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GeV C.W. ELECTRON MICROTRON
DESIGN REPORT

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FOREWORD

Although extensive debate continues about its precise characteristics, there is a broad consensus in the nuclear science community that an electron accelerator capable of furnishing intense GeV C.W. electron beams of high quality will open new frontiers in nuclear physics. During the past several years, that sentiment has taken the form of a recommendation reached by several national reviews to construct a national 2 GeV C.W. electron accelerator facility. This report describes an accelerator design and program for research developed as part of the effort to give detailed form to the technology and dramatize the research possibilities it presents. It is part of the national effort to establish the technical feasibility of a national C.W. accelerator laboratory. It is increasingly evident that the design energy requested by the community will be considerably higher than 2 GeV if adequate national resources are available. The technical issues pursued in arriving at the 2 GeV conceptual design presented in this report are unchanged in advanced designs incorporating multisided microtron geometries for operation at higher energy. For that reason we expect this report to have a major impact on planning for the national facility whatever its maximum beam energy.

This report is the result of the collective efforts of a large number of people. The names of the members of the GeV Electron Microtron Project who contributed to the accelerator design are given below:

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ABSTRACT

Rising interest in the nuclear physics community in a GeV C.W. electron accelerator reflects the growing importance of high-resolution short-range nuclear physics to future advances in the field. In this report major current problems are reviewed and the details of prospective measurements which could be made with a GeV C.W. electron facility are discussed, together with their impact on an understanding of nuclear forces and the structure of nuclear matter. The microtron accelerator has been chosen as the technology to generate the electron beams required for the research discussed because of the advantages of superior beam quality, low capital and operating cost and capability of furnishing beams of several energies and intensities simultaneously. A complete technical description of the conceptual design for a 2 GeV double-sided C.W. electron microtron is presented. The accelerator can furnish three beams with independently controlled energy and intensity. The maximum current per beam is 100 μ amps. Although the precise objective for maximum beam energy is still a subject of debate, the design developed in this study provides the base technology for microtron accelerators at higher energies (2 - 6 GeV) using multi-sided geometries.

I. OVERVIEW

Electromagnetic probes in the form of intense electron and photon beams have provided the nuclear physicist with much of the precision data now available on the structure of nuclei and the properties of nuclear matter. Present concepts of nuclear sizes and shapes derive in large measure from results of electron-scattering studies. The various excitations of nuclear systems ranging from giant resonances and high spin states to isobar-hole excitations in nuclei have been revealed in great detail with electromagnetic interactions. The utility of these probes stems from several of their properties. Their interactions with nuclear matter are the best understood of the elementary processes, they are sufficiently weak that distortion of the nuclear structure is negligible, and they can give rise to large momentum transfers to target nuclei. Precisely because of these features, electromagnetic reactions are expected to play a major role in attacking the unsolved problems of contemporary nuclear physics.

The basic continuing challenge of the field is the formulation of a fundamental theory of the nuclear force and the structure of nuclei. The evidence of recent years is that an understanding of nuclear phenomena at short distances, i.e. lengths small compared to the nucleon size (~ 1 fermi), is particularly deficient. Our knowledge of the basic nucleon-nucleon force at short range is largely phenomenological. Meson exchange currents in complex nuclei have been detected, but their properties and influence on nuclear structure has been only crudely outlined. At short distances, the distinction between nuclear and hadronic structure is conceptually questionable. A consistent description of nuclear structure must take account of sub-nucleonic degrees of freedom whether they be described as hadronic resonances such as

the $\Delta(3,3)$, or as excitations of the quark constituents. In a sense, this short-range domain of nuclear structure is the interface between nuclear and elementary particle physics. Lepton scattering is the most powerful tool for exploring these questions. However, because the spacial resolution with which structure is probed is inversely proportional to the momentum transfer, q , measurements must be made with $q \approx 1-2 \text{ GeV}/c$ ($5-10 \text{ fm}^{-1}$). Therefore GeV electron beams are required to study this area of physics.

The rising interest in the nuclear physics community in a GeV C.W. electron accelerator reflects the growing awareness of the importance of high-resolution short-range nuclear physics to future advances in the field. At the same time, progress in accelerator technology has made possible for the first time, elimination of one of the principal limitations to experiments with electromagnetic probes, the poor duty factor which characterizes all high-intensity electron accelerators built to date. The prospect of high-intensity coupled with high duty factor will make possible coincidence measurements, which because of their selectivity and complete characterization of nuclear reactions, will become a major component of future research programs. As a result of these developments, a strong consensus has developed within the nuclear physics community that the next major research facility should be a high-intensity C.W. GeV electron accelerator. The work presented in this report is part of a national effort to develop the technology necessary to design and construct a national accelerator facility. Among the technologies available, the Argonne design group has chosen the microtron concept because of its promise of lower capital and operating cost. In this report an extensive description of the research program envisaged with GeV electrons is presented together with a complete conceptual design for a 2 GeV microtron.

The details of the prospective measurements determine the design objectives for the accelerator and provide its scientific justification. With 2 GeV beams it will be possible to extend measurements of the basic properties of nucleons to provide rigorous tests of quark models for hadronic structure. Experiments on the few-nucleon systems at high momentum transfer will be sensitive to short-range features of the nuclear wave functions which reveal the interplay of the nucleon and sub-nucleon degrees of freedom in the structure of these benchmark nuclei. The principal contribution which the proposed accelerator will make for the structure of complex nuclei result from the increased energy, beam intensity, and duty factor which allow one to conduct experiments that are marginal or not feasible with current accelerators. The accelerator will be invaluable for the study of the effect of non-nucleonic degrees of freedom on nuclear matter. Electroproduction of hypernuclei will open this new dimension of nuclear structure to quantitative exploration for the first time. Experiments will not be restricted to strong interactions. Measurements are proposed which will test our understanding of weak neutral currents by observation of parity-violating effects. The common thread through all of these prospective initiatives is the requirement of high-duty factor at high-intensity and energy.

The double-sided 2 GeV electron microtron has been chosen as the accelerator system to generate the electron beams required for the research discussed because of the advantages of superior beam quality, low capital and operating cost, and capability of furnishing beams of several energies and intensities simultaneously. Only moderate r.f. power is required because of the recirculation of the beam 37 times through the same accelerating structures to reach 2 GeV. Use of a booster race track microtron provides an effective injection energy into the double-sided system at 185 MeV, thereby

avoiding some of the serious problems arising from the vertical defocusing forces which characterize the geometry of the double-sided microtron. Orbit containment is achieved by means of mirror symmetric quadrupole multiplets on the dispersed return paths. The optics system maintains a dispersive free beam at the center of the linacs. Waists are provided at the midpoints of the linac structures and midpoints of the dispersive straight sections and transport is achromatic from the exit of one linac to the entrance of the next. These features of the optics will minimize the effects of regenerative beam breakup, the primary limitation on the maximum current which can be accelerated. Multiple beam extraction is accomplished by subharmonic modulation of the micropulse structure of the beam coupled with conventional extraction technique applied in the dispersive straight sections. The flexibility of operation of the microtron will facilitate a broad multifaceted research program in the associated experimental areas, and the excellent beam quality of the microtron beams will have a significant impact on meeting the challenges of high-energy spectrometer design at acceptable cost.

II. PHYSICS JUSTIFICATION

A. INTRODUCTION

The interaction of the charge and current in nuclei with electromagnetic fields reveals the underlying structure and dynamics of these complex systems. When investigating such dynamic objects as nuclei, it is essential that a well understood probe be used and further the probe should not alter the object under investigation. For a study of the nucleus, both the photon and electron satisfy these requirements. Advances made by scientists and engineers in developing ever more useful photon and electron beams coupled with the emerging awareness of non-nucleonic degrees of freedom inside the nucleus motivate the facility described in this document. In the material that follows no attempt is made to discuss all the research that can be done. Insofar as the facility will be unique, it would be operated as a national (and international) center, available to scientists based on the merit of their proposed research, the scientific justification emerges from the community as a whole. In addition to specific proposals to construct and operate high-energy C.W. electron accelerators, other studies have dealt with the general and specific nature of the envisioned research program. Two reports are particularly useful in this regard; "Future Directions in Electromagnetic Nuclear Physics" [Do 81] and "Prospectives in Electro- and Photo-Nuclear Physics" [Ge 81]. A reading of these resource papers is essential to develop a fully informed view of the excitement and promise of nuclear research with GeV electrons. In the next few pages a brief outline of the physics involved in electron and photon scattering from nuclei will be

presented. In further sections a few topics not extensively treated in existing literature are highlighted.

Figure II-1 diagrams the interaction between a photon and a nuclear system in which the nucleus changes from state α to state β with the absorption of a photon of energy $E_{\beta\alpha} \equiv E_{\beta} - E_{\alpha}$ which carries momentum $E_{\beta\alpha}/c$. The same transition can also be induced by the scattering of a charged particle which provides the photon. As shown in Figure II-2 the charged particle transfers energy $E_{\beta\alpha}$ to the nucleus via photon exchange, however, the momentum transferred to the nucleus ($\vec{q}$) is equal to the change in momentum of the charged particle ($\vec{P} = \vec{P}_1 - \vec{P}_2$). In principle this momentum transfer may be any value $|\vec{P}| > E_{\beta\alpha}/c$. The ability of the nucleus to absorb the differing momentum transfers reveals the underlying dynamical changes relating states α and β . The scattering amplitude for such a collision is written

$$M_{\beta\alpha}^{\mu} \approx j_{\mu}^e(q) \frac{4\pi e^2}{q^2} J_{\beta\alpha}^{\mu}(q) \quad (\text{II-1})$$

where $j_{\mu}^e(q)$ is the current carried by the electron, $\frac{4\pi e^2}{q^2}$ the photon propagator and $J_{\beta\alpha}^{\mu}(q)$ the transition current of the nuclear system. The first two terms are known exactly from quantum electrodynamics. Therefore, the only unknown in the scattering process is the nuclear current ($J_{\beta\alpha}^{\mu}$) which is the quantity to be measured in experiments and theoretically modeled.

The discussion presented above is exact within the confines of quantum electrodynamics and the one photon approximation. At the level of 1% the one photon approximation is valid for every nuclear scattering that has been investigated either theoretically or experimentally.

Figure II-1. Feynman diagram for photon absorption.

Figure II-2. Feynman diagram for inelastic electron scattering.

Gauge invariance imposes a continuity condition on all electromagnetic currents so the nuclear current satisfies.

$$\square J_\mu \equiv \nabla \cdot \vec{J} + \frac{\partial \rho}{\partial t} = 0 \quad (\text{II-2})$$

This condition is employed to great advantage to avoid complications in $\vec{J}$ by employing the commutator between the nuclear Hamiltonian (H) and the charge density (ρ).

$$\nabla \cdot \vec{J} = - \frac{\partial \rho}{\partial t} = \frac{-1}{\hbar} [H, \rho] \quad (\text{II-3})$$

Confrontation between theory and experiment is usually carried out via form factors. The elastic scattering of an electron from a spin zero nucleus requires only one form factor, the so-called monopole form factor which is just the charge distribution. The measured yield is written as

$$\left(\frac{d\sigma}{d\Omega} \right)_{el} = \sigma_M G_{el}(q^2)$$

where σ_M is the cross section due to a point charge whose charge is equal to that of the target.

$$\sigma_M = \frac{4Z^2 \alpha^2 E^2}{q} \cos^2 \frac{\theta}{2} \quad (q = 2E \sin \frac{\theta}{2})$$

The form factor $G_{el}(q^2) = (\frac{d\sigma}{d\Omega})_{el} / \sigma_M$ is a direct measure of the charge

distribution of the target nucleus. Using a Fourier transform the spatial distribution of the charge is revealed via

$$\rho(r) = \int G_{el}(q^2) e^{i\vec{q} \cdot \vec{r}} d\vec{q}.$$

Measurements must be carried out to sufficiently high momentum transfer (q) to make the assignment of the charge distribution unique at short distances. Extended structures like nuclei evidence obvious non-pointlike behavior at momentum transfer larger than 200 MeV/c.

In addition to the monopole form factor there exist electric (E) and magnetic (M) form factors $F_{\ell}^{E(M)}(q^2)$ with $|J_{\alpha} - J_{\beta}| \leq \ell \leq |J_{\alpha} + J_{\beta}|$ and a parity change $\pi_{\alpha}\pi_{\beta} = (-1)^{\ell}$ for electric and $(-1)^{\ell+1}$ for magnetic transitions. For electron scattering from nuclei with spin J equal a half integer, one has even electric multipoles from monopole ($\ell = 0$) to the $2J-1$ pole and all odd magnetic multipoles from magnetic dipole ($\ell = 1$) to the $2J$ magnetic pole. The different dependence on the transferred momentum allows these form factors to be separated and permits a detailed characterization of the current and charge distribution in these nuclear ground states.

At high bombarding energy a large fraction of the cross section corresponds to final states with two or more particles in the continuum. In this case the yield is characterized by a so-called structure factor rather than a form factor. The cross section for transferring energy ω and momentum $\vec{q}$ to a nucleus of mass μ_A via electron scattering is written as

$$\frac{d\sigma}{d\Omega dE} = \frac{4\pi}{M_T} \sigma_M \left\{ \left[\frac{q}{q} \right]^4 S_L(\vec{q}, \omega) + \left[\frac{q^2}{2q^2} + \tan^2 \frac{\theta}{2} \right] S_T(\vec{q}, \omega) \right\}; \quad q^2 = \vec{q}^2 - \omega^2/c^2$$

The experimental separation of these structure factors $S(\vec{q}, \omega)$ into their

longitudinal (L) and transverse (T) components is accomplished by employing different beam energies to fix q and vary θ . Non-nucleonic degrees of freedom such as meson exchange currents and real and virtual Δ 's are expected to have a much stronger influence on S_T , thus providing a means of studying the role of these exotic degrees of freedom. Detailed specification of the structure function can be made by detecting one or more particles in coincidence with the scattered electron. Coincidence experiments which measure the single particle momentum distribution of nucleons employing quasi-elastic scattering via the longitudinal mode should be viewed as complementary to elastic scattering. The latter measures the spatial charge distribution, while the former is determined, in principle, by the proton momentum distribution. They are related via their Fourier transforms.

As was mentioned earlier the confrontation between theory and experiment in electronuclear physics comes in the comparison of measured form factors with those calculated from nuclear theory. Years of careful study with a variety of probes have provided a relatively clear picture of many aspects of nuclear structure. In particular, independent particle models of the nucleus involving nucleons interacting via a two body force reproduce nuclear spectra and account very well for relative transition rates between the low-lying levels. Fundamental questions arise when comparing theory and experiment for absolute transition strengths, because of the limited vector spaces that can be accommodated in present day calculations.

Thus there appears to exist a satisfactory model for describing nuclei and their properties as long as absolute transition rates are not required. There is little information regarding the behavior of nucleons when they get close to one another say on the order of 0.7 fm less. The strong short range behavior of the nucleon-nucleon force scatters the nucleon far off

the energy shell and must introduce new non-nucleonic degrees of freedom. A clear characterization of this process is a goal of quantum chromodynamics. These non-nucleon degrees of freedom may strongly influence transition rates but are difficult to uncover at low energy. Probes with several hundred MeV and above make the presence of these non-nucleon degrees of freedom manifest and account can then be taken of their presence at lower energy via a proper theory. For example, pion exchange currents modify the $p + n \rightarrow d + \gamma$ capture rate at thermal energies by only 10% but at momentum transfers of 600 MeV/c, and greater, achieved in $e + d \rightarrow e + (n,p)^{S=0,T=1}$ the effect of meson exchange currents on the cross section is a factor of 10. Therefore, non-nucleonic degrees of freedom which produce small effects in traditional nuclear structure are made explicit by their dominant roles at momentum transfers from $q = 200$ MeV/c upward.

The short range behavior of the nuclear force is well parameterized by variety of meson exchange descriptions. Unfortunately, the extensive and precise nucleon-nucleon scattering experiments do not provide sufficiently detailed information to select between competing descriptions at interaction distances less than 1.0 fm. It is certain that careful study of the structure of the lightest nuclei will shed much needed light on the nucleon-nucleon interaction. (For example see the proposal by R. J. Holt in Future Directions in Electromagnetic Nuclear Physics) [Do 81].

To calculate form factors from wave functions the current carried by a nucleon must be made explicit. The currents associated with nucleons are well defined one body operators as long as the particles are not relativistic. In the same spirit [Th 73, Du 76] the current associated with pion exchange can be written as a two-body operator in nucleon coordinates. The timelike component of this two-body operator is small for small pion

momenta and hence pionic modification of charge densities can safely be assumed to be small.

As mentioned earlier one of the advantages of the electromagnetic interaction is that only a single scattering occurs within a nucleus. The penalty to be paid for this weak coupling is the small size of resulting cross sections. Consider the expression for elastic scattering from a spin zero nucleus

$$\frac{d\sigma}{d\Omega} = \frac{Z^2 \alpha^2}{4E^2 \sin^4 \frac{\theta}{2}} G_{el}^2(q^2) = \frac{Z^2 2.07}{4E^2 \sin^4 \frac{\theta}{2}} G_{el}^2(q^2) \times 10^{-32} \text{ cm}^2/\text{sr}$$

with E in GeV, $q = 2 \frac{E}{c} \sin \frac{\theta}{2}$. Figure II-3 shows the differential cross section for elastic scattering from Pb^{208} .

Such small cross sections have a strong influence on accelerator characteristics and spectrometer design. Often the most interesting cross sections are those at the largest momentum transfer resulting in cross sections on the order of $10^{-38} \text{ cm}^2/\text{sr}$ and smaller. Thus, it is imperative to produce large beam currents as well as spectrometers with large azimuthal acceptance if nuclear charge densities are to be examined to high momentum transfer. Typical luminosities (L) for 100 μA and 100 mg/cm^2 $A = 60$ target (consistent with 2 MeV/gm energy loss) are

$$L = I(\text{no. of electrons/sec}) \times n (\text{no. of target atoms/cm}^2) = 6 \times 10^{35} \text{ cm}^{-2} \text{ sec}^{-1}$$

A 10^{-2} sr detector will produce one count per day for a $2 \times 10^{-39} \text{ cm}^2/\text{sr}$ cross section. High beam energy is helpful in that the Mott cross section at forward angles increases by E^2 for fixed momentum transfer. However the

Figure II-3. Differential cross section for elastic scattering from ^{208}Pb at $E_1 = 502$ MeV [Ca 79a].

rapid decrease of $G_{e1}^2(q^2)$ with q^2 (note at $q = 3 \text{ fm}^{-1}$, $G_{e1}^2(q^2) = 1.6 \times 10^{-10}$ for Pb^{208}) limits the range of useful elastic scattering for heavy nuclei to $q \leq 3.5 \text{ fm}^{-1}$ while for light nuclei $q \leq 4.5 \text{ fm}^{-1}$ seems a realistic limit.

Of course, inelastic processes do not drop off as rapidly with momentum transfer as elastic scattering, in particular nucleon knockout and meson production cross sections dominate the observed yield as the momentum transfer increases. Elastic and simple inelastic scattering on all but the lightest nuclei ($A \leq 4$) do not require beam energies much in excess of 1 GeV. However to measure the momentum distribution of nucleons up to momenta where short range correlations become important (450-500 MeV/c) it will be shown in a following section that at least 2.0 GeV electrons are required. The production of hypernuclear states via the creation of K mesons requires considerably more than 1 GeV with an energy the order of 2 GeV appearing optimal.

At momentum transfers in excess of 10 GeV/c the weak and electromagnetic properties of nucleons can be quantitatively treated in terms of the couplings of their constituent quarks. In the region of high momentum transfer the quarks are treated as asymptotically free, allowing the predictive power of QCD to be utilized. Deeply inelastic electron scattering from nucleons has provided much of the support for quark models and quantum chromodynamics. However, this theory as presently formulated requires the quark couplings via gluons to become stronger as their separation increases (low momentum transfer), hence the theory (QCD) loses predictive power at distances normally important in nuclear physics. A major long term goal of the proposed facility is to investigate phenomena essential to bridge the domains of high momentum transfer (asymptotically free quarks) and the longer range phenomena associated with nuclei. There have been a few pioneering

efforts exploring these frontiers in inclusive experiments carried out at SLAC. The electron accelerator proposed herein will play a major role in this important program, leading to meaningful descriptions of the nucleon, higher baryon resonances, and mesons, merging into quark degrees of freedom at very short distances. All of these must be synthesized into a useful theory of hadronic matter.

B. HADRON PHYSICS AND FEW-BODY SYSTEMS

1. Nucleon Form Factors

Recent developments in hadron physics present an opportunity to describe hadron dynamics in terms of constituent quarks and gluons. The observation of asymptotic freedom in deep-inelastic electron scattering revealed the simplicity of the quark description at large momentum transfer. At lower momentum transfer, roughly for $q^2 < 4(\text{GeV}/c)^2$, the region of interest in nuclear physics, a quantitative understanding of the quark dynamics is essential. The MIT bag model [Ch 74] has provided a framework for understanding many properties of hadron spectroscopy. The quarks are viewed as being restricted to a small volume of space (the bag) and the dynamics of confinement are replaced by the simpler dynamics of the boundary conditions at the bag surface. Because such a system does not preserve chiral symmetry alternative bag models have been proposed [Br 79, Mi 80] in which the baryon is viewed as a 3 quark bag surrounded by a pion cloud. Each of these models provides a framework for calculating the properties of the nucleon, e.g. static and transition form factors. A 2 GeV C.W. electron accelerator can provide experimental determinations of the electromagnetic properties of the hadrons with the precision necessary to test these calculations

The most basic observables are the electric and magnetic form factors of the proton and neutron (G_E^p , G_M^p , G_E^n , and G_M^n). The proton form factors are the best determined and are usually fit by a dipole parameterization with

$$G_E^p = [1 + 1.41 (\text{GeV}/c)^{-2} q^2]^{-2} \quad G_M^p = \mu_p G_E^p \quad (\text{II-4})$$

where μ is the nucleon magnetic moment. However, significant deviations from the dipole form factor have been observed at low and high momentum transfer and several other parameterizations have been suggested. The neutron form factors are much more uncertain. They can be extracted from $e^- + d$ elastic and quasifree scattering reactions, but only with assumptions concerning the deuteron wave function and the two-body currents. A measure of this uncertainty may be that the values for $G_E^n(q^2)$ obtained from $d(e^-, e^-)d$ and $d(e^-, e^-n)p$ analyses are not completely consistent.

A new technique has been suggested [Ar 81] to measure G_E by measuring the polarization of the recoil nucleon scattered by longitudinally polarized electrons. With this technique the proton electric form factor can be measured to 2% up to $q^2 = 2(\text{GeV}/c)^2$ at 2 GeV. Measurements of the neutron electric form factor from quasifree scattering of neutrons in a deuterium target by polarized electrons also seem feasible to the 20% level, a substantial improvement over our current knowledge.

These measurements should be performed in a kinematic region where the relative energy between the outgoing nucleons is large in order to minimize the effects of final state interactions and where the momentum transfer to the proton is small so that the uncertainty in the deuteron wave function is negligible.

Measurements of this precision will allow a distinction between differing models of the neutron electric form factor which takes on a particular significance in the bag models of the hadrons. Each description makes very specific distinguishing predictions about the neutron charge distribution. The rms charge radius is 0 in the MIT model and 0.34 fm in the cloudy bag model [Th 81]. Accurate measurement of the neutron electric form factor at momentum transfers accessible with a 2 GeV accelerator would provide

an important test of these models. The prediction of the momentum dependence of the neutron electric form factor in the cloudy bag model is shown in Figure II-4. Accurate data will provide a sensitive constraint on the bag radius, one of the fundamental parameters of the theory.

