 3.2x2 cm Rose shims near the edge of the pole face, and a 2-point approximation to the Kumagai profile for the pole edges. The pole profile is evident in Figure 20, which also displays the coil location and the flux lines calculated by POISSON for an excitation of 1.66 tesla. A major benefit of these "machined-in" corrections is that the magnet can be much narrower. This saves many tons of steel. The magnet's field uniformity was checked at various excitations; it worked within specifications.

C.3.b MOTER Studies of the QQQD Design

Starting with the first-order optics from the TRANSPORT studies, detailed ray-tracing studies were performed with the code MOTER. This code permits a detailed evaluation of spectrometer designs, including all ray-tracing effects (finite fringe fields on the magnets, field

Figure 20: A section view of the HMS dipole, with flux lines as calculated by POISSON for an excitation of 1.66 tesla.

deviations relative to the mid-plane field, misalignments of elements, superimposed multipole errors in the elements, detector multiple- scattering, and detector resolution) while simultaneously giving results from the “software” corrections. The software corrections in MOTER consist of a polynomial mapping of two “measured” position and two “measured” angle coordinates at the “focal plane” to the coordinates at the target; in the mapping, the spot size on the target in the dispersive direction is assumed to lead to incoherent errors in the other coordinates. One specifies for MOTER which terms are to be included in the polynomial for each reconstructed coordinate; the values of the coefficients for the terms can be specified and fixed or can for calculated by MOTER. Random errors in each of the “measured” parameters can be included before reconstruction is performed, thereby simulating measurement errors due to detector resolution and/or multiple scattering. MOTER calculates the standard deviation of the “error function” for each target location coordinate; this “error function” is simply the distribution function of the differences between the reconstructed value of the coordinate for the rays considered and the “real” (ie. input) value of the coordinate. The standard deviation of this function is thus the resolution for the reconstructed coordinate. In addition, MOTER notes and then discards any ray that exceeds the physical limits of the magnets and/or apertures specified in the input; the discarded rays are not included in any error function calculation.

MOTER was run for the HMS QQD design with 400 independent rays populating a phase space uniformly from -5% to $+5\%$ in momentum offset, uniformly from -0.01 cm to $+0.01$ cm in spot size in the dispersive direction, and uniformly over an ellipse in angle whose major and minor radii were 82.5 mr in the dispersive plane and 25 mr in the non-dispersive plane, respectively. MOTER solved for eight, eight, six, and six coefficients for momentum, out-of- plane angle, in-plane angle, and projected longitudinal target po-

sition, respectively. The highest order of any of the terms included in the reconstruction polynomial fit was third. After the coefficients were extracted from the fit to the nominal spectrometer configuration, they were fixed during all subsequent runs during which various effects were examined. MOTER studies were also carried out for a variety of "tunes" of the basic QQD configuration that might provide different compromises in solid angle, resolving power (D/M), target length, and vertex reconstruction precision. The most different optical tune involved the change from the nominal parallel-to-point focussing in the non-dispersive plane to a near point-to-point tune. As will be seen, this tune greatly improves the projected longitudinal position reconstruction resolution but at the expense of angle resolution.

An "effective solid-angle" study was done with MOTER; it was run with the magnet apertures shown in Table 14 for a variety of operating conditions with the solid angle fixed as an ellipse as previously specified. The input spot size and momentum width were kept small for each run and the centroid of each was varied manually. Sufficient random rays were traced until 400 reached the detectors for each combination of target position and momentum offset. The fraction of the rays making it through the system (the transmission efficiency) was multiplied by the solid-angle given by the angular ellipse; this product was defined as the "effective solid-angle." Figure 21 shows the transmission efficiency as a function of position along the extended target and as a function of deviation from the central momentum. Figure 22 shows the same calculations in a slightly different format, namely as a function of momentum offset for a series of different interaction points along the target.

Table 15 compares the system performance under four basic conditions: 1) a purely academic condition to study the effect of a realistic detector package when the HMS has a pinhole aperture and no momentum spread in the incident particles; 2) the same case as 1), but with the full $\pm 5\%$ momentum acceptance; 3) a case in which we consider the full geometrical acceptance, but with no momentum spread in the incident particles; and 4) the HMS under realistic operating conditions with full acceptance in both solid angle and momentum. The calculations with finite solid angle were all performed assuming an extended target of 10 cm length along the beam direction and the spectrometer placed at a scattering angle of 90° , so that the "Y" resolution corresponds to the transverse position reconstruction capability of the spectrometer-detector package combination. This table also presents results for two different optical tunes for the HMS. The first, the parallel-to-point tune, represents the nominal design for the spectrometer. The point-to-point mode provides improved position resolution for vertex reconstruction (essential, for example, for coincidence measurements involving the STAR) at some sacrifice in other characteristics of the HMS.

As can be seen, limiting the phase space can improve the momentum and out-of-plane angle resolution; however, the in-plane angle and projected longitudinal target position resolutions are dominated by measurement error effects. The entries in Table 15 are for measurement errors of 0.17 mm in position (considered to be a conservative value) and 0.25 mr in angle; the latter represents the error coming from the 0.17 mm position resolution

"30 CM" TRANSMISSION EFFICIENCY PARA-PT MODE

"30 CM" TRANSMISSION EFFICIENCY - PT-PT MODE

Figure 21: Plot of the transmission efficiency of the HMS as a function of the source location transverse to optic axis of spectrometer (in the scattering plane) for a series of momentum offsets, as calculated by MOTER. Results are shown for both parallel-to-point and point-to-point modes. The effective solid angle is obtained by multiplying the efficiency by 6.4 msr.

"30 CM" TRANSMISSION EFFICIENCY PARA-PT MODE

"30 CM" TRANSMISSION EFFICIENCY PT-PT MODE

Figure 22: Plot of transmission efficiency of the HMS as a function of momentum offset for a series of source locations transverse to optic axis of spectrometer (in scattering plane) as calculated by MOTER. Results are shown for both parallel-to-point and point-to-point modes. The effective solid angle is obtained by multiplying the efficiency by 6.4 msr.

Table 15: MOTER Calculations of the Performance of the HMS for Different Solid Angles and Momentum Acceptances.

Solid Angle (msr)	Momentum Bite	Standard Deviations			
		$\delta p/p$ (%)	ϕ (mr)	θ (mr)	Y (mm)
Parallel→Point Tune					
0.0	±0%	0.015	0.63	0.15	3.00
0.0	±5%	0.042	0.74	0.18	3.03
6.4	±0%	0.025	0.74	0.29	3.17
6.4	±5%	0.057	0.91	0.35	3.37
Point→Point Tune					
0.0	±0%	0.008	0.61	0.67	0.20
0.0	±5%	0.053	0.77	0.69	0.61
6.4	±0%	0.031	0.71	0.70	0.25
6.4	±5%	0.058	0.83	0.77	0.64

Table 16: MOTER Calculations of the Performance of the HMS for Different Detector Resolutions and Momentum Acceptances.

Detector Angular Resolution (mr)	Momentum Bite	Standard Deviations			
		$\delta p/p$ (%)	ϕ (mr)	θ (mr)	Y (mm)
Parallel→Point Tune					
0.00	± 5%	0.046	0.55	0.30	1.10
	±10%	0.071	0.93	0.39	1.39
0.25	± 5%	0.057	0.91	0.35	3.37
	±10%	0.095	1.71	0.54	3.50
1.00	± 5%	0.068	2.77	0.78	11.54
	±10%	0.112	3.26	1.01	11.18
Point→Point Tune					
0.00	± 5%	0.057	0.55	0.32	0.20
	±10%	0.103	1.41	0.56	0.45
0.25	± 5%	0.058	0.83	0.77	0.64
	±10%	0.104	1.55	0.95	1.25
1.00	± 5%	0.068	2.50	2.73	2.31
	±10%	0.119	2.95	3.01	4.42

over a 1 m drift or a combination of a more realistic position resolution of 0.10 mm and 0.20 mr of multiple scattering, which corresponds to the approximate performance expected at 3 GeV/c based on estimates that are discussed on the detector section of this document. At 6 GeV/c, the angle measurement error is dominated by the position measurement error; therefore, resolutions at 6 GeV/c are expected to be better than those presented in the table.

The effect of detector resolution on the performance of the HMS is presented in Table 16 for both tunes of the spectrometer and for both the nominal $\pm 5\%$ and a larger $\pm 10\%$ momentum acceptance. Again, the effects of a 10 cm extended target have been included. As expected, the spatial and angular resolution of the HMS are quite sensitive to the angular resolution of the detector package.

The sensitivity of the HMS performance to the effects of an extended target are presented in Table 17. In interpreting this table it is important to recall that the “Y” coordinate is measured perpendicular to the optic axis of the spectrometer, so, for example, a Y resolution of 1.06 mm for a scattering angle of 10° and a z-offset of 5 cm corresponds to a position uncertainty of $[1.06 \text{ mm}/\sin(10^\circ)]$ or 6.1 mm along the beam direction.

MOTER was also used to evaluate in detail the sensitivity of the HMS performance to

Table 17: MOTER Calculations of the Resolution of the HMS as a Function of the Position of the Interaction Point in the Target. Z is Measured Along the Beam Direction.

Scattering Angle	Z Offset (cm)	Standard Deviations			
		$\delta p/p$ (%)	ϕ (mr)	θ (mr)	Y (mm)
Parallel→Point Tune					
10°	+5	0.140	1.98	0.37	3.27
90°	+5	0.047	0.84	0.39	3.26
	0	0.050	0.85	0.37	3.19
90°	-5	0.051	0.83	0.38	3.28
10°	-5	0.144	2.03	0.39	3.26
Point→Point Tune					
10°	+5	0.138	1.82	0.78	1.06
90°	+5	0.063	0.85	0.80	0.66
	0	0.059	0.84	0.77	0.63
90°	-5	0.062	0.82	0.79	0.68
10°	-5	0.132	1.71	0.76	1.02

a broad variety of possible operational and manufacturing errors. Table 18 presents the results of the first of these studies in which each element of the HMS was intentionally mispowered by 0.2%. The effects were to modify the centroid values of the reconstructed distributions and leave the widths essentially unchanged. Not unexpectedly, the largest sensitivity in powering the HMS is that of the dipole field; a field error in the dipole leads to a significant error in the momentum identification of the particles being analyzed.

Allowed multipole field errors in the HMS quadrupoles were studied by the MOTER calculations that are summarized in Table 19. The 3% octupole and 3% (for Q1 and Q2) or 4% (for Q3) dodecapole fields in this table are values at the pole tip; they correspond to approximately 2% octupole and 1.5% dodecapole at the radii of the warm bores of the quadrupoles. The final entry in each tune represents combined field errors in the quadrupoles that appear to be readily achievable on the basis of TOSCA evaluations of magnetic fields in the quadrupoles.

MOTER was also used to study the alignment accuracy and reproducibility required for the elements of the HMS and for the carriage that supports these elements. These studies involved rotation or displacement of single elements or groups elements of the HMS by 1 mr or 2 mm, respectively. The study was initially performed with "perfect" quadrupoles, ie. ones with no higher multipoles. As can be seen from Table 20, rotation about the x-axis primarily affected the θ and Y reconstruction, while rotations about the y axis primarily affected the ϕ and $\delta p/p$ reconstruction. Linear displacements in the x and y directions had similar effects. These effects are simply manifestations of the first-order transport

Table 18: Reconstructed Distributions from the (0.2%) Mispowering Study.

Mispowered Element	Centroids				Standard Deviations			
	$\delta p/p$ (%)	ϕ (mr)	θ (mr)	Y (mm)	$\delta p/p$ (%)	ϕ (mr)	θ (mr)	Y (mm)
None	-0.001	-0.02	-0.03	0.12	0.057	0.91	0.35	3.37
Q1	-0.003	-0.05	-0.02	0.09	0.051	0.89	0.36	3.22
Q2	0.001	0.00	-0.02	0.10	0.050	0.84	0.43	3.28
Q3	-0.004	-0.05	-0.02	0.09	0.052	0.84	0.36	3.23
Dipole	0.033	-0.01	-0.02	0.09	0.049	0.84	0.35	3.20

Note: The observed centroid motions due to quadrupole mispowering were small relative to the widths. Thus, dipole mispowering, i.e. integral of $B \cdot dl$, is the crucial parameter and must be known to the accuracy of the desired momentum resolution.

Since misalignment effects frequently come primarily from non-linearities of the system, the linear displacement calculation presented in Table 21 was repeated with the addition of a dodecapole field to each quadrupole; the strength of the dodecapole was 2% that of the quadrupole at the pole. There was essentially no change in the resolutions. A series of MOTER calculations involving motion of the spectrometer as a whole were also performed to evaluate the stability requirements for the support carriage. These calculations are summarized in Table 22.

The centroid shifts that appear in these alignment studies provide a measure of the required stability and reproducibility of the mechanical supports of the HMS and the alignment tolerances for the elements on the carriage. If a ratio of centroid shift to standard deviation is calculated for each parameter, that ratio times 2 mm indicates how much a given element can move before the resolution is degraded by 40%. This "allowable error" is smallest for a non-dispersive plane motion of Q2 where it is 0.2 mm. It is clear from Table 20 that rotations of the elements about their axes at the level of 1 mr or translations at the level of 2 mm significantly affected the properties of the HMS *if these rotations are unknown*. It was found that the shifts observed in these misalignment studies could be corrected readily with the reconstruction procedure if the size of the displacement is known. In general, the effects are readily correctable if: 1) the error is known, or 2) the reconstruction is done relative to a point calibrated with "real" particles and the magnets do not move. In summary, constancy of alignment is far more important than absolute alignment. The results of all of these alignment and assembly tolerance studies are summarized in Table 23, which presents the design limits that have been used for the engineering studies of the HMS presented later in this section.

The tolerance studies presented in the previous tables were also repeated for the point-

Table 19: The Effects of Unwanted Multipole Components on the Properties of the HMS.

Element <i>Multipole Component</i>			Standard Deviations			
Q1	Q2	Q3	$\delta p/p$ (%)	ϕ (mr)	θ (mr)	Y (mm)
Parallel→Point Tune						
<i>None</i>			0.057	0.91	0.35	3.37
<i>Octupole</i>						
+3%			0.084	1.35	0.58	3.59
<i>Dodecapole</i>						
-3%			0.072	1.19	0.62	3.53
	-3%		0.083	1.05	0.95	4.52
		-4%	0.088	0.92	0.67	3.99
+3%			0.063	1.18	0.40	3.21
	+3%		0.099	1.20	1.01	4.68
		+4%	0.070	0.88	0.42	3.41
+3%	+3%	+1.5%	0.064	1.03	0.54	3.66
Point→Point Tune						
<i>None</i>			0.058	0.83	0.77	0.64
<i>Octupole</i>						
+3%			0.078	1.13	0.88	0.68
<i>Dodecapole</i>						
-3%			0.061	0.86	0.80	0.67
	-3%		0.059	0.84	0.87	1.70
		-4.0%	0.073	0.85	0.81	0.71
+3%			0.058	0.87	0.76	0.67
	+3%		0.077	0.95	0.98	1.77
		+4.0%	0.061	0.84	0.76	0.71
+3%	+3%	+1.5%	0.059	0.87	0.86	1.61

Table 20: MOTER Calculations of the Reconstructed Distributions After Rotation of Single Elements of the HMS by 1 mr.

Element	Motion	Centroid Displacement				Standard Deviations			
		$\delta p/p$ (%)	ϕ (mr)	θ (mr)	Y (mm)	$\delta p/p$ (%)	ϕ (mr)	θ (mr)	Y (mm)
Q1	x	0.000	-0.02	-0.33	-2.50	0.049	0.84	0.35	3.21
	y	0.048	2.35	-0.02	0.09	0.050	0.85	0.36	3.21
	z	-0.001	-0.02	-0.03	0.12	0.049	0.86	0.37	3.22
Q2	x	-0.001	-0.02	1.87	-5.67	0.049	0.83	0.35	3.19
	y	-0.079	-0.31	-0.02	0.09	0.049	0.84	0.35	3.20
	z	-0.001	-0.02	-0.04	0.17	0.052	0.86	0.41	3.30
Q3	x	-0.001	-0.02	-0.07	-1.44	0.049	0.83	0.36	3.20
	y	0.044	-0.21	-0.02	0.09	0.050	0.84	0.36	3.21
	z	-0.001	-0.02	-0.04	0.14	0.050	0.84	0.37	3.25
D (alone)	x	-0.001	-0.02	0.52	2.44	0.049	0.84	0.39	3.27
	y	-0.105	2.04	-0.02	0.09	0.051	0.86	0.36	3.21
	z	-0.001	-0.02	-0.02	0.08	0.049	0.84	0.35	3.21
D (+det.)	x	-0.001	-0.02	1.51	-7.37	0.049	0.84	0.36	3.23
	y	-0.290	1.11	-0.02	0.09	0.059	0.90	0.40	3.28
	z	-0.001	-0.02	-0.02	0.10	0.049	0.84	0.35	3.20
Detector	x	-0.001	-0.01	-0.62	12.42	0.049	0.84	0.54	3.58
	y	0.055	2.65	-0.02	0.09	0.057	0.88	0.35	3.21
	z	0.001	-0.02	-0.02	0.07	0.049	0.84	0.35	3.21

Table 21: MOTER Calculations of the Reconstructed Distributions After Misalignment of Single Elements of the HMS by 2 mm.

Element	Motion	Centroid Displacement				Standard Deviations			
		$\delta p/p$ (%)	ϕ (mr)	θ (mr)	Y (mm)	$\delta p/p$ (%)	ϕ (mr)	θ (mr)	Y (mm)
Q1	x	0.162	3.10	-0.02	0.09	0.052	0.91	0.38	3.23
	y	-0.001	-0.02	-1.30	3.39	0.049	0.82	0.35	3.18
	z	-0.002	-0.03	-0.02	0.09	0.049	0.84	0.36	3.21
Q2	x	0.133	1.37	-0.02	0.10	0.051	0.86	0.37	3.23
	y	-0.001	-0.02	-2.55	8.18	0.050	0.82	0.37	3.21
	z	-0.001	-0.02	-0.02	0.09	0.049	0.84	0.35	3.21
Q3	x	0.116	0.68	-0.02	0.09	0.050	0.85	0.36	3.21
	y	-0.001	-0.02	-0.80	3.41	0.049	0.83	0.35	3.19
	z	-0.001	-0.02	-0.02	0.09	0.049	0.84	0.35	3.20
Dipole	x	0.015	0.52	-0.02	0.09	0.049	0.84	0.35	3.20
	y	-0.001	-0.02	0.15	0.60	0.049	0.84	0.35	3.20
	z	-0.001	-0.02	-0.02	0.09	0.049	0.84	0.35	3.20
Detector	x	0.040	0.52	-0.02	0.09	0.049	0.84	0.35	3.20
	y	-0.001	-0.02	0.10	0.89	0.049	0.84	0.35	3.20
	z	-0.001	-0.02	-0.02	0.09	0.049	0.84	0.35	3.20

Table 22: MOTER Evaluations of the Effects of Movements of the Whole Spectrometer on Its Performance.

Motion	$\delta p/p$ (%)	ϕ (mr)	θ (mr)	Y (mm)	$\delta p/p$ (%)	ϕ (mr)	θ (mr)	Y (mm)
Rotations by 1 mrad								
x-axis	-0.001	-0.02	-1.06	0.05	0.049	0.83	0.35	3.21
y-axis	0.000	1.04	-0.03	0.10	0.050	0.84	0.36	3.21
z-axis	-0.001	-0.02	-0.03	0.09	0.049	0.84	0.35	3.20
Offsets by 2 mm								
x	0.130	1.78	-0.02	0.10	0.051	0.88	0.37	3.23
y	-0.001	-0.02	-0.02	2.07	0.049	0.83	0.35	3.20
z	-0.002	-0.03	-0.02	0.09	0.049	0.84	0.35	3.20

Table 23: Tolerance Summary for the HMS for Parallel-to-Point Optics.

To Preserve Knowledge of:

Momentum to: 0.1%
 In-plane Angle to: 1 mr
 Out-of-plane Angle to: 2 mr
 Target Position to: 1 cm

It is necessary to control:

Dipole Field Uniformity	$\delta B_y/B_0 < 0.1\%$ $B_x/B_0 < 0.4\%$
-------------------------	---

Undesired Multipole Fields	Q1	Q2	Q3
<i>Known Multipoles</i> (at pole)			
Octupole	1.5%		
Dodecapole	3%	3%	3%
<i>Unknown Multipoles</i> (within aperture)	0.2%	0.3%	0.5%

Mechanical Alignments	Q1	Q2	Q3	Dipole	Detector	Whole
Unknown Shifts (mm)	1.5	1	2	4	2	1
Unknown Rotations (mr)	1	0.5	2	1	0.5	1

Table 24: Tolerance Summary for the HMS for Point-to-Point Optics.

To Preserve Knowledge of:

Momentum to: 0.1%
 In-plane Angle to: 1 mr
 Out-of-plane Angle to: 1 mr
 Target Position to: 1 mm

It is necessary to control:

Dipole Field Uniformity	$\delta B_y/B_0 < 0.1\%$ $B_x/B_0 < 0.1\%$
-------------------------	---

Undesired Multipole Fields	Q1	Q2	Q3
<i>Known Multipoles (at pole)</i>			
Octupole	1.5%		
Dodecapole	3%	3%	3%
<i>Unknown Multipoles (within aperture)</i>	0.2%	0.3%	0.5%

Mechanical Alignments	Q1	Q2	Q3	Dipole	Detector	Whole
Unknown Shifts (mm)	1.0	0.2	1	4	2	1
Unknown Rotations (mr)	0.5	0.2	1	0.5	0.2	1

to-point optics mode for the HMS. The results of the point- to-point tolerance studies are summarized in Table 24 in a format identical to that of Table 23. As can be seen from this table, the tolerances on the field quality are identical to those for the HMS in the parallel-to-point mode except for a factor of four tighter tolerance on the x-component of the dipole field; POISSON calculations of the current design for the HMS dipole indicate that it already meets this specification. The mechanical alignment tolerances are generally about a factor of two tighter for the point-to-point mode for the HMS, with the exception of the specification for unknown shifts for Q2, which is a factor of five tighter. These specifications are at or near the limit of what can be achieved with straightforward technology, and our ability to achieve them will probably be unknown until the HMS is installed in Hall C and detailed measurements can take place. In the event that we cannot achieve the full alignment specifications, the performance of the HMS will degrade somewhat. The most sensitive performance specification is the reconstruction of the target position to 1 mm in the point-to-point mode. This specification will degrade roughly in proportion to the degree to which the mechanical alignment specifications degrade, so achieving a very reasonable performance even in the demanding point-to-point mode should be straightforward.

Table 25: A Comparison of the Calculated Performance of the HMS with the Design Goals.

Characteristic	Design Goal	Calculated Performance	
		Parallel→Point Tune	Point→Point Tune
Maximum central momentum	6 GeV/c	6 GeV/c	6 GeV/c
Momentum bite $[(p_{max}-p_{min})/p_0]$	20%	10%	10%
Momentum resolution $[\delta p/p]$	0.1%	0.06%	0.06%
Solid angle	10 msr	6.4 msr	6.4 msr
Minimum scattering angle	$< 10^\circ$	$< 12.5^\circ$	$< 12.5^\circ$
Angle measurement precision			
in scattering plane	0.1 mr	0.4 mr	0.8 mr
out-of-plane	1.0 mr	0.9 mr	0.8 mr
Target length	20 cm	10 cm	10 cm
Vertex reconstruction accuracy	~ 1 mm	3.4 cm	0.6 mm

C.3.c Anticipated Performance of the QQQD Design

The degree to which the QQQD design has met the goals set forth in Table 12 is presented in Table 25. As can be seen from this table, which summarizes the calculations described above for the case of 0.25 mr resolution in the detector package and for the full solid angle and momentum bite of the HMS, real-world compromises have resulted in a somewhat reduced solid angle and allowable target length relative to the design goals. In addition, the angular resolution in the scattering plane is somewhat poorer than the design goals. The vertex reconstruction of order 1 mm, which is essential for use with extended targets and with second-arm spectrometers such as the STAR, has been achieved at the sacrifice of angular resolution in the scattering plane via the use of the parallel-to-point tune. A higher performance can be achieved using the parallel-to-parallel tune when this vertex reconstruction is not required. The overall performance of the QQQD design comes remarkably close to meeting the rather ambitious design goals set for it, and the Hall C Steering Committee, which has reviewed this performance in detail, is unanimous in its enthusiasm for the design presented here.

A reconfiguration of the system in which the quadrupoles were moved closer to the dipole was examined to reduce the minimum forward angle. At the expense of about a factor of two in solid angle, but no change in momentum resolution, it was possible to reduce the minimum scattering angle by 30%, so if it is 12.5 degrees in the baseline configuration, then it could be about 9 degrees for the reconfigured system. Simulation attempts to make a significant gain in solid angle by moving the magnets closer to the

Figure 23: A schematic representation of the detector package planned for the HMS spectrometer.

target as would be permitted at scattering angles of 20 degrees or more were unsuccessful. Radical retuning of the quadrupoles, eg. reversing their polarities could produce much better momentum resolutions but always at the expense of solid angle (approximately a factor of 3 reduction); these modes were therefore considered uninteresting.

C.4 Detector Package

The detector package for the High Momentum Spectrometer will be a straightforward design using currently available technology. It is shown schematically in Figure 23. The primary function of the detector package will be to identify relatively high energy electrons in a modest background of negative pions and measure their trajectories in the region of the HMS focal plane. Some experiments will also use the HMS to analyze high momentum protons, so the detector package provides some π/p separation as well. An important consideration is multiple scattering in the forward part of the system since the track reconstruction precision within the detector package will determine the ultimate resolution of the spectrometer.

C.4.a Drift Chambers

Since ultimate resolutions depend on the precision of the track reconstruction, multiple scattering must be minimized in the tracking apparatus. The design goal is $170\mu\text{m}$ position resolution and $.25\text{ mr}$ angular resolution. (All resolutions are RMS unless otherwise indicated.) Separating the drift chambers by $\approx 1\text{ m}$ implies an angular resolution on the order of 0.15 mr . Multiple scattering in the chambers, vacuum exit window, and atmosphere between the chambers will dominate the angular resolution at low momenta.

We propose building three identical drift chambers. They are based on a successful design [Bo81] which achieves $140\mu\text{m}$ resolution and efficiency greater than 98% even at rates up to 2.5 kHz/wire-mm . The scheme consists of $\approx 1\text{ cm}$ wide drift cells with planes separated by $\approx 2\text{ cm}$. For position measurement redundancy, each chamber would provide X and Y position, as well as two stereo (i.e. U and V) measurements. That is, four planes per chamber with a total width of $\approx 10\text{ cm}$. The expected gas mixture is argon and ethane in roughly equal parts.

The RMS multiple scattering angle is well approximated by the formula [Hi75]:

$$\phi_{RMS-Plane} = \frac{14\text{ MeV}/c}{p\beta} \sqrt{\frac{L}{L_R}}$$

where L/L_R is the length of the scatterer in radiation lengths. Relevant scatterers include the vacuum exit window (15 mil mylar, $L/L_R=1.3\times 10^{-3}$), chamber windows ($2\times 2\text{ mil}$ mylar, $L/L_R=0.4\times 10^{-3}$), chamber gas ($L/L_R=0.4\times 10^{-3}\text{ Ar}$, $L/L_R=0.2\times 10^{-3}\text{ ethane}$), and $\approx 1/2$ the one meter air gap ($L/L_R=1.6\times 10^{-3}$). The total thickness is 3.9×10^{-3} radiation lengths, giving a multiple scattering error of 0.44 mr at $2\text{ GeV}/c$ ($\beta=1$). It should be possible to use new materials to fabricate a thin ($\approx 5\text{ mil}$) vacuum window, and to install a helium bag between the drift chambers ($L/L_R=0.1\times 10^{-3}$ for the helium, 0.2×10^{-3} for the bag window) yielding a total $L/L_R=1.7\times 10^{-3}$ or 0.29 mr at $2\text{ GeV}/c$.

C.4.b Čerenkov Counter

We propose a straightforward atmospheric pressure Čerenkov counter with an active radiator length of 1.5 m . Filled with nitrogen ($n-1=2.7\times 10^{-4}$) the threshold momentum is $22\text{ MeV}/c$ for electrons and $6.0\text{ GeV}/c$ for pions [Wo84]. Consequently, it will be fully sensitive to electrons, yet insensitive to pions.

The number of photons per cm of radiator length is $\approx (n-1) \times 10^3$ or ≈ 41 total [Wo84]. Taking a 10% light collection and photocathode efficiency implies an average of 4.1 photoelectrons. Assuming single photoelectron detection (which is presently available with low noise, large photocathode tubes), the efficiency would be $\approx 98\%$. The efficiency for triggering on pions due to the production of energetic δ -electrons should be less than 5×10^{-4} for

a nitrogen-filled detector.

C.4.c Scintillator Hodoscopes

Following the third drift chamber is an XY hodoscope pair. These would be used for pattern recognition and coincidence timing. The scintillator hodoscopes are completely straightforward devices and timing resolutions of 0.15 ns are routinely obtained with counters of this size [At80].

C.4.d Shower Counter

Additional triggering and e/π identification is afforded by the segmented shower counter system. It will be constructed of F2 lead glass blocks arranged in four layers with 5 blocks per layer, with the blocks lying lengthwise along the dispersive direction. Each 1 m long 15 cm $\times$ 15 cm block is ≈ 5 r.l. thick giving a total thickness of 20 r.l. The specific arrangement of the blocks allows one to determine the longitudinal development of the shower giving better e/π discrimination.

The choice of F2 glass is dictated primarily by the placement of the PMT's perpendicular to the incident particles. A glass with small light attenuation is required to minimize the effects of pulse height variation with particle position. While most of these variations can be corrected for off-line, a strong position dependence of the light output can cause considerable problems for triggering. The high transmission of F2 Pb glass and the use of two tubes on each of the front blocks should minimize this problem.

Previous experience with Pb glass calorimeters of this type indicate the design meets the required performance specifications. One can expect a typical energy resolution for the energy range of the HMS of $\sigma_E \sim 5\%/E^{1/2}$. The expected pion rejection is difficult to estimate for the particular energy range and geometry of the HMS calorimeter. In order to better understand the performance, we have performed Monte Carlo calculations with the GEANT code. We have included Čerenkov light production, light attenuation, light collection, and PMT quantum efficiency. An example of such a calculation is shown in Figure 24 where we histogram events versus PMT pulse height for 0.8 GeV/c pions and electrons. The electrons deposit less than 10% of their energy in the last two layers of Pb glass. (At 6 GeV/c, one needs the full 20 radiation lengths to contain the shower.) On-line pion rejection is therefore improved if only the first two layers are used. Based on these calculations we anticipate a pion rejection of $\sim 100:1$ off-line and $\sim 5:1$ On-line at 0.8 GeV. The pion rejection is considerably better at 4 - 6 GeV and the pion backgrounds are expected to be less. This pion rejection, when coupled with that expected from the threshold gas Čerenkov counter should be more than adequate for most applications.

π/e Separation in Shower Counter at 0.8 GeV/c.

Figure 24: GEANT simulation of pions and electrons in the HMS shower counter at 0.8 GeV/c.

Figure 25: The detector stack superimposed on top of particle trajectories as traced through the HMS. The rays represent $\Delta\theta = 0, \pm 82.5$ mr and $\Delta p = 0, \pm 5\%$ in the dispersive direction, and $\Delta\theta = 0, \pm 22$ mr and $\Delta y_{\text{target}} = 0, \pm 5$ cm in the transverse direction.

C.4.e Penetration Scintillators

It will be possible to place a single scintillation counter just beyond the shower counter to detect particles which punch through leaving a minimum ionizing signal (e.g. muons from pion decay).

C.4.f Shielding

The detector stack will be surrounded in all directions, including the back, with a 1 m thick heavy concrete shielding hut. This follows the design of the SLAC 8 GeV/c spectrometer and the CEBAF High Resolution Spectrometers.

C.4.g Transverse Dimensions and Location Relative to Focus

Figure 25 shows rays traced through the spectrometer in the dispersive and transverse directions. Superimposed on these rays is the outline of the detector stack, showing its placement relative to the foci. The rear shielding wall is placed so that it just approaches the wall of the experimental hall at a scattering angle of 90° .

