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**FABRICATION OF A 180° ELECTRON
SCATTERING FACILITY**

**Final Report
for Period January 2, 1975 - January 1, 1978**

RECEIVED

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January 1978

**Prepared For
The United States Department of Energy
under Contract No. E(11-1)-2545**

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ABSTRACT

A system of four dipole magnets to be used for 180° electron scattering studies at the 400 MeV William F. Bates Electron Linear Accelerator of Middleton, Massachusetts has been constructed and tested. The first three magnets through which the incident beam passes have similar pole shapes and serve only as beam transport elements. The fourth magnet directs the incident beam onto a target, and also receives and deflects the back-scattered electrons into a large magnetic spectrometer operating in an energy-loss mode. The system may be used for both elastic and inelastic electron scattering without moving the spectrometer. The incident beam and the post-target beam travel along the same line. Tests show that a constant solid angle is maintained for scattering regardless of the energy loss suffered by the electron in the target. A resolution inherent to the system of less than 2.5×10^{-4} was found.

FABRICATION OF A 180° ELECTRON SCATTERING FACILITY

I. Introduction

Electron scattering at 180° is a useful method of measuring magnetic and transverse electric electron-nuclear interactions when in normal scattering at forward angles the longitudinal Coulomb contributions and large radiation tails would dominate the cross sections.¹ Information about nuclear spin and convection current distributions can be obtained, as well as other information about nuclear energy levels and the nuclear continuum.²

In order to detect electrons in a relatively background free environment, and to obtain a high enough energy resolution so as to be able to distinguish closely spaced nuclear energy levels from one another, it is necessary to use a magnetic spectrometer. However, there is a limit to the scattering angles which can be observed with a spectrometer, because at both far forward and backward angles, the spectrometer will block the incident beam. It is necessary, therefore, to insert an additional magnet into the beam line if 180° scattered electrons are to be observed. This additional magnet deflects the incident beam onto a target, and the 180° backscattered beam passes back through the same magnet and is deflected into a spectrometer, as shown in Fig. 1. The use of a single separator magnet for 180° scattering has been^{1,3} successful when beam currents were small and it was not important to direct the post-target beam along the same line as the incident beam. As can be seen in Fig. 1, if the magnetic field is reduced so that inelastically scattered electrons are directed into the spectrometer, then the post-target beam is steered in a different direction than for the case of elastic scattering. For the high intensity beams of modern accelerators, the post-target beam steering can create severe radiation and background

FIG. 1

problems. In order to avoid post-target beam steering, it is necessary to put additional magnets in the beam line⁴, as shown in Fig. 2.

The Bates Electron Linear Accelerator is capable of producing average beam currents of 50 to 100 μA . These currents are about two orders of magnitude larger than the beam currents used in the early systems.^{2,3} Therefore, it is essential for the Bates case to take care in handling such high intensity beams, and to dispose of them in a well-shielded area. Since it is impractical to move a large shielding house when observing differing inelastic excitation energies, the simple scheme of Fig. 1 cannot be used by itself. The basic magnet system of Fig. 2 is much more suitable for the beam conditions at the Bates Linear Accelerator. In June of 1974 a proposal was submitted to the Atomic Energy Commission seeking funds for the construction of a refined version of the system shown in Fig. 2 which was to be used at the Bates Accelerator.

There are several additional advantages of the basic system of Fig. 2 over other systems. Since the spectrometer remains at a fixed angle, obviously there are no problems associated with sliding vacuum seals. Also since the electrons scattered from the target always take the same path through the last magnet regardless of the electron energy (although the incident beam travels through a different path if inelastic scattering is to be observed), then the solid angle presented to the spectrometer is constant and independent of the scattered electron.

A four-magnet system suitable for 180° scattering of electrons is shown in the position for elastic scattering (solid lines) and inelastic scattering at $\frac{1}{2}$ the incident momentum (dotted lines).

FIG. 2

II. Design Parameters

The system was designed for use with an incident beam which was to be dispersion matched to the Bates 900 MeV/c spectrometer. In referring to the magnets as shown in Fig. 3, dipole 1 will be denoted as D1, dipole 2 as D2, etc. The basic design parameters are given in Table 1.

It can be seen from Table 1 that the system was designed for a maximum beam energy somewhat beyond the present Bates Linear Accelerator capabilities in anticipation of possible future upgrading of the accelerator, even though the cross sections at 454 MeV, or $q^2 = 20.6 \text{ fm}^{-2}$, are generally expected to be very small.

The beam spot size chosen is much wider than is usually used, but it might correspond to a beam spot size after multiple scattering through a long, thick target. The momentum spread corresponds to the known dispersion of the incident beam. The small divergence of the incident beam is characteristic of linear accelerator beams and permits simplified beam transport to the target. The magnetic fields chosen for D1, D2, and D3 (16 kilogauss or 1.6 Tesla) are high, but reasonable, for good quality low carbon magnet steel. The field of D4 is smaller than those of the other magnets because its gap is larger. The magnets are all connected in series and take the same main currents. Table 2 gives the specifications of the magnets which were met by the manufacturer.

The maximum magnet current given in Table 1 is based upon magnetic field measurements after the magnets were shimmed following detailed magnetic field measurements. The reasons for the shimming will be discussed in the next section.

As indicated in Fig. 3, the dipole magnets D1, D2, and D3 are all of C-type

Figure 3

Outline of the 180° scattering system. Beam directions are indicated for the case of elastic scattering from an infinitely massive nucleus with no recoil. Distances are indicated between optical centers in inches

Table 2

January 18, 1977

MAGNET SPECIFICATIONS
180° SCATTERING SYSTEM

Manufactured by Alpha Scientific, Inc.
28971 Hopkins St., Suite 1
Hayward, California 94545

Delivered November 19, 1976

Price for four magnets and coils: \$38,251.75

D1:

Main Coils:

Rated Current: 360 Amps D.C.
For 108,000 Ampere Turns
Resistance: 0.260 ohms

300 turns per magnet, 150 turns per coil
Each coil is 15 turns wide by 10 turns
high wound in 2 turn high pancakes.
Water hoses are rated at 300 psi.

Trim Coils:

Rated Current: 18 Amps D.C.

Hot Voltage: 25 VDC

Resistance: 1.38 ohms

Cooling: 1.5 GPM @ 40 psi

Weight: 5500 lbs.

Nominal Gap: 3.122"

D2: Specifications the same as D1 except Nominal Gap: 3.253" Weight: 6885 lb.

D3: Specifications the same as D1 except Nominal Gap: 3.252" Weight: 6885 lbs.

D4: Rated Current: 360 Amps D.C. for 110,000 Ampere Turns Weight: 8500 lbs.
Resistance: 0.362 ohms

Cooling: 1.8 GPM at 40 psi

Removable pole tips separated by 4.500", i.e., gap: 4.500"

Maximum fields at 360 Amp: D1, D2, and D3: 16,000 gauss

D4: 11,200 gauss

without overheating.

Note: A booster pump is necessary to reach rated currents. Tentative
specification for booster pump: 12.3 gpm at 210 psi.

yoke construction, and D4 is of H-type yoke construction. All magnets have parallel flat pole pieces. The pole tips of D4 are contained inside its vacuum chamber, whereas the other pole tips are in air. The pole piece shapes of D1, D2, and D3 are similar, but are held in different orientations to the beam. The dipoles D2 and D3 move over the surface of their vacuum chamber so that the correct beam transport conditions are met for inelastic scattering according to the equation $\frac{p}{p_0} = \frac{B}{B_0} = \tan \frac{1}{2} \alpha / \tan \frac{1}{2} \alpha_0$, where p is the momentum of the scattered electron, B is the magnetic field in D1, D2, D3, and the gap-scaled field in D4, and α is defined as in Fig. 2. The variables subscripted with zero are the values for elastic scattering with no recoil.

Beyond the system of four magnets it is necessary to deflect the beam again so that electrons backscattered at 180° from a Faraday cup or beam catcher will not enter back into the system. It was decided to construct a pair of rectangular air-core coils 305 cm long by 80 cm wide to be located about 16 m downstream from the target. These coils would deflect the incident beam downward about 3° so that the returning backscattered beam would be deflected upward 3° above its path, or a total of 6° above the beam line. This construction is discussed further in the next section.

III. Component Design and Construction

A. Beam Optics

The computer program TRANSPORT⁵ was used to make first order calculations on the system. Final calculations were made by using the computer code RAYTRACE.⁶ The details of the optics calculations are given in the Internal Report #4 of the Medium Energy Nuclear Physics Group of the University of Massachusetts, a copy of which is attached as Appendix A of this report.

B. Magnet Steel

Most of the steel for the magnets was obtained from a rejected side of the Bates spectrometer. This piece was referred to as #214 and was made of 1005 low-carbon, high-permeability, Lukens magnet steel. It weighed over 16 tons. The reason for its rejection as a spectrometer side was because of the presence of a void running the length of the 136 inch long x 20 1/2 inch thick x 51 inch oblong piece. Since the total weight of the completed magnets was calculated to be 13.89 tons, it is apparent that most of the parts for the magnets of the 180° system could be cut from piece #214. About \$1100 worth of additional steel was required. Small pieces cut from piece #214 which were not large enough for magnet parts were made into field clamps by the University of Massachusetts shops after they were roughly cut with very large bandsaws by a commercial firm.

Although the steel provided by piece #214 saved us the cost of buying large quantities of steel, the cost of flame cutting it, sawing it, and of transporting it from the Boston based cutting firm to the California based magnet manufacturer totaled \$11,500. This amount should be added to the \$38,252 cost of magnet fabrication in evaluating the actual cost of the magnets. The use of piece #214 did not save much money in the cost of steel, but it did provide a higher quality steel than was readily obtainable for the magnets at that time.

C. Magnets

Figure 4 shows a pole profile for D3. Magnets D1 and D3 are similar.

Several cost saving features were used in constructing the magnets. Instead of machining the rather complicated shapes of the pole pieces of D1, D2, and D3 by using a computer controlled contour milling machine on one complete pole piece at a time, we instead joined two pieces of steel to make each individual pole piece, thus permitting the use of less-expensive machining time on lathes and shapers to make the poles. The surfaces that were to be joined together were surface ground so that a good fit would be obtained. Although the beam passed over the joint of each pole, there was no noticeable effect, nor could any noticeable effect be detected when the magnetic fields were mapped. The joint was so smooth that it looked like a small scratch on the pole piece surface.

Another cost-saving feature was to approximate a Rogowski equipotential contour curve on the pole face surface by two carefully chosen straight lines on the faces traversed by the beam, one at about 21° with respect to the vertical, followed by one at about 47° near the pole root. A single straight line sloped at about 20° with respect to the vertical was used on the pole edges not traversed by the beam.

In constructing the magnets we purposely specified gaps with little excess to clear the vacuum chamber. We did this in anticipation of the necessity of shimming within the yoke structure to make the magnets D1, D2, and D3 come to the same fields for given energizing currents, i.e., to make them magnetically equal. The shims for D1 changed its gap from 3.122" to 3.434", of D2 from 3.254" to 3.440", and of D3 from 3.252" to 3.408". Parallelism of better than

FIG. 4 D3 POLE PROFILE AND COIL

0.002" across the entire poles was maintained, even at high energizing currents, although the poles of C-magnets must deflect because of the forces between the poles. The gap in D4 was determined by a pole gap spacer accurately machined to a height of 4.500". Nevertheless, D4 was also shimmed so that its field was compatible with those of the other magnets. The magnets were found to be magnetically equal to within 0.5% after shimming. For the incident beam to travel along the same line after it traversed the system as before it entered the system, it was necessary to have $\int B \, dl = 0$ for the path length through the entire system. It was for this reason, and in this sense, that care was taken to make the dipoles magnetically equal.

D. Vacuum Chambers

Another reason for shimming the magnets was to provide adequate space for the clearance of the vacuum chamber by the poles. Rather than spending large amounts of money in heat treating in special furnaces our long stainless steel vacuum chamber for D1, D2, and D3, so as to prevent warpage and twisting of the steel upon welding, we took no special precautions. Instead we let it warp, and then machined off the excess due to warpage in the regions where the poles were to be located, and counted upon shimming the magnets to provide clearance. This permitted us to obtain the main vacuum system for about \$11,000.

Since the vacuum chamber in the region over which D2 and D3 moved had to be over $24 \frac{1}{2}$ inches wide, as shown in the assembly drawing of Fig. 5, it was necessary to provide a vertical rib in the midpoint of the chamber to prevent the atmospheric pressure from causing the chamber to cave inward. The chamber was divided into three parts, as shown in Fig. 5, one flat chamber for D1, one

FIG. 5

flat chamber for D2 and D3, and a round chamber for D4. The flanges on the ends of the center chamber also prevented the deflection of the chamber due to atmospheric pressure.

The round chamber of D4 has a relatively thin top and bottom of $\frac{1}{8}$ inch stainless steel that served as a Purcell homogenizing filter for D4, in that the D4 pole tips were contained inside the vacuum chamber. A spacer was constructed to keep the poles an accurate distance apart and parallel, but also to provide adjustment so that correct location of the pole tips with respect to the beam line could be obtained.

The T-piece on the target side of the D4 vacuum chamber contains the target changing mechanism.

E. Field Clamps

Field clamps were constructed at the entrance to D1, the exit of D2, the entrance of D3, and at all entrances and exits of D4. These field clamps effectively reduced the long tail on the fringing fields to zero, and permitted the field edges to be shaped to the desired forms in agreement with the optics calculations of Appendix A. The field clamp pole tips were iteratively varied after detailed field mapping was undertaken as described in Appendix B, Internal Report #10 on "Magnetic Field Measurements of the 180° Scattering System Dipoles". The field clamp for D1 was of an H-frame type, as was the D4 exit to the spectrometer. All of the other field clamps of necessity had to be of a C-frame type because of space constraints put on them by the vacuum chamber. The D2-D3 field clamps were constructed so as to have the same flux return and move as a unit with D2 and D3 as these magnets move inward for higher inelastic conditions.

F. Support Structure

Figures 6 and 7 show the support structure layout. As can be seen in Fig. 7, the system had to straddle a cable trench, and be built over a cable tray which is attached to the spectrometer. Three heavy steel base plates, as shown in Fig. 6, were bolted and epoxied to the floor. Vertical I-beams were bolted to these base plates to support an I-beam system as shown in Fig. 6. The I-beam system has some unusual features. It is supported on the left in Fig. 6 by a 12 inch wide, 1 inch thick steel spring which could deflect to take into account thermal expansion. The right hand end was supported on a pinned bearing from the pivot post of the spectrometer. The bearing prevented any torque from being applied to the side of the pivot post chamber which is evacuated for normal scattering and precisely located. The three smaller I-beams were attached to the main 12 WF79 I-beam by means of steel tongues passing through the web of the 12 WF79. Thus these smaller I-beams could exert no torque on the 12 WF79 which would cause it to twist, and consequently cause D1 to be cocked perpendicular to the beam line.

Dipole D4 was placed on a support plate which had been surface ground so that it could be easily positioned in the horizontal plane by means of adjustment screws. It could be moved vertically by a three point support system below its support plate. Dipole D1 was similarly supported, as can be seen in Fig. 5.