2. Nucleon-Bag Deformation

Since the proton is the only simple stable baryon target, its spin $\left(\frac{1}{2}\right)$ restricts observation to the $L = 0$ Coulomb and $L = 1$ magnetic interactions via the static moments. By studying the transition form factors between baryon states, higher multipoles can be measured. This is particularly important at the moment because of the theoretical predictions of strong quadrupole deformations of the nucleon and isobar bags. For example, model attempts to calculate the ground-state configurations of a system of quarks and scalar particles lead to nonspherical oblate solutions with the lowest energy [Pa 80]. From a completely different perspective, a sizable deformation appears to be required to reproduce the nucleon weak axial coupling constant [Ve 81]. Intuitively, this could be expected by noting that the pion coupling to the 3 quark bag is via $(\vec{\sigma}_N \cdot \vec{k}_\pi)$. The energy of this coupling provides a pion pressure which compresses the poles, producing an oblate nucleon. This deformation, or equivalently the d-state probability of the quark wave functions, is most easily measured by the $L = 2$ nucleon-delta electromagnetic transition rates. The transverse E2 amplitude (E_{1+} in the high energy physics notation) is measured in pion-photoproduction reactions where the average of the results of many analyses [Ke 80] is an $\frac{E2}{M1}$ ratio of $0.14 \pm .016$ in agreement with the value 0 predicted from the simple symmetric quark model. However there is some model dependence (not included in the above uncertainty) in the extraction of the amplitudes and a larger E2

Figure II-4. Neutron electric form factor for different bag radii (solid lines) and experimental electric form factor (vertical lines) taken from [Th 82].

amplitude is not totally excluded. The multipole amplitudes for electroproduction of the $\Delta(1232)$ are shown in Figures II-5 and II-6. The dominant M1 amplitude (M_{1+}) does not show the same momentum dependence as the nucleon amplitudes. While the transverse E2 amplitude is small, qualitatively consistent with the photoproduction results, the longitudinal C2 amplitude (S_{1+}) is ~10% of the M1 amplitude, and apparently not zero, differing from what the symmetric quark model would suggest. To date, no quark model has been able to reproduce these results. Simple, non-relativistic estimates with d-state admixtures as large as those suggested by the chiral bag model give E2 and C2 amplitudes of ~5% of the M1 amplitude without an obvious explanation of the factor of 3 to 5 difference in the experimentally-determined amplitudes. An important future research program will be improved experimental determination of the small amplitudes. For the $N(938) \rightarrow \Delta(1232)$ transition, the coincidence cross section is given by [Si 71]:

$$\frac{d^5\sigma}{dE_e d\Omega_e d\Omega_\pi^*} = \frac{\alpha E_e'}{2\pi^2 E_e} \frac{K}{k^2} \frac{1}{1-\epsilon} \frac{d\sigma}{d\Omega_\pi^*}; \quad \epsilon \equiv \left[1 + 2 \left(1 + \frac{\omega^2}{q^2} \tan^2 \frac{\theta_e}{2}\right)\right]^{-1} \quad (II-5)$$

$$K = (M_\Delta^2 - M_n^2)/2M_n$$

$$\begin{aligned} \frac{d\sigma}{d\Omega_\pi^*} = & A_0 + A_1 \cos\theta_\pi + A_2 \cos^2\theta_\pi + \sqrt{2\epsilon(1+\epsilon)} (D_0 + D_1 \cos\theta_\pi) \sin\theta_\pi \cos\phi_\pi \\ & + \epsilon C_0 \sin^2\theta_\pi \cos 2\phi_\pi \end{aligned} \quad (II-6)$$

In the limit that only the Born terms and the $\Delta(1232)$ amplitudes are important the coefficient D_1 is sensitive to C2. Experimentally, the simplest technique is to vary the virtual photon polarization to determine these amplitudes. At typical momentum transfers $[0.2 \text{ (GeV/c)}^2 \lesssim q^2 \lesssim 0.7 \text{ (GeV/c)}^2]$, the experimental uncertainty on the small amplitudes can be reduced to better than $\pm 3\%$ of the M1 amplitude. Previous works have only studied the $p(e^-, e^-p)\pi^0$

Figure II-5. Magnetic form factors of the N(938) to $\Delta(1232)$ transition compared to the nucleon dipole form factor (G_D). The form factor G_m is related to the transition amplitude M_{1+} by

$$G_m = \left[\frac{6M_N^2}{\alpha} \frac{|\vec{q}|}{(P_2)^2} \frac{\Gamma_\Delta}{\sin^2 \gamma_{33}} M_{1+}^2 \right]^{1/2}.$$

This figure is taken from [Tr 76].

$\Delta(1232)$ ELECTROPRODUCTION AMPLITUDES

Figure II-6. The ratio $\text{Re}(E_{1+}^* M_{1+})/|M_{1+}|^2$ and $\text{Re}(S_{1+}^* M_{1+})/|M_{1+}|^2$ as a function of q^2 for π^0 electroproduction of the $\Delta(1232)$. This figure is adapted from [Tr 76].

reaction, while a new facility will also make comprehensive $p(e^-, e^-n)\pi^+$ experiments feasible. The improvement in the statistical uncertainty, and the possibility of measuring the electroproduction amplitudes in different isospin channels are both important improvements necessary to establish this fundamental property of the nucleon. These experiments may provide the only clean way to study possible tensor forces between quarks.

3. The Two-Nucleon System

The two-nucleon system provides the simplest opportunity to study the force between nucleons, and the response of a correlated pair of nucleons to external probes. Most of our understanding of the nucleon-nucleon (N-N) interaction is derived from N-N scattering experiments. Unfortunately, these studies can provide little constraint on the off-shell behavior of the N-N amplitudes. Such information is important in a variety of problems in nuclear physics, including the key issue of describing a many-nucleon system. Electromagnetic studies seem to be particularly suited for these investigations and have already revealed much important information to characterize the two-nucleon system.

The introduction of two-body forces between hadrons leads directly to the question of two-body currents, or meson exchange currents. The $n + p \rightarrow d + \gamma$ capture reaction and the $d(e, e')pn$ reactions provided the first clear evidence of the importance of such effects. The electrodisintegration data are illustrated in Figure II-7 along with the impulse approximation (IA) and IA plus exchange current calculations. It is now realized that invariably as measurements are made at higher momentum transfer, these correlations between nucleons become important. More recently, Kisslinger [Ki 82] has considered the question of two baryon currents within the framework of a

Figure II-7. Electrodissintegration of the deuteron to final n-p states with excitation energy of 1 to 4.5-MeV. The calculations are the impulse approximation (IA, dashed curve) and the impulse approximation plus meson-exchange corrections plus $\Delta(1232)$ corrections (IA + MEC + Δ , solid curve) [Fa 76].

quark model. In this model a short-range two-baryon current which arises in a phenomenological quark shell model is added to the conventional one-nucleon and pionic currents. This model gives an excellent representation of the electrodisintegration cross section at 180° for the deuteron.

At the present time, even the elastic form factors for electron-deuteron scattering are not well determined. Since the deuteron is a spin-one nucleus, three form factors--charge, quadrupole and magnetic--are necessary to describe the elastic scattering. The charge and quadrupole form factors have not been isolated empirically. The reason for this difficulty can be seen from the form of the elastic scattering formula [Ha 80]:

$$\frac{d\sigma}{d\Omega} = \sigma_M [A(q^2) + B(q^2) \tan^2(\theta/2)] \quad (\text{II-7})$$

where

$$A(q^2) \equiv F_C^2 + (8/9)\tau^2 F_Q^2 + (2/3)\tau F_M^2,$$

$$B(q^2) \equiv 4/3 (1 + \tau) F_M^2$$

and $\tau = q^2/4M_d^2$. Here F_C , F_Q and F_M are the deuteron form factors. Clearly, measurements of the cross section allow only the determination of $A(q^2)$ and $B(q^2)$. In practice, $A(q^2)$ is determined at forward angles while $B(q^2)$ is measured at large angles. Hence, only F_M can be isolated in cross section measurements. The quadrupole form factor is related directly to the d-wave component of the deuteron wave function. Thus, a determination of F_Q would constrain the tensor part of the N-N force. The charge form factor is sensitive to the s-wave part, and is expected to further constrain the short range part of the deuteron wave function.

At high momentum transfers two difficulties arise in interpreting the elastic scattering data: the effects of meson exchange currents (MEC) and the uncertainty in the electromagnetic form factors of the nucleon. The uncertainty in the neutron electric form factor leads to a significant uncertainty in the electric form factors for the deuteron above $q = 0.6 \text{ GeV}/c$. Presently, there is no clear empirical information with regard to the effect of MEC on isoscalar observables in nuclei. Calculations [Ha 80] indicate that the MEC corrections to F_M are significant for all values of momentum transfer studied thus far and are sensitive to the particular N-N model chosen for the calculation. However, the corrections to the electric form factors are not sensitive to the N-N model. One of the main effects of the MEC is to shift the first diffraction minimum of F_C to lower values of momentum transfer. Measurements of $A(q^2)$ and $B(q^2)$ alone do not provide sufficient information to determine the location of the minimum in the diffraction pattern since in the region where F_C is expected to be small, F_Q becomes large. Polarization experiments promise to provide the most clear means to isolate F_C and F_Q .

The expression for the tensor polarization t_{20} of the recoiling deuteron after elastically scattering with the electron, is given by [Ha 80]

$$t_{20} = -\frac{1}{\sqrt{2N}} \left\{ \frac{8}{9} \tau^2 F_Q^2 + \frac{8}{3} \tau F_C F_Q + \frac{2}{3} \tau F_M^2 \left[\frac{1}{2} + (1+\tau) \tan^2 \left(\frac{\theta}{2} \right) \right] \right\} \quad (\text{II-8})$$

where $N = A(q^2) + B(q^2) \tan^2(\theta/2)$. Below a momentum transfer of $0.8 \text{ GeV}/c$ the magnetic form factor has a small effect on t_{20} ; thus, this quantity is directly dependent on F_C and F_Q . If the measurement is performed in a momentum transfer region where F_M is negligible, then t_{20} reduces to

$$t_{20} = -(2)^{1/2} X(X + 2)/(1 + 2X^2)$$

where $X = 2/3 \tau F_Q/F_C$, a quantity which is independent of the electric form factors of the nucleon. The sensitivity of t_{20} to the isoscalar pair current contribution to the MEC is shown in Figure II-8. The sensitivity is greatest between $q \approx 0.8$ (GeV/c) and 1.2 GeV/c. This is precisely the region of momentum transfer which a high duty factor and current 2-GeV electron accelerator would render accessible for a measurement of t_{20} .

Coester and Osterbee have calculated the tensor polarization with a relativistic deuteron wave function, which is equivalent to including the pair current [Co 75]. They point out that there are classes of "exotic" deuteron wave functions which are not constrained by present measurements of the static properties of the deuteron or of $A(q^2)$ and $B(q^2)$. The tensor polarization was found to be extremely sensitive to the nature of the short range part of the wave function. Recently, the form factors for the deuteron have been calculated [Ko 78, Ki 82] within the framework of quark models. A striking feature of one of these calculations [Ko 78] is a shift in the first zero of the charge form factor from the values $0.6 \text{ GeV/c} < q < 0.8 \text{ GeV/c}$ expected for conventional models to a value greater than 1.6 GeV/c. Consequently, experiments which are sensitive to individual form factors for the deuteron should prove useful for observing the effects of quarks in nuclei.

In the simplest approximation coincidence electrodisintegration measurements provide a direct measure of the deuteron single particle wave functions. In the impulse approximation for the $d(e, e'p)n$ coincidence experiment

CALCULATIONS OF t_{20} FOR "REASONABLE" N-N MODELS

Figure II-8. Calculations of t_{20} for $e + d$ elastic scattering for 3 N-N potentials. The effect of including meson exchange currents in the calculations is also shown.

$$\frac{d\sigma}{d\Omega_e, d^3p} = \kappa \frac{d\sigma^{(P)}_{e,p}}{d\Omega_e} |\phi(p)|^2 \quad (\text{II-9})$$

where $\phi(\vec{p})$ is the deuteron wave function in momentum space, $d\sigma(\vec{p})/d\Omega_e$ is the elastic electron-proton cross section with off-shell corrections, κ is a kinematical factor describing the density of final states and E_B is the deuteron binding energy. Here,

$$|\phi(p)|^2 = |\int u_0(r) j_0(pr) r dr|^2 + |\int u_2(r) j_2(pr) r dr|^2$$

where $u_0(r)$ and $u_2(r)$ are the s- and d-wave parts of the deuteron wave function, respectively. The goal of this work is to measure the cross section in the vicinity of 0.4 to 0.6 GeV/c where the s-wave component is expected to vanish, and thus, to provide a measure of the d-wave part of the wave function. The theoretical calculations for several deuteron wave functions are compared with these experiments in Figure II-9. Of course, it is not known precisely at what value of momentum transfer the s-wave part of the wave function vanishes. Current theories place this minimum somewhere between 0.4 and 0.6 GeV/c. The work at Saclay extends only to a momentum transfer of 0.35 GeV/c just short of the expected minimum.

Even at relatively low momentum transfer, there seem to be problems with our understanding of the two-nucleon system. For example, it is well known that there is a large discrepancy between the experimental results and all present theoretical calculations for the cross section of deuteron photodisintegration at 0° [Hu 76, Lo 77]. Despite the introduction of meson exchange currents, rather drastic modifications of the tensor component of the N-N interaction or corrections to the electric dipole operator, none of the

Figure II-9. The experimental "effective nucleon momentum distribution" at the deuteron compared to various theoretical calculations. Each theoretical curve is normalized (by ~ 0.82) to give a best fit to the data [Rb 81].

calculations can reproduce the data. These findings shake the underpinnings of our understanding of even the simplest nucleus.

Recently, there have been two reports of narrow structures in the excitation function for the $\gamma + d$ reaction: a structure at $E_\gamma \sim 400$ MeV has been observed in the $d(\gamma, p)x$ and $d(\gamma, p\pi^-)x$ reactions [Ar 81b]. These data are illustrated in Figure II-10 where the ratio of the experimental counting rate to the expected quasifree cross section is presented as a function of energy. A resonance was found which has a width of 40 MeV and a mass of 2.23 (GeV/c)^2 which is near the mass of the suspected 3F_3 dibaryon resonance. In addition, a study of the polarization of the emitted proton from the $D(\gamma, \vec{p})$ reaction near $E_\gamma = 500$ MeV revealed a rapid fluctuation in the polarization [Ka 77]. This fluctuation has also been attributed to the effect of a dibaryon resonance. It is essential to study these regions in more detail, and to extend the investigation to higher energies where additional dibaryon resonances may occur [Ho 79].

4. Three and Four Body Systems

A fundamental theory of complex nuclei must be based on an understanding of the basic forces and currents among the constituent nucleons and a description of the many-nucleon system in terms of the elementary amplitudes. The three- and four-body systems are uniquely important tests of this procedure, since they are sufficiently simple many-body problems that exact or nearly exact calculations of the nuclear structure can be performed. Since the binding energies per nucleon are greater than that in the deuteron, with a corresponding decrease in the average N-N separation, these systems may provide a "better source" of nucleon pairs than does the deuteron to study correlation effects. Consideration of a non-relativistic

Figure II-10. Ratio of the experimental counting rate to calculated quasifree contribution for the $d(\gamma, p)X$ reaction as a function of photon energy. The solid curves give the expected behavior based on other calculations of the process.

description of nuclei as composed of nucleons interacting only with two-body forces runs into immediate problems in failing to account for the binding energies of ^3H and ^3He (Table II-1). The discrepancies become even more serious for ^4He . This has lead to the introduction of 3-body forces and agreement with the experimental values can be obtained with this procedure [Ca 81a]. These calculations are also successful in reproducing the Coulomb energy difference between ^3He and ^3H , a long standing problem.

Table II-1. Binding Energies of 3 and 4 Nucleon Systems

	Experiment (MeV)	Calculations (MeV)	
		2 body	2 and 3 body*
		interactions	interactions
^3H	8.48	7.0 ± 0.1	8.1 ± 0.1
^3He	7.72	6.4 ± 0.1	7.7 ± 0.1
^4He	28.3	22.8 ± 0.5	29.1 ± 0.4

*(Ca 81a)

Electron scattering has played an important role in highlighting the deficiencies of the current calculations. The elastic charge form factors for ^3He and ^4He [Mc 77; Ar 78] are shown in Figures II-11 and II-12 along with several theoretical form factors. There is significant disagreement for $q^2 > 0.5 (\text{GeV}/c)^2$. Mesonic exchange effects are certainly important in this region of momentum transfer though their exact magnitude is still open to question [Ha 78]. If the results, with some mesonic corrections are transformed to a point nucleon density, the resulting ^3He density (shown in

Figure II-11. The charge form factor of ${}^3\text{He}$ with HEPL, Orsay and SLAC data (see Ref. [Si 78]). The curves represent more-or-less state-of-the-art theoretical calculations, namely: solid line, Hadjimichael [Ha 78]; dotted line, Haftel and Kloet [Ha 77a]—with a limited set of processes included; dashed line and dash-dot line, calculations of Nunberg and Prosperi and of Borysowicz and Riska, respectively, as quoted by Sick [Si 78]. The inset shows the corresponding point-like nucleon density; light shading, using experimental data below 20 fm^{-2} ; dark shading, using all the data; thin solid line, theoretical results [Ha 78] obtained by Bessel-transforming the form factor calculated in the range $0 < q^2 \lesssim 50\text{ fm}^{-2}$ (solid curve in main figure).

Figure II-12. Charge form factor for elastic electron scattering from ${}^4\text{He}$ [Ar 78]. The curves represent various calculations.

Figure II-11) has a central depression which may provide some insight into the source of the discrepancy. It is significant that the calculations with three-body forces can produce a central depression in the nucleon density, though not in quantitative agreement with the experimental form factor (Ca 81a]. It is easy to understand why three-body forces might have such an effect and it is clear that this approach needs further investigation [No 81]. Similar effects are observed in ^4He which also appears to have a central depression in the point proton density.

While the charge form factors of ^3He and ^4He are known out to $q^2 > 2.6 (\text{GeV}/c)^2$, the magnetic form factor for ^3He and the charge and magnetic form factors for ^3H are not as well studied. The comparison of these two 3-nucleon systems is particularly important since, while the structure of the two are related as they are mirror nuclei, the mesonic exchange effects are different for the transverse and longitudinal form factors. It appears that measurements of the magnetization densities out to $3 (\text{GeV}/c)^2$ will be feasible with an accelerator of the type proposed, greatly improving our knowledge of these quantities.

As mentioned in the introduction, an alternative method for studying the ground state momentum distribution is by quasifree scattering. In the one-photon exchange impulse approximation:

$$\frac{d\sigma}{dE d\Omega} = (Z \sigma_{ep} + N \sigma_{en}) \frac{dy}{dE} F(y) \quad (\text{II-10})$$

$$F(y) = 2\pi \int_y^\infty \rho(k) k dk \quad y = \frac{\vec{p} \cdot \vec{q}}{|\vec{q}|} = p_{||} .$$

The variable y is defined to project out the component of the nucleon momentum

parallel to the momentum transfer. The scaling of the cross section in y allows some testing of Eq. (II-10). The results of such measurements for ^3He are shown in Figure II-13, and the scaling seems to be at least approximately satisfied. The results are systematically higher than Faddeev calculations at the larger momentum transfers. Similar data on ^4He also shows evidence that the nuclear form factor is underestimated at large momentum transfer, the same conclusion that is evident from the elastic scattering studies.

Of course (e^-, e^-N) coincidence experiments on the three and four body systems will also provide direct information of the ground state wave functions. Each of the complementary techniques is important, as in each case the effects of the nuclear structure and the effects of nonnucleonic degrees of freedom are intertwined, and it is only if consistent results can be obtained from several approaches that both the nucleon and non-nucleon degrees of freedom will be experimentally determined.

Figure II-13. High q $e+{}^3\text{He}$ quasielastic data [Sl 80] plotted as a function of the scaling variable y . The dashed curve is calculated with a ${}^3\text{He}$ wave function obtained by solving the Faddeev equations.

C. COMPLEX NUCLEI

For nuclei with A greater than 4, the strong interaction between nucleons does not allow a rigorous solution of the many-body problem. These nuclei are described instead either via Hartree-Fock calculations using effective interactions, restricted shell model calculations with effective interactions, or phenomenological collective models which emphasize particular nuclear properties. The long range goal is to obtain a description of these complex nuclei in terms of fundamental particles and their interactions. For energies up to 1 GeV the description is mainly in terms of nucleons plus effects due to meson exchange. Pion exchange has recently become a qualitative part of nuclear physics and it is hoped that the phenomena in this regime (<1 GeV) can be interpreted in terms of nucleons, Δ , π and ρ mesons. This would then provide a firm foundation for establishing the role of the quark degrees of freedom in hadronic matter. The principal contributions which the proposed accelerator will likely make for nuclear structure arise from the increased beam intensity and duty factor which allow one to conduct experiments that are marginal or not feasible with current accelerators. In this category are many coincidence experiments such as $(e,e'N)$ and inelastic scattering to closely spaced states which require good energy resolution. However, there are some important experiments where the high energy feature is required, and these will be pointed out.

The study of complex nuclei involves the use of various techniques depending on which aspect of nuclear structure is being emphasized, so the following discussion is partitioned into several categories. Since a comprehensive summary [Do 81] of electromagnetic interactions with nuclei

exists, our emphasis will be on areas where the proposed accelerator can provide significant new information.

1. Ground State Densities

a. Elastic Charge Scattering

Electron scattering experiments have provided the most reliable information regarding nuclear density distributions that are available. Indeed, the test of validity for a theoretical calculation of charge densities is agreement with results from electron scattering. As discussed in the introduction to this section, only charge densities are obtained from the scattering on targets with zero total angular momentum. Scattering of hadronic probes has indicated that the matter distribution is quite similar to the charge distribution, insofar as the hadronic particles can probe the interior of reasonably heavy nuclei.

Recently, substantial efforts [Ge 81] have been made to extend the range of elastic charge scattering in selected nuclei out to momentum transfers of $\sim 3.8 \text{ fm}^{-1}$, where cross sections are $\sim 10^{-37} \text{ cm}^2/\text{sr}$. The rapid decrease in cross section with increasing momentum transfer (e.g. Figure II-3) indicates that extensions of only a few tenths of an inverse Fermi will be feasible even with the orders of magnitude improvement in data acquisition capability. Nevertheless, even this small increase in range can significantly reduce the "model-dependent" uncertainties in central densities (See Figure II-14). In addition, the proposed capabilities (higher currents, larger-acceptance spectrometers, better resolution) will permit similar detailed study of nuclei away from closed shells and nuclei with intrinsic deformation. At present, the technical difficulties of target thickness,

Figure II-14. The charge densities for several representative nuclei. Solid curves correspond to "model-independent" experimental results [Ca 79a]. The theoretical curves of Gogny [Go 79] are labelled: DI-density dependent Hartree-Fock; DI+RPA-density dependent Hartree-Fock with RPA correlations.

resolution and intensity have restricted the range of momentum transfer over which these nuclei have been investigated.

