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Argonne National Laboratory

ENERGY-ANALYZING SYSTEM FOR THE ARGONNE 60-inch CYCLOTRON

by

W. J. Ramler, J. J. Livingood,
G. W. Parker, J. Aron,
and M. C. Oselka

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Chemistry Division

*Physics Division

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ENERGY-ANALYZING SYSTEM FOR THE ARGONNE 60-in. CYCLOTRON

by

W. J. Ramler, J. J. Livingood,
G. W. Parker, J. Aron,
and M. C. Oselka

The extracted beam of ions from Argonne's 60-in. cyclotron,* installed in 1952, has a total energy spread of about 1%. Increased sophistication of experiments within recent years has called for an analyzing system capable of reducing the spread to the lowest feasible value. This report describes the system of magnets, ancillary hardware, and the resulting dispersive and achromatic operation. An energy resolution (full width at half maximum, FWHM) of $\Delta E/E = 0.08\%$ has been obtained for alphas of 43.2 MeV.

I. INTRODUCTION

The beam-transport system shown in Fig. 1 is a composite of effort over the years. Initially, experimental tunnel No. 1 was the only existing external beam room; the equipment between the cyclotron and this area has been in operation for several years.**

With the increased experimental sophistication, experimental tunnel No. 2 was constructed and the equipment designed for the projection of both the raw ions and a highly resolved particle group of $<0.1\%$ FWHM energy spread into this area. This new leg of the transport system was coupled to the existing 15° port of the first switch magnet. The constraints that governed the choice of magnet parameters to achieve the desired resolution were: the location of this new external beam area, the direction of beam, the cyclotron tuner, and the existing floor area between the tuner and vault walls. Fortunately, these constraints were compatible with the use of two magnets, each with a radius of 40 in. and a 120° bending angle. Each is used at unity magnification with the bending in opposite directions, so that their dispersions add. To keep the gap height to a reasonable size, vertical focusing was provided, thus making both magnets double focusing.

*W. J. Ramler and G. W. Parker, The Argonne 60-inch Cyclotron, ANL-5907 (Feb 1959). W. J. Ramler, R. Benaroya, G. W. Parker, and J. Aron, Argonne Cyclotron--Helium-3 Conversion, ANL-7171 (Feb 1966).

**W. J. Ramler, External Beam Focusing System -- Argonne 60-inch Cyclotron, Sector-focused Cyclotrons, NAS-656 (1959).

Fig. 1. Plan of Beam-transport and Analyzing System

II. DISPERSIVE DESIGN

To obtain the desired characteristics as indicated above, we chose to use uniform-field magnets [$n = -(\rho/B)(dB/d\rho) = 0$] with equal, finite entrance and exit angles. Such magnets are simpler to build and to make operate over the field range required (250 to 480 kG-in., i.e., 6.25 to 12 kG with $\rho = 40$ in.) than are magnets with $n = 0.5$ and normal entrance and exit. Furthermore, for a 120° bend, and the same radius, magnification, and dispersion, the $n = 0$ magnets have object and image distances that are only 74% of those of the $n = 0.5$ variety. In addition, with $n = 0$, the required gap height is less, since the vertical envelope begins to contract at the entrance edge, rather than well within the magnet.

Because of the fringing field, the magnet field may be considered to extend to the "effective edge," which lies beyond the iron edge by a small distance proportional to the gap height. The bending angle θ is measured from these effective edges, and in first-order theory, the equivalent thin lens formed by the edge angle u is considered to be located at the effective edge. Object and image distance and the separation between magnets are measured from the effective edges.

For equal entrance and exit edge angles u , chosen to have the value $\tan u = \rho/S_0$, where S_0 is the object distance, double focusing will occur for the particular object distance if

$$S_0 = 2\rho \cot \frac{\theta}{2}.$$

The radial and vertical magnifications will then be

$$M_x = M_z = -1,$$

so that the double-focused image distance, S_i , equals the object distance.* For each magnet, the resolution function, F (dispersion coefficient D per unit radius and per unit magnification), is

$$F = -\frac{D}{M_x \rho} = \frac{S_0}{\rho} \sin \theta + 2(1 - \cos \theta) = 4.$$

The expression relating energy resolution to F , ρ , and w_0 can be established, where w_0 is the full width of the input slit at the object plane of the first magnet and of the output slit at the image plane of the second magnet. It is to be noted that the image of the first magnet serves as an object for the second magnet, and an intermediate slit is not necessary.

*J. J. Livingood, A Review of Dispersive and Achromatic Passage of Charged Particles through One, Two, or Three Magnets, ANL-7114 (to be published).

In practice, such a slit is included to minimize radiation in the second magnet system. Now, let $p + \Delta p$ and $p - \Delta p$ be the momenta of the images that just fail to be transmitted through the last slit. Then the momentum resolution of the pair of magnets (provided they bend in opposite directions) is

$$R_p = \frac{\Delta p}{p} = \frac{w_0}{\rho_1 F_1 - \frac{\rho_2 F_2}{M_{x1}}}$$

Since the magnets are identical and $M_{x1} = -1$, this gives

$$R_p = \frac{\Delta p}{p} = \frac{w_0}{2\rho F}$$

The FWHM energy resolution of essentially nonrelativistic ions, transmitted through the pair of magnets is

$$R_E = \frac{\Delta E}{E} = 2 \frac{\Delta p}{p} = \frac{w_0}{\rho F} = \frac{w_0}{4\rho}$$

Chosen magnet parameters to establish a first-order energy resolution of 0.075% and satisfy the housing constraints are:

$$w_0 = 0.120 \text{ in.},$$

$$n = 0,$$

$$\theta = 120^\circ,$$

$$\rho = 40 \text{ in.},$$

$$S_0 = S_i = 2\rho \cot \theta/2 = 46.19 \text{ in.},$$

$$u = 40.9^\circ,$$

and

$$\tan u = \frac{\rho}{S_0} = 0.8660.$$

Construction of the magnets produced the constants listed below. Note that they differ from the chosen values for reasons that will be given later.

$$w_0 = 0.120 \text{ in.},$$

$$n = 0,$$

$$\theta = 120^\circ,$$

$$\rho = 39.86 \text{ in.},$$

$$S_0 = S_i = 47.39 \text{ in.},$$

and

$$u = 41.7^\circ.$$

The object and image distances are measured from the magnet's effective edges, which are at a distance (measured along the orbit) of 1.515 in. from the iron edge. Between magnets, the distance between effective edges is $S_1 = 2S_0 = 94.78$ in. or 97.81 in. from iron to iron. Figure 1 shows the layout of the system.

Assuming $w_0 = 0.120$ in., the calculated first-order resolution for the magnet pair is $R_E = 0.075\%$. Somewhat poorer performance is to be expected because of aberrations that are not included in first-order theory and induced errors resulting from tolerances in construction. As noted later, measurements show an actual resolution of about 0.08%.

III. ACHROMATIC DESIGN

For experiments where intensity is more important than resolution, it is desirable that the two 120° magnets be so used that the radial image formed by the pair should be nondispersed, i.e., achromatic. For a pair of identical magnets, bending in opposite directions, with $n = 0$ and vertical focusing supplied by equal entrance and exit edge angles u , it can be shown that a nondispersed radial image will be formed after the second magnet when the object and image distances are alike and have the value of each magnet's focal length,* that is,

$$S_0 = S_i = \frac{\rho(1 + \tan u \tan \theta)}{\tan \theta - 2 \tan u - \tan^2 u \tan \theta}.$$

For $\theta = 120^\circ$, $u = 41.7^\circ$, and $\rho = 39.86$ in., this gives

$$S_0 = S_i = 10.12 \text{ in.},$$

or a distance of 11.63 in. ($10.12 + 1.51$) from the iron edge of the magnet. The separation between magnets is irrelevant. A change from dispersive to achromatic mode of operation can be effected simply by changing the positions of the input and output slits.

*J. J. Livingood, ibid.

The vertical image distance of the first magnet is

$$S_{iz1} = \frac{S_0(1 - \theta \tan u) + \rho \theta}{\frac{S_0}{\rho}(2 \tan u - \theta \tan^2 u) + \theta \tan u - 1} = 83.30 \text{ in.}$$

Since the separation of the effective edges of the magnets has been established as $S_1 = 94.78$ in. for the radial dispersive mode, the vertical object distance for the second magnet is $S_0 = 94.78 - 83.3 \approx 11.5$ in. Then, by an equation analogous to the one just above, the second vertical image distance is $S_i = 81.6$ in. Hence, the achromatic system as described is not double focusing. (Double focusing could be achieved by changing the separation of the magnets, but this is impractical.)