The chambers will measure 100×80 cm, giving a total of ≈ 1200 wires to read out. The lead glass blocks are 1 m long, and the geometry with five $15 \text{ cm} \times 15 \text{ cm}$ blocks per layer

appears to be ideal.

C.4.h Proton Identification

The detector stack we have described has been designed to identify electrons in a background of negative pions. If proton identification (among, presumably, a background of positive pions) is needed, it is of course possible to modify the detector stack appropriately. However, the system described above already provides some proton discrimination.

Use of other Gases and Higher Pressures in the Čerenkov Counter

If the Čerenkov counter were filled with atmospheric pressure pentane for which $(n-1) = 1.8 \times 10^{-3}$ [Zr68] then the threshold momentum for pions is 2.3 GeV/c in which case it could be used to veto π^+ in order to identify protons. Still larger values of n can be achieved by pressurizing the gas [Zr68], although this implies pressure windows on the Čerenkov counter which would increase multiple scattering, electron radiation, and high energy δ -electrons.

Time-of-flight Measurements

The timing resolution of the hodoscope counters (≈ 0.15 ns) could in principle be used to identify pions from protons by measuring the flight time through the spectrometer relative to the beam pulse. However, for the 25 m flight path, $\Delta T_{p\pi} = T_p - T_\pi$ approaches the time between beam pulses ($\nu \approx 1$ GHz) only at the highest momenta, and there the separation in flight times is not very well resolved. It might be more fruitful to put a set of hodoscope counters upstream of the first drift chamber and use the ≈ 5 m flight path to identify lower momentum protons ($\Delta T_{p\pi} = 1.8$ ns at 2 GeV/c) and use the Čerenkov counter at higher momenta. This of course increases the multiple scattering angle. For a practical scintillator thickness of 3 mm, the multiple scattering would be ≈ 0.65 mr for 2 GeV/c protons. Specific experiments desiring this capability must therefore consider the attendant loss in momentum and angle resolution.

C.4.i The Data Acquisition System

The following is a brief description of a data acquisition system for Hall C based on the assumption that each detector system (e.g. the high momentum spectrometer) will produce on the order of 2 Kbytes of data/event, and that the entire events will be acquired at rates of no more than a few KHz.

Each detector package would be interfaced to a separate fastbus crate to allow parallel readout of the different spectrometers. (An additional benefit of this configuration is that all systems could be tested and debugged simultaneously.) Data from all of the individual crates would be stored in one or more memory modules residing in a master fastbus crate. This memory would be of sufficient size to average out fluctuations in the event rate.

From the master crate, the data would be forwarded to one of the processors in a multi-node processor farm. By 1990 a single node of this farm should have the processing power of 10-20 micro-Vaxes, and by 1995, single nodes might be in the range of 50-100 micro-Vaxes. The total processing power of the farm would depend on the needs (and resources) of the experiment, potentially in excess of several thousand μ Vaxes equivalent.

The processor farm could be used as a high level trigger, passing only a fraction of the events received. Alternatively, it could be used merely to format (pre-analyze) and tag the events. Accepted events would be written to either 9-track tape, or (preferably) to a higher density medium such as helical scan tape (2 Gbytes in a pocket size cassette).

The performance of the system would scale with the number of crates of processors in the system. A single fastbus master can read out ADC and TDC information from a slave module at up to 40 Mybytes/sec, with a setup overhead of 1-2 microseconds. A typical crate containing 15 modules and producing 2 Kbytes of data would have an event processing time of under 100 μ sec, and could reach rates of several kilohertz if dead time is not too critical. If dead time is a factor, the slave modules could provide additional buffering. If higher rates are needed, data compression in the slave modules, or fewer slaves per crate would give some improvements.

Current processor farm architectures can handle input data rates of up to 20 Mbytes/sec, degraded somewhat by the control computer's ability to schedule the multiple nodes. At this rate, the software in the node would need to give a rejection factor of more than 10:1 to reduce the amount of tape produced.

The user interface to the system would be a modest host system (to control the data acquisition crates and the processor farm) plus a cluster of graphics workstations. The workstations would run data analysis programs against a sample of the on-line data to verify the operation of the detectors and the experiment as a whole. It is proposed that these workstations also be linked to all of the fastbus crates via ethernet. This would serve two purposes: first, during setup, each fastbus crate could be operated independently by a workstation to test a single detector package. Secondly, during on-line operation, the ethernet link could be used to monitor a single crate upstream of the rest of the readout system. A 68020-type micro residing in fastbus could provide access to the raw data as well as status and statistics information. A schematic of the proposed data acquisition system is shown in Figure 26. Software for the system will include access to a relational database to store calibration constants, electronic logs of the experiment, and run parameters (spectrometer angles, etc.) X-windows and standard graphics packages (GKS or PHIGS) will provide an interactive interface independent of hardware (at least in principle).

Figure 26: Block diagram of the proposed data acquisition system.

Figure 27: A general schematic of the quadrupole.

C.5 The Engineering Design of the Cold Iron Superconducting Quadrupoles

The Hall C design group has tentatively selected a Cold Iron Superconducting quadrupole design to achieve the optical requirements of the HMS. The cold iron quadrupole design is based on a conformal mapping of a window frame dipole into a quadrupole. This concept is being prototyped on a small scale at the MSU cyclotron lab. The major elements are hyperbolic poles with planar coils (current sheets tilted 5 degrees relative to the symmetry axes). This combination of a uniform current sheet and a hyperbolic pole gives rise to a quadrupole field. It can be thought of as a linear combination of an iron quadrupole and a Panofsky quadrupole. The 5 degree tilt of the current sheets is an approximation to the hyperbolic sheet derived from the conformal map. The Cold Iron quadrupole uses a laminated pole assembly on which a superconducting Rutherford cable is wound. The four poles thus wound are pressed together under modest pressure (1200 lbs/in of coil) to achieve the desired coil preload. These coils retain sufficient preload to prevent motion under magnetic forces when cooled to liquid helium temperature. They are fully restrained mechanically, and thus will reach their design field without training. This procedure has enjoyed tremendous success in a variety of applications (1000 Tevatron magnets, 800 HERA magnets, LHC and SSC prototypes, etc.). Such magnets are typically designed to 95% of the critical current carrying capability of the conductor and have been very successful. We have deliberately chosen to operate at less than half the critical current in the worst case and only 20% in the mildest case. Figure 27 shows the general arrangement of components making up a cold iron quadrupole.

Table 26: HMS Quadrupole Design Parameters.

	Q1	Q2/Q3
Gradient (G/cm)	605	445
Pole Radius (cm)	25	35
"Good Field" Radius (cm)	22	30
Pole Tip Field (T)	1.512	1.56
Magnet Effective Length (cm)	189	210
Coil Cross Section Area (cm ²)	9.30	12.93
Current Density (A/cm ²)	16,178	16,800
Turns/pole	76	110
Operation current	2,171	1,976
Total Length (feet)	4,000	6,100
Stored Energy (10 ⁶ J)	0.25	0.5
Ideal Design Criteria:		
Deviation in Gradient $\leq 2.0 \times 10^{-3}$ out to warm radius		
Error in Field $\leq 2.0 \times 10^{-4}$ out to warm radius		

C.5.a Magneto-Statics

The proposed conductor is similar to the Rutherford-type cable in use at Fermilab. Table 26 lists the characteristics that have been specified for the HMS quadrupoles. The Fermilab Tevatron cable is under study as a possible common conductor for the HMS cold iron quadrupoles. This cable consists of 23 strands of superconducting wire twisted and formed into a $.307 \times .055$ inch rectangular cross section. Each superconducting wire has 2100 Nb-Ti alloy filaments with a copper to superconductor ratio of 1.8/1 by volume. The cable will be 1/2 lap insulated using spiral-wrapped .001 inch thick $\times$.375 wide kapton tape. A summary of the cable properties is given in Table 27.

Figure 28 shows the cross-sectional view of the cold iron and coil of the first quadrupole magnet, Q1. The hyperbolic pole radius is 25.0 cm and the useful bore radius is 22.0 cm. The asymmetric shape of the iron is necessary for mechanical clearance when the spectrometer is moved to its most-forward scattering angle ($\sim 12.5^\circ$).

Figure 29 shows a close-up of the conductor near the steel. Notice the air gaps around the conductor and the angle of tilt of the conductor. This is a reasonable approximation to the hyperbolic curve one would expect from the conformal mapping of a window frame dipole. The notch in the pole tip near the top of the conductor is for a mechanical support plate to prevent buckling of the conductor, and also serves as a conduit for bubble clearing. The air gaps around the conductor and the exact angle of tilt of the conductor were determined by an optimization of the field quality using harmonic analysis results from POISSON.

Table 27: Summary of the Cable Characteristics.

Cross Section:	
Width:	0.7798 cm
Thickness:	0.1257 cm
Strand Diameter:	0.0681 cm
No. strands/cable:	23
Filaments:	8 μ m diameter Nb-Ti alloy
Filaments/strand:	2100
Copper to superconducting ratio:	1.8/1 by volume
Strand twist pitch:	1.270 cm
Cable twist pitch:	5.7150 cm
Cable short-sample current (min):	3000 A @ 3.0 T and 4.2 K
Strand-short-sample current (min):	140 A @ 3.0 T and 4.2 K
Copper Resistivity Ratio:	$R(9.5 \text{ K})/R(273 \text{ K})=0.023$ (43.5 to 1)
Insulation:	0.001 in thick x 0.375 in wide Kapton, double 1/2 width lap.

Figure 28: Cross-sectional view of HMS quadrupole Q1.

Figure 29: Close up view of the conductor in Q1 near the iron.

Figure 30: Plot of the field lines of Q1 near the iron.

Figure 30 is a plot of the field lines for a quadrant solution of the magnet Q1. Notice the asymmetric turning of the field lines. The peak B-field in the iron along the x-axis is 1.64 Tesla and along the y-axis is 1.26 Tesla (maximum values). The highest fields occur near the top of the conductor and are 1.85 Tesla.

Table 28 shows the multipole coefficients for the field as obtained from a harmonic analysis of the field calculated using POISSON. The radius of the arc for the calculation of the vector potential and the normalization radius were set equal to the useful bore radius of 22 cm. The next allowable term after the $N=2$ (quadrupole) is of the order of 10^{-3} weaker in strength. Figure 31 shows the field as calculated using the POISSON-determined multipole coefficients, and Figure 32 shows the field gradient obtained from these coefficients. Notice the flatness of the curve out to near the useful radius region. Figure 33 is a plot of the field gradient uniformity. The solid line is the design criteria that we wish to obtain out to the good field radius. The field gradient uniformity is the deviation of the total field gradient from that of the field gradient due to the quadrupole term itself. Figure 34 is a plot of a

Table 28: Q1 Multipole Amplitudes Calculated Using POISSON.

Multipole N	Relative Amplitude
2	1.32×10^4
6	1.06×10^1
10	2.48×10^1
14	0.56×10^1
18	0.57×10^1

Figure 31: Q1 field calculated from the POISSON coefficients.

Figure 32: Q1 field gradient from POISSON coefficients.

Figure 33: Plot of POISSON calculated Q1 field gradient uniformity.

Table 29: Q2/Q3 Integrated Multipole Field Strengths Calculated Using TOSCA (R = 38 cm).

Multipole N	Relative Field Integral
2	1.02×10^4
6	6.67×10^1
10	3.66×10^1
14	1.12×10^1

POISSON calculation of the field error for Q1. Again the solid line shows the design criteria. The field error is the deviation of the total field from the quadrupole field.

A three-dimensional magnetostatic analysis of the quadrupole design has been undertaken using the TOSCA code; these calculations are presently being refined. Figure 35 displays plots of the $n=2$ (quadrupole), $n=6$ (dodecapole), and $n=10$ (icosapole) Fourier components for Q3 at the maximum useful radius and excitation. The field values are plotted as a function of θ , the cylindrical coordinate polar angle) for $0^\circ \leq \theta \leq 90^\circ$ and for values of z , the position along the axis, from the center of the magnet to well beyond the edge of the iron. We are analyzing the results of this calculation to determine the z -dependence of the multipoles and their integrated strength relative to the quadrupole field. Preliminary results from these calculations are shown in Table 29. The TOSCA Q3 results indicate a N_6/N_2 ratio of approximately 0.0065 for this large quadrupole. The three dimensional simulations are not yet at a stage of accuracy comparable to the POIS-

Figure 34: Plot of Q1 field error from POISSON calculation.

SON calculations and are presented here to indicate the ongoing work on the design of the quadrupole. We plan to incorporate multipole correction windings into the design of the quadrupoles whose design strength will be determined from these calculations, and whose operating excitation will be determined from a careful mapping of the fields of the actual quadrupoles.

Figure 36 shows the forces on the conductor in Q1 and within the iron for a current density of 16178.2 A/cm^2 . The calculated forces are listed in Table 30 for the regions indicated in Figure 36. The forces in the conductor stack have been used in the preload calculations detailed in section C.5.c below. The forces on the yoke have been analyzed using the finite-element analysis code IDEAS.

C.5.b Mechanical Fabrication of the Iron

POISSON and TOSCA have been used to determine the optimal pole geometry given a rectangular uniform current density tilted at 5° relative to the symmetry axes. Laminated poles have been chosen as the most cost effective and accurate method to generate the desired internal shape (see lamination details in Figure 37). Laser cutting has been found to be by far the least expensive process for cutting the laminations to the required accuracy. The pole ends will be formed from relatively thick pieces ($\sim 2 \text{ in.}$) and have the end contours of the pole cut into them. The laminations will be stacked, compressed and welded just like a conventional quadrupole.

C.5.c The HMS Quadrupole Coils

Two types of geometries are under study for the quadrupole coil end turns. Q1 will have a "semi-constant perimeter" end. Q2 and Q3 could have either Bedstead ("saddle coil")

Figure 35: TOSCA calculations of the $n=2$, 6, and 10 fields in Q2/Q3. The calculated fields are shown for one quadrant of the quadrupole as a function of the distance along the axis from the center and the azimuthal angle (for the first 90°)

Figure 36: Forces within Q1 on the conductor and iron.

Table 30: Calculated forces in Q1.

Region #	$F_{(x)}$ (lb/in)	$F_{(y)}$ (lb/in)	R (cm)	ϕ (deg.)
Fe				
2	2.168×10^1	-1.518×10^2	5.549	-81.873
3	-1.712×10^3	-8.144×10^2	-16.321	-154.557
4	-2.043×10^1	-1.078×10^2	25.310	-100.731
Conductor				
5	2.193×10^2	-1.260×10^1	-3.515	-3.288
6	2.213×10^2	-9.090×10^1	-15.383	-22.331
7	2.127×10^2	-1.341×10^2	-22.387	-32.239
8	-1.758×10^1	2.219×10^2	4.040	94.529
9	-9.258×10^1	2.213×10^2	15.524	112.699
10	-1.392×10^2	2.100×10^2	22.754	123.538

Figure 37: Details of quadrupole iron laminations.

or "semi-constant perimeter" end turns, depending on the detailed results of the harmonic analysis of these geometries now under way using TOSCA. Until these studies have been completed, the design presented here must be regarded as preliminary. The required length of conductor will be wound directly onto the poles. This will guarantee proper coil to pole alignment and eliminates the need for a separate winding fixture. The coil will be wound under tension and clamped to the pole during the winding process. The finished coil is then clamped to the pole by the permanent end clamps. These are necessary to prevent motion of the coil ends during excitation and to prevent motion of the coil prior to final assembly of the cold mass. The coil when subjected to the clamping force must be restrained against buckling. The fact that each coil is tilted by 5° from the symmetry axis means that the mid-plane point must be supported. Furthermore, the straight coils themselves are unstable against buckling, so a mechanical restraint is essential. Q_1 which is the shortest coil (4 in) would be safe against buckling if merely filled with epoxy, but the Q_2 and Q_3 coils, which are roughly 50% longer, will have to be supported by a stainless steel plate to prevent buckling. The four-pole assembly will be pressed together over the inner helium bore tube and the tube slightly compressed (to form a spring) during preloading. This will support the coil at the symmetry planes and resist the main buckling tendency by forcing the stainless anti buckling plate against the coil side. The helium bore tube will "spring back" during cool down and follow the differential motion of the coil (see buckling plate detail, Figure 38).

Q2 and Q3 Coil Geometry

The Q_2/Q_3 coils have a rectangular cross section of $.311 \times 6.543$ inches containing 110 turns; one option is that it will be wound in the Bedstead-type geometry shown in Figure 39. with the cross section of the end turns bent 90° outward and then bent back again to form

Figure 38: Quadrupole buckling plate detail.

Figure 39: Q2 and Q3 coil geometry.

Figure 40: Q1 coil cross section.

the bedstead (saddle). This end geometry makes it easier to mechanically restrain the coil to withstand the forces at the end of the magnet.

Q1 Coil Geometry

The Q1 coil has a rectangular cross section of $.311 \times 4.484$ inches containing 76 turns, as shown in Figure 40. Because of the narrow width of the return yoke of Q1 it is not possible to wind the ends in the same Bedstead type geometry as Q2 and Q3. The geometry of the Q1 coil in the region of the corner is shown in Figure 41.

Coil Winding Technique

The coils will be wound directly onto the laminated yoke quadrants in order to assure proper conductor placement. The laminated yoke quadrant will be fitted with a coil clamping bar which allows the yoke to be rotated 360 degrees. This assembly will then be mounted on a turntable. The pre-insulated conductor will be fed from a spool through a tensioning device and an insulation Hipot tester to the yoke turntable. the coil will be wound without epoxy, and mechanically clamped during winding to secure the conductor. Figure 42 is a schematic of the winding setup.

Figure 41: Diagram of the yoke winding of Q1 in the region of the corner.

Figure 42: Cold iron quadrupole coil winding system.

Q3 Test Winding

The test winding of the Q3 coil was made on a winding mandrel which simulated the Q3 yoke. The number of turns was reduced to 76 and the length of the mandrel was reduced to 24 inches in order to reduce the amount of conductor required. The mandrel was mounted on trunions which allow it to rotate 360° and was then mounted onto a turntable. The wire was fed from the spool through a simplified tensioning mechanism which applies approximately 3,000 psi cable tension onto the winding mandrel. The cable was manually painted with epoxy as it was wound on the mandrel. The winding was started by feeding the cable through the mandrel and clamping it to the end of the mandrel. The turntable was then rotated 90° to form the first bend. The mandrel was then rotated clockwise 280° which forms the end turn. The cable was then clamped in place and the turntable was rotated 180° and the mandrel was rotated another 280° to complete the first turn. Two complete turns were made. The end of the third turn was fed around an off ramp to the outside of the first two turns. Two more complete turns were then made. The procedure was then repeated until 76 full turns were completed. This procedure was documented in Figure 43, which shows photographs of this process taking place at CEBAF. A realistic estimate of the manpower and time required to manufacture these coils was obtained from these test winding efforts. In addition, these tests aided in developing a practical winding technique and geometry.

C.5.d Quench behavior

The quadrupole coils do not have to be protected by any internal or external means; all of the energy stored in the field can be dumped into the magnet in the event of a quench. However, safety issues and prudence will lead us to incorporate a quench protection circuit as a backup. The calculated hot spot temperature and the maximum internal voltage developed during a quench are shown on Figures 44a and b; they are well within the safe operating limits for the coil.

In order to avoid a quench due to a micro slip, the coil must be preloaded, so that coil motion during operation is suppressed. To achieve this condition, the coil has to be under constant compression during its operation, and only elastic motion is permitted.

Assuming no friction between the coil and attached iron, dimensional changes from room temperature to the operating condition along the coil height are as follows:

- differential thermal contraction between conductor block and the iron:

$$\Delta H_d = 1.7 \times 10^{-2} in$$

- coil deformation along the coil block axis due to Lorentz loading (assuming an elastic coil modulus, $E_{coil} = 4 \times 10^5$ psi)

$$\Delta H_m = 7.6 \times 10^{-3} in$$

Figure 43: Photographs of the quadrupole test coil being wound.

Figure 44: Quadrupole hot spot temperatures (a) and maximum internal voltages (b).

The minimum coil preload required to compensate for these dimensional changes is:

$$P = E_{coil} A \frac{(\Delta H_d + \Delta H_m)}{H} = 960 \text{ lb/in}$$

where : $E_{coil} = 4.5 \times 10^5 \text{ psi}$ – the elastic coil modulus;
 $A = .318 \text{ in}^2$ – the coil cross section per inch; and
 $H = 4.6 \text{ in}$ – the coil height.

Adding 50% for unknown deformation, we estimate that the preload required is about 1500 *lb/in* per coil block. To suppress coil buckling under this loading, the Helium cryostat tube is inserted into the cryostat. By deforming it, a positive force component is provided which holds the unsupported coil end. To increase the critical buckling load, a support buckling plate 3/16" thick is provided. Using transformed area method, we find that the radius of gyration of this assembly is 6.8×10^{-2} in, and the critical load (according the Euler criteria) is 1.2×10^4 lb. Applying the secant formula, and assuming eccentricity equal to the conductor width, the ultimate buckling load is 7000 lb, well above the required preload.

C.5.e Cold Mass Assembly and Force Analysis

The four laminated poles with their coils in place will be assembled under external pressure applied along four axes. This will achieve the desired coil preload. The external pressure will be supplied by hydraulic cylinders or bolts pending final cost review. The force required is 10,000 pounds per inch of magnet. The current plan is to press the four poles together using 20 hydraulic cylinders (10 horizontal, 10 vertical) of 36,000 pounds each on 6 inch centers. This is a very modest hydraulic system considering the large size (~ 1 meter diameter) of the pole assembly. The four poles will then be welded together using tie plates in a manner similar to common practice for conventional quadrupoles. (See Figure 45).

The cold mass is completely testable in a vertical dewar and we will require such testing. The cavity test dewars at CEBAF could accommodate such a test as could the vertical dewar at MSU. Several of our potential vendors also have appropriate test capability in-house. Basic tests such as achieving full excitation and a rotating coil measurement of the multipole content of the field would be performed.

The Inner vessel

The inner vessel must provide a positive force component to balance the coil precompression forces at room temperature. It must also be stable for quench pressure of 3 atmospheres. In order to provide positive loading the vessel must be deformed to compensate for:

Figure 45: Assembly of the quadrupoles.

- the differential thermal contraction of the coil with ground insulation and the iron in radial direction, equal to $\Delta_1 = 9.2 \times 10^{-3}$ in;
- the magnet yoke deformation in radial direction due to the gross magnetic loading (see Figure 36), equal to $\Delta_2 = 1.7 \times 10^{-3}$ in; and
- the deformation from Lorentz forces, equal to $\Delta_3 = 3.5 \times 10^{-3}$ in.

The total required deformation at room temperature is:

$$\Delta_{min} = \Sigma \Delta = 1.5 \times 10^{-2} \text{ in.}$$

Assuming an additional 50% for unknown deformations, we anticipate that the total initial deformation of the inner vessel is $\Delta = .023$ in. This deformation is equivalent to 260 pounds per unit length.

We plan to make the inner vessel from a 16" diameter, 0.25" thick SS316LN tube; the stress within this tube is calculated to be 27000 psi, which is about 50% of the yield strength for SS316LN ($S_y=41000$ psi) at 300 K. At 4 K max stress within the tube is 11000 psi due to the remaining tube deformation of 8×10^{-3} -in. If a quench occurs it is calculated to cause an external pressure on the tube of 45 psi. According to ASME code, Section VIII Div I, subsection UG-28, the external pressure that this prestressed tube can withstand

before collapse is 83 psi if we limit the out-of-roundness of .125 in.; therefore we have a safety margin of nearly a factor of two.

The outer vessel

The outer vessel has been designed according to ASME Section VIII, Div I "Unfired Pressure Vessel Code" for an operating pressure of 45 psi (corresponding to the quench pressure). The vessel is a weldment of 3/8" SS304 plates reinforced by rings spaced 6" apart along the vessel, to keep total stress in the range recommended by ASME (20000 psi).

The Iron

A stress plot within the iron due to magnetic loading within the coil and the iron was shown in Figure 36. The maximum Von Mises stress of $1.0 \times 10^5 \text{ Nt/cm}^2$ (2800 psi) is negligible. Additional stress due to the tube deformation can increase this stress no more than a factor of two, giving still a negligible number. This stress does not take account of the outer vessel effect, which should decrease this stress to an even more negligible value.

The Suspension Rods, Current Leads and Cryogenics

The constant tension support rod design was developed at CEBAF based upon experience at MSU on the K800 cyclotron coil. This rod design is so successful that every superconducting magnet design at CEBAF is using them. These rods are mounted at predetermined angles to the coil so that after cooldown the contraction of the coil and the rod are matched such that some preload tension persists, guaranteeing that the coil will remain centered in the cryostat at all times; the design is shown in Figure 46.

The cryostat is suspended by 8 constant-tension links, 4 at each end, arranged to follow the contraction of the coil and preserve its alignment during the magnet cooldown. A cross section of one of the links is shown in detail in Figure 47. The links were designed for acceleration loads of .5 g in all directions. The cold mass weight of 6 tons and this acceleration load will produce a tensile stress of 55000 psi in the 5/8" dia. link (bending stresses in the links are eliminated through the use of ball joints). This load can be taken by Nitronic 50 steel ($S_{ymin} = 60,000$ psi).

The Cold Iron Quadrupoles will be bath cooled in 1 ATM liquid helium and conventional commercial vapor cooled leads mounted in the helium reservoir will be used. A common service port design is underway and will be used for all three quadrupoles and the dipole. This service port will have the current leads, supply and return bayonets, relief valves, control valves, helium reservoir and instrumentation. Design and analysis work is

Figure 46: Quadrupole tensioning system.

Figure 47: Detail of the suspension link for the HMS cold iron quadrupole.

proceeding in preparation for eventual procurement of the Cold Iron Quadrupoles. We believe that this design is a simple cost effective solution to the HMS optical requirements.

C.5.f Cryostat and Magnet Heat Load

Cryostat

The rest of the system is rather conventional; it employs nested concentric cylinders for helium and vacuum vessels. We will use appropriate amounts of MLI insulation and a LN₂ shield to suppress heat loads of all kinds. The LN₂ shield under consideration is an inflated double wall design that acts as a reservoir, guaranteeing that the nitrogen is in contact with all surfaces which must be at 80 K. This is a far more successful technique than using trace tubed copper panels which must be conduction cooled with flowing LN₂ to achieve adequate heat transfer. The inflated panels will be particularly efficient in the bore tube where space is not at a premium.

Magnet heat load

There are three major sources of heat load in Q1: radiation; conduction through the suspension system; and dissipation in the coil. These are estimated as follows:

- Radiation

$$Q_1 = \frac{\sigma(T_1^4 - T_2^4)}{\frac{1}{\epsilon_1} + \frac{1}{\epsilon_2} - 1} A = 1.4 \text{ W}$$

where $A = 9.3 \text{ m}^2$, the cold mass surface area

$\sigma = 5.6 \times 10^{-8} \frac{\text{W}}{\text{m}^2 \text{K}}$, the Boltzman constant

$\epsilon_1 = \epsilon_2 = .05$, the emissivity of SS

$T_2 = 5 \text{ K}$, the cryostat temperature

$T_1 = 100 \text{ K}$, the LN₂ shield temperature (assumed)

- The suspension system (conduction)

Assuming that the links are intercepted 2/3 of their length from the cold end, and that the intercept temperature is 100 K:

$$Q_2 = 11.4 \text{ W}$$

- Power loads (for 2000 A each)

$$Q_3 = 4 \text{ W}$$

- The total theoretical heat load, Q , is given by the sum of these components:

$$Q = Q_1 + Q_2 + Q_3 = 17 \text{ W}$$

Figure 48: Schematic of the HMS cryostable dipole.

C.6 The Engineering Design of the HMS Dipole

C.6.a Magneto-Statics

The dipole for the Hall C High Momentum Spectrometer is a superconducting, cryostable magnet; it is shown schematically in Figure 48. The basic parameters of the HMS dipole are summarized in Table 31. It is configured to achieve a 25° bending angle for 6 GeV/c momentum particles with a field uniformity of 1×10^{-3} over its 42 cm gap at a central field excitation of 1.66 T. The pole assembly provides good field quality in a cost efficient manner by incorporating shims on either side of the pole tip assembly and a stepped Purcell gap. The Purcell gap increases the magnetic field uniformity along the median plane. High field uniformity has been achieved over a large fraction of the pole width by the addition of a 3.2×2 cm rose shim near the edge of the pole face the use of a two-point approximation to the Kumagai profile on the pole edges. We have also made provisions for the addition of a pair of auxiliary coils at the edges of the gap between the poles to compensate further for the fringe field fall off, if their use proves necessary (based on 2-d POISSON calculations, they will not be required). The ability of this configuration to achieve the performance requirements for the HMS was studied by modelling the aperture field using the two-dimensional computer code POISSON. A plot of the flux lines obtained from this calculation is shown in Figure 49. The calculated field uniformity in the mid-plane is shown as the solid curve in Figure 50 as a function of transverse position along the median plane of the aperture. The field values within the ellipse traversed by particles of interest are indicated as the points that make up the "spikes" in the figure. As can be seen from this figure, the calculated field is within its 10^{-3} specification throughout the region of interest. Figure 51 shows the calculated magnetic field parallel to the median plane for a central (perpendicular to the median plane) field of 1.66 T. The magnitude of B_y stays well below the design limit of $< 4 \times 10^{-3} B_y(x = 0)$ throughout the region of interest. As can be seen from these plots, the field achieved by this combination of "tricks" provides the degree of uniformity required to meet the optical requirements of the HMS.

Table 31: HMS Superconducting Dipole Specifications.

Gap	42 cm
Vacuum Chamber Width	60 cm
Pole Tip Field @ 6 GeV	1.66 T
Maximum Field	2.0 T
Bend Angle	25°
Bend Radius	12.05625 m
Effective Length	5.26 m
Pole Face Rotations	-6°, -6°
Coil Configuration:	4.12×10 ⁵ A-turns/pole @ 2 T two double pancakes/pole 15 rows and 4 layers/pole (ie. 60 turns/pole) 3 mm spacer between pancakes 3 mm spacer between rows
Coil Cooling	Thermal Siphon 4.3 K LHe
Coil size	3.4 × 7.3 in
Operating current	6,881 A max @ 2 T

Figure 49: A flux line plot of the HMS dipole at 1.66 tesla excitation.

Figure 50: HMS dipole field uniformity at 1.66 tesla excitation. The solid curve is the calculated mid-plane field. The points that make up the “spikes” represent the calculated values of B_y off the mid-plane at a given value of x that are within the ellipse traversed by the particles of interest. The two horizontal lines at ± 0.001 are the allowed field deviations.

BX/BY(0) FOR X= 0.00 TO 30.00 Y=0 TO 20.00

Figure 51: Variation of the x-component of the field in the HMS dipole along the median plane at 1.66 tesla excitation. the points that make up the “spikes” represent the values of $B_x(x,y)/B_y(0,0)$ for y-coordinate values that are within the ellipse traversed by allowed particle trajectories in the dipole. The two horizontal lines at $\pm 4 \times 10^{-3}$ represent the allowed field deviations for the parallel-to-point mode for the HMS; for the point-to-point mode the allowed field deviations are $\pm 1 \times 10^{-3}$.

Figure 52: HMS dipole field uniformity at 0.83 tesla excitation. The solid curve is the calculated mid-plane field. The points that make up the “spikes” represent the calculated values of B_y off the mid-plane at a given value of x that are within the ellipse traversed by the particles of interest. The two horizontal lines at ± 0.001 are the allowed field deviations.

The performance of the HMS dipole has also been checked for a variety of excitations ranging down to 1/10 of the design operating field of 1.66 tesla (corresponding to a central momentum of 6 GeV/c). Figures 52 and 53 show examples of these calculations from the results obtained at 0.83 tesla. Again, the design requirements are met throughout the region of interest.

C.6.b Mechanical Fabrication of the Iron

The pole pieces for the HMS will be machined to the large, 12 meter bend radius. The pole tip assembly is shown in Figure 54. The pole tip assembly also serves as the vacuum chamber inside the dipole, eliminating the need for a separate vacuum system. The return path iron has been divided into segments of approximately 20 tons each. The dipole will be assembled in “building block” fashion onto the carriage in the hall with the use of the overhead crane. Both the blocks and the assembly procedure are illustrated in Figure 55. None of the yoke pieces will be curved. All except the four triangular end pieces will have a rectangular shape.