In Pb, a benchmark target for these studies, a major fraction of the central peak arises theoretically from the $4s_{1/2}$ protons that fill the shell at $Z = 82$. Quite recently, an experimental comparison of the charge densities of ^{206}Pb and ^{205}Tl revealed a difference (Figure II-15) corresponding to the radial wave function of a $4s_{1/2}$ proton, in accord with the shell model description. Similar comparisons, involving pairs of nucleons, have been obtained for several nuclei in the f-p shell. For intrinsically deformed even-even nuclei, elastic scattering and inelastic scattering to the ground-state rotational band are directly related to the intrinsic shape of the nucleus. The sensitivity of electron scattering to details of both the charge density and the transition density coupled with the low probability for multiple-Coulomb excitation allow "model-independent" measurements of the multipole decomposition of permanently deformed intrinsic-state density distributions.

Despite the long impressive history of elastic charge scattering of electrons, new information is needed. Precision measurements over a wide range have been obtained for only a few nuclei. Because of the rapid decrease in cross section with increasing q and scattering angle, present facilities require an inordinate amount of time for these studies. Orders of magnitude increases in counting rates are expected from the proposed facility so that these fundamental studies may be undertaken.

Figure II-15. Ratio of elastic cross sections for ^{205}Tl and ^{206}Pb reflecting the effect of the $4s_{1/2}$ proton whose wave function in momentum space has a peak near 2 fm^{-1} . The curve is a prediction of mean field theory [Fr 81].

b. Elastic Magnetic Scattering

For targets with $J > 0$ odd magnetic multipoles also contribute to elastic electron scattering. While the longitudinal form factor is determined principally by the charge density, at large momentum transfers the transverse form factor is dominated by magnetization currents due to both protons and neutrons. In high-spin, odd-A nuclei the highest allowed multipole, $M(2J)$ is dominant at high q , and arises primarily from the last unpaired nucleon, thereby allowing investigation of the radial distributions of valence nucleons.

While the description of magnetic scattering appears to be relatively simple and extraction of nuclear structure relatively straightforward, there appear to be significant discrepancies [De 80] between experimental results and theoretical calculations. At both low and high momentum transfers (see Figure II-16) there are deviations from detailed mean field predictions that seem to be independent of the detail of the form of the radial wave function for the valence nucleon. Accurate knowledge of the rms radius of this last neutron orbit is crucial to fix Coulomb energy differences. The 5-10% deficiency in calculated Coulomb energy differences is one of the long standing problems in nuclear structure physics.

The capabilities of the proposed accelerator will allow studies of these orbitals to be continued under diverse kinematic conditions, while the improved resolution at higher beam intensities makes a wider variety of nuclei accessible to investigation with reasonable data acquisition rates.

Figure II-16. The experimental results and the theoretical predictions for the magnetic form factors. The contributions of the highest magnetic moments M_5 and M_7 to the magnetic form factors are given separately [De 80].

2. Inelastic Scattering

a. Discrete State Inelastic Electron Scattering

The most important influence on nuclear structure by electron scattering probably occurs in the analysis of inelastic scattering of electrons that leads to discrete excited states of the nucleus. Detailed measurements of angular distributions are transformed into transition densities that can be compared with those predicted by theoretical models.

The low-lying collective excitations have long been investigated with both hadronic probes and electrons, but it is only recently that electron scattering facilities have possessed the capability for resolution and the momentum range to allow extraction of the radial dependence of transition densities. For reasons mentioned earlier, such detailed studies are currently quite difficult. Although, qualitative agreement between experiment and theory is obtained, significant discrepancies are observed, particularly in regions dominated by large momentum transfer. An extensive program of measurements of collective excitation, involving both rotational and vibrational states of nuclei, would provide means for distinguishing between various competing models for describing the structure of the excitations. In particular, the special features of the interacting boson approximation could be tested in transitional nuclei.

While collective excitations involve a coherent superposition of many particle-hole configurations, other states may be reached only via excitation of a single particle-hole configuration built upon the nuclear ground state. The analysis of inelastic scattering to these non-collective states provides insight into the wave functions of these states and also allows detailed comparison with shell-model descriptions of the states. Of considerable interest recently [Li 78] are the "stretched" particle-hole

transitions observed in nuclei near closed shells. In these cases, the particle-hole pair involves promotion of a nucleon from the maximum j state in one major oscillator shell up into the maximum j state in the next oscillator shell, and the recoupling of angular momenta to the maximum, i.e. "stretched," value. Since the density of such large J states is small and excitation of the states is maximal at large momentum transfer, these states are observed even when they occur in the midst of a high level density of low spin states.

The particularly simple form of the stretched-transition operator leads to a distinctive momentum dependence for the form factor, and allows such transitions to be readily identified. The total observed strength can be compared to calculated sum-rules based on the occupancy of the hole-orbital in the ground state. In studies to date not more than about 50% of the predicted strength has been observed, so investigations capable of seeing weaker transitions and looking for meson-exchange effects at higher momentum transfer in these magnetic transitions may help resolve the discrepancy. Studies of spin dependent transitions for high and low angular momentum suggest the presence of non-nucleonic degrees of freedom involving π 's, ρ 's and Δ 's.

Study of discrete excited states would be greatly facilitated with the proposed accelerator since the higher intensity beams coupled with high resolution would allow observation of weak states in the presence of the radiative tails of strong peaks, particularly the elastic scattering peak. Extension of investigations to higher momentum transfer allows more precise study of the radial dependence of longitudinal transition densities. Similar studies of transitions into the "giant resonance" region coupled with coincident measurement of the decay modes from this region would permit

separation of contributions from overlapping resonances and identification of higher multipoles. In these studies the high duty factor is particularly useful.

b. Inelastic Scattering at Higher Energy

In the region of excitation above giant resonances but below meson production, the cross-section is dominated by quasi-elastic scattering from individual nucleons. By studying inclusive electron scattering, single particle features of the nuclear medium can be explored. The nuclear response functions $S_L(\vec{q}, \omega)$ and $S_T(\vec{q}, \omega)$ (longitudinal and transverse) are used to relate the experimental results to the properties of the nuclear medium. The flexibility of the proposed accelerator will allow separation of S_L and S_T over a wide range of momentum and energy.

In the response function energy dependence at fixed q ($\vec{q} \gg \omega$), the most prominent feature is the quasi-elastic peak, which, if nucleons were at rest, would be a sharp line. The centroid shift reflects the binding of the nucleons while the Fermi momentum generates a width for the peak. The longitudinal scattering should be relatively unaffected by mesonic degrees of freedom and should be directly related to descriptions of a nuclear medium involving nucleons, and correlations between them. The transverse scattering, on the other hand, reflects the same nucleonic phenomenon, but includes the effects of meson exchange and Δ formation to a much greater degree.

At present, experimental results for both response functions have features that are not understood. For ^{56}Fe , experimentalists [Al 80] find that for q between 300 and 400 MeV/c the Coulomb sum rule

$$C(\vec{q}) = (4\pi/M_T) \int_0^{\omega_{MAX}} S_L(\vec{q}, \omega) d\omega$$

has an observed magnitude of only 50% to 80% respectively (see Figure II-17) of the value calculated with a Fermi gas model having an average interaction energy of 35 MeV and a Fermi momentum $k_F = 260$ MeV/c. Estimates of the effects omitted are not sufficient to resolve the discrepancy, and it would be of great interest to be able to extend the measurements to q greater than $2k_F$ so that one would have greater confidence that all the strength has been detected.

The transverse response function $S_T(\vec{q}, \omega)$ is found to agree with values from the Fermi gas model in the region of ω near the peak cross-section for quasi-elastic scattering. However, at higher ω , in the region between the quasi-elastic peak and the region where the pion production cross section dominates, the observed magnitude of S_T is a factor of 2 larger than the calculated value. This feature has also been observed in ^{12}C [Ba 81] and other nuclei. While the contributions from some additional mechanisms have been calculated, there does not seem to be an adequate explanation of the greater magnitude.

The higher energy and intensity provided by the proposed facility will allow studies of deep-inelastic electron scattering which probe regions not currently accessible to investigation. At present, separation of the response functions S_L and S_T at fixed $\vec{q}$ can be achieved only up to momentum transfers approaching twice the Fermi momentum. As mentioned above, higher $\vec{q}$ measurements would provide a much cleaner test of the Coulomb sum-rule. The increased capabilities can provide better data over a wider range of $\vec{q}$ and ω .

Figure II-17. The Coulomb sum rule $C(\vec{q})$ for Fe compared with prediction for a Fermi gas over the range of experimentally available $\vec{q}$.

with which to test theoretical calculations and sum-rules; discrepancies could no longer be attributed to incomplete experimental results.

3. Coincidence Studies

In coincidence experiments, the chance coincidence rate is proportional to the square of the instantaneous count rate while the real data rate is linearly proportional to the count rate. With present accelerators, the ~1% duty factor causes the time averaged true coincidence counting rate to be 10^4 times lower than the limits set by chance coincidences. In addition, low cross sections, e.g., 10^{-36} cm²/MeV² sr², require long runs at the present time. It is clear that a 100% duty factor accelerator with a 100 μ A beam capability would allow measurements with adequate statistical accuracy down to perhaps 10^{-38} cm²/MeV² sr². Such a facility would also make (e,e'n) experiments feasible with data comparable to current (e,e'p) results. It is therefore anticipated that a sizeable fraction of a nuclear structure research program would consist of such coincidence studies.

a. Discrete States

It has long been recognized that single nucleon knockout using the (e,e'N) reaction is probably the best tool for the investigations of nucleon momentum and separation energy distributions in nuclei. The weak interaction of the electron, together with flexibility in choosing the kinematic conditions of the outgoing nucleon for a given momentum transfer to the nucleus, provides an optimum arrangement for studying the single particle properties of nuclei. Moreover, electrons easily penetrate nuclei so that the interior of nuclei is accessible to investigation, in contrast to hadronic probes that are restricted to studies of the nuclear surface. The utilization

of (e,e'p) reactions in spectroscopic studies has so far been limited by the requirement of coincidence experiments involving low cross sections coupled to accelerators with low duty factors, ~1%. A high current, 100% duty factor electron accelerator will greatly enhance experimental capability for this type of measurement.

In the intermediate energy regime where the Plane Wave Born approximation is essentially valid, the (e,e'p) reaction is viewed as elastic scattering on a bound, moving proton which is knocked out of the target nucleus (Figure II-18). Neglecting distortion effects (both proton and electron) the coincidence cross section can be written as:

$$\frac{d^4\sigma}{dE'd\Omega_e dT'd\Omega_p} = K \left(\frac{d\sigma}{d\Omega}\right)_{ep} S(\vec{p}, E_s)$$

where $(d\sigma/d\Omega)_{ep}$ is the elastic electron-proton cross section with kinematic and off-mass-shell corrections, $S(\vec{p}, E_s)$ is the nuclear spectral function, and K is a kinematic factor. (The factorization is strictly valid only in PWBA.) $S(\vec{p}, E_s)$ is the combined probability to find a proton with momentum $\vec{p}$ in the target nucleus and to remove it with separation energy E_s . As can be seen from the figure, conserving energy and momentum

$$E_s = E_1 - E_2 - T_{p'} - T_B$$

$$\vec{p}_B = \vec{p}_1 - \vec{p}_2 - \vec{p}' = -\vec{p}$$

where T_i is the kinetic energy of the particle i , and E_i is the energy of the electron with momentum $\vec{p}_i$.

Figure II-18. The quasi-free (e,e'p) process in Plane Wave Born Approximation.

In the case of a spin-zero target with the residual nucleus in a discrete final state J , a one-step knockout process can only excite this state to the extent that there is a proton present in an orbital J in the target. The spectral function, $S(\vec{p}, E_g)$ is proportional to the spectroscopic factor for the particular final state times the momentum-space representation of the proton density in the bound orbital. In practice, the nuclear medium causes distortion of the outgoing proton wave, so that extraction of nuclear structure information is more complicated than in the Plane-wave Born Approximation. However, the distortion effects can be minimized by selecting outgoing proton energies of several hundred MeV where the nucleon mean free path is three times larger than at 50 MeV.

As a specific example of the science that can be studied, consider $^{12}\text{C}(e, e'p)^{11}\text{B}$ where some data [Mo 76] already has been obtained. This data, although of considerable interest, was limited to $q < 300$ MeV/c. It is precisely in the region $q \approx 300 - 450$ MeV/c, that one expects deviations of nucleon wave functions from those derived from mean field approximations. The strong interaction between nucleons at distances ~ 0.65 fm should strongly modify the momentum space wave function thereby giving rise to "short-range correlation" effects. The spectrum of ^{11}B states in Figure II-19, offers a variety of possibilities for extracting orbital wave functions and for testing the dominance of single-proton knockout. The most recent $(e, e'p)$ data is shown in Figure II-20 where, because of the low counting rate, the data is binned into low and high momentum groups in order to improve statistics, and also to separate $1s$ knockout (which peaks at low q) from $1p$ knockout (which peaks at higher q). Evidence for discrete final states is seen for the ground state and in three other peaks. The following points could be studied with the experimental capabilities of the proposed accelerator.

Figure II-19. Energy levels of ^{11}B up to 8 MeV.

Figure II-20. Missing (separation) energy spectra for $^{12}\text{C}(e,e'p)^{11}\text{B}$ with incident electrons of 497 MeV and duty cycle = 1% [Mo 76].

1) Since the ground state ($3/2^-$) and first excited state ($1/2^-$) are seen to be excited in the first two peaks, one could map out the momentum distribution of the $1p_{3/2}$ and $1p_{1/2}$ orbitals separately. The magnitudes reflect the spectroscopic factors for the ^{11}B states.

2) Better resolution and a measurement of the momentum distribution would decide whether the fourth peak corresponds to excitation of the $7/2^-$ or the $1/2^+$ state near 6.7 MeV. From Figure II-20, it seems that it may be the $1/2^+$ state since it is relatively stronger at low q .

3) The $7/2^-$ state and the $5/2^-$ state at 4.45 MeV should be very weakly excited by single-proton knockout, so an $(e,e'p)$ study would show whether this expectation is confirmed. The $5/2^+$ state at 7.29 MeV and the $3/2^+$ state at 7.98 MeV offer the possibility of looking for weak $(1d_{5/2})^2$ and $(1d_{3/2})^2$ admixtures in the ^{12}C ground state.

The momentum distributions, $S(\vec{p})$ at fixed E , should be measured out to as high a momentum as is feasible. The experiment should be repeated at several incident electron energies. It is assumed that complete spectra covering a wide range of excitation energy (~ 100 MeV) would be obtained throughout. Such a study would require incident electron energies ranging from ~ 500 MeV to ~ 1500 MeV.

The experiment would then provide data for coincident scattered electrons and ejected protons under kinematic conditions where the excitation energy is precisely known, the momentum transfer to the nucleus covers a wide range for each state, and the kinematic regime is varied sufficiently to provide separation of longitudinal and transverse form factors so as to ascertain the impact of distortion effects and higher order processes. We would expect to determine the wave function up to high momenta of individual

orbitals through the longitudinal component, and be able to investigate contributions due to meson exchange currents in the transverse component.

b. Excitation above Bound Levels

Above about 8 MeV, the residual nucleus becomes unstable to emission of nucleons and heavier particles, and the spectrum of E_s becomes a continuum as in Figure II-20. Current measurements of $(e,e'p)$ have concentrated on interpreting the spectral function in terms of broad distributions of the strength for removal of protons from valence orbitals and more deeply bound orbitals. The results are then average momentum distributions and centroids of binding energy for each orbital. In comparing the summed strength to sum-rules for the occupancy of the orbitals, there are deviations from one's expectations. There is also a general lack of agreement with the basic Koltun [Ko 72] sum-rule which relates the mean separation energy and mean kinetic energy to the known total energy per proton. The integrals with current spectral functions do not provide enough binding energy. The measurement of orbital momentum distributions for discrete states may prove helpful in resolving the question about the current procedure.

c. Relation of $(e,e'N)$ to (γ,N)

The discussion has considered only one-step proton knockout where, as in Figure II-18, the electron interacts via a virtual photon. If the left hand edge of the figure were obliterated, the diagram could equally well describe a (γ,p) reaction. Indeed, photo-ejection of nucleons provides the same information as $(e,e'p)$ but the restriction to real photons limits the minimum momentum transfer to values of $q \approx 250$ MeV/c or greater. One of the main objectives in the $(e,e'p)$ studies is to provide a sizeable overlap in

Figure II-21. The $1p$ shell momentum distribution for ^{12}C deduced from the data for the $(e, e'p_0)$ reaction (open circles) and the (γ, p_0) reaction (solid circles) after making distortion and other corrections. The momentum distributions calculated from an Elton-Swift potential are also shown; the solid line is the $1p_{3/2}$ distribution and where it is distinguishable the dashed line shows the effect of a 10% $1p_{1/2}$ admixture [F1 77].

momentum between $(e,e'p)$ and (γ,p) results. In Figure II-21, the current status of such overlaps is exhibited for ^{12}C , one of the few nuclei for which there is some overlapping data (around 300 MeV/c.). In order to compare the momentum distributions from $(e,e'p)$ and (γ,p) reactions, corrections must be made for final state (i.e. p-nucleus) distortions. These corrections have been made [Fi 77] in the data of Figure II-21 where the agreement in the overlap region suggests that PWBA suitably corrected is reasonably adequate.

There are serious problems that must be considered in addition to merely providing an overlap between two probes that supply the same information. The interaction between electrons (photons) and protons is relatively strong while the e-neutron interaction is quite weak proceeding only via the magnetic moment. It is experimentally observed, however, that (γ,n) cross sections on $T = 0$ nuclei are of the same magnitude as (γ,p) cross sections, in disagreement with a simple model of the scattering process. Gari and Hebach [He 76] use a different theoretical approach in which they separate the contributions to the (γ,n) amplitude into pieces from one-body currents, exchange currents and initial-final state correlations. Their calculations require a number of approximations, but they do achieve approximate agreement with both the (γ,p) and (γ,n) data. They find that at low photon energies, the largest contribution is not the simple one-body scattering, but rather the meson exchange current component. This indicates that the interpretation of the spectral function at high momentum in terms of the single-particle momentum space wave function may be seriously in error.

This may not be an insurmountable problem, however, and in fact is particularly interesting. At low momentum transfer, there is no reason to expect sizeable deviations from the modified PWBA for $(e,e'n)$ reactions, while there is already evidence for such deviations in the (γ,n) reactions. As

noted earlier, mesonic degrees of freedom are expected to be more important in the transverse response function, which is the only term present in (γ, n) reactions. The electron may scatter from protons via longitudinal scattering. With the proposed facility, $(e, e'N)$ studies are feasible over the entire range required to establish overlap with (γ, N) data for both longitudinal and transverse response functions. A careful examination of the momentum dependence of $(e, e'p)$, $(e, e'n)$, (γ, p) and (γ, n) reactions on $T = 0$ nuclei, including separation into longitudinal and transverse response functions for several discrete final states should then establish the range of validity of the modified PWBA approach and extend the range of reliable data to significantly higher momenta. In addition, these $(e, e'N)$ studies may provide a means for explicitly measuring the effects of meson exchange currents.

In summary, a major facet of the proposed nuclear structure program is expected to involve studies of $(e, e'N)$ reactions. The relative simplicity of electromagnetic interactions coupled with the flexibility in choosing kinematic conditions provides a capability for investigating the spatial interior region, in other words the deeply bound states, of nuclei which cannot be reached with hadronic particles.

A natural extension of single nucleon ejection is the ejection of several correlated nucleons or clusters. To the extent that the impulse approximation is valid, $(e, e'X)$ reactions, (where X is a group of correlated nucleons) explore such range correlations. For small energy losses, these experiments investigate cluster wave-functions in a manner complementary to heavy-ion induced reactions. For larger energy losses questions of pre-formation of clusters become relevant. When the photon wave length is comparable to the nucleon size, the momentum dependence of short-range

correlations should become amenable to investigation. At present, this subject suffers from a dearth of data, which would be rectified with the proposed facility.

D. STUDY OF NON-NUCLEONIC DEGREES OF FREEDOM IN NUCLEI

1. Present Status

One of the major areas in need of investigation in nuclear physics is the effect of non-nucleonic degrees of freedom on the properties of nuclear matter. Some aspects of these have been referred to, to some extent above, in connection with meson exchange currents, for instance. Our present understanding of nuclear matter in its ground state certainly implies some assumptions about non-nucleonic degrees of freedom and the short-range high-momentum components of the effective nucleon-nucleon interaction, and internucleon correlations. By far the most promising tool for the exploration of these questions lies in electromagnetic probes in the GeV range. Since our understanding of this regime is still at a very rudimentary level the discussion in this section is, of necessity, more qualitative than other aspects of electron physics.

There are two major developments which make it possible to study non-nucleonic degrees of freedom inside the nucleus with increased vigor. First are the theoretical methods, which in concert with modern computers have become sufficiently accurate that the consequences of conventional nuclear models in describing several important nuclear quantities can be explored in an almost "exact" way. The outcome of these investigations demonstrate unambiguously the limitation of conventional "nucleonic" theories of nuclei. For example, in Figure II-22 and Table II-1, one notes that nuclear saturation cannot be described by Brueckner theory [Da 81], variational theory [Ca 81a], nor by the most recent Green's function Monte Carlo method [Za 81a]. Another specific instance of the limitations of present theory is in Figure II-23,

Figure II-22. Nuclear saturation calculated from conventional nuclear theory. The results are from [Da 81].

Figure II-23. Point proton charge density of ${}^3\text{He}$ calculated from conventional nuclear theory including a three-body force. The results are from [Ca 81a].

which illustrates that the density of ${}^3\text{He}$ calculated by the variational method [Ca 81a] including three-body forces, deviates significantly from the data.

The second advance is experimental, new data from the facilities at LAMPF, SIN, TRIUMF, Bates, etc., provide direct contact with nuclear properties in the region where the internucleon distances are short and the excitation energy is large enough to be at least comparable to the pion rest mass. Data on pion-nucleus interactions have revealed some of the gross properties of Δ -propagation inside nuclei. Many of the features of Δ -nucleus reactions can be described in terms of the formation of a Δ -nucleon hole state, and its subsequent decay [Hi 79]. Δ -formation is also a dominant feature in the excitation function of photo-nuclear reactions, and Figure II-24 shows a comparison of inclusive proton spectra at three laboratory angles for the ${}^{12}\text{C}(\gamma, p)$ and ${}^{12}\text{C}(\pi, p)$ reaction [Mc 80]. The data are virtually indistinguishable, demonstrating that it seems to be the dynamics of Δ propagation and decay rather than the excitation mechanism which determines the proton spectra.

Although intermediate energy data have indicated several possible avenues for study, we are still far from a complete description of non-nucleonic degrees of freedom within the nucleus. This is evident from the fact that exchange current calculations involving other than the well established one-pion exchange often produce quantitatively very different results [Rh 79]. Furthermore, there are several different approaches to including relativistic effects. Most studies [Fr 77] are based on a low velocity $(v/c)^2$ - expansion of current operators. Another approach [Ar 81] uses the covariant three-dimensional quasi-potential formalism deduced from relativistic field theory. Both approaches yield reasonable agreement with the present data, but their predictions differ greatly at higher energy or

Figure II-24. Proton spectra from reactions $^{12}\text{C}(\gamma, p)$ and $^{12}\text{C}(\pi^+, p)$ are compared. The results are from [Mc 80].

momentum transfer. To resolve these problems, it is necessary to have data in the region where both the non-nucleonic degrees of freedom and the relativistic effects are important. Such data are not obtainable with present facilities.