IV. DIMENSIONS OF THE MAGNETS' APERTURES

To obtain maximum particle transfer through the analyzing system, the required radial and vertical apertures of the magnets must be established, based on the size and divergence of the beam as it leaves the object slit and on the momentum spread developed by the cyclotron.

To determine the vertical divergence, the beam was focused by a quadrupole doublet to a spot $2x_0$ wide and $2z_0$ high at the future location of the object slit for dispersive use of the magnets. A slotted diaphragm and an aluminum plate were placed at two positions further downstream; from an autoradiograph of the plate, the maximum vertical slope z'_0 at the object slit could be determined. A second run, with the diaphragm rotated 90° , gave the maximum radial slope, x'_0 . The results (at the "dispersive" object slit) are

$$\begin{aligned} z_0 &= \pm 0.060 \text{ in.} & x_0 &= \pm 0.060 \text{ in.} \\ z'_0 &= \pm 0.010 \text{ rad} & x'_0 &= \pm 0.006 \text{ rad.} \end{aligned}$$

As described earlier, a change in the positions of the object and image slits makes the magnets act nondispersively; i.e., the ions of all energies are focused to a single achromatic image. (This condition is used when intensity is more important than homogeneity of energy.) The calculated source half-widths and maximum divergences (at the "achromatic" object slit) are then

$$\begin{aligned} z_0 &= \pm 0.0827 \text{ in.} & x_0 &= \pm 0.0827 \text{ in.} \\ z'_0 &= \pm 0.0072 \text{ rad} & x'_0 &= \pm 0.0043 \text{ rad.} \end{aligned}$$

By the methods described in Appendix A, the height of the beam envelope was determined for both modes of operation at those locations

in each magnet where it can reach a peak (at the entrance and exit edges). The greatest value was 1.08 in. (at the exit from the first magnet when the system is used achromatically).

Similarly, the width of the beam envelopes was calculated at the entrance and exit points (to establish beam tube width external to the magnets). The largest value was 1.98 in., found at the entrance to the second magnet when the system is used dispersively. Hence, beam tubes with 2.0-in. ID would have been adequate, but 3-in. tubes were employed to improve pumping speed.

The maximum radial width of the beam, when inside these magnets, occurs close to their midpoints. These widths were found for each magnet, for both the dispersive and achromatic cases. The greatest is 3.23 in., in the second magnet under dispersive conditions. (In the first magnet, the maximum width is only 1.25 in., but it was more economical to purchase two identical magnets rather than one each of different minimal widths.)

The gap dimensions used are therefore 1.08 and 3.23 in. To allow for the wall thickness of the vacuum chambers, the iron-to-iron gap was specified as 1.75 in., and the radial width of uniform field was set at 4 in. To obtain this latter specification, the radial pole width was made 13.5 in. (as suggested by the manufacturer).

V. COMPONENT ARRANGEMENT

Figures 1-6 show the arrangement of the beam-transport and energy-analyzing system; Appendix B lists the assembly drawings.

This overall system serves several functions. First, the extracted projectiles enter the cyclotron's target box, which can be at tank vacuum, isolated and evacuated, or pressurized. This chamber serves as an isotope production station, and two target ports are provided. If the required irradiation requires sophistication in regard to energy measurements, particle uniformity, particle density, etc., the beam is then allowed to pass through into the beam-transport system. Greater beam concentration is accomplished by the squeeze coil, which is essentially a device that changes the "n" value of the cyclotron's fringing field and provides only radial focusing. [Such a device enables 50% of the total extracted beam to be focused onto a 1-cm-diam target at the downstream side of the switch magnet (SM-1).] Vacuum isolation is provided by a 4-in., automatically operated valve (BV). The beam then enters a $1\frac{7}{8}$ -in.-ID (2-in.-OD) tube, and additional focusing is accomplished by the quadrupole doublet (Q-1 and Q-2). Each quadrupole has a bore of 2 in. and a length of 8 in., the separation between quadrupole centers being 12 in. This doublet provides a focal length of 30 in. and an intense beam concentration, such as $500 \mu\text{A}/\text{cm}^2$, at the

121-861

Fig. 2. Overall View of Beam-transport and Analyzing System

Fig. 3. Cyclotron into Tunnel No. 1;
Elevation Drawing

121-858

Fig. 4. View of Switch Magnet SM-1 and Analyzing Magnet AM-A

ELEV. SWITCH MAGNET-1 TO ANALYZING MAGNET-A

ELEV. ANALYZING MAGNET-A TO ANALYZING MAGNET-B

ELEV. ANALYZING MAGNET-B TO SWITCH MAGNET-2

ELEV. SWITCH MAGNET-2 TO WALL

ELEV. TUNNEL-2

Fig. 5. Switch Magnet SM-2 into Tunnel No. 2;
Elevation Drawing

121-862

Fig. 6. View of Analyzing Magnets AM-A and AM-B, and Switch Magnet SM-2

stripping foil port. Vertical and horizontal beam positioning is provided by the steering coil (SC-1).^{*} The downstream direction of the beam is governed by a 12-in.-diam circular switch magnet (SM-1). It can deflect the beam not at all, to the right (15 and 25°) for irradiations in the cyclotron vault or in experimental tunnel No. 1, or to the left (15 and 30°) so that the particles enter the new energy analyzing system for use in experimental tunnel No. 2. This latter arrangement is discussed below.

The quadrupole doublet (Q-1 and Q-2), steering coil (SC-1), and switch magnet (SM-1) are necessary to the operation of the analyzing system. About 15% of the extracted beam, without squeeze coil, is accepted by this doublet and focused onto either the dispersive (DS-1) or achromatic slit (AS-1). The steering coil (SC-1) serves as a supplementary means of directing the beam into the correct vertical and horizontal position for entrance into the first analyzing magnet. The dispersive and achromatic slits are approximately 48.9 and 11.1 in. upstream, respectively, from the

^{*}R. Benaroya and W. J. Ramler, Deflection Coil for an External Accelerator Beam, Nucl. Instruments & Methods 10, 113-120 (1961).

iron edge of this magnet. An arrangement of metal bellows has been included on both the up- and downstream side of the dispersive slit to facilitate axial movements of about $\pm 1\frac{3}{4}$ in. for maximizing the analyzing system. The analyzing magnet (AM-A) accepts the ions (inside chamber width = 4 in.; inside height = 1.438 in.), bends them 120° , and (in the dispersive mode) focuses them to an image midway between the two magnets. (A $2\frac{7}{8}$ -in.-ID tube is used in the region between magnets.) An intermediate slit located at this spot serves as both a catcher of unwanted particles and a beam-position monitor. This image then serves as an object for the second magnet in which the particles are again bent 120° but in the opposite direction. A second image then occurs at either the dispersive or achromatic slits, depending upon the mode of operation. A quadrupole doublet (Q-3 and Q-4) contains the beam for the focusing by the downstream doublets. After the achromatic slit (AS-2), the beam tube is again $1\frac{7}{8}$ -in. ID, and this size is maintained throughout the rest of the system.

The direction of the beam into tunnel No. 2 is governed by the second switch magnet (SM-2), which has a 12-in.-diam circular pole. A total deflection of 40° is provided. The beam passes through the 7-ft concrete shielding wall by means of an evacuated tube ($1\frac{7}{8}$ -in. ID), which in turn is mounted in a 6-in.-ID water-filled tube (FT). The ends of the beam tube are supported by movable end plates (Fig. 7), which permits vertical and

121-1211

Fig. 7. Beam Feedthru Supports. Adjustable wall mounts for beam tubes through 7-ft concrete wall; one required for each side of wall.

horizontal adjustments for alignment. When work must be done in the experimental tunnel with the cyclotron operating, internal shielding plugs (RP) are remotely controlled and inserted into the wall beam tube without interrupting the vacuum. These plugs consist of water-filled bellows, which can be withdrawn into a Y branch of the beam tube for beam passage.

Four beam lines have been provided--0, 10, 25, and 40°. The 25 and 40° lines are routinely used; the 10° line is reserved for the "short-term" type experimenter; the 0° part is provided for alignment purposes as well as beam-energy checks using the foil degrader.* When the 40° port is used, the switch magnet provides sufficient vertical and radial focusing so that quadrupoles are not required in the region between the switch and the vault wall. In this line, a steering coil (SC-2) provides radial and vertical adjustments in the beam's position. The 10 and 25° ports both require a steering coil and a quadrupole doublet between the switch and the wall.