Dipoles D2 and D3 are on a single support plate which has linear roller bearings attached below it. These bearings roll upon two two-inch diameter case-hardened steel rods which rest in long V-blocks. These blocks were adjusted vertically so that as D2 and D3 were moved inward, the deflection of the 12 WF79 I-beam was compensated. Thus D2 and D3 moved approximately in a horizontal plane

-17-

FIG. 6

SHEET 2 of 3

to within 40 mils over the whole range of their movement over $17 \frac{1}{2}$ inches. This range corresponded to about 20% above the elastic position to about 80% below the elastic position, i.e., to an inelastically scattered electron with an energy of $0.20 E_0$, where E_0 is the energy of the incident electron before scattering. The magnets were aligned to be level at the elastic position. For the inelastic positions, the deflection angles are less, and the precision of leveling the magnet is less important.

G. Magnet Movement and Position

Magnets D2 and D3 could be moved on their roller bearing support rather easily by one person pushing on their combined weight of 7 tons. A ball-screw assembly was attached below their support plate and is driven by a stepping motor. The position of the support plate can be determined by a linear potentiometer attached below the support plate with its movable arm attached to the horizontal I-beam. A reference voltage to a stepping motor control board can be set. The stepping motor will drive the magnets in or out until the voltage across the potentiometer equals the reference voltage as determined by an error signal amplifier.

H. Target Changer

A target changer holds eight foil targets and is mounted horizontally in the T-section of the D4 vacuum chamber shown in Fig. 5. It is driven by a stepping motor and is electronically controlled similar to the magnet positioning device described in the last section. All of the electronics for both of these controls were built at the University of Massachusetts. The target changer is coupled to a gear system and motor outside of the vacuum system by means of a simple rotary seal.

I. Correction Coils

As was pointed out in section III C on Magnets, shimming was undertaken in an attempt to make the magnetic path lengths for the incident beam equal in each magnet so that for the complete system $\int B dl = 0$ was satisfied. This ensures that the incident beam and the post-target beam will travel along the same line. Although the shimming made the magnetic path lengths nearly equal to within 0.5%, it is necessary that they be equal to a higher accuracy than 0.5%. For example, if there is a difference of 0.5% in a D1 with respect to the other magnets, where D1, D2, and D3 are operating at a nominal 10 kilogauss, and the beam energy is 100 MeV, then at the beam catcher position 18 meters downstream from D1, the beam would be off-center by about 10 cm. In order to account for such differences and others due to hysteresis in the dipoles, and in the field clamps, trimming correction coils were placed above and below each of the main coils on D1, D2, and D3, each pair of which is capable of supplying 5% of the ampere turns of the main coils. This was a conservative approach in designing the dipoles to be magnetically equal. In the test runs to be described in section VII, it was found that only a few amperes of correction coil current was necessary to steer the beam correctly.

J. Power Supplies

An old Temescal power supply rated at 500 Volts and 500 Ampere, which was formerly used at the now defunct Cambridge Electron Accelerator, was improved upon so that it had better than 10^{-4} long term stability at all power levels. Since this power supply will deliver 250 kilowatts of power, and since the four dipoles only require 150 kilowatts, this power supply was readily adapted for use

with the 180° scattering system. Also the supply was designed to run into a 1 ohm load. The total resistance of the coils in all four magnets is 1.14 ohms, and hence the system is well-matched to the power supply.

The three power supplies for the correction coils were purchased from Kepco at a special reduced price because the particular model of power supply that we ordered was no longer being manufactured, and they wanted to clear their stock. However, these were voltage regulated supplies which had to be converted to current regulated supplies, and be remotely controlled. Their ratings are 14 volts at 30 ampere.

Other power supplies were needed to drive the dump coils. In this case some old inductrol quadrupole magnet supplies from the now defunct Yale Hilac were obtained. Eight such supplies could be operated in series to give 8×21 volt output at 400 ampere. The regulation of these supplies is poor, but it does not matter for beam dumping.

K. Magnetic Field Monitoring

A rotating coil with digital readout was purchased for both field mapping, as described in Appendix B, and for monitoring the magnetic field of D4, the separator magnet. The probe has an absolute accuracy of a few parts in 10^4 and a reproducibility of a few parts in 10^5 . It operates over all field ranges, and it measures average values in inhomogeneous fields, features lacking in nuclear magnetic resonance probes. The readout was remotely connected to a digital voltmeter.

L. Beam Dumping Coils

Two models of beam dumping magnets were made, one with steel pole pieces, and another with simple air core coils. It was decided to order construction of the

full-scale air core coils because of ease of installation as well as economy. The air core coils are 10 feet long by 2.6 feet wide. They are wound three coils in parallel to give a 6 x 12 turn configuration. The D.C. resistance is 0.169 ohms at 20° C in each coil. Two coils in series match the available power supply combination fairly well. Each coil gives 28,800 ampere turns and takes 27 kilowatts of power. The long 10 ft. dimension of these coils is along the beam direction. The 2.6 ft. dimension is tilted inward at the top by 20° so that there is some vertical focusing of the diverging post-target beam which is bent downward by at least 3°. The coils eventually will be placed on a 2 foot diameter beam pipe.

M. Support Chamber

In order to support the large 12WF79 I-beam mentioned in section III F and shown in Fig. 6, it was necessary to construct a special vacuum chamber that would fit upon the rest of the pivot post assembly. This vacuum chamber is shown in the lower right hand corner of Fig. 6. It has a cradle for the pin and bearing on the right-hand end of the large 12WF79 I-beam, as well as two outriggers for two of the three screw supports for the support plate of D4. This chamber provided the base for the support of D4 and additionally gave the correct mating surface for the scattering chamber used in normal forward angle studies. When 180° scattering experiments are not in progress, magnet D4 can be lifted out together with its vacuum chamber, target changer, pole tips, field clamps, and support plate, all as one unit. Then the cover plate may be removed, a shim chamber put in place, and finally the normal forward angle scattering chamber lowered into position. The change-over from 180° scattering to normal scattering takes less than a day's time.

IV. Component Costs and Other Costs

A. Approximate Expenditures

Below are listed the approximate costs of some of the major components and other costs of this project. These are not final figures, but are only approximate estimates. The University of Massachusetts accounting office will provide a correct final report which may not categorize items the same as this report.

Digital Rotating Coil Gaussmeter	\$ 1,900.83
Correction Coil Power Supplies	992.65
Vacuum Bellows	2,190.00
Vacuum Chambers	12,853.00
Steel Cutting for Magnets	11,800.00
Steel Cutting for Field Clamps	1,613.53
Four Dipole Magnets and Coils	37,932.39
Shim Chamber	3,647.00
Support Structure Base Plates	469.08
Main Support Structure	5,663.00
Magnet Support Plates	2,311.00
Roundway Bearing Assembly	1,594.00
Electronics for Target and Magnet Positioning	4,000.00
Dump Coils	5,593.00

Total: Major Equipment Items	\$92,559.48
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General Supplies	\$10,000.00
Overhead	37,721.00
Scientific Personnel	61,237.00
Draftsmen	4,600.00
Secretarial	2,000.00
Technicians	8,000.00
Travel	3,500.00
Fringe Benefits	828.94
Other Costs	4,500.00

Total Project Cost	\$224,946.42
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Budget	\$229,000.00
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Remainder to be Returned to Agency	\$ 4,053.58
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B. Comments on Expenditures

As can be seen above, the total project cost is within the allotted budgeted amount of \$229,000.00. However, there were several major expenditures on power supplies that were unnecessary because available power supplies from the Cambridge Electron Accelerator and the Yale Hilac were put to use. This permitted the amounts originally set aside for power supplies to be used for other project applications. One of these major applications was the design and construction of the support structure. This was initially proposed as a Massachusetts Institute of Technology responsibility, as agreed upon and stated on page 51 of the Research Proposal Submitted by the University of Massachusetts to the Atomic Energy Commission on June 3, 1974. The University of Massachusetts took over all phases of the support structure design and fabrication after about one year from the start of the project. The Bates engineers served in an advisory capacity but actually did no work on the structure. The support structure was one of the more difficult parts of the project and took considerable engineering and drafting time which probably cost nearly as much as the power supplies.

The Massachusetts Institute of Technology was also to design, to supply, to fabricate, or to purchase a vacuum chamber from target to beam dump. The University of Massachusetts purchased bellows for this large beam dumping vacuum chamber. At the time of the writing of this report, some of the major components of this two-foot diameter beam dumping pipe have been delivered to the Bates Laboratory, but they have not been installed yet. This will be discussed further under the next section.

V. Construction Schedule

Schedule charts, such as the two shown on the next two pages, were made out early in the project. However, delays in the delivery of components, in design, and sometimes in seeking bids, necessitated frequent revisions of these schedules. Also it was necessary to have the installation coincide with a major shutdown of the spectrometer room area. One of the major delays was in designing the support structure and in seeking bids for it. Because of technical details it was necessary to seek bids on this item two times.

In the planning stage, many meetings were held at the Bates accelerator and several meetings were held at the University of Massachusetts in which the details of design, installation, time schedules, manpower, etc. were discussed. Dr. Claude Williamson of the Bates Laboratory deserves praise for his very significant part in organizing and planning these meetings.

There is one item that is an M.I.T. responsibility that is not complete yet. All other items are complete. The one incomplete item is the beam dumping vacuum chamber. The carriage for the support of this beam dump pipe is constructed, and it is expected that installation will begin in the near future. The last section of this beam dumping pipe, a three foot diameter pipe which fits beyond the beam dumping coils has been completely designed by Bates engineers and bids have been received. The completion of this portion of the beam dumping system will be essential for experiments requiring a low background.

On the third page following this one is given the completion schedule for some of the major components, and on the fourth page is given a chronology of the contract.

UMASS ASSEMBLE OUTGAS TEST VACUUM CHAMBER PROVIDE YOKE and FOR FIELD CLAMP INSERT FIELD CLAMPS FOR D1 and D4 BEAM MONITORS TARGET CHANGER FABRICATE TEST

Preliminary Schedule Chart 180° Scattering System

Completion Schedule of Some Major Components

Item	Company	Purchase Order Date	Estimated Completion Schedule	Expected Shipping Date	Date Item Was Delivered
Steel Cutting	Metcut	4/8/76	4 weeks	5/8/76	6/18/76
Magnet Fabrication	Alpha Scientific	4/26/76	26 weeks	10/25/76	11/19/76 (D4 pole tips) (12/16/76)
Vacuum Chamber	High Voltage Engineering	5/14/76	12 weeks	8/9/76	7/30/76
Support Chamber	High Voltage Engineering	12/17/76	12 weeks	3/11/77	4/29/77
Dump Coils	Alpha Scientific	9/28/76	12-16 weeks	1/19/77	8/8/77
Support Structure	Framingham Welding	4/3/77	8-10 weeks	6/3/77	6/30/77
Roundway Bearing Assembly	Framingham Welding	5/23/77	4 weeks	6/23/77	8/9/77
Shim Chamber	High Voltage Engineering	—	—	9/6/77	9/10/77

Chronology of the Contract

June 3, 1974	Proposal sent to the Atomic Energy Commission
November 18, 1974	Revised budget sent to the Atomic Energy Commission
December 20, 1974	Nuclear Science Division of Physical Research approved contract
March 7, 1975	Contract sent from the Chicago Operations Office to the University of Massachusetts
April 14, 1975	University of Massachusetts Treasurer's Office approved contract
May 1, 1975	Funds available for use in Accounting Office
January 2, 1977	Contract extended for one year
December 31, 1977	Last day of Contract

VI. Installation

Preceding the installation of the system in the beam area, a large program of field mapping had to be completed, and a preinstallation assembly of the complete system was necessary.

The field mapping of the magnets started in December of 1976, within two weeks after they were delivered. This required a magnet testing area to be established with proper water flow for the magnet coils, as well as the activation of the Temescal power supply obtained from the Cambridge Electron Accelerator. The fields were mapped with and without the field clamps. The field clamp pole tips were then empirically changed until the proper field shape was obtained. This process of mapping fields, interpreting the data, adjusting the field clamps, etc., took over nine months for all four magnets.

A program of vacuum testing of all vacuum components and of the outfitting of the D4 vacuum chamber took place at the University of Massachusetts, and later at Bates.

A preassembly area was selected in the Bates warehouse. The support structure, the roundway linear bearing assembly, the magnet support plates, and the magnet drive system were assembled and made operational between July and early September, 1977. In order to do this, it was necessary to make a mock spectrometer-pivot-post on which to place the support chamber.

Finally in late September of 1977, the structure was taken apart in the preassembly area and moved to the spectrometer room. Previous to that time some major rerouting of spectrometer water pipes was necessary, vacuum pumps had to be moved, and some other items on the spectrometer carriage system had to be relocated. Generally the area near the spectrometer is filled with cables, water

pipes, vacuum apparatus, etc. Hence it was necessary to accommodate the 180° system into this rather congested area. The letters in Appendix C describe the activity during the installation period fairly well.

VII. Performance Tests

Appendix D is a proposal to the Bates Program Advisory Committee of the "In-Beam Tune-Up of the 180° Scattering System". The proposal describes briefly most of the tests which were finally performed on the system in which a total of 107 hours of beam time were planned, and 108 hours were found to be necessary. Runs were made at 90, 100, 200, and 210 MeV at a time when the performance of the accelerator was not optimum. The runs took place on October 22 and 23, October 30, November 7 and 8, and December 10, 1977.

Among the tests performed were the establishment of the correction coil currents for steering the beam through the system properly. This was done by varying the correction coil currents until the beam hit wires which were mounted on forks and surveyed into the correct positions where the beam had to pass. The radiation coming from the wires was detected external to the vacuum chamber by means of photomultiplier tubes with plastic scintillators attached to them. It was found that once the correct current was established for the beam path for elastic scattering as shown in Fig. 2, for a magnet angle α_0 and for an incident energy E_0 , then a simple linear scaling was sufficient to determine the currents needed for other angles α for inelastic scattering conditions. Sets of wires were located between D1 and D2, centered between D2 and D3, and between D3 and D4. The beam was directed to hit all three wires and simultaneously pass through a ZnS viewing screen at the target positions, and another screen 10 meters downstream.

The location of the beam entering the system could be determined by turning the system off and observing the beam going directly downstream to the target position. Thus the beam could be traced through the entire system.

Operation of the system for inelastic scattering was tested by observing the ^{12}C 15.11 MeV M1 transition and by observing the proton elastic peak at various bombarding energies. Since the proton recoil energy is so large, e.g., 60 MeV for 200 MeV electrons, this is equivalent for observing inelastic scattering. Figure 8 shows an example of a proton peak taken for a bombarding energy of 200 MeV. Figure 9 shows a spectrum taken on ^{27}Al at low beam current and consequently poor statistics. It illustrates that background is low in this region near the elastic peak and that the system can be used for obtaining inelastic data.

Figure 10 shows an elastic peak taken on a thin ^{27}Al target in an attempt to measure the resolution capabilities of the system. It is seen from the figure that the system is capable of at least 2.5×10^{-4} resolution. This resolution is within the limits set forth in the original proposal of 3×10^{-4} . The target position was moved from its usual location when this resolution was obtained. The target position movement was necessary because it was found that the spectrometer could not be cocked to the 1.33° that was required for the design. Before installation it was thought that the spectrometer could be cocked to 1.5° . Since it cannot be cocked the required amount it was necessary to move the target upstream to obtain the correct object distance for the spectrometer. It is also possible to improve the resolution by (1) Selecting rays in the focal plane arrays and making corrections for them by using the on-line computer and (2) Carefully adjusting the upstream quadrupole magnets so as to better match the dispersion of the beam upon the target to the dispersion of the spectrometer.