We are in a transition period in developing a new theory of the nucleus including non-nucleon degrees of freedom, and more experimental data are needed to better define the interactions between mesons, Δ 's and other excitations within nuclear matter. Two approaches to the theoretical treatment of non-nucleonic degrees of freedom in nuclei are currently under development. Guided by hadronic spectroscopy, one may add new degrees of freedom one by one as the range of energy-momentum transfer to nuclei increases. Most of current research, such as exchange current calculations and the isobar-hole model, etc., belong in this category and have achieved several important advances. But one could also hope to build on the development of quantum chromodynamics (QCD), and to express nuclear properties in the high momentum-transfer region directly in terms of the quark and gluon degrees of freedom. At the present time, the fact that the confinement of quarks inside hadrons is not understood poses a fundamental difficulty. However, by introducing bags [De 75, Br 79] or confining potentials [De 75a] to provide confinement phenomenologically, QCD-based quark models have successfully described many properties of hadrons. Extensions [De 78] of these models to the nucleon-nucleon force and the properties of the many-nucleon systems are now being seriously investigated.

As a start, one may consider only the lowest two non-nucleon degrees of freedom: the pion and the Δ , and assume that the Δ and π couple to nucleons by the $\pi N \rightarrow \Delta$ and $N \Delta \rightarrow NN$ interactions. Such a nuclear theory will already contain mechanisms for generating significant three- or four-nucleon

forces, which are apparently needed to resolve the problem of nuclear saturation (Fig. II-22,II-23), and contain the dominant features for describing the phenomena related to pion production and Δ -excitation. Nuclear theories of this type are being extensively pursued [Hi 79, Be 81b] in the area of hadron-nucleus interactions.

The dynamics of Δ -propagation depend sensitively on the energy and momentum of the Δ . We can test the dynamics of such models by using either pions or electrons as probes, with a Δ in the nucleus created by the well-known mechanism $\pi N \rightarrow \Delta$ and $\gamma N \rightarrow \Delta$. This mechanism is illustrated in Figure II-25, where $U_{\Delta}(\vec{q}, \omega)$ represents the average Δ -nucleus potential describing Δ -propagation [Le 81]. We note that the present meson facilities will only probe U_{Δ} in a very limited region of the q - ω plane, as illustrated in Figure II-26 where the region accessible to electrons is also shown. A 2-GeV electron accelerator will explore Δ -propagation in the q - ω region which cannot be reached by any meson facility or the existing electron facilities. Electromagnetic interactions in this region of higher energy transfers will address the whole host of questions of how nuclear matter responds to relatively large transfers of energy and momentum. The questions of longitudinal-transverse, or multipole, decompositions will very much depend on the coordinate frame in which the experiment is analyzed [e.g. the center of mass with a (free) nucleon, that with a Δ or with some other entity, as the whole nucleus]--this choice in turn clearly implies model assumptions. It seems probable that the data will have to be viewed from a highly empirical perspective and the choice of coordinate frame guided by the data.

For a more complete understanding, and especially to study the properties of a very hot and dense nuclear system which can be produced in

Figure II-25. The Δ -formation dynamics included by π^- or γ absorption. It may be described by the average Δ -nucleus potential $U_{\Delta}(\vec{q}, \omega)$ as discussed in [Le 81].

Figure II-26. Contour plot of an idealized nuclear response function for electron inelastic scattering as a function of momentum transfer and energy transfer. The kinematic limits for a 2-GeV beam and for existing beams (.8 GeV) are indicated. Also shown is the energy-momentum relation for pion-induced reactions. The two contour ridges represent quasifree nucleon knockout and quasifree delta production.

stellar processes or in relativistic heavy-ion collisions, it is also necessary to know the propagation of higher hadronic modes inside the nucleus. In the $\omega > 0.8$ GeV region, mesonic modes [Do 81], such as ρ , ω and ϕ meson, can be excited electromagnetically. It is apparent from Figure II-26 that the propagation of these more complex non-nucleonic degrees of freedom inside the nucleus can also be explored in a wide region of $|\vec{q}|-\omega$ plane accessible to a 2-GeV electron accelerator. The development in this direction then will reach into a regime of nuclear phenomena which will motivate further theoretical development. Also, in such a high $\vec{q}-\omega$ region, certain QCD-type nuclear models proposed recently will face direct tests.

2. Possible Experiments

Compared with other hadronic probes such as protons, pions and kaons, the electromagnetic process can explore the properties of non-nucleonic degrees of freedom embedded deep inside the nucleus, because the electromagnetic coupling is weak. Furthermore, the analysis of results becomes much simpler because the electromagnetic coupling is known. By using the proposed 2-GeV electron accelerator, one can easily obtain extensive data of reactions such as $(e, e'\pi)$ and (γ, π) at energies well above threshold and at high momentum transfer. Because of the 100% duty factor, accurate coincidence measurements of reactions such as $(e, e'p)$ $(e, e'\pi)$ or even $(e, e'\pi N)$ can be carried out. Such data will tell us about Δ -nucleus dynamics and mesonic currents.

The details of experiments of the above type have been documented [Do 81], and need not be repeated here. In the following, we will only discuss two specific classes of experiments as examples, to demonstrate the usefulness of the 2-GeV electron accelerator.

a. Electroproduction of the Δ in nuclei.

Important strides in understanding the behavior of the Δ in a nuclear medium can be made by using electrons in (e,eX) coincidence experiments. This was illustrated above in Figure II-26. Kinematically, pions and photon-induced reactions are very similar, due to the light mass of the pion. The major difference between the two is that the photon interacts throughout the nuclear interior unlike the pion which is likely to form a Δ at the nuclear surface. This distinction may not be too important on a small nucleus such as ^{12}C . In the energy-momentum plane of the (e,e') reaction, the two ridges in Figure II-26 correspond to quasifree nucleon knockout, and quasifree Δ production. Along the quasifree Δ production ridge, an almost on-shell Δ can be produced in the nucleus while the average Δ -nucleus relative momentum may be varied (Figure II-27). In this fashion the momentum dependence of the Δ -nucleus interaction can be studied in a controlled way. A typical experiment is illustrated schematically in Figure II-28. For electron (photon) or pion induced reactions, by studying the shower of particles emitted following the decay of Δ in the nucleus, one can deduce how many particles were involved in the interaction as a function of Δ momentum, and the extent that the pion or Δ is on- or off-shell. A typical multiplicity distribution [Mc 80] from a pion-induced reaction is shown in Figure II-29 where the average number of interacting nucleons deduced from the velocity of the reference frame in which the proton distribution is isotropic is ~ 5 . At the bottom of Figure II-28, the expected distribution for a high- q electron-induced (photon-induced) reaction is shown. The centroid of the distribution should shift as the Δ momentum is varied and the distribution may also change.

The second region of the energy-momentum plane where Δ effects are likely to be important is that of high momentum transfer with low

Figure II-27. Quasifree production of Δ by (e, e') scattering. Only the pion-production final state is shown, while other final states without pions can also occur. By varying $\vec{q}$ and ω , the energy and momentum of the produced Δ can be controlled.

Δ EXCITATIONS IN NUCLEI

PION OR PHOTON REACTIONS ($c\vec{q} \approx \omega \approx 300 \text{ MeV}$)

ELECTRON INDUCED REACTION WITH $|c\vec{q}| \gg \omega \approx 300 \text{ MeV}$

Figure II-28. Schematic representation for the expected proton distribution for a typical experiment with (a) pion and photon-induced reactions (b) inelastic (e, e') with $|c\vec{q}| \gg \omega \approx 300 \text{ MeV}$.

Figure II-29. Analysis of the energy and momentum distributions from 220-MeV pion absorption on Ta from [Mc 80]. In this plot, the invariant cross section is plotted in the plane of rapidity $Y \equiv v_{||}/c$, where $v_{||}$ is the velocity parallel to the beam and $p_{\perp}$ (momentum perpendicular to the beam). The different size points represent different levels of cross sections, and each group of points represents a measurement of a single angle of the energy distribution of protons. The circles represent the best fit to these contours in which the nucleons are emitted most nearly isotropically and the arrows represent the rapidities corresponding to absorption by 2, 3, or more nucleons.

(~200-400 MeV) energy transfer. The investigation in this region is tied very closely to the understanding of all questions of high-momentum components and inter-nucleon correlations in the nucleus. In this region, the nucleus has to absorb the large momentum of the virtual photon and must rely on either the existence of significant high-momentum components of the single-nucleon wave functions or the interactions with multi-nucleon correlations within the nucleus. Since meson exchange is expected to be the primary means by which the momentum is spread through the nucleus, the strong pion-nucleon- Δ coupling implies that the isobar degrees of freedom will be particularly important. Experiments such as these will prove to be invaluable in untangling the dynamics of nuclear structure as well as the reaction mechanisms in this region. The determination of the number of nucleons which share the transferred momentum will be particularly significant. By doing the same type of experiment, one may even approximate a Rosenbluth separation in order to gain more quantitative information.

b. Electroproduction of Hypernuclei

The study of the structure of nuclei containing strange baryons is one of the tantalizing frontier areas of nuclear research. The question of how the symmetries and simple degrees of freedom of nuclei may be modified when, in addition to neutrons and protons, a third kind of quasistable particle is introduced, provides potentially highly informative tests of the foundations of models of nuclear structure. There has been a substantial increase in the amount of data available on hypernuclear structure from the (K^-, π^-) strangeness exchange reaction [Po 81]. However, at this time the experimental limitations of this reaction have restricted us to rather poorly

defined glimpses of the structure--some features are apparent but much is left to the imagination of the physicist interpreting the data.

The study of hypernuclei with electromagnetic probes is centered on the $N(\gamma, K^+) \Lambda$ or $N(e, e' K^+) \Lambda$ (or Σ) reactions. Here, as we shall see, it is feasible to do experiments with reasonable energy resolution and counting rate, comparing favorably with the $N(K^-, \pi^-) \Lambda$ process. Also, the nucleus is highly transparent to electromagnetic probes and reasonably transparent to K^+ , as opposed to a high degree of opacity for π^- and K^- . Thus the interior of the nucleus is likely to be probed more effectively. The disadvantage of the reaction is an inherent momentum mismatch of $q \gtrsim 350$ MeV/c which will tend to reduce relative cross sections for low-spin states and enhance high spin ones ($L \gtrsim 4$ in a light nucleus). This selectivity could actually be an advantage. The well-matched (K^-, π^-) reaction shows the strongest low-spin Λ -nucleon hole excitations. The (γ, K^+) or $(e, e' K^+)$ reactions will, on the other hand, selectively show the simple high-spin hypernuclear particle-hole states. Thus, from the combination of data one will get the low-spin particle-hole states as well as the stretched high-spin ones, and one may hope to extract information on the range and the spin dependence of the Λ -N effective interaction.

It is clear from electroproduction of any excitation [Bj 66] that cross sections are $\sim \pi/\alpha$ (or a few percent) of photoproduction cross sections. But, since monochromatic bremsstrahlung photons have to be tagged, electroproduction experiments have a large advantage in counting rate. Following Bernstein et al. [Do 81] who discussed photoproduction of a hypernuclear state on a ^{12}C target, we may estimate rates as follows. Let us plan for 1 MeV resolution. This allows the use of $1/2 \text{ g/cm}^2$ target. A 100 μA electron beam is assumed as well as two 30-msr magnets with 20% kaon survival

in the K^+ spectrometer. The choice of electron angle is limited by the bremsstrahlung peak at 0° --but 10° ($\pm 5.6^\circ$ for 30 msr) seems reasonable. The optimum kaon angle as may be seen in Figures II-30 and II-31, is $\theta_K \approx -12^\circ$ for $E_e = 2$ GeV and $E_{e'} = 0.9$ GeV. Here, the estimated cross section is

$$\frac{d^3\sigma}{d\Omega_e d\Omega_K dE} \approx 0.7 \times 10^{-4} \frac{\mu b}{\text{sr}^2 \text{ GeV}}.$$

Assuming a momentum bite of $\Delta p/p = 30\%$ in each spectrometer we get counting rates of ~ 54 cts/hr for the $(\Lambda 1s_{1/2})(N 1s_{1/2})_{1+}^{-1}$ state with a ^{12}C target, for which a form factor was estimated in [Do 81].

Clearly electroproduction will open up the field of hypernuclear physics to much more detailed qualitative studies than have been possible hitherto, and allow the quantitative exploration of this new dimension of nuclear structure.

Figure II-30. Cross section for the reaction $^{12}\text{C}(e, e' K^+) ^{12}\text{B}(1s_{1/2})(1s_{1/2}^{-1})_{1+}$ for fixed geometry, with the electron and the kaon on opposite sides of the beam direction (10° and -12°).

Figure II-31. Angular distribution for electroproduction of the same state as in Fig. II-30 for the inelastic electron energy and angle fixed at 0.9 GeV and 10° . The kaon angles are on the opposite side of the beam.

E. PARITY VIOLATION AND NEUTRAL WEAK CURRENTS

While an electron at low energy interacts primarily via photon exchange it has been discovered over the past decade that it also interacts weakly via the exchange of a neutral weak boson, the Z^0 . The large mass of the Z^0 (~ 100 GeV) greatly suppresses this exchange at low momentum transfer, however it is clear that electron scattering can play a large role in the study of the weak interaction. Both the charge changing and neutral weak interactions are known to have parity violating parts. Thus the small effects of these weak interactions can be uncovered by detecting pseudoscalar interaction terms in physical processes e.g. $(\vec{\sigma} \cdot \vec{p})$. In particular, this may be done with electron beams by observing the difference in yield between right handed ($h = \frac{\vec{\sigma} \cdot \vec{p}}{|\vec{p}|} = +1$) and left handed ($\frac{\vec{\sigma} \cdot \vec{p}}{|\vec{p}|} = -1$) electrons. This difference or asymmetry is written as

$$A \equiv \frac{d\sigma_R - d\sigma_L}{d\sigma_R + d\sigma_L} \quad (\text{II-11})$$

This asymmetry is due to parity violation which in our present framework can arise from two sources. It can be caused by a direct interference between the dominant electromagnetic scattering and the parity violating part of the Weak Neutral Current (WNC) Figure II-32. The asymmetry can also be brought about by a parity admixture in the nucleus caused by weak

$$A_{EM} = \frac{4\pi Q}{q^2}$$

$$A_W \approx \frac{g}{q^2 + M_{Z^0}^2}$$

Figure II-32. Feynman diagrams for electromagnetic (γ) and weak neutral (Z_0) scattering of an electron from a hadronic system.

interactions amongst the hadrons. Thus

$$\begin{aligned}
 A &= \frac{(A_{EM} + A_{WNC}^{PC} + A_{WNC}^{PV} \pm A_N^{PV})^2 - (A_{EM} + A_{WNC}^{PC} - A_{WNC}^{PV} \mp A_N^{PV})^2}{2 A_{EM}^2} \\
 &= 2 \frac{(A_{WNC}^{PV} A_{EM} \pm A_{EM} A_N^{PV})}{A_{EM}^2}
 \end{aligned}
 \tag{II-12}$$

in obvious notation. In special cases the last term may be large. It will be discussed at greater length below. The order of magnitude of the asymmetry is given by

$$A = \frac{A_{WNC}^{PV}}{A_{EM}} \approx \frac{10^{-5}}{M_p^2 (4\pi\alpha/q^2)} = \frac{10^{-4} q^2}{M_p^2}
 \tag{II-13}$$

which produces small effects for (1 GeV/c or smaller) momentum transfer. Thus asymmetry experiments are difficult and require considerable ingenuity in addition to an intense longitudinally polarized electron beam. The discussion of parity violating effects and the utility of a few GeV C.W. electron accelerator for this research is well done in FDENP [Do 81]. We will only briefly review the present status of the subject and present an experimental program with slightly different emphasis from FDENP [Do 81].

To examine the effects of parity violation in the nucleus one can employ a general formalism for the asymmetry in the scattering of polarized electrons from nuclei developed by Brian Serot [Se 79]. He considers two sources of parity violation as the source of the observed asymmetry. The first is the effect of the weak neutral current on the electron-nucleus interaction while the other is parity violation in the initial and/or final nuclear state. This latter effect is usually very small and is due to the

weak interaction between the hadrons in the nucleus. The observed asymmetry in this case is caused by the interference between the transverse parts of the normal parity and parity violating electric and magnetic amplitudes between the initial and final states. Very much less is known about the weak interactions between hadrons (in fact the weak neutral current part of this interaction has not yet been observed). In recent years however, very considerable progress [Ha 80, Br 80, Ha 81, To 82] has been made in determining the relevant parity violating nucleon-nucleon amplitudes from observed parity violation and relating [De 80] these amplitudes to weak interactions between quarks. This latter step is very important as it is at this level that the Weinberg-Salam unification of the weak and electromagnetic interactions is formulated. The roadblock in this important program to explore the hadron-hadron weak interaction is the absence of data: the experiments are very difficult. It is therefore of great importance to examine if a high-resolution large solid-angle magnetic spectrograph coupled with an intense C.W. polarized beam provide a significant tool to carry out these studies.

A moment's reflection indicates why such a scheme could work. The C.W. and high resolution features are required because nuclear parity mixing will only be large when two levels of the same angular momentum and opposite parity are nearly degenerate ($\Delta E \lesssim 100$ keV). Thus the states must be experimentally resolved and the yield counted event by event. High current (50-100 μ A) is required because the cross sections will, in general, be small $\frac{d\sigma}{d\Omega} \leq 10^{-30}$ cm². The small cross section appears necessary because the asymmetry will only be large when the normal parity transition amplitude is suppressed. The "figure of merit" (M) for a given experiment is the product

$$A^2 \frac{d\sigma}{d\Omega} \equiv M .$$

This product fixes the time scale required to achieve the requisite statistical accuracy in a given case. The order of $1/A^2$ events is needed to have sufficient statistics to observe the effect. With a magnetic spectrograph with acceptance of approximately 20 - 30 msr and 100 μ a of polarized beam values of M as small as

$$M = A^2 \frac{d\sigma}{d\Omega} = 4 (N+Z) 10^{-40} \text{ cm}^2$$

can be observed in a single day where $(N+Z)$ is the atomic number of the target. A 30 mg/cm² target is assumed.

A specific case, the mixing of the ground ($J_{\pi}^{\pi} = \frac{1}{2}^{+}$) and first excited ($J_{\pi}^{\pi} = \frac{1}{2}^{-}$) 110 keV state of ¹⁹F has been examined. All the nuclear parameters necessary to determine the value of M have been measured. At high energies $E_1 = 1.5$ GeV the predicted value is $M = 1.7 \times 10^{-41} \text{ cm}^2$ while at lower energy the values are much more favorable. It appears from this study that the best hope of studying parity violation in the nucleus with electrons requires a different facility from the one proposed here. However, it does mean that the corresponding term of eq. II-12 can be neglected at the energies of interest to us.

The situation with regard to the weak neutral current carried by the nucleon is much more promising. At this writing there is no reason to call into question the "standard model" of the WNC developed by Glashow [Gl 61, Gl 70], Salam [Sa 68], Weinberg [We 67] and others. A recent comprehensive

review [Ki 81] concludes that the "standard model" can account for all experiments involving lepton-lepton and lepton-quark couplings.

There does not exist an extensive body of precise data on WNC, as the principle sources of experimental information are neutrino interactions and small asymmetries in the deep inelastic scattering of left and right handed electrons. The very nature of these experiments requires that they be carried out at high momentum transfer. Virtually nothing has been observed at low momentum transfer ($q < \text{few GeV}/c$). There are several questions of principle to be addressed regarding the hadronic currents. Will the WNC carried by nuclei simply be the sum of the vector and axial vector WNC carried by the constituent quarks? The answer is very likely yes in the case of the vector current because of CVC. It is quite unlikely to be the case for the axial current. For example, it has not proven straightforward to obtain the observed value of 1.25 for g_A from a quark model of the nucleon.

To date only one measurement [Pr 79] of a parity violating effect has been carried out with polarized electrons. It was performed at SLAC and involved the asymmetry in deep inelastic scattering from deuterium. At a beam energy of 19.4 GeV and a scattering angle of 4 degrees, the observed asymmetry was $15.2 \pm 2.5 \times 10^{-5}$. This result confirmed the "standard model" and leads to a value of $0.23 \pm .015$ for $\sin^2 \theta_w$ though a large value is found for a parameter $S = 1.74 \pm 0.36$ which should be 1 in the "standard model."

An experiment [So 77, So 79] is currently in preparation at the Bates Electron Accelerator to measure A in elastic scattering from ^{12}C . As the ^{12}C ground state has $J = 0$ only the vector part of the nuclear weak current may enter (coupled with the axial vector WNC carried by the electron). Further, as the ^{12}C ground state is $T = 0$ only the isoscalar WNC

interactions play a role. The WNC can be written

$$J^N = J^C T_3 - 2 \sin^2 \theta_w J^{EM} \quad \text{II-14}$$

where J^C is the charge changing weak current and J^{EM} is the electromagnetic current. It is evident that the Bates experiment directly measures $\sin^2 \theta_w$. The size of the asymmetry in this case is given by

$$A = -3.2 \times 10^{-4} \frac{q^2}{M_p^2} P \sin^2 \theta_w$$

where P is the longitudinal polarization of the beam. At a bombarding energy of 150 MeV and $\theta = 60^\circ$, $A = 2 \times 10^{-6}$ is predicted for the "standard model." The analysis for this case is particularly simple and direct because the nuclear form factors are identical for the weak and the electromagnetic scattering. Thus the experiment carried out to design specifications will provide an accurate value for $\sin^2 \theta_w$.

It should be noted that even though the size of the asymmetry increases directly with q^2 it is not necessarily a great advantage to perform the measurements on phenomena other than deep inelastic scattering at high q^2 because the electromagnetic cross section falls off at least as fast as $\frac{1}{q}$. Thus considering the statistical error in A one finds

$$\frac{\Delta A}{A} \sim \left(\frac{d\sigma}{d\Omega} \right)^{-1/2} \sim q^2 \quad \text{II-15}$$

This compensates for decreased sensitivity which varies directly as q^2 (see Eq. II-12). Of course, the eventual limit is set by systematic errors and it

is difficult to see how an asymmetry much smaller than $A = 10^{-7}$ can be measured, a limit now reached in polarized proton experiments.

With a polarized beam of 50 - 100 μ a from a 2 GeV C.W. electron accelerator it should be quite feasible to measure asymmetries at momentum transfers of the order of one GeV/c on the proton. The C.W. feature of the accelerator makes a laser driven GaAs polarized electron source easy to operate as the state-of-the-art in laser technology is not pressed. Furthermore, the C.W. nature of the beam allows pulse height analysis on individual events if that should prove necessary. (Note that this would only be desirable for $A > 5 \times 10^{-5}$).