Figure 53: Variation of the x-component of the field in the HMS dipole along the median plane at 0.83 tesla excitation. the points that make up the "spikes" represent the values of $B_x(x,y)/B_y(0,0)$ for y-coordinate values that are within the ellipse traversed by allowed particle trajectories in the dipole. The two horizontal lines at $\pm 4 \times 10^{-3}$ represent the allowed field deviations in the parallel-to-point mode; in the point-to-point mode the allowed field deviations are $\pm 1 \times 10^{-3}$.

Figure 54: The pole tip assembly of the HMS dipole.

Figure 55: A schematic of the HMS dipole assembly procedure.

C.6.c The HMS Coils

Figure 56 shows the general arrangement of the enclosure for the main superconducting, racetrack coil. The inner, L-shaped steel piece will be part of the winding fixture, and the coil will be wound directly onto it. After winding, the coil will be clamped and bolted firmly in place by a second L-shaped bracket. The cross section of the packaged coil is shown in Figure 57. As can be seen from this figure, the coil consists of two double pancakes with 3 mm thick G10 hex spacers between the rows and 3 mm thick G10 sheets between the layers.

The design of the dipole will include provisions for the possible future addition of four small, water-cooled, normal-conducting coils placed along the pole tip spacers perpendicular to the pole face on each side of the gap. These coils may be added if the field uniformity achieved in the actual magnet does not meet expectations and perform as required over the ± 30 cm gap width. A cross section of one of these coils, together with a table of its parameters, is shown in Figure 58.

C.6.d Cryostable Conductor Design

The requirement that the HMS dipole be capable of reaching 2 tesla excitation leads to a maximum operating current for the coil of 6,881 Amperes. Cryostability at this field is desirable and achievable within the original overall coil cross section by using an enhanced surface on the conductor. This is shown in the cross section in Figure 57. This technique

Coil Enclosure

Figure 56: HMS Dipole racetrack coil enclosure.

Figure 57: The coil cross section.

Figure 58: Cross section of one of the auxiliary, water-cooled coils that may be placed along the pole-tip spacers of the HMS, if needed.

is well-established, and similar conductors have been measured extensively so that reliable data on steady state and transient heat load behavior for this kind of coil is available. More important are the tests that indicate that this kind of coil exhibits unconditional cryostability.

The classic method of Steckly for evaluating cryostability involves computation of the ratio of Joule heating to Newtonian cooling. If this ratio, α , is less than one, unconditional cryostability will result.

$$\alpha = \frac{\rho I^2}{P_W \cdot A_{cu} \cdot H}$$

Where $I = 6,881$ Amperes, the operating current
 $\rho = 4.1 \times 10^{-10} \Omega m$ the resistivity at 2 T for RRR=50 Copper
 $P_W = 6.04 \times 10^{-4} m^2$ the wetted perimeter
 $A_{cu} = 1.363 \times 10^{-4} m^2$ the Cu area, and
 $H = 2,600 W/m^2$ is the heat flux.

Evaluating this equation for the parameter values listed leads to a value of $\alpha = 0.907$; since this is less than one, the coil will be cryostable.

Figure 59: The coil temperature vs protection resistance for a quench of the HMS dipole coil.

Cryostable coils generally require an energy removal circuit to cover the possibility that an unrecoverable quench occurs. This can only happen if the helium level drops below the coil during operation. Figure 59 shows the resulting maximum temperature versus the discharge resistance as computed by the program QUENCH. As indicated in the figure, a series resistance of 0.005Ω or an invert voltage of 34 volts is all that is required to keep the maximum temperature to 116 K in the worst case analysis. In practice as the current is lowered the coil will eventually reach a cryostable current and completely recover. Therefore, the maximum temperature will always be less than the calculation predicts. There are many choices for the superconducting cable insert. This design is based upon a standard 0.8 mm strand with a copper-to-superconductor ratio of 1.8:1. the current margin is 729 of the manufacturers guaranteed performance at the 2 tesla field. This is 65% of the actual short sample limit. The operating current density is $2,306 \text{ A/mm}^2$, which is substantially below the commonly cited value of $5,500 \text{ A/m}^2$ at 2 tesla.

C.6.e Cold Mass Assembly and Force Analysis

The Cryostat

The coil will be wound on the machined stainless steel bobbin, built from $1/2$ " thick plates. After winding, the coil will be clamped with approximately 12" long angles along the bobbin perimeter. The end of the cryostat will be reinforced with a 4" high box to

Figure 60: HMS dipole coil support structure.

reduce deflection and stress of the cryostat in the transverse direction.

Eight support cylinders (four on each side) will be attached to the cryostat structure to reduce coil deformation and stress due to the Lorentz forces during the excitation of the magnet; they will transfer the mechanical load through vacuum vessel to the yoke as shown in Figure 60. Initially (at room temperature) the gap between the tip of the post and vacuum vessel will be about .03" so the magnet is free to shrink in both the longitudinal and transverse directions without introducing any bending load to the post. At 4 K a gap will remain between the tip of the post and vacuum vessel will as a result of the thermal contraction of the cryostat. When the magnet is energized, the cryostat will deform outward until the support post engages with the vacuum vessel and the remaining deflection will occur locally between the posts. A plot showing the calculated stress levels within the cryostat at full excitation is shown in Figure 61. Each post will experience a compressive load of about 32,000 pounds at full field. The posts, which will have a cross sectional area of 3.5 in², will each carry a compressive stress of about 9,200 psi, about 50% of the recommended maximum value $S_y=18,000$ psi. The liquid He container will be sealed with a C-shaped piece welded around the coil case. The design pressure of the LHe container is 30 psi. The stress within this container was evaluated according to Section VIII of the ASME "Unfired Pressure Vessel Code," Div. 1, and kept within the ASME-recommended value of 23,000 psi.

Figure 61: HMS dipole stress plot indicating final stress levels within the cryostat.

Vacuum Shell

The vacuum shell has been designed to carry a maximum external pressure of 15 psi. The shell will be built with SS304 plates reinforced with posts spaced every 12" and meets the specification of Section VIII of the ASME "Unfired Pressure Vessel Code," Div. 1.

Magnet Suspension

The magnet cryostat will be suspended within the vacuum vessel by 8 tension links (4 at each end). These links will be tilted 30° outward from the cryostat plane and 15° toward the center to accommodate the thermal contraction of the cryostat in all three magnet planes; it is shown in Figure 62. The link diameter will be .75"; they are designed to carry the full cryostat weight of ~ 8 tons, and can withstand vertical up and vertical down forces corresponding to 5 and 2 times gravity. As the expected shipping loads are ± 1.0 g laterally and ± 1.5 g axially, there should be no problems associated with transportation or operation of the cold mass within the cryostat. The design tensile stress for the support links is 97,000 psi, which is about $1/2$ the S_y of Nitronic 60 stainless steel (cold swagged 54%).

C.6.f Magnet Heat Load

The 4 K magnet structure will be suspended within the vacuum vessel and surrounded by an 80 K shield that will be cooled by LN_2 circulating within tubes attached to the shield.

Figure 62: The HMS cryostat suspended within the vacuum vessel.

Superinsulation will be wrapped on the shield within the 1" space left for this purpose. The heat loads on the cold mass can be calculated in a straightforward manner.

Heat Load to the 4.2 K Structure from Radiation

The heat load, Q_R , on the 4.2 K structure due to radiation can be estimated using the expression:

$$Q_R = \frac{\sigma(T_1^4 - T_2^4)}{\frac{1}{\epsilon_1} + \frac{1}{\epsilon_2} - 1} A$$

where $A = 30 \text{ m}^2$, the cold surface area

$T_1 = 100 \text{ K}$, the temperature of LN_2 shield (assumed)

$T_2 = 5 \text{ K}$, the temperature of the cryostat

$\epsilon_1 = 0.5$, the emissivity of SS

$\epsilon_2 = 0.3$, the emissivity of Cu; and

$$\sigma = 56.69 \times 10^9 \frac{\text{W}}{\text{m}^2 \text{K}^4}$$

Substituting these values yields

$$Q_R = 3.3 \text{ W}$$

Heat Load to the 4.2 K Structure due to Conduction

The conduction heat load can be divided into five parts associated with the loads due to: the support column; the suspension links; the heat shield support spacers; the power leads; and the joint resistance. In this section we calculate each of these quantities in turn.

- Support column

The heat load from conduction through the support column is given by:

$$Q_{C1} = \frac{A_c}{L_c} \int_4^T \kappa dT$$

where T = the intercept temperature of 100 K (assumed)
 A_{cc} = the cross section area of the central column (3.5 in^2)
 L = the length of the 4 K to 100 K column section (6 in)

$$\int_4^{100} \kappa dT = .51 \frac{W}{\text{in}} \text{ for G-10, so}$$
$$Q_{C1} = 8 \left(\frac{3.5}{6} .51 \right) = 2.4 \text{ W}$$

- Suspension links

The heat load from conduction through the suspension links can be calculated knowing that the suspension link is intercepted 2/3 of the distance from the cold end and the intercept temperature is 100 K:

$$Q_{C2} = \frac{A_L}{L_L} \int_4^{100} \kappa dT$$

where A_L = the cross section of the suspension rods ($.44 \text{ in}^2$)
 L_L = the length of the link across the 4 to 100 K gradient (4 in), and

$$\int_4^{100} \kappa dT = 13.4 \text{ W/in. so}$$
$$Q_{C2} = 8 \frac{.44}{4} 13.4 = 11.8 \text{ W}$$

- Heat shield support spacers

If we assume that we use a total of 80 spacers of 3/16" diameter G-10 (two spacers on each side, spaced 1' apart for the length of the shield), then the conduction through the spacers is given by:

$$Q_{C3} = 80 \frac{A_s}{L_s} \int_4^{80} \kappa dT$$

where A_s = $.028 \text{ in}^2$, the cross section area of the spacer
 L_s = the spacer height, $3/8''$

$$\int_0^{80} \kappa dT = .5 \text{ W/in.}, \text{ so}$$

$$Q_{C3} = 80 \frac{.028}{.735} .5 = 3 \text{ W}$$

- The fluid consumption by the power leads (per two 5000 A) corresponds to:

$$m = 14 \text{ l/hr}$$

- Joint resistance

To calculate the heat load due to the joint resistance we note:

A typical resistivity for 50 Sn/50 Pb at 2 T is $\rho = 7 \times 10^{-9} \Omega m$

Assuming a joint thickness $t = .005''$, and area $A = 6'' \times 0.7''$

$$R = \rho \frac{\ell}{A} = 8 \times 10^{-12} \Omega$$

$$Q_{C4j} = I^2 R = 5000^2 \cdot 8 \times 10^{-12} = 2.1 \times 10^{-4} \text{ W/joint}$$

For 8 joints, $Q_{C4} = 4 \times 10^{-3} \text{ W}$, which is negligible.

- The total heat load due to conduction

$$\begin{aligned} Q_C &= Q_{C1} + Q_{C2} + Q_{C3} + Q_{C4} + \text{leads} \\ &= 2.4 + 11.8 + 3 + 4 \times 10^{-3} + 14 \text{ l/hr} \\ &= 20.5 \text{ W} + 14 \text{ l/hr} \end{aligned}$$

Heat load to the LN₂ structure

The heat load to the LN₂ structure is made up of three components: radiation and conduction through the superinsulation; conduction through the supports, and conduction through the suspension links. These may be estimated as follows:

- Radiation and conduction through superinsulation

The heat load is given by:

$$Q_{RC} = \frac{A}{L} \kappa \Delta T$$

where κ , the apparent thermal conductivity of a superinsulation blanket having 50 layers/inch, is:

$$\kappa = 1.04 \times 10^{-4} \frac{\text{W}}{\text{m K}}$$

In this expression

$\Delta T = 220 \text{ K}$, the temperature gradient

$\ell = 1'' = .025 \text{ m}$, the insulation thickness

$A = 35 \text{ m}^2$, the cold surface area.

$$\text{Substitution yields : } Q_{RC} = \frac{35}{.025} \cdot 1.04 \times 10^{-4} \cdot 220 = 32 \text{ W.}$$

- Conduction through the support cylinders

$$Q_{SC} = \frac{A_{cc}}{L_{cc}} \int_{80}^{300} \kappa dT$$

where $A_{cc} = 3.5 \text{ in}^2$, the area of the central column

$L = 2 \text{ in}$, the length of the column across the $80 \rightarrow 300 \text{ K}$ gradient

$$\int_{80}^{300} \kappa dT = .96 \text{ W/cm} = 2.4 \text{ W/in for G-10, so}$$

$$Q_{SC} = 4 \left(\frac{3.5}{2} \cdot 2.4 \right) = 17 \text{ W}$$

- Conduction through the suspension links

$$Q_{SL} = 8 \frac{A}{\ell} \int_{80}^{300} \kappa dT, \text{ where}$$

$A = .44 \text{ in}^2$, the cross section of the suspension links

$L = 2 \text{ in}$, the link length across the gradient

$$\int_{80}^{300} \kappa dT = 27.6 \text{ W/cm} = 70.1 \text{ W/in for SS304, so}$$

$$Q_{SL} = 8 \cdot \frac{.44}{2} \cdot 70.1 = 123 \text{ W}$$

- The total heat load to the LN_2

The sum of all the components is: $Q_T = 32 + 17 + 123 = 172 \text{ W}$.

C.7 Procurement Strategy for HMS Magnets

The CEBAF Request For Proposal (RFP) for each magnet type will include a Technical Requirement and a Reference Conceptual Design. The vendor will be free to propose alternative designs, subject to review and approval by CEBAF. We encourage innovation and desire to benefit from vendor experience, leading to the most efficient design in terms of function and cost. However, magnetic field characteristics must be defined in detail by the CEBAF staff, based upon an in-depth understanding of the physics and optics requirements. The vendor bears full and clear responsibility for meeting the configuration and technical requirements for these elements. The cold Fe quadrupoles concept has

Table 32: Summary of CEBAF HMS Cold Iron Quadrupole Magnet Procurement Plan.

CEBAF's RESPONSIBILITIES	VENDOR's RESPONSIBILITIES
<ul style="list-style-type: none"> • Reference Design: <ul style="list-style-type: none"> • Specifications (Magnetic) • (Mechanical) • Conductor • Insulation • Length, Bore, etc. • # of Cycles Required • Cool down Rates • POISSON & TOSCA Calculations • IDEAS Stress Analysis • Heat Loss Calculations • Our Test Windings Experience • Pertinent Parts of Technical Advisory Panel Report sent with reference design. 	<ul style="list-style-type: none"> • Mechanical Tolerances • Coil Placement Tolerances • Field Quality • Cryogenic Performance • Heat Loss Performances • Achieving Full Field • Winding Coils • Cryostat Assembly • Welding Procedure • Conductor Choice • Cryostable Design if possible (may not be for Q1) • Detailed Mechanical Design • Fabrication of Quadrupoles • Forces: <ul style="list-style-type: none"> • Magnetic • Thermal • Preload • Warranty

been chosen because it meets technical specifications, is relatively inexpensive, is simple to manufacture, and is anticipated to be highly reliable. The dipole is cryostable and therefore, a conservative design. The installation of the quadrupoles will be done under the direction of the CEBAF staff. Table 32 gives a breakdown of CEBAF's and the vendor's responsibilities.

It is anticipated that the dipole components will be fabricated by two vendors. The iron field return pieces, which are low technology items by nature, will be procured separately from the high technology cryostable coil/pole tip assembly. The components would then be assembled and tested at CEBAF by a commercial rigging firm and our staff, respectively. Table 33 gives a breakdown of CEBAF's and the vendor's responsibilities.

The procurement plan for the three cold iron quadrupoles and the cryostable dipole for the HMS spectrometer will be undertaken following the procedure summarized here:

1. Preliminary Technical Requirement: Draft version of performance requirements; spatial constraints; reference conceptual design, identified as prelude to forthcoming RFP for the items. Each recipient will be invited to make "closed session" presentation. They are to present their credentials and comment upon our requirements/reference

Table 33: Summary of CEBAF HMS Cryostable Dipole Magnet Procurement Plan.

CEBAF's RESPONSIBILITIES	VENDOR's RESPONSIBILITIES
<ul style="list-style-type: none"> • Reference Design: <ul style="list-style-type: none"> • Specifications & Tolerances (Magnetic) • (Mechanical) • Conductor • Insulation • Length, Bend, edge Angle etc. • # of Cycles Required • Cool down Rates • Forces: <ul style="list-style-type: none"> • Magnetic • Thermal • Preload • POISSON & TOSCA Calculations • IDEAS Stress Analysis • Heat Loss Calculations • Pertinent Parts of Technical Advisory Panel Report sent with reference design. • Assembly of Magnet at CEBAF Site 	<ul style="list-style-type: none"> • Mechanical Tolerances • Coil Placement Tolerances • Field Quality • Cryogenic Performance • Heat Loss Performances • Winding Coils • Cryostat Assembly • Welding Procedure • Conductor Choice • Cryostable Coil Design • Detailed Mechanical Design • Fabrication of Dipole Components • Full Field Performance <p>Meeting Assembly Tolerances Coil Placement Tolerances Possible Assembly at CEBAF</p>

concept.

2. Draft RFP: To include CEBAF technical requirement incorporating any modifications resulting from TAP Review and/or pre-TAP vendor conference. Includes draft procurement plan: selection criteria; etc.
3. Vendor Meeting Potential vendors invited to respond to CEBAF draft RFP, regarding technical and business content.
4. RFP (Request for proposals)
5. Proposal Due Date: To be scheduled
6. Proposal Evaluation: Based upon technical proposal; corporate/ institutional capabilities/experience; cost. Selection criteria point system to be employed for demonstrated objectivity. Evaluation committee: in-house and external members.
7. Call for Best and Final Offer:
8. DOE Approval:
9. Contract Award:
10. Despondent Respondent Debriefing: Immediately following contract award.

C.8 A Polarized Target for Use with the HMS

The investigation of nucleon and nuclear structure will be significantly enhanced through the use of polarized lepton beams and polarized targets. In inclusive reactions, $\vec{A}(e, e')$ and $\vec{A}(\vec{e}, e')$, it is possible to measure additional structure functions that are dependent on the spin degrees of freedom. In exclusive measurements it is possible to separate the various response functions and multipoles of the nucleon resonances. For instance it would be interesting to study the Roper resonance ($P_{11}1440$) by measuring the target asymmetries in single neutral pion production. Alternately, one can use the HMS in conjunction with a polarized target to measure the neutron electric form factor, as is described in section C.1.c.

The University of Virginia has proposed the design and construction of polarized solid state NH_3 and ND_3 targets. These will be general purpose devices, suitable for use in several of CEBAF'S planned experimental halls. The initial experiment planned for this target is a measurement of the charge form factor of the neutron by using the HMS to study the scattering of polarized electrons from polarized deuterons in deuterated ammonia (ND_3).

C.8.a Physics with a Polarized Target

The major effort to date in nuclear physics using electromagnetic probes has focused on and been limited to the measurement of only two of the five possible nuclear response functions, the usual longitudinal and transverse response functions in the single photon exchange approximation. In inclusive electron scattering, with no polarization, only two of these structure functions are accessible. These are measured in quadratic terms, i.e., F_L^2 and F_T^2 , and therefore their relative signs are not observable in the ordinary Rosenbluth separation.

To unravel the interference between these structure functions, and to obtain a more complete picture of certain reactions we need to turn to different classes of experiments. These reactions involve a coincidence measurement of the outgoing particles, polarization of the nuclear targets or the electron beam. For instance, detecting hadrons out of the scattering plane in coincidence with scattered electrons from the $A(e, e'x)B$ reaction will give access to the two other response functions. This class of experiments are in their earlier stages at various electron facilities. However, the programs are limited by the pulsed nature of these beams and unavailability of higher energies at these facilities. CEBAF will be the ideal place for these coincidence experiments.

Another class of experiments using electron beams involve polarization observables in which one takes advantage of a polarized target and/or a polarized beam in exclusive or inclusive experiments. These experiments are denoted by $\vec{A}(e, e')$, $\vec{A}(\vec{e}, e')$, and $\vec{A}(e, e'x)$. For example, Figure 63 shows the kinematics of the $\vec{A}(\vec{e}, e')$ reaction, in which the target is polarized and direction of the polarization is specified by polar and azimuthal angles, θ^* and ϕ^* respectively.

C.8.b Practical Issues Concerning the Polarized Target

For the last two decades, polarized targets have been used in high energy physics. But, operation of these targets in intense beams was limited by substantial loss of polarization caused by radiation damage. In the past few years however, there has been significant progress in finding new target materials with higher resistance to radiation damage and with higher degrees of polarizabilities. High polarizations are produced using dynamic nuclear polarization method on irradiated target materials such as ammonia NH_3 and ND_3 . For instance, one is able to achieve up to 90 percent maximum polarization for protons and 45 percent for deuterons at a temperature of 200 mK at 2.5 T magnetic field.

For physics points of view, in reactions involving polarized targets, it is desirable to have the capability of changing the spin orientation. This requires a polarizing magnetic field with flexible orientation in space. This ideal polarized target would allow complete mapping of the observables in momentum transfer space. However, technically it is very difficult to implement into the system such a degree of freedom in the polarization direc-

Figure 63: Schematic diagram of inclusive electron scattering from polarized targets with polarized electrons, $\vec{A}(\vec{e}, e')$.

tion. This would be even more difficult when considering the need for a target with large accessibility for the incoming and outgoing particles. The question of access is crucial for coincidence experiments in which the scattered electrons are detected on one side and the outgoing hadrons on the other side of the beam line. A related issue of importance is the effect of the polarizing magnetic field on the optics of the HMS spectrometer; this question has not yet been studied in detail.

Another major limitation on the operation of a polarized target is the amount of beam a target can handle before beam heating reduces the polarization to an unacceptable level. This limitation is actually related to heat dissipation off the beads. At SLAC and Bonn it has been demonstrated [Se82] that with the present target materials and techniques beams of as much as tens of nanoamperes could be tolerated by the target with beam rastering. One of the major improvement in polarized target materials in the past few years was the development of radiation doped ammonia [Me84]. Ammonia has higher content of protons or deuterons (17% by weight) than most other materials. The paramagnetic radicals essential for polarizing are introduced by irradiation techniques rather than chemical ones. In this process the target material is irradiated at < 90 K by electron beams to produce the required radicals.

Higher polarization is produced by increasing the magnetic field and/or lowering the temperature. For instance, The Bonn polarized target used in a $\gamma - d$ experiment operated at 2.5 T and 200 mK, while a ^4He refrigerator can produce a 1 K temperature. A $^3\text{He} / ^4\text{He}$ mixture in evaporation mode can achieve temperatures down to 0.5 K. In frozen spin

targets a $^3\text{He} / ^4\text{He}$ dilution refrigerator is used to produce very low temperatures. As the cooling power of a dilution refrigerator operating at these low temperatures is low, the beam intensity which can be tolerated on target is limited.

The conflicting experimental requirements between sub-Kelvin temperatures (a very low cooling capacity) and high electron beam intensities (requiring high cooling capacity) means that a reasonable compromise is necessary between the operating temperature, type of refrigerator and the magnetic field.

C.8.c Principles of Operation of the Polarized Target

The principle of polarized target is based on the Zeemann effect where a spin I particle in a magnetic field B will have $2I+1$ sub-levels. For spin half particles in a magnetic field B and at a thermal equilibrium temperature T , the population of the two sub-levels is determined by Boltzman statistics as

$$\frac{N^\uparrow}{N_\downarrow} = \exp\left(\frac{-\Delta E}{KT}\right) \quad (6)$$

where $\Delta E = 2\mu H$ and μ is the magnetic moment of a spin-1/2 particle. Polarization of such particles is defined as

$$P_v = \frac{(N^\uparrow - N_\downarrow)}{(N^\uparrow + N_\downarrow)} \quad (7)$$

combining equations 6 and 7 will give the polarization

$$P_v = \tanh(\mu B/KT). \quad (8)$$

Similarly for spin $I=1$ particles, such as the deuteron the polarization is given by

$$P_v = \frac{4 \tanh(\mu B/KT)}{3 + \tanh^2(\mu B/KT)} \quad (9)$$

These two equations imply that for higher polarization a higher magnetic field at a lower temperatures is required . However, even with a high magnetic fields and low temperatures, polarizations achieved in a thermal equilibrium are far too small for any practical measurement. For instance, at 0.5 K thermal equilibrium and 2.5 tesla, protons have a polarization of only 0.5% while polarization of electrons is 99% . This is due to the large magnetic moment of electrons. Also it takes relatively a long time for protons before this level of thermal equilibrium could be reached. From Eq. 8 and 9 it is clear that for a given temperature and magnetic field, protons ($I=1/2$) will reach a higher polarizations than deuterons($I=1$). Also for a given sample at a temperature T with a polarizing field B , there is a limit on the maximum polarization that can be achieved. It is essential for polarized deuteron targets to be operated at lower temperatures in order to achieve a polarization level for a practical measurement. Operating at lower temperatures will limit the beam current that can be tolerated by the target.

Figure 64: Schematic diagram of a polarized target system.

The large polarization of electrons can be exploited to enhance the nuclear polarization if one could couple these highly polarized free electrons to the target nuclei. In fact, this coupling is the basis of a process called dynamic nuclear polarization (DNP). In this process the high electron polarization is transferred to the proton through microwave irradiation. The unpaired electrons with the high polarization are introduced into the target material as paramagnetic centers through chemical doping (e.g., Cr.V) or via ionizing radiation (e.g., NH_2 in NH_3). The DNP process then uses microwave irradiation to polarize the protons in the material by coupling the electron and proton spin system and allow the transfer of much of the electrons' polarization to the proton. A schematic representation of the elements of a target to realize this scheme is shown in Figure 64.

C.8.d Target Materials

For many scattering experiments which require high beam intensities, a major disadvantage of most target materials has been the susceptibility to the effects of radiation damage. Under the effects of ionizing radiation the target materials lose polarization at a rate related to the integrated flux.

Generally, the polarization at any integrated flux I is

$$P = P_0 \exp(I/I_0) \quad (10)$$

where P_0 is the starting value and I_0 is the characteristic flux. Butanol-Porphyraxide is the best of the standard materials and has $I_0 = 5 \times 10^{14}$ protons / cm^2 . Some of the radiation damage effects may be annealed away by warming up the material to a temperature of ≈ 150 K (for Butanol ≈ 120 K). However, some longer term effects remain which means that the material has to be changed after a few anneals. In practice, this can be done no more frequently than about every 8 hours.

However, in the past few years, ammonia NH_3 and ND_3 have been developed as highly radiation resistant materials. There is also the advantage that there is 17.5% of H by weight compared to 13% in Butanol. With Ammonia, the paramagnetic centers are introduced by irradiation. The ammonia is irradiated at liquid Argon temperatures by an electron beam (for convenience) to a level of $\approx 10^{17} e^- / \text{cm}^2$. This can be done in a rather simple dewar arrangement. Subsequent polarization shows that a level of $\approx 70\%$ can be obtained at $1/2$ K and 2.5 T. The radiation resistance appears to be a factor of two or three times better than butanol and all the damage can be annealed away at 80 K. This means that an ammonia target can be annealed many times and used for the course of an experiment. There is also evidence that in situ irradiation at ≈ 1 K also leads to high polarizations. At the present time, the maximum attainable polarization are 92% for NH_3 and 44% for ND_3 obtained at 200 mK and 2.5 T. The corresponding average polarizations are 28% for NH_3 and 13% for ND_3 .

Incident beams on polarized target operating at low temperatures create different kinds of radicals in the target materials, some of which diminish the overall polarization of the sample. Annealing of samples helps these radicals to recombine and also allows for a faster polarization.

C.8.e Schedule and Budget

The design and construction of a polarized NH_3 target, capable of operating 1 K and with 5 T magnet), is estimated to take about three years. This includes the bidding process, design, assembly and the testing of all components. The estimated manpower required is during that time is presented in Table 34. It is expected that the design and implementation of this project will demand a senior physicist, a post-doctoral research associate and a electro-mechanical technician for a period of about three years. It is also expected that during the course of this project, the experience of other polarized target groups will be utilized through consultation. The manpower presented in the table covers the design and drafting, machine shop, construction and assembly of the system, testing and diagnosis of the entire system; it includes three years of a senior physicist, a research associate (post-doctoral), and a electro-mechanical technician. All of this work will be undertaken at the University of Virginia.

The estimated cost of the polarized target system are presented in the detailed Hall C budget that is appended to this document. This cost includes the costs of components and of the manpower required for design and construction of a target system. The cost of

Category	Average Level (Persons)	Total PYE (Persons)
Senior Physicist	1.	3.
Research Associate	1.	3.
Mechanical Technician	0.6	2.
Electrical Technician	0.6	2.
Drafting	0.25	0.5

Table 34: Manpower Requirements for the Polarized Target Project.

the major components is based on estimates or quotes from manufacturers, from manufacturers' catalogues, and from previous experience of the University of Michigan polarized target group for the target they now have at Brookhaven and their cost estimates for a new target they are now constructing for future use at Brookhaven. This new target is similar in many ways to the targets which we intend to use for electron scattering experiments.

C.9 Cryogenic Targets for Use with the HMS

In addition to the polarized target described above, two cryogenic targets are planned for Hall C. Both of them will take advantage of the 15 K cold He gas line that will be available in the end station for refrigeration. The high power target will be generally useful for planned studies of few- body systems, while the lower power target will serve for high-accuracy calibration measurements. The two targets are described briefly in the sections below.

C.9.a A Vertical Flow, High Power LH2/LD2 Target

The high power (250 watt) Hall C cryo-target will consist of a counter- current heat exchanger, forced convection loop filled with LH2/LD2, and refrigeration supplied by the 15 K cold He gas line from the end station refrigerator. By using the cold He gas line at 15 K, an equivalent load of less than 75 watts at 4.5 K is placed on the endstation refrigerator; the refrigerator is rated for 1,900 watts at 4.5 K. The cryogenics personnel at CEBAF have approved of this mode of operation of the refrigerator, and are planning for it in the design of the refrigerator. There will also be a solid target wheel attached to the bottom of the target. The whole apparatus can be raised and lowered to allow the electron beam to enter either the cryogenic target or the solid targets. The LH2/LD2 target flask will connect to the cooling loop via a vertical penetration through the top of the scattering chamber. The system will be capable of dissipating up to 250 watts of beam power.

Figure 65: Schematic of a high- power LH2/LD2 target

The circulating LH2/LD2 target loop is shown schematically in Figure 65. The components of the loop are the circulating fans, a 10 cm target cell, the LH2/LD2-gaseous He counter-flow heat exchanger, and three heaters for refrigeration load balancing. The system will have gauges for loop pressure, carbon resistor temperature sensors, carbon resistor level sensors, and a microphone to hear that the fans are actually operating. The flow loop volume will contain approximately 15 liters and will be constructed of stainless steel. The target flask will be curved aluminum with a thickness of approximately 0.01 cm. The target thickness as seen by the electron beam will be 10 cm. The electron beam will be rastered to avoid window damage.

C.9.b A Low Power LH2/LD2 Calibration Target

The low power (<15 watt) calibration cryo-target will consist of a cold head heat exchanger, a condensation loop filled with LH2/LD2, and refrigeration supplied by the 15 K cold He gas line from the end station refrigerator. There will also be a solid target wheel attached to the bottom of the target. The whole apparatus can be raised and lowered to allow the electron beam to enter either cryogenic target, dummy flask or the solid targets. The LH2/LD2 target flask will connect to the cooling loop via a vertical penetration through

Figure 66: Schematic of a low-power LH2/LD2 target

the lid of the scattering chamber. The system will be capable of dissipating up to 15 watts of beam power.

The LH2/LD2 target is shown schematically in Figure 66. The components include a 10 cm target cell, the LH2/LD2-gaseous He counter-flow heat exchanger and a heater for refrigeration load balancing. The system will have gauges for loop pressure, carbon resistor temperature sensors, carbon resistor level sensors, and a precision servo system to stabilize the pressure to better than ± 0.2 psi. This corresponds to a density variation of less than 0.1%. Thus, with a careful measurement of the target flask shape will be possible to know precisely (to several %) the length of LH2/LD2 seen by the beam.