In the tunnel, two additional quadrupole doublets are used in each beam line (Fig. 8). The upstream doublet (Q-7 and Q-8) maintains a somewhat parallel beam until the final doublet (Q-9 and Q-10) focuses the beam

121-1209

Fig. 8. Tunnel No. 2 Quadrupoles

* W. J. Ramler, J. L. Yntema, and M. C. Oselka, Energy Degrading-Focusing of Cyclotron Beam, Nucl. Instruments and Methods 8, 217-220 (1960).

into a 3- to 4-mm spot. Beam envelope locators (BEL) facilitate the initial tuning of the accelerator and the transport system, and assist in monitoring the position of the beam throughout the irradiation.

Controls for all components are centrally located in the control room of the cyclotron, thereby enabling the operators to adjust and maximize the operation of the overall system. Closed-circuit television is used to view beam patterns at the slits or at target positions. When possible, optical viewing is preferred, and the image is projected into the control room by an arrangement of mirrors and water ports in the shielding wall.

VI. DESCRIPTION

Appendix B lists the assembly drawings of the ancillary components. The discussion that follows describes the vacuum seals, dispersive, achromatic, and monitoring slits, analyzing magnets and vacuum chambers, supports for the analyzing magnets, characteristics of all magnets, and the beam radiation plugs for the shielding walls. In general, the remainder of the component information is either in published form or in the drawings as referenced in Appendix B. The design and arrangement of the vacuum pumping is discussed in a following section.

A. Vacuum Seals

Two classes of vacuum seals are employed throughout the transport and analyzing complex. In areas subjected to intense neutron and gamma flux, nonorganic seals are used to minimize degradation effects, thus decreasing the frequency of repairs and the residual radiation exposure to operating personnel. Figure 9 sets forth the basic details of an all-metal seal (LEAF), which is a sexless flanged joint employing Series 1100 aluminum-foil gaskets (about 0.002 in. thick).

Figure 10 shows the second type of nonorganic seal, which provides the additional feature of electrical insulation. Such an arrangement has proved to be quite simple and inexpensive as compared to ceramic designs. To obtain reliability in sealing, the indium gasket must be preformed as shown.

All other seals are an organic type and can be readily demounted. Ladish Tri-Clover couplers* (2 and 3 in.), Hycar (Viton now available) rings, and quick-disconnect clamps* are used to make an assembly (Fig. 11).

*Ladish Company, Tri-Clover Division, Kenosha, Wisconsin.

121-1280

Fig. 9. All-metal Vacuum Seal (LEAF)

121-1279

Fig. 10. Nonorganic, Electrically Insulating Vacuum Seal

121-1278

Fig. 11. Organic Vacuum Seal. Typical quick-disconnect seals with Ladish Co. components

B. Dispersive Slits (DS--Two Required)

Each dispersive-slit assembly contains two horizontal and two vertical water-cooled, 5/16-in.-thick jaws, their front sides separated by a distance of about 7/16 in. Horizontal (w_0) and vertical (w_z) slit dimensions are established by these jaws, and the slit is symmetrically positioned on the central axis of the assembly.

Since the radial width of the slit is critical in establishing the energy resolution of the analyzers, the precision of setting of the radial-drive mechanism throughout the range from fully closed to maximum 0.350 in., is ± 0.0005 in. This precision is accomplished by departing from the lead-screw or rack-and-pinion techniques and using spiroid gears with precision bearings and cams. Both jaws are coupled together to maintain symmetry about the centerline. Beyond 0.350 in., a quick-operating mechanism permits the jaws to move to a width of 2 in. without any precision in the dimension of the opening.

Since the vertical height (w_z) of a slit is not as critical as the radial width, the vertical-drive mechanism is simple. A screw-type drive provides reliability to about ± 0.005 in. At present, both the radial and vertical drives are manually operated.

All four jaws are electrically isolated from each other with the type of vacuum seal shown in Fig. 10. Slits are water-cooled (1.5 gpm at 55 psi for each pair) and are constructed of copper with a gold plating of 0.020 in.

Jaw edges are rectangular, and, because of the filtering action of the magnets, specific shaping to minimize slit scatter of these edges was not undertaken.

The slit housing and numerous components are constructed of Type 310 stainless steel. A viewing port in each of the two assemblies permits the slits to be inspected without interrupting the vacuum. The port is sufficiently large so that when the window is removed, one can mount degrading or target foils on the jaws, or quartz for beam diagnostic studies.

Overall dimensions of dispersive-slit assembly are 13 in. along the beam path and about 22 in. for both the radial and vertical directions, including the drive mechanisms. Its weight is about 75 lb and an adjustable floor pedestal is used for its support. Argonne Dwg. No. 211-CY-M-1247-E sets forth the mechanical details, and Fig. 12 is a photograph of the DS-2 assembly in position on the beam line. (The dispersive slit is to the left.)

121-1217

Fig. 12. View of Dispersive (DS-2) and Achromatic (AS-2) Slit Assemblies

C. Achromatic Slits (AS--Two Required)

The achromatic slits require less sophistication than the dispersive slits. Four jaws are provided, and the precision of setting slit width and

height is ± 0.005 in. Each jaw is independently adjustable, manually operated, and electrically insulated. The design is identical to that of the dispersive horizontal slits. A slit range from fully closed to a 1-in. opening is provided.

Both jaws are of copper (without gold plating) and are series water-cooled. A common water header is used, and for a pressure of 55 psi, a flowrate of 1.5 gpm is established.

Each assembly (60 lb) is mounted directly on an analyzing magnet (AS-1 on AM-A), and alignment is achieved by shifting the mounting bracket (see Fig. 5). Since the assembly is located in a fringing field, all components are constructed of nonmagnetic materials, Type 310 stainless steel being used for the housing.

Along the beam path, the housing dimension (including viewing window) is 13 in. for AS-1 and 6.5 in. for AS-2. With drive mechanisms, the overall radial and vertical dimensions are each 19.5 in. Figure 12 is a photograph of the unit in position (achromatic slit to the right), and Dwg. No. 211-CY-M-1306-E sets forth the details of the assembly.

D. Intermediate Slit (IS--One Required)

An intermediate slit, located at the image-object plane at the midpoint between the two magnets, provides a variable radial-slit width ranging from 0 to $1\frac{1}{2}$ in. with a dimensional tolerance of 0.010 in. The intermediate slit determines the radial alignment of the beam and acts as a scraper of unwanted particles, thereby minimizing the radiation effects on the downstream side of the system.

A commercial-type 3-in.-OD Type 304 stainless-steel cross is used as the housing for the two independently controlled, motor-driven jaws. Each jaw is electrically insulated, water-cooled, and mounted on a circular tube, which has a sliding O-ring seal with the tee housing; it is shown on the beam tube on the left side of Fig. 4. Drawing No. 211-CY-M-1737-D sets forth the mechanical details. The overall dimension along the beam path is 6 in., and about 24 in. is required in the radial direction.

E. Beam Envelope Locaters (BEL--Six Required)

The design of the beam envelope locater is similar to that of the intermediate slit. However, four water-cooled jaws determine the alignment of the beam envelope and its spatial distribution. The displacement of both sets of jaws is such that their front surfaces are $9/16$ in. apart. Figure 13 is a photograph of the assembly, and Dwg. No. 211-CY-M-1801-D shows the details. The overall dimensions are 5 in. along the beam path and about 16 in. for both the radial and vertical directions.

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Fig. 13. Beam Envelope Locator Assembly

F. Current Monitoring of Slits

Since all slit jaws are electrically insulated, provision is made for individual current readout in the Control Room. Two Cary Model 30 electrometers with recording outputs serve as the monitors for any two slit jaws. At present, selection is accomplished by a switching matrix. In the near future, an oscilloscope presentation will show the magnitude of the intercepted current on each jaw of a slit assembly, thereby providing a more feasible means of determining the effect of changing tuning parameters.

G. Chamber for Analyzing Magnet (AMC--Two Required)

The vacuum chamber for each analyzing magnet was constructed of Type 310 stainless steel. Construction materials of low permeability are necessary to preserve the quality of the magnetic field, and either Inconel X, K-Monel or some of the stainless-steel alloys would suffice. For this case,

the Type 310 alloy was chosen, because it has a permeability of about 1.003 and will remain unchanged in cold-working, whereas the permeability of the Type 304 can increase to a value as great as 7.

Each chamber has a mean radius of 40 in., a maximum outside height of 1.688 in., and a minimum inside dimension of 1.438 in. The top and bottom plates each have a thickness of $1/8$ in. The inside radial width is 4 in. The mean radius was based upon original calculations and is a negligible deviation from the magnet curvature of 39.86 in.