The asymmetry associated with elastic scattering for the proton is most interesting. A prescription [Ho 78] using quarks has been worked out using as input the charged weak and electromagnetic scattering results on the nucleon. This procedure should not be considered reliable, especially for the hadronic axial current, though the result does have the virtue that it yields the same result as Equation II-14. An illuminating way to present the result for this asymmetry is to assume the "standard model" and to treat all the nucleon form factors as having a common dipole form

$$F(q^2) = \frac{C}{[1 + q^2/.71 \text{ (GeV/c)}^2]^2}.$$

The constant C depends on the value of the form factor at $q = 0$. We find using the "standard model"

$$A = \frac{G_F^2}{\sqrt{2} 2\pi\alpha} \frac{Q_N \left[(1 - \mu_p^2 \frac{q^2}{4M^2}) K + (1 + \mu_p)^2 q^4 - 1.25 (1 + \mu_p)(4MEq^2 + q^4) \right] - \mu_N(1 + \mu_p)q^4 + \frac{q^2}{4M^2} \mu_N \mu_p K}{\left[1 - \mu_p \frac{q^2}{4M^2} \right]^2 K + q^4 (1 + \mu_p)^2} \quad (\text{II-16})$$

where $\mu_p = 1.79$, $\mu_N = -1.91$, $K = 8M^2 E^2 + 4MEq^2 + 2M^2 q^2$, $G_F = 1.01 \times 10^{-5}/M_p^2$, $Q_N = (1/2 - 2\sin^2\theta_w) = .036 \pm .018$. The denominator is the electromagnetic scattering from the proton with the first term being the longitudinal part and the second the transverse. In the numerator the quantity $Q_N = (1/2 - 2\sin^2\theta_w)$ is viewed as the neutral weak charge on the proton and it is seen to be <0.05 . The term beginning with 1.25 (the axial vector coupling constant) is multiplied by Q_N because the NWC vector charge of the electron is $-1/2 + 2\sin^2\theta_1$ in the standard model. These terms are greatly suppressed because $\sin^2\theta_1$ is approximately $1/4$. The dominant terms are those associated with the WNC magnetic properties of the proton which are identified with the electrical properties of the neutron in this case. The converse would be true if the target were a neutron! The asymmetries presented in [Do 81] have to be shown by Soulder et al. to lead to experiments which can yield better than 10% results in 100 hours of beam time. This experiment and a measurement of the asymmetry associated with Δ^+ production via $ep \rightarrow e'\pi p$ provides stringent tests of our understanding of WNC carried by the nucleon.

III. DESCRIPTION OF GEM

A. OVERVIEW OF THE ACCELERATOR FACILITY

1. Introduction

A double-sided 2 GeV electron microtron has been chosen as the accelerator system to be used to generate the electron beams required to pursue the research program outlined in the previous section. This option has the advantages of superior beam quality, low capital and operating cost, and capability of furnishing beams of several electron energies simultaneously. Only moderate r.f. power is required because of the basic feature of all microtron designs, recirculation of the electron beam through the same r.f. accelerating section many times. The principle of operation is illustrated in Figure III-1, where the evolution of the double-side geometry from the classical version of Vekster [Ve 44] is presented. The microtron coherence condition requires that the orbit geometry be adjusted to insure that the transit time from exit from the r.f. accelerating section to entrance on the subsequent traversal of the same section be an integral multiple of the r.f. period, thereby insuring uniform acceleration to the extraction energy. In the approximation that the electron velocity, $v/c = 1$, this corresponds to the usual microtron condition that successive orbits increase in length by an integral number of r.f. wave lengths. The maximum energy attainable in the classical geometry shown at the top of Figure III-1 is limited by the finite length of the r.f. cavity. In the race track geometry, which was developed to avoid this limitation, the magnetic field is split into two half circular sectors separated by sufficient drift space to allow insertion of a linac

MICROTRON PRINCIPLE

INCREASE IN LENGTH OF SUCCESSIVE ORBITS
SHOULD BE AN INTEGRAL NUMBER OF R.F. WAVELENGTHS

$$2\pi\Delta R = \nu\lambda$$

$$(\pi-2)\Delta R = \nu\lambda$$

$$\Delta R = \Delta W / e B c$$

Figure III-1. Various designs for electron microtrons. The circular geometry of the "classical microtron" corresponds to the design of Veksler [Ve 44]. The double-sided geometry has been proposed [Ka 79] as an option for accelerating electrons to energies above 1 GeV.

section of substantial accelerating power. This geometry is commonly used to accelerate electrons to energies of a few hundred MeV. In order to avoid the prohibitive costs of the massive return magnets required for high energy operation (>500 MeV) the double-sided geometry shown at the bottom of Figure III-1 has been proposed [Ka 79]. This system requires about $1/5$ the volume of steel of the conventional race track design. In addition the region of r.f. phase stable operation is much larger than that of the race-track geometry. The double-sided geometry has an additional advantage which stems from the high energy gain per turn. The maximum current possible in the microtron is limited by the phenomenon of microwave beam breakup which results from transverse modes excited by the electron beam in the r.f. accelerating structures. Because of the high energy gain per turn, fewer turns are required to reach the extraction energy, and the resulting threshold current for beam breakup should be correspondingly larger.

In this section we present the complete detailed design of the 2 GeV C.W. microtron developed by the ANL project. The basic accelerator design incorporates a C.W. double-sided microtron [Ka 79] the individual elements of which are described in the following sections. The maximum design energy of the accelerator is 2.0 GeV. Variable-energy extraction from 0.5 to 2.0 GeV in approximately 25 MeV steps of three beams with individually controlled energies is planned. The energy spread in each beam will be $\sim 10^{-4}$. The design objective for beam current is 100 μ amps per extracted beam with the option of independent current control from near zero to 100 μ a for each of the three extracted beams. A current stability of 1-5% will be necessary to make maximum use of the 100% duty factor. The design value for the extracted beam radius is 0.4 mm and for beam divergence is ± 0.5 mr. The maximum beam

emittance is 0.2π mm-mr. The accelerator has been designed to accelerate transversely polarized electrons without depolarization.

2. Accelerator Design

The basic components of the microtron include an electron gun, chopper-buncher, a 5 MeV linac injector, a 30 - 180 MeV Race Track Microtron (RTM), a longitudinal phase space matching section, a 180 - 2005 MeV Double-Sided Microtron (DSM), extraction systems, and the various transport lines. A plan view of the accelerator is shown in Figure III-2.

The electron energy at the output of the gun will be 100 keV. The beam will be chopped and prebunched at 100 keV. Independent current control for every third bunch will be provided by transversely directing every third bunch through independent slits with a one-third subharmonic deflecting structure. The 100 keV beam will be injected into a 5 MeV linac and then for a single pass into one of two 25 MeV linacs used in the DSM. After extraction from the DSM linac at 30 MeV, the electron beam will be injected into the RTM and accelerated to 180 MeV in 25 revolutions at 6 MeV per revolution. Transverse focusing in the RTM will be provided with mirror symmetric quadrupole systems in the return paths of the RTM.

The DSM will be built with two 25 MeV linacs and four 90° sector bending magnets. Each linac will use eight 2.25 meter on-axis coupled structures operated at 2.4 GHz. The beam optics in the DSM will use a quadrupole system that is mirror symmetric about the midpoint of the short straight sections. Waists will be provided at the midpoints of the linac structures and midpoints of the dispersive straight sections (see Figure III-2) and transport will be achromatic from the exit of one linac to the entrance of the other linac.

Figure III-2. Plan view of the Argonne 2 GeV microtron.

A longitudinal phase space matching section using bending magnets and an RF cavity will be provided between the exit of the RTM and the injection point in the short straight section of the DSM. A one-third subharmonic RF cavity will be located in the transport section between the RTM and the DSM to permit multiple energy extraction from the DSM. The one-third subharmonic cavity will displace the energy of the first and third bunches relative to the second so that extraction of individual bunches will be possible because of the physical displacement during passage through the dispersive straight sections of the DSM due to the energy differences. Final extraction will be accomplished by an electrostatic septum followed by a magnetic septum. The extraction septa will be moved between the orbits to select the different energies for extraction.

B. INJECTION SYSTEM

1. Performance

The performance for the injector is set by the design requirements of the 2 GeV extracted beam and is based on the injector design for the Los Alamos - NBS 185 MeV microtron [Pe 81]. A maximum electron current of 0.35 ma is required from the gun in order to provide three extracted beams of 100 μ a each. The beam in every third bunch must be controllable from almost 0 to 100 μ a. The extraction energy of the electron gun will be 100 keV. The regulation on the extraction voltage must be $\pm 0.1\%$ for 0 to full load and a possible $\pm 10\%$ line voltage variation. Emittance at 100 keV must be within a normalized emittance ellipse of 4π mm-mr for injection into the 5 MeV linac. In addition to the C.W. mode of operation, a pulsed mode will be required for tune-up and diagnostics. The design requires a pulse that is shorter than the time for the first complete revolution in the booster microtron. A pulse length of 0.06 μ sec has been chosen for that purpose. The design specifications for the emittance of the beam out of the injection linac at 5 MeV are a transverse emittance (unnormalized) of 1.0π mm-mrad and a longitudinal emittance of 20π keV-degrees. The transverse emittance allows for 2.75 times dilution in acceleration to 5 MeV.

2. Injector Components

The injector components will consist of an electron gun, chopper, independent intensity control system, 2 MeV $\beta = 0.979$ RF tapered capture section, 3 MeV pre-accelerator and the injector beam transport system. Figure III-3 shows the physical layout of the injector components.

The electron gun design is based on the one selected by the NBS-Los Alamos project. A modulating anode will be used for control because of the

Figure III-3. Physical layout of the injector components.

smaller available emittance compared to a gridded gun. The gun voltage will be applied between a grounded final anode and the cathode so that control variations on the modulating anode will not affect the beam energy. The pulsing capability will be achieved in this design by locating the pulser in the high voltage terminal. The gun optics will be arranged to bring the output beam to a waist of approximately 4 mm diameter at an accessible location where the first lens, L_1 , will be located. A transverse, emittance limiting aperture, A_1 , will also be located at the waist. A gun current of 2.1 ma will be required after the aperture in order that the beam can be chopped into $\pm 30^\circ$ segments of r.f. phase.

A one-half frequency subharmonic (1200 Mhz), TM_{110} mode transverse deflecting cavity will be located immediately after the A_1 aperture. The combination of a transverse deflecting structure, drift length, and aperture limiting slit will be used as a $\pm 30^\circ$ chopper. The one-sixth of the beam that survives will enter a prebuncher at the fundamental frequency of 2400 Mhz.

The deflection that will be provided by the TM_{110} cavity is given by (Ha 66)

$$x(m) = 44.3 \times 10^{-4} \left(\frac{s + \frac{h}{2}}{\gamma} \right) \left[\frac{P_L \lambda_0^{1/2}}{0.6 + h/\lambda_0} \right]^{1/2} \sin \frac{\pi h}{\beta_e \lambda_0} \quad (III-1)$$

where s = distance from the end of the deflector to the aperture,
 h = length of the cylindrical TM_{110} cavity,
 P_L = power consumed by the cavity in watts,
 γ = M/M_0 ,
 λ_0 = free space wavelength at the operating frequency of the cavity,
 β_e = normalized velocity of the electrons

All lengths are in meters.

The aperture, A_2 , will be adjusted to equal $\pm 0.26x$ to obtain a $\pm 30^\circ$ chopped beam assuming the beam width will be negligible. The width of the aperture will have to be reduced for beams of finite width. The prebuncher, a reentrant cavity operated at 2400 Mhz, will be located after the chopper aperture. The electron energies will be modulated by less than ± 1 kV to minimize the effect on the longitudinal emittance. The cavity will use less than 30 watts C.W. power. The drift distance from the reentrant cavity to the tapered preaccelerator section will be 1.0 meter. This combination will reduce the angular spread from $\pm 30^\circ$ to $\pm 5^\circ$ at the entrance to the tapered preaccelerator section.

The independent current control system will be designed to fit into the 1.0 meter drift length. A deflecting cavity operating in the TM_{110} mode at the one-third subharmonic frequency of 800 Mhz will be phased so that the first of three bunches will receive a positive deflection, the second will receive zero deflection, and the third will receive a negative deflection. The length of the cavity will be adjusted to equal $\beta_e \lambda_0$, so that three parallel beams will result with a deflection, x , given by

$$x(m) = 40.4(10^{-4}) \frac{\beta_e \lambda_0}{2\gamma} [P_L \lambda_0^{1/2}]^{1/2} \quad (III-2)$$

where the parameters are defined as in equation III-1.

Each of the three bunches will be separated by 1 cm for a value of $P_L \approx 1350$ watts. Each of the paths will have separately adjustable apertures in the x and y directions allowing independent adjustment of the intensity of each of the three bunches. An identical cavity will be located downstream of the independent apertures. It will be phased so that the displacements of the

individual bunches will cancel, placing all bunches back on the same trajectory. The difference in phase angle, $\Delta\phi$, between the two cavities will be $\pi - \frac{\omega s}{\beta c}$ where s is the distance between cavities.

A tapered preaccelerator (TAP) section will be located at the end of the prebuncher drift length. The TAP section will consist of two meters of in-line r.f. structure [Sc 76, He 79] in which the lengths of the r.f. cavities will increase smoothly to match the increasing velocity from $\beta = 0.55$ to $\beta = 0.98$, corresponding to an increase in energy from 100 keV to 2.0 MeV. The operating frequency will be 2.4 GHz. A final preaccelerator section will be located after the TAP section. There will be two one meter long r.f. accelerator structures operating at 2.4 GHz. The first structure will be designed for $\beta = 0.985$ and the second structure will be designed for $\beta = 0.995$.

C. BOOSTER MICROTRON

1. Basic Parameters

The electron beam must be accelerated from the injection energy of 30 MeV to an extraction energy of 180 MeV in the booster microtron with a minimum dilution of its transverse and longitudinal phase space. A conventional race track configuration will be used for the booster system. To preserve good energy definition the change in harmonic number per turn in the Race Track Microtron (RTM) will be equal to one. This choice will provide the largest range of stable phase angles and minimum requirements in phase stability. To meet the RTM resonance condition:

$$\lambda = \frac{2\pi\Delta W}{eBc} = 0.125 \text{ m}, \quad (\text{III-3})$$

the energy gain per turn, $\Delta W = V_0 \cos\phi_s$, and the effective magnetic field of the end magnets, B, will be 6.0 MeV and 10.0 kilogauss. The extraction energy of 180 MeV will require 25 turns of acceleration. The orbit radius of the injected beam will be 10.0 cm and the radius of the final orbit, 60.0 cm. The corresponding orbit separation in the return path drift space will be 3.98 cm. These parameters are summarized in Table III-1. A transverse beam emittance of $0.16 \pi \text{ mm-mr}$ and a longitudinal emittance of $30 \pi \text{ keV-degree}$ has been assumed at the injection point of the RTM. The requirement of a final energy spread of 200 keV in the circulating beam in the DSM microtron will impose no limitation on the operation of the RTM. Calculations show that the energy spread in the RTM will be between 1/3 and 1/2 that of the DSM for beams of identical longitudinal emittance in the absence of dilution. To insure operation with $\Delta E < 200 \text{ keV}$ in the DSM, the energy spread in the RTM

Table III-1. Race Track Microtron Parameters

Injection energy	30 MeV
Extraction energy	180 MeV
Energy gain/turn	6 Mev
Number of recirculations	25
Magnetic field	10.05 kg
Minimum orbit radius	10.00 cm
Maximum orbit radius	60.00 cm
Orbit separation	3.98 cm
R.F. wave length	12.5 cm
Mode number	1
Accelerating field	1.4 Mv/m
Synchronous phase	20°
End magnet separation	8.0 m

should not exceed 70 keV. This value will be well within the limits of the current design, and will allow a sizable phase space dilution.

2. End Magnet and Linac Design

A plan view of the booster RTM is presented in Fig. III-4. The separation of the end magnets will be sufficient to accommodate a 4.6 meter linac section similar to those in the main DSM, and return paths containing the necessary focusing and steering elements to give good optical transmission. A distance of 8.0 meter is assumed in Fig. III-4. The possibility of a more compact configuration will be studied. The parameters of this design have been chosen to correspond to the end magnet design planned for the NBS-LANL-185 MeV microtron [De 81]. The width of the end magnets will be larger than required for simple acceleration in order to accommodate the lateral translation of the last return orbit so that the beam will make a complete turn without r.f. acceleration. This "drift orbit" will provide the longitudinal phase shear required for the matching of the extracted beam to the DSM. The matching technique is described in section III-E.

Asymmetries in the overall guide field geometry will be prevented by use of mirror image end magnets of identical design. The NBS-LANL design (see Figure III-5) which has been adopted for this proposal [De 81] is expected to have a field uniformity of 2×10^{-4} . Such a high precision will be necessary to maintain the RTM resonance condition and minimize geometric aberrations. Fig. III-5 shows a clamp to obtain sharp edge field profiles. Considerable care will be taken to minimize attendant geometric aberrations and

Figure III-5. Side view/section of booster end magnet.

longitudinal dispersion. The higher injection energy in the ANL design (30 MeV compared to 17 MeV in the NBS system) will give an additional margin against these effects. A relatively large gap height of 6 cm was chosen to minimize mid-plane field fluctuations which are a source of dilution of the beam emittance. The design incorporates Purcell filters to homogenize the field. Any necessary field trimming will be accomplished by use of pole face windings, magnetic shimming, and modifications of the clamp geometry. The use of shaped pole edges as a means of providing better definition of the field edge and of limiting differential saturation will also be explored. A field uniformity of $\pm 2 \times 10^{-4}$ will limit the phase error to less than $\sim \pm 2^\circ$ on each pass. For a synchronous phase angle of $\phi_s = 20^\circ$ and a maximum accelerating voltage of $V_0 = 6$ MeV, the corresponding energy spread will be ± 70 keV.

The linac accelerating section will be a slightly lengthened version of the basic 3 meter waveguide described in the section III.D. For operation with an accelerating gradient of 1.4 MeV/m and a synchronous phase of 20° , a structure length of 4.6 meters will be required. The power dissipation in the wave guide will be approximately 90 kw. The r.f. power required will be supplied from the power driving system for the main accelerator.

3. Orbit Optics

Most of the microtrons built to date have been pulsed accelerators using high gradient r.f. linac sections [Er 79, Gr 81]. As a result the drift distances between end magnets are relatively short and the requirements for transverse focusing of the beam are easily met with simple optical systems. The problem of transverse beam containment in a C.W. accelerator will be more severe for several reasons. Much longer straight sections will be required to accommodate the linac sections since only moderate gradients are acceptable

for continuous operation. In addition the tune of the recirculation optics is a crucial factor in determining the threshold for beam breakup which arises from the interactions of the beam with transverse r.f. modes of the accelerating structure [Ra 81]. Beam breakup is unique to long pulse or continuous operation. To minimize its importance, it would appear that one could impose strong focusing on the beam by means of quadrupole multiplets on the microtron return paths tuned to minimize the beam displacement in the linac sections. In principle one should design the optics system to produce a waist in the linac center. Unfortunately, such a confinement system is usually characterized by a betatron phase per pass of 180° or a multiple thereof, which will itself result in beam loss because of excitation of an integer betatron resonance.

We present here an approach which achieves dispersion free optics in the linac by use of a configuration similar to normal quadrupole focusing schemes but which provides in addition a means of varying the horizontal tune so as to avoid the destabilizing integral betatron resonances should that be necessary. Transverse focusing will be obtained in the RTM by installing quadrupoles in the return paths. The horizontal plane optics should provide a dispersion free beam in the linac. This will be accomplished by constructing two mirror symmetric quadrupole systems in each return path. The optical system located between points 1 and 3 (shown in Fig. III-4) occupies a length L . The requirement of a dispersion free beam in the linac specifies the horizontal behavior of the system, e.g.

$$M_{13}(x) = \begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix} \quad (\text{III-4})$$

where $M(x)$ is the conventional first order transfer matrix [Br 720] and the value of L is arbitrary. The transfer matrix for one revolution is:

$$M_{AA}(x) = M_{A1}M_{13}M_{3A} \quad (\text{III-5})$$

$$M_{A1} = M_{3A} = \begin{pmatrix} -1 & -\frac{\ell}{2} \\ 0 & -1 \end{pmatrix}$$

M_{A1} (and M_{3A}) correspond to a drift length $\ell/2$ followed (or preceded) by a 180° sector bending magnet. The total transformation for n turns will be

$$M_{AA}(x) = \begin{pmatrix} 1 & n(L + \ell) \\ 0 & 1 \end{pmatrix} \quad (\text{III-6})$$

Evidently $(L + \ell)$ will have to be small for successful orbit containment. Since ℓ will be significant ($\equiv$ distance between sector dipoles), L will have to be negative. Acceleration will be ignored in this discussion. In the vertical plane the transformation will be arbitrary.

Previous designs have used two mirror symmetric quadrupole doublets in the return paths. They are tuned to give a parallel to parallel transformation in the horizontal plane and a 90° phase shift for the vertical plane for each revolution. Unfortunately these systems exhibit a positive value of L and the horizontal envelope is unbounded. These designs are said to rely upon fixed weak horizontal focusing quadrupoles between linac and dipoles, and the reduction of geometric transverse emittance is accomplished by means of acceleration for horizontal containment.

In the design proposed here, an additional horizontal focusing quadrupole (Q3) will be located at point 2, the midpoint of the return path. Figure III-6 shows the behavior of the dispersion function (η_x) for this system on a return orbit corresponding to 30 MeV energy. The value of η_x will be 2ρ at the exit of the first dipole and the entrance to the second dipole; it will be zero in the centers of Q2 and Q4 and somewhat less than -2ρ in the center of Q3. Thus, it will be possible to adjust Q2 and Q4 freely without affecting the η_x function. The positions of Q2 and Q4 allow variation in horizontal focusing. Table III-2 contains the data for the 30 MeV return path. Figure III-7 shows what the beam envelopes will be for a tune which will provide both transverse planes with beam waists in the middle of the return path, and at point A, the linac center. A beta value of 1.5 m will be maintained at point A. The transfer matrix for one turn in the vertical plane will be

$$M_{AA}(y) = \begin{pmatrix} -0.91 & 0.65 \\ -0.28 & -0.91 \end{pmatrix} \quad (\text{III-7})$$

for which the betatron phase shift will be 155° . In the horizontal plane the phase shift will be 720° and $M_{AA}(x) = I$ where I is the unit matrix. The value of the beta function will be $\beta = \beta_{\min} = 1.5$ m in the linac centers. Good orbit containment will be achieved using five weak quadrupoles on each return path. The beam radius will be less than 4 mm throughout.

The betatron phase shift per turn of this 5-quadrupole system corresponds to an integer resonance betatron instability, and could present problems in spite of the limited number of orbits (25) to extraction. Should it prove necessary, by inserting weak vertical focusing quadrupoles at each end of the linac, one can reduce the horizontal betatron wavelength below

Table III-2. Beam elements for 30 MeV return path. ($l = 8.0$ m, $\rho = 10.00$ cm)

Element	Action	Effective	
		Length (cm)	Strength (kG or kG/cm)
$l/2$	Drift	400.00	
B_1	180° bend	31.42	10.18
D_1	Drift	50.00	
Q_1	HFQ	10.00	0.065
D_2	Drift	148.36	
Q_2	VFQ	10.00	-0.065
D_3	Drift	176.64	
Q_3	HFQ	10.00	0.111
D_3	Drift	176.64	
Q_4	VFQ	10.00	-0.065
D_2	Drift	148.36	
Q_5	HFQ	10.00	0.065
D_1	Drift	50.00	
B_1	180° bend	31.42	10.18
$l/2$	Drift	400.00

Figure III-6. Booster microtron dispersion ray.

Figure III-7. Booster microtron beam envelopes.

2 oscillations per turn while preserving the essential waist to waist features of the 5-quadrupole system. Such a modified optical configuration was developed to demonstrate feasibility. A power of 0.3 m^{-1} for the weak quadrupoles and a beta function of 10.0 m at the linac center were chosen for the starting conditions at 30 MeV. With moderate changes in the quadrupole configuration in the dispersive straight section a dispersion-free beam is maintained in the linac with a horizontal beta function of 10.0 m at all energies. In Figure III-8b the maximum beam sizes observed on each turn are presented. The beam size decreases with energy. Most important, the horizontal betatron tune, ν_x , shown in Figure 8a varies from 1.69 per turn at 30 MeV to 1.87 per turn at extraction while ν_y asymptotically drops to 0.24. A sensitivity study shows that the system is stable to quadrupole strength errors with a precision of $\sim 1\%$ providing satisfactory control of beam size.