D The Short Orbit Spectrometer (SOS)

D.1 Introduction

An examination of the proposed experimental program for Hall C at CEBAF reveals a major emphasis on coincidence experiments involving a "core" spectrometer and a second arm capable of detecting particles with momenta < 2 GeV/c with moderate energy and angular resolution. In most cases, the core spectrometer serves to tag a virtual photon, which induces a reaction in a nuclear target resulting in the ejection of a hadron in the energy range (0.2-2.0 GeV) which is observed in the second spectrometer. Nuclear physics topics addressed in these experiments include color transparency, nucleon propagation, pion electroproduction, and hyperon physics. All of these programs require an acceptance in the hadron spectrometer as large as possible in solid angle and momentum to maximize operational efficiency. In addition, relatively short spectrometer drift lengths are required in experiments involving detection of pions or kaons in order to minimize decay losses. Because the requirements for energy resolution in this class of experiments is moderate, typically $\sim 10^{-3}$, an optimized design with a short optical length less than 10 m will provide a well matched spectrometer capability. Excellent particle discrimination will be essential for detection of pions and kaons in the presence of high background fields. Operation at luminosities as high as $10^{38}/\text{cm}^2 \text{ sec}$ frequently will be required. To provide this second arm capability we propose the construction of a short-orbit spectrometer, the SOS, based on a QDD design which has been developed recently at the Los Alamos Meson Physics Facility. The QDD configuration provides a large momentum acceptance, with good energy resolution and solid-angle acceptance in a very compact geometry which can meet the needs of a broad spectrum of studies appropriate for Hall C at CEBAF. In this conceptual design document we begin with a discussion of the scientific justification for the instrument, which is followed by a discussion of design considerations, a presentation of the proposed spectrometer configuration, and finally cost and construction schedules.

D.2 Scientific Justification

A short-orbit spectrometer with large acceptance and moderate resolution coupled to the high momentum spectrometer (HMS) in Hall C will provide unique opportunities in a rich and varied research program. The initial set of research proposals which have been designed to be compatible with the HMS-SOS coincidence configuration provide a compelling demonstration of its possibilities. The topics addressed include: the energy and mass dependence of nucleon propagation in nuclei as measured in the $(e,e'p)$ reaction; longitudinal charged pion electroproduction in ^2D , ^3He , and ^4He ; electroproduction of kaons and hypernuclei; and proton polarization in the $d(\gamma,p)n$ reaction. In the sections that follow we discuss each of these in turn.

D.2.a A(e,e'p) Reactions

The propagation of the nucleon through the nuclear medium is a fundamental characteristic of the nuclear many body problem and quasi-free electron- proton scattering provides an excellent tool with which to investigate this process. Since the electron-nucleon vertex is well understood at moderate momentum transfers, the reaction may be viewed as tagging protons that emerge from the entire nuclear volume. With a variety of targets ranging from ^{12}C to ^{181}Ta , it will be possible to study the propagation through the nuclear medium of protons with energies that range from 400 MeV to 2 GeV. This program, a continuation of lower energy studies at Bates, will provide a test of various phenomenological descriptions of proton propagation that range from low-energy optical potentials, with or without relativistic corrections, to high-energy Glauber models.

The Energy Dependence of Nucleon Propagation in Nuclei

In the experiments proposed to study the energy dependence of nucleon propagation in nuclei, the electron kinematics are fixed to restrict the scattered electron energies to be close to the quasi-free peak at which the reaction mechanism has a large single-nucleon component. The integrated quasi-free coincidence yield provides a measure of the macroscopic attenuation, averaged over the binding energies of single-particle states and the angular range of the quasi-free angular correlation. With the quality of data expected from CEBAF, the A dependence of the absolute coincidence yield may provide the best measure of proton propagation and the ratio of coincidence to single yields will provide important information on the reaction mechanism. In the measurements at momentum-transfers below $2 (\text{GeV}/c)^2$ the A dependence of the quasi-free yield for four targets will be examined. For selected momentum-transfer a Rosenbluth separation will be performed to study the reaction mechanism. A consistent data set covering a large range of proton energies will be unique and provide an important survey of the reaction mechanism in the quasi-free regions.

The kinematic requirements for this study involve coincident detection of the scattered electron and recoil proton. For emerging protons at the lower end of the energy range, the electrons would be detected in the spectrometer with high momentum capability, while the proton would be detected in a lower momentum device. For the higher energy proton studies, the configuration would be similar to that of the color transparency experiment, since the proton momentum would exceed the expected range of the "low-momentum" arm. The resolution requirements in this experiment are modest, $\delta p/p = 0.001$, as is the maximum momentum of the detected particles, $\sim 4 \text{ GeV}/c$. In order to optimize this study, however, both spectrometers should have acceptances as large as possible, preferably 5 msr or more.

Color Transparency: $A(e,e'p)$ at high Q^2

There is an intriguing prediction of perturbative QCD that the component of the nucleon wavefunction that is relevant for high Q^2 exclusive processes has a small transverse size, $\sim 1/Q$. After the scattering, this state then evolves back into a standard nucleon. It is interesting to speculate that the scattered nucleon may therefore have a significantly reduced cross section for interacting with other nucleons just after the scattering for times corresponding to length scales of the order of nuclear dimensions, i.e. fermis. Since such a Fock state component has a small color dipole moment, this novel effect has been termed "color transparency". An ideal environment in which to study this process is exclusive $(e,e'p)$ scattering at high Q^2 . Such an experiment has been proposed by a Caltech-Argonne collaboration. Since it is clear that this process will become more apparent as the momentum transfer is increased, the A dependence of the quasi-free reaction will be studied up to the highest momentum-transfer attainable in a search for evidence of color transparency. The experiment will provide important information on the approach to the predictions of perturbative QCD in exclusive processes expected at high- momentum transfer, and also provides the possibility of studying the underlying theory of the string interaction in the nucleus directly using the electromagnetic interaction as a probe.

The kinematics for the proposed experiment involve detection of the recoil proton in a high momentum spectrometer with coincident detection of the scattered electron in a second, lower momentum spectrometer. The highest Q^2 proposed in the letter of intent, $9(\text{GeV}/c)^2$, requires a 6 GeV beam and detection of a recoiling proton with 5.7 GeV/c momentum; for lower incident electron energies, the momentum of the recoil proton may exceed that of the incident beam. Because of the Jacobian relating the two laboratory solid angles, there is kinematic focussing that compresses the laboratory solid angle of the recoil proton into the acceptance cone of the high momentum spectrometer. The resolution needed from the high momentum spectrometer is only that required to achieve enough accuracy in missing energy to permit discrimination of pion production in the final state. Assuming an acceptance of 9 msr for the electron arm, at the highest energies with a 100 μA beam, a coincidence rate of about 1/minute is expected for a spectrometer solid angle of 6 msr.

D.2.b Pion Elastic Form Factor Measurements

A study of longitudinal charged pion electroproduction below the delta resonance, in ^2D , ^3He , and ^4He will focus on kinematics where the charge scattering process dominates. In the excitation region below the $\Delta(3,3)$ the longitudinal component of charged pion electroproduction on the nucleon is viewed in terms of quasi-free scattering of virtual pions into the continuum. To the extent that such charged scattering dominates, electroproduction provides a means of probing the properties of the pion field of the nucleon. In nuclear matter the properties of the pionic field will be modified by the presence of pion exchange currents. Calculations of the change in the average number of pions in nuclei which can be

attributed to multi-nucleon interactions, give a pion excess per nucleon which is slightly negative for virtual pion momenta of 100-150 MeV/c, and positive for higher values with a maximum in the region of 400 MeV/c. The magnitude of the excess is a function of nuclear binding, increasing rapidly in the light nuclei. One explanation of the "EMC effect" in deep inelastic muon scattering, i.e. enhanced scattering in heavy nuclei at low values of the scaling variable, x , is an increase in the density of sea quarks in nuclear matter arising from this pion excess. However, more recent data from Drell Yan studies of antiquark structure functions in nuclei and the failure to observe a significant enhancement of the longitudinal spin-isospin response in polarized proton scattering by nuclei argue against a significant pion excess in nuclear matter. The apparent absence of an excess is a challenge to the conventional understanding of nuclear forces in terms of pion exchange and delta excitation. If confirmed in future experiments, these conclusions will require a reformulation of models of the medium and short-range properties of nuclear forces.

It is proposed that pion electroproduction be studied in the direction of the momentum transfer where the charge scattering by the pion field dominates. In this direction, interference cross sections are negligible and a Rosenbluth separation of longitudinal and transverse cross sections can be made by means of measurements at the same momentum transfer, but different incident energies and angles. Separations are planned at momentum transfers of 2.5 and 10 fm⁻². Direct comparison of the cross sections per nucleon in deuterium and the helium isotopes with the experimental value for the free nucleon will provide estimates of the strength of the nuclear pion field. If current conceptions of pion exchange currents in nuclei are correct, electroproduction will be suppressed at the lower momentum transfer and enhanced at the higher momentum transfer by the nuclear pion excess. Because pion momenta in this experiment are typically ~300 MeV/c, a short orbit pion spectrometer is essential to minimize decay losses and background contamination of the observed pion spectrum.

D.2.c The Electroproduction of Kaons and Hypernuclei

Similar considerations arise in studies of the electroproduction of kaons on light or complex nuclei. The detection of positive kaons provides a convenient technique for study of hypernuclear states. In these studies the kaon momentum may be as low as a few hundred MeV/c and the maximum acceptances that can be achieved are of utmost importance. In general, for energies at which the unstable hadrons are detected in the typical experiment, the decay lengths are short compared to the optical spectrometer lengths planned for the core instruments at CEBAF. In a typical CEBAF experiment the hadron will be observed in coincidence with the scattered electron and the missing mass spectrum reconstructed from the kinematic quantities measured for the scattered electron and hadron. High detection efficiency for the unstable hadron and low backgrounds from decay products can be achieved by minimizing decay losses in the hadron spectrometer. One will detect kaons in the momentum range beginning at a few hundred MeV/c and higher; the decay lengths for pions and kaons in the momentum ranges 0-400 and 0-2000 MeV/c respectively are plotted in Figure 67. If one demands the losses be less than 50%, a spectrometer system

Figure 67: The mean decay length for pions (solid line, top scale) and kaons (dashed line, lower scale) as a function of particle momentum.

with a central orbit length in the range 5-10 meters is required.

Two initiatives proposed for the Hall C complex address the physics of hypernuclei through studies of nuclear kaon electroproduction. One addresses the electroproduction of kaons and the very lightest hypernuclei. Data on the $(e,e'K^+)$ reaction on deuterium will be used to study the hyperon- nucleon interaction and the K-nucleon-Y coupling. Measurements on ^3He and ^4He will provide data where the beginnings of interactions in a nuclear medium may be investigated. The data will test theoretical estimates of yields for electroexcitation of hypernuclear states and serve as a benchmark for measurements in heavier nuclei.

The second proposal to study hypernuclei concerns studies of the spin doublet splitting in p-shell hypernuclei. Very high missing mass resolution will be necessary to observe these splitting which are predicted to be in the 100-200 keV range. Their observation will put strong constraints on the potential which describes the lambda-nucleus interaction. A staged approach is planned. In the initial experiments the SOS system will be used to investigate kaon production and electron-kaon coincidence rates. A septum dipole will separate the forward-going scattered electron and kaon. A dedicated low energy virtual photon trigger will be used to measure the residual electron energy, and the SOS with a special detector package to measure the kaon momentum. Based on the experience gained with this initial system, the collaboration plans to construct, at a later date, a higher resolution kaon spectrometer.

D.2.d Proton Polarization in the $d(\gamma,p)n$ Reaction

The SOS has also been proposed as the spectrometer system to be used in a "single arm" study of the proton polarization in the electro- disintegration of the deuteron in the GeV range. Theoretical studies have suggested that polarization observables at high momentum transfer are a sensitive probe of the underlying quark gluon structure of the deuteron. A bremsstrahlung beam would be used for these experiments, with observation of the ejected proton in the SOS with a focal plane polarimeter. By the choice of kinematics which restrict events to the ~ 100 MeV interval near the tip of the bremsstrahlung spectrum, one can limit observations to two-body reactions. In this case, measurement of the proton angle and momentum determine the incident photon energy. The proton polarization is measured by means of the focal plane polarimeter. In the first such experiment, observations would be made at angles corresponding to $\sim 90^\circ$ in the center-of- mass, and for incident photon energies up to ~ 2 GeV.

D.3 Design Objectives

The requirement common to all the experiments outlined above, is a spectrometer system which has been optimized for large acceptance in solid angle and momentum, with the

Table 35: Design Objectives.

Solid angle	10 msr
Central momentum at B_{nom}	1.5 GeV
Momentum acceptance	40%
Dispersion	< 2.5 cm/%
Resolving power (D/M)	100 cm
Optical length	5-10 m
Angular range	$> 10^\circ$

additional constraints that energy resolution be at least 10^{-3} , and the optical length be sufficiently short that decay losses for pions and kaons be acceptable. A spectrometer with these properties is well matched to the high momentum spectrometer whose momentum resolution will also be 10^{-3} .

The requirement of large momentum acceptance, $\Delta p/p_0$, in a focal plane of moderate size can only be accommodated by limiting the dispersion, and consequently the instrument resolving power which is measured by the ratio of dispersion to magnification, D/M. For $\Delta p/p_0 \approx 40\%$ in a focal plane with a length less than 1 m, the dispersion cannot exceed 2.5 cm/%. Short optical length also constrains the resolving power. For a given basic focussing-spectrometer configuration and central momentum, there is a strong correlation between the optical length and the maximum attainable resolving power. A relatively short optical length limits the total area of bending field available for the designer. Application of "Brown's rule" together with conservative assumptions about the phase space parameters of the particle beam in the spectrometer lead to the conclusion that, for a central orbit length of ≤ 8 meters and a central momentum of 1.5 GeV/c, economically acceptable design are feasible with ratios of D/M in the range of 10^{+3} cm.

However, if the dispersion in the focal plane is limited in order to accommodate a large acceptance in momentum, such ratios will be difficult to reach. One option available to the designer is to decrease the magnification in the dispersive plane. But such an option is effective only if the monoenergetic beam spot size on target is large. Because of the excellent emittance of the CEBAF beams, the beam spot is expected to be only ~ 0.1 mm, already comparable to the precision with which position at the focal plane can be determined. Consequently, high resolving powers accomplished by magnifications < 1 will not be realized in actual operation.

The design objectives for an instrument which meets the acceptance requirements for the experiments discussed in Section D.2 are presented in Table 35. They are appropriate to an instrument which has been optimized for a compact focal plane, large momentum acceptance, while maintaining moderate energy resolution. The compact focal plane will

facilitate minimum detector volume, efficient shielding, and in turn, operation at very high luminosities.

D.4 Spectrometer Design

The design objectives outlined in the previous section are very similar to the goals developed during the design stage for the Medium Resolution Spectrometer at LAMPF. Indeed, except for a major concern with spin precession in proton polarization measurements at LAMPF, the specifications are nearly identical. (Recent interest in polarization measurements at CEBAF may increase the overlap.) In an effort to optimize the design, LAMPF and H. Enge examined a number of design concepts [Bopc] in a manner similar to that followed for the Hall C second arm. Our conclusion, as well as that at LAMPF, was that the optimum choice for a moderate resolution spectrometer with large solid angle and momentum acceptance is a QDD design. As a result, a spectrometer of this design, the MRS, has been constructed at LAMPF and is being commissioned at the present time. It is proposed that an essentially identical spectrometer be constructed for Hall C at CEBAF and that it incorporate any additional knowledge derived from experience with what may be considered the prototype for SOS.

D.4.a Optics

In order to allow measurements at small angles and also, in first order, to decouple the momentum determination from measurement of the scattering angle, the spectrometer will bend in the vertical direction. The basic optical design is QDD with point-to-point focussing in both the radial and transverse directions. The $\bar{D}$ indicates a dipole that bends in the opposite direction from the first dipole. The dipole edges are rotated to provide both radial and transverse focussing and curvatures of the edges provide higher order aberration corrections. The design has been studied thoroughly with both TRANSPORT and RAYTRACE calculations.

As may be seen in Figure 68, the SOS spectrometer consists of three basic elements: a quadrupole that focuses in the transverse (horizontal) direction; a dipole that bends the central trajectory 33° ; and a second dipole that bends the central trajectory 15° in the opposite direction. The quadrupole focuses in the transverse direction and is the primary element that maintains acceptance in the horizontal plane. The rotation of the edge angles of the first dipole provides radial focussing (transverse defocussing) at both the entrance and exit of the dipole while the curvature of the entrance edge introduces sextupole corrections that act primarily upon the geometrical variables. The second dipole, bending in the reverse direction, is quite short and has rotated and curved edges at both the entrance and exit. This dipole, roughly triangular in shape, acts primarily as a quadrupole doublet; the entrance edge focuses radially while the exit edge focuses transversely. Since the pole is relatively short and wide with curvatures on the edges, the shape of this dipole

Figure 68: Schematic of the medium resolution spectrometer at LAMPF.

reminds one of a bear claw. Several features of this design are unique. The large rotations of the pole edges provide rather strong focussing over the full width of the beam, while the use of a reverse bend allows the separation between the two dipoles to be quite small and still retain the radial quadrupole action at both of the interior edges. This strong focussing results in a short distance from the exit of the second dipole to the nominal focal point and, overall, a very short spectrometer, ~ 7.4 m, for the momentum range to be covered. Moreover, the design is quite flexible and may be retuned for special purposes.

With these optical elements, the design fulfills the desired goals in a highly satisfactory manner. The design momentum is $1.5 \text{ GeV}/c$ with a total bite of 40%, i.e. from $1.8 \text{ GeV}/c$ to $1.2 \text{ GeV}/c$, for dipole fields of 1.7 T; the quadrupole tip field being 0.93 T. Studies have shown that dipole and quadrupole fields may be increased to allow $2.05 \text{ GeV}/c$ particles to be detected. The relevant elements of the first order transfer matrix are listed in Table 36. The dispersion of $\sim 1 \text{ cm}/\%$ (normal to the central trajectory) combined with magnification of ~ 0.4 results in a D/M value of $\sim 2.2 \text{ m}$, i.e. implying a first order resolving power that appears to greatly exceed the resolution goals to be discussed later. More important, the dispersion allows a compact focal-plane detector package to minimize sensitivity to room background. In the middle, the focal plane tilt is $\sim 70^\circ$ from the normal to the central trajectory, a value that is acceptable for trajectory analysis with wire chambers near the focal surface. Higher order aberrations have been analyzed and partially corrected by the curvatures of the pole edges. The net bend angle of 18° minimizes spin precession for particles that traverse the spectrometer so that the SOS is well suited for polarization

Table 36: First-order transfer matrix-elements of the Los Alamos MRS Spectrometer (elements not listed are zero).

Matrix Element	Units	Value at 7.4 m
$(x x_0)$		-0.41
$(x \delta p'p)$	cm/%	0.92
$(x' x'_0)$	mr/cm	-11.4
$(x' x'_0)$		-1.6
$(x' \delta p'p)$	mr/%	1.21
$(y y_0)$		-5.29
$(y' y_0)$	mr/cm	-9.19
$(y' y_0)$		-0.19
$(\delta p'p \delta p_0/p_0)$		1.0

studies.

In addition to the standard design discussed above, a number of additional tunes have been considered. In all of these tunes the first dipole is set for the desired momentum while the quadrupole and second dipole are adjusted to obtain double-focussing under various conditions. For example, a tune in which the second dipole is turned off results in a distance to the focal point that is ~ 2 m longer and a larger D/M, but has larger aberrations and a smaller solid angle. For particular purposes, it may be useful to explore these other options that do not involve physically changing the mechanical components.

D.4.b Construction

As indicated in Figure 68, the two dipoles share a common support structure and return yoke. Indeed, in the standard tune the second dipole serves as a part of the return yoke for the main dipole. The pole tips and coils are mounted directly upon the main frame made of 12" steel, the gap between the tips being determined by the cross members of the return yoke. The pole tips are mounted with Purcell filters at the base to maintain high field quality. The return yoke has been sized to accommodate a 2 T field in the main dipole and a very small field in the bear claw. This method of support assures precise gap alignment and an extremely rigid structure; worst case deflection calculations show deflections of 4 mils for 40 psi forces and less than 1 mil (0.001") under vacuum. In addition to forming the magnetic circuit, the return yoke also provides substantial shielding between

the target location and the detector stack. The quadrupole support structure is mounted directly upon the dipole structure to, once again, provide a rigid, reliable alignment of the various components independent of stresses that may be placed upon the structure under unusual circumstances. The result is an extremely compact, less than 5 m long, 110-ton spectrometer that may be moved without concern for misalignments among the critical components.

The quadrupole design is also somewhat unusual in that the top and bottom sections are magnetically decoupled. The side supports, each of which is sufficient to rigidly position the two parts of the quadrupole, are non-magnetic plates so that the field is not affected by removal for measurements at far forward angles. The quadrupole coils do not intercept the scattering plane so it is possible to bring a beam pipe between the upper and lower poles if the circumstances require it. In order to maximize small angle capability, the forward corners of the dipole yoke are notched at mid-height to accommodate a beam pipe. Field studies show that the flux at that location in the yoke is so small that neither the performance of the spectrometer nor the trajectory of the beam is affected by the notches. As a result, the SOS is expected to operate at angles as small as 11° without modification of either the spectrometer or the beam transport!

D.4.c Detector Package

The small cross sectional area of the envelope for analyzed particles permits a compact detector package with high flexibility for detection of a wide variety of particles. The detector package will be connected rigidly to the spectrometer yoke to assure stability of calibrations. While no detailed design of the detector package has as yet been undertaken, it is assumed that it will consist of at least two sets of multi-directional wire chambers, two planes of segmented plastic scintillator hodoscopes, and Čerenkov counters. In part of the program, a Freon 114 threshold Čerenkov counter will be required, while an Aerogel counter with $n=1.03$ will be used in other sections. Care will be taken in the construction of the hodoscopes to allow precise time-of-flight measurements either in the detector stack or in conjunction with the HMS. In addition, for experiments in which pions or electrons are detected, a shower counter will be useful.

One possible configuration for a detector package intended for use in detecting pions in the presence of electrons is shown in Figure 69. The wire chambers cover the full area of transmitted beam, provide trajectory information and precede all other detectors to minimize multiple scattering; the chamber at the rear is redundant, but may assist in trajectory analysis at high rates. The scintillator hodoscopes allow time-of-flight measurements not only between the detectors in the SOS package, but also relative to the similar detectors in the HMS and the rf structure. This redundant TOF measurement allows for more effective particle identification, particularly at relatively low energies. To distinguish between pions and electrons at higher energies a threshold gas Čerenkov and a highly segmented Pb-glass shower counter are utilized. The individual components of the detector package for pion detection are discussed in the sections below.

Figure 69: A schematic view of a pion detector package for the Short Orbit Spectrometer. The elements of the detector system from left to right are two wire chambers, a segmented scintillator, a gas Čerenkov counter, a third wire chamber, a segmented scintillator, a lead glass pre-radiator, and a lead glass shower counter.

For experiments in which other particles are detected, the detector package will be modified as needed. For example, Aerogel Čerenkov counters are particularly useful when kaons or protons are detected. The detailed form of the hodoscopes will be optimized for various experiments. A proton polarimeter may be placed at the rear of the stack if needed. In any event, there will be adequate space available for any detector within the shielding hut planned.

The shielding for the detector package may also be compact since the detector is quite compact. A hut composed primarily of concrete will shield the package from room and direct radiation in any direction. The shielding will be of modular construction to maintain flexibility and accommodate the needs of a variety of experiments. In order to assure this, the shielding will be mounted separately on its own movable support structure that will also permit ready access to the detector stack. A minimum flight path of 4 meters will be provided within the hut, but the modular construction will allow even longer flight paths or larger transverse dimensions for specific needs, e.g. a proton polarimeter. Although the detector package is relatively compact, the need for sufficient shielding results in a total shielding weight roughly equal to that of SOS, i.e. ≈ 100 tons even for the minimum anticipated detector package.

Multiwire Drift Chambers

Position measurements with a resolution of approximately $100\ \mu\text{m}$ will be provided by three identical sections of multiwire drift chambers. Drift cells will be 1 cm wide and plane separation nominally 2 cm. Each chamber will contain one X and one Y plane in addition to two stereo (U and V) planes. The active area of the sections will be 40×60 cm. Each section of four planes will be about 10 cm in depth. An argon, ethane, and CO_2 gas mixture will be used. Coincidences between the scintillator hodoscopes will provide triggers to enable the readout of the drift chambers and also will act as reference time for drift measurements. The system will utilize individual wire readout, i.e. there will be an amplifier, discriminator and TDC channel associated with each anode wire; the outputs will be CAMAC compatible form for data acquisition. The arrangement planned minimizes deadtime per wire, less than 200 nsec, and together with the segmentation provided by the scintillators, allows efficient operation in the environment of Hall C, even for backgrounds much higher than expected.

Multiple scattering in the chambers and the atmosphere in the drift volume between the first two MWDC sections will dominate the angular resolution of the instrument. Chamber windows (9 mils of mylar equiv., $L/L_r = 0.8 \times 10^{-3}$), and chamber gas ($L/L_r = 5 \times 10^{-3}$) will give an rms error in scattering angle of 0.6 mr at 1 GeV/c. The system as configured in Figure 69 should provide position measurements with sufficient accuracy to enable measurement of angles to about 3 mr for each detected particle. This will allow traceback to the target and discriminate against background events caused by scattering in the entrance aperture or walls of the spectrometer.

Čerenkov Counter

An atmospheric pressure Čerenkov counter with an active radiator length of 1.5 meters will be used to identify and reject electrons. The radiator gas will be $\text{C}_2\text{Cl}_2\text{F}_2$ which has an index of refraction of 1.00141. The resulting thresholds for electrons and pions will be 9.6 MeV and 2.6 GeV respectively. Based on the operation of a similar system currently in use at Fermilab, we expect an average of about 25 photoelectrons for a fully relativistic particle. The counter will be used in an anticoincidence mode in the spectrometer trigger. The (unwanted) rejection of pions due to their mis-identification because of the production of energetic delta electrons in the radiator gas should be below 10^{-3} .

Scintillator Hodoscopes

Hodoscope planes will be located behind the second and third MWDC sections. These will be used for crude pattern recognition and coincidence timing. The scintillator hodoscopes are conventional devices and, with photomultipliers at both ends of the scintillator paddles, timing resolutions of 0.15 nsec are routinely obtained with counters of the dimensions envisioned. At low energies, the rate of energy loss within the scintillators may be useful for discriminating against protons.

Shower Counter

Additional triggering and e/π identification for the upper momentum range of the SOS is afforded by the segmented shower counter system. It will be constructed of 10 cm $\times$ 10 cm F2 lead glass blocks arranged in a pre-radiator plane and five radiator planes with 5 blocks per layer (Figure 69). The thickness of the shower array will be in excess of 20 r.l. The geometry of the segmentation allows one to determine the longitudinal development of the shower and optimize the requirements on the shower distribution to the pion energy range under study. The choice of F2 is dictated primarily by the placement of the PMT's perpendicular to the incident particles. A glass with small light attenuation is required to minimize the effects of pulse height variation with particle position. Except for a finer granularity, the SOS shower counter is almost identical in geometry to the shower counter planned for the HMS. The expected energy resolution for the momentum range of interest is $\sigma_E \approx 5\%/E^{0.5}$. The response expected for that counter for 0.8 GeV/c pions and electrons, calculated using the GEANT Monte Carlo code, is shown in Figure 24. A pion rejection ratio of approximately 100:1 off-line and approximately 5:1 on line are indicated by these calculations.

Figure 70: Flight times as a function of particle momentum for pions, kaons, and protons in the SOS assuming a target to detector distance of 7.5 m.

Time-of-flight Measurements

Measurement of the particle flight times in the SOS will provide additional particle discrimination with a selectivity that is a strong function of the particle momentum. The timing resolution of the scintillator hodoscopes will be approximately 150 psec. The time mark for flight time measurements will be determined by the time of observation of the electron in the HMS spectrometer. By correlating that time to the rf microstructure, the time jitter in the electron arm will be made small compared to the uncertainty in the hadron flight time. A plot of the flight times for pions, kaons and protons in SOS is shown in Figure 70. In measurements of pion electroproduction, time-of-flight will provide complete discrimination against coincident protons; for pions below 400 MeV/c, where initial experiments are planned, time-of-flight will provide discrimination against electrons to supplement that obtained with the gas Čerenkov detector.

The total count rates for negative pions plus electrons and for positive pions plus protons within the acceptance of SOS as a function of spectrometer momentum setting are presented in Figure 71. The estimates were obtained from the inclusive cross section

Figure 71: Total count rates for electrons+ π^- and protons+ π^+ within the acceptance of SOS as a function of the central momentum of the spectrometer. The rates were evaluated for a nominal luminosity of 10^{38} for a carbon target with the spectrometer set an angle of 20° relative to the beam direction. The shaded area represents the region in which the dead time per wire in the multiwire drift chambers, described in the text, exceeds a nominal value of 5%.

Table 37: Short Orbit Spectrometer Parameters.

SPECTROMETER:	Configuration	QDD	
	Horizontal Open. Angle	120 mr	
	Vertical Open. Angle	80 mr	
	Solid Angle	9 msr	
	Focal Plane Dimensions	40×120 cm	
	Tilt Angle	70 deg	
	Central Momentum at B_{nom}	1.5 GeV	
	Momentum Acceptance	40%	
	Dispersion	0.92 cm/%	
	Optical Length	7.4 m	
	D/M	2.2 m	
	Angular Range	> 11 deg	
	Total Weight	110 tons	
	Distance, Target-Q1	1.5 m	
QUADRUPOLE:	Magnetic Length	0.8 m	
	Aperture	25 cm	
	B_{nom} , Pole Tip	1.0 T	
DIPOLE(S):	Gap	16 cm	
	Pole Face Rot., Entr.	-40.6	-40.6 deg
	Exit	-40.6	+45.9 deg
	Radius Curvature Exit	-2.5	2.25 m
	Bending Radius	2.94	2.94 m
	Angle	33	-15 deg

model codes of Lightbody and O'Connell for a carbon target at a luminosity of 10^{38} and a spectrometer angle relative to the incident beam of 20° . In order to provide a reference for the reader as to operational limits on the luminosity imposed by the properties of the detector package, the shaded region of Figure 71 has been indicated. In this region the dead time per wire in the multiwire drift chambers exceeds 5 % when drift time and electronic discrimination times are incorporated. It is seen that count rate limitations exist over only a small region of central momenta at a luminosity of 10^{38} .

D.4.d Anticipated Performance

The spectrometer parameters for SOS are presented in Table 37. As was indicated above,

the $D/M > 2$ m suggests that the first-order resolving power should exceed 20,000 for the 0.1 mm beam spot anticipated from CEBAF. Consideration of the optics, however, shows that this is an unrealistic estimate of the momentum resolution. A reasonable estimate of wire-chamber and, hence, position resolution is ~ 0.1 mm. For the present design, however, a magnification of ~ 0.4 implies a size of 0.04 mm for a monoenergetic beam at the detector. Therefore, even under ideal circumstances, without aberrations, the best resolution possible is worse than $1/9000$. Aberrations, however, also contribute to degradation of resolution and measurement errors further deteriorate performance. A simple method for accounting for most of these effects is outlined in Section D.6, where it is seen that inclusion of the major aberrations and reasonable expectations of measurement errors results in a realistic error of $< 8 \times 10^{-4}$ for a large fraction of the acceptance of the SOS. This resolution more than satisfies that design goal. Moreover, if there are significant advances in detector technology, it might be possible improve the momentum resolution. Similarly, estimates for the uncertainties in the other variables readily obtained with the procedure and all are within the design goals. Among the proposals that constitute the scientific justification for the SOS are several that require extended targets, such as LD, that are several centimeters long. Targets as long as four cm transverse to the central ray can be viewed with nearly the full solid angle and longer targets can be accommodated for experiments that can accept a reduced solid angle depending upon the tune.