Water cooling is used only on the vertical walls. Wall construction was accomplished by milling three grooves, $7/32$ in. deep along the length of a $5/16$ -in.-thick, prefinished flat bar. Grooves were capped by welding a $3/32$ -in.-thick cover plate to the bar. The resulting center channel, $9/16$ in. wide, is used for the infeed of the coolant, and the two outside grooves, each $5/16$ in. wide, are used as a return path. This member was then formed to the proper wall shape by rolling, and all closure welds were located on the external side. Top and bottom plates were welded to the walls with full-penetration welds.

Figure 14 provides a plan view and cross section of a chamber. At the upstream end, an observation window (2.7-g/cm^3 density, nonbrowning glass) was placed so that a sliding screen could be positioned within the chamber for observing the size and shape of the beam envelope. Because of physical constraints, the envelope can only be azimuthally viewed to about $\theta = 60^\circ$ (position of the radial "bust").

End flanges for both chambers were designed for metal seals (Sect. B-B). Since these regions are difficult to service, gold O rings were chosen to provide greater reliability.

Each chamber is shimmed into the magnet gap and is held in position by having both ends fastened to an aluminum table (Fig. 2). After the chamber and table are aligned, the table is bolted directly to the floor.

H. Parameters of Constructed Analyzing Magnets (AM--Two Required)

The analyzing magnets, constructed commercially, were supplied by Spectromagnetic Industries. In the process of their design, two changes were incorporated to improve performance.

- (1) The edge angles u were increased from a calculated $u = 40.7^\circ$ to $u = 41.7^\circ$, to allow for the fact that the beam trajectory is slightly bent in the fringing field before it reaches the idealized thin lens that supplies the vertical focusing. This new value was determined by analyzing field plots from somewhat similar magnets already manufactured by Spectromagnetic Industries.

Fig. 14. Chamber for Analyzing Magnet

(2) The end faces of the magnets were bowed outward, each with radius R , to eliminate the image widening caused by a finite radial divergence of the beam at the object. The required radius can be computed from an expression given by Hintenberger,* which, for the symmetric case under consideration, is

$$\frac{1}{R} = \frac{\rho}{S_0^2} \left(\frac{\rho}{S_0} + 3 \tan u \right) \cos^3 u.$$

With the parameters of the constructed magnets, this gives $R = 38.5$ in. as the required effective radius. Application of the more detailed second-order theory of Brown, Belbeoch, and Bounin** shows that the aberration disappears if $R = 38.75$ in. The exact value is far from critical, however, and the magnets, as delivered, have an effective radius of $R = 36.4$ in. Spectromagnetics chose this value to minimize cost of machining.

Final optic parameters of each magnet are

$$n = 0,$$

$$\theta = 120^\circ \text{ effective,}$$

$$\rho = 39.86 \text{ in.,}$$

$$u = 41.7^\circ,$$

$$S_0 = S_i = 47.39 \text{ in.,}$$

and

$$R_1 = R_2 = 36.4 \text{ in.}$$

As now operated, the existing cyclotron requires two field values, 280 kG-in. (${}^3\text{He}^{2+}$) and 380 kG-in. (${}^2\text{D}^+$). The maximum value of 480 kG-in. for the analyzing magnets was established to match the possible future conversion of the cyclotron to an AVF-type accelerator.

It is to be noted that the lengths S_0 and S_i are measured to the effective edges of the magnet. The effective edge (along the beam trajectory) for 9.24 kG is 1.515 in. beyond the iron; this value reduces to 1.512 in. for 7.25 kG. Thus, the physical separation of the magnets was set at $2(47.39 + 1.515) = 97.81$.

As built, the poles are 13.5 in. wide and have a homogenizing gap behind them. Over the specified radial width of 4 in., field homogeneity was

*H. Hintenberger, Improved Magnetic Focusing of Charged Particles, RSI 20, 748-750 (1949).

**K. L. Brown, R. Belbeoch, and P. Bounin, First and Second Order Magnetic Optics Matrix Equations for the Midplane of Uniform Field Wedge Magnets, RSI 35, 481-485 (1964).

established for both 7.15 and 9.2 kG (${}^3\text{He}^{2+}$ and ${}^2\text{D}^+$ operation). NMR measurements at 57 points, distributed on a grid 6 in. wide straddling the central path and extending to within 3 in. of the ends, show a maximum field deviation of one part in 1000, for the field levels of 7.15 and 9.2 kG.

A typical B-H curve is shown in Fig. 15. Hysteresis effects do exist, and if the coil current is raised to a maximum value of 525 A and then returned to the ${}^4\text{He}^{2+}$ operating value, the resulting field will be about 70 G higher than required. This is sufficient to shift the beam about 0.47 in. at the position of the intermediate slit.

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Fig. 15. B-H Curve for Analyzing Magnet

apart. A mounting pad of unique design is placed between the head of each jack and the base of the magnet. Figure 16 shows the design features. Such an arrangement maintains the load on the central axis of the jack screw, thus minimizing side slippage when the magnet is being levelled. Figures 5, 16, 17, and 18 show the overall support structure for the analyzing magnets (AM-A and AM-B) and the switch magnet (SM-2).

Positioning of these magnets was quite simple. Initially, the optic-beam axis was scribed on the top side of each magnet, and the external beam lines were layed out on the vault floor. In turn, each magnet was moved to a position that approximated the required location and then elevated (jacked) and levelled. Exact positioning was achieved by using the overhead crane to partially lift the magnet off its jacks and sliding it until the required position was achieved; final elevation was achieved by trimming the jacks. Such mounts have proved to be quite satisfactory and inexpensive.

Each magnet power supply (60 kW at 545 A and 110 V) has a 1×10^{-4} short-term and a 3×10^{-5} long-term stability for the field range from 6 to 12 kG. These stabilities apply for the following conditions: 10% line-voltage variation; 10% load change; and an ambient or cooling-water temperature change of 5°F . In addition, the sum of ripple and noise currents is less than 1×10^{-4} . Each supply is controlled at a station approximately 150 ft distant.

I. Support Structure for Analyzing Magnet (Two Required)

Support is provided by structural I beams, which in turn are mounted on three screw jacks 120°

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Fig. 16. Schematic Diagram of Pad and Jack for Magnets

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Fig. 17. View of Analyzing-magnet Support

Fig. 18

View of Support Structures

121-1218

VII. SUMMARY OF MAGNET CHARACTERISTICS AND TRANSFER OF POWER SUPPLIES

The general characteristics of all beam-transport, analyzing-system magnets are tabulated in Table I.

TABLE I. Characteristics of Beam-transport and Analyzing-system Magnet

	Analyzing Magnets, AM-A and AM-B	Switching Magnet, SM-1	Switching Magnet, SM-2	4-in.-long Quadrupole Sets	8-in.-long Quadrupole Sets	Steering Coils, SC
No. Required	2	1	1	5	2	3
Type	Double focus 120° sector Edge angle 41.7° C-type yoke	H frame Circular pole	H frame Circular pole	Hyperbolic Pole tip	Hyperbolic Pole tip	Special*
Manufacturer	Spectromagnetic Industries, Inc.	Pacific Electric Co.	Pacific Electric Co.	ANL	ANL	ANL
Weight, lb	25,000 (17,000 lb ASA-1010 Steel)	4,350	7,270	225	420	53
Pole Dimensions	13.5 in. wide, 39.86-in. radius, 120° bending angle	12-in. diam	12-in. diam	4 in.	8 in.	9 in.
Pole Gap	1.758 in.	1-3/4 in.	2-1/2 in.	2-in. bore	2-in. bore	2-in. bore
Dimension of Effective Field	Radial width = 4 in. (where $n = 0$)	14.22-in. (11.6 kG) diam	15.75-in. (17.3 kG) diam	4.9 in. length	9.2-in. length	11.2-in. length
Total 20°C Resistance of Coils, ohms	0.177 (2 coils)	1.060 (2 coils)	0.352 (2 coils)	36.5 (4 coils, series connected)	68 (4 coils, series connected)	74
Max Field or Gradient	AM-A: 12.99 kG AM-B: 12.53 kG	13.17 kG	19.4 kG	4650 G/in.	4700 G/in.	570 G
Max Current, A	545	2.0	425	4.0	3.7	2.3
Max Voltage, V	110	2500	150	150	250	170
Max Power, kW	60	5.0	50	0.58	1.088	0.2
Cooling Req'd.	8 gpm @ 55 psi	2 gpm @ 55 psi	7 gpm @ 55 psi	None	None	1 gpm @ 55 psi
Symbol Designation	AM-A AM-B	SM-1	SM-2	Q-5-6, 7-8, 9-10, 11-12, 13-14 17-18, 19-20	Q-1-2, 3-4, 15-16	SC-1, -2, -3, and -4
Associated Power Supplies	Solid State 2-545 A 1-110 V DC 0.005% reg.	Electronic ±0-2500 V DC 0.01% reg.	MG set with solid- state field reg. ±0-545 A ±0-115 V 0.01% reg.	Amplidyne with elec- tronic field reg. ±0-4 A ±0-250 V 0.1% reg.	Amplidyne with elec- tronic field reg. ±0-4 A ±0-250 V 0.1% reg.	Amplidyne with elec- tronic field reg. ±0-2 A ±0-250 V 0.1% reg.