Fig. 8

FIG. 9

Fig. 10

Figure 11 shows the first attempt at measuring the charge scattering parabola about 180° by varying the magnet angle α as defined in Fig. 2. The two solid curves shown in Fig. 11 are those calculated for elastic scattering from the spinless nucleus ^{12}C . There is a small amount of charge scattering at 180° because the electron is not completely relativistic and does not have unit helicity. This is represented by a small m^2/E_0^2 term in Eq. 1 of Appendix D. The second solid line is calculated for the finite opening solid angle of the spectrometer which receives some charge scattering at angles other than 180° . There are also multiple scattering contributions not shown in Fig. 11 which would give better agreement with the experimental points. The long-tail multiple scattering contributions will be evaluated in the future. However, Fig. 11 does show that a minimum in the scattering was obtained and that it is possible to accurately find the 180° scattering angle by this method. It should be noted that the size of the cross sections is very small and that at the time this curve was taken, a high beam current was unavailable. This measurement will be repeated when higher beam currents are available.

The measurement of the proton peak at various energies in the tune-up runs and in later runs showed that within statistics the solid angle viewed by the spectrometer was a constant. It was found to be relatively easy to change energies and hence momentum transfers.

During a later run backgrounds were investigated. It was found that a major portion of the background increases as electrons are observed further and further below the elastic peak energy. It was established that this background came from elastic scattering from the end-window of the vacuum pipe. This was done by placing many layers of polyethylene foil beyond the end window and then

ELASTIC CHARGE SCATTERING FROM ^{12}C NEAR 180°

FIG. 11

attempting to observe the large proton elastic peak which results because of the proton's large magnetic moment. Instead of seeing a sharp peak, a broad bump was observed, which decreased as the energy of the observed electrons decreased. This is clear evidence that the elastic scattering from the end window is a major contribution to background. Although the beam dump coils were operating at the time, their effect on the background was minimal because the beam dump vacuum pipe did not extend through them. It is expected that background can be reduced in the future through the use of the complete beam dumping arrangement.

Although we were unable to run at all of the energies indicated in the proposal given in Appendix D, the fields of the magnets were mapped at higher fields, corresponding to higher energies, and there is no reason to expect marked deterioration of performance at higher energies. All of the major objectives set forth in the original proposal for "The Fabrication of a 180° Scattering System" have been met.

Appendix E lists scientific and technical personnel who have participated in this project.

It is planned to publish a report on the design, construction, and performance of this system in the open literature.

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APPENDIX A

UNIVERSITY OF MASSACHUSETTS

MEDIUM ENERGY NUCLEAR PHYSICS GROUP

INTERNAL REPORT #4

APRIL 5, 1976

J.B. Flanz and D.V. Webb

OPTICS CALCULATIONS FOR A 180° SCATTERING SYSTEM

I. General

A. Performance Characteristics:

The best means of observing magnetic multipole transitions is afforded by the selective excitations of these transitions by backward angle electron scattering, particularly 180° electron scattering. In 180° scattering, one cannot introduce a spectrometer into the incident beam line, thus the incident and scattered beams must be separated. This can be accomplished by introducing a separator magnet of some form between the target and spectrometer.

The presence of the separating magnet must be taken into account as a part of the total optical system. One can expect the object distance between the target and spectrometer to be increased, resulting in a smaller image distance for the spectrometer. Also the solid angle presented to the spectrometer is smaller. In 180° electron scattering the cross sections one measures are apt to be very small; so it would be desirable to have as large a solid angle as possible presented to the spectrometer. Another problem can be encountered in 180° electron scattering, with the introduction of just one separating magnet, occurring when one looks at the inelastically scattered electrons. To observe electrons of these energies one must move the spectrometer relative to the magnet necessitating a sliding vacuum seal, and further a variation of solid angle which will result because of the spectrometer rotation. Also the beam passing through the target may go off in various directions. We have attempted to overcome these handicaps through the design of a four-magnet 180° scattering system.

The varying solid-angle problem is solved as discussed in 1968 by Peterson.¹ A four-magnet system is used instead of a three-magnet system to take advantage of the extra pole edges which will be used in

making beam trajectory corrections, or improving the system optics. A four-magnet system would deflect the electron beam as shown in ^{the} diagram¹ below.

The incident beam is bent out of the incident beam line, then back to the target. The scattered beam is then bent towards the spectrometer. By moving the center two magnets inwards, thereby reducing the bending angle of the beam system, the spectrometer can remain in one position to look at all inelastically scattered electrons. To prevent variable focusing effects on the beam, when these magnets are moved, the edges labeled 2, 3 and 6 and 7 must be circular with the beam passing through these edges radially. Thus we begin designing a 180° scattering system by considering four circular dipole magnets.

The final magnet system will be used at the Bates Linear Accelerator. This facility uses a dispersion matching beam and spectrometer system. Presently the resolution of the Bates spectrometer is better than 1 part in 10^4 . This along with a solid angle of $30 \text{ mr} \times 180 \text{ mr}$ or $(5\frac{1}{4} \text{ msr})$ makes the instrument a very powerful data taking device. The angular resolution of the spectrometer is determined by the counting system in use and can be expected to be $\leq 4 \text{ mr}$. In designing a 180° scattering system to be compatible with the Bates system we would like to take advantage of the good momentum and angular resolution, and the large solid angle.

II. Design Philosophy

A. Existing Constraints

Certain physical constraints affect the design of the four-magnet system. The system is constrained to fit in the available space between the quadrupole Q7 and the scattering chamber in the spectrometer room at the Bates accelerator. The Bates spectrometer can only be rotated to back angles of 160° , so the separating magnets must be able to bend a beam through an angle of at least 20° , but there is some leeway in this since the spectrometer can be cocked through an angle of about 1.5° , to give a total angle of about 21.5° .

The beam parameters used in the following optics calculations are reasonable upper limits attainable at Bates. They are as follows:

$\Delta x = \pm .5 \text{ cm}$	$\Delta\theta_{\text{inc}} = \pm 0.05 \text{ mr (horizontally converging)}$
$\Delta y = \pm 1.7025 \text{ cm}$	$\Delta\phi_{\text{inc}} = \pm 0.1 \text{ mr (vertically converging)}$
$\frac{\Delta p}{p} = 0.486\%$	$\Delta\theta_{\text{scatt}} = \pm 90 \text{ mr (vertical)}$
	$\Delta\phi_{\text{scatt}} = \pm 15 \text{ mr (horizontal)}$

An optics evaluation with these beam parameters will tend to overestimate any undesirable effects of the beam handling system. Another type of constraint involves the resolution of the spectrometer at Bates. The 180° scattering system should not introduce sizeable aberrations into the beam which would adversely affect the over-all resolution of the spectrometer.

B. Desirable Conditions

In considering the optics of this four-magnet system, several conditions must be met.

- 1) A minimum spot size should be obtained on the target for a monoenergetic beam.
- 2) The beam height at the target should be unchanged from its height without the 180° system. This will permit the beam to be focused on target with the system off so as to establish the desired dispersion of the beam for the system when it is enlarged. An upstream quadrupole can be utilized to adjust the dispersion.
- 3) The spot size at the focal plane of the spectrometer should be unchanged after the introduction of the magnet system. This can be accomplished in two ways. One can consider only the focal plane in the calculations to be sure that the magnets are not affecting the spot size. Or one can consider the virtual image of the target and prepare a suitable beam profile there. In this case the virtual image should be at the object position of the spectrometer in both the x and y planes.

To realize these conditions the five magnet edges 1, 4, 5, 8, and 9 are free to be varied so as to minimize aberrations which might be introduced by these magnets.

Finally, we would like to take advantage of the full solid angle of the Bates spectrometer so that the gap of the separating magnet and the position of the target will be determined.

C. Compromises

The corrections mentioned above can be made to any of the magnet edges. As shown in Fig. 1, the first magnet has the largest "lever arm" and hence the most effect on the incoming beam, since it is the farthest from the target. Corrections to the field would have larger effects on the beam at the target position than corrections applied to other magnets. However, a more symmetrical solution was utilized,² in which corrections were made to each magnet. Due to the increased

symmetry of this approach, more second-order coefficients were minimized so as to make the system more transparent. The only disadvantage to this approach is that we must make larger corrections on all the magnets instead of taking advantage of just the first magnet. On the other hand, it is also expected that in this method less new aberrations would appear in the system when operating in the inelastic mode.

This system is designed for a maximum energy of 450 MeV. This was a compromise based on the projected capabilities of the Bates accelerator and the fields attainable by the magnets that will be built. We have designed the magnets to reach a maximum field of 16 kgauss. With this field and the design bending angle, which will be discussed later, the maximum energy useable by the magnet system will be 454.82 MeV.

The 180° system would be easiest to design if all four magnets were alike. But solid angle considerations, and resolution requirements cause the fourth magnet (nearest the target) to have a larger gap and to have a more complex shape than the other three magnets. This compromise on the ideal four-magnet system turns out to be more difficult to design but the results are rewarding. Cost and space considerations make it impractical to make magnet 1 physically symmetric to magnet 4.

The design was begun with circular magnets of radius 17.77 cm and one of radius 24.36 cm. The spacing along the original beam line between D1 and D2, and between D3 and D4 is 46 in and between D2 and D3 it is 35 in. These considerations allow the magnets to attain the desired field and fill the available space in the spectrometer room without interfering with the spectrometer. A detailed analysis yielded results which required modifications to the pole shapes.

III. Optics Calculations

A. General

To help in designing beam elements that satisfy our optical conditions the University of Massachusetts Group has obtained two computer programs from MIT. One code originated at Stanford and is called TRANSPORT.^{3,11} The second one was written at MIT and is called RAYTRACE.^{4,11}

The following brief description of these codes is supplemented by more detailed theory in the references cited and in an appendix to this report.

TRANSPORT helps in following the path of a beam of charged particles through magnetic and electrostatic beam elements. The initial particle momentum is specified (in GeV/c), as well as six parameters related to the physical extent of the beam. The beam elements can be thought of as optical lenses. A mathematical theory for lenses describing their effect on a ray of light is represented by matrices which operate on the coordinates of the incoming ray to give the coordinates of the outgoing ray. An analogous method is employed in the TRANSPORT code.^{3,5,6} A parameter of the beam is expanded in a Taylor series in terms of its other parameters as follows:

$$x_f = \frac{\partial x_f}{\partial x_1} x_1 + \frac{\partial x_f}{\partial y_1} y_1 + \frac{\partial x_f}{\partial \theta_1} \theta_1 \\ + \frac{\partial x_f}{\partial \phi_1} \phi_1 + \frac{\partial x_f}{\partial \delta_1} \delta_1 + \text{higher order terms.}$$

In TRANSPORT notation, for example, $\partial x_f / \partial y_1 \equiv (x/y)$ is the coefficient in the expansion of the final x coordinate of the ray in terms of the initial y coordinate. The first order matrix acting on the x and θ coordinates is defined by the equation:

$$\begin{pmatrix} x_f \\ \theta_f \end{pmatrix} = \begin{pmatrix} (x/x) & (x/\theta) \\ (\theta/x) & (\theta/\theta) \end{pmatrix} \begin{pmatrix} x_1 \\ \theta_1 \end{pmatrix}$$

The two by two matrix ~~is~~ called the transfer matrix ^{and the} elements of the matrix are transfer matrix elements. Transport calculates the elements up to second order and thus is good only to second order approximations to the beam trajectory.

This code has a fitting routine which allows one to set constraints on any first or second order matrix element while determining parameters for the beam elements.

RAYTRACE is a more accurate raytracing routine. The particle momentum is specified along with a set of rays whose trajectory one wishes to follow. The Lorentz force law can be used to give the acceleration $\ddot{x}_i$ of an ion through a system of magnetic fields $\vec{B}$

$$\ddot{x} = K(B_z \dot{y} - B_y \dot{z})$$

$$\ddot{y} = K(B_x \dot{z} - B_z \dot{x})$$

$$\ddot{z} = K(B_y \dot{x} - B_x \dot{y}), \text{ where } K \text{ is a constant.}$$

This code is designed to solve this set of equations given a proper empirical description of $\vec{B}(x,y,z)$. It integrates these equations and traces the particle path. The accuracy of this code is limited by the accuracy of the integration technique and description of the magnetic field. This code takes into account up to fourth order effects.

A note here about the coordinate system used when discussing these codes is appropriate. The z axis always points along the particle trajectory. The y axis is parallel to the magnetic field lines. A negatively charged ion beam bends in a dipole magnet in such a way that the y axis is turning clockwise when looking down at it. In the 180° system, coordinates are used as shown in Fig. 6.

The momentum of the incoming beam is dispersed along the y direction, before it enters the system.

B. Results

Initially TRANSPORT calculations were made using the four circular dipoles mentioned earlier. We began with three small magnets of effective field boundary (EFB) 17.77 cm (7.00 in) and a large magnet of EFB 24.36 cm (9.59 in). The beam parameters listed earlier were used. This presented a beam with a height of ± 2.62 cm, and $(y/xy) = -3.0 \times 10^{-1} \text{ cm}^{-1}$ at the target. The (y/xy) coefficient represents the correlation that the final y coordinate of the beam at the target has with the initial x and y coordinates. Since the input beam can be pictured as a rectangular ladder of horizontal momentum lines, this correlation describes a skewing of the isomomentum lines that would enlarge the spot size of a monoenergetic beam. The skewing must be minimized to preserve the resolution of the system. Using TRANSPORT to minimize (x/xy) , and requiring a beam height of ± 1.702 cm at the target, we obtained a pole face rotation of 6.32° on both D2 and D3 edges 4 and 5, and concave curvatures of radius -26.19 cm on edges 1, 4, 5, and 8. (See Fig. 1). Using these values gave $(y/xy) = 3.2 \times 10^{-15} \text{ cm}$. Thus we have essentially flat isomomentum lines at the target.

These parameters serve as starting parameters to be used in the RAYTRACE program. Using this program, higher^{order} aberrations can be investigated. An iterative search for the best parameters was made. A sample of 19 rays as given below in Table I were traced through the four magnets. Rays 2 through 5 are used to find a focus after the last magnet. Rays 1, 6-19 are used to define a beam profile and determine the rotation from the horizontal of the isomomentum lines. The magnet field shape used in the calculation is based on a Fermi shape defined by Fig. 2 and Table 2. The coefficient of the equations are in Table II. We used the clamped fringe field on all concave faces, the short tail, unclamped on the convex faces, except for face 9 (exit face), where we used the long tail, unclamped fringe field.

Concave curvature of -21.93 cm and rotations of 8.0° gave minimum deviations from the horizontal, i.e., minimum skewing, and slight vertical defocussing of the beam within 2.5% of the original height. The aberrations are not sensitive to the last magnet's target side, so that edge will be shaped flat. These are the final optical values considered. The skewing given by these values was .08 mm for rays 16 and 18 and .08 mm for rays 17, 19 as shown in Fig. 3a. This satisfies the first two optical conditions discussed in section IIB. To satisfy the last condition, RAYTRACE was used to find the virtual object position of the target through the last magnet. Using the rays in Table III that began from the same point in the target plane but which had differing divergences, they were traced through D4 toward the spectrometer and projected back to find the virtual object position. (as below)

As discussed in Section I, we required that the virtual image of the target be at the object position of the spectrometer in both the x and y directions. Thus the virtual image must be stigmatic, i.e., the x and y rays appear to originate from points on the virtual image so the vertical and horizontal image distances are the same. Finally, it is here that we require the minimization of the skewing of iso-momentum lines to insure good resolution compatible with the spectrometer.