Under typical experimental conditions, the SOS should operate at luminosities in excess of 10^{38} cm² sec. Possible luminosity limits generated by backgrounds in the detector package arising from beam-generated electromagnetic processes in the primary target were explored in a computer Monte Carlo simulation. A spectrometer geometry closely approximating that of the SOS was constructed, with detector volumes between the quadrupole exit and enhance to the dipole section and at the focal plane. The spectrometer scattering angle was 20° closely approximating the geometry typical of a pion electroproduction measure. A carbon target was used. The forward detector volume counted at a high rate and would be saturated in operation at a luminosity of 10^{38} /cm² sec. However, at the focal plane no events were observed. The data establish that the event rate due to target generated background is below the rates which will arise from genuine inclusive electron/positron, proton, and pion cross sections in carbon. Consequently, it is reasonable to assume that the luminosity limit for the SOS will be imposed by real inclusive particle spectra rather than incoherent background radiation. Inclusive cross sections for the carbon target indicate the luminosity limit will be in excess of 10^{38} /cm² sec.

D.5 Schedule and Budget

A proposed schedule for engineering, construction, and testing of SOS is shown in Figure 72. Although the SOS design is adapted from that of the LAMPF MRS spectrometer, there may be substantial changes in the quadrupole design to facilitate operation at small scattering angles. The spectrometer carriage will require a complete redesign to accommodate the 13-foot beam height in Hall C. The shielding and detector specifications for the

Figure 72: Proposed construction schedule for the short orbit spectrometer. With reasonable contingency and allowance for testing the project construction period is three years.

CEBAF program can only be fulfilled with design specific to CEBAF needs. Engineering, procurement, and fabrication times for the various components is based on the experience in constructing MRS at Los Alamos National Laboratory.

The proposed budget for the construction of SOS is given in the WBS 6.7.2 section of the Hall C budget that is appended to this document. The purchase and fabrication costs are based on the final MRS budget, with allowance for the engineering modifications required to adapt the instrument to the CEBAF program. It is estimated that 2-3 man years of ANL engineering and technical support will be required during the construction period. That effort will be provided as part of the construction project.

D.6 SOS Appendix: Estimating Measurement-Dependent Resolution Errors

One of the problems associated with the evaluation of a spectrometer design is the ability to measure the relevant physical parameters with the desired accuracy under reasonable experimental conditions. This appendix outlines a simple method of estimating the design dependent errors in the measurement of the physical parameters that arise, specifically, from the unavoidable uncertainties that are involved in the detection of particles passing through a detector package located near the focal planes of a magnetic spectrometer. The procedure yields a simple, albeit reasonably accurate, estimate of the uncertainties in the input parameters in terms of the input variables and the measurement errors.

We present a simple method for evaluating the effect of measurement errors, such as those due to multiple scattering in the detector, upon the momentum deduced for the incident particle. The discussion does not deal with limitations on resolution that result from the fundamental properties of the optical elements, i.e. aberrations, or attempts to correct for them. The method may be briefly summarized as follows: A transform is obtained for particles propagating from the detector to the target. This reverse transform and derivatives, together with values of variables that are obtained from forward transformation of the initial ray, are used to estimate the errors in the deduced components of the initial momentum that result from imperfections in each of the measured quantities. The method is generally useful for estimating the sensitivity to measurement errors for any of the initial variables.

The discussion utilizes the magnet optics program TRANSPORT [Br67] and the conventions adopted in it. With a right-handed coordinate system in which x and y are transverse to the longitudinal coordinate z that follows the central, reference trajectory, the components of the vector are: (1) x = the displacement, in cm, relative to the reference trajectory in the bend plane at position z ; (2) $\theta = x' = dx/dz$ = the angle of the ray, in mr, relative to the reference trajectory, in the bend plane at z ; (3) y = the displacement, in cm, transverse to the bend plane of the central trajectory at z ; (4) $\phi = y' =$ the angle of the ray, in mr, relative to the bend plane; (5) ℓ = the path length difference, in cm, between

that of the central trajectory and for the particle at z ; and (6) δ = the fractional deviation, in percent, of the ray from the reference value, i.e. $\Delta p/p$. Since a magnetic system is conservative, δ is constant for a given ray. The magnitudes of the terms in the transform depend upon the units used for each variable; the standard units being indicated above. The components of the final vector, (f) , are obtained from the initial vector, (o) , by

$$X_i(f) = \sum R_{ij}X_j(o) + \sum T_{ijk}X_j(o)X_k(o) + \sum U_{ijkl}X_j(o)X_k(o)X_l(o) + .. \quad (11)$$

where X_i represents the components of the vector, R_{ij} is the 1st-order transform matrix, T_{ijk} is the 2nd-order transform, and U_{ijkl} the 3rd-order transform.

In the following discussion, the numbers 1 through 6 are frequently substituted for the components of the vector, e.g. $x=1$, $\theta=2=x'$, etc., while R_{ij} may also be written as $(i|j)$, e.g. $(1|6)$, and T_{ijk} as $(i|jk)$. We also assume a single measurement position, e.g. z being the location of the nominal focus, and the size of the initial beam spot in the bend direction is made quite small, i.e. $x(o) \approx 0$.

Consider a magnetic spectrometer design that has been developed with the use of a matrix formulation such as TRANSPORT. The design consists of a series of elements, fields, and drift lengths that are incorporated into TRANSPORT to yield a transform of the type shown in Equation 11 in which the final components are expressed in terms of the initial components or ray. This transform, determined for the z of the nominal focal point, will be termed the Forward transform and the elements are indicated with superscript F.

If the identical elements, fields, and drift lengths are reconfigured in precisely the reverse order, the transform so generated will be termed the Reverse transform and its elements will either have no superscript or the superscript R. Equation 11 with the reverse transform gives $X_i(o)$ in terms of $X_i(f)$ where i indicates the variables 1 to 6; i.e. the Reverse transform gives the initial variables that result from the transformation of measured quantities, so that

$$X_i(o) = \sum R_{ij}^R X_j(f) + \sum T_{ijk}^R X_j(f)X_k(f) + \sum U_{ijkl}^R X_j(f)X_k(f)X_l(f) \quad (12)$$

The Reverse transform will be utilized to estimate the errors in the initial variables that result from uncertainties in measurements with the detector package. Of particular interest is the error in δ that results from multiple scattering in the detector stack. To estimate this, Equation 12 can be used to solve for $x(o)$. The 2nd-order result for x at the target in terms of the variables at the x -focus is of the form

$$\begin{aligned} x(o) = & \delta^2(1|66) + \delta[(1|6) + (1|16)x(f) + (1|26)\theta(f)] \\ & + [(1|1)x(f) + \sum (1|jk)X_j(f)X_k(f)] \end{aligned} \quad (13)$$

where the sum is over variables 1-4 only. For $x(o)=0$, Equation 13 is obviously of the form $A\delta^2 + B\delta + C = 0$ and can be solved for δ , where B and C are in the brackets. Taking the derivative of δ gives the simple form $d\delta = -(\delta B' + C')/(2A\delta + B)$, where the prime indicates differentiation. Since the variables (1-4) are independent, the derivatives may be grouped

by variable, so that the $d\delta$ may be written as

$$d\delta = -[R_{16} + T_{116}x(f) + T_{126}\theta(f) + 2T_{166}\delta]^{-1} \times \\ \left[dx(f)[R_{11} + 2T_{111}x(f) + T_{112}\theta(f) + T_{116}\delta] + \right. \\ d\theta(f)[T_{112}x(f) + 2T_{122}\theta(f) + T_{126}\delta] + \\ \left. dy(f)[2T_{133}y(f) + T_{134}\phi(f)] + d\phi(f)[T_{134}y(f) + 2T_{144}\phi(f)] \right] \quad (14)$$

where $X_i(f)$ is the value of the variable "measured" at the focal position and the matrix elements are those of the reverse transform. The differentials, e.g. $d\theta(f)$, can be considered as the uncertainties in the measured values of the variables. A similar equation may be obtained for each of the other variables if Equation 12 is constructed and differentiated for them.

Equation 14 and its analogs for the other variables can be used to estimate errors in the initial variables with a high degree of accuracy if precise values for the (f)inal variables are inserted. It is also seen that a reasonable estimate for the ERROR can be obtained by inserting the values of the final variables from the 1st-order transform of the input ray. For $x(o)=0$, Equation 14 then takes the form,

$$d\delta = -[R_{16} + (T_{116}R_{16}^F - T_{126}R_{26}^F + 2T_{166})\delta - T_{126}R_{22}^F\theta(o)]^{-1} \times \\ \left[dx(f)[R_{11} + (2T_{111}R_{16}^F - T_{112}R_{26}^F + T_{116})\delta - T_{112}R_{22}^F\theta(o)] + \right. \\ d\theta(f)[(T_{112}R_{16}^F - 2T_{122}R_{26}^F + T_{126})\delta - 2T_{122}R_{22}^F\theta(o)] + \\ dy(f)[(T_{134}R_{43}^F - 2T_{133}R_{33}^F)y(o) + (T_{134}R_{44}^F - 2T_{133}R_{34}^F)\phi(o)] + \\ \left. d\phi(f)[(2T_{144}R_{43}^F - T_{134}R_{33}^F)y(o) + (2T_{144}R_{44}^F - T_{134}R_{34}^F)\phi(o)] \right] \quad (15)$$

where, on the basis of the relations between transforms, $x(f)=(1|6)\delta$, $\theta(f)=-(R_{22}^F\theta(o) + R_{26}^F\delta)$, etc., and the terms without superscripts refer to the reverse transform. The structure of the equation fulfills the primary objective of expressing the error in δ in terms of the input ray and the explicit measurement errors at the detector. This a general result for the transform between target and nominal focal point independent of the mode of transverse focussing.

In order to illustrate the previous remarks, numerical values will be inserted into Equation 15 using the TRANSPORT outputs for the SOS spectrometer. The result is

$$d\delta = -[2.2212 - (0.0456)\delta + (0.0254)\theta(o)]^{-1} \times \\ \left[dx(f)[-2.422 + (0.0151)\delta - (0.0114)\theta(o)] + \right. \\ d\theta(f)[(0.0061)\delta - (0.00029)\theta(o)] + \\ dy(f)[(0.096)y(o) - (0.00052)\phi(o)] + \\ \left. d\phi(f)[(0.014)y(o) + (0.00)\phi(o)] \right] \quad (16)$$

It is then reasonable to test the approximation of Equation 15 for values of the variables that are representative for the SOS. Since $d\delta$ depends primarily upon δ and θ , the values

chosen are $y(o)=0$, $\phi(o)=50\text{mr}$, $\theta(o)=33.3\text{mr}$, and $\delta=10\%$. Insertion of these values into Equation 16 yields

$$d\delta = dx(f)(2.05) + d\theta(f)(0.077) + dy(f)(0.028) + d\phi(f)(0.0). \quad (17)$$

Evaluation of $d\delta$ by inserting the same input ray into the 3rd- order transforms with measurement errors gives

$$d\delta = dx(f)(2.01) + d\theta(f)(0.066) + dy(f)(0.18) + d\phi(f)(0.011). \quad (18)$$

For reasonable measurement errors, i.e. $dx(f), dy(f) \approx 0.01\text{cm}$ and $d\theta(f), d\phi(f) \approx 1\text{ mr}$, the approximation provides a good estimate of the error in the momentum measurement. The agreement between the values in the bend plane is particularly useful, inasmuch as these terms are the dominant ones. The large fractional errors in the transverse terms arise from poor agreement between the 1st-order and higher-order values for $y(f)$ and $\phi(f)$. As was remarked in the discussion following Equation 14, similar approximations may be obtained for the other input variables by simply differentiating Equation 12 for each variable. For the SOS, examination of the matrices indicates that the simplest estimate for the error in ϕ , namely the 1st-order term, is adequate. On the other hand, the large magnification in the transverse direction, y , results in a relatively small 1st-order term for the error in the transverse target position so that the 2nd-order terms become important even though each individual term is small. The error in the target position is, however, always less than 2.5 mm. for any acceptable ray.

In summary, a simple method is presented for estimating the errors in the deduced values of input kinematic variables that result from the unavoidable uncertainties in the measurements with a detector package near the focal plane. The error may be evaluated for specific input rays within the acceptance of the spectrometer and explicit errors in each of the variables measured.

E The Hyper-Nuclear Spectrometer System (HNSS)

The relatively high energy and exceptional beam quality at CEBAF will make it possible to study the splitting of individual levels in hypernuclei via high resolution ($e,e'K$) coincidence measurements on complex nuclear targets. Kinematics dictate that the electron and kaon both be detected at very small angles relative to the beam line, although the maximum momentum of both particles is modest. A group from the University of Houston has designed a Hypernuclear Spectrometer System (HNSS) for this program consisting of a pair of high resolution, small angle spectrometers. The high quality of these instruments makes them also useful for other low- q^2 electroproduction experiments that require similar kinematics. This instrumentation would take the form of movable pair of short, high-resolution spectrometers. The kaon spectrometer resolution has been estimated to be of the order of 120 keV FWHM. The net resolution estimated for a 0.01 gm/cm^2 target is given in Table 38.

This resolution may be improved somewhat by reducing the target thickness while increasing the beam current to maintain a constant luminosity. However, the dominant resolution contribution comes from the primary beam so the overall resolution can be reduced significantly from the value presented in Table 38 only through the use of a dispersed beam. A schematic of the HNSS is shown in Figure 73.

E.1 Hypernuclear Physics at CEBAF

E.1.a Introduction

The field of hypernuclear physics is some thirty-four years old, but it has not progressed at as rapid a rate as other fields of nuclear science because existing beams of kaons and energetic pions are of such poor quality. Thus, although we have learned a few things about

Table 38: Hypernuclear Spectrometer System (HNSS) Design Goals.

Primary Beam	$(\delta p/p \simeq 10^{-4} \text{ at } 1.8 \text{ GeV/c})$	180 keV
Inelastic Electron	$(\delta p/p \simeq 3 \times 10^{-4} \text{ at } 0.3 \text{ GeV/c})$	90 keV
Kaon Spectrometer	$(\delta p/p \simeq 10^{-4} \text{ at } 1.2 \text{ GeV/c})$	120 keV
Kaon Energy loss	$(1.7 \text{ MeV/gm/cm}^2) \times 10 \text{ mg/cm}^2$	17 keV
Overall Resolution		235 keV

Figure 73: The spectrometer layout for $(e,e'K)$. The kaon spectrometer bends vertically.

Λ binding energies and the Λ -nucleus potential in light nuclear systems, many questions are yet to be investigated. This proposal emphasizes that the physics of strange nuclear systems may address fundamental issues that should shed light on our current understanding of hadronic many body systems, and that these issues can be explored at CEBAF. In fact the features of CEBAF, including beam quality, as well as the properties of the electromagnetic interaction can provide unique information not attainable at other facilities.

Because of the weak spin dependence of the Λ -nucleus interaction, splitting of levels within major shell orbits will be small [Br78,Ch79,Ma81] (see Figure 74). A recent (π,K) reaction populating hypernuclei in heavier mass targets shows strong reaction strength to a series of particle-hole states deeply embedded within the nucleus [Pi88]. In effect the reaction removes a valance neutron and replaces it with a Λ in any of the lower shell orbitals within the nucleus.

This series of levels may be analyzed to determine if a repulsive Pauli pressure affects the level positions, particularly in heavy systems [Mi88]. Although the present fit to the data shows no evidence of unusual behavior it has been pointed out that the difference between this fit and a shift to be expected from partial quark deconfinement, would be about 1.5 MeV for the 1s shell in Pb [Dopc]. The expected magnitude of the shift points out that one must precisely measure the level structure of many heavy hypernuclei to extract such information.

Figure 74: Representative predicted level splitting for p shell hypernuclei.

In addition, the effective interaction potential for p-shell hypernuclei predicts various level splitting, and in particular those within a given spin multiplet [Mi85]. This interaction predicts doublet splitting of order 100 to 200 keV. However, the parameter set is not without difficulties [Ch89]. High resolution data is needed to identify transitions to specific levels. Present spectra using hadronic beams are limited to resolutions of about 2 MeV FWHM. The quality of the beam at CEBAF offers the unique possibility of obtaining spectra with an order of magnitude better resolution.

E.1.b Kinematic and Cross Section Constraints

The kinematics of the elementary amplitude in (γ, K) and $(e, e'K)$ are important not only to define the required experimental apparatus but also to determine the relative sticking probability of the recoiling Λ to the nucleus. This probability is, of course, included in the dependence of the hypernuclear cross section as a function of the momentum transfer, q^2 . In the (γ, K) reaction the minimum momentum transfer is obtained when the angle between the photon and kaon is zero. In a heavy hypernucleus the nuclear recoil energy may be neglected, but the minimum momentum transfer is about 177 MeV/c which is attained at high incident momentum. Typical momentum transfers range from 250 to 450 MeV/c.

In the $(e, e'K)$ reaction the minimum momentum transfer is attained when the angle, θ_K , between the kaon and the virtual photon angle is zero. The transition form factor falls off rapidly for $q^2 > 400$ MeV/c, but may peak at intermediate values of q^2 . At the peak of the elementary cross section, 1.3 GeV/c, a typical momentum transfer for CEBAF energies is about 300 MeV/c and the momentum transfer is roughly independent of θ_K to angles of about 15° . Kaon distortion effects have been estimated to reduce the theoretical cross sections by 10% in light systems to 60% in heavier systems [Do86].

Electromagnetic production of hypernuclear levels will strongly populate unnatural parity states starting from a $J^\pi = 0^+$ nuclear target. This contrasts to hadronic production mechanisms where the spin flip amplitude is small. In addition, since the momentum transfer is large, one would also expect to selectively excite states of high angular momentum.

The above considerations show that for the $(e, e'K)$ reaction one should use an energy difference between the incoming and outgoing electrons of approximately 1.5 GeV, providing a virtual photon of approximately this energy. In addition, for maximum rate the kaon spectrometer should be placed near the angle of the outgoing virtual photon. If the momenta of the outgoing particles are kept as low as possible then one expects to obtain the best energy resolution and lowest background for a fixed $\Delta p/p$ spectrometer system.

If placed at forward angles, the electron spectrometer will limit the luminosity on the target by the singles rate in its detector, which cannot exceed about $10^8/\text{sec}$. This rate is determined by the necessity to correlate an electron event with a detected kaon. It has been suggested that the electron spectrometer could be placed at zero degrees to

take advantage of the enhanced virtual photon flux at these energies [Hy85]. At this angle one would use only 10^{-3} or so of the available beam intensity. However, for very small angles the counting rate for a given combination of angle and momentum in the electron spectrometer for the energy loss of interest is dominated by Møller scattering events. It is necessary to increase the scattering angle to a value where the Møller scattering is modest compared to the reaction of interest, or to select a central momentum and solid angle for the spectrometer for which the Møller electrons are not transmitted to the focal plane. When the spectrometer is placed at some finite, but small, angle the decrease in photon flux can be compensated by increased beam intensity. One can maximize the rate of hypernuclear formation and the true-to-accidental ratio by placing the electron spectrometer near but excluding a scattering angle of zero degrees.

Because of the high rates envisioned for the electron spectrometer, several methods have been proposed to allow high rates with reduced accidental coincidences. One method is to disperse the beam perpendicular to the bend direction in the spectrometer. This would allow a spatial as well as a time coincidence, and a luminosity increase of a factor of 10 might be possible. This method has the disadvantage of placing more severe constraints on the magnetic spectrometers in order to accept the larger source size. An alternative technique is to use segmented targets and require the electron and kaon to simultaneously come from the same target. This increases the luminosity by increasing target thickness, but keeps the resolution essentially constant. In this case the spectrometer should have greater longitudinal acceptance. We propose dispersion of the beam, which has the additional advantage of decreasing the power density loss in the target while improving the resolution.

E.2 The Design of the Hypernuclear Spectrometer System

The spectrometer design proposed here (Figure 73) is based on the premise that resolution in the resulting hypernuclear system is to be optimized. The kaon and electron spectrometers must be moveable to forward angles ($\geq 5^\circ$). This allows thin samples and reduced energy loss which is important to the resolution. At forward angles, the count rate is limited by rates in the electron spectrometer. One expects a low hadronic background in the kaon spectrometer. This facilitates detectors employing particle identification, as well as possible hadronic tagging methods for background and quasi-free suppression of the resulting spectrum.

It is assumed that the beam initially will not be dispersed. This simplifies the spectrometer design, and puts fewer demands on the beamline. However, the capability of a dispersed beam is very desirable and this option must be implemented in the future. Since both the electron and kaon spectrometers are simultaneously required to operate to within 5° of the incident beam, a magnetic dipole is placed at zero degrees to bend the kaons and electrons into their separate spectrometers. The scattered electrons, because of their low momentum, are bent well away from the beam. Unfortunately, the primary beam is also bent by this dipole to an angle of 4° . Thus, the primary beam must be handled properly

Table 39: Representative Thresholds for K Photo-production from a Nucleon with the Kaon Emitted at 1.2 GeV and 10° Scattering Angle.

Reaction	Threshold (Gev/c)
$\gamma + p \rightarrow K\Lambda$	1.55
$\gamma + p \rightarrow K\Sigma$	1.67
$\gamma + p \rightarrow K^*(892)\Lambda$	1.87
$\gamma + p \rightarrow K\Lambda(1405)$	2.00
$\gamma + p \rightarrow K^*(892)\Sigma$	2.02
$\gamma + p \rightarrow K\Lambda(1520)$	2.20
$\gamma + p \rightarrow \phi(1020)p$	2.30

to ensure it is captured by the beam dump.

We have chosen an incident beam of 1.8 GeV/c, with a virtual photon energy of 1.5 GeV/c. The production cross section tends to peak near this value for reasonable momentum transfers. In addition the energy of all the particles is kept at low values which is important for resolution, and reduces the size of the spectrometers. If the incident electron beam is kept below 1.8 GeV, the accidental kaon flux in the spectrometer is also kept to a minimum as illustrated by Table 39 which lists various thresholds for kaon photoproduction. It is important to keep the length of the kaon spectrometer as short as possible because of kaon decays. Figure 75 shows the kaon survival ratio per meter as a function of kaon momentum. The central kaon momentum for the design of the kaon spectrometer was chosen as 1.2 GeV/c with a momentum acceptance of $\Delta p/p = \pm 60$ MeV/c. Assuming this acceptance then Figure 76 shows that the electron spectrometer must also have an acceptance of ± 60 MeV/c which results in a $\Delta p/p \simeq \pm 20\%$ at 300 MeV/c.

E.2.a The Kaon Spectrometer

The layout of a prototypical kaon spectrometer is shown in Figure 73. The spectrometer optics have been corrected to 4th order. The spectrometer parameters are given in Table 40. Of particular relevance is the acceptance of 14.0 msr and the length of 8 m. The beam profile is shown in Figure 77. The spectrometer bends vertically.

The spectrometer resolution is shown in Figure 78. The solid curve is the resolution (FWHM) with the $(x|\theta_x)$ correlation removed. Other correlations are minor, but can also be corrected in the data analysis, further improving the resolution. However, since the actual resolution is then dominated by the spatial resolution of the drift chambers, these

Figure 75: Kaon survival per meter as a function of kaon momentum.

Figure 76: Kinematics for (e,e'K) on a C target.

Table 40: Kaon Spectrometer Parameters.

Quadrupole	
length	80 cm
diameter	40.64 cm
field	6 kG (plus higher-order)
Dipole	
radius	226 cm
angle	80°
field	18.06 kG
gap	16 cm
Dispersion	8.3 cm/%
D/M	8.6 cm/%
Range	$\pm 5\%$
Solid angle	14 msr
Peak width at waist	0.76 - 2.1 cm
Transverse images	~ 2.5 cm
Focal surface	at 48°, and curved

Figure 77: Beam profile for the kaon spectrometer.

Figure 78: Resolution of the kaon spectrometer across the focal plane.

corrections will be of little significance. An angular resolution of about 0.5 mr is obtained.

E.2.b The Electron Spectrometer

The layout of the electron spectrometer is shown in Figure 79. The spectrometer is a split-pole magnet designed by H. Enge [En67] and is presently at the University of Illinois. In order to achieve the required momentum acceptance ($\Delta p/p \simeq 20\%$), Enge has proposed [Enpc] a modification of the magnet poles. Spectrometer parameters are shown in Table 41. This spectrometer must bend horizontally due to the large correlation of θ with momentum introduced by the zero degree dipole.

The focal plane for this spectrometer is located near the back face of the magnetic pole piece. Resolution without correction for angle position correlation is about 3×10^{-4} so that only a focal plane detector is needed. Of course, components in the detector package are necessary for timing and particle identification as well as position.

E.2.c Particle Tracking and Identification in the Kaon Spectrometer

The particle tracking system planned for the kaon spectrometer consists of three (x,y) drift chambers with a wire spacing of 1 cm and four planes each (to reduce left right ambiguities),

Figure 79: A layout of the Enge split pole spectrometer.

Table 41: Electron Spectrometer Parameters.

Momentum	240 - 360 MeV/c
Design central momentum	276 MeV/c
Total length	~5 m
Solid angle acceptance	1.6 msr
Horizontal	25 mr
Vertical	20 mr
Momentum bite	$\pm 2\%$
Focal plane dimension	
Length	104 cm
Tilt	50°
Horizontal	80 cm
Momentum resolution	3.8×10^{-4}

placed before the focal plane. A Monte Carlo calculation indicates that these chambers would provide a position resolution of about 0.3 mm on an (x,y) plane at the position of the focus. We assume a drift time resolution of about 3 nsec.

Because it is expected that the ratio of pions and electrons to kaons in the spectrometer will be large, a kaon identification scheme will be required. This system consists of two layers of scintillators (S1,S2), and two layers of Čerenkov detectors (C_π, C_p) and time of flight. The scintillation and Čerenkov detectors are segmented along the focal plane. A coincidence between S1 and S2 indicates a charged particle event and starts the drift time for the chambers as well as opening an ADC gate for the Čerenkov light.

The Čerenkov detectors are designed to separate pions, C_π , and protons, C_p . The radiators are selected to detect particles above the velocity thresholds corresponding to the momentum of the particles in question. Of course, all particles with velocities higher than these threshold will also radiate, but for protons, for example, the lucite radiator is designed so that only the light from protons strikes the window surface at an angle less than the critical angle, and thus can escape the radiator. The characteristics of each Čerenkov detector is summarized in Table 42.

Essentially, the kaon events are triggered by the signal S1·S2 gated by $\overline{C_\pi \cdot C_p}$. However, under the expected experimental conditions it is quite possible to have more than one track through the electron arm. Therefore, it is necessary to segment the counters and to institute a method to trigger the system on good events. The trigger is discussed in section E.3.b below.

Table 42: Characteristics of Čerenkov Detectors.

Detector	Particle	Radiator	Index	Rejection	K Efficiency
				Rate	Loss
C_π	π, e	Aerogel	1.07	1×10^{-3}	0.02
C_p	p	Lucite	1.54	2×10^{-4}	0.02

E.2.d Timing

It has been proposed that time of flight can be used for particle discrimination between kaons and pions. Over the 8 m or so length of the kaon spectrometer the pions and kaons will be separated by about 2 nsec. Off line, this information can be used to further exclude pion accidentals, but it would be difficult to implement time of flight in the trigger without imposing additional time structure on the beam. We presently exclude this possibility because the instantaneous rate is already high and the event rate low. Thus, there is little, if any, flexibility left to manipulate the time structure in the beam. Particle identification at the needed level can be accomplished by Čerenkov detectors. The π^+/K^+ ratio is about 450:1 (180/0.4).

E.2.e Electron Focal Plane Detector

The focal plane detector for the electron spectrometer covers 120 MeV/c in a spatial distance of 80 cm giving a dispersion of 150 keV/mm. With a position resolution of 0.6 mm this would give an energy resolution of 90 keV for the electron arm. If the focal plane drift chambers have a wire spacing of 2.5 mm then each wire would have a rate of 8×10^5 . Wire length would be about 10 cm. Drift chambers with a 2.5 mm drift distance have operated previously at rates of 10^6 /wire over a 2 cm wire length at Brookhaven National Laboratory. These chambers have an RMS spatial resolution of 0.15 mm and a total drift time of about 40 nsec. Their time resolution between planes is about 20 nsec. Similar chambers, used in a MWPC mode with wire spacing of 0.47mm and unsupported wire length of 18 cm were used in experiment E705 at FNAL [Co89] in a particle flux of 10^7 particles/cm²-sec.

Behind the drift chamber would be a set of 60 scintillator segments each covering 2 MeV/c. These segments are used for timing information, and consist of two scintillators in coincidence. The rate in each scintillator and the coincidence rate per scintillator segment is 3×10^6 . The trigger rate is then equal to the accident rate between the kaon and electron arms or about 0.04/sec.

E.3 Experimental Details

E.3.a Particle Fluxes in the Spectrometers

A knowledge of the background flux of various particles in the spectrometers is necessary to develop the detector system, trigger, and eventual counting rate. We have estimated these rates by the use of relevant experimental data wherever it exists, or, if necessary, by Monte Carlo calculations from known cross sections. The computer program, "EPC", written by J. O'Connell and J. Lightbody is used to determine the pion and proton flux in the kaon spectrometer [Bo66,Oc88]. We are interested in the inelastic electron and π^- flux in the electron spectrometer; and the π^+ , e^+ , and proton flux in the kaon spectrometer.

We may estimate the lepton flux in both the kaon and electron spectrometers for both bremsstrahlung and pair production. The lepton flux occurs through:

1. bremsstrahlung in which the incident electron scatters into the spectrometer; and
2. pair production from a virtual photon moving in the direction of the e^+e^- pair.

The bremsstrahlung flux at forward angles may be determined using the peaking approximation in which a bremsstrahlung photon is emitted along the incident electron direction and the energy degraded electron then Mott scatters from the target. That part of the peaking approximation which corresponds to emission of the photon after scattering is thus ignored. Application of the equations given in Ref. [Do86] results in a cross section:

$$d^2\sigma/d\Omega_e dp_e = 4.2 \mu b/sr \cdot MeV/c;$$

for a 1.8 GeV incident electron with a 300 MeV scattered electron at 5° . This cross section is consistent with experimental results given in reference [Do86].

The bremsstrahlung flux at zero degrees was determined from: $dN_e = (\chi/\chi_0) \cdot (dE_e/E_\gamma) \cdot N_e$; where (χ/χ_0) is the target thickness in radiation lengths, dE_e is the energy acceptance of the spectrometer, and E_γ is the energy of the photon. For a 10 mg carbon target, this results in a rate of $1.2 \times 10^8/sec \cdot \mu A$. Here we have used $\chi/\chi_0 = 2.3 \times 10^{-4}$, $dE_e = 120$ MeV, and $E_\gamma = 1500$ MeV.

We may also use the virtual photon flux to create an e^+e^- pair with a flat energy spectrum up to the maximum value of 1.8 GeV/c. For the present geometry the cross section to electroproduce a positron into the kaon spectrometer at 5° on a carbon target is:

$$d^2\sigma/d\Omega_\pi dp_e = 6 \mu b/sr \cdot MeV/c$$

The approximation used here is comparable to the approximation used above for the bremsstrahlung calculation.

The computer code "EPC" predicts the pion and proton production cross section at

5° on a carbon target as:

$$\begin{aligned} d^2\sigma/d\Omega_\pi dp_{\pi^+} &\approx .03 \mu b/sr \cdot MeV/c \\ d^2\sigma/d\Omega_p dE_p &\approx .0028 \mu b/sr \cdot MeV/c \end{aligned}$$

One may maximize the event rate or the signal to noise ratio. We choose to maximize the signal to noise ratio and thus to place the electron spectrometer at zero degrees. For an electron spectrometer acceptance of 120 MeV/c and a bremsstrahlung flux of 2×10^8 the incident beam flux would then be about 10^{13} electron/sec. This produces a kaon rate, after scaling for the present luminosity, of about 0.4/sec over the entire momentum acceptance of the kaon spectrometer.