*Nonuniformity does not exceed 1×10^{-3} for the field range from 6.27 to 12.04 kG or 250 to 480 kG-in.

See R. Benaroya and W. J. Ramler, Deflection Coil for an External Accelerator Beam, Nucl. Instruments & Methods **10**, 113-120 (1961).

To minimize the total number of quadrupole and steering coil power supplies, operating requirements for each beam line were established and programmed into a control system. Power supplies are expediently transferred by using a Ledex Model No. 250-377-246 stepping switch. One power supply (eight total) is connected to each switch (eight total), which in turn is connected to several loads (ten max). All controls are interlocked to prevent the interruption of an energized circuit. A map of the entire system is located at the instrumentation and indicates the activated elements along the beam path.

VIII. VACUUM

An initial analysis indicated that high-speed series pumping could not be achieved because of the low value of conductance (1.7 liters/sec) between the input and output ends of the overall analyzer. Sectionalizing the system produced parallel pumping paths connected to one common manifold and one centrally located pump. Effective conductance was then increased to 30 liters/sec, which more closely matched the speed of the small turbomolecular pump of Welch (No. 3101A).

The pumping speed characteristic of the turbo pump (140 liters/sec, blanked off) is essentially flat from 10^{-4} to 10^{-7} Torr for air, helium, or nitrogen. Backstreaming of contaminants is negligible, thus eliminating the need for cryogenic traps or baffles. From test experience, this unit functions well mechanically and requires very little maintenance.

Roughing is accomplished by a Kinney Model KDH-80 mechanical pump, which pumps through a bakeable Zeolite (Linde 13X) oil trap to a separate manifold, which in turn is valved and connected to each individual pumping line.

Figure 19 is a schematic diagram of the vacuum system. (Conductance calculations are given by Aron.*) As shown, the facility is divided into six sections. The first section encompasses the target box of the cyclotron. The other sections provide the isolation required to facilitate the setup of irradiations and to minimize the downtime for maintenance and repair. By the proper setting of the beam-line valves (BV), and the related pumping-line valves (HV and RV), a section can be isolated, let up to atmosphere so that changes or repairs can be made, and then pumped to its operating pressure without disturbing the rest of the system. With the exception of the manual-type valves at each pump, all other valves are electro-pneumatically operated. Figure 19 lists the sizes and model numbers of all valves.

*J. Aron, Conductance Calculations -- Cyclotron Beam Transport-Analyzing System, Building 211 Design Note (1966).

Fig. 19. Vacuum System Schematic Diagram

Residual-gas load effects are minimized by the use of aluminum and stainless steel. Aluminum (6061) tubing is used from the pumps at the service floor up to the floor of the cyclotron vault. To minimize the effect of iron contaminants in the aluminum (region of magnetic field) and because of reasons of fabrication, the rest of the system is constructed of nonmagnetic type (304 and 310) stainless steels.

With an effective pumping speed of 15 liters/sec, the time for the rough pump-down of the entire complex from atmosphere to 10^{-2} Torr is about 5 min, and an additional 6 to 10 min is required by the turbo pump to reach 5×10^{-6} Torr. This is a typical operating level and does not affect the operation of the cyclotron. Precise tests have not been conducted in regard to the deposition of foreign material on target foils, but at this writing, we have experienced no such difficulty.

All vacuum systems require protection and instrumentation, and this facility is no exception. All valves are interlocked to prevent simultaneous rough and high-vacuum pumping. Thermocouple protective circuits (TCP) and readout (TC) are used in each section (Fig. 17) to sense unscheduled pressure increases and to close related valves, thereby protecting the rest of the system and the cyclotron from a vacuum failure. In addition, these units will not permit the inadvertent opening of a valve between a high- and a low-vacuum section.

Both the TCP and the TC use a thermocouple gauge (GE Model No. 865186065) as a sensor. The TC gauge is coupled by a selector device to a matched meter movement for vacuum readout at either the local station or the control room. The TCP sensor is the start of a control chain (always connected); its output is directed into an optical meter relay (Assembly Products Instruments, Inc., Model 503), which provides one protection link in the overall control of the vacuum facility.

The high vacuum (10^{-3} to 10^{-7} Torr) is monitored by a Penning type ion gauge (Televac Model 7-A), its control and readout being accomplished in the control room.

A master control map of the vacuum system, located in the cyclotron control room, has lights indicating the status of all functions and includes controls for monitoring of vacuum at all stations, as well as controls for the valves and pumps. Smaller control maps in the cyclotron vault and experimental tunnels indicate operating conditions and provide controls for the "local" sections of the beam-transport system.

IX. OPERATION

When the system is operating in the dispersive mode, resolved beams of ${}^2\text{D}^+$, ${}^3\text{He}^{2+}$, and ${}^4\text{He}^{2+}$ have been obtained in Experimental Tunnel No. 2 with a FWHM energy resolution of about 0.08%. For scattering-type experiments that require this resolution along with precise beam collimation, associated currents have been greater than $0.3 \mu\text{A}$. For the achromatic mode, the overall system can transport 10% of the total extracted cyclotron beam into Tunnel No. 2 with about 1% ($1 \mu\text{A}$) being available in the scattering chambers.

A. Setup

From Fig. 1, it is seen that the beam must traverse several magnets, slits and collimators, vacuum valves, and the vault wall before reaching the selected experimental station in Tunnel No. 2. Prior to the initiation of an irradiation, each magnetic field (quadrupole, steering, and analyzing) is set to a predetermined level by a precision measurement of the magnets' excitation current. A digital voltmeter and a current shunt are used for this determination. For the analyzing magnets, a secondary check of the field is made with a permanently mounted Rawson-Lush Model 824 rotating gaussmeter. Each gaussmeter is located in the region of $\theta = 60^\circ$ and is placed about 3 in. away from the azimuthal centerline of the pole tips, where the field has the same strength as at the orbits.

Typical settings for each of the analyzing magnets are:

<u>Projectile</u>	<u>Energy, MeV/nucleon</u>	<u>Magnetic Field, kG</u>	<u>Bρ, kG-in.</u>
${}^4\text{He}^{2+}$ & ${}^2\text{D}^+$	~ 11.1	9.45	377.10
${}^3\text{He}^2$	~ 11.4	7.13	284.20

All other magnet settings are governed by the choice of machine parameters and the required beam characteristics requested by the experimenter.

For the dispersive operating mode, the usual widths of the input and output slits are 0.120 in., which corresponds to a measured FWHM energy resolution of 0.08%;* vertical full-slit height will range from 0.120 to 0.240 in., the latter being the dimension normally used.

If beam intensity rather than resolution is the prime requirement, then the analyzing magnets are operated in the achromatic mode with the radial and vertical slit dimensions being 1 in. to accept the full beam.

*David Borlin, internal ANL memorandum (Dec. 1, 1965).

All other slits, such as the intermediate slit and the beam envelope locator, are used to assist in establishing proper beam alignment and to monitor beam stability throughout an irradiation.

B. Tuning

After the accelerator has been tuned to produce the desired extracted beam characteristics, the target-box shutter is opened, allowing the beam to enter the transport system. The first quadrupole doublet focuses about 10 to 15% of the total extracted beam (TEB) through the steering and switch magnet (30° port) into an approximate spot size of 0.120-in. diameter at either the dispersive or achromatic slits. The image formed at either slit becomes the object for the first analyzing magnet. Now, we shall consider the dispersive mode of operation. When aligned, approximately 5 to 8% of the TEB enters and traverses the first stage of magnetic analysis. The upstream steering coil is adjusted while the current on the jaws of the input and midpoint slits are monitored for the appropriate equality of particle distribution, both radially and vertically. For an initial setup with the energy then existent, the analyzing fields are adjusted for maximum beam.

From time to time, an experimenter will require the duplicating of a prior projectile energy. The analyzer fields are then preset, and the parameters of the accelerator are varied to match the analyzers.

When the system is aligned, no losses occur in the traversal of the path between the input and output dispersive slits. Five to 8% of the TEB reaches the output slit; about one-fifth of this will pass through and be available at the entrance to the experimental station. If a collimator 34 in. long, with a succession of defining apertures of 0.120-in. ID is connected to a station, the transmitted beam will be reduced to about 0.3 to 0.5% of the TEB. For example, if the total extracted beam is 100 μA , about 0.3 to 0.5 μA ($\Delta E/E = 0.08\%$) will be transmitted through the collimator.