There is a small approximation made here in not including an incoming magnet system. The final calculations included these magnets and approximated a scattering event by rotating the beam after it reached the target by the desired angle. The final beam profiles at the virtual object are shown in Fig. 3b and 3c. These picture the skewing at the virtual object position for assumed vertical scatterings of $\pm 5^\circ$. The total skewing between these two scatterings will

present a spot size to the spectrometer which will determine the momentum resolution. The condition requiring placement of the virtual image position at the object position of the spectrometer fixes the angle the rays must be bent through the large magnet. Finding this angle is an iterative procedure involving changing the path length P in the magnet so as to find its effect on the virtual object position. We use the relation $P = (\pi l / 180) 2\alpha$, where 2α is the bending angle and l the bending radius. A field of B kg deflects an electron of momentum p in units of GeV/c in a circular arc of radius ρ meters according to the equation

$$P = \frac{B\rho}{33.356}$$

The small magnets were designed to operate at a maximum field B of 16 kilogauss, and the large magnet at a maximum field of 11.77 kG. The position of the last magnet is then determined as follows, as is the cocking angle of the spectrometer?

The virtual image was found at 58.84 cm from the last magnets pole edge, closest to the spectrometer, so as to ensure it was 3.403 m from the spectrometer entrance pole edge. A bending angle of 21.233° was used allowing a maximum energy of 454.82 Mev/c. This involves setting the spectrometer at 160° , and cocking it 1.233° .

In order to make the beam stigmatic at the virtual object position, a rotation of 5.4° was put on the exit face (9) of the last dipole (D4). Also a negative curvature of $-.0112 \text{ cm}^{-1}$ was designed for the exit face in order to minimize aberrations. The final skewing calculated at the virtual object position is, (using the rays in Table I.):

<u>Scattering</u>	<u>Ray</u>	<u>$\Delta P/P$</u>	<u>Skewing</u>
$+5^\circ$	16,18	.24%	.0130 cm
-5°	16,18	.24%	.0193 cm
$+5^\circ$	17,19	-.24%	.0190 cm
-5°	17,19	-.24%	.0128 cm

This indicates that an intrinsic resolution for our 180° scattering system of $.5 \times 10^{-4}$ can be reached if one uses the full solid angle. (See Figures 3b and 3c.) Scatterings of smaller angles would result in better resolution.

A plot of various rays through the complete four-magnet system was made to understand how the dipoles affect the beam before achieving the final results. This plot appears in Figures 5a and 5b. There is a crossover of the rays in the x plane inside the third dipole due to the finite extent of the beam. This crossover is the cause of the narrower beam at the target. The system would have to be lengthened if the crossover were to be between D2 and D3. But this does not affect the dispersion matching and resolution conditions. There is another crossover in the x plane due to the momentum dispersion along the y direction for rays starting out at the x position. This causes the skewing (rotation) of the beam profile seen in Fig. 3a. Finally we can see the action of the rotation of D2 and D3 pole faces in Fig. 5c, preventing the y extent of the beam from growing too large. Figure 5d, is a schematic interpretation, of the other figures, showing the magnets.

The following table summarizes the final results of the optics calculations. These are not the values to be machined on the pole faces, they lack additional mechanical corrections which will be discussed.

MAGNET	FACE	RADIUS OF CURVATURE	ROTATION
D1	1	-21.93cm	0.0°
	2	17.77	0.0
D2	3	17.77	0.0
	4	-21.93	8.0
D3	5	-21.93	8.0
	6	17.77	0.0
D4	7	24.36cm	0.0°
	8	∞	0.0
	9	-89.29	5.4

For a diagrammatic representation of these numbers on the the pole faces see figures 4a,b,c.

III. From Optics to Hardware.

The calculations discussed in the previous section depend somewhat on our ability to specify the shape of the magnet fields in the four dipoles. Certain mechanical devices that have been developed will help us to obtain the desired fields in the finished magnets.

So that the field shape will not be a function of magnet excitation, and furthermore, so that a constant flux density through the pole and the gap will be maintained, a Rogowski pole contour^{8,9} should be used. However, a contour which is two straight bevels approximately following the Rogowski shape is known to obtain much the same results.¹⁰ Other magnets already built use such substitutes for the costly Rogowski contour, and provide effective field boundaries suitable for our use. (see Fig. 4a). The fringe fields used in the magneto-optical calculations have been taken from these empirically established contours.

Field clamps that cut off the long tail on the fringing field and hold the shape of the effective field boundary are to be applied to all concave surfaces. In particular this prevents D2 and D3 from having overlapping fringing fields. (See system diagram, Fig. 1) The large magnet further requires field clamps on the straight target face to minimize the field at the target and on the convex beam entrance face to smooth transition regions of the pole profile.

Magneto-static field calculations done by Enge using TRIM¹¹ and actual measurements show that field clamps of the type we are using push in the EFB from the mechanical magnet boundary. If the clamp is positioned such that its edge is about one gap (D) away from the magnet edge, the EFB will be pushed in relative to the pole edge by about 0.23 D. We use this correction to the physical size of the pole for the small magnets, although we are awaiting final testing before deciding the precise location and shape of these clamps.

We follow similar criteria on the entrance and target face of the large magnet. At the concave, exit face of the large magnet the field clamp must be higher up on the pole than stated in Enge's findings to avoid the scattered beam, so its effect on that face will be smaller. Our estimates show this to be consistent with the EFB being only about 0.1 D inside the exit face pole boundary.

Care was taken to adjust the contours on the sides of the magnets. On these faces there will be no beam so we are not concerned with the shape of the fringing field, but we would like to make sure that there is sufficient uniform field region in the center of the magnet. This was done by steepening the angle of the contour and making the magnets wider thus increasing the lip size and the uniform field region. This changes the shape of the fringe field on the edge where the beam does not pass, but increases the uniform region. The beam will be at the most 1.0 cm wide and we have provided at least 3.8 cm of uniform field in the magnet entrance (Magnetic field uniform to better than 1 part in 10^3).

A correction was also made to the faces that will not use field clamps to hold the field profile. This corrects the radii of the edges of the mechanical boundary for the fact that the pole is finite. Since the calculations assume that the edges of the magnets are infinite in extent these magnet edges which do not have devices which control the shape of the field must be corrected.

A more detailed report on all these corrections to the optics calculations is being written.

IV. Installation

Once the 180° system is installed at the Bates Linear Accelerator a number of things must be considered before one can begin taking meaningful data with it.

The magnets must be aligned so that we know that the beam will go through the proper magnetic fields, and see the proper rotations of pole faces. This may be accomplished by using a LASER, or a theodolite with alignment pins which are to be placed in accurately located holes in the pole pieces.

Once this is accomplished the dispersion of the beam must be matched to the spectrometer. Figures 3 show the relationship of the beam at the target to the virtual object image. We will use the beam at the target as a reference to adjust the dispersion. According to Figure 3 the dispersion of the beam at the target is changed by 2.5%. This difference must be corrected by adjusting one of the quadrupoles upstream of the 180° system. The dispersion at the virtual object differs from that of the target by 3%. Thus we know how to adjust the dispersion at the target, to match the spectrometer dispersion.

Then the system will be ready to be used to locate where on the focal plane of the spectrometer 180° scattering occurs. For this we need information about the vertical and horizontal scattering angles, since both of these give momentum transfer information, or contribute to non- 180° scattering. The method to be used, is based on the fact that the cross sections at 180° are at a minimum. So on a plot of $d\sigma/d\Omega$ vs. θ_{scatter} we expect to see a minimum.

Currently at Bates the transverse array measures the horizontal scattering angle to a resolution $\Delta\theta_H$ determined by the wire spacing, and the vertical array can be used to measure the vertical scattering angle. There is not sufficient information yet on the vertical angle resolution, since it is ^{not} essential to ordinary electron scattering. We propose to close the vertical slits, sometime before the 180° system is installed, and to measure the correlation between vertical scattering angle defined by the slits and the angle of incidence through the focal angle of the spectrometer, i.e., the angular resolution $\Delta\theta_v$.

The mean square departure from 180° will be

$$(\Delta\theta_S)^2 \approx (\Delta\theta_{\text{Horizontal}})^2 + (\Delta\theta_{\text{Vertical}})^2.$$

Thus the true ^{rms} scattering angle is $180^\circ - \Delta\theta_S$. On-line software can be developed to determine the true scattering angle. Storing this information on-line can do more than just determine the setting for 180° scattering.

Because of the different angular dependence of the Coulomb and transverse electron and magnetic multipoles, we may be able to separate out the Coulomb and transverse admixtures in a state by measuring at various angles near 180° by varying the slit openings.

TABLE I

<u>RAY</u>	<u>X(cm)</u>	<u>Y(cm)</u>	<u>θ(mr)</u>	<u>ϕ(mr)</u>	<u>$\Delta P/P$</u>
1	0	0	0	0	0
2	0	0	.1	0	0
3	0	0	-.1	0	0
4	0	0	0	.1	0
5	0	0	0	-.1	0
6	.5	0	0	0	0
7	-.5	0	0	0	0
8	0	.85	0	0	+.12%
9	0	-.85	0	0	-.12%
10	.5	.85	0	0	+.12%
11	.5	-.85	0	0	-.12%
12	-.5	.85	0	0	+.12%
13	-.5	-.85	0	0	-.12%
14	0	1.7	0	0	+.24%
15	0	-1.7	0	0	-.24%
16	.5	1.7	0	0	+.24%
17	.5	-1.7	0	0	-.24%
18	-.5	1.7	0	0	+.24%
19	-.5	-1.7	0	0	-.24%

FRINGE FIELD FOR MAGNET OF GAP D

$$\frac{B}{B_0} = \frac{1}{1 + e^S}; \text{ where } S = c_0 + c_1 s + c_2 s^2 + \dots,$$

$s = x/D$, and x is the distance
from the virtual field boundary
and D is the gap.

coefficients	ENGE NIM 26, UNCLAMPED	SHORT TAIL, UNCLAMPED	LONG TAIL, UNCLAMPED	ENGE NIM 26, CLAMPED
c_0	0.5427	0.4952	0.6149	-0.0170
c_1	1.3111	1.9725	1.2450	1.8055
c_2	-0.3944	-0.7466	-0.5426	-0.2819
c_3	0.0909	0.2897	0.2332	0.5680
c_4	-0.0218	-0.0591	-0.0545	0.3817
c_5	0.0046	0.0052	0.0069	0.0966

TABLE II

Table 3.

<u>FOR X PLANE</u>					<u>FOR Y PLANE</u>				
<u>Ray</u>	<u>X(cm)</u>	<u>θ(mr)</u>	<u>Y(cm)</u>	<u>ϕ(mr)</u>	<u>Ray</u>	<u>X(cm)</u>	<u>θ(mr)</u>	<u>Y(cm)</u>	<u>ϕ(mr)</u>
1	0	0	0	0	1	0	0	0	0
2	0	15.	0	0	2	0	0	0	90
3	0	-15.	0	0	3	0	0	0	-90
4	.5	0	0	0	4	0	0	1.7	0
5	.5	15.	0	0	5	0	0	1.7	90
6	.5	-15.	0	0	6	0	0	1.7	-90
7	-.5	0	0	0	7	0	0	-1.7	0
8	-.5	+15.	0	0	8	0	0	-1.7	90
9	-.5	-15.	0	0	9	0	0	-1.7	-90
10	.5	0	1.7	0	10	.5	0	1.7	0
11	.5	15.	1.7	0	11	.5	0	1.7	90
12	.5	-15.	1.7	0	12	.5	0	1.7	-90
13	-.5	0	-1.7	0	13	-.5	0	-1.7	0
14	-.5	15.	-1.7	0	14	-.5	0	-1.7	90
15	-.5	-15.	-1.7	0	15	-.5	0	-1.7	-90

FIG. 1

Fig. 2(a)

Fig. 2(b)

Fig. 3a

Fig 3 b

Fig 3c

FINAL OPTICS CALCULATION
OPTICAL BOUNDARIES OF MAGNET

DIPOLE 1

Fig. 4a

← SIDE
PROFILE

← MODIFIED
ROGOWSKI
CONTOUR

OPTICAL BOUNDARY OF

DIPOLES 2, 3

Note: Side Profiles
Similar to
Fig 5a

Fig. 4b

OPTICAL BOUNDARY OF DIPOLE D4

Figure 4c

Fig. 5a

Fig. 5b

Fig. 5C

REPRESENTATION OF RAYS INITIALLY WITH
SAME X COORD., BUT DIFFERENT Y COORD.,
OR DIFFERENT MOMENTA. WHEN RAYS COIN-
-CIDE BEAM IS VERTICAL, WHERE THEY DIVERGE
BEAM IS ROTATED.

TARGET

REPRESENTATION OF RAYS INITIALLY WITH
SAME Y COORDINATE, BUT DIFFERENT X
COORDINATES.

TARGET

-Figure 5d-

COORDINATE SYSTEM USED IN
TRANSPORT/RAYTRACE
CALCULATIONS

Figure 6

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APPENDIX B

Medium-Energy Nuclear Physics

Internal Report #10

Addendum

11/30/77

J. Flanz

R. Hicks

Additional measurements were taken on the D4 magnet dipole to analyze the field boundary curvatures created by modified field clamps. Raytrace was used to evaluate the optics of the 180° system using the measurements obtained from field mapping. Improvements are noted and suggested changes and methods are mentioned. Results of tune-up runs are reported.

I. Field Measurement of D4

Field clamps which were modified as suggested in Internal Report #10 were installed on the D4 magnet. On September 29, 1977, a detailed field mapping was performed. The lathe bed was set parallel to the yoke to an accuracy of about $< 1^\circ$. The measurements were done with a current setting of 226.6 amps. Table I gives the results of the B field vs current measurement which took place before the detailed field mapping.

Following the procedures outlined in Report #10, MAPD4 and FERMD4 were used to generate Fringe Field coefficients and Virtual Field Boundaries(VFB). From these VFB's the curvatures of the field boundaries were calculated and the results are reported in Table IIA, B + C.

One particular question that existed during analysis, was in the curvature determined for the D5 exit side. The measurements extended out into the center of the window frame field clamp and a minimum field of 4 gauss was measured. If one calculates a curvature from the VFB's obtained by inputting a 4 gauss final field (BZERO) into FERMD4, the result is different than going all the way and calculating a Fringe Field to zero. The difference is between a

negative curvature of approximately -80 cm for the former as opposed to -35 cm for the latter. The field undoubtedly goes to zero beyond the field clamp, even though the lathe bed could not reach that far. The results, therefore, will be based on the Fringe Field that fits the measured points out to a field of zero! This may be a picky point, but it is mentioned only to give the reader an awareness in looking at the results of field mappings or of the fitting of these measurements. For example, in the case of the D2/D3 concave measurements, the pole pieces are close enough so that one must take this into account, as well as the residual field in the field clamps.

The results obtained were favorable, although the field clamps were not the only change in the magnet. The total air gap in the magnet had changed as a result of shimming the yoke to more closely match the fields in the other three magnets. This increased gap therefore changes the fringing field. In any case, the VFB for D5* exit was brought out, but so was the VFB of D4 entrance (as a result of the shimming). But the difference decreased from 1.344 cm to .895 cm. The rotation angle improved on D5 exit from 2.17° to 2.58° . This is not quite near 5.4° as designed, but the rotation angle on the field clamp was not increased and we did not expect a great change. Finally the rotation angle on D4 entrance was cut down from 3.02° to 1.45° by addition of the small shim. However, predictably, the curvature was changed from 26.95 cm to 18.16 cm. Here now we have the results of the final measurements of the dipoles. There was one more mechanical change, this time to the D1 field clamp, which will be discussed later.