The virtual photon flux may be estimated by $.015 \times N_e \times dE_\gamma/E_\gamma$ [Mo69]. This gives about 10^{10} photons/sec. The positron rate in the kaon spectrometer may be obtained from the cross section estimate obtained previously. Thus,

$$\begin{aligned} N_e &= (6 \times 10^{-30})(10^{13})(6 \times 10^{23}/12)(.01)(.01)(120) \\ &= 3.6 \times 10^4/sec \end{aligned}$$

The proton and pion flux estimates are similarly:

$$\begin{aligned} N_\pi &= 180/sec \\ N_p &= 18/sec \end{aligned}$$

E.3.b The Trigger

Because of the high rates in the electron spectrometer the trigger must be carefully constructed. We propose to segment the electron spectrometer into 60 bins, each covering a momentum bite of 2 MeV/c. In addition, the kaon spectrometer would be segmented in 12 bins of 10 MeV/c each. Then for a given hypernuclear mass the momentum of the electron and kaon are correlated. For a target mass $\gg$ the kaon momentum, a 2 MeV/c electron momentum and a 20 MeV hypernuclear mass bite require approximately a 18 MeV/c kaon momentum bite. Therefore requiring the electron segment to be in coincidence with three kaon segments centered about the kaon segment corresponding to the central value of the hypernuclear mass and electron momentum, all coincident events are captured. This would reduce the accidental trigger rate to:

$$N_{ACC} = (0.16) \left(\frac{3}{60 \times 12} \right) \times 60 = 0.04/sec$$

The rate in each electron segment would be 3×10^6 . The probability of two events in 4 nsec, which is twice the resolving time of the electronics, would then be $\sim .01$, and

the probability of 2 hits or more for any trigger about 0.6. In the off line analysis this multiplicity can be reduced since this rate would be spread over a number of mass bins.

The coincidence trigger may be formed by programmed logic array IC's which would accept, as inputs, the 60 channels of electron segments and the 12 channels of kaon segments. These devices are capable of handling singles rates up to 25 MHz and would be pre-programmed for a specific momentum tune of the spectrometers. The coincidence output will form the trigger.

E.3.c Accidentals

Accidental coincidences will determine the total trigger rate. The singles rate in the electron spectrometer will be about 2×10^8 /sec so with a time coincidence of 2 nsec one expects

$$N_{ACC} \approx (2 \times 10^8)(2 \times 10^{-9})(0.4) = 0.16/sec$$

The events will be more or less equally spread over the 120 MeVx120 MeV energy matrix formed by the electron and kaon spectrometers, so the number of accidentals per 230 keV in binding energy will be:

$$N_{ACC}/bin \approx (0.16)(.23)(7 \times 10^{-5}) = 2.8 \times 10^{-6}/sec$$

This is probably sufficient for an on-line trigger. Section E.3.b above discuss the trigger in more detail.

E.3.d Count Rate for $^{12}\text{C}(e,e'\text{K})^{12}_\Lambda\text{B}$

As an example of the use of the HNSS for an experiment of interest we consider here the possibilities for the investigation of the spin doublet splitting in p-shell hypernuclei in order to further determine the ΛN interaction. As a representative count rate for such an experiment we estimate the rate for the production of the ground state of $^{12}_\Lambda\text{B}$. We assume a beam momentum of 1.8 GeV/c with an inelastic electron at 0° and an energy of 300 MeV. The kaon spectrometer is placed at its minimum angle of 5° so that the reaction kaon momentum is 1205 MeV/c. The cross section to the ground state of $^{12}_\Lambda\text{B}$ is assumed to be 50×10^{-33} cm²/sr. We choose a 10 mg/cm² ^{12}C target with a beam intensity of 10^{13} electrons/sec. Using the kaon spectrometer parameters from Table 40, and assuming an electron spectrometer of 2 msr acceptance with $\Delta p/p \simeq 20\%$, the following rate is determined (see section E.3.a):

$$\begin{aligned} R &= (6 \times 10^{23}/12)(.01)(50 \times 10^{-33})(.014)(1.2 \times 10^{10})(.4)(.8) \\ &= 1.3 \times 10^{-3}/sec (= 4.8/hr) \end{aligned}$$

Here a 40% kaon survival rate and 80% detection efficiency is used. The signal to noise rate is then quite large (~ 400).

E.3.e Resolution

The kaon spectrometer resolution has been shown to be of the order of 120 keV FWHM. For a 0.01 mg/cm^2 target we expect the following resolution.

Primary beam	$(\delta p/p \simeq 10^{-4} \text{ at } 1.8 \text{ GeV/c})$	180 keV
Inelastic electron	$(\delta p/p \simeq 3 \times 10^{-4} \text{ at } 0.3 \text{ GeV/c})$	90 keV
Kaon spectrometer	$(\delta p/p \simeq 10^{-4} \text{ at } 1.2 \text{ GeV/c})$	120 keV
Kaon energy loss	$(1.7 \text{ MeV/gm/cm}^2) \times 30 \text{ mg/cm}^2$	17 keV
Overall Resolution		235 keV

However, the dominant resolution contribution comes from the primary beam and only a dispersed beam can reduce this value significantly. The resolution as a function of target mass number is shown in Figure 80. The sharp rise at small mass is due to angular resolution. It is seen that over most of the mass range the resolution is dominated by the resolution of the primary beam.

E.4 Planned Evolution of the Hypernuclear Physics Program at CEBAF

We propose to initiate a series of high resolution measurements of electroproduced hypernuclear structure. As previously emphasized, electroproduction will excite both natural and unnatural parity states. Thus, with sufficient resolution, a direct measurement of the spin dependent level structure of p shell hypernuclei can be obtained. We propose to undertake this program in a series of steps, leading to a high resolution instrument capable of resolving level splitting of the order of a 100 keV or so. We believe from the spectrometer studies described above, that such an instrument coupled with a dispersed beam is technically possible, and we are committed its development.

As the first phase of this work we will investigate the characteristics of the electron tagging spectrometer. This would encompass the modification of the Enge splitpole magnet now at the University of Illinois to improve its momentum acceptance. In addition, we will secure a dipole for placement at zero degrees in order to separate kaons and electrons, and build a detector package for the electron spectrometer. We will then investigate the response of this device in the electron beam in Hall C. Rates, backgrounds, resolutions, and

Figure 80: System resolution as a function of target mass.

target cooling will be investigated. We anticipate beams of no more than 10^{13} electron/sec on target.

The second phase will consist of coupling the electron spectrometer with the SOS spectrometer to investigate kaon production and electron-kaon coincidence rates. It is anticipated that the resolution of the hadron arm would be about 10^{-3} which would result in missing mass resolutions of 1 to 2 MeV. These resolutions would be sufficient to measure rates, and test instrumentation, but not sufficient to measure level splitting. The third phase would be the implementation of a high resolution hadron spectrometer coupled with the electron spectrometer in a way to obtain resolutions on the order of 100 keV. This would require a dispersed electron beam on target and perhaps a dispersion matched system. Work on the design of such an instrument is in progress and would continue during the first two phases.

F The Symmetric Toroidal Array Spectrometer (STAR)

Our extensive experience with single-arm electron scattering has demonstrated the value of isolating the two electromagnetic response functions (longitudinal and transverse) that are accessible in conventional (e,e') measurements. In coincident electron scattering from unpolarized targets three additional responses involving the interference of transverse and longitudinal polarization states can be accessed. The measurement of all five responses permits the complete reconstruction of the charge and current distributions of the system under study. The superb quality, high intensity, cw beam of CEBAF provides an excellent opportunity to use this approach to explore the structure of fundamental systems such as the nucleon, ^2H , ^3H , ^3He , and ^4He with unprecedented precision. Out-of-plane detection capability is required to isolate the five response functions.

The symmetric toroidal array spectrometer (STAR) has been designed to support a program of this physics at CEBAF. It will provide for the simultaneous detection of hadrons, in coincidence with electrons detected with the HMS, at eight azimuthal angles located symmetrically around the momentum transfer vector. Systematic errors in the measurement of the small azimuthal asymmetries that permit the extraction of the response functions are minimized by this approach.

STAR is also well-suited for other programs of high interest to the CEBAF community. Its large solid angle and multi-hadron detection capability will permit the exploration of short range correlations in nuclear systems through the $(e,e'2p)$ reaction. Its symmetry will facilitate recoil polarimetry experiments; for example the charge form factor of the neutron can be measured by using the $d(\vec{e},e'\vec{n})$ reaction and detecting the polarization of the neutron by a second scattering, $H(n,p)$, with STAR serving as the proton detector.

STAR can also serve as a large solid angle electron spectrometer at forward or backward scattering angles by orienting the device along (parallel or anti-parallel to) the beam direction. At large backward scattering angles transverse form factors of nuclear systems (eg., $F_M(Q^2)$ for ^3He) can be studied at very large momentum transfers. At forward scattering angles STAR can be used for measuring parity violation in polarized electron scattering; its azimuthal symmetry is essential for limiting systematic errors in experiments of this type.

The STAR collaboration is planning to seek funding for this spectrometer primarily through the National Science Foundation. As a consequence, this report does not include detailed budget information for the STAR. It is presented here to document its impact on the scientific program planned for Hall C, and on the design of the HMS and the hall itself. The STAR will be subjected to TAP and PAC review at CEBAF prior to the submission of a formal proposal for its funding and construction.

F.1 Physics Program Overview

The desirability of an out-of-plane detection capability at CEBAF has been discussed repeatedly. Without this capability, the full potential of electron scattering coincidence measurements is severely restricted. Out-of-plane detection allows the complete separation of all five of the nuclear response functions that are accessible with polarized electron beams. Numerous calculations indicate that different aspects of nuclear phenomena manifest themselves most clearly in the isolated responses. The most convincing demonstration of the value of isolated responses is provided by single-arm measurements that have separated the longitudinal-transverse responses using the Rosenbluth technique. There is a precise analogy between Rosenbluth separations in single arm electron scattering, and out-of-plane measurements in coincident electron scattering. The report of the task force on out-of-plane experiments at CEBAF contained in RPAC-III [Gr88] is particularly informative, and includes discussions of both the physics of interest and the dynamic ranges that will be required for the important kinematic variables.

Despite the unanimity of opinion on the desirability of an out-of-plane detection facility, this capability is not present in the first complement of equipment proposed for Halls A and C. As is the case for all 4π detectors, low luminosity ($L \leq 10^{34} \text{ cm}^{-2}\text{s}^{-1}$) out-of-plane measurements will be possible with the CLAS in Hall B. The STAR is designed to provide an optimal instrument for a high luminosity ($L \approx 10^{37} \text{ cm}^{-2}\text{s}^{-1}$), medium resolution, out-of-plane electron scattering program.

As the design studies of the STAR were undertaken, it became clear that this spectrometer would also serve for other programs of great interest to the nuclear physics community, including: studies of the electro-weak interaction through measurements of parity violation; investigations of multi-nucleon ejection, such as $(e, e'2N)$; recoil polarization measurements, such as $d(\vec{e}, e'\vec{n})$; and large solid angle (e, e') measurements at backward scattering angles.

In the remainder of this section we review each of the potential research programs in turn. The discussion presented for the physics programs envisaged for the STAR is neither complete nor exhaustive. Rather, it is meant to provide a summary of progress towards defining the first generation of experiments that can be pursued using this unique spectrometer. As the design options narrow and the capabilities of the STAR become better understood, priorities will emerge in the physics program. Many more details of the experiments discussed in this section can be found in the appendices to the STAR progress report [ST89].

F.1.a STAR's Out-of-plane Program

The Nucleon

Experimental investigations of the nucleon will be a centerpiece of the research program of STAR. Out-of-plane detection in a high luminosity environment, and, eventually, the use of polarized targets and/or the measurement of recoil nucleon polarization will be required for the study of the nucleon with the electromagnetic probe, because the overlapping nature of the resonances in the excitation spectrum of the nucleon makes the analysis of simpler experiments problematic. The design of STAR is compatible with the use of extended polarized targets, and the axial arrangement of the eight spectrometer gaps offers an optimal configuration for the implementation of focal plane polarimeters. These features make STAR an ideal spectrometer system for the study of the nucleon, and provide a clear path of evolution from the first-generation experiments discussed here.

The program planned [Al88,ST89] on the nucleon is an extensive one. It includes: the careful study (isolation of all five responses) of $H(e, e'\pi^0)$ at threshold; tests of the validity of soft pion theorems; and an investigation of how chiral symmetry is broken. Electroproduction data of sufficient accuracy to shed light on these issues are not available at present. The recent photoproduction results from Saclay [Ma86] and Mainz [Be89c] are impressive, and indicate the wealth of information that can be accessed with STAR.

The detailed study of nucleon resonances forms another important aspect of the STAR program. We intend to focus on a few selected resonances using out-of-plane detection and polarized beams (also polarized targets and recoil polarization whenever count rate considerations permit) to study their responses as a function of the momentum transfer. The most obvious candidates are the $P_{33}(1232)$, the $P_{11}(1440)$ and the $S_{11}(1535)$. These resonances are the least difficult to isolate; the first two because of their favorable location in the excitation spectrum, and the $S_{11}(1535)$ because of the distinctive η decay by which it can be tagged. The good missing mass reconstruction offered by STAR (a few MeV at typical CEBAF energies) is an important advantage for resonance studies.

Another exciting, but technically very demanding part of the planned program concerns the $(e, e'K)$ reaction. The physics motivation of this experiment focuses on the dynamics of strange quark electroproduction and on strange hyperon spectroscopy. The importance of the issue of the role of strangeness in the nucleon makes the study of this reaction particularly attractive.

Few Nucleon Systems

One of the basic goals of nuclear physics is the exact description of finite nuclei in terms of the fundamental ingredients of a given theoretical approach, traditionally nucleons and mesons, and more recently quarks and gluons. In general, drastic approximations must be

made to solve the nuclear many-body problem. In the few-nucleon systems the situation is easier to control. For the $A = 2$ and $A = 3$ few-nucleon systems exact solutions are available in a non-relativistic framework. It is for this reason that electromagnetic experiments in this area have had such an impact on the field; their comparison with theoretical calculations allows direct and unambiguous conclusions about the shortcomings of a given microscopic approach. However, the experimental situation still leaves much to be desired. For example, separated longitudinal and transverse responses in (e, e') and $(e, e'p)$ are available only for low momentum transfers ($q \leq 550 \text{ MeV}/c$); most of this work has appeared only during the last three years. This situation is largely due to the lack of high energy cw electron accelerators and appropriate instrumentation. An extensive program in few-nucleon systems provides an important scientific justification for both CEBAF and the STAR.

The $d(\vec{e}, e'p)$ reaction is particularly interesting since it has been explored extensively by theorists. A consistent picture has emerged for low momentum transfers ($\leq 15 \text{ fm}^{-2}$). It is representative of the physics issues that can be addressed by isolating the various responses for few-body systems. As an example, we show in Figure 81 the five structure functions of the deuteron as calculated by Arenhövel [Ar87] at $Q^2 = -0.34 \text{ GeV}^2$. He found that the transverse and the transverse-transverse responses are particularly sensitive to the contribution of meson exchange currents and to the admixture of N^* and Δ in the deuteron wavefunction, while the longitudinal and transverse-longitudinal interference exhibit a high sensitivity to the choice of wavefunctions, and therefore provide an excellent testing ground for microscopic theories.

F.1.b $(e, e'2N)$ measurements

Despite the profound significance of two-body densities in nuclear physics, there is very little experimental information about them. The theoretical effort on two-body densities over the last three decades has focused largely on the reproduction of the saturation property of nuclear matter. The experimental evidence incorporated into these calculations has been derived largely from single-arm elastic electron scattering.

Recently, a number of precise experiments have produced results that are particularly difficult to explain within the independent particle model. Present theoretical work attributes this difficulty to short-range correlations, which are not accounted for in the independent particle model. Substantial efforts are now underway to calculate the effects of two-body correlations in finite nuclei microscopically and to investigate how they are manifested in (e, e') and $(e, e'p)$ reactions [Be89c]. As a result, predictions about $(e, e'2N)$ constrained by the available (e, e') and $(e, e'p)$ data, are beginning to emerge.

The $(e, e'2N)$ reaction offers a clear advantage for the study of short-range correlations in nuclei relative to other techniques, such as the measurement of sum rules or the study of the separated $(e, e'p)$ response functions in carefully-chosen regions of the (q, ω) plane, because it maps out the dynamical short range correlation, providing a direct test

Figure 81: The five structure functions for the $d(\vec{e}, e'p)$ reaction corresponding to quasi-free kinematics ($E_i=4 \text{ GeV}$, $\theta_e=9^\circ$, and $Q^2=-0.34 \text{ GeV}^2$). The effects of non-nucleonic degrees of freedom in the various functions are shown explicitly. The calculations were provided by Arenhövel.

of the observable of interest. It is a particularly hard experiment, which is limited primarily by the low cross sections that characterize exclusive processes. Experiments of this type have not been mounted to date due to the limitations of available electron beams and detections systems. Exploratory studies have been performed at Saclay and are now underway NIKHEF. The large solid angle of the STAR spectrometer and its ability to perform simultaneous measurements at eight different angles will make it a useful tool for mounting an $(e, e'2N)$ program at CEBAF. Such a program will benefit substantially if the STAR is augmented by a simple, large solid angle neutron detectors (for $(e, e'pn)$ studies). These auxiliary detectors would be placed in the backward scattering angle region, while the STAR spectrometer would be placed along $\vec{q}$. ^3He is widely recognized as the target of choice for initiating this program. Measurements on ^3He will be followed by ^4He and heavier systems.

F.1.c The STAR as a recoil Polarimeter

The large solid angle of the STAR, together with its azimuthal symmetry make it an ideal recoil polarimeter. It can be used to analyze the polarization of the emerging reaction product through a second scattering from a target placed at the object point of STAR. An example of the use of STAR in this mode would be a measurement of G_n^E through the $d(\vec{e}, e'\vec{n})$ reaction. The physics interest in the precise determination of G_n^E is well-recognized, and the technique of accessing it through a $d(\vec{e}, e'n)$ measurement has been discussed repeatedly in the literature and at CEBAF.

F.1.d Parity Measurements

Measurements of parity violation in polarized electron scattering can be used to determine the neutral weak current of nuclear targets. The structure of these currents has two parts: a set of general coupling constants; and some information about the structure of the target. In the electro-weak model of Glashow, Salam and Weinberg [Am87], the coupling constants depend only on one parameter, $\sin^2\theta_W$. This quantity is well-determined by measurements of the W and Z boson masses within the limit imposed by small electro-weak radiative corrections. Testing the electro-weak model in a different environment, for example, in the Z coupling to quarks in electron-nucleus scattering, would provide important additional information. The structure information contained in the neutral weak current itself is also of interest. If the standard model is assumed to be correct, there is a precisely defined relationship between the electromagnetic and neutral weak currents (i.e. the set of coupling constants is defined). In particular the same structure information enters each current in different ways. For example, each of the electromagnetic and weak neutral currents of the nuclear target may be broken up into components according to the flavor of the quark that is coupled to the Z [Mc89, Be89, Be89a, Ca89]. These components may be written as individual quark flavor components of the ordinary electromagnetic form factors. More specifically, it is possible to measure a new quantity for the proton using parity-violating

electron scattering [Mc89,Be89a], the flavor singlet contribution to the usual Pauli (F_2) form factor. This form factor is sensitive to the strange quark component of F_2 . The strange quark component of F_2 can be extracted [Be89] with a model of the relation between the proton and the neutron flavor structure, a combination of the proton and neutron electromagnetic F_2 and the flavor singlet F_2 . This quantity is of interest in light of measurements by the EMC group at CERN (of the Ellis- Jaffe sum rule [As88]) and in light of the so-called pion-nucleon sigma term [Ja88], both of which suggest a significant strange quark contribution to some proton observables. It might be possible to extend a measurement of the flavor singlet F_2 planned for MIT-Bates [Be89a] and/or to measure or place limits on the corresponding F_1 form factor [Ca89].

Parity-violation measurements at CEBAF energies will necessarily be done with the electrons scattered at relatively small angles since the figure of merit for these experiments declines rapidly for momentum transfers in excess of $\sim 0.5 \text{ GeV}^2$ (corresponding to 40° at 1 GeV and 10° at 4 GeV). The STAR would be deployed with its axis at 0° for such measurements (i.e. with the beam passing through the center of the instrument). This arrangement will likely provide the largest $\mathcal{L}\Delta\Omega$ of any instrument at CEBAF in the forward direction, with the possible exception of the array of simple counters proposed for use in connection with initial parity experiments on the proton [Ca89]. The STAR has the advantages of considerable magnetic "shielding" and hardware momentum resolution (see Section F.2) as compared to these counters. It also retains the important attribute of symmetry about the beam axis. Therefore, for any parity experiment in which resolution on the scale of nuclear level spacings is important, the STAR will be by far the best of the instruments currently under consideration for CEBAF.

If there are problems with either of the initial parity-violation measurements proposed using counters [Ca89], it is possible that both could be done with the STAR by sacrificing solid angle. The measurements proposed are for $Q^2 = 0.1 \text{ GeV}^2$ ($\theta = 10^\circ$ at 2 GeV) and $Q^2 = 0.02 \text{ GeV}^2$ ($\theta = 4^\circ$ at 2 GeV), both on the proton. The first would match the backward angle measurement at the same Q^2 proposed at MIT-Bates [Be89a]. The second would attempt to measure in a kinematic region where all hadronic form factors are negligibly different from their static values. In this case the measured asymmetry would be approximately 10^{-7} and the desired uncertainty 10^{-8} . A very thorough understanding of the STAR would be required before such an experiment could be undertaken.

One of the main issues for any parity experiment using the STAR, and one which is largely distinct from questions of the systematic uncertainties, is simply the ratio of signal-to-background. For large asymmetries ($\sim 10^{-5}$) it might be possible to make 5% measurements by counting individual events at 10 MHz rates, thereby permitting significant improvements in the signal-to-background ratio. However, for smaller asymmetries, an integrating detector would be required and any traceback or "slow" discrimination would be practically impossible. It will be important to understand background rates with the STAR in the 0° orientation at an early date.

F.1.e Backward angle (e, e') measurements

The transverse cross section in inclusive electron scattering is highly sensitive to the structure of the currents and magnetism in the target under study. The isolation of this small part of the inclusive electron scattering cross section requires measurements at backward angles where the cross section becomes very small. A characteristic example is the deuteron breakup reaction at threshold [Ar87], where typical cross sections are as low as 10^{-40} cm^2 (a value characteristic of neutrino cross sections). By placing the axis of a toroidal spectrometer such as the STAR along the beam direction upstream of the target, one can exploit the azimuthal symmetry of the instrument to obtain increased solid angle ($\sim 100 \text{ msr}$) and thus provide access to this important physics.

F.2 Design Considerations for the STAR

There are many ways to mount out-of-plane measurements, and a number of them have been examined in some detail. These studies have identified three rather fundamental considerations that can help to define an acceptable range of spectrometer configurations for continued investigation [La89]. The first consideration is that simultaneous, azimuthally-symmetric, out-of-plane observations are very desirable from the point of view of both systematic error reduction and the efficient separation of nuclear responses. The control of systematic errors has been recognized as a potentially serious problem for out-of-plane experiments in general [RPAC3].

Second, at higher energies it becomes progressively more important to be able to reach small opening angles, θ_{pq} . This implies that the individual sectors that make up the spectrometer must be very compact. Stand-alone magnetic elements typically cannot be configured symmetrically at adequately small θ_{pq} for beam energies above 1 GeV.

The third fundamental consideration derives from certain attractive features associated with dipole fields. Because measurements on light nuclei and those requiring polarized targets will form an integral part of the out-of-plane program, it is important to assess the relative merits of possible spectrometer designs with respect to extended targets. Expressions for the uncertainties in the momentum and angular variables that are important for the determination of the nuclear response functions can be written in terms of a particular spectrometer design's first-order transport matrix elements, and the uncertainties in the interaction point that arise from having an extended target. For a first-order dipole magnet there are, in general, fewer terms in these expressions than are found for non-dipole configurations such as the $B \sim 1/R$ fields of the wedge shaped segments of a superconducting toroid. In addition, for a device of fixed size, dipole fields can have a larger average $\int B \cdot dl$ over the acceptance, and hence a larger range of maximum momenta, than can be achieved with other configurations. This has a significant impact on the important question of compactness.

Taken together, these three considerations make a strong case in favor of an iron-dominated, multi-gap toroid spectrometer as the best device for out-of-plane measurements at high energies. This is the design option on which we have concentrated most of our efforts.

F.3 Design Goals

The development and optimization of a specific conceptual design for the STAR spectrometer depends critically on the scope of the physics program that will be addressed. It is clear that a large multi-gap toroid would have a variety of uses in addition to the out-of-plane measurements for which it is particularly suited. Among the many potential applications that have been explored in letters of intent [Al88,Al88a,Ca89] and at the May 1989 collaboration meeting [SC89] are: stand-alone 180° electron scattering and parity violation experiments; programs of $(e, e'p)$ and $(e, e'2N)$ measurements done in coincidence with the HMS electron spectrometer; pseudoscalar meson electroproduction; and the use of the STAR as a recoil polarimeter.

We have attempted to tailor the STAR design to match the widest possible range of experimental physics. A careful review of both the proposed measurements and the recommendations [RPAC3] in the Report of the Task Force on Out-of-Plane Experiments at CEBAF results in the list of performance goals for an optimal STAR spectrometer presented in Table 43. Several physical factors place bounds on how closely a realizable toroidal spectrometer can approach the rather ambitious design goals set for accessibility to θ_q and θ_{pq} . The design peak magnetic field, B_0 , and the targeted maximum momentum establish a scale for the size of the device. This size is reflected in a "bulk-limitation" on the minimum value that the angle θ_q can achieve without beam-line interference. Because the opening angle is changed by altering the distance from the device to the target position, the bulk-limit also depends on θ_{pq} . Furthermore, both the size of the spectrometer and the room available in the experimental hall combine to put a "wall-limit" on the minimum possible value of θ_{pq} . This limit also generally depends on θ_q . The height of the beam line above the hall floor has an additional impact on the optical configuration of the toroid. Practically speaking, only inwardly-focusing designs, for which the exiting trajectories cross the symmetry axis of the toroid, are possible. Outward focus, with rays bending away from the central axis, would result in a device with a radial extent far too large to be accommodated reasonably.

All of these considerations argue for a spectrometer that is as small as is reasonably possible. This condition translates directly into a requirement for the highest possible design B_0 consistent with constraints on field flatness and reproducibility. Unfortunately, the cost of achieving high fields tends to increase much more rapidly than linearly with B_0 , and in fact quickly comes to dominate the overall cost of the device. For this reason it is important to understand how the performance characteristics of the STAR trade off against the design maximum field. The discussion in the following section will show that

Table 43: Design Goals for the STAR Spectrometer.

Angular acceptance (solid angle Ω)	as large as possible
Nominal momentum bite	$\Delta p/p \approx 15\%$
Range of in-plane angles	$0^\circ < \theta_q < 180^\circ$
Range of opening angles about $\vec{q}$	$0^\circ < \theta_{pq} \leq 50^\circ$
Range of azimuthal angles about $\vec{q}$	$0^\circ \leq \phi_{pq} \leq 360^\circ$
Maximum central momentum	$p_{\max} \approx 1.5 \text{ GeV}/c$ for small θ_{pq} $p_{\max} \approx 3.0 \text{ GeV}/c$ for large θ_{pq}
Extended target resolution (in coincidence w/ HMS)	momentum: $\delta\delta_0 \approx 10^{-3}$ opening angle: $\delta\theta_0 \approx 10^{-3}$ azimuthal angle: $\delta\phi_0 \approx 10^{-3}$
Extended target resolution (stand-alone mode)	momentum: $\delta\delta_0 \approx 5 \times 10^{-3}$
The ability to accommodate:	axial electron beams; and a focal plane polarimeter

most of the desirable optical characteristics of the present STAR design tend to be rather weakly dependent on B_0 , and that the main consequences of lower fields are reductions in the solid angle and in the accessible ranges of θ_q and θ_{pq} .

F.4 The STAR Conceptual Design

We have pursued a conceptual design study for a Symmetric Toroidal ARray (STAR) spectrometer that addresses the many design considerations outlined above. The instrument has eight azimuthally-symmetric sectors, each consists of an inward-bending, singly-focusing dipole having a gap width of 40 cm. The nominal maximum central momentum varies monotonically from 3.0 GeV/c at an opening angle, θ_{pq} , of 5° , to 1.5 GeV/c at $\theta_{pq} = 50^\circ$. The condition that the maximum central momentum follow that behavior with opening angle was taken as a fixed design specification for both versions of the STAR; it provides a good match to the requirements of the physics program. The momentum acceptance is 15% of the central value. The base or reference design, STAR-20, assumes a 20 kG maximum magnetic field. A modification of this design, STAR-15, with maximum fields of 15 kG, has been developed in parallel with the reference design. Figure 82 presents sectional layouts and a table summarizing the gross physical characteristics of the two design options. In both cases, central trajectories are shown for target positions corresponding to opening angles between 5 and 50 degrees. For each sector of each spectrometer, all of these central rays are constrained to pass through a common point, as is required by the

Characteristic	STAR-20	STAR-15
B-max (kG)	20	15
Gap width (cm)	40	40
# of gaps	8	8
# of coils	16 (8 radial)	8
$\delta p/p$ (%)	15	15
NI (MA-turns)	5.5	3.8
Stored energy (MJ)	~ 53	~ 32
Coil length (m)	~ 12.9	~ 13.8
Pole area (m ²)	~ 9.7	~ 11.3
Total weight (tons)	~ 720	~ 903
Max o.s. radius (m)	3.3	3.5
Max o.s. length (m)	5.0	5.7
Overall length (m)	9.0	10.5

Figure 82: Sectional plans for the two STAR options under consideration. Central trajectories corresponding to opening angles between 5° and 50° are shown. The shaded area indicates additional iron required by STAR-15. The principal characteristics of the two designs are listed in the Table.

Table 44: A Summary of Important Characteristics of the STAR-15 and STAR-20 Spectrometer Configurations. The STAR-15 and STAR-20 are Both Iron-dominated Toroids with Superconducting Coils Having Eight Azimuthally-symmetric 40-cm Wide Dipole Gaps with Maximum Fields of 1.5 and 2.0 T, Respectively. The Momentum Acceptance is $\Delta p/p = 15\%$.

θ_{pq} (deg)	Target Distance (m)	$p_{\max}$ (GeV/c)		Ω_{tot} (msr) 8 gaps		Optical Length (m)		$ D/M $	
		STAR	STAR	STAR	STAR	STAR	STAR	STAR	STAR
		15	20	15	20	15	20	15	20
5	16.0	2.99	3.07	6.9	7.4	23.6	22.8	7.2	8.7
10	7.9	2.50	2.65	24	26	16.1	15.2	4.8	5.7
15	5.2	2.18	2.35	41	46	13.8	12.8	4.2	4.8
20	3.9	1.98	2.15	56	65	12.7	11.7	4.1	4.6
30	2.4	1.72	1.89	79	97	11.5	10.4	4.3	4.7
40	1.7	1.58	1.73	94	125	10.9	9.7	5.0	5.2
50	1.2	1.50	1.64	106	153	10.6	9.2	5.8	6.0

convergent optics condition. The overall length of STAR-15 is about 1.5 m greater than that for STAR-20, and it requires a somewhat larger pole-face area as indicated by the shading in the lower half of Figure 82. Both versions require a beam height above the floor of at least 4 m.

For reference, short summaries of the important ion optical characteristics of the two versions of the STAR are shown in Table 44. A more detailed discussion can be found in [La89]. The two design options have very similar distributions of the $(x | x)$ matrix element with respect to opening angle, corresponding to magnifications that are always less than one. Because of the rather large bend angles, α , the dispersions, $(x | \delta)$, are also reasonably large. As a result, the resolving power, $|D/M|$, for both of these instruments is quite good, falling between 4 and 8 depending on the opening angle.

The range of angular acceptances has been calculated in first order for the pole-gap width of 40 cm. The very large acceptances that are possible with the STAR are among the features that make it particularly attractive. However, the solid angle distribution is one of the more significant ways in which the STAR-15 and STAR-20 versions differ from each other. Although the values of Ω_{tot} are nearly identical at small opening angles, the total acceptance of the STAR-15 option becomes almost a third smaller than that for STAR-20 by the time θ_{pq} reaches 50 degrees. The impact that this difference might have on the physics program needs careful evaluation.