APPENDIX A

Calculation of Width and Height of Beam Envelope

In first-order theory, the radial deviation of the path from the central ray after passing through the j th "optic element" (a drift space, a magnet's edge, a magnet's body, etc.) may be written as

$$x_j = a_j x_0 + b_j x'_0 + c_j \frac{\Delta p}{p},$$

and the radial slope as

$$x'_j = d_j x_0 + e_j x'_0 + f_j \frac{\Delta p}{p}.$$

Here x_0 is the half-width of the object, and x'_0 is the maximum slope of an ion as it leaves the object; p is the standard momentum, while Δp is either the half-spread from the accelerator or the half-spread of the analyzed beam, whichever is appropriate. The coefficients $a_j, b_j, \dots, f_j$ are obtained by multiplying together, in proper order, the matrices that describe a drift space, an edge, and the body of a magnet. They are functions of the bending angle and radius (θ and ρ), the field index (n), the object distance (S_0), the magnets' separation (S_1), a distance (S_2) past the second magnet, and the common angle u of all four edges. (All distances are measured from the effective edges.) Later in this appendix the relevant expressions for these coefficients will be quoted without proof.

The radial phase-space ellipse (where x' is plotted against x) is given by

$$\alpha_j x_j^2 + 2\beta_j x_j x'_j + \gamma_j x_j'^2 = 1.$$

Under the reasonable approximation that the object's ellipse is "upright," the coefficients α_j, β_j , and γ_j are related to $a_j, b_j, \dots, f_j$ by the relations given below.

Let

$$N_1 \equiv \left(\frac{x_0}{\rho x'_0} \right)^2,$$

this being determined from measured values of the source parameters x_0 and x'_0 . Also define the following:

$$N_{\alpha j} \equiv e_j^2 + (d_j \rho)^2 N_1;$$

$$N_{\beta j} \equiv e_j \frac{b_j}{\rho} + a_j (d\rho) N_1;$$

and

$$N_{\gamma j} \equiv \left(\frac{b_j}{\rho} \right)^2 + a_j^2 N_1.$$

Then it can be shown that

$$\alpha_j = N_{\alpha j} \frac{1}{x_0^2},$$

$$\beta_j = -N_{\beta j} \frac{\rho}{x_0^2},$$

and

$$\gamma_j = N_{\gamma j} \frac{\rho^2}{x_0^2},$$

where the N 's are computed as numerics, while the expressions $1/x_0^2$, ρ/x_0^2 and ρ^2/x_0^2 are left in algebraic form. Then the half-width of the envelope at the j th station is given by

$$\begin{aligned} x_{j\max} &= (\gamma_j)^{\frac{1}{2}} x_0 x'_0 + c_j \frac{\Delta p}{p} \\ &= (N_{\gamma j})^{\frac{1}{2}} (\rho x'_0) + c_j \frac{\Delta p}{p}, \end{aligned}$$

in which the numerical value of $\rho x'_0$ is a constant. The first term in $x_{j\max}$ is the contribution arising from ions with momentum p ; the second term represents the contribution of those with $p + \Delta p$, where Δp is the half-spread in momentum in the cyclotron's beam, previously estimated from scattering experiments.

1. Radial Envelopes for Dispersive Case

a. Basic Data

$$n = 0 \quad \theta = 120^\circ = 2.0944 \text{ rad} \quad \rho = 39.86 \text{ in.}$$

$$\text{Edge angles} \quad u = 41.7^\circ \quad \tan u = 0.8910$$

$$\text{Object distance} \quad S_0 = 47.39 \text{ in.} \quad S_0/\rho = 1.1889$$

$$\text{Image distance} \quad S_i = S_0 \quad S_i/\rho = 1.1889$$

$$\text{Magnets' separation} \quad S_1 = 2S_0 \quad S_1/\rho = 2.3778$$

(These distances are measured from the effective edges 1.51 in. outside the iron along the flight path.)

From experimental observation,

$$x_0 = 0.060 \text{ in.}, \quad x'_0 = 0.006 \text{ rad.}$$

Hence,

$$\rho x'_0 = 0.2392 \text{ in.}$$

and

$$N_1 = \left(\frac{x_0}{\rho x'_0} \right)^2 = 0.0629.$$

Measurements with solid-state detectors have shown that the spread in energy in the cyclotron's beam is about ± 100 keV for 21.6-MeV deuterons.

Hence,

$$\frac{\Delta p}{p} = \frac{\Delta E}{2E} = \frac{10^5}{2 \times 21.6 \times 10^6} \approx \frac{1}{400};$$

and

$$\rho \frac{\Delta p}{p} = \frac{39.86}{400} \approx 0.1.$$

b. Radial Width at Entrance to First Magnet

$$a_2 = 1,$$

$$\frac{b_2}{\rho} = \frac{S_0}{\rho} = 1.1889;$$

$$c_2 = 0;$$

$$N_{\gamma_2} = \left(\frac{b_2}{\rho} \right)^2 + a_2^2 N_1 = 1.4764;$$

$$x_{2\max} = (N_{\gamma_2})^{\frac{1}{2}} (\rho x'_0) + c_2 \frac{\Delta p}{p} = 0.2906 + 0;$$

and

$$\text{Full width} = 0.58 \text{ in.}$$

c. Radial Width at Bust Inside First Magnet

Algebraic substitutions for the expressions for a_3 , b_3 , d_3 , and e_3 (not quoted here) yield the following equations:

$$N_{\alpha 3} = 1 + 2 \frac{S_0}{\rho} \tan u + \left[\left(\frac{S_0}{\rho} \right)^2 + N_1 \right] \tan^2 u = 4.2907;$$

$$N_{\beta 3} = \frac{S_0}{\rho} + \left[\left(\frac{S_0}{\rho} \right)^2 + N_1 \right] \tan u = 2.5044;$$

and

$$N_{\gamma 3} = \left(\frac{S_0}{\rho} \right)^2 + N_1 = 1.4764.$$

For these symmetrical magnets, the bust occurs very close to the midpoint. Hence, the angular position of the bust is

$$\theta' = \frac{\theta}{2} = 60^\circ, \quad \sin \theta' = 0.8660, \quad \cos \theta' = 0.5000.$$

It can be shown that for the bust we have

$$N'_{\gamma 4} = N_{\alpha 3} \sin^2 \theta' + 2N_{\beta 3} \sin \theta' \cos \theta' + N_{\gamma 3} \cos^2 \theta' = 5.7559;$$

also,

$$\frac{c'_4}{\rho} = 1 - \cos \theta' = 0.5;$$

$$x_{\text{bust}} = (N'_{\gamma 4})^{\frac{1}{2}} (\rho x'_0) + c'_4 \frac{\Delta p}{p} = 0.5734 + 0.0500 = 0.6234;$$

and

$$\text{Full width} = 1.25 \text{ in.}$$

Considerable effort can be saved in computing beam widths at later stations by calculating certain far-downstream coefficients that will degenerate to earlier stations when the distances are given appropriate values. Figure 20, where station numbers are encircled, will make this clear.

Fig. 20. Identification of Station Numbers and Distances

The coefficients for Station 7 are

$$a_7 = (\cos \theta + \tan u \sin \theta) - \frac{S_1}{\rho} (\sin \theta - 2 \tan u \cos \theta - \tan^2 u \sin \theta) \quad (A)$$

$$\begin{aligned} \frac{b_7}{\rho} = & \sin \theta + \left(\frac{S_0}{\rho} + \frac{S_1}{\rho} \right) (\cos \theta + \tan u \sin \theta) \\ & - \frac{S_0 S_1}{\rho^2} (\sin \theta - 2 \tan u \cos \theta - \tan^2 u \sin \theta) \end{aligned} \quad (B)$$

$$\frac{c_7}{\rho} = 1 - \cos \theta + \frac{S_1}{\rho} [\tan u (1 - \cos \theta) + \sin \theta] \quad (C)$$

d. Radial Width at Exit from First Magnet

In Eqs. (A), (B), and (C), set $S_0/\rho = 1.1889$ and $S_1/\rho = 0$, so that a_7 , b_7 , and c_7 become a_5 , b_5 , and c_5 . We obtain