Horizontal steering magnet pairs at each end of the return paths will be used to make corrections in orbit angle and position for errors arising from misalignment or magnetic field variations. Vertical steering corrections, presumably much weaker, will be made as needed in a similar fashion. In the NBS RTM a range of adjustment of ± 50 gauss on the highest energy orbit is sufficient to compensate end-magnet errors of $\pm 2 \times 10^{-4}$. Vertical corrections can be weaker by a factor of ~ 10 , since only alignment errors must be corrected.

Figure III-8. Behavior of horizontal and vertical beam tunes, upper section, and maximum beam sizes, lower section, as a function of turn in the booster microtron.

4. Injection and Beam Diagnostics

Injection into the RTM will be accomplished with little deterioration in beam quality because of the high injection energy. Herminghaus [He 76a] has pointed out that fringe field defocusing effects in end magnets limit the energy gain possible in a RTM with good beam quality. He suggests that a reasonable limit is a factor of ten. In the present design the gain will be ~ 6 and a simple scheme of direct displaced injection into an end magnet and subsequent translation with correction dipoles into a correct orbit will be possible with no significant loss of beam quality. The scheme is shown in Figure III-9. Extraction will be accomplished in the same manner as in the Aladdin microtron injector [Gr 81] for the University of Wisconsin Synchrotron light source. A local magnet recess and field depression at the position of the last orbit decreases the total deflection so that the beam will exit the end magnet at about 10° to the normal return trajectory.

Stable operation of the booster system will require accurate monitoring of beam intensity, transverse position, and bunch phase on the linac line and on individual orbits in the return paths. We will study techniques currently employed on the MAMI [He 76a] microtron, and those under development for operation of the NBS-LANL microtron. In these accelerators, beam position will be monitored by means of non-intersecting r.f. resonance cavities as outlined by Herminghaus [He 76a]. Operating experience with the Mainz and NBS systems will serve as a guide as to the need for monitors on the return paths. Position monitoring at the entrance and exit to the linac on the 14 MeV, 20 turn microtron, MAMI I, has provided sufficient control for routine operation to date. Current and phase will be measured by using similar non-intercept r.f. techniques.

Figure III-9. Booster microtron injection detail.

Accurate measurements of beam emittance will be more difficult because of the high quality of the microtron beams. At points in the microtron lattice where the beam is sufficiently divergent, emittance measurement will be considered through the use of high speed wire scanners. With current techniques such measurements are possible with a spacial resolution of about 0.1 mm.

D. DESIGN OF THE DOUBLE-SIDED MICROTRON

1. Coherence Conditions

The microtron coherence condition requires that the time taken by an electron to travel along a trajectory from linac exit to linac entrance be an integral multiple of the r.f. field period. For the double-sided microtron this requirement can be written in the form [Ch 80]:

$$\frac{(\pi-2)W_{1,i}}{eBc} + \frac{S_i}{\beta_{1,i}} = \mu_{1,i}\lambda \quad (\text{III-8})$$

$$\frac{(\pi-2)\Delta W}{eBc} + S_i \left(\frac{1}{\beta_{n+1,i}} - \frac{1}{\beta_{n,i}} \right) = v\lambda$$

$$i = 1, 2$$

Where the index, i , refers to the first or second half turn on the n th orbit whose energy is given by W_{ni} . The other parameters are:

- c = velocity of light
- e = electrical charge of the electron
- B = magnetic field of bending magnets
- S_i = orbit length from exit of i^{th} linac to entrance of next linac in the limit of vanishing electron energy
- β_{ni} = normalized electron velocity after the i^{th} linac on n^{th} turn
- μ_{ni} = harmonic number for the i^{th} orbit between linacs on the n^{th} turn
- λ = free space wavelength at the fundamental frequency
- v = mode number

In the approximation that $\beta = 1$, the above equations reduces to the familiar coherence condition for the DSM:

$$\frac{(\pi - 2)\Delta W}{eBc} = \nu\lambda \quad (\text{III-9})$$

where ΔW is the energy gain per turn. Eq. III-9 is equivalent to the requirement that successive orbits increase in length by ν r.f. wavelengths.

The Argonne design will be characterized by the parameters

$\mu_{11} = \mu_{12} = 139$, $\lambda = 0.125$ m, $B = 1.523$ T, $\nu = 1$ and $\Delta W = 50$ MeV. The long straight sections in which the linacs are located will be 24.69 m in length. The magnet-linac drift distances at each end will differ by ≈ 3 cm to accommodate the path length difference in the two half turns of each full orbit arising from the corresponding 25 MeV energy difference. The linacs will be constructed of eight accelerating structures each 2.25 meters long with 0.25 meter separations. The short straight sections between the sector magnets will be a maximum of 11.2 meters and a minimum of 2.4 meters, allowing space for the beam optics and other elements necessary for operation of the machine.

The phase stable region of the double-sided microtron extends over r.f. phase angles from 0 to the arctan $(4/\pi\nu)$, which corresponds to 0 to 51.9 degrees in the design presented here. The energy spread of the beam is given by [Ch 80]

$$\delta W_{\max} = \sqrt{\frac{\tan\phi_s}{4\pi\nu}} \Delta W \delta\phi_{\max} \quad (\text{III-10})$$

where $\delta W_{\max}$ = maximum energy deviation from the synchronous energy for bunch motion in $\delta W \delta \phi$ space for which the corresponding maximum phase difference from ϕ_s is $\delta \phi_{\max}$

ϕ_s = phase stable angle

In this design $\phi_s = 14$ degrees. According to equation III-10, an energy spread of ± 100 keV will occur if the maximum phase difference is kept with $\pm 0.5^\circ$ of the phase stable angle.

The ellipses which characterize particle motion in longitudinal phase space are upright in the middle of the two linacs and in the drift space between the sector magnets. The maximum energy spread will be ± 57.7 keV and the maximum spread in phase angle ± 0.52 degrees in the middle of the two linacs for a phase space area of 30π keV-degrees. The maximum energy spread will be ± 64 keV and the corresponding angular spread is ± 0.46 degrees in the short drift space between the two 90° sector magnets. The basic parameters of the design are tabulated in Table III-3.

2. Sector Magnets

One of the major challenges of the DSM concept is the design of sector magnets which will provide guide fields of the required profile with requisite precision and stability. In the Argonne design the pole faces and edges will be shaped to a degree of tolerance necessary to provide a magnetic field that will satisfy the coherence conditions for acceleration. This is regarded as the most critical aspect of the magnet design and is intimately related to the beam optics which are addressed in the next section of this proposal. The Argonne design will use pole-face rotation at the entrance and

Table III-3. Double-Sided Microtron Design Parameters.

Basic parameters	
Maximum energy	2 GeV
Current	300 μ a
Energy spread, $\Delta E/E$	$\approx 10^{-4}$
Beam emittance	$\leq 0.2\pi$ mm-mr
Injection energy	180 MeV
Energy gain per turn	50 MeV
Synchronous phase, ϕ_s	14°
Stability limit	51.9°
Accelerating field, E	1.4 MV/m
Number of recirculations	37
Length, long straight sections	24.69 m
Maximum length, short straight section	11.17 m
Wavelength, λ	12.5 cm
Mode number, ν	1
Magnetic field	1.523 T
Linac length	19.75 m
Number of linacs	2
R.f. power losses	0.94 MW
Shunt impedance, $Z T^2$	75 M Ω /m
Maximum orbit radius, $R_{\max}$	4.38 m
Minimum orbit radius, $R_{\min}$	0.39 m
ΔR	0.1095

exit of the 180° sector magnet bending system to reduce vertical defocusing. The precise shape of the pole face edges will be established in an extensive magnet measurement program. A schematic pole face cross section is shown in Figure III-10. Other areas that will be addressed will be the stability of the magnetic field with time and the repeatability of the field at turn-on. Relatively straightforward engineering techniques will be used to investigate the effects of temperature variations and of small shifts in the magnet support structures. Finally passive and active correction elements will be included in the design to compensate for the expected variations.

The drawing in Figure III-11 shows the preliminary design for the sector magnet and provides some idea of its size. The sketch in Figure III-12 shows a radial section through its thickest part. The gap will extend over a relatively large area and will have relatively high field density. The yoke thickness that will be needed at a given azimuthal position will, therefore, be about the same as the pole depth at that location. The yoke thickness will vary from the thickest, as shown in Figure III-12, to one that will be about 12 cm near the ends in order to minimize the core mass. This leads to the yoke design shown in Figure III-11 which will be made from several sections that become progressively smaller as they approach the ends.

The two pole tips, (A) in Figure III-12 will each be machined from a single piece of SAE 1010, electro-fine steel. The tolerances to which this can be done have been determined to be ± 0.05 mm. The primary excitation coil, (B), will support the nominal gap field of 1.523T plus an extra 10%. There will be a passive end guard, (C), surrounding the primary excitation coil. The design shown will provide a very short tailed field edge with the help of the secondary coil, (D). Further edge hardening may be obtained by attaching steel shims to the pole faces.

Figure III-10. Idealized magnet pole face cross section.

2-GeV MICROTRON SECTOR MAGNET

Figure III-11. Preliminary sketch of DSM sector magnet.

SECTION THROUGH SECTOR MAGNET

Figure III-12. Radial section of DSM sector magnet.

Other field corrections will be supplied as required by additional passive and active elements. The additional passive corrections will mostly be in the form of small steel shims along some of the beam paths. These will correct some of the multipole field errors. These shims as well as the ones mentioned above will be installed and adjusted in the sector magnets after assembly is completed and some field measurements have been taken. Active correction elements will be segmented pole face coils centered on the nominal paths of the beam orbits. These coils will extend over about 22.5° of orbit path length and will have an inside width of 4.5 cm and a conductor section width of 1 cm. This coil will provide a maximum correction field strength that is about 2% of the central field and which will be flat to $\pm 1\%$ over a 1 cm wide radial area centered on the nominal beam orbit. Three coil segments along each beam path will allow adjustment of the exit point, the exit angle, and the path length of the beams. The important parameters of a preliminary sector magnet design are listed in Table III-4.

Table III-4. Sector magnet parameters.

I. Core

Cord length of gap	6.5 m
Maximum pole depth	1.4 m
Outer radius of gap	4.5 m
Gap height	4 cm
Nominal field strength	1.523 T
Pole piece thickness	19 cm
Mass of 2 pole pieces	30 Tons
Mass of yoke	300 Tons

II. Main Coils

	<u>Primary</u>	<u>Secondary</u>
Conductor material	Hollow copper	
Conductor size	1 cm x 1 cm x 0.5 cm	
Coil size per pole	10 cm x 13 cm	4 cm x 4 cm
Number of turns	80	16
Maximum supply current	365 A	
Voltage	100 V	20V
Power	37kW	8kW
Coolant	Water	
Coolant flow	11 gpm	2 gpm
Conductor mass	500 kg	100 kg

III. Pole Face Correction Coils

Orbit energy	2 GeV	500 MeV
Total length of 3 segments	1.5 m	0.4 m
Conductor material	Hollow copper	
Conductor size	4.5 mm x 4.5 mm x 2.2 mm	
Coil minimum size per pole	1 cm x 1 cm	
Minimum number of turns	8	
Maximum supply current	200 A	
Maximum total voltage	10 V	2.4 V
Maximum power	2 kW	0.5 kW
Coolant	Water	
Coolant flow	0.8 gpm	0.3 gpm
Conductor mass	4 kg	0.5 kg

3. Orbit Optics

a. Injection Transport System

The transport system will consist of four bending magnets and one quadrupole. A layout is shown in Figure III-13. The dipole magnets will each bend the beam by 20° and the system will be mirror symmetric about the HF quadrupole Q; the dipole edge angles on B2 and B3 were calculated to be 30.6° . The parameters selected for the transport system are tabulated in Table III-5. For these parameters the system is achromatic but not isochronous.

Table III-5. Transport system parameters

Dipole-quadrupole separation	0.295 m
Dipole-dipole separation, l	0.2 m
Bending radius in dipoles, ρ	0.2 m
Quadrupole power (5 MeV)	4.54 m^{-1}
Dipole-triplet separation	0.5 m
Inter-dipole edge angles	31.2°
Angular deflection per dipole	20°

Figure III-13. Transport system from injector to DSM linac.

The beam parameters in the injection system must be matched to those of the linac for successful propagation through the linac sections. Symmetric quadrupole triplets will be used for transverse focusing in the linac. The main linac of the DSM will be split into eight sections, each 2.25 meters long. The space between each RF section will be 0.25 m. Symmetric quadrupole triplets will occupy each of these spaces. The outer quadrupoles will be 0.04 meter long horizontally focusing (HF) quadrupoles and the center quadrupole will be a 0.08 meter long vertically focusing (VF) quadrupole. The interspace between the doublets and triplet will be 0.015 m. The quadrupole strengths will be adjusted to give a 90° phase shift from the center of one linac section to the next. Since the energy of the particles will increase by 4.2 MeV per section, the strength of each triplet will be increased correspondingly. This system will produce beam waists in the center of the linac sections with matched beta functions of $\beta_x = \beta_y = 1.6 \text{ m}$. Extraction of the twiss parameters in the linac sections back to point 1 of the injector (see Figure III-13) yields twiss parameters for the injector beam which can be easily achieved with conventional matching elements.

b. Isochronous Match and Transfer to RTM

The 30 MeV beam exiting from the LINAC will pass through the ninth symmetric quadrupole triplet and will be bent 20° to the left by the first dipole of a chicane system as shown in Figure III-14. The four dipoles and intervening quadrupoles will form an isochronous bending system with a net bend of 170° . The matching system of two doublets will produce $\beta_x = \beta_y = 1.5 \text{ m}$ waists in the center of the RTM. The 30 MeV beam will be translated by bending magnets into a 30 MeV return path which then passes

Figure III-14. Transport system for injection into the RTM.

through the RTM system. No phase slip occurs in the system illustrated above. The beam optics systems from 5 MeV injection to the RTM system have been merged and coded into the Beam Design Program TRANSPORT. The starting emittance was 1.0π mm-mr at 5 MeV and the initial ellipse parameters were those corresponding to a matched beam at the injection point. The envelopes through the system will be as shown in Figure III-15.

c. Transverse Optics of the Double-Sided microtron, 180-2005 MeV

The extracted beam from the Race Track Microtron (RTM) will be injected into the Double-Sided Microtron (DSM) in a dispersive-straight section at 180 MeV electron kinetic energy. The DSM will accelerate the beam to 2005 MeV in 36.5 turns. At these energies the active focusing will be effected by the elements external to the two LINACS in the DSM. The requirements will depend upon beam energy and dipole edge angles. Figure III-16 shows the layout for a half-turn. The LINAC centers are indicated by points A and B. The path external to the two LINACS will be from point i to f. The transfer system will perform an achromatic translation from i to f; the same beam sizes will be obtained, i.e., $\beta_i = \beta_f$ (equal betas) but the phase plane ellipses will be rotated by 90° ($\alpha_f = -\alpha_i$) with $\alpha_i < 0$ (diverging). The optical system will be a quadrupole array which is mirror symmetric about the midpoint 3. The general goal will be to maintain beam waists at points A, 3 and B. However, the system will be variable without disrupting the achromatic translation, i.e., $\beta_i \neq \beta_f$ and $\alpha_f + \alpha_i \neq 0$. The incident beam conditions will be chosen to provide a waist with $\beta = \beta_A$ in the center of the first linac. Thus the entrance beam will be given by $\beta_e = \beta_A + S^2/\beta_A$ and $\alpha_e = S/\beta_A$ where S is the Linac half-length chosen to be 9.75 m).

Figure III-15. Beam envelopes in injection, linac and matching sections to RTM.

Figure III-16. Schematic for beam optics of DSM.

Beam will be injected at 180 MeV with an assumed emittance of $5/180\pi$ mm-mr and the envelopes that will result for ten turns $\Delta E = 500$ MeV are shown in Figures III-17(a) and III-17(b) for $\beta_A = 1.5$ m. The minima represent the waists in the Linac centers (points A and B). The peaks represent the action of the transfer sections $i \rightarrow f$ where diverging ellipse with $\alpha = \alpha_i$ will be rotated by 90° to give $\alpha = \alpha_f (\equiv -\alpha_i)$.

The system that will satisfy the requirements stated above will be mirror symmetric about the midpoint 3. The dipole entrance angle θ_1 is shown as positive in Figure III-16. The exit angle $\theta_2 = -45^\circ$. The standard DSM design has $\theta_1 = -45^\circ$. This angle will be very important - the inverse focal length due to the dipole alone will be $-(\tan\theta_1 + 1)/(\rho \text{ focusing})$ in the horizontal plane. The corresponding quantity will be $-(\tan\theta_1^* + \tan\theta_2^* - \pi/2 \tan\theta_1^* \tan\theta_2^*)/\rho$ in the vertical plane. The reduced angles θ^* represent a correction due to soft-edge focusing. These focusing terms will be very important at the lower energies. Independent of the beam conditions arriving at the dipole entrance, the dipole will effect a horizontal crossover downstream of point 2 (for $\theta_1 \neq -45^\circ$) and a diverging vertical beam whose virtual source will appear to lie within the dipole. Since the horizontal focal length will increase with energy, the crossover will move away from point 2 as the energy increases. The optical system lying between points 2 and 4 as designed will contain these orbits and effect the achromatic translation. The use of $\theta_1 > 0$ will make the vertical problem less severe but will decrease the horizontal focusing beam.

The dispersion ray at the dipole exit will be $\eta_2 = \rho$ and will have $\eta_2' = 0$ for a -45° exit angle; the transform to point 4 will give $\eta_4 = \eta_2$, $\eta_4' = \eta_2'$ in order to obtain an achromatic translation. The 2×2 horizontal

Figure III-17. Beam envelopes in the DSM between 180 - 430 MeV and 430 - 680 MeV.

transfer matrix will be telescopic, i.e.

$$M_{42} = \begin{pmatrix} 1 & a \\ 0 & 1 \end{pmatrix} \quad (\text{III-15})$$

which can be expanded as

$$M_{42} = \begin{pmatrix} 1 & a/2 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & a/2 \\ 0 & 1 \end{pmatrix} \quad (\text{III-16})$$

or in the language of phase shifts and Twiss Parameters as

$$M_{42} = \begin{pmatrix} \sqrt{\frac{\beta_4}{\beta_2}} (\cos\psi + \alpha_2 \sin\psi) & \sqrt{\beta_2 \beta_4} \sin\psi \\ 0 & \sqrt{\frac{\beta_2}{\beta_4}} (\cos\psi - \alpha_4 \sin\psi) \end{pmatrix} \quad (\text{III-17})$$

where ψ represents the phase change from points 2 to 4 and β_i, α_i represent ellipse parameters at point i ($i = 2$ or 4). Normally, β_A will be equal to β_B , β_2 will be equal to β_4 , and α_4 will be equal to $-\alpha_2$, so that $\tan\psi = 2\alpha_2/(1 - \alpha_2^2)$ and $a/2 = \beta_2\alpha_2/(1 + \alpha_2^2)$. The distance $a/2$ is the location of the horizontal waist measured downstream from point 2. The total system will give a net transfer matrix from i to f which has the form

$$M_{fi} = \begin{pmatrix} r & s \\ t & r \end{pmatrix} \quad (\text{III-18})$$

in either the horizontal or vertical plane.

Two types of systems will be used to deal with $\theta_1 \neq -45^\circ$ optics:

(1) A five quadrupole design and (ii) a three quadrupole system. Both will have a quadrupole singlet at the center symmetry point 3. The five quadrupole

Figure III-18. Optical systems for the DSM.

system will be used at low and intermediate energies where space is adequate and the second scheme will be used at higher energies $E > 1300$ MeV. Figure III-18 shows the thin-lens layouts along with the behavior of the dispersion ray. The systems will be totally symmetric about the midpoint 3. The quadrupole polarities will be reversed to H-V-H above 1800 MeV; then the Q1 to Q2 spacing will be increased to a maximum as the energy is raised. In the five quadrupole system, the identical lenses Q1 and Q5 will be spaced further in from the dipoles as the value of $a/2$ increases with energy so that the condition $a/2 = \beta_2 \alpha_2 / (1 + \alpha_2^2)$ will be met. The Q2 ($\equiv$ Q4) strength will be adjusted to yield a vertical waist at the midpoint so that $\alpha_3(y) = 0$; the optimum Q2 location also will yield a horizontal waist at the midpoint so that $\alpha_3(x) = 0$. The Q2 strength is obtained from a quadratic equation - thus two different values for β_2 (x or y) will be possible. The dispersion ray will pass through zero in Q2 and Q4 so it will be possible to change the tune with these lenses without altering the achromatic translation.

In the three quadrupole scenario, the Q1 $\equiv$ Q3, and Q2 strengths will be tuned to produce $\eta_3 = 0$ and a horizontal waist so that $\alpha_3(x) = 0$. The optimum Q1 location will yield a minimum value for $|\alpha_3(y)|$. The Q1 to Q2 spacing will be reduced with increasing energy. For $\theta_1 = 30^\circ$ this system will be useful over an energy range from ~ 1300 to 1800 MeV. Above 1800 MeV the value for $a/2$ will exceed the distance between points 2 and 3.

Examples of systems designed at 430 MeV, and 1680 MeV using the five-lens and three-lens scheme are shown in Figures III-19 and III-20. Matrices of the form described by equation III-18 will be produced in this system. The values of $\beta_1 = \beta_A + (9.75)^2 / \beta_A = 64.875$ m and $\alpha_1 = -9.75 / \beta_A = -6.5$ are used for these graphics. The beam emittances were assumed to be

Figure III-19. Beam envelopes at 430 MeV in DSM.

Figure III-20. Beam envelopes at 1680 MeV in DSM.

Figure III-21. Beam dispersion rays at 430 and 1680 MeV in DSM.

$(5/E)\pi$ mm-mr. Beam waists will occur at the midpoints. Figures III-21(a) and III-21(b) show the behavior of the dispersion ray for both systems.

4. DSM R.F. System

High r.f. efficiency is one of the primary requirements governing the choice of accelerating structure for the DSM. Various geometries for cavity structures characterized by high shunt impedance have been investigated because of their potential improved efficiency. The most successful of these is the side-coupled cavity geometry [Kn 68] developed at Los Alamos National Laboratory for the LAMPF accelerator. The optimization of this geometry led to a clear advance in conversion efficiency of r.f. to beam power. More recently two designs, the on-axis coupled structure [Sc 77] and the Andreev disc and washer structure [An 72] have been studied extensively. The disc and washer structure shows promise for attaining the highest shunt impedances. Unfortunately, the LANL group recently has uncovered serious problems with HEM_{110} -like deflecting modes which probably preclude its application to electron accelerators. These r.f. modes (see Appendix A) are responsible for regenerative beam breakup which limits the current which can be accelerated in a recirculating machine.

The on-axis coupled structure is shown in cross section in Figure III-22. This geometry has several advantages which make it an attractive choice for the DSM. Fabrication is simplified because of the coaxial geometry and because the coupling cavities are in-line the overall radius of the structure is less than other geometries. Excitation of transverse deflecting modes can be suppressed by minimizing the cell-to-cell coupling for HEM_{110} -like modes. This is accomplished by rotating [Sc 79] the coupling slots which connect adjacent cavities. Because the Q of the coupling cavity is an order

Figure III-22. On axis coupled cavity structure.

of magnitude less than that of the accelerating cavity these higher modes will be "Q-spoiled" by the basic geometry. These reasons have led the Mainz group to choose the on-axis coupled geometry for the MAMI system of cascaded microtrons and are the basis for our decision to use it for the accelerating structure of the DSM linacs.