II. Preparation for RAYTRACE Input

Now that we know the pole face curvatures and rotations, we must calculate the path lengths through the magnets and drift spaces between them. This is

* D5 exit meaning D's exit face towards the spectrometer.

most reminiscent of calculations done in Internal Report #4 which described optics calculations. Now it is time to complete the circle and discuss the optics of the 180° system as it has been built, as compared to how it had been designed. Table II compares the Fringe Field coefficients, VFB's and curvatures of the pole faces as they have been measured with the designed values.

We note the fringe field of D1 convex is very close to the assumed fringe fields. On the other hand, the clamped magnets were not as well clamped as had been expected according to our initially assumed fringe field coefficients. The measured curvatures and rotations for the most part are not too different from the designed values, and where they deviated strongly an effort was made to modify them (e.g., D1 field clamp - see below).

We also note that the incoming measured VFB of D4 does not equal the outgoing VFB and we have to note this in calculating the path length through a magnet, and in calculating the proper incoming bend for elastic scattering. Consider a dipole with incoming VFB = R_1 and outgoing VFB = R_2 . The radius of curvature of an electron is ρ and its total angle of bend is $\theta = \theta_1 + \theta_2$ as defined below:

Figure I

We can now see the following:

$$\tan \theta_1 = \frac{R_1}{\rho} \quad (1)$$

$$\tan \theta_2 = \frac{R_2}{\rho} \quad (2)$$

$$\theta_1 + \theta_2 = \theta \quad (3)$$

we need the following identity:

$$\tan(\theta_1 + \theta_2) = \frac{\tan\theta_1 + \tan\theta_2}{1 - \tan\theta_1 \tan\theta_2} \quad (4)$$

Two additional formulas which will be useful relate the Path Length (P.L.), through the magnet with the bending radius and bend angle, and finally relate the B field needed to produce bending radius (ρ) with an incident electron momentum:

$$\text{Path Length} = \text{P.L.} = \frac{2\pi\rho}{360} (\theta_1 + \theta_2) \quad (5)$$

$$B(\text{tesla}) \rho(\text{meters}) = 33.356 P(\text{GeV}/e) \quad (6)$$

Using eq. 1 through 4 we derive:

$$\rho^2 - \frac{(R_1 + R_2)}{\tan\theta} \rho - (R_1)(R_2) = 0 \quad (7)$$

Solving this equation for all four dipoles and using eqs (5) and (6) will give the path length and B field needed for momentum P. Table III summarizes these results for ρ for D1 through D4 and various bend angles.

Now if we consider the diagram below we can calculate the drift distances between the dipoles:

$$D_3' = \frac{46''}{\cos \theta} - R_{2A} - R_{1B} \quad (8)$$

$$D_2 = 35'' - R_{2B} - R_{1C} \quad (9)$$

Table IV is a reproduction of the input parameters given for the incoming beam (through D1, D2, D3, and D4) used in RAYTRACE.

III. Raytrace Results

Table V contains a list of the rays input into the RAYTRACE code to determine the quality of the beam as it appears on the target after traveling through the 4 magnets. The results can be summarized by comparing the vertical difference between RAYS 8 and 9, and 10 and 11. This difference is equivalent to a spot size for a monoenergetic part of the beam. If the incident beam is dispersed, as we have assumed, where .49% is spread over 3.4 cm or 6.94 cm/%, then a skewing of the isomomentum lines, as determined by the difference above of .1 cm gives a confusion in the momentum direction equivalent to a resolution of 1.4×10^{-4} . Now we note that the main differences between the magnets as they are and as they were designed is the curvature on D1. If we run RAYTRACE again and change the curvature of D1 closer to the design value we obtain a

difference between rays 8 & 9 of .04 cm, corresponding to a resolution of 5.8×10^{-5} at the target. For this reason the D1 field clamp was machined into a more triangular looking piece making it look like the D2 and D3 field clamps. The same rays as above were traced back from the target through D5 and back to the virtual object position of the Spectrometer to determine the confusion of the beam as a result of the separating magnet. The difference of rays 8 & 9 and 10 & 11 is .02 and .02, contributing to a resolution of 2.9×10^{-5} . This is due to the curvature of the D5 exit side. It can be made smaller, if the design value was used, the resolution improves to 1.4×10^{-6} . A change on this field clamp is unfortunately hard to make now and its effect on the resolution is not too bad, so we will have to accept the results it gives. Of course, these two effects must be considered jointly in the total resolution and another RAYTRACE run will give these results later.

IV. Further Considerations Due to Mechanical Constraints and RAYTRACE Results

There is a major mechanical constraint which tends to affect the optical results in a major way. The Spectrometer is now at 160.01° and rotated through 1.1° . The 180° system was designed to mate with the spectrometer when it was pivoted at 160° and rotated through 1.233° . (The Spectrometer was pivoted to 160.01° rather than 160° to help in connecting the 180° system, or to make up for the lack in rotation). The following diagram is to be compared to the similar one in report #4 for comparison of design and actuality!

FIGURE III

We see the first evident result is that D4 must be moved downstream from the design position as must D1 through D3. From this we see that D4 is now closer to the virtual object point of the spectrometer. The design distance of the VOP from the VFB of D5 exit was 58.841 cm while now we calculate it to be 53.909 cm. For the elastic scattering bend and for an outgoing ray of 21.090 instead of 21.233 this means that the target position must be changed from its design position. In addition the effect of the reduced pole face rotation on D5 exit causes us to consider RAYTRACE in calculating the optimum target position. In particular it will bring the virtual image of the target closer to the spectrometer than designed, which is helpful in our case.

If the target is in the wrong place the following scattering angle dependent resolution effect exists: A set of rays diverging from the target at the same

point looks to the spectrometer at its virtual object position as though it diverged from 2 different positions on the target. There is a spot size for isomomentum rays which causes a loss in resolution. This effect can be as large as 1×10^{-3} if the target position is sufficiently off. As the diverging angle decreases so does the effective spot size of the VOP. It is interesting that we observed this effect in looking at a 35 mg BeO target during the second tune-up run of the 180° scattering system. As we closed the vertical angle slits of the spectrometer in half, the resolution of the Be elastic peak improved by almost that factor. If the target was in the correct position this should not happen. Table VI contains a list of rays used to find the target position which will be focused (after the rays bounce off of it and go through D4) at the VOP of the spectrometer.

The final result of this calculation gives the target location at 9.10 cm behind the VFB of the D4 target side. The confusion of rays here due to the above mentioned effect is practically zero!

The last step now is to trace the rays through the four magnet system to the target with the correct incoming bend angle for elastic scattering; fake a scattering by rotating the coordinate system through a scattering angle, and then go back through D4 towards the spectrometer and trace backwards to the virtual object point of the spectrometer. Table VII displays the output of RAYTRACE for the above procedure for 180° scattering. The parameters used in this raytrace run are those of Table IV. Following Table VII in Table VII Fig. A and B we have a representation of the beam envelope at the Spectrometer's Virtual Object Position. This can be compared with the similar figures in Internal Report #4. We note the tilting of the beam envelope due to the

curvature of the outgoing edge of D5. This tilt is larger than shown in Report #4 since the curvature of this face on the dipole is larger than designed. But, as mentioned before, the difference caused in the resolution is not great. Furthermore the tilt is small enough so that no counts will be lost off the edge of the focal plane detector system.

Finally, a quick glance at Table VII gives us an idea of the ultimate resolution due to the 180° system. The difference between RAYS 8 & 9 or 10 & 11 in the vertical (4) direction is .0627 cm. From Section III we can convert this to 9.036×10^{-5} . The statement is then: The 180° scattering system presents a beam to the spectrometer which has a confusion in the momentum of less than 1 part in 10^4 of the incident energy of the beam.

Some other facts may be of interest to the reader. The large separating magnet has a dispersive effect on the scattered beam. This effect is $3.5\text{mr}/1\%$ energy loss. An effect of this order ensures a fairly constant solid angle for the entire range of spectrum accepted by the spectrometer. The spectrometer accepts 6% of the incident energy on its focal plane, whereas our 180° system allows 9% to enter the spectrometer due to magnet dispersion. This dispersion and the tilt of the beam envelope will have no visible effect on the focal plane detector system since there is parallel to point focusing in the horizontal direction. Also, there are no second order terms coupling the horizontal and vertical direction, obviously for the spectrometer to be working properly. Thus we predict the 180° system to cause no effects at the focal plane that cannot be explained by the fact that the spectrometer is looking at 180° scattered electrons (e.g., such as charge scattering parabola).

V. Results of Test Runs

At the time of this report, three tune-up experiments have been performed using the 180° system at the Bates accelerator. There are several results of interest.

The first encouraging accomplishment was the ability to steer the beam through the four magnets and hit the target in the scattering chamber, as well as the downstream target using the current settings calculated from the magnet measurements. This gives some indication that we understand the shape of our magnetic field profiles fairly well. With some fiddling of trim currents we feel we can steer the beam through the correct path and hit our harpwires as well as the targets. This ensures the beam is entering and exiting the magnet pole faces properly. Furthermore, once a setting is found for one energy and one bend angle, one can extrapolate that setting for any beam energy and bend angle and be very close to a proper beam trajectory solution.

The second encouraging effect came as we took data on the carbon elastic peak. Although we had not yet set the magnets so that the horizontal scattering angle accepted by the spectrometer was 180° we were able to see that there was a minimum in counts in the center of the vertical angle spectrum. This minimum should occur for any horizontal angle setting for a 0^+ nucleus. Fig. 4 shows the vertical angle spectrum for run NOV180.3.

Next we changed the bend angle through the magnets to map out the horizontal charge scattering parabola. Fig. 5 shows the results of this measurement, as well as a calculation by RAND et al for the theoretical charge parabola including finite solid angle and multiple scattering effects.

Fig. 6 shows an aluminum spectrum obtained during the last tune-up run. The target position has not yet been optimized although the procedure had been started on our last run. Also the dispersion using Q7 and the focusing using Q0 were not adjusted. The beam switchyard parameters were all set at book values. Next run we will vary these parameters. But without varying them we obtained an aluminum spectrum that demonstrated a resolution of $\approx 3 \times 10^{-4} E_0$ or 30 keV. This is very encouraging.

A final result obtained is shown in Fig. 7 where we have plotted the cross section obtained for the 15.11 MeV level of ^{12}C at 180° on a form factor curve comparing it with other data. From this we can begin to have faith in the data we are obtaining at 180° .

TABLE I

I(Amps)	B(kgauss)	T _{IN} (°C)	T _{OUT} (°C)
0.0	.010	29.9	30.01
50.3	1.615	29.95	30.86 +
100.8	3.210	29.97	32.00 +
151.2	4.801	30.47	35.60 +
201.5	6.378	30.30	38.69 +
251.7	7.945	30.40	44.60 +
302.0	9.494	31.40	64.57
226.6	7.165		53.76°C

A reasonable fit to the B vs I data yields the equation

$$B(\text{kgauss}) = 0.03160 I(\text{Amps}) + 0.01903$$

TABLE II A

MAGNET	GAP	C0	C1	C2	C3	C4	C5
D1 convex	3.4345" 8.724 cm	.4358	1.7552	-.8175	.4447	-.0915	.0060
D1 concave	"	.2365	1.8328	-.6323	.8739	-.1364	.0054
D2 concave	3.440" 8.7376 cm	.2246	1.8906	-.6016	.8911	-.1588	.0066
D3 concave	3.408" 8.6563 cm	"	"	"	"	"	"
D4 entrance	4.5" 11.43 cm	.2810	2.0772	-.8239	.7293	-.0602	-.0036
D4 target	4.5"	.2844	2.0958	-.7453	.7808	-.1844	.0120
D5 exit	4.5"	.3221	1.8748	-.8163	.7143	-.0939	.0012

TABLE II 8

MAGNET	R_{VIRT}^M	$CURV^M$	ROT^M	$R_{VIRT}^{D\dagger}$	$CURV^D$	ROT^D	x for B(zero)
D1 Convex	16.483 cm	18.694 cm 7.36"	$\approx .395^\circ$	17.77 cm 7"	17.77 cm	0.0°	77 cm
D1 Concave	17.621 cm	-32.269 cm -12.704"	$\approx .394^\circ$	17.77 cm	-21.93 cm	0.0°	40 cm
D2 Concave	17.901 cm	-21.602 cm -8.505"	7.311°	"	"	8.0°	42 cm
D3 Concave	"	"	"	"	"	8.0°	"
D4 Entrance	23.851 cm	18.156 cm 7.148"	1.45°	24.36 cm 9.59"	24.36 cm	0°	57 cm
D4 Target	23.058	27.908 cm 10.987"	$.084^\circ$	24.36 cm	flat ∞ cm	0°	61 cm
D5 Exit	22.956	-32.102 cm -12.639"	2.576°	24.36 cm	-89.29 cm -35.15"	5.4°	59

*M = measured values

† D = design values

Design

Fringe Field
Coefficients

	C0	C1	C2	C3	C4	C5
I Small Magnet						
A) Unclamped	.4952	1.9725	-0.7466	0.2897	-0.0591	0.0052
B) Clamped	-0.0170	1.8055	-0.2819	0.5680	0.3817	0.0966
II Large Magnet						
A) D4 entrance & target	-0.0170	1.8055	-0.2819	0.5680	0.3817	0.0966
B) D5 exit	.4952	1.9725	-0.7466	0.2897	-0.0591	0.0052

TABLE III

θ	$\rho D_1(\text{cm})$	$\rho D_2/D_3(\text{cm})$	$\rho D_4(\text{cm})$
2.5°	781.482	787.879	1074.905
5.0°	390.555	393.760	537.196
7.5°	260.162	262.297	357.846
10.0°	194.903	196.503	268.085
12.5°	155.698	156.976	214.161
15.5°	129.520	130.583	178.154
17.5°	110.786	111.694	152.385
20.0°	96.703	97.495	133.016
21.233°	90.968	91.713	125.127
21.5°			