$$a_5 = 0.2716,$$

$$\frac{b_5}{\rho} = 1.1889,$$

and

$$\frac{c_5}{\rho} = 1.5000.$$

Then

$$N_{\gamma 5} = \left(\frac{b_5}{\rho} \right)^2 + a_5^2 N_1 = 1.4184;$$

$$x_{5\max} = (N_{\gamma 5})^{\frac{1}{2}} (\rho x'_0) + c_5 \frac{\Delta p}{p} = 0.2846 + 0.1500 = 0.4346;$$

and

$$\text{Full width} = 0.87 \text{ in.}$$

e. Radial Width at Image Formed by First Magnet

In Eqs. (A), (B), and (C), set $S_0/\rho = 1.1889$ as before, but now let $S_1/\rho = S_i/\rho = S_0/\rho = 1.1889$. Then a_7 , b_7 , and c_7 become the coefficients at the image:

$$a_i = -1,$$

$$\frac{b_i}{\rho} = 0,$$

and

$$\frac{c_i}{\rho} = 4.1185.$$

Then

$$N_{\gamma i} = \left(\frac{b_i}{\rho}\right)^2 + a_i^2 N_1 = 0.0629;$$

$$x_{imax} = (N_{\gamma i})^{\frac{1}{2}} (\rho x_0') + c_i \frac{\Delta p}{p} = 0.060 + 0.412 = 0.472;$$

and

$$\text{Full width} = 0.94 \text{ in.}$$

Note that for $\Delta p = 0$, the full width is 0.120 in., as expected for a magnet with unity magnification, the object being of width 0.120 in.

f. Radial Width at Entrance to Second Magnet

In Eqs. (A), (B), and (C), again set $S_0/\rho = 1.1889$, but now let S_1 be the separation between the effective edges of the magnets: $S_1/\rho = 2S_0/\rho = 2 \times 1.1889 = 2.3778$. We then obtain

$$a_7 = -2.2714,$$

$$\frac{b_7}{\rho} = -1.1889,$$

and

$$\frac{c_7}{\rho} = 6.7371.$$

Then

$$N_{\gamma 7} = \left(\frac{b_7}{\rho} \right)^2 + a_7^2 N_1 = 1.7382;$$

$$x_{7\max} = (N_{\gamma 7})^{\frac{1}{2}} (\rho x_0') + c_7 \frac{\Delta p}{p} = 0.3151 + 0.6737 = 0.9888;$$

and

$$\text{Full width} = 1.98 \text{ in.}$$

For stations further downstream, we need the following, where a_7 , b_7/ρ , and c_7/ρ have the numerical values found previously:

$$d_7 \rho = a_7 \tan u - [\sin \theta - 2 \tan u \cos \theta - \tan^2 u \sin \theta]$$

$$= -3.0933;$$

$$e_7 = \frac{b_7}{\rho} \tan u - \frac{S_0}{\rho} (\sin \theta - 2 \tan u \cos \theta - \tan^2 u \sin \theta)$$

$$+ \tan u \sin \theta + \cos \theta$$

$$= -2.0592;$$

and

$$f_7 = \frac{c_7}{\rho} \tan u + \tan u (1 - \cos \theta) + \sin \theta$$

$$= 8.2052.$$

g. Radial Bust in Second Magnet

$$N_{\alpha 7} = e_7^2 + (d_7 \rho)^2 N_1 = 4.8425;$$

$$N_{\beta 7} = \frac{b_7}{\rho} e_7 + a_7 (d_7 \rho) N_1 = 2.8903;$$

and

$$N_{\gamma 7} = \left(\frac{b_7}{\rho} \right)^2 + a_7^2 N_1 = 1.7382.$$

The bust is very close to the magnet's center.

$$\theta' = \frac{\theta}{2} = 60^\circ, \quad \sin \theta = 0.866, \quad \cos \theta' = 0.5000;$$

$$N_{\gamma 8}' = N_{\alpha 7} \sin^2 \theta' + 2N_{\beta 7} \sin \theta' \cos \theta' + N_{\gamma 7} \cos^2 \theta' = 6.5693;$$

$$\frac{c_8'}{\rho} = \frac{c_7}{\rho} \cos \theta' + f_7 \sin \theta' - (1 - \cos \theta') = 9.9742;$$

$$x_{\text{bust}} = (N_{\gamma 8}')^{\frac{1}{2}} (\rho x_0') + c_8' \frac{\Delta p}{p} = 0.6126 + 0.9974 = 1.6100;$$

and

$$\text{Full width} = 3.22 \text{ in.}$$

h. Radial Width at Exit from Second Magnet

In the following expressions, we use the numerical values that have already been determined for $a_7, \dots, f_7$:

$$a_9 = a_7 \cos \theta + d_7 \rho \sin \theta = -1.5431;$$

$$\frac{b_9}{\rho} = \frac{b_7}{\rho} \cos \theta + e_7 \sin \theta = -1.1889;$$

and

$$\frac{c_9}{\rho} = \frac{c_7}{\rho} \cos \theta + f_7 \sin \theta = 2.2372.$$

Then

$$N_{\gamma 9} = \left(\frac{b_9}{\rho} \right)^2 + a_9^2 N_1 = 1.5630;$$

$$x_{9\text{max}} = (N_{\gamma 9})^{\frac{1}{2}} (\rho x_0') + c_9 \frac{\Delta p}{p} = 0.2988 + 0.2237 = 0.5225;$$

and

$$\text{Full width} = 1.05 \text{ in.}$$

i. Radial Width at Image Formed by Second Magnet

Since each magnet has unity magnification, so does the pair. Hence, the half-width of a single-momentum image will be the half-width

of the source, 0.060 in. We need calculate only the contribution to the width that arises from dispersion:

$$\begin{aligned} \frac{c_{10}}{\rho} &= \frac{c_7}{\rho} \left[\cos \theta + \frac{S_2}{\rho} (\tan u \cos \theta - \sin \theta) \right] \\ &+ f_7 \left[\sin \theta + \frac{S_2}{\rho} (\tan u \sin \theta + \cos \theta) \right] \\ &- \frac{S_2}{\rho} \left[\tan u (1 - \cos \theta) + \sin \theta \right] - (1 - \cos \theta) = -8.2362, \end{aligned}$$

where we let $S_2 = S_1 = S_0$, so $S_2/\rho = 1.1889$, and c_7/ρ and f_7 have the values determined previously. Then

$$x_{10} = 0.060 + |c_{10}| \frac{\Delta p}{p} = 0.060 + 0.824 = 0.884;$$

Full width of image = 1.77 in.

The argument for using the absolute value of c_{10} (since c_{10} is negative) is best given with the aid of Fig. 21. The systems' magnification (M), x_0 , and $\Delta p/p$ are all positive, but c_{10} is sufficiently negative so that the tip of the $p + \Delta p$ image has a negative displacement x_{10} . The distance from the p images' tip to the $p + \Delta p$ image's tail is $|c_{10}| \Delta p/p + 2Mx_0$. The half-width of the pattern (from the axis to the tail of the $p + \Delta p$ image) is obtained by subtracting Mx_0 , as indicated; thus,

$$\text{Half-width} = Mx_0 + |c_{10}| \frac{\Delta p}{p}.$$

Fig. 21. Schematic Representation of Images

2. Vertical Envelopes for Dispersive Case

To first order, dispersion plays no part in vertical motion; therefore the vertical displacement and slope at the j th station are given by

$$z_j = \bar{a}_j z_0 + \bar{b}_j z'_0$$

and

$$z'_j = \bar{d}_j z_0 + \bar{e}_j z'_0,$$

where z_0 and z'_0 are the half-height and maximum slope at the object, and $\bar{a}_j, \dots, \bar{e}_j$ may be obtained from the radial coefficients $a_j, \dots, e_j$ by a simple conversion process (not described here). The relevant expressions for $\bar{a}_j, \dots, \bar{e}_j$ will be quoted, as needed.

The vertical phase-space ellipse is described by coefficients $\bar{\alpha}_j, \bar{\beta}_j$, and $\bar{\gamma}_j$, which are related to $\bar{a}_j, \dots, \bar{e}_j$ by expressions of the same form as those between α_j, β_j , and γ_j , and $a_j, \dots, e_j$.

a. Basic Data

From experimental observation,

$$z_0 = 0.060 \text{ in.}, \text{ and } z'_0 = 0.010 \text{ rad.}$$

Hence

$$\rho z'_0 = 0.3986,$$

and

$$\bar{N}_1 = \left(\frac{z_0}{\rho z'_0} \right)^2 = 0.0226.$$

All other parameters are the same as for the radial case.