Both the distance from the target position to the front of the spectrometer, and the total optical length from target to focus are shown in the tables. Path lengths are

Figure 83: Variation in the location of the focal surface of the STAR about the convergence point as the opening angle changes between 5 and 50 degrees.

generally small enough so that either version of the spectrometer would be practical for applications involving short-lived particles like pions. As a point of reference, the short-orbit spectrometer (SOS), which has been optimized for these applications, has a nominal optical length of 7.5 m.

The physical extent of the focal surface has been estimated using a 40 cm pole-gap width and a 15% momentum bite; the characteristic dimensions in the x (dispersion) and y (transverse) directions are on the order of a meter [La89]. As the opening angle is changed, the actual position of the optical focal surface moves about the convergence point in the manner indicated in Figure 83. An appropriate detection package will contain a number of wire planes that are distributed in a volume surrounding the convergence point so as to permit trajectory reconstruction over the entire acceptance and range of opening angles. The geometric constraints on the volume that is actually available for detectors behind the symmetric toroidal array have been investigated in detail. In order to help clarify the nature of the potential interference problems that can arise between adjacent sectors of the spectrometer, a perspective view of the STAR-20 configuration is given in Figure 84. For the STAR-20 option, the available detection volume is very well matched to the spectrometer's acceptance. For STAR-15, about 10% of the nominal ϕ_y acceptance could be lost because of space constraints.

A number of possible coil configurations for the STAR have been explored with the 2-D magnetostatics code POISSON [La89]. It is clear that 3D field modeling and investigations into the optimization of the coil configuration for the STAR are very high priorities.

Figure 84: Perspective view of the STAR-sector median-planes showing 30° opening angle central rays, and the detector volumes behind the spectrometer.

We note at this point that a cluster of eight spectrometers can become an ideal device for measuring polarization structure functions if it can be equipped with focal plane recoil-polarimeters. In general, the proton can have polarization components along all three axes, and the various kinematic terms that enter in combination with the polarization structure functions depend on the trigonometric arguments ϕ_{pq} and $2\phi_{pq}$. A recoil spectrometer for protons can only measure two of the polarization components, excluding the component in the direction of the proton's flight. However, when a proton is bent by the magnetic field of the spectrometer, the two components in the bend plane become mixed because of precession. Since the polarization axes are defined by the direction of the scattered proton and that of $\vec{q}$, the orientation of these axes in the lab depends on the azimuthal location of the proton spectrometer about $\vec{q}$. Any attempt to decompose the structure functions of a particular polarization component by moving a single spectrometer to various azimuthal angles would be frustrated unless the spectrometer also could be rotated to stay fixed with respect to the polarization axes.

A fundamental advantage of the STAR is that the bend plane of each of the eight sectors is always in the plane defined by the proton and $\vec{q}$. Thus, the polarization defined perpendicular to this plane, P_y , can be measured independently with four of the sectors. In addition, the P_x , and P_z components will be mixed in the same ratio for all eight sectors of the spectrometer. This will allow the extraction of mixed polarization structure- functions from the ϕ_{pq} , the $2\phi_{pq}$, and the helicity dependent terms. It will be possible to compare these mixed polarization functions directly with theoretical predictions.

The optical simplicity of a STAR sector, consisting as it does of a single dipole, makes it mandatory that higher-order aberrations be corrected with software. This approach is reasonable in general if the aberration error sensitivity is less than the respective first-order sensitivity. The radius of curvature, R_1 , of the entrance edge is the only design parameter that is not fixed by first-order constraints, and consequently the only hardware degree of freedom that can be used to modify higher-order terms.

Second-order transport has been used to estimate upper bounds for the contributions of aberration terms to the momentum and angular resolution uncertainties, and to investigate the dependence of the most important non-zero second-order matrix elements on R_1 . It can be shown [La89] that for a momentum resolution on the order of 10^{-3} , it is necessary that the quantity $[(x | \theta\delta)/(x | \delta)^2]x_{f_{\max}}$ times $\Delta\theta_0$ be kept $< 0.1\%$. For the STAR-20, this quantity varies from 5×10^{-2} for $\theta_{pq} = 5^\circ$ to 1×10^{-2} for $\theta_{pq} = 60^\circ$, and is almost independent of $1/R_1$ for values of θ_{pq} between 5 and 60 degrees. It is clear that the software correction of chromatic aberrations should not be a problem if the uncertainty $\Delta\theta_0$ can be kept to the order of milliradians

Similar estimates of the impact of geometric aberrations can be made [La89]. Again we find that, as long as the angular uncertainties can be kept at or below the few milliradian level, no problem with software corrections would be anticipated. This is particularly true if the entrance curvature R_1 is chosen to be in the neighborhood of - 5 m.

We have seen that the optical characteristics of the two versions of the STAR are quite

Figure 85: Limitations on possible opening angles accessible to the STAR arising from the size of the experimental hall.

similar, and that, as has been indicated above, the important differences in performance are related primarily to differences in physical size. The angular restrictions on θ_{pq} due to the area available in the experimental hall (the wall-limit), and on θ_q due to the diameter of the toroid itself (bulk-limit) can be estimated for the STAR-20 and -15 options. The results are summarized in Figure 85. Spectrometer overall lengths were taken from the Table in Figure 82 with an additional 0.5 m allowed for backside shielding. Intersections with the dimensioned horizontal lines indicate minimum permitted opening angles θ_{pq} . This minimum depends strongly on θ_q in Hall C.

It is important to note that very small opening angles, which cannot be reached by the STAR in its standard orientation, can be achieved by using the large angular acceptance of a single dipole sector of the STAR in the small-angle configuration illustrated in Figure 86. Values of θ_{pq} between 0 and a few degrees are easily attained in this way.

The bulk limit on θ_q can be reduced dramatically if the main electron beam is permitted to penetrate one of the in-plane pole-gaps of the STAR. This is illustrated in Figure 87. It is possible to conceive of a removable superconducting conduit, capable of locally excluding the magnetic field of the dipole gap, that could be placed along the electron beam line. When in place, this invasive transport line would interfere only with symmetric in-plane measurements; all of the out-of-plane capability of the STAR would be retained.

Figure 86: In the small-angle configuration, the large acceptance of one sector of the STAR is used to make measurements at opening angles between 0° and a few degrees.

Figure 87: If invasive transport of the main electron beam is considered, a substantial improvement in the range of accessible scattering angles is possible.

Figure 88: Summary of possible angular configurations for the STAR.

A summary of all of the restrictions that limit the range of angles that are accessible to the STAR is presented in Figure 88. It is clear that the invasive bulk limit represents a substantial improvement over the non-invasive limit, particularly for larger θ_{pq} .

F.5 Anticipated Performance

A complete evaluation of the STAR conceptual design will require a major effort devoted to the development of Monte Carlo simulations of particular experiments that are representative of the broad range of applications for the spectrometer. This work is underway, and progress has been made toward demonstrating the feasibility of the fundamental asymmetry separation techniques.

In this section, we will concentrate on a number of first-order, analytical studies and simple Monte-Carlo investigations that provide useful information about how closely the STAR spectrometer is likely to meet the design goals listed in Section F.3 above. In particular, we will look at extended target resolution, magnetic field uniformity requirements,

sources of systematic errors, and counting rate limitations on luminosity.

F.5.a Extended Targets

The performance of the STAR spectrometer with extended scattering targets is a particularly important issue because of the prominent part that studies involving few-body nuclei and polarized targets will play in the physics program. The STAR's ability to accommodate extended targets is very dependent on the details of particular experimental geometries. Two fundamentally different arrangements are possible. In the first (geometry I), the STAR is used alone, with the main electron beam transported along its symmetry axis. This configuration is typical of both small-angle and large-angle (near 180°) single-arm electron scattering experiments, and of the proposed parity measurements. This geometry also puts the greatest demand on the optics of the STAR. In the second arrangement (geometry II), the STAR will be used in coincidence with the HMS, and the two spectrometers will typically be deployed at different scattering angles on opposite sides of the beam line.

The parameters δ_o , θ_o , and ϕ_o describing the momentum and direction of the emitted particle are critical for the determination of the nuclear response function. Expressions for the uncertainties in δ_o , θ_o , and ϕ_o can be derived [La89] in terms of the STAR's first-order transport matrix and the uncertainties in x_o , y_o , and z_o that are associated with the origin of the event within the extended target. Uncertainties in the determination of positions and angles at the focal plane also enter. For a dipole magnet, $(x | y)$, $(\theta | y)$, and $(\phi | y)$ are zero. The STAR optics allow an independent extraction of y_o from y_f , but in general, it is necessary to depend on the small diameter of the electron beam and the known length of the target to set limits on x_o and z_o . The determination (vertex reconstruction) of the transverse coordinate, $y_{e'}$, by the second spectrometer that is employed for coincidence measurements in geometry II, also provides an important additional cut on x_o and z_o that is not available in geometry I. These considerations are illustrated in Figure 89.

In the course of the development of the present STAR conceptual design, the ratios and reciprocals of the transport matrix elements that appear in the uncertainty expressions for δ_o , θ_o , and ϕ_o were explicitly minimized. These expressions, together with estimates of the beam quality ($D < 0.1$ mm), vertex reconstruction capability of the HMS ($y_{e'} \approx 1$ mm), and focal-plane position resolution (≈ 0.15 mm), can be used to explore the uncertainties inherent in measurements of δ_o , θ_o , and ϕ_o for various specific experimental configurations.

As would be expected, the extended target resolutions are generally better in the coincidence mode, geometry II, than in the single-arm mode of geometry I. In geometry II, the sectors of the STAR are not symmetric relative to the target axis, which results in an azimuthal dependence of the experimental-resolution uncertainties. In the following, we will assume a target length of 10 cm, and consider a typical kinematic configurations taken from among the experimental reactions proposed for the STAR, a possible $d(e, e'p)$ experiment [Al88a]. The estimated uncertainties for a typical data point this experiment are shown in Figure 90. Here, as would be expected, the fact that the electron is scattered

Figure 89: Vertex reconstruction from the electron spectrometer, and the small diameter of the incident electron beam, put limits on the possible point of origin of a coincident event in the target.

Figure 90: An example of uncertainties in the momentum and angular variables arising from finite target size for the STAR when operated in coincidence with the HMS. Target length and spectrometer configuration as indicated.

EXTENDED TARGET UNCERTAINTIES STAR(20)
Theta-pq = 10/170 degrees

Figure 91: An example of uncertainties in the momentum and angular variables arising from finite target size for the STAR-20 spectrometer in its “stand-alone” configuration.

through a small angle gives a poorly-defined “cut” on the target. Even so, both $\Delta\delta_0$ and $\Delta\theta_0$ fall below the level of 10^{-3} , and $\Delta\phi_0 \leq 10^{-4}$. In another case of interest that has been examined carefully [La89], a measurement of the $N \rightarrow \Delta$ reaction at $Q^2 = 3 \text{ GeV}^2/c^2$, the electron is scattered through a larger angle, so the information provided by the HMS provides a significantly stronger constraint on the location of the scattering center. In this reaction the uncertainties were found [La89] to be of order 10^{-4} or less. In general, it appears that there will be no problem in meeting the geometry II design goals for extended target resolutions, even for disadvantageous cases where the HMS is placed at very forward scattering angles.

We next consider the stand-alone geometry I. Here the electron beam is axial, and the sectors of the STAR are disposed with azimuthal symmetry about the target. The experiments that will utilize this configuration, such as “180°” ($e, e'p$) [Al88a], and parity violation [Ca89], tend to require very small (or very large) scattering angles, and make rather modest resolution demands, typically on the order of $\sim 5 \times 10^{-3}$. The thin-target intrinsic resolution of the STAR in the axial orientation can be on the order of $\sim 5 \times 10^{-5}$, which is very good. This high intrinsic resolution is of particular value because both the calibration of the STAR and measurements of relative efficiencies among its eight sectors will be done in this symmetric configuration. Results for the geometry, $\theta_{pq} = 10^\circ$ (170°), with a 5 cm long target, are plotted in Figure 91. We see that the most sensitive resolutions rather rapidly move to the 10^{-3} level. Extending the target to 10 cm causes a further deterioration by a factor of two [La89]. If, in addition, θ_{pq} is opened to 15° (165°), another factor of two is lost. Even at this point, the momentum and opening (scattering) angle

Figure 92: Maximum allowed integral dipole field deviation as a function of opening angle central trajectory.

resolutions are about 6×10^{-3} . This degree of uncertainty is at the level of the stand-alone extended target design specification.

F.5.b An Estimate of the Required Field Uniformity

It is important to investigate the demands that the resolution requirements place on the reproducibility and uniformity of the magnetic fields of the spectrometer. This can be done in an approximate manner by determining the effects that changes in field strength have on the first order transport matrix elements of the system [Br70]. The design requirements, that $\Delta\delta_0, \Delta\theta_0$, and $\Delta\phi_0 \leq 10^{-3}$, puts an upper bound on permitted multipole variations [La89]. In Figure 92, the maximum allowed deviation in the dipole strength, $(\Delta B \Delta L) / \int B \cdot dl$, is plotted as a function of opening angle for the STAR spectrometer. We see that the uniformity requirement is never below the level of 10^{-3} , and tends to be even more relaxed for the smaller values of θ_{pg} .

The effects of errors in the quadrupole strengths that are introduced by the design pole-edge rotations have also been investigated. Figure 93 shows the maximum permitted uncertainty in the effective entrance and exit angles, $\Delta\beta_1$ and $\Delta\beta_2$, as a function of θ_{pg} . Both tolerances are on the order of 10 mr. Although these calculations are only first-order

Figure 93: Maximum allowed integral quadrupole field deviation expressed as permitted deviations in the effective entrance and exit edge-rotations relative to design values.

estimates, they indicate that it is unlikely that extreme measures will be required to achieve the necessary field quality in the STAR.

F.5.c Sources of Systematic Errors

At some level, each sector of the STAR can be thought of as an independent dipole spectrometer. Each is positioned with some inherent uncertainty relative to what can be thought of as an ideal symmetry axis. The symmetry axis itself can be defined with great accuracy because the actual center-line of the STAR is unobstructed over its full 10 m length. If the individual sectors were calibrated independently, the relative position-uncertainties would contribute to an overall systematic error in any asymmetry measurement. However, once the positions of the sectors are rigidly fixed by the support system, a simultaneous calibration of the array of spectrometers would greatly reduce any systematic errors associated with the mis-location of the individual elements. No new systematic errors of this sort would be introduced in any subsequent repositioning of the STAR during experimental use (subject, of course, to certain conditions on rigidity that will be discussed in the following paragraphs).

The inherent symmetry provides a number of possibilities for simultaneous calibration for the STAR sectors. For example, the STAR-axis can be very well positioned along the electron beam-line. This line itself can be established quite accurately because of the long drift distances involved in the beam's passage through the hall. Measurements of forward scattering from the $p(e, e'p)$ reaction could then provide both the relative efficiencies of the spectrometer segments at better than the 1% level (protons detected), and the opening angle calibrations to a few hundredths of a degree (electrons detected). The latter is

possible because of the very rapid drop in the inelastic electron cross section with increasing opening angle.

As a part of normal usage, the entire spectrometer will move both in an arc about the target position, and radially in the scattering plane. It is important to understand at what level the absolute positioning of the elements of the STAR, relative to the calibrated alignment axis, must be maintained during the course of changes in its orientation. It is clear that the ability to rotate the STAR about its symmetry axis would also be very desirable, and would introduce additional calibration possibilities.

The effect of undetected misalignments of a sector of the STAR on the uncertainties $\Delta\delta_0$, $\Delta\theta_0$, and $\Delta\phi_0$ can be estimated in first order with TRANSPORT. Translations and rotations of the dipole elements result in changes in the observed coordinates of a ray at the focal plane. These changes are then reflected in uncertainties in the extracted experimental parameters. Overall, we can conclude [La89] that the position tolerances that must be maintained on the elements of the STAR, through changes in orientation, are rather modest. They are on the order of 1 mr for rotations and a few mm for translations. A reasonably engineered supporting structure should be able to achieve these tolerances easily for a device with the tight geometry and inherent symmetry of the STAR.

We now return to the discussion of systematic errors introduced into asymmetry measurements because of alignment (pointing) uncertainties. For the moment we restrict ourselves to central trajectories. Questions related to finite acceptances will be examined below. The most important cumulative effect resulting from pointing errors in the beam direction, in the direction of the electron arm, and in the direction of the STAR center-line, is a displacement of the momentum transfer vector, $\vec{q}$, relative to the true symmetry-axis of the STAR. The beam and electron-arm pointing error contributions will be common to all methods of making asymmetry measurements. The STAR, however, exhibits distinct advantages over other out-of-plane spectrometer configurations in terms of the absolute alignment and relative calibration properties, as described at the beginning of this section. In addition, the symmetry of the STAR serves to minimize the sensitivity of certain asymmetries such as A_{TT} to the uncertainty in $\vec{q}$.

We have calculated the consequences of pointing uncertainties for several of the proposed asymmetry measurements, using the formalism developed in reference [La89] and the rather conservative assumptions that the beam direction can be established to 0.2 mr, the STAR axis to 0.4 mr, and the central rays to both the electron arm and the individual STAR-sectors to 0.9 mr. A typical result is presented in Figure 94, where the solid lines show calculations by Arenhövel [Ar87,Al88a] of A_{LT} and A_{TT} for the $d(e,e'p)$ reaction at 4 GeV and a momentum transfer of 20 fm⁻². The dashed lines in this figure indicate the degree of uncertainty in the determination of these asymmetries that arises from the above systematic pointing errors. We see that the sensitivity is not large in this case, except at the smallest opening angles. For this particular example, one would expect the interesting physics to be found just where the effect of pointing errors is least; at small angles, quasi-elastic processes tend to dominate. Similar results were found for this reaction at

Figure 94: An example of the uncertainties arising from pointing (alignment) errors in an asymmetry measurement of the $d(e, e'p)$ reaction using the STAR.

Table 45: The Effect of a Q -symmetric Acceptance Test on Rates for the $d(e, e'p)$ Reaction at $E_e = 4$ GeV Using a 0.5 gm/cm^2 LD₂ Target and a Beam Current of $10 \mu\text{A}$.

θ_{pq}^{cm} (deg.)	θ_{pq}^{lab} (deg.)	(Rates: counts /hour /sector)				Time for A_{TT} to 1% (hours)
		R_{TT}		R_{LT}		
		(naive)	(tested)	(naive)	(tested)	
30	13.2	165	66	330	300	38
50	22.2	198	79	396	356	32
70	31.5	137	55	274	246	45
90	41.3	90	36	180	162	69

30 fm^{-2} .

We have also investigated [La89] the effects of systematic pointing errors for the case of an $N \rightarrow \Delta$ measurement at 4 GeV with $q^2 = 28 \text{ fm}^{-2}$ [Al88]. The effect of systematic pointing errors was seen to be reasonably small, particularly in the case of A_{TT} , even though this experiment involves measurements at very small opening angles ($\theta_{pq} < 10^\circ$).

We now move on to the potentially more difficult question of systematic errors arising from the finite acceptances of the sectors of the STAR. The momentum transfer vector $\vec{q}$, for a particular event, is determined by the energies and directions of the incident electron beam and the inelastically-scattered coincident electron. The most naive approach to measuring experimental asymmetries would be to adjust the acceptance of the electron spectrometer so that the range of $\vec{q}$ -directions, $\Delta\Omega_q$, approximately matches the acceptance of a STAR sector. Events then could be summed for each sector, and asymmetries computed from the appropriate sums, differences, and ratios of these numbers. In fact, the results of this procedure would not be far wrong if the momentum acceptance were symmetric, and if there were no opening angle dependence to the coincident cross section. Realistically, there can be very strong θ_{pq} dependences, and large systematic errors can be introduced by such a simple analysis.

A far better approach is to use a q -symmetric acceptance test (the “cone test”) to select only those events that are appropriate for the formation of asymmetries. For an event to pass this test, it must be possible for other coincident hadrons, which have the same q and θ_{pq} as those of the event, to reach each of the segments of the STAR that are needed to form the particular asymmetry under investigation. A simple Monte-Carlo calculation has been carried out to demonstrate the power of this acceptance condition. The solid lines in Figure 95 correspond to the values of A_{LT} and A_{TT} obtained from a PWIA calculation of $d(e, e'p)$ at 4 GeV with $Q^2 = 1.16(\text{GeV}/c)^2$. If the asymmetries are inferred from the scattering data using the naive approach described in the previous paragraph, the open square points result. The error bars are statistical, and arise from the number of Monte-Carlo events that were generated, which matches the conditions listed

Figure 95: A Monte Carlo calculation of systematic errors arising from finite acceptance effects in the STAR. The solid line corresponds to the input PWIA result. Open square points and dotted lines correspond to the asymmetries that would be inferred using a completely naive approach; the solid diamond points correspond to asymmetries that would be extracted using a q -symmetric acceptance criterion for the data analysis.

in Table 45. It is very clear that substantial systematic deviations arise. By contrast, the solid diamond points in the figure were obtained using the q -symmetric "cone test" acceptance condition. These points are completely consistent with the input calculation. We also note the rather important point that a substantial fraction of the total number of events actually do pass the cone test. Table 45 shows the per-sector rates corresponding to the TT and LT asymmetries for the above example. For LT, 90% of the naive events also pass the cone test; the fraction is 40% in the more restrictive case of TT. The overall rates are such that a 1% measurement can be accomplished for the least favorable asymmetry in a few days of running time.

We conclude that the geometry and symmetry of the STAR give it many highly desirable properties with regard to the control systematic errors. In particular, it will be possible to fully utilize the very large acceptances of this spectrometer in the course of asymmetry measurements.

F.5.d Luminosity Limits

The absolute maximum luminosity that is permitted for the beam on the target will be fixed by what the tolerable singles rates are in the elements of the focal plane. It is worthwhile to differentiate between two sources of these singles: reactions in the target itself that fall within the acceptance of the spectrometer; and various beam-related backgrounds arising in the experimental hall that penetrate the shielding. The latter are, of course, very dependent on the details of the spectrometer geometry and its shielding configuration. Computer codes like GEANT can be used to examine aspects of this problem, but the performance of analogous real spectrometers can be very informative. Preliminary runs at Bates with a prototype OOP- spectrometer [Do88a] have indicated that luminosities of 10^{38} may not be unreasonable [SC89]. The Bates OOPS, with its very shallow spectrometer bend angle, is likely to be more problematic from the point of view of backgrounds than is the STAR. A schematic representation of a likely shielding arrangement for the STAR is shown in Figure 96. There are no direct lines-of-sight from the target to the detectors, and there is ample space to place baffles along the perimeter of the pole-gap if the reduction of single-bounce backgrounds is determined to be important.

As an example, we considered a case where the eight sectors of the STAR are in coincidence with the HMS electron arm in a $d(e, e'p)$ measurement at $E_e = 4$ GeV, with $\theta_e = 17^\circ$ and $\theta_q = 51^\circ$ [Al88a]. Calculations were done for a 0.5 gm/cm^2 LD_2 target and a luminosity of $10^{37}/\text{cm}^2\text{-sec}$. This is a particularly interesting geometry because as the opening angle, θ_{pq} , is increased, the singles rate asymmetry between forward and backward sectors of the STAR can become large. The e^- , p , π^+ , and π^- singles rates were estimated using the computer codes QFS and EPC [Li88]. The proton and electron rates are $< 10^3/\text{sec/MeV}$ for all θ_{pq} , and the π^+ rate is $< 10^3/\text{sec/MeV}$ for $\theta_{pq} < 35^\circ$, and rises to $5 \times 10^3/\text{sec/MeV}$ for $\theta_{pq} = 50^\circ$.

We have also looked [La89] into more subtle count-rate limitations due to accidental

Figure 96: Schematic representation of shielding for the STAR.

coincidences between target-related singles. The quantity of interest is the fractional statistical error, df/f , that can be obtained for a given coincidence measurement in a fixed running time, T . For conservative assumptions about the characteristics of the HMS and STAR detector packages, we found that the accidental coincidence luminosity limit for small opening angles is well above 10^{37} , but that for larger θ_{pq} the limit is reduced by as much as an order of magnitude. This reduction comes about because of the increasing singles rates in the most forward sector of the STAR. The counting rates in individual channels were always below about 1 kHz in the electron spectrometer, and below about 0.2 kHz in any sector of the STAR. These focal plane rates are so low that efficiency changes arising from rate differences among the sectors of the STAR will be a very unlikely source of false asymmetries.

The luminosity limits and counting rates in the example above have not taken advantage of a number of possible improvements, including: fine tuning coincidence windows; the incorporation of particle rejection schemes into the detection package; and the utilization of state-of-the-art electronics and computer processing to improve resolving times and lower dead times. We have explored [La89] several rather informative variations of the configuration parameters, and conclude that even for the more extreme experimental geometries it is likely that a well-chosen configuration of data acquisition elements and detection hardware would permit luminosities on the order of $10^{37}/\text{cm}^2\text{-sec}$.

F.6 Summary

We have explored the concept of the STAR spectrometer in some detail and have investigated many of the potentials and limitations that are inherent in this kind of device. We have examined the considerations that constrain the optimization of the design optics and

permit the associated broad program of physics to be addressed in as complete a manner as possible. The range of basic designs that have emerged tend to be rather conservative from the point of view of state of the art engineering. Considering the wide scope of the STAR's capabilities, it is not surprising that it is a potentially expensive device; and considerable effort has gone into the exploration of a number of design variations and performance trade-offs with an eye to possible attendant cost reductions. This work leads us to believe that the STAR could make unique contributions to a particularly wide range of physics in a very cost effective manner.

G PAVEX, Instrumentation for Parity Violation Experiments at CEBAF

G.1 Physics Overview

In the “Standard Model” of electroweak interactions essentially one free parameter, the weak mixing angle $\sin^2\theta_W$, predicts the structure of the weak neutral current J_μ^Z in terms of the familiar electromagnetic current J_μ^γ :

$$J_\mu^Z = J_\mu^3 - \sin^2\theta_W J_\mu^\gamma \quad (19)$$

where J_μ^3 is the third component of “weak isospin.” Because of this relationship, measurements of the form factors corresponding to J_μ^Z can be interpreted in a straightforward manner if one assumes the standard model. Measurements of a wide variety of weak neutral current processes show exceptionally good agreement with this simple model [Am87], and yield a “best” value of $\sin^2\theta_W$ of ≈ 0.23 .

Because the weak neutral current has both vector and axial vector parts, we can measure the form factors of J_μ^Z directly by measuring the parity violation that results from the interference between J_μ^Z and J_μ^γ . In particular, for elastic $\vec{e}p$ scattering, the parity violating asymmetry is given by [Re74,Ca78,Po87,Do88,Be89,Mc89]:

$$\begin{aligned} A_{\vec{e}p} &\equiv \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow} \\ &= -\frac{G_F Q^2}{\pi\alpha\sqrt{2}} \frac{1}{\xi} \left[\varepsilon G_E^\gamma G_E^Z + \tau G_M^\gamma G_M^Z \right. \\ &\quad \left. - \frac{1}{2}(1 - 4\sin^2\theta_W)(1 - \varepsilon^2)^{1/2} \sqrt{\tau(1 + \tau)} G_M^\gamma G_A^Z \right] \end{aligned} \quad (20)$$

$$\equiv -\frac{G_F Q^2}{\pi\alpha\sqrt{2}} [A_E + A_M + A_A] \quad (21)$$

where $\xi = \varepsilon (G_E^\gamma)^2 + \tau (G_M^\gamma)^2$ and the rest of the notation is conventional. A measurement of this asymmetry provides detailed information on the weak neutral current form factors $G_{E,M,A}^Z$, since the electromagnetic form factors $G_{E,M}^\gamma$ are well known from conventional unpolarized elastic electron scattering measurements. If we assume that the standard model is correct and we assume that the proton and neutron are good states of strong isospin, we can write the currents in equation 19 in terms of u, d , and s quarks and derive simple relationships between the weak vector form factors for the proton and the electromagnetic vector form factors of the proton and neutron, as well as form factors for the “strange quark current” [Be89]:

$$\begin{aligned} G_E^Z(q^2) &= \left(\frac{1}{4} - \sin^2\theta_W \right) G_{E_p}(q^2) - \frac{1}{4} G_{E_n}(q^2) - \frac{1}{4} G_E^s(q^2) \\ G_M^Z(q^2) &= \left(\frac{1}{4} - \sin^2\theta_W \right) G_{M_p}(q^2) - \frac{1}{4} G_{M_n}(q^2) - \frac{1}{4} G_M^s(q^2) \end{aligned}$$

Figure 97: Sensitivity of the measured parity violating asymmetry to various contributions for a fixed beam energy of 2 GeV and forward electron scattering angles θ .

The proton electromagnetic form factors G_{E_p} and G_{M_p} are well known. The analogous neutron electromagnetic form factors G_{E_n} and G_{M_n} are not as well known, but we expect that they will be measured to good precision by experiments planned for MIT-Bates and CEBAF. Consequently, a measurement of $A_{\bar{e}p}$ can yield information about the strange quark form factors G_E^s and G_M^s (i.e. the matrix element $\langle p | \bar{s} \gamma_\mu s | p \rangle$) and also the test the standard model by extracting the equivalent value of $\sin^2 \theta_W$ via electron-quark couplings. These experiments are important for both particle and nuclear physics in that they provide direct information on the non-perturbative QCD structure of the proton (in the case of $\langle p | \bar{s} \gamma_\mu s | p \rangle$ [Mc89]) and on the “standard model” of electroweak interactions (in the case of $\sin^2 \theta_W$ [Ly87, Ly87a]).

It is possible to extract $G_{E,M}^s$ and $\sin^2 \theta_W$ separately by varying kinematic quantities. Figure 97 shows the dependence on each of the terms $A_{E,M,A}$ in equation 21 as a function of the electron scattering angle θ for a fixed beam energy of 2 GeV. At these relatively forward angles, the contribution of the axial form factor is negligible. At $Q^2 = 0.1 \text{ GeV}^2$, the measurement is primarily sensitive to the magnetic term, so G_M^s (whose value at $Q^2 = 0$ is not constrained by available data [Mc89]) could be inferred from such a measurement. After the recently-approved experiment at MIT-Bates that will isolate G_M^s at backward angles [Be89a] has been completed, a complementary, forward angle measurement at CEBAF could extract the value of G_E^s . In any case, if the result is consistent with $G_E^s = G_M^s = 0$

Figure 98: Our present concept of an experimental arrangement for a measurement of the parity violation asymmetry at $Q^2 = 0.1 \text{ GeV}^2$.

it would place important new limits on modifications of the standard model.

G.2 Experimental Setup

Since CEBAF will provide intense, low emittance, and highly polarized electron beams soon after it begins operations, it will be an ideal laboratory for studying electroweak interactions and for using the electroweak interaction to study the structure of the nucleon. A schematic view of an experimental setup that should be able to carry out a number of measurements of interest is shown in Figure 98. At $Q^2 = 0.1 \text{ GeV}^2$, we would detect the recoil protons and measure Q^2 using time-of-flight techniques. It has been estimated that the "soft photon" backgrounds from the beam striking the target are tolerable in the sense that the signal-to-noise ratio is relatively large. The $Q^2 = 0.1 \text{ GeV}^2$ measurement would be made using the proton scintillation counter arrays. Note that the proton counters are in separate, ϕ -symmetric modules, each with several scintillation detectors segmented in the direction of θ_p . A flight path of about 2 m from the target to these detectors will give sufficient energy (and therefore Q^2) resolution via time-of-flight. Thin, low-Z sheets in

front of the proton counters should provide sufficient shielding from very low energy (i.e. keV) gamma rays. The counters are relatively insensitive to high energy gamma rays. The count rate from elastic $\bar{e}p$ scattering would be $\approx 4/\text{micropulse}$ or between 1 and $2 \times 10^8/\text{sec}$, integrated over all proton counters. A special-purpose data acquisition system, probably based on a simple parallel network of fast processors and memory, will be needed.

Our initial measurements aimed toward parity violation in elastic $\bar{e}p$ scattering will consist of a feasibility study. The apparatus will consist of a small prototype section of the device shown schematically in Figure 98 and all the necessary beam monitoring and control apparatus. The prototype will be constructed using operating funds from CEBAF and the collaborating institutions, while the beam line instrumentation is included in the general complement of equipment for the hall that is contained in the CDR.