The design will use a value of $\beta = 1$ at $f = 2400$ MHz. An effective shunt impedance (ZT^2) of 70 to 75 $M\Omega/\text{meter}$ is expected on the basis of measurements with existing structures at Chalk River. The structures will be operated at a gradient of 1.43 MeV/meter with a synchronous phase, $\phi_s = 14^\circ$, resulting in an accelerating field of 1.4 MeV/m. The power input will be 43.9 KW/m including 15.5 KW/m beam loading. The power dissipation of 28.5 KW/m in the waveguide will be relatively high; but it will be possible to handle it with good water cooling in the periphery of the beam aperture. The total r.f. power required will be 1842 KW including 265 KW for the injector and booster microtron. The accelerating structures will be built in 2.25 meter sections. The 10% coupling factor of the in-line cavity W.G. is considered adequate for this length. Power will be fed into the center of the structure through an r.f. coupler connected by flanges to two 1.125 meter sections.

R.f. power will be provided by high power klystrons. At least one, the Varian-8270, is presently available at 2380 MHz. Its operating efficiency is 50% and it delivers 450 kW r.f. power. Varian has stated that they could develop a 1 MW klystron at 60% efficiency for \$500,000. Such an improvement in efficiency would save 1 MW of operating power. Thompson CSF has also indicated an interest in developing a 1 MW klystron with 70% efficiency.

The DSM linac will use 4 VKS-8270 klystrons and will require 3.2 MW of dc power if the other tubes are not developed in time. A three phase rectifier unit will provide the power for the klystrons. It will be capable

of delivering 16.5 A at 65 KV with an output ripple voltage of 1% or less peak-to-peak at full load. The power supply will have a crow bar using two ignitrons and appropriate switchgear that will be capable of shorting the output and turning off within 50 ms. An r.f. circulator will be located in the output of each klystron to prevent reflected power from causing damage.

Each klystron will supply four 2.25 m sections through four power splitters, as shown in Figure III-23. The sum of the accelerating fields in the four sections will be compared to a reference and the r.f. drive to the klystron will be automatically adjusted to maintain a constant field within the four structures. Each of the 2.25 M sections will have its own motor driven phase shifter. The phases of the individual r.f. sections will be controlled to within one degree with the closed loop feedback system shown in Figure III-24.

Figure III-23. RF power distribution in the DSM.

Figure III-24. Closed loop phase control system for the DSM.

5. Multiple Energy Extraction

One of the inherent features of microtrons is the ease with which the beam can be extracted with a negligible deterioration of beam quality. In the DSM this is possible because of the orbit separation in the dispersive straight section. Deflection of the beam in a particular dispersed orbit with a septum magnet prior to entry in a sector magnet will induce a large change in the exit angle into the linac straight section. The beam can then be captured in a secondary septum and guided into an extraction beam line. Using this scheme extraction is possible in principle from any orbit from injection to maximum possible energy. The versatility of the microtron can be further enhanced if the circulating beam can be split so that selected fractions are extracted on specific orbits. In this manner simultaneous extraction at multiple energies can be realized. In the Argonne design this will be accomplished by inducing an energy structure on the micropulse train and utilizing the resulting orbit separation of the micropulses in the dispersive straight section, to extract specific fractions of the circulating beam on given orbits.

The energy structure will be imposed by means of subharmonic modulation of individual beam micropulses. A subharmonic cavity operating at 800 MHz will be located in the beam line from RTM to the DSM so that beam will be modulated before injection into the DSM. The r.f. phase will be adjusted to give three sets of bunches A, B and C (see Figure III-25) with different energies.

MULTI-BEAM EXTRACTION BY SUBHARMONIC BUNCHING

PHASE OF BUNCHES IN SUBHARMONIC FIELD

SCHEMATIC OF LONGITUDINAL PHASE SPACE DIAGRAM

Figure III-25. Generation of bunch-to-bunch energy differences for multiple energy extraction with a one-third frequency subharmonic cavity.

	Energy	Phase
A bunches	$W = W_1 + \delta W$	$\phi = \phi_1 + \delta \phi$
B bunches	$W = W_1$	$\phi = \phi_1$
C bunches	$W = W_1 - \delta W$	$\phi = \phi_1 - \delta \phi$

The A and C bunches will make coherent longitudinal oscillations around the synchronous phase, ϕ_s . The number of phase oscillations per turn, ν_s , is given by the relation

$$\cos \nu_s \pi = 1 - \pi/2 \tan \phi_s \quad (\text{III-19})$$

The choice of ν_s will be such that at the desired extraction energies the orbit separation in the short straight sections between bunch A (or C) and bunch B will be close to a maximum. The choice of ϕ_s will be a compromise between a large enough orbit separation and a negligible non-linear effect.

As an example we assume that the beam size in the short straight section (SSS) will be about 1 mm so that a 2.0 mm orbit separation will provide adequate space for an electrostatic septum of the type commonly used at high-energy accelerators. The electrostatic septum will be followed by a septum magnet. Without focussing elements the natural dispersion function in the SSS will be just r so that

$$\delta x = r \frac{\delta W}{W} = \frac{1}{Bc} \delta W = 2.19 \delta W, \quad (\text{III-20})$$

where δW is in MeV and δx is mm.

The focusing elements in the straight sections will cause the dispersion function at the SSS center to have a minimum ($<r$) for low energies and a maximum ($>r$) for high energies so that the actual requirement on δW for a given δx will be energy dependent. Using the natural dispersion for illustration purposes and assuming that $\delta W_{\max}$ will be 0.912 MeV, a 2.0 mm displacement of the beam will occur at all energies. On preceding passages through the SSS the bunches A and C will have occupied positions on an upright ellipse described by

$$\beta \delta W^2 + \frac{\delta \phi^2}{\beta} = R^2 \quad (\text{III-21})$$

where $R = \sqrt{\beta} \delta W_{\max}$. For $\phi_s = 14^\circ$ ($\nu_s = .29$) the Twiss parameter β will be 0.1273/MeV giving $R = 0.244 \text{ MeV}^{1/2}$. The phase point ($\sqrt{\beta} \delta W, \delta \phi / \sqrt{\beta}$) moves on a circle of radius R rotating by $2\pi\nu_s$ each turn. In particular, during some passages the groups A and C will have $\delta W = 0$, $\delta \phi = \pm \beta \delta W_{\max} = \pm 0.115$ (6.6°). At other locations inside the DSM the ellipse will not be upright and the motion equation will become

$$\beta \delta W^2 + 2\alpha \delta W \delta \phi + \gamma \delta \phi^2 = R^2 \quad (\text{III-22})$$

$$\beta\gamma - \alpha^2 = 1$$

where β, γ, α will be the Twiss parameters for the position under consideration.

In the Argonne design the subharmonic cavity will be located in a dispersion-free region in the beam transport line between the 180 MeV RTM and the DSM. The beam will be injected into the short straight section of the DSM by means of a dipole triplet (see Figure III-1) which will be designed to produce a negative shear of $\delta \phi_1 = -0.5913 \delta W_1 / \text{MeV}$. Inserting this quantity

into equation III-21 gives:

$$\delta W_1 = \frac{R}{\sqrt{\beta + \frac{(0.5913)^2}{\beta}}} \quad (\text{III-23})$$

The values of δW_1 required to match the beam corresponding to the parameters given above for the short straight section of the DSM is 191 keV. This would correspond to a subharmonic cavity voltage of 220 keV.

The dispersion function at the cavity must be nearly zero, otherwise bunches A and C, having exited from the cavities off their equilibrium orbit positions would execute coherent betatron oscillations about these orbits. In progressing through the DSM the positions of these orbits would move due to the δW , $\delta\phi$ rotation of the longitudinal phase space. In the SSS extraction orbit, δW would have to be near a maximum but also the amplitude of the betatron coherent oscillation for either bunch would have to be greater than zero at the same time. In the Linac sections, where the dispersion is zero, the bunches A and C would occupy different phase positions of the betatron oscillation for each energy. In general the 36.5 linac beams would occupy different parts of the transverse phase space. The amplitude of the betatron oscillations at a location in the microtron corresponding to beam energy, W , and betatron function, β , would be

$$\Delta x = \sqrt{\frac{W_0}{W}} \sqrt{\frac{\beta}{\beta_0}} \sqrt{\eta^2 + (\alpha_{x0}\eta_0 + \beta_{x0}\eta'_0)^2} \frac{\delta W}{W} \quad (\text{III-24})$$

where W_0 would be the beam energy, η_0 , η'_0 would be the dispersion function and its derivative and α_{x0} would be the horizontal Twiss parameters at the

subharmonic cavity location. The dispersion η_0, η'_0 will be made sufficiently small in amplitude so that the induced betatron oscillation in the SSS will not be as large as the displacement due to the energy kick.

E. PHASE SPACE MATCHING

1. Introduction

For energies above 30 MeV the variation in the longitudinal beam properties can be described by a combination of linear matrices operating on the conjugate variables of energy error, δW , and phase angle error, $\delta\phi$. The longitudinal phase-ellipse area occupied by the beam, i.e. beam emittance, is assumed to be conserved during the acceleration process. If variation in the r.f. synchronous phase angle, ϕ_s , to be constant during traversal of the linac, the matrix operator for a linac section will be

$$L = \begin{pmatrix} 1 & 0 \\ -eV_0 \sin\phi_s & 1 \end{pmatrix}, \quad (\text{III-25})$$

and the corresponding operator for a hard-edge dipole magnet will be

$$D = \begin{pmatrix} 1 & \frac{\pi\nu}{\Delta W} \\ 0 & 1 \end{pmatrix}. \quad (\text{III-26})$$

The corresponding beam vector is $\begin{pmatrix} \delta\phi \\ \delta W \end{pmatrix}$, and the energy gain per turn $\Delta W = meV_0 \cos\phi_s$ with $m = 1$ for the RTM and $m = 2$ for the DSM. The value of ν in equation III-26 corresponds to the integer number of wavelengths between recessive traversals through the linacs of the microtron. The value of ν will be unity for this design. These matrices can be used to obtain the Twiss parameters which characterize the matched longitudinal phase ellipse behavior at any point in the RTM or DSM. In either microtron under optimum conditions the acceptance ellipse will be upright at the center of the linac and at the center of the straight sections. The longitudinal acceptance is traced through the microtrons in Figure III-26.

RTM $\phi_s = 20^\circ$ $\nu_s = 0.273$

DSM $\phi_s = 14^\circ$ $\nu_s = 0.292$

Figure III-26. Longitudinal phase ellipses at each location in Figure III-27.

Figure III-27. Points along trajectory of RTM and DSM where longitudinal ellipses are calculated.

The points along the trajectories of the RTM and DSM where the longitudinal ellipses are calculated are presented in Figure III-27. The phase space ellipses in Figure III-26 correspond to an emittance of 30π keV-degrees in a RTM with $\phi_s = 20^\circ$ and a DSM with $\phi_s = 14^\circ$. As the data show, the variation in phase is much tighter in the DSM than in the RTM for a matched beam.

Therefore, to avoid substantial longitudinal dispersion, phase space matching will be required between the RTM and DSM as well as at injection into the RTM. Transverse phase space matching will also be necessary. The system required for transverse matching will be discussed separately since in first order its effects are orthogonal to longitudinal phase space.

2. Longitudinal Phase Matching at 30 MeV.

The 5 MeV beam will be injected into a linac of the DSM through a chicane system. After acceleration, the 30 MeV beam will be guided from the DSM by the optical system shown in Figure III-14 to the point of injection into the RTM. The acceptance phase ellipse at the injection point to the RTM is shown as point B in Figure III-26. The Twiss parameters of the phase ellipse will be

$$\begin{aligned}\alpha &= \frac{\pi}{\sin\theta} \tan\phi_s &= 1.1554, \\ \beta &= \frac{2\pi}{\sin\theta} \frac{1}{\Delta W} &= 1.0581 \text{ (rad/MeV)}, \\ \gamma &= \frac{1}{\sin\theta} eV_0 \sin\phi_s &= 2.2066 \text{ (MeV/rad)},\end{aligned}\tag{III-27}$$

where $\cos\theta = 1 - \frac{\pi}{2} \tan\phi_s$, and $\phi_s = 20^\circ$.

The phase ellipse will be given by

$$(\delta\phi)^2 + (\alpha\delta\phi + \beta\delta W)^2 = \beta\epsilon, \quad (\text{III-28})$$

where $\epsilon = 30\pi$ keV-degrees. The phase ellipse tilt parameter $\gamma = -\alpha/\sqrt{1+\alpha^2}$ will be negative. The energy half width will be 34.0 keV and the half phase half width will be 1.35° . A 170° bend will be required to transport the 30 MeV beam from the linac exit to the RTM injection point. Since it will be possible to achieve the required match at the linac exit, the 170° bend system will be designed to be isochronous, thereby preserving the longitudinal phase ellipse shape and tilt of the beam at the linac exit.

Longitudinal matching will be done by adjusting the synchronous phase angle of the beam at the 5 MeV injection point with respect to the phase at injection into the RTM. The synchronous phase angle slip in the linac from 5 MeV to 30 MeV will be about $\sim 50^\circ$. Choice of the negative synchronous phase angle at 5 MeV will control the effective energy and phase angle shear of the beam as it passes through the linac. The phase space ellipse will be sheared positive in energy for $\delta\phi > 0$ during the first 10 MeV of acceleration. When the synchronous phase, ϕ_s , slips into the positive region a negative energy shear will take place.

A detailed numerical simulation code was developed, which traces longitudinal phase ellipse, synchronous angle and energy through the linac. Starting with a matched ellipse for the RTM ($\phi_s = 20^\circ$) at 30 MeV with a synchronous angle $\phi_{s \text{ out}}$, the phase ellipse and the synchronous angle ϕ_s is tracked back to 5 MeV. The Figure III-28 shows the resulting phase half width $\delta\phi_{\text{max}}$ and energy half width δW_{max} of the ellipse for various $\phi_{s \text{ out}}$.

Figure III-28. Longitudinal phase ellipse half phase angle width, $\delta\phi_{\max}$, and half energy width, $\delta\phi_{\max}$, at 5 MeV for various synchronous angles.

The phase ellipse tilt parameter γ is also indicated. At 5 MeV phase angle shear due to the spread in electron velocities will also be present so that $\delta\phi_{\max}$ varies about $\pm 1^\circ$ from the corresponding 30 MeV ellipse half width. Although the $\delta\phi_{\max}$, $\delta W_{\max}$ and the tilt γ are correlated, the results of Figure III-28 show a beam of $\delta\phi_{\max} = 0.5^\circ$ to 2.5° , $\delta W_{\max} = 20$ KeV to 100 keV from the 5 MeV injector will provide an acceptable match. The emittance growth when $\delta_{\max} = 20$ keV will be negligible, but it will be about 30% when $\delta W_{\max} = 90$ keV.

3. The Longitudinal Phase Matching at 180 MeV

After acceleration from 30 MeV to 180 MeV the beam will be extracted from the return path of the RTM. The phase ellipse is shown at point C of the RTM in Figure III-26 for an emittance of 30π keV-degrees. The energy half-width will be 34.0 keV and the phase angle half-width will be 1.06° . The acceptance ellipse at point C of the DSM will be 65 keV and 0.47° . The matching of the two ellipses will be accomplished by a positive phase shear induced before extraction from the RTM, followed by a positive energy shear induced with a matching cavity, which will in turn be followed by a negative phase angle shear in a dipole triplet transport system. A matching system is shown schematically in Figure III-29.

A large phase angle shear will be generated before passage through the matching cavity in order to minimize the influence of errors in r.f. phase synchronization between the RTM linac and the matching cavity. This will be accomplished by a 20 cm displacement of the beam on its return path in the RTM at 180 MeV. As a result the displaced 180 MeV ray will propagate through the RTM a second time undergoing two 180° bends without traversing the linac

INTER-MICROTRON BEAM MATCHING SYSTEM, SCHEMATIC

Figure III-29. Schematic of beam matching system between booster and double-sided microtrons.

section. The phase angle shear due to a dipole is given as

$$\Delta\phi = \frac{2\pi}{\beta\lambda} \rho (\theta - \sin\theta) \frac{dW}{W} . \quad (\text{III-29})$$

where

- λ = free space wavelength at the fundamental frequency
- β = velocity of particle normalized to the speed of light,
- ρ = bending radius,
- θ = bending angle of magnet,
- δW = energy difference relative to synchronous energy, and
- W = energy of particle.

The large phase shear for a particle with a positive energy error, δW , will be achieved by a large bending angle, θ , and by a large radius of curvature, ρ . The drift space between the dipoles will produce no phase shear since the path lengths are identical for all energy errors, δW . The phase shear due to 10° "translating" bends system will be negligible ($\sim -0.02^\circ$). At the extraction point, the phase half width will be 2.27° .

The extracted beam will pass through a matching cavity and a sub-harmonic cavity, a system of 80° left bend, drift length, d , 80° right bend, drift length, d , and a 80° left bend in order to transform the tilted ellipse to an upright ellipse. The sector dipoles will have equal bending radii. The negative phase shear will be achieved by having a shorter path length for higher energy particles and a longer path length for lower energy particles. The phase shear rate, i.e. the ratio of phase angle shear and the energy error of the particle, will be a function of the bending radius and the drift distance, d . The sequence of longitudinal phase ellipses that will exist at

the return path of the RTM, at the extraction point of the RTM, after the matching cavity and after the triple dipole system are shown in Figure III-30.

The energy and phase angle shear rates required in the r.f. matching cavity and triple dipole system for a longitudinal phase space match to the DSM can be determined by using first order transport theory. The operating parameters of Table III-1 were assumed for the RTM in calculations which were carried out for two choices of synchronous phase in the DSM. The operating conditions for the r.f. matching cavity and triple dipole system required to obtain the specified shear rates are tabulated in Table III-7. The conditions that are obtained are independent of beam emittance and can easily be realized in a transport line of conventional design.

Table III-7. Parameters for matched operation of RTM-DSM beam transport line.

		Case 1	Case 2
		$\phi_{\text{DSM}} = 14^\circ$	$\phi_{\text{DSM}} = 33^\circ$
R(cm)	B(kG)	d(cm)	d(cm)
50	12.01	33.75	21.25
60	10.01	33.30	17.40
70	8.58	30.10	13.30
Matching Cavity Voltage (MeV)		0.8120	1.5475

R, B, and d are the bending radius of the triple dipole system, guide field required, and dipole separation.

Figure III-30. Longitudinal phase ellipse matching process at 180 MeV.

4. The Choice of Synchronous Phase Angle ϕ_s for DSM and RTM

The longitudinal phase stability condition will restrict the range of synchronous phase angle,

$$0 < \tan\phi_s < \frac{2\pi}{\pi}, \quad (\text{III-30})$$

which for the RTM will be between 0 and 32.48° and for the DSM will be between 0 and 51.85°. As seen in Figure III-26, the matched ellipse for the DSM will be more elongated towards higher energy for larger values of ϕ_s . Stronger energy shear will be required in the matching cavity for larger values of ϕ_s . The value of ϕ_s will be chosen to optimize simultaneous extraction at three different energies, minimize energy dilution due to phase jitter between linacs, and avoid synchrotron-betatron motion resonances.

5. Transverse Phase Matching at 180 MeV

At the center of RTM linac, the values of β_x and β_y will be 1.5 m for $\epsilon_x = \epsilon_y = 27.78 \times 10^{-3} \pi$ mm-mr and $\eta = 0$ and $\eta' = 0$. The x and y envelopes will form waists. This beam will be transported to the DSM dipole from the center of the RTM linac. The beam will enter the DSM dipole with a pole face rotation of -45° and will exit with +30°. Four quadrupoles will be placed between the RTM exit and the triple 80° bend system. Two doublets and a singlet will be required to catch the beam between the triplet dipoles and the DSM dipoles. The quadrupole magnet strength and locations that will be required are listed in Table III-8. All quadrupoles are 0.1 m long.

Table III-8. Quadrupole strengths required for transverse phase space matching between booster and main microtron.

Q1	0.1832 KG/cm HF
Q2	0.3478 KG/cm VF
Q3	0.0908 KG/cm HF
Q4	0.2282 KG/cm HF
QD1	0.9024 KG/cm VF
QD2	0.9439 KG/cm HF
QD3	2.3717 KG/cm HF
QD4	4.9457 KG/cm VF

Figure III-31 shows the horizontal and vertical envelopes and Figure III-32 shows the dispersion trajectory for matched conditions. The matching cavity and subharmonic cavity if placed at the section where $\eta = 7.52 \text{ mm/\%}$, $\eta' = 0$ will induce a maximum betatron oscillation amplitude of $\approx 0.8 \text{ mm}$.

Figure III-31. Horizontal and vertical beam envelopes in the 180 MeV transverse phase matching.

Figure III-32. Dispersion trajectory from RTM to DSM.

F. 2 GeV MICROTRON VACUUM SYSTEMS

Pumping of the microtron vacuum chamber will be accomplished with turbomolecular pumps in the straight section areas, appendage ion pumps in the linac areas, and a combination of turbomolecular and distributed ion pumps in the sector magnet areas. The required pressures within the sector magnets and short straight sections, the linacs, and the beam lines to the experimental areas are 1×10^{-5} and 5×10^{-7} and 1×10^{-6} Torr, respectively.

The most difficult region to pump will be the vacuum chamber in the sector magnets of the Microtron. The chamber for this area is currently designed to be a stainless steel wall sandwiched between the magnet poles. There will be double gasket seals between these walls and each pole face. Holes will penetrate this wall at 37 points along the cord of the chamber and a point at one end to allow beam passage. Other penetrations along the arc will be used to provide access for the vacuum pumps. Limited access for appendage pumps, the high impedance characteristics of the gap, the inability to bake, and the high outgassing of the mild steel pole faces will limit the attainable pressure in this region. The present design is to use eight 150 l/sec ion pumps distributed along the arc length of the 4 cm gap. The ion pump housing is designed to be part of the chamber wall and will permit the maintenance and repair of the pumps without any major dismantling of the magnet or excessive loss of operating time. Additional distributed pumping is provided through the 37 holes along the cord side of the gap and leading to the short straight section pipes. Two 1000 l/sec turbomolecular pumps are mounted to a manifold that intersects the 37 pipes as close as practicable to the chord side of the magnet. The total gas load in each sector magnet is 3.7×10^{-3} Torr l/sec which includes only the outgassing of the pole faces and seal gaskets. One half of the outgassing load from the 37 short straight

sections is 2×10^{-5} Torr ℓ /sec. The pump locations and mounting geometries for the current design give an average pressure in the sector magnet chambers of about 4×10^{-6} Torr after 40 hours. A sector chamber will be roughed down using a mobile pumping station at each end of the magnet. This station will consist of a 1000 ℓ /sec turbomolecular pump and a 50 cfm rotary piston pump. Two of these will permit each of the sectors to be evacuated in a serial fashion.

The chamber design described above does have the desired quality of economy. Other designs will, of course, be considered for the final machine. Among these will be a chamber that is independent of the magnet and is fabricated from tin-walled stainless steel tubing and intersecting pumping manifolds.

Pumping of the linac sections will present no special problems as long as cleanliness is maintained throughout the installation. Valves on each end of the linac will permit its isolation. The total gas load for each of the eight sections in each linac is estimated to be 4.5×10^{-6} Torr ℓ /sec. Each linac is to contain fifteen 60 ℓ /sec appendage ion pumps. a 1000 ℓ /sec turbomolecular pump and a 50 cfm rotary piston pump on each end of the linac line will be used for roughing down the linacs to the starting pressure of the ion pumps, as well as contributing to the pumping of the linacs and sectors during operation.