The body of an $N = 0$ magnet does not generate vertical forces; they are produced only by the fringing fields at the slanted edges. Beam envelopes peak in height at these points, and not elsewhere.

b. Vertical Height at Entrance to First Magnet

$$\bar{a}_2 = 1;$$

$$\frac{\bar{b}_2}{\rho} = \frac{S_0}{\rho} = 1.1889;$$

$$\bar{N}_{\gamma 2} = \left(\frac{\bar{b}_2}{\rho} \right)^2 + \bar{a}_2^2 \bar{N}_1 = 1.4361;$$

$$z_{2\max} = (\bar{N}_{\gamma 2})^{\frac{1}{2}} (\rho z_0') = 0.4776;$$

and

Full height = 0.95 in.

c. Vertical Height at Exit from First Magnet

Use $S_0/\rho = 1.1889$. Then,

$$\bar{a}_4 = 1 - \theta \tan u = -0.866;$$

$$\frac{\bar{b}_4}{\rho} = \frac{S_0}{\rho} (1 - \theta \tan u) + \theta = 1.0648;$$

$$\bar{N}_{\gamma 4} = \left(\frac{\bar{b}_4}{\rho} \right)^2 + \bar{a}_4^2 \bar{N}_1 = 1.1508;$$

$$z_{4\max} = (\bar{N}_{\gamma 4})^{\frac{1}{2}} (\rho z_0') = 0.4275;$$

and

Full height = 0.86 in.

d. Vertical Height at Entrance to Second Magnet

Use $S_0/\rho = 1.1889$, and $S_1/\rho = 2.3778$. Then,

$$\bar{a}_6 = (1 - \theta \tan u) + \frac{S_1}{\rho} \tan u (\theta \tan u - 2) = -1.1498;$$

$$\frac{\bar{b}_6}{\rho} = \left(\frac{S_0}{\rho} + \frac{S_1}{\rho} \right) (1 - \theta \tan u) + \theta$$

$$+ \frac{S_0}{\rho} \frac{S_1}{\rho} \tan u (\theta \tan u - 2) = -1.3320;$$

$$\bar{N}_{\gamma 6} = \left(\frac{\bar{b}_6}{\rho} \right)^2 + \bar{a}_6^2 \bar{N}_1 = 1.804;$$

$$z_{6\max} = (\bar{N}_{\gamma 6})^{\frac{1}{2}} (\rho z_0') = 0.537;$$

and

Full height = 1.07 in.

e. Vertical Height at Exit from Second Magnet

Use $S_0/\rho = 1.1889$, and $S_1/\rho = 2.3778$. Then,

$$\bar{a}_8 = \frac{S_1}{\rho} \tan u [-2 + 3\theta \tan u - (\theta \tan u)^2]$$

$$-4\theta \tan u + 1 + 2(\theta \tan u)^2 = 0.7459;$$

$$\frac{\bar{b}_8}{\rho} = \frac{S_0}{\rho} [1 - 4\theta \tan u + 2(\theta \tan u)^2] + \frac{S_1}{\rho} (1 - \theta \tan u)^2$$

$$+ \frac{S_0}{\rho} \frac{S_1}{\rho} \tan u [-2 + 3\theta \tan u - (\theta \tan u)^2] + 2\theta(1 - \theta \tan u) = -0.9576;$$

$$\bar{N}_{\gamma 8} = \left(\frac{\bar{b}_8}{\rho} \right)^2 + \bar{a}_8^2 \bar{N}_1 = 0.9296;$$

$$z_{8\max} = (\bar{N}_{\gamma 8})^{\frac{1}{2}} (\rho z_0') = 0.3843;$$

and

$$\text{Full height} = 0.77 \text{ in.}$$

3. Envelope Dimensions for Achromatic Case

The same procedures are followed as in the dispersive case, except that the object distance (measured to the effective edge) is now $S_0 = 10.12 \text{ in.}$, so that

$$\frac{S_0}{\rho} = \frac{10.12}{39.86} = 0.2540.$$

Also

$$\frac{S_2}{\rho} = 0.2540.$$

But since the magnets keep their original separation, we again have $S_1/\rho = 2.3778$.

This change in object slit distance means that the upstream quadrupole pair must be weakened to form an image on the new position of the object slit (Fig. 22). Consequently, the radial and vertical size of the object is altered as well as the radial and vertical divergences.

Fig. 22. Slit Location in Dispersive and Achromatic Use

Using subscripts d and a for the dispersive and achromatic system, we have

$$x_{0a} = \frac{Q_a}{Q_d} x_{0d} = \frac{135.58}{98.31} x_{0d} = 1.3791 \cdot 0.060 = 0.0827 \text{ in.};$$

$$x'_{0a} = \frac{Q_d}{Q_a} x'_{0d} = \frac{98.31}{135.58} x'_{0d} = 0.7251 \cdot 0.006 = 0.0043 \text{ rad};$$

$$z_{0a} = \frac{Q_a}{Q_d} z_{0d} = 1.3791 \cdot 0.060 = 0.0827 \text{ in.};$$

$$z'_{0a} = \frac{Q_d}{Q_a} z'_{0d} = 0.7251 \cdot 0.01 = 0.00721 \text{ rad};$$

$$\rho x'_{0a} = 0.1714, \quad N_1 = \left(\frac{x_{0a}}{\rho x'_{0a}} \right)^2 = 0.233;$$

$$\rho z'_{0a} = 0.287, \quad \bar{N}_1 = \left(\frac{z_{0a}}{\rho z'_{0a}} \right)^2 = 0.0831.$$

The detailed calculations for the achromatic case will not be given, but the results are embodied in Table II.

TABLE II. Computed Beam Envelopes Assuming Cyclotron Emits

$$\text{Beam with } \frac{\Delta p}{p} = \frac{1}{400} \left(\text{i.e., } \frac{\Delta E}{E} = \frac{\pm 100 \text{ keV}}{21.6 \text{ MeV}} \right)$$

<u>DISPERSIVE ARRANGEMENT</u>			$x_0 = \pm 0.060 \text{ in.}$	$z_0 = \pm 0.060 \text{ in.}$
			$x'_0 = \pm 0.006 \text{ rad}$	$z'_0 = \pm 0.010 \text{ rad}$
	<u>First Magnet</u>	<u>Second Magnet</u>		
<u>Width, in.</u>				
Entrance	0.58	1.98 (max value)		
Bust	1.25	3.23 (max value)		
Exit	0.87	1.04		
Image	0.94	1.77		
<u>Height, in.</u>				
Entrance	0.95	1.07		
Exit	0.85	0.77		
<u>ACHROMATIC ARRANGEMENT</u>			$x_0 = \pm 0.083 \text{ in.}$	$z_0 = 0.083 \text{ in.}$
			$x'_0 = \pm 0.0043 \text{ rad}$	$z'_0 = 0.0072 \text{ rad}$
	<u>First Magnet</u>	<u>Second Magnet</u>		
<u>Width, in.</u>				
Entrance	0.19	1.83		
Bust	0.06	2.53		
Exit	0.62	0.94		
Image	none	0.16		
<u>Height, in.</u>				
Entrance	0.22	0.24		
Exit	1.08 (max value)	1.03		
Vacuum chamber inside dimensions: width = 4.00 in., height = 1.438 in.				

APPENDIX B

Assembly Drawings for Ancillary Hardware

The following is a tabulation of assembly drawings (not included in this report) for the ancillary hardware of the beam-transport and energy-analyzing system as referenced in Figs. 1, 3, and 5.

1. Cyclotron to Switch Magnet SM-1

<u>Item</u>	<u>Drawing No.</u>
(1) Gate Valve	CYC-2042-D-1
(2) Target Box (Irradiation Port No. 1), Beam Shutter, and Irradiation Port No. 2	CYC-512-D-1
(3) Squeeze Coil	CYC-1150-D-1
(4) Irradiation Port No. 3	CYC-1197-DD-1
(5) Bellows (4 in.)	Drawing not available
(6) Beam Valve (BV; 4 in.)	Purchased (Consolidated Vacuum Corporation, VST-43)
(7) Quadrant Detector	CYC-1152-D-1
(8) Quadrupole Doublet (8 in. long; Q-1 and Q-2)	CYC-1148-C-1
(9) Quadrupole (Q-1 and Q-2) Magnet Table	CYC-1101-D-1
(10) Quadrupole (Q-1 and Q-2) Magnet Support Carriage	CYC-1102-E-1
(11) Steering Coil (SC-1)	CYC-1145-C-1
(12) Stripping Foil	211-CY-M-1882-A
(13) Switch Magnet (SM-1)	Purchased (Pacific Electric Motors Co.)
(14) Switch Magnet (SM-1) Support Carriage	CYC-1147-D-1
(15) Switch Magnet Chamber (SMC-1)	CYC-1149-D-1

2. Switch Magnet SM-1 to Tunnel No. 1

The following listing of transport hardware is for