H Beamline Instrumentation

The control and measurement equipment to be used in the Hall C beam line after the last magnetic element will consist of beam current, position and profile monitors, most of which are being developed and tested here at CEBAF and will be used in the circulation arcs and the beam switchyard of the accelerator.

The resolution and accuracy requirements in Hall C are such that special attention should be paid to the following issues:

- Determination of the incident beam energy
- Control of beam position, emittance and energy stability
- Determination of the beam current, total charge and luminosity
- Precision measurement of beam polarization

Figure 99 gives the layout of the beam as it enters the Hall C. It shows the position of the last eight dipoles which bends the beam 37.5 degrees from the beam switchyard into the hall.

Each dipole has a quadrupole and a pair of steering magnets associated with it. Good knowledge of the field maps of these bending dipoles would enable us to measure the beam energy to 1 part in 10^{-4} . After the last dipole, there are quadrupoles followed by a space left for a 5 quadrupole rotator and a laser back scattering polarimeter. A set of quadrupoles focus the beam on target. Each of these quadrupoles comes with a beam position, current and profile monitor and a pair of steering coils. Each such unit is shown in Figure 100. The last quadrupole element is still about 20 meters from the target position.

To determine the beam position, current and angle of approach of the beam on the target, we place a set of position and current monitors 4 meters and 0.5 meters upstream of the scattering chamber. Just outside the scattering chamber we plan to have a beam position and current monitor. At the target position, within the scattering chamber, we plan to have a profile monitor. At present, no elements have been planned to be placed downstream of the target, but one can conceive of placing a current and a profile monitor to ensure that the beam is properly channeled into the beam dump.

Several issues still need to be resolved with respect to the instrumentation for Hall C. These include:

- beam dispersion on target to achieve better energy definition;
- beam orientation measurement when using a polarized electron source; and
- a beam rastering system, with precise information on the beam spot location as a function of time.

Figure 99: Layout of beam channel from beam switchyard to Hall C.

Figure 100: The beam monitor package for the HMS beamline; each of the quadrupole beam focussing system consisting of a quadrupole, beam position, current and profile monitor and a pair of steering coils.

In the remainder of this section we review plans for beam position, current, and profile monitoring. Then our plans for a laser backscatter polarimeter to monitor the beam polarization are presented.

H.1 Beam Position Monitors

Several different types of beam position monitors are being considered for use along various sections of the accelerator. The object of the monitors is to obtain an absolute beam centroid position determination to within 100 microns which is slightly better than the dimensions of the beam (140 microns). One would also prefer to make this determination in a continuous and non-intrusive method as possible. Moreover, since several hundred of these will be required in the arc sections of the accelerator as well as near the injector and beam switchyard, the cost of each individual monitor also becomes a factor. Unless the demands of the beam position determination in Hall C becomes incompatible with those required for the accelerator, we plan to use the same monitors as those for the accelerator. A few different types of these monitors are being developed here at CEBAF to meet the special needs of the machine. The dynamic range of most of these monitors is between 10^{-10} A.m and 10^{-6} A.m. It is therefore clear that for currents below $1 \mu\text{A}$, one needs to devise some other means to monitor the beam position.

H.1.a Microwave Cavity Monitors

A pair of half wave guide cavity monitors which operates on the 3 GHz harmonic of the RF measures the beam position in the arcs continuously without effecting the beam. The cavity which operates in the TM_{110} mode gives the product of the position and beam current of the beam whereas the other cavity operating in the TM_{010} mode gives the beam current. The positional accuracy is rated to be 1 mm at $1 \mu\text{A}$ and 0.1 mm or better at $10 \mu\text{A}$ or higher. Since its cost is rather high ($\sim \$2300$ per pair of stainless steel cavities $\sim \$2700$ for electronics) the plan is to have only a few of these in the accelerator beam line and they will be used to warn and activate the loop monitor system in case of drift.

H.1.b Inductive Loop Beam Position Monitors

The inductive loop monitors determine the position by amplitude modulating the beam at a relatively low frequency (in this case 10 MHz) [Ad89]. Because of the relaxed mechanical tolerances on 10 MHz pickups compared to microwave pickups and the availability of low cost electronic components in this frequency range, these monitors are expected to be significantly cheaper ($\sim \$500$ + electronics). The expected beam position determination is 100 microns at $1 \mu\text{A}$ and gets better at higher beam currents. The monitor is being developed at CEBAF so as to be able to detect separately the position of each of the five different beams residing simultaneously within the CEBAF linacs. One obtains this

by pulsing the amplitude modulation for a period of less than one circulation time in the machine ($4.2 \mu\text{sec}$). In addition, the time interval between pulses of modulation should be greater than five circulations ($21 \mu\text{sec}$) to allow one pulse to exit the machine before the next one is introduced.

H.1.c RF Pickup Monitors

Plans are underway to develop an RF pickup monitor for the determination of the beam position and current without modulating the beam and with position and current determination accuracies comparable to those obtained with the loop monitors. No details of these monitors are available yet.

H.2 Current Monitors

Several devices are being looked into, some of which are being designed here at CEBAF for our specific needs.

H.2.a Microwave Cavity Monitors

These have been discussed earlier in the section of the position monitors. The current resolutions one obtains are of the order of 1%. As stated earlier, these are rather expensive compared to the loop monitors, and a few might be used along the beam line for absolute calibration purposes.

H.2.b Inductive Loop Monitors

The inductive loop monitors as described above can also be used as very accurate relative current monitors if one adds the inductive loop pickups from both pairs which are transverse to each other. The resolution is rated to be also of the order of 1%. One can then calibrate these against an absolute current monitor system.

H.2.c Parametric DC Current Transformer

A parametric DC current transformer (Unser monitor) [Un89] measures the total number of circulating charged particles without requiring any timing information for proper operation. It makes use of high permeability alloys with amorphous structure and provides a precise, absolute calibration without any ambiguity ($0.2 \mu\text{A}$ over its full range of up to $250 \mu\text{A}$). Its operation is similar to the ZFCT (zero flux current transformer), which consists of a toroidal

current transformer and an operational amplifier, connected together in a closed feedback loop. The current to be measured (e.g. the beam) passes through the center of the toroid and is the single turn primary winding. The operational amplifier maintains the dynamic balance between primary and secondary current over a wide frequency range (down to the MHz region). An auxiliary circuit with a magnetic modulator/demodulator, using a pair of toroidal modulator cores, senses the DC error between primary current and feedback current and corrects this error in the feedback loop. This maintains the main toroid at zero flux (static and dynamic) and extends the frequency range to DC. The feedback current is measured with a precision resistor. The parametric current transformer (PCT) differs from the ZFCT in the electronic circuit and a parametric amplification scheme reduces the effect of amplifier noise. These monitors are expensive (~\$13000), and present plans are to use only a few of these in the accelerator beam line and calibrate the rest of the relative current monitors with respect to these.

H.2.d RF Pickup Monitors

These are the same as described above to determine the beam centroid position. They are still in the process of development here at CEBAF and possibly could also be used as relative current monitors.

H.2.e Faraday Cups

For low beam intensities of the order of $1 \mu\text{A}$ or less, one could possibly think of using high powered Faraday cups before the beam dumps to make an absolute determination of the charge collected during an experimental run. At 4 GeV, the power deposited by a $1 \mu\text{A}$ beam is 4 kW, and extensive cooling of this device would be necessary.

H.3 Profile Monitors

There are basically two types of profile monitors which give a profile of the beam as they interact with it.

H.3.a Foils

Plans are to use Aluminium oxide (chromium doped) foils to intercept the beam to determine its position. Used in conjunction with CCD pickup TV monitors, one could obtain a resolution of approximately 200 microns. A 4" x 4" foil is about \$1000 and the mechanical assembly of the plunger is about \$1000. A CCD camera is about \$1200 whereas a simple TV monitor is about \$200.

H.3.b Wire Scanners

These wire scanners are constructed in the shape of a harp with two wires strung perpendicular to each other and at an angle of 45 degrees to the beam. These scanners intercept the beam horizontally and are able to achieve a resolution of 10 microns in both the x and y position. The mechanical hardware costs about \$1400 and the electronics about \$200.

H.4 Laser Backscatter Polarimeter

We propose to measure the electron beam polarization using laser backscatter polarimetry. The effectiveness of this technique depends crucially on the electron beam energy and it appears to be the optimum method for electron beam energies greater than ≈ 2 GeV.

Assuming that $E \gg m \gg k$, where E is the electron beam energy, m is the electron mass, and k is the energy of the incident laser photon, the energy of the backscattered photon in the lab system is given by

$$k' = \frac{2k_R\gamma}{1 + 2k_R/m + \gamma^2\theta^2}$$

where $\gamma = E/m$, $k_R = 2\gamma k$ is the energy of the laser photon in the electron rest frame, and θ is the laboratory angle of the backscatter photon relative to 180° scattering. Assuming a conventional Ar^+ laser ($\lambda=514.4\text{nm}$), we have $k_R \ll m$ at CEBAF energies and so $k'_{max} = 2k_R\gamma = 4k\gamma^2$ or $k'_{max} = 147$ MeV for $E=2$ GeV, and $k'_{max}=588$ MeV for $E=4$ GeV. It appears that backscatter photon energies in excess of ≈ 100 MeV would be detectable in the CEBAF environment at 0° with respect to the beam direction, with suitable signal to noise rates given attainable laser photon densities.

The longitudinal analyzing power, i.e. the asymmetry expected for 100% polarized electrons and photons, is given (for $k_R \ll m$) by the expression

$$A_L = 2k_R/m \frac{(1 - \cos\theta_R)\cos\theta_R}{1 + \cos^2\theta_R} \approx k_R/m$$

averaging over scattering angles θ_R in the electron rest frame. For our typical Ar^+ laser, this gives $A_L = 3.4\%$ at $E=2$ GeV and $A_L = 7.4\%$ at $E=4$ GeV.

The combination of decreasing backscattered photon energy and decreasing analyzing power as one decreases the beam energy leads us to conclude that other techniques, e.g. Moller scattering, be used for E lower than about 2 GeV.

The cross section for Compton scattering is rather independent of energy and is roughly given by $\sigma \approx \pi r_0^2$ where $r_0 = e^2/m = 2.8 \times 10^{-13}$ cm is the "classical electron radius". The laser backscatter rate also depends (linearly) on beam current and laser power, and in a more complicated fashion on details of the "laser-electron interaction region". However for

10 W laser and $100\mu\text{A}$ of electrons, one obtains a rate $\approx 1\text{kHz}$ for a 1 m long interaction region with electron and laser beam cross sections of 1 mm^2 . In order to measure a 50% electron polarization to 1%, one would then need ≈ 10 hr at $E=2\text{ GeV}$ and ≈ 2.5 hr at $E=4\text{ GeV}$ to obtain enough statistical precision. These parameters all seem to be well within the limits of reality.

I Hall C Monitoring and Control Systems

The control and monitor system for Hall C must be capable of furnishing different levels of access for various users. At a general supervisory level, the operators in the Machine Control Center must be capable of overseeing the aspects of experimental hall operations that relate to personnel safety and machine integrity. They must be able to monitor the end station operation and intervene if necessary. This intervention will generally be of a "go/no go" nature. Under normal conditions the running of the end station will be under the control of the people in the counting house. If a potentially hazardous situation is seen by the accelerator operators, they will be able to turn off beam to the hall and take any actions necessary to secure the hall from damage.

Generally the running of the experiment will be left to the physics group in the Counting House. Often this group will include outside personnel who are not trained in the operation of the many pieces of complex machinery. Because of this, there will be control access restrictions at this level. The intent of these restrictions is to limit casual or unnecessary entry to critical control functions. Although control entry is limited at this operational level, full system data will be available for logging or informational purposes. As much as possible the actual control complexities of the experimental equipment will be transparent to the users at this level. Communication to the machinery will largely be limited to the down loading of set points. Where necessary the proper "knobs" will be furnished although in many cases the adjustment range will be restricted to that needed for the experiment. All critical control functions will be protected by pass words or hardware locks. The control and monitor of the experimental hall will be fully accessible to qualified CEBAF staff members.

There will be a significant degree of redundancy in the monitoring of the Hall C equipment. This will allow experimentalists to watch key equipment even if the main instrumentation and control link is not available. The redundant instrumentation also allows an independent check of the information in the other data stream. If the experimenters have special instrumentation needs, they can be handled by this system.

The primary link between the experimenter and the Hall C equipment (other than the detectors) is through the main instrumentation and control computer in the Counting House. The hardware and software used here will be the same as that used for the control and monitoring of the accelerator. Reuse of the accelerator Instrumentation and Control technology will give lower initial cost as well as lowering operational costs. The experimental users will be able to access all parameter values being monitored by the main instrumentation and control system. The control points that are available to them will be adjusted on a case by case basis. There are no plans for a high speed data link between the experimenters' data acquisition computers and the Hall C control system. A slow speed serial link will be adequate for this interconnection.

The control and monitoring of Hall C equipment will be handled by the standard CEBAF configuration of a top level computer in the Counting House linked to one or more

satellite processors. These satellites are coupled to CAMAC crates which house the input and output modules. Most of the control functions are handled by the local computers which substantially reduces the amount of data which must flow between the Counting House master control computer and the local processors. The satellite computers can be accessed locally by attaching a terminal. This makes the commissioning and maintenance of the equipment much easier. Rather than requiring someone in the counting house control room to be in close communication with people down in the hall, the personnel in the hall can exercise the equipment.

The redundant instrumentation system is quite similar to the main loop except that it is restricted in scope because it is primarily for monitoring. Because it is not involved in control loops, there will be much less need for local processors. For the most part the instrument will be housed in CAMAC modules.

Because of the anticipated high beam power and complex, hazardous equipment planned for Hall C, the Safety System is a very important of the overall instrumentation and control plans. This system will be closely coupled to the accelerator safety system, the main Hall C control system and the experimenters' instrumentation system. A schematic of the Hall C control system is shown in Figure 101.

The changeable nature of the experiments in hall C dictates that a versatile, robust monitor and control system be installed. As the experiments and experimenters change it will be necessary to quickly and easily modify the control systems to suit the new conditions. This will necessitate modular hardware and software as well as a good plan which includes standards and procedures which will lead to productive use of available beam time. These requirements can be met with the hardware, software and methods that are being developed at CEBAF.

Figure 101: A Schematic of the Hall C control system.

J Hall C Management

The organization of the scientific effort in Hall C is centered around the Hall C "Instrumentation Collaboration" whose purpose is to exploit efficiently the scientific potential of CEBAF End Station C. The term "Instrumentation Collaboration" refers to a federation of "Scientific Collaborations," each having commitments to specific programs of research and to the design, construction, and operation of the specific instrument(s) required to conduct that research. Each scientific collaboration is led by internally-chosen spokesmen. The collaborations interact with the CEBAF management through the Hall C co-program managers, who receive advice from and disseminate information through the Hall C steering committee. This committee provides a forum for discussion of issues of common interest to all users of Hall C and its facilities.

There are presently two program managers for Hall C, one a member of the CEBAF staff, and the second a member of the user community. They have been appointed by CEBAF management with the advice of the CEBAF User's group. The co-program managers have overall responsibility for the assembly and operation of the end station. They coordinate the activities of the various scientific collaborations that make up the Hall C "Instrumentation Collaboration," and provide a unified voice to the CEBAF management and funding agencies for the Hall C scientific programs. Their functions include: the identification and encouragement of cooperation between user collaborations with similar scientific goals; the allocation of common CEBAF resources among the various scientific collaborations; the development and application of uniform engineering standards and cost estimating for the design of equipment presented to CEBAF management for consideration; and the development of uniform "quality control" standards for user-constructed equipment. They will facilitate the integration of each user group's equipment into the experimental area, will serve as arbitrators to settle disagreements among the user collaborations on common technical standards issues, and will monitor the progress of the scientific collaborations in the design and construction of instrumentation. Finally, with the help of the scientific collaborations, they will defend to CEBAF and the funding agencies the case for the allocation of CEBAF resources to Hall C programs.

The spokesmen of the Scientific Collaborations will provide the leadership and the focal point for CEBAF interactions with the users. They are responsible for forming the collaborations and for generating proposals for scientific research and instrumentation. They will defend their scientific programs and instrumentation designs to the CEBAF directorate, and to CEBAF PAC's and TAP's as appropriate. It will be their responsibility to ensure that their collaboration has sufficient strength to construct and exploit the proposed instrumentation, and to oversee the work of their collaboration to realize an approved instrument. They will coordinate the construction and installation of the instrument to CEBAF-defined standards, working closely with the Hall C co-program managers.

The Hall C Steering Committee is appointed by CEBAF management with the advice of the co-program managers and the User group. The co-program managers will be ex-

officio members of the committee, and the remaining membership will generally include the spokesmen (or their suggested alternates) for each of the scientific collaborations that are currently active in the Hall C research program. Additional members may be appointed from users of Hall C and the CEBAF scientific staff as judged appropriate by CEBAF management. The main purpose of the Steering Committee is to provide a forum for conducting the Hall C business outlined above and to coordinate communications with and between the User Collaborations. One of the committee's principal functions in the early stages of the planning for Hall C has been to encourage the evolution of user-proposed designs into instruments of maximum flexibility and utility. The present membership of the Steering Committee is listed in Table 6; it includes representatives from each of the major user collaborations that is currently planning a research program in Hall C.

The Hall C instrumentation breaks down into two components: the common, moderate resolution High Momentum Spectrometer; and a number of user-constructed second arms and other facilities. In order to proceed with the development and construction of the instrumentation required for the Hall C research programs in the most cost-effective and scientifically productive manner, we have defined the following "split" of responsibilities:

The HMS "Core" Spectrometer:

- Optics designed by CEBAF and users.
- CEBAF provides funds for construction.
- CEBAF does all engineering and construction.
- Detector package to be built by the users.
- Data acquisition hardware provided by CEBAF & coded by users.

User-Constructed Second Arms and Other Facilities:

- Designed primarily by users with CEBAF engineering assistance.
- Funding to come primarily through user collaborations.
- CEBAF to build/assemble only items inappropriate or impossible for users.
- Detector packages to be built by the users.
- Data acquisition hardware provided by CEBAF & coded by users.

Appendix

CEBAF Hall C

Manpower, Schedule, & Costs

Hall C Manpower Required & Identified (1990-1994)

TASK	CEBAF Eng. & Tech. [FTE Years]	CEBAF Phys. & DA [FTE Years]	USERS Phys. & Tech. [FTE Years]	Contract Labor [FTE Years]	TOTALS
HMS					
Magnets	13	8		4	25
Carriage	4	4		2	10
Systems	6	8		1	15
Data Acq.		10	4		14
Detector	4	6	16		26
SOS/HNSS					
Magnets			4	4	8
Carriage			8	2	10
Systems	3	4	4	1	12
Data Acq.		4	4		8
Detectors			10		10
Beamline Instr.	8	9		7	24
Targets	4	4			8
Management		4	2		6
TOTALS	42	61	52	21	176

The listed manpower is CEBAF operations funded manpower + user supplied labor. These figures do not include manpower for which the vendor cost estimate includes EDIA and/or vendor installation.

Hall C Manpower by Year (1990-1994)

TASK	1990 [FTEs]	1991 [FTEs]	1992 [FTEs]	1993 [FTEs]	1994 [FTEs]	TOTALS
CEBAF STAFF						
Physicists/Postdocs/DA	7	12	14	14	14	61
Engineers/Designers	6	5	5	5	5	26
Technicians	0	2	4	5	5	16
Contract Labor	0	0	7	8	6	21
USERS	4	9	13	13	13	52
TOTALS	17	28	43	45	43	176

Hall C Construction Schedule Summary (Calendar Year)

Construction Schedule HMS Quadrupoles (Calendar Year)

Construction Schedule HMS Dipole (Calendar Year)

Construction Schedule HMS Carriage & Shield (Calendar Year)

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Construction Schedule for HMS Detector Built by University Based Users (Calendar Year)

Construction Schedule SOS (Calendar Year) (For HMS/SOS Coincidence at Turn On)

Construction Schedule Hall C Support Systems (Calendar Year)

HALL C COST ESTIMATE SUMMARY (1989 \$K)

WBS 6.7.	ITEM	Sub Total	Total	BASIS OF ESTIMATE
	HMS			
1.1	QUADRUPOLES (Q1, Q2, & Q3)	1,750	7,153	External Cost & Schedule Study
1.2	DIPOLE (unassembled)	2,838		Vendor Steel Quote & CEBAF
1.3	CARRIAGE & SHIELD	1,235		External Engineering Design
1.4	VACUUM SYSTEM	50		CEBAF
1.5	CRYOGENICS SYSTEM	75		CEBAF
1.6	POWER SUPPLIES & CABLES	228		CEBAF
1.7	DETECTOR, PS & READOUT	731		HMS Detector Collaboration
1.8	CONTROLS & INTEGRATION	50		CEBAF
1.9	INSTALLATION & ALIGNMENT	196		CEBAF
	SOS/HNSS			
2.1	MAGNETS	738	2,278	LANL MRS Costs
2.2	CARRIAGE & SHIELD	494		CEBAF
2.3	VACUUM SYSTEM	40		CEBAF
2.4	POWER SUPPLIES & CABLES	162		CEBAF
2.5	DETECTOR, PS & READOUT	373		A.N.L. and CEBAF
2.6	CONTROLS & INTEGRATION	58		CEBAF
2.7	HEAT REJECTION	23		CEBAF
3.1.1	SHIPPING OF SPLIT POLE#	20		CEBAF
3.1.2	REFURBISH SPECTROMETER	230		CEBAF
3.2	BEAM SPLITTER DIPOLE	140		CEBAF
	TARGETS			
4.1	250 WATT LH2/LD2 TARGET	250	500	CEBAF
4.2	POL. NH3 (CEBAF PORTION)	250		University of Virginia
	BEAM LINE			
5.1	BEAM RASTERING & SERVO	50	815	CEBAF
5.2	BEAMLINE VAC. SYSTEM & PIPE	65		CEBAF
5.3	SCATTERING CHAMBER	220		CEBAF
5.4	BEAM DUMP	100		SLAC Costs
5.5	CABLING (CONTROL & SIGNAL)	90		CEBAF
5.6	MAGNET MEASURING	140		LANL Costs
5.7	BEAM LINE POLARIMETER	150		CEBAF
	COUNTING HOUSE			
6.1	MAIN COMPUTER & DRIVES	105	700	CEBAF
6.2	FAST ELECTRONICS	365		CEBAF
6.3	CABLING (TIMING & RF)	30		CEBAF
6.4	ELECTRICAL EQUIP.	200		CEBAF
	TOTAL \$K		11,446	

Costs are to completion and do not include CEBAF EDIA, escalation, or DOE contingency.

HMS Superconducting Cold Fe Quad Q1	\$/mwk	Manweeks	Cost (K\$)
ESTIMATE OF VENDOR LABOR			
Project Management	3,000	15	45
Design Engineering	2,800	20	56
Designers	2,400	18	43
Site Preparation	2,000	3	6
Tooling Fabrication	2,000	3	5
Quality Assurance	3,000	4	12
Cold Mass Assembly	2,200	8	18
Vertical Dewar Test	2,600	6	16
Final Assembly	2,200	6	13
Final Test	3,000	5	15
Primary and Multipole Coil Winding	2,200	18	40
Subtotal: Contractors Labor			268
Q1 MATERIALS & SUPPILES			
Q1 Superconductor			14
Q1 Laminations 9600 lb			11
Q1 End Block Assembly 450 lb			25
Q1 Helium Vessel			13
Q1 LN2 Shield			3
Q1 Vacuum Vessel			12
Q1 Support Assembly: Eight			16
Q1 Insulation			1
Q1 Cryogenic Service Tower			9
Subtotal: Subcontracts and Materials			103
COMMON ITEMS FRACTION FOR Q1			
Tooling: \$20K/3			7
Instrumentation & Controls: \$45K/3			15
Computer Service: 28K/3			9
Facility Charge: \$50K/3			17
Shipping: \$30K/3			10
AFI: \$18K/3			6
Subtotal Common Items (fraction for Q1)			64
Subtotal Engineering Total Q1:			435
Vendors Contengency: Labor@25%, M&S@10%			84
Profit			52
TOTAL Q1			570

This cost estimate generated using input from an external cost, schedule and design study.

HMS Superconducting Cold Fe Q2 & Q3	\$/mwk	Manweeks	Cost (K\$)
ESTIMATE OF VENDOR LABOR			
Project Management	3,000	15	45
Design Engineering	2,800	20	56
Designers	2,400	18	43
Site Preparation	2,000	3	6
Tooling Fabrication	2,000	3	5
Quality Assurance	3,000	4	12
Cold Mass Assembly	2,200	8	18
Vertical Dewar Test	2,600	6	16
Final Assembly	2,200	6	13
Final Test	3,000	5	15
Primary & Multipole Coil Winding	2,200	20	44
Installation at CEBAF			20
Subtotal: Contractors Labor			293
Q2 MATERIALS & SUPPILES			
Q2 Superconductor			21
Q2 Laminations			19
Q2 End Block Assembly			30
Q2 Helium Vessel			22
Q2 LN2 Shield			4
Q2 Vacuum Vessel			18
Q2 Support Assembly: Eight			16
Q2 Insulation			1
Q2 Cryogenic Service Tower			9
Subtotal: Subcontracts and Materials			139
COMMON ITEMS FRACTION FOR Q2			
Tooling: \$20K/3			7
Instrumentation & Controls: \$45K/3			15
Computer Service: 28K/3			9
Facility Charge: \$50K/3			17
Shipping: \$30K/3			10
AFI: \$18K/3			6
Subtotal Common Items (fraction for Q2)			64
Subtotal Engineering Total Q2:			495
Vendors Contingency: Labor@25%, M&S@10%			93
Profit @ 10%			59
Total Q2			647
Total Q3 (Identical to Q2 Less Tooling & Eng. Cost.)			532
TOTAL: ESTIMATE OF VENDORS QUOTE Q1+ Q2 + Q3			1,750

This cost estimate generated using input from an external cost, schedule and design study.

HMS Super Conducting Dipole	\$/mwk	Manweeks	Cost (K\$)
ESTIMATE OF VENDORS LABOR			
Project Management	3,200	34	109
Design	3,200	70	224
Facility Prep.	2,000	19	38
Coil Winding	2,200	51	112
Cryostat Assembly	2,200	76	167
QA/QC	2,800	4	11
Subtotal Contractor Labor			661
VENDORS SUBCONTRACTS			
Conductor			80
Helium Vessel/Structure & Bobbin			80
Vacuum Vessel			60
Heat Shield			10
Cold Mass Supports (16@4.5K \$ each)			72
Subtotal Subcontracts			302
ESTIMATE MATERIALS AND SERVICES			
Coil Insulation			15
Cryogenic Components (Valves, etc.)			8
Superinsulation			7
Current Leads			15
Instrumentation			10
Shipping (cryostat only)			15
Winding Tooling			26
Assembly Fixture			20
Travel			7
Subtotal M + S			123
Total Labor + M & S + Sub Contracts			1,086
Contingency on all Labor @ 25%			165
Contingency on Materials @ 25%			106
Profit @ 10 %			136
Estimate HMS Dipole Coil & Cryostat			1,494
ESTIMATE OF 440 T (Machined Yoke & Poles) (Based on budgetary quotes provided by Vendors)			
Material (440 Tons)			774
Machining and Assembling (at factory)			448
Freight and Insurance			122
Total for Finished Dipole Steel (FOB CEBAF)			1,344
TOTAL COST OF HMS DIPOLE (unassembled)			2,838
Assembly of Dipole at CEBAF			196
TOTAL COST HMS DIPOLE ASSEMBLED			3,034

HMS CARRIAGE & SHIELD	Cost (K\$)
Central Bearing	80
Structural Beam System	125
Dipole Support Brackets	50
Gantry (Shield)	25
Bogies (24 wheels/4 wheels boggie) (25k/Boggie)	150
Drive Units	20
Mechanical Jacks	55
Power Units for Jacks	20
Quadrupole Mounts	6
Detector Mounts	5
Shield House	250
Alignment & Installation	25
Rails	65
Vendor Engineering	100
Sub Total Carriage	976
Vendor Contingency @15%	146
Profit @10%	112
TOTAL HMS CARRIAGE & SHIELD	1,235

HMS Power Supply Cost Estimates - 1989 \$ K

Description	Qty	Unit \$ K	Total \$ K
<hr/>			
Power Supplies*			
10VDC 2500A .001%	3	40.0	120.0
10VDC 5000A .001%	1	54.0	54.0
10VDC 750A .001%	1	38.0	38.0
AC Cable (480V)	3000 ft.		1.0
Panelboard	1	1.5	1.5
Cable Tray	125 ft.		2.0
Misc. (supports, nut & bolts, etc...)			2.0
750 MCM cable	2700 ft.	0.0035/ft.	9.5
<hr/>			
TOTAL			228.0

* Price estimate based on average of budgetary quotes from several vendors.
Prices may be somewhat less if supplies could be ordered in conjunction
with power supplies for the other halls.

Hall C HMS Detector Collaboration (Users)	Institution	Cost (K\$)
DRIFT CHAMBERS (three total)	Hampton U.	
Construction 1.5 mo@ \$50/hr + parts		74
Instrumentation 300 wires @200/channel		180
Gas Handling System		30
Construction Supplies & Tools		25
Subtotal for 3 (each package is XYUV)		309
CHERENKOV COUNTER	UVA, ANL	
Construction 1.5 mo @ \$50/hr + parts		18
Photomultipliers 3 @ \$7.5K each		23
Instrumentation		2
Subtotal (Cherenkov Counters)		43
HODOSCOPE COUNTERS (35 per plane x 2)	MIT	
Plastic Scintillator		21
Photomultipliers 2 @\$600		84
Bases 2@\$100		14
ADC/Disc./TDC 2@\$250		35
Subtotal (70 counters)		154
SHOWER COUNTER DETECTORS (20 blocks)	CIT	
Lead Glass / SciFi		30
Photomultipliers 2@\$750		30
Bases 2@\$100		4
ACD/Disc./TDC 2@\$250		10
Subtotal (Shower Counters)		74
MISCELLANEOUS		
Penetration Scintillator		2
Drift Chamber Signal Cables		10
Photomultiplier Signal Cables (190 PMTs)		24
High Voltage Cables		25
High Voltage Power System (e.g. LRS 1440)		40
Chamber High Voltage		10
Detector Support Structure		40
Subtotal (Miscellaneous)		151
TOTAL HMS Detector		731

SOS Spectrometer+Enge Split Pol. Refurbish	# FTE's	Rate/y (K\$)	Cost (K\$)
VENDOR EDIA			
Project Engineering	1.00	70	70
Design	1.00	49	49
Buyer	0.15	35	5
Engineering			11
Tech. Assoc.			7
Contract Officer			3
Subtotal Vendor EDIA			145
HARDWARE COST ESTIMATE			
Magnets (Derived from LAMPF MRS)			641
Vacuum (Derived from LAMPF MRS)			35
Carriage			280
Power Supplies & Cables (Derived from LAMPF MRS)			140
Heat Rejection (Derived from LAMPF MRS)			20
Shield			150
Detector			200
Instrument/Control (Derived from LAMPF MRS)			50
Enge Split-Pole (Shipping)			17
Enge Split-Pole (Refurbishing)			200
Beam Splitter Dipole			122
Subtotal Vendor Manpower & Hardware			1,855
Vendor Contingency @15%			278
TOTAL COST (SOS & Split-Pole Refurbish)			2,278

HALL C SUPPORT SYSTEMS	Cost (K\$)
Beam Rastering & Servo System	50
Beam Transport Pipe & Vacuum System	65
Scattering Chamber + Hardware	210
Beam Dump (Copy of SLAC system)	100
Cabling (Control & Signal)	90
Counting House-Control Room fast signal Cables	30
Data Acquisition Computer and Tape Drives etc.	105
Scattering Chamber Shielding	10
High Power (250 W) Target Flask & Heat Exchanger	250
Magnet Measurement Equipment	140
NH3 Polarized Target (CEBAF Portion)	250
Electrical Equipment -Transformers, Switch Gear	200
Beam Line Polarimeters (Moller & Laser R & D)	150
Counting House Fast Elect. and Computer Interface	365
TOTAL End Station Support Systems	2,015

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