A	=	0.000000
B	=	92.612000
C	=	8.723000
D	=	89.812000
E	=	1.671300
F	=	21.500000
G	=	0.000000
H	=	0.000000
I	=	0.000000
J	=	0.000000
K	=	0.000000
L	=	0.000000
M	=	0.000000
N	=	0.000000
O	=	0.000000
P	=	0.000000
Q	=	0.000000
R	=	0.000000
S	=	0.000000
T	=	0.000000
U	=	0.000000
V	=	0.000000
W	=	0.000000
X	=	0.000000
Y	=	0.000000
Z	=	0.000000
AA	=	0.000000
AB	=	0.000000
AC	=	0.000000
AD	=	0.000000
AE	=	0.000000
AF	=	0.000000
AG	=	0.000000
AH	=	0.000000
AI	=	0.000000
AJ	=	0.000000
AK	=	0.000000
AL	=	0.000000
AM	=	0.000000
AN	=	0.000000
AO	=	0.000000
AP	=	0.000000
AQ	=	0.000000
AR	=	0.000000
AS	=	0.000000
AT	=	0.000000
AU	=	0.000000
AV	=	0.000000
AW	=	0.000000
AX	=	0.000000
AY	=	0.000000
AZ	=	0.000000
BA	=	0.000000
BB	=	0.000000
BC	=	0.000000
BD	=	0.000000
BE	=	0.000000
BF	=	0.000000
BG	=	0.000000
BH	=	0.000000
BI	=	0.000000
BJ	=	0.000000
BK	=	0.000000
BL	=	0.000000
BM	=	0.000000
BN	=	0.000000
BO	=	0.000000
BP	=	0.000000
BQ	=	0.000000
BR	=	0.000000
BS	=	0.000000
BT	=	0.000000
BU	=	0.000000
BV	=	0.000000
BW	=	0.000000
BX	=	0.000000
BY	=	0.000000
BZ	=	0.000000
CA	=	0.000000
CB	=	0.000000
CC	=	0.000000
CD	=	0.000000
CE	=	0.000000
CF	=	0.000000
CG	=	0.000000
CH	=	0.000000
CI	=	0.000000
CJ	=	0.000000
CK	=	0.000000
CL	=	0.000000
CM	=	0.000000
CN	=	0.000000
CO	=	0.000000
CP	=	0.000000
CQ	=	0.000000
CR	=	0.000000
CS	=	0.000000
CT	=	0.000000
CU	=	0.000000
CV	=	0.000000
CW	=	0.000000
CX	=	0.000000
CY	=	0.000000
CZ	=	0.000000
DA	=	0.000000
DB	=	0.000000
DC	=	0.000000
DD	=	0.000000
DE	=	0.000000
DF	=	0.000000
DG	=	0.000000
DH	=	0.000000
DI	=	0.000000
DJ	=	0.000000
DK	=	0.000000
DL	=	0.000000
DM	=	0.000000
DN	=	0.000000
DO	=	0.000000
DP	=	0.000000
DQ	=	0.000000
DR	=	0.000000
DS	=	0.000000
DT	=	0.000000
DU	=	0.000000
DV	=	0.000000
DW	=	0.000000
DX	=	0.000000
DY	=	0.000000
DZ	=	0.000000
EA	=	0.000000
EB	=	0.000000
EC	=	0.000000
ED	=	0.000000
EE	=	0.000000
EF	=	0.000000
EG	=	0.000000
EH	=	0.000000
EI	=	0.000000
EJ	=	0.000000
EK	=	0.000000
EL	=	0.000000
EM	=	0.000000
EN	=	0.000000
EO	=	0.000000
EP	=	0.000000
EQ	=	0.000000

```

ELECTRON MOMENTUM = 450.000 MEV/C
ENTRANCE FRINGE FIELD STEP = 3.500 CM
UNIFORM FIELD STEP = 3.000 CM
EXIT FRINGE FIELD STEP = 2.500 CM
OFF MIDPLANE DIFFERENTIAL STEP = .500 CM
FIELD ROUTINE MTP = 2
RHO = 89.750 GM

```

TRANSLATE-ROTATE

X0 = 0.000090

```

      YO = 0.000000
      ZO = 0.000000
THETA X = 0.000000
THETA Y = 0.000000
THETA Z = 180.000000

```


TABLE NO 5

DIPOLE MAGNET D2

A = 0.000000
 B = 59.098000
 D = 0.737500
 R = 90.547000
 BF = 1.657700
 PHI = 21.500000
 ALPH = 0.000000
 BETA = 7.311000
 NOX = 0.000000
 BET1 = 0.000000
 GAMMA = 0.000000
 DELT = 0.000000
 Z11 = 62.165000
 Z12 = -16.463000
 Z21 = -17.790100
 Z22 = 20.000000
 C01 = .435800
 C02 = 1.755200
 C03 = -.817500
 C04 = .448700
 C05 = -.091500
 C06 = .005000
 C11 = .224600
 C12 = 1.890600
 C13 = -.601600
 C14 = .891100
 C15 = -.158600
 C16 = .006600
 BR1 = 0.000000
 BR2 = .086200
 XCR1 = 0.000000
 XCR2 = 0.000000
 DLS1 = 0.000000
 DLS2 = 0.000000
 RAP1 = .853193
 RAP2 = -.046292
 S01 = 0.
 S02 = 0.
 S03 = 0.
 S04 = 0.
 S05 = 0.
 S06 = 0.
 S07 = 0.
 S08 = 0.
 S09 = 0.
 S10 = 0.
 S11 = 0.
 S12 = 0.
 S13 = 0.
 S14 = 0.
 S15 = 0.
 S16 = 0.
 S17 = 0.
 S18 = 0.

ENTRANCE ELECTRON MOMENTUM = 60.000 KEV/D
 FRINGE FIELD STEP = 3.000 CM
 UNIFORM FIELD STEP = 3.000 CM
 EXIT FRINGE FIELD STEP = 2.000 CM
 OFF MIDPLANE DIFFERENTIAL STEP = 2.300 CM
 FIELD ROUTINE NTYP = 2
 RHO = 90.467 CM

DIPOLE MAGNET D3

A = 0.000000
 B = 85.244000
 D = 0.737500
 R = 90.547000
 BF = 1.657700
 PHI = 21.500000
 ALPH = 7.311000
 BETA = 0.000000
 NOX = 0.000000
 BET1 = 0.000000
 GAMMA = 0.000000
 DELT = 0.000000
 Z11 = 20.000000
 Z12 = -17.801000

DIPOLE MAGNET 03

A = 0.000000
 B = 85.244000
 C = 8.737600
 R = 90.547000
 BE = 1.657700
 PHI = 21.600000
 ALPH = 7.311000
 BETA = 0.000000
 NOX = 0.000000
 BET1 = 0.000000
 GAMMA = 0.000000
 DELT = 0.000000
 Z11 = 20.000000
 Z12 = -17.901000
 Z21 = -16.483000
 Z22 = 62.165000
 C01 = .224600
 C02 = 1.890600
 C03 = -.501800
 C04 = .891100
 C05 = -.158800
 C06 = .006600
 C11 = .433800
 C12 = 1.755200
 C13 = -.817500
 C14 = .444700
 C15 = -.891500
 C16 = .006000
 BR1 = .006200
 BR2 = 0.000000
 XCR1 = 0.000000
 XCR2 = 0.000000
 DLS1 = 0.000000
 DLS2 = 0.000000
 R01 = -.046292
 R02 = .053493
 S01 = 0.
 S02 = 0.
 S03 = 0.
 S04 = 0.
 S05 = 0.
 S06 = 0.
 S07 = 0.
 S08 = 0.
 S09 = 0.
 S10 = 0.
 S11 = 0.
 S12 = 0.
 S13 = 0.
 S14 = 0.
 S15 = 0.
 S16 = 0.
 S17 = 0.
 S18 = 0.

ELECTRON MOMENTUM = 450.000 MEV/D
 ENTRANCE FRINGE FIELD STEP = 2.500 CM
 UNIFORM FIELD STEP = 3.000 CM
 EXIT FRINGE FIELD STEP = 2.000 CM
 OFF MIDPLANE DIFFERENTIAL STEP = 2.500 CM
 FIELD ROUTINE MTYP = 2
 RHO = 90.467 CM

TRANSLATE-ROTATE

X0 = 0.000000
 Y0 = 0.000000
 Z0 = 0.000000
 THETA X = 0.000000
 THETA Y = 0.000000
 THETA Z = -180.000000

TABLE D D

DIPOLE MAGNET 04

A = 0.000000
 B = 9.100000
 D = 1.430000
 R = 123.537000
 BF = 1.215000
 PHI = 21.200000
 ALPH = 1.430000
 BETA = 0.000000
 NDX = 0.000000
 BET1 = 0.000000
 CANA = 0.000000
 DELTA = 0.000000
 T11 = 36.000000
 T12 = 23.855000
 T21 = 23.095000
 T22 = 9.100000
 C01 = 2.281000
 C02 = 2.077200
 C03 = 0.000000
 C04 = 0.000000
 C05 = 0.000000
 C06 = 0.000000
 C11 = 2.281000
 C12 = 2.095000
 C13 = -0.745300
 C14 = 0.780800
 C15 = 0.000000
 C16 = 0.000000
 BR1 = 0.000000
 BR2 = 0.000000
 XCR1 = 0.000000
 XCR2 = 0.000000
 DLS1 = 0.000000
 DLS2 = 0.000000
 RAP1 = 0.055000
 RAP2 = 0.035000
 S02 = 0.
 S03 = 0.
 S04 = 0.
 S05 = 0.
 S06 = 0.
 S07 = 0.
 S08 = 0.
 S09 = 0.
 S10 = 0.
 S11 = 0.
 S12 = 0.
 S13 = 0.
 S14 = 0.
 S15 = 0.
 S16 = 0.
 S17 = 0.
 S18 = 0.

ELECTRON MOMENTUM = 450.000 MEV/C
 ENTRANCE FRINGE FIELD STEP = 3.000 CM
 UNIFORM FIELD STEP = 3.000 CM
 EXIT FRINGE FIELD STEP = 3.000 CM
 OFF MIDPLANE DIFFERENTIAL STEP = 0.500 CM
 FIELD ROUTINE MTYP = 2
 RHO = 123.457 CM