The beam transport lines between the 2 GeV microtron and the experimental areas will total about 300 m. Ten centimeter diameter aluminum pipe is to be used for these lines. To avoid loss of vacuum integrity and permit rapid replacement of equipment due to the expected radiation environment, beam line joints will have metal seals and quick disconnect clamping. Eight 60 ℓ /sec ion pumps spaced approximately 46 m apart will

maintain the beam lines at an average pressure of about 1×10^{-6} Torr. A valved port in each line will allow it to be pumped down from atmosphere using mobile pumping stations composed of a 1000 l/sec turbomolecular pump and a 50 cfm rotary piston roughing pump.

APPENDIX A

REGENERATIVE BEAM BREAKUP

The maximum electron current which can be accelerated in 100% duty factor recirculating accelerators is determined by the onset of regenerative beam breakup (RBBU). This phenomenon which is peculiar to recirculators, arises because C.W. beams can excite transverse deflecting modes in the linac sections. These modes produce forces on the injected beam which drive it out of the acceptance region of the accelerator on its first traversal of the linac when its magnetic rigidity is lowest. This type of breakup has been studied in some detail by Volodin and Hanson [Vo-75], Herminghaus and Euteneur [He-79], Vetter [Ve 80] and Rand [Ra 81]. The description by Rand is based on the standing wave treatment of Schwettman and Vetter [Sc 79].

The lowest order transverse modes which can cause RBBU are the TM_{110} mode and more generally the HEM_{110} mode. The field pattern for these modes is shown in Figure A-1. They act as deflecting modes because of the odd spacial dependence of the transverse H field under reflection about the linac center. Any small beam displacement from central orbit will result in an additional deflection of the beam which will be focusing or defocusing depending on the r.f. phase of the field. The beam is most sensitive to such forces on its initial traversal of the linac when its momentum is lowest. The coupling of such beam motion to the r.f. modes arises from resulting displacement of the recirculated beam which under favorable conditions can couple additional energy into the transverse mode and produce a regenerative growth in the beam displacement. The coupling is possible because of the spacial properties of the longitudinal electric field which result in energy transfer from beam to the transverse mode if the phase of the displacement is correct. There will be some threshold current above which the rate at which

REGENERATIVE BEAM BREAKUP

 $\text{HEM}_{110} / \text{TM}_{110}$

$$E_z \sim k r e^{i\theta}$$

H FIELD LINES

E FIELD LINES

Figure A-1. Schematic representation of Regenerative Beam Breakup. Upper portion shows the field configurations for a typical deflecting mode. The lower portion describes a typical configuration beam configuration leading to beam breakup.

energy is transferred to the mode exceeds the rate at which it is dissipated in the walls of the cavity. Should this happen the stored energy in the mode will grow according to the time dependence:

$$E = E_0 \exp \left[\frac{(I - I_s) \omega t}{2 I_s Q} \right]$$

increasing the beam displacement until it is lost. I_s is the threshold starting current and Q is the quality factor for the transverse mode.

The mechanism for RBBU is illustrated schematically in Figure A-1 in a double sided microtron. Assume some noise or residual field causes a small deflection of the first turn. Depending on the recirculating optics the return pass may experience a substantial displacement and if the beam phase is correct, the electrons will experience a retarding field. A transfer of energy from the beam to the deflecting mode will result. The increased field strength in this mode will cause an additional deflection of the first turn beam, which will in turn increase the power in the deflecting mode until the beam is lost. The mechanism is complex and the recirculation optics play a crucial role since they determine both the lateral position and phase of the beam. To develop a credible model for the process in a specific recirculator one must know the properties of the transverse deflecting modes in the linac structures, their frequencies and Q 's, the details of the orbit containment optics, and the exact geometries of the particle trajectories. The linac and beam optics in a specific design must be optimized for maximum starting current.

Rand has developed an approximate formula which does not take account of the detailed features of the accelerator structure or of the beam optics of the accelerator, but which is useful for estimating the magnitude

starting current for regenerative breakup, and assessing its dependence on various parameters. The Rand "rule of thumb" for DSM's is

$$I_s \approx \frac{M(\gamma_1^* + \gamma_0) L_s}{Q_L N^2 L_0 (n-1)}$$

where M varies from 1 to 5×10^4 amps depending on the recirculation optics. γ_1^* is the electron energy at the center of the first isolated linac section, γ_0 is the energy gain per turn in units of $m_0 c^2$, L_s is the linac section length and L_0 is the total linac length, N is the number of sections per linac. Finally n is the number of turns to extraction energy, and Q_L is the loaded Q of the HEM deflecting mode. Evaluating this relation for the ANL design we find an estimated starting current for beam breakup of 0.7 ma, for a breakup mode with $Q_L = 1.5 \times 10^4$. This is to be compared with a design objective of 0.3 ma for the total beam current. It is evident from this formula that high injection energy, minimum number of recirculations, and highest accelerating voltage gradient together with shortest possible linac produce highest starting currents.

A more detailed treatment of this model of RBBU has been [Ra 81a] used to estimate starting currents for a number of proposed recirculating accelerators. Parameters for these systems as used in the calculations are tabulated in Table A-1 together with the estimates for a minimum (worst) value and a typical value. Because the properties of the transverse modes in the r.f. structures are unknown, a continuous spectrum of frequencies extending over the full range of interest was assumed. The results for the ANL design indicate that the design objective is comfortable within the limit for RBBU. The calculations for the Stanford recyclotron which using a superconducting linac under 3 turn operation gives results in rough agreement with the

Table A-1. Regenerative BBU in Proposed Recirculating Accelerators

Institute	NBS/LANL	NBS/LANL	MIT	Stanford	Stanford	ANL	NBS/LANL	MIT
R.F. Type	NC/D+W		NC/TW	SC	SC	NC/D+W	NC/D+W	NC/D+W
Recirc. Type	RTM		RC	RC	RC	DSM	DSM	RC
Final Energy (MeV)	185		740	125	2050	2005	1985	1980
Passes	15		2	3	10	40	36	14
Structure L (m)	4.0	8.0	.35	5.66	.81	4.0	4.0	4.0
Loaded Q	1.5×10^4	1.5×10^4	2×10^4	3×10^7	2×10^7	1.5×10^4	1.5×10^4	1.5×10^4
Beam Optics	$\pi/2$	Min β	$\sigma = 4.0$	$\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$	$\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$	Min β	Min β	$\sigma = 4.0$
BBU Energy (MeV)	8.0	8.0	58.8	10	51.7	7.5	187.5	20.0
I_B (mA) calc. worst	750	850	120 mA	20	190	720	1800	720
I_B (mA) typ.	1900	2100	120 mA	24	340	1900	6500	2100
Design	550	550	10 mA	23		300	300	300

SC = Superconducting, NC = Normal Conducting, D+W = Disc and Washer, RC = Recyclotron, RTM = Racetrack Microtron, DSM = Double-sided Microtron

observed starting currents of ~ 20 μ amps. These results serve as a benchmark test of the calculations, and the experimental confirmation gives some confidence in the treatment. Nevertheless, the approximate character of the theory and the extrapolation to room temperature linacs suggests that a careful calculation using a model of the accelerator design is still requisite to establishing scientific feasibility.

Attempts to observe RBBU in room temperature recirculators thus far have failed. A 14 MeV 20 turn race track microtron has operated routinely [Au 81] with C.W. beams of up to 90 microamps. Attempts to test breakup calculation have been made [Eu 81] by looking for amplification of transverse beam noise imposed by means of an r.f. cavity on the injection path. The beam noise, at $\nu = 4175 - 4205$ MHz was detected by a similar cavity at the output of the RTM. No evidence of a resonance of beam noise was observed, although the region near 4200 GHz is expected to be particularly troublesome.

In summary, the limited evidence available suggests that there is not a fundamental limit imposed on the design presented here at the operating levels proposed. However, it will be necessary to develop detailed computer simulation of beam behavior to optimize any prospective microtron design and establish paper proof of scientific feasibility.

APPENDIX B

EFFECTS OF SYNCHROTRON RADIATION IN A DSM

In this appendix, the equations are developed for calculating energy loss, radiated power, spread in beam energy arising from quantum fluctuations, and transverse emittance growth. Source material is drawn from references by J. D. Jackson [Ja 67] and Matthew Sands [Sa 71].

In the discussion which follows we use accelerator parameters appropriate to the DSM design described in section III of this report. The energy radiated by an electron in traversing a 90° bend is given by

$$\delta E(\text{KeV}) = 22.125 \frac{[E(\text{GeV})]^4}{\rho(\text{m})} \quad (\text{B-1})$$

where the radius of curvature ρ is given as

$$\rho(\text{m}) = \frac{33.3567 E(\text{GeV})}{B_0(\text{KG})}$$

The field we assume $B_0 = 15.23 \text{ KG}$ so we can rewrite (B-1) as

$$\delta E(\text{KeV}) = 10.1089 [E(\text{GeV})]^3 \quad (\text{B-2})$$

Thus at $E = 2 \text{ GeV}$ an electron radiates 323.485 KeV/turn. We can calculate the total power radiated by the beam for each turn. The result is

$$P_F(\text{watts}) = 8.85 \frac{I(\text{amps}) E^4(\text{GeV}) \times 10^4}{\rho(\text{m})} \quad (\text{B-3})$$

for 100 μA and $E = 2 \text{ GeV}$ the loss is 32.35 watts.

The critical quantum energy is given by

$$u_c = \hbar \omega_c = \frac{3}{2} \hbar c \frac{\gamma^3}{\rho}$$

where $\gamma = E/m_e$ ($u_c = 0.40545 \times 10^4$ eV at $E = 2$ GeV). The mean square energy spread introduced per radian of bend is given as

$$\langle (\Delta E)^2 \rangle = \frac{55\gamma}{2\sqrt{3} \cdot 137} \frac{u_c^2}{27}$$

and for a $\pi/2$ bend we obtain the value

$$\langle (\Delta E)^2 \rangle = 64.9373 \frac{E^7 (\text{GeV})}{\rho^2 (\text{m})} \quad (\text{B-4})$$

with the result in $(\text{keV})^2$. For the double-sided microtron $E/\rho = 0.029979$ B₀(KG) giving $\langle (\Delta E)^2 \rangle = 13.537 E^5 (\text{GeV})$. This expression can be integrated around the machine

$$\langle (\Delta E)^2 \rangle_{\text{TOT}} = 27.074 \sum_{i=1}^n E_i^5 (\text{GeV}) \quad (\text{B-5})$$

where i represents half turns in the machine we obtain the rms $[\langle (\Delta E)^2 \rangle]^{1/2} = 110$ keV.

The actual spread in beam energy is measured by the root-mean-square (rms) deviation from the mean beam energy. If we assume on the average, n photons are emitted by an electron during a bend of π radians, the resulting total rms deviation will be related to the rms fluctuation for single quantum emission according to the equation

$$\begin{aligned} \langle (\Delta E - \langle \Delta E \rangle)^2 \rangle &= n (\langle u^2 \rangle - \langle u \rangle^2) \\ &= \langle (\Delta E)^2 \rangle - \delta E^2/n \end{aligned}$$

where n is given by [Sa 71]

$$n = \frac{10^4 \pi E(\text{GeV})}{2\sqrt{3} 137}$$

with ΔE and δE given by equations (B-2) and (B-4). To obtain the beam spread at the extraction energy of 2 GeV this expression must be summed over n half turns. Neglecting the effect of synchrotron oscillations induced by photon emission we find

$$\langle (\Delta E - \langle \Delta E \rangle)^2 \rangle = 20.899 \sum_{i=1}^n E_i^5 (\text{GeV}) \quad (\text{B-6})$$

Evaluating this equation in the same manner as B-5 we find 97 keV for the rms energy spread induced in the beam by quantum fluctuations.

The mean square angular divergence introduced by a 180° bend can be written as [Eu 81]

$$\langle (\Delta \theta)^2 \rangle = \frac{n \langle u^2 \rangle}{2E^2} = \frac{\langle (\Delta E)^2 \rangle}{2E^2} \quad (\text{B-7})$$

At 2 GeV the rms value is 10.4×10^{-6} radians. The total mean square angle for the machine is

$$\langle (\Delta \theta)^2 \rangle_T = \frac{13.537}{10^{12}} \sum_{i=1}^n E_i^3 \quad (\text{B-8})$$

The calculated rms angle is 0.046×10^{-3} radians. This factor will not cause significant deterioration of the beam emittance but the associated coherent betatron motion amplitude will be the order of 0.6 mm.

APPENDIX C

BEAM DIAGNOSTICS AND CONTROLS

Because of the complexity of the microtron system described in this report, the large number of optical elements, and the requirement of independent multiple beam operation, a highly developed system of beam diagnostics will be required to optimize the beam steering, focusing, and phasing for reliable operation. A variety of instruments for measuring various properties of the beam are already in use or under development. The diagnostic devices to be used include light sensitive screens for TV viewing, rectangular or cylindrical low Q cavities for position sensing, phase detection, and intensity measurements, and moving wire scanners for beam profile measurements. Beam loss monitors will be provided at critical stages in the accelerator.

A relatively powerful computer software and hardware system will be required to provide accelerator control and data monitoring for the source and injector linac, the 180 MeV RTM, the 2 GeV DSM, and the extraction beam lines. The system will provide both autonomous and network control of each station of a distributed multiprocessor system. Microprocessors will provide local component control and simple task computational capability at individual stations, while high level processors at the central station will provide overall system control and comprehensive computational capability.

The accelerator design will incorporate the ability to provide a notched or pulsed beam so that the behavior of individual orbits can be observed in the linac and dispersion free regions by following the beam pulse through the diagnostic system as a function of time. Consideration will be

given to providing energy spectrometers between the linac injector and RTM, the RTM and DSM, and after the DSM.

The beam profile, phase angle, and intensity will be measured at the exit of the injector linac. Moving wire scanners will be set in three locations so that matched beam conditions can be provided into the RTM beam injection transport system. The output phase, beam intensity, and beam position will be measured with non-intercepting, low Q r.f. cavities in either the cylindrical TM_{110} -like modes used at Mainz [He 76a] and the University of Illinois or the square cross section TM_{210}/TM_{120} mode devices under development for the NBS-LANL Microtron.

The RTM will have non-intercepting, low Q r.f. cavities for beam position and r.f. phase at the linac straight section entrance and exit, and on each of the 25 orbits. Moving wire scanners will be located in the entrance and exit beam lines to tune the injection and extraction beam lines. The beam optics for the RTM will be adjusted with moving wire scanners located in the linac straight section to be used with the pulsed beam and with several moving wire scanners located periodically in the return paths. The capability will be provided to relocate them in any of the 25 return orbits. Light sensitive screens capable of being viewed by a TV camera will be located in all the return paths so that a coarse view of the beam will be possible by driving the screen in place.

The DSM will have non-intercepting, low Q r.f. cavities for beam positional phase detection on all the return orbits and in the linac straight sections. Intensity monitors will be located in several of the return paths with the ability to move them into any of the 72 return paths. Moving wire scanners will be located in the linac sections to be used with pulsed beams and will be located in several return paths with the ability to move them into

any of the 72 return paths. Light sensitive screens will also be located in all 72 return paths so that a coarse view of the beam size and position can be made with TV cameras by driving the screens into the beam.

Location of energy spectrometers of conventional design will be considered in between the linac injector and RTM, the RTM and DSM, and after the DSM. Multiple wire detectors would be used to determine energy spread at the high dispersion point on the spectrometers. Conventional radiation detection equipment will be used inside and outside of the accelerator building as a part of a safety system to reduce or stop the beam current in the event of excessive beam loss by the accelerator.

The central computer system will be based on two high-capability minicomputers. One central processing unit will be used to control most of the various accelerator systems: source, injector linac, all microtron linacs, and the various inter-accelerator beam lines. The second will be devoted to the two microtron orbit diagnostic and control systems as well as the relatively mundane tasks of external beamline monitoring and control. In this way relatively more computing power will be brought to bear on the orbit control problem. If additional capability is found to be necessary, three types of computing enhancements will be added to this CPU: a high-speed floating-point processor which includes several transcendental functions, as well as polynomial evaluation hardware; a separate "satellite processor" to off-load either the computation or display tasks; an array processor will be added if the nature of the problems are appropriate.

The CAMAC serial highway protocol will be used to link the CPU's with the various accelerator systems. Operating at a 1 MHz byte-serial rate and driven by a microprocessor-based highway driver, this system will provide

the necessary data interchange speed. Local microcomputer-based controls will be provided for most major accelerator systems.

APPENDIX D

CONVENTIONS FOR SYMBOLS USED IN SECTION II

A	asymmetry of longitudinally polarized electron scattering from nuclei.
$A(q^2), B(q^2)$	structure function for elastic electron scattering.
A_{EM}	electromagnetic transition amplitude between two nuclear states.
$A_{WNC}^{PC(PV)}$	transition amplitude due to the weak neutral current for the parity conserving (PC) or parity violating (PV) component.
A_N^{PV}	transition amplitude due to parity violation in initial or final nucleus state.
α	fine structure constant (except on p. 89).
$C(\vec{q})$	value of the Coulomb sum rule.
c	speed of light.
$E_{\beta\alpha}$	photon energy absorbed in inducing a transition between nuclear states α and β .
E_1	incident electron energy (lab).
E_2	scattered electron energy (lab).
E_s	separation energy of nucleon in nucleus
e	charge of an electron.
$F_L^{E(M)}(q^2)$	electric (E) or magnetic (M) form factors of a nucleus with $ J_\alpha - J_\beta \ll J_\alpha + J_\beta $.
F_C, F_Q, F_M	charge, quadrupole and magnetic form factors, respectively for the deuteron.

$F(y)$	longitudinal nucleon momentum distribution in the nucleus.
$G_{el}(q^2)$	form factor of a spin-zero nucleus for elastic electron scattering.
$G_{E(M)}^{p(n)}$	electric (E) or magnetic (M) form factor for a neutron (n) or a proton (p).
$G_D(q_\mu^2)$	dipole form factor of the nucleon.
g_A	axial vector coupling constant.
h	helicity of an electron, $h = \frac{\vec{\sigma} \cdot \vec{p}}{ \vec{p} }$.
J	four-current of a nucleus.
$J_\mu^e(q)$	electronic current.
$J_{\beta\alpha}^\mu(q)$	transition current between nuclear states α and β .
J^N	Weak neutral current.
J^C	charge changing weak current.
J^{EM}	electromagnetic current of a nucleus.
k_F	Fermi level of nucleons in the nucleus.
$\vec{k}_\pi$	three momentum of a pion in the nucleus.
$\mu_P(N)$	magnetic moment of a proton or neutron (N).
M_p	mass of the proton.
$M_{\beta\alpha}^\mu$	transition probability between nuclear states α and β .
M_T	mass of the target nucleus.
$\vec{p}_1$	momentum of incident electron.
$\vec{p}_2$	momentum of scattered electron.
P	longitudinal polarization of electron beam.
$P_{ }$	momentum transfer to nucleon in nucleus in longitudinal direction.
M_{l+}	M1 transition amplitude in the $H(\gamma, \pi^+)n$ reaction.

S_{1+}	longitudinal quadrupole (E2) transition amplitude for the $H(\gamma, \pi^+)n$ reaction.
$\vec{q}$	three-momentum transfer to a nucleus.
q, q^μ	four-momentum transfer to a nucleus.
Q_N	neutral weak charge of the proton.
ρ	charge density of the nucleus.
$S(\vec{q}, \omega)$	structure factor of the nucleus.
$S_L(T)$	longitudinal (transverse) structure factors of the nucleus.
σ_M	differential cross section for electron scattering from a point charge (Mott cross section).
$\vec{\sigma}$	Pauli spin vector of a nucleon.
$\sigma_{ep(n)}$	differential cross section for electron scattering from a free proton (neutron).
T_i	kinetic energy of particle i with energy E_i (lab frame).
t_{20}	tensor polarization (alignment) of the deuteron.
$\tau \equiv \vec{q}^2/4M_d^2$	ratio of the square of the ratio of momentum transfer to twice the deuteron mass.
θ	scattering angle of electron in the reaction plane (lab frame).
θ_W	the Weinberg angle.
$u_{0(2)}(r)$	radial part of the s-(d-) wave part of the deuteron wave function.
U_Δ	effective N- Δ interaction potential.
ω	electron energy transfer.
W_p	missing mass; for a proton target $W_p^2 = M_p^2 - q^2 + 2M_p\omega$.

$$X \equiv 2/3 \tau F_Q / E_C$$

a quantity which is independent of the electric form factor of the nucleon.

$$y = \frac{\vec{p} \cdot \vec{q}}{|\vec{q}|}$$

scaling variable which projects nucleon momentum component parallel to momentum transfer.

$$Y \equiv v_{||} / c$$

rapidity, ratio of the detected nucleon velocity parallel to incident beam to C.

$$Y_o \equiv v_{\perp} / c$$

ratio of velocity of emitted nucleons which perpendicular to incident beam.

CONVENTIONS FOR SYMBOLS USED IN SECTION III

$\alpha_i, \beta_i, \gamma_i$	Twiss parameters as a function of orbit position S_i .
β_e	electron velocity normalized to the velocity of light.
γ	ratio of total energy to the particle rest energy.
γ_0	energy gain per turn in units of the electron rest energy.
γ_1	electron energy at the center of first isolated linac section in units of the electron rest energy.
ϵ	emittance in transverse (longitudinal) phase space.
ϕ	"phase angle" between particle and peak r.f. voltage.
η	dispersion function.
η^1	slope of dispersion function.
θ_1	DSM sector magnet edge angle at linac edge.
θ_2	DSM sector magnet edge angle at dispersive edge.
λ	wavelength at operating frequency of microtron linac r.f. system.
λ_0	r.f. wavelength of chopper system.
$\mu_{n,1}$	harmonic number for the i^{th} orbit between linacs on the n^{th} turn in a double-sided microtron.
ν	microtron mode number.
ν_x, ν_y	number of betatron oscillations per revolution.
ρ	bending radius.
ϕ_s	r.f. synchronous phase angle.
ψ	phase advance of the betatron oscillation.
ω	r.f. angular frequency.
$A_1 A_2$	emittance limiting apertures in injector system.

B	magnetic flux density.
$B1-B4$	bending magnets of injection transport system.
c	velocity of light in vacuum.
$D1-D4$	steering magnets in booster microtron.
e	electric charge of the electron.
h	length of cylindrical TM_{110} cavity in injector system.
I, I_b	beam current.
I_s	threshold starting current for beam breakup.
l	end magnet separation in booster microtron.
L_o	total linac length in DSM.
L_s	section length in DSM linac.
M_{AB}	beam optical transfer matrix for point A to point B.
m_o	electron rest mass.
m	relativistic electron mass.
n	number of recirculations.
N	number of linac sections in DSM.
P	linac r.f. power per unit length.
Q	r.f. quality factor.
Q_L	loaded Q for HEM deflecting mode.
S	DSM linac half-length.
S_i	orbit length from the exit of the i^{th} linac to entrance of next linac in the limit of vanishing electron energy.
V_o	peak r.f. accelerating voltage.
W	electron total energy.
W_{ni}	energy of particle in n^{th} orbit at i^{th} half turn.

$x(i), y(i)$	particle position relative to central orbit at position i .
zT^2	effective shunt impedance of r.f. structure.

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