DIPOLE MAGNET DS

A = 3.1415926
 B = -63.909000
 C = 123.456789
 D = 1.234567
 E = 2.345678
 F = 3.456789
 G = 4.567890
 H = 5.678901
 I = 6.789012
 J = 7.890123
 K = 8.901234
 L = 9.012345
 M = 10.123456
 N = 11.234567
 O = 12.345678
 P = 13.456789
 Q = 14.567890
 R = 15.678901
 S = 16.789012
 T = 17.890123
 U = 18.901234
 V = 19.012345
 W = 20.123456
 X = 21.234567
 Y = 22.345678
 Z = 23.456789
 AA = 24.567890
 AB = 25.678901
 AC = 26.789012
 AD = 27.890123
 AE = 28.901234
 AF = 29.012345
 AG = 30.123456
 AH = 31.234567
 AI = 32.345678
 AJ = 33.456789
 AK = 34.567890
 AL = 35.678901
 AM = 36.789012
 AN = 37.890123
 AO = 38.901234
 AP = 39.012345
 AQ = 40.123456
 AR = 41.234567
 AS = 42.345678
 AT = 43.456789
 AU = 44.567890
 AV = 45.678901
 AW = 46.789012
 AX = 47.890123
 AY = 48.901234
 AZ = 49.012345
 BA = 50.123456
 BB = 51.234567
 BC = 52.345678
 BD = 53.456789
 BE = 54.567890
 BF = 55.678901
 BG = 56.789012
 BH = 57.890123
 BI = 58.901234
 BJ = 59.012345
 BK = 60.123456
 BL = 61.234567
 BM = 62.345678
 BN = 63.456789
 BO = 64.567890
 BP = 65.678901
 BQ = 66.789012
 BR = 67.890123
 BS = 68.901234
 BT = 69.012345
 BU = 70.123456
 BV = 71.234567
 BW = 72.345678
 BX = 73.456789
 BY = 74.567890
 BZ = 75.678901
 CA = 76.789012
 CB = 77.890123
 CC = 78.901234
 CD = 79.012345
 CE = 80.123456
 CF = 81.234567
 CG = 82.345678
 CH = 83.456789
 CI = 84.567890
 CJ = 85.678901
 CK = 86.789012
 CL = 87.890123
 CM = 88.901234
 CN = 89.012345
 CO = 90.123456
 CP = 91.234567
 CQ = 92.345678
 CR = 93.456789
 CS = 94.567890
 CT = 95.678901
 CU = 96.789012
 CV = 97.890123
 CW = 98.901234
 CX = 99.012345
 CY = 100.123456
 CZ = 101.234567
 DA = 102.345678
 DB = 103.456789
 DC = 104.567890
 DD = 105.678901
 DE = 106.789012
 DF = 107.890123
 DG = 108.901234
 DH = 109.012345
 DI = 110.123456
 DJ = 111.234567
 DK = 112.345678
 DL = 113.456789
 DM = 114.567890
 DN = 115.678901
 DO = 116.789012
 DP = 117.890123
 DQ = 118.901234
 DR = 119.012345
 DS = 120.123456
 DT = 121.234567
 DU = 122.345678
 DV = 123.456789
 DW = 124.567890
 DX = 125.678901
 DY = 126.789012
 DZ = 127.890123
 EA = 128.901234
 EB = 129.012345
 EC = 130.123456
 ED = 131.234567
 EE = 132.345678
 EF = 133.456789
 EG = 134.567890
 EH = 135.678901
 EI = 136.789012
 EJ = 137.890123
 EK = 138.901234
 EL = 139.012345
 EM = 140.123456
 EN = 141.234567
 EO = 142.345678
 EP = 143.456789
 EQ = 144.567890
 ER = 145.678901
 ES = 146.789012
 ET = 147.890123
 EU = 148.901234
 EV = 149.012345
 EW = 150.123456
 EX = 151.234567
 EY = 152.345678
 EZ = 153.456789
 FA = 154.567890
 FB = 155.678901
 FC = 156.789012
 FD = 157.890123
 FE = 158.901234
 FF = 159.012345
 FG = 160.123456
 FH = 161.234567
 FI = 162.345678
 FJ = 163.456789
 FK = 164.567890
 FL = 165.678901
 FM = 166.789012
 FN = 167.890123
 FO = 168.901234
 FP = 169.012345
 FQ = 170.123456
 FR = 171.234567
 FS = 172.345678
 FT = 173.456789
 FU = 174.567890
 FV = 175.678901
 FW = 176.789012
 FX = 177.890123
 FY = 178.901234
 FZ = 179.012345
 GA = 180.123456
 GB = 181.234567
 GC = 182.345678
 GD = 183.456789
 GE = 184.567890
 GF = 185.678901
 GG = 186.789012
 GH = 187.890123
 GI = 188.901234
 GJ = 189.012345
 GK = 190.123456
 GL = 191.234567
 GM = 192.345678
 GN = 193.456789
 GO = 194.567890
 GP = 195.678901
 GQ = 196.789012
 GR = 197.890123
 GS = 198.901234
 GT = 199.012345
 GU = 200.123456
 GV = 201.234567
 GW = 202.345678
 GX = 203.456789
 GY = 204.567890
 GZ = 205.678901
 HA = 206.789012
 HB = 207.890123
 HC = 208.901234
 HD = 209.012345
 HE = 210.123456
 HF = 211.234567
 HG = 212.345678
 HH = 213.456789
 HI = 214.567890
 HJ = 215.678901
 HK = 216.789012
 HL = 217.890123
 HM = 218.901234
 HN = 219.012345
 HO = 220.123456
 HP = 221.234567
 HQ = 222.345678
 HR = 223.456789
 HS = 224.567890
 HT = 225.678901
 HU = 226.789012
 HV = 227.890123
 HW = 228.901234
 HX = 229.012345
 HY = 230.123456
 HZ = 231.234567
 IA = 232.345678
 IB = 233.456789
 IC = 234.567890
 ID = 235.678901
 IE = 236.789012
 IF = 237.890123
 IG = 238.901234
 IH = 239.012345
 II = 240.123456
 IJ = 241.234567
 IK = 242.345678
 IL = 243.456789
 IM = 244.567890
 IN = 245.678901
 IO = 246.789012
 IP = 247.890123
 IQ = 248.901234
 IR = 249.012345
 IS = 250.123456
 IT = 251.234567
 IU = 252.345678
 IV = 253.456789
 IW = 254.567890
 IX = 255.678901
 IY = 256.789012
 IZ = 257.890123
 JA = 258.901234
 JB = 259.012345
 JC = 260.123456
 JD = 261.234567
 JE = 262.345678
 JF = 263.456789
 JG = 264.567890
 JH = 265.678901
 JI = 266.789012
 JJ = 267.890123
 JK = 268.901234
 JL = 269.012345
 JM = 270.123456
 JN = 271.234567
 JO = 272.345678
 JP = 273.456789
 JQ = 274.567890
 JR = 275.678901
 JS = 276.789012
 JT = 277.890123
 JU = 278.901234
 JV = 279.012345
 JW = 280.123456
 JX = 281.234567
 JY = 282.345678
 JZ = 283.456789
 KA = 284.567890
 KB = 285.678901
 KC = 286.789012
 KD = 287.890123
 KE = 288.901234
 KF = 289.012345
 KG = 290.123456
 KH = 291.234567
 KI = 292.345678
 KJ = 293.456789
 KK = 294.567890
 KL = 295.678901
 KM = 296.789012
 KN = 297.890123
 KO = 298.901234
 KP = 299.012345
 KQ = 300.123456
 KR = 301.234567
 KS = 302.345678
 KT = 303.456789
 KU = 304.567890
 KV = 305.678901
 KW = 306.789012
 KX = 307.890123
 KY = 308.901234
 KZ = 309.012345
 LA = 310.123456
 LB = 311.234567
 LC = 312.345678
 LD = 313.456789
 LE = 314.567890
 LF = 315.678901
 LG = 316.789012
 LH = 317.890123
 LI = 318.901234
 LJ = 319.012345
 LK = 320.123456
 LL = 321.234567
 LM = 322.345678
 LN = 323.456789
 LO = 324.567890
 LP = 325.678901
 LQ = 326.789012
 LR = 327.890123
 LS = 328.901234
 LT = 329.012345
 LU = 330.123456
 LV = 331.234567
 LW = 332.345678
 LX = 333.456789
 LY = 334.567890
 LZ = 335.678901
 MA = 336.789012
 MB = 337.890123
 MC = 338.901234
 MD = 339.012345
 ME = 340.123456
 MF = 341.234567
 MG = 342.345678
 MH = 343.456789
 MI = 344.567890
 MJ = 345.678901
 MK = 346.789012
 ML = 347.890123
 MN = 348.901234
 MO = 349.012345
 MP = 350.123456
 MQ = 351.234567
 MR = 352.345678
 MS = 353.456789
 MT = 354.567890
 MU = 355.678901
 MV = 356.789012
 MW = 357.890123
 MX = 358.901234
 MY = 359.012345
 MZ = 360.123456
 NA = 361.234567
 NB = 362.345678
 NC = 363.456789
 ND = 364.567890
 NE = 365.678901
 NF = 366.789012
 NG = 367.890123
 NH = 368.901234
 NI = 369.012345
 NJ = 370.123456
 NK = 371.234567
 NL = 372.345678
 NM = 373.456789
 NO = 374.567890
 NP = 375.678901
 NQ = 376.789012
 NR = 377.890123
 NS = 378.901234
 NT = 379.012345
 NU = 380.123456
 NV = 381.234567
 NW = 382.345678
 NX = 383.456789
 NY = 384.567890
 NZ = 385.678901
 OA = 386.789012
 OB = 387.890123
 OC = 388.901234
 OD = 389.012345
 OE = 390.123456
 OF = 391.234567
 OG = 392.345678
 OH = 393.456789
 OI = 394.567890
 OJ = 395.678901
 OK = 396.789012
 OL = 397.890123
 OM = 398.901234
 ON = 399.012345
 OO = 400.123456
 OP = 401.234567
 OQ = 402.345678
 OR = 403.456789
 OS = 404.567890
 OT = 405.678901
 OU = 406.789012
 OV = 407.890123
 OW = 408.901234
 OX = 409.012345
 OY = 410.123456
 OZ = 411.234567
 PA = 412.345678
 PB = 413.456789
 PC = 414.567890
 PD = 415.678901
 PE = 416.789012
 PF = 417.890123
 PG = 418.901234
 PH = 419.012345
 PI = 420.123456
 PJ = 421.234567
 PK = 422.345678
 PL = 423.456789
 PM = 424.567890
 PN = 425.678901
 PO = 426.789012
 PP = 427.890123
 PQ = 428.901234
 PR = 429.012345
 PS = 430.123456
 PT = 431.234567
 PU = 432.345678
 PV = 433.456789
 PW = 434.567890
 PX = 435.678901
 PY = 436.789012
 PZ = 437.890123
 QA = 438.901234
 QB = 439.012345
 QC = 440.123456
 QD = 441.234567
 QE = 442.345678
 QF = 443.456789
 QG = 444.567890
 QH = 445.678901
 QI = 446.789012
 QJ = 447.890123
 QK = 448.901234
 QL = 449.012345
 QM = 450.123456
 QN = 451.234567
 QO = 452.345678
 QP = 453.456789
 QQ = 454.567890
 QR = 455.678901
 QS = 456.789012
 QT = 457.890123
 QU = 458.901234
 QV = 459.012345
 QW = 460.123456
 QX = 461.234567
 QY = 462.345678
 QZ = 463.456789
 RA = 464.567890
 RB = 465.678901
 RC = 466.789012
 RD = 467.890123
 RE = 468.901234
 RF = 469.012345
 RG = 470.123456
 RH = 471.234567
 RI = 472.345678
 RJ = 473.456789
 RK = 474.567890
 RL = 475.678901
 RM = 476.789012
 RN = 477.890123
 RO = 478.901234
 RP = 479.012345
 RQ = 480.123456
 RR = 481.234567
 RS = 482.345678
 RT = 483.456789
 RU = 484.567890
 RV = 485.678901
 RW = 486.789012
 RX = 487.890123
 RY = 488.901234
 RZ = 489.012345
 SA = 490.123456
 SB = 491.234567
 SC = 492.345678
 SD = 493.456789
 SE = 494.567890
 SF = 495.678901
 SG = 496.789012
 SH = 497.890123
 SI = 498.901234
 SJ = 499.012345
 SK = 500.123456
 SL = 501.234567
 SM = 502.345678
 SN = 503.456789
 SO = 504.567890
 SP = 505.678901
 SQ = 506.789012
 SR = 507.890123
 SS = 508.901234
 ST = 509.012345
 SU = 510.123456
 SV = 511.234567
 SW = 512.345678
 SX = 513.456789
 SY = 514.567890
 SZ = 515.678901
 TA = 516.789012
 TB = 517.890123
 TC = 518.901234
 TD = 519.012345
 TE = 520.123456
 TF = 521.234567
 TG = 522.345678
 TH = 523.456789
 TI = 524.567890
 TJ = 525.678901
 TK = 526.789012
 TL = 527.890123
 TM = 528.901234
 TN = 529.012345
 TO = 530.123456
 TP = 531.234567
 TQ = 532.345678
 TR = 533.456789
 TS = 534.567890
 TT = 535.678901
 TU = 536.789012
 TV = 537.890123
 TW = 538.901234
 TX = 539.012345
 TY = 540.123456
 TZ = 541.234567
 UA = 542.345678
 UB = 543.456789
 UC = 544.567890
 UD = 545.678901
 UE = 546.789012
 UF = 547.890123
 UG = 548.901234
 UH = 549.012345
 UI = 550.123456
 UJ = 551.234567
 UK = 552.345678
 UL = 553.456789
 UM = 554.567890
 UN = 555.678901
 UO = 556.789012
 UP = 557.890123
 UQ = 558.901234
 UR = 559.012345
 US = 560.123456
 UT = 561.234567
 UJ = 562.345678
 UV = 563.456789
 UW = 564.567890
 UX = 565.678901
 UY = 566.789012
 UZ = 567.890123
 VA = 568.901234
 VB = 569.012345
 VC = 570.123456
 VD = 571.234567
 VE = 572.345678
 VF = 573.456789
 VG = 574.567890
 VH = 575.678901
 VI = 576.789012
 VJ = 577.890123
 VK = 578.901234
 VL = 579.012345
 VO = 580.123456
 VP = 581.234567
 VQ = 582.345678
 VR = 583.456789
 VS = 584.567890
 VT = 585.678901
 VU = 586.789012
 VV = 587.890123
 VW = 588.901234
 VX = 589.012345
 VY = 590.123456
 VZ = 591.234567
 WA = 592.345678
 WB = 593.456789
 WC = 594.567890
 WD = 595.678901
 WE = 596.789012
 WF = 597.890123
 WG = 598.901234
 WH = 599.012345
 WI = 600.123456
 WJ = 601.234567
 WK = 602.345678
 WL = 603.456789
 WM = 604.567890
 WN = 605.678901
 WO = 606.789012
 WP = 607.890123
 WQ = 608.901234
 WR = 609.012345
 WS = 610.123456
 WT = 611.234567
 WU = 612.345678
 WV = 613.456789
 WW = 614.567890
 WX = 615.678901
 WY = 616.789012
 WZ = 617.890123
 XA = 618.901234
 XB = 619.012345
 XC = 620.123456
 XD = 621.234567
 XE = 622.345678
 XF = 623.456789
 XG = 624.567890
 XH = 625.678901
 XI = 626.789012
 XJ = 627.890123
 XK = 628.901234
 XL = 629.012345
 XM = 630.123456
 XN = 631.234567
 XO = 632.345678
 XP = 633.456789
 XQ = 634.567890
 XR = 635.678901
 XS = 636.789012
 XT = 637.890123
 XU = 638.901234
 XV = 639.012345
 XW = 640.123456
 XX = 641.234567
 XY = 642.345678
 XZ = 643.456789
 YA = 644.567890
 YB = 645.678901
 YC = 646.789012
 YD = 647.890123
 YE = 648.901234
 YF = 649.012345
 YG = 650.123456
 YH = 651.234567
 YI = 652.345678
 YJ = 653.456789
 YK = 654.567890
 YL = 655.678901
 YO = 656.789012
 YP = 657.890123
 YQ = 658.901234
 YR = 659.012345
 YS = 660.123456
 YT = 661.234567
 YU = 662.345678
 YV = 663.456789
 YW = 664.567890
 YX = 665.678901
 YY = 666.789012
 YZ = 667.890123
 ZA = 668.901234
 ZB = 669.012345
 ZC = 670.123456
 ZD = 671.234567
 ZE = 672.345678
 ZF = 673.456789
 ZG = 674.567890
 ZH = 675.678901
 ZI = 676.789012
 ZJ = 677.890123
 ZK = 678.901234
 ZL = 679.012345
 ZM = 680.123456
 ZN = 681.234567
 ZO = 682.345678
 ZP = 683.456789
 ZQ = 684.567890
 ZR = 685.678901
 ZS = 686.789012
 ZT = 687.890123
 ZU = 688.901234
 ZV = 689.012345
 ZW = 690.123456
 ZX = 691.234567
 ZY = 692.345678
 ZZ = 693.456789
 AA = 694.567890
 AB = 695.678901
 AC = 696.789012
 AD = 697.890123
 AE = 698.901234
 AF = 699.012345
 AG = 700.123456
 AH = 701.234567
 AI = 702.345678
 AJ = 703.456789
 AK = 704.567890
 AL = 705.678901
 AM = 706.789012
 AN = 707.890123
 AO = 708.901234
 AP = 709.012345
 AQ = 710.123456
 AR = 711.234567
 AS = 712.345678
 AT = 713.456789
 AU = 714.567890
 AV = 715.678901
 AW = 716.789012
 AX = 717.890123
 AY = 718.901234
 AZ = 719.012345
 BA = 720.

TABLE V

COORDINATES OPTIC AXIS SYSTEM

	X	THETA	Y	PHI	ZI	DELP
1	0.00	0.00	0.00	0.00	0.0	0.00
2	-.50	0.00	0.00	0.00	0.00	0.00
3	.50	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	-1.70	0.00	0.00	-.24
5	0.00	0.00	1.70	0.00	0.00	.24
6	.50	0.00	-.85	0.00	0.00	-.12
7	-.50	0.00	-.85	0.00	0.00	-.12
8	-.50	0.00	-1.70	0.00	0.00	-.24
9	.50	0.00	-1.70	0.00	0.00	-.24
10	.50	0.00	1.70	0.00	0.00	.24
11	-.50	0.00	1.70	0.00	0.00	.24
12	0.00	.10	0.00	0.00	0.00	0.00
13	0.00	.10	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	.10	0.00	0.00
15	0.00	0.00	0.00	-.10	0.00	0.00
16	0.00	.10	0.00	.10	0.00	0.00
17	0.00	0.00	0.00	0.00	0.00	0.00

END OF FILE ENCOUNTERED. FILENAME = INPUT
 ERROR NUMBER 69 DETECTED BY INPUT AT ADDRESS 0015
 CALLED FROM RAYTRAC AT LINE 61

TABLE VI

COORDINATES OPTIC AXIS SYS. EN						
	X	THETA	Y	PHI	ZI	DELP
1	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	20.00	0.00	0.00
3	0.00	0.00	0.00	-20.00	0.00	0.00
4	0.00	5.00	0.00	0.00	0.00	0.00
5	0.00	-5.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	45.00	0.00	0.00
7	0.00	0.00	0.00	-45.00	0.00	0.00
8	0.00	5.00	0.00	20.00	0.00	0.00
9	0.00	-5.00	0.00	20.00	0.00	0.00
10	0.00	0.00	0.00	-20.00	0.00	0.00
11	0.00	-5.00	0.00	-20.00	0.00	0.00

TABLE VII

TABLE VII

COORDINATES OPTIC AXIS SYSTEM

	X	THETA	Y	PHI	ZI	DELP	XO	XS	YO	YS
1	0.00	0.00	0.00	0.00	0.00	0.00	-.0000	-.0000	.0000	.0000
2	-.50	0.00	0.00	0.00	0.00	0.00	.4633	.4693	.0000	.0000
3	.50	0.00	0.00	0.00	0.00	0.00	-.4562	-.4199	.0000	.0000
4	0.00	0.00	-1.70	0.00	0.00	-.24	.0336	-2.4310	-1.7993	.0050
5	0.00	0.00	1.70	0.00	0.00	.24	-.2503	-.6888	1.8219	.0000
6	.50	0.00	-.85	0.00	0.00	-.12	-.4153	-1.2865	-.9450	-.4500
7	-.50	0.00	-.85	0.00	0.00	-.12	.5069	-.3505	-.9122	.0313
8	-.50	0.00	-1.70	0.00	0.00	-.24	.4985	-1.9090	-1.7692	.4565
9	.50	0.00	-1.70	0.00	0.00	-.24	-.4258	-2.9079	-1.8319	.0000
10	.50	0.00	1.70	0.00	0.00	.24	-.7041	-1.1532	1.8540	.0000
11	-.50	0.00	1.70	0.00	0.00	.24	.2087	-.1715	1.7913	.0000
12	0.00	.10	0.00	0.00	0.00	0.00	.0199	-.0890	.0000	.0000
13	0.00	-.10	0.00	0.00	0.00	0.00	-.0199	.0890	.0000	.0000
14	0.00	0.00	0.00	.10	0.00	0.00	-.0000	-.0005	.0343	.1020
15	0.00	0.00	0.00	-.10	0.00	0.00	-.0000	.0005	.0343	-.1020
16	0.00	.10	0.00	.10	0.00	0.00	.0198	-.0895	.0343	.1014
17	0.00	-.10	0.00	-.10	0.00	0.00	-.0199	.0888	.0343	-.1020

RAYTRACE RESULTS AT V.O.P. of Spectrometer for 180° scattering

TABLE VII FIG A

TABLE VII FIG D

FIGURE 4.

ELASTIC CHARGE SCATTERING FROM ¹²C NEAR 180°

FIGURE 5

^{27}Al : 7 mg cm^{-2} , $E_0 = 101.5 \text{ MeV}$

(Run 180,20)

Course Spectrum

FIG. 6

Fig. 7

APPENDIX C-1

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LABORATORY FOR NUCLEAR SCIENCE
CAMBRIDGE, MASSACHUSETTS 02139

November 2, 1977

Dr. George Rogosa
Assistant Director for Nuclear Sciences
Division of Physical Research
U. S. ERDA
Washington, DC 20545

Dear George:

The enclosed memorandum from Claude Williamson speaks clearly to some essential points in connection with the joint J. Mass.-Bates construction and installation of a 180° magnetic analysis system as an adjunct to the Bates energy-loss spectrometer. I send it along for some pleasant reading, and as an indication of the good success of this first of such user-spearheaded experiences at Bates. Congratulations should be accorded to Jerry Peterson and his colleagues at Amherst for taking initiative and committing themselves to their part in this very substantial task.

As Claude notes in the latter part of his memo, a beam was quickly carried to and through the system on the first try, week before last, during the late and wee hours of Saturday night and Sunday morning. Several scattering runs were made on a target of carbon. One very short run was taken also on a thin aluminum target which, although it accumulated relatively few counts, nevertheless appears to be good enough to demonstrate an encouraging upper limit of better than 10⁻³ for the system's resolution.

In drawing attention to the contributions of others Claude has successfully (and characteristically) minimized his own part in the effort. His role was indeed outstanding, as was the case also when he similarly coordinated the completion of the energy-loss spectrometer for Bates several years ago. He deserves the highest commendation for both jobs.

With best wishes.

Sincerely,

Peter Demos

PTD:VJH

(INTER-DEPARTMENTAL)

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LABORATORY FOR NUCLEAR SCIENCE

October 26, 1977

TO: P. T. DEMOS
FROM: C. WILLIAMSON
SUBJECT: 180° SCATTERING SYSTEM

I am pleased to be able to report to you that this project appears to be approaching a successful completion. As you know, I agreed to your request in early 1976 to act as coordinator for Bates on this joint project with the University of Massachusetts. Professor Gerald Peterson has been the director of the effort on the part of UMass. This was the first major design project at Bates instigated and largely carried out by one of our outside user groups. As with all such projects, there were rough spots that we had to work out by mutual interaction, but overall the effort was one of amicable cooperation and mutual respect. It was a rewarding experience to me personally to have the chance to work with the group at the University of Massachusetts as well as with our own people at Bates on this project.

I should particularly like to bring to your attention the contributions made by some of our own people that might otherwise go unnoticed. In the Engineering Department we owe a great debt of gratitude to George Karageorge who has with great patience and diligence watched over the engineering aspects of the project, especially at the critical interface between the MIT and UMass parts of the effort. We are also indebted to Mr. Henk Fischer for his design and engineering work on many of our parts of the project and his inflexible insistence on quality engineering throughout the system.

October 26, 1977

Page 2

On the Operations side, I would point to Mr. Lyman Stinson as a tower of strength in seeing to completion the critical assembly operations. He has given to us far more than the call of duty, and it was on him that we all relied for the difficult, tedious, and sometimes frustrating job of creating a system from an assortment of parts. His ability in dealing with the technical and human problems that arose in this effort was truly outstanding.

Finally, I should like to give credit to the people who do the hardest jobs and often get the least credit - the Mechanical and Electrical Groups. The enthusiasm and dedication of these people far beyond the simple giving of a day's work for a day's pay made it possible to get this system on the air. As of last Saturday evening, many of these people had worked thirteen consecutive days (and most evenings) without a day off. In these groups I should like especially to single out the following individuals: Thomas Meagher, Eugene DiFrancesco, David Kelley, Michael Kilkelly, and Robert Terenzoni in the Mechanical Group; and Albert Libertini, Kenneth Hatch, John Bavineau, and Harry Lenchitz in the Electrical Group. As always, we were indebted to Mr. Joseph Stanowicz, Mechanical Group Foreman, for his organizational ability and perceptive suggestions.

We introduced the first beam into this system at about Midnight, Saturday, October 22. No difficulty was experienced in finding a 140 MeV beam with all four magnets off, and in centering it on a monitor target near the beam dump. The magnets were then powered to the level calculated for the particular position of the two movable center magnets. When the beam was restored, the spot on the downstream monitor target (about 30 feet from the target position) had moved less than one inch. No great

October 26, 1977

Page 3

difficulty was encountered in adjusting the trim coils to center the beam on the monitor target and at the same time hit all three "harp" beam position monitors in the three drift spaces between the four magnets of the system. This was achieved for several combinations of magnet position and magnetic field, and it appears that interpolation for intermediate combinations is straightforward. A series of runs at 90 MeV was also made on a 60 mg/cm² carbon target in which the elastic peak was observed while varying the magnetic fields in all magnets and the position of the two middle magnets. This was done in an attempt to map out the 180° scattering parabola for the system. The observed resolution was about 260 keV, virtually all of which could be accounted for by target thickness effects. A very short run was taken on a thin aluminum target, but the statistics were so poor that only an upper limit of about 6×10^{-4} could be placed on the resolution.

Although we have run only about 24 hours of beam into the system, the results seem to indicate that the 180° system is now in an operational state. We still have a considerable amount of work remaining to understand the system, but the construction phase can now be considered essentially complete.

mc

The Commonwealth of Massachusetts
University of Massachusetts
Amherst 01003

DEPARTMENT OF PHYSICS AND ASTRONOMY
 NUCLEAR PHYSICS GROUP
 Graduate Research Center

November 22, 1977

Professor Peter T. Demos
 Laboratory for Nuclear Science 20D-038
 Massachusetts Institute of Technology
 Cambridge, MA 02139

Dear Peter:

I want to take this opportunity to express my sincere thanks to those at the Bates Accelerator Laboratory who cooperated in bringing the 180° scattering apparatus to its present status. The total project is not finished until the beam dumping pipe and dumping coils are installed, a Bates responsibility, but at this point, I am pleased to report that it appears that the rest of the completed system will meet design specifications.

First I want to acknowledge the very large efforts by Claude Williamson in planning and coordination. In the three year period since it was known that this project would be funded, we have had many successful planning and review meetings in which completion schedules were set, and in which Bates and UMass efforts were coordinated to meet those schedules. Claude's part in organizing these meetings and in seeing that plans were carried forward were important to the success of the project.

With regard to the engineering aspects, George Karageorge, Hank Fischer, and Danny Baker dealt with their aspects of the project in their usual professional manner. They also helped and gave suggestions to our less experienced UMass student engineers with attitudes of patience and tactfulness.

In the preinstallation period, Joe Stanowicz, Gene Di Francesco, Bob Terenzoni, and Tom Meagher dealt successfully with many of the most critical mechanical aspects of the project. Without their ingenuity in solving these problems that were not foreseen on the drawing boards, the project would not have arrived at its present state.

Finally in the installation period, Lyman Stinson and the Mechanical and Electrical Groups worked overtime and weekends for several weeks unstintingly. Again everyone mentioned above contributed, but also Mike Kilkelly, Dave Kelley, Al Libertini, Ken Hatch, John Bavineau, and Harry Lenchitz put in long hours to "shoehorn" our system into its proper location. We expected problems at

Professor Peter T. Demos

Page 2

November 22, 1977

this phase, and we got them, but thanks to the really tremendous effort put forth by the Bates people, these problems were overcome. Lyman Stinson, as usual, showed a tremendous devotion to getting the job done quickly and properly. As users of the Bates facility, we could not have asked for better cooperation. At times the installation activity was really intense, with plumbing, electrical, steel cutting, surveying, mechanical, and vacuum work all taking place simultaneously.

The project has been a pleasant experience for us as outside users, as we have sincerely enjoyed working with the Bates team. I hope that our experiences will provide a stimulus for other users.

Sincerely yours,

Gerald A. Peterson
Professor of Physics

GAP:dam

APPENDIX D

PROPOSAL

BATES ELECTRON LINEAR ACCELERATOR

IN BEAM TUNE-UP OF THE 180° SCATTERING SYSTEM

J.B. Flanz, K.R. Halliday, K. Itoh, G.A. Peterson,
H. deVries, D.V. Webb, and A. Williams

The University of Massachusetts, Amherst, Massachusetts

and

W.C. Barber, S. Kowalski, and C.F. Williamson

Massachusetts Institute of Technology
Cambridge, Massachusetts

SPOKESMAN: G.A. Peterson

SEPTEMBER, 1976

ABSTRACT

Before measuring magnetic levels in detail with the 180° scattering system, certain tune-up experiments must be performed to ascertain the working order of the system. The beam must be steered properly through the system. The dispersion must be matched to the spectrometer. We must understand the beam transport plus spectrometer focal plane optics. Finally, we must determine the working configuration for the 180° scattering angle. We estimate that we will require 107 hours of beam time starting in early February.

I. SYSTEM TEST

After the installation of the 180° system, several in-beam tests are required. Although many tests can be made before this stage, we restrict the discussion here to tests which require an electron beam.

A. Magnet Current Adjustment

The first test that must be made using an actual electron beam is to steer the beam through the 180° beam transport system and its beam monitors, and finally to have it pass through a BeO target. The main coil, correction coil, and possibly dumping coil currents will be adjusted to accomplish this. Figure 1 shows a sketch of the system.

For these measurements we will require the following modest beam parameters:

Energies: 90, 140, 190, 240, 290 and 340 MeV

Energy Resolution: $\Delta p/p = 10^{-3}$ (non-dispersed)

Current per Pulse: Unimportant, but high enough to cause a viewing screen to be visible on a TV monitor and high enough so that the beam can be easily detected on our electrical current monitors.

Average Current: Unimportant

Pulse Width and Repetition Rate: Not critical

Time Required at Each Energy: Six hours at 90 MeV, 3 hours at the other energies for a subtotal of 21 hours.

B. Dispersion Matching, Resolution Test

The dispersion of the beam should be matched to the spectrometer as closely as possible. According to our calculation, the dispersion of the beam at the target is changed by 2.5% by the 180° system when compared with the existing optical system consisting of the spectrometer and the existing beam transport system.

This small difference might be corrected by adjusting either the quadrupoles upstream of the 180° system, or by changing the field clamps in the 180° system magnets.

These tests will be carried out by measuring elastic peaks and making the resolution as high as possible. A carbon target, a polyethylene (CH₂) target, and a niobium or vanadium target will be used for this purpose. The inelastic scattering from the 15.11 MeV excitation of ¹²C will also be useful as a check on the resolution when the system is operated for observing inelastic scattering. We expect a system resolution of less than 3×10^{-4} . For these measurements we will require the following beam parameters:

Energies: 90, 190, and 290 MeV.

Energy Resolution: $\Delta p/p = 5 \times 10^{-3}$ (dispersed)

Current per Pulse: Not a critical parameter

Average Current: 10 μ A or greater

Pulse Width and Repetition Rate: Not critical

Time Required at Each Energy: 12 hours at 90 MeV, 8 hours each
at 190 and 290 MeV for a subtotal of
28 hours.

These measurements might be done together with part A.

C. Transverse Wire Proportional Chamber Tests

It is of interest, especially for 180° scattering, to know the angular distribution of the scattered electrons in both the horizontal and vertical planes. The transverse wire chamber which measures the horizontal angle has not been fully studied yet. We propose to use beamtime before the installation of the 180° system so as to understand how the horizontal spectrometer slit configuration relates to the distribution of "hit" wires on the drift chamber. With this information, the software can be developed to relate the momentum of the scattered electrons to the total scattering angle. Four hours of beam time is requested for this measurement.

D. A Check of the Scattering Angle and Determination of the Average Scattering Angle

The elastic scattering angle θ of electrons of energy E_0 by nuclei of atomic number Z without spin is described by

$$\frac{d\sigma}{d\Omega} = \left(\frac{Ze^2}{2E_0}\right)^2 \frac{\csc^4 \frac{\theta}{2}}{1 + \frac{E_0}{Mc^2} \sin^2 \frac{\theta}{2}} \left(\frac{m^2 c^4}{2E_0^2} + \cos^2 \frac{\theta}{2}\right) |F(q)|^2. \quad (1)$$

As $\theta \rightarrow 180^\circ$,

$$\frac{d\sigma}{d\Omega} \sim \left(\frac{180 - \theta}{2}\right)^2 + \text{Const.} \quad (2)$$

In the 180° system, back-scattered electrons are deflected 21.2° by the fourth magnet so that they pass into the spectrometer set at 160° , but cocked at 1.2° .

In order to ascertain the 180° scattering angle, we should measure the counting rates from elastic scattering from spinless ^{12}C by changing the scattering angle in steps of about 0.2° around 180° thus mapping the parabola of counts versus scattering angle around 180° as indicated by Eq. 2. The scattering angle can be varied by moving the central two magnets back and forth about their 180° scattering position. The elastic scattering goes to a minimum at 180° . However, because of a finite spectrometer solid angle, the average scattering angle is less than 180° .

For these measurements we will require the following beam parameters:

Energies: 110, 210 and 290 MeV

Energy Resolution: $\Delta p/p = 5 \times 10^{-3}$ (dispersed)

Current per Pulse: Not a critical parameter

Average Current: 20 μA or higher

Other Parameters: Unimportant

Time Required at Each Energy: 5 hours each for a subtotal of 15 hours.

This measurement is expected to be a "fine-tuning" measurement in comparison to the measurements of parts A and B. We plan to use a thick carbon target and to avoid the diffraction minimum at about 1.8 fm^{-1} .

E. Measurement of Background Levels

Since many cross sections to be measured with the 180° scattering system will be small, estimates of background levels will be needed. These should include measurements of target dependent and target independent backgrounds. Furthermore, if the beam dumping system is in place, its performance will need to be optimized. We request 12 hours for this purpose.

F. Measurement of Dependence of Counting Rate on Object Distance (Target Study)

In long gas targets used for 180° scattering, the counting rate should drop off for those electrons which do not scatter from the optimum target object distance. We request 6 hours of beam time to study this effect with solid targets.

Summary of Beam Time Requests

Part A: Magnet Current Adjustment	Elastic	21 hours
	Inelastic	21 hours
Part B: Dispersion Matching, Resolution Test		28 hours
Part C: Transverse Wire Chamber Tests		4 hours
Part D: Scattering Angle Determination		15 hours
Part E: Background Measurements		12 hours
Part F: Target Study		6 hours
TOTAL TIME REQUIRED		<hr/> 107 hours

We estimate that these tests might commence in early February.

References

1. J.B. Flanz and D.V. Webb, Internal Report #4, University of Massachusetts, Medium-Energy Nuclear Physics Group, April 5, 1976.

APPENDIX E

Scientific and Technical Personnel

<u>Name</u>	<u>Major Contribution</u>
S.H. Chen	Drafting
Ann L. Dressler	Drafting
John M. Finn	Consideration of measurements with system
Jacob B. Flanz	Beam optics, magnet design, magnetic field measurements, dump coil design, tune-up experiment
Thomas Gallant	Drafting
Kenneth R. Halliday	Engineering aspects of magnets, vacuum chamber, and support structure
Michael Hargrove	Drafting
David Huse	Technician
Gerald A. Peterson	All phases of the project
Hooshang Shamash	Target changer design
Arnold Sweeney	Machining
Hans de Vries	Beam optics, magnetic field measurements
David V. Webb	Beam optics, magnet design, field clamp design, magnetic field measurements
Christopher Woodward	Technician
Richard York	Target and magnet position electronics, tune-up run

Participants only in installation and tune-up runs:

Ross S. Hicks
 Akio Hotta
 Richard Lindgren
 Brett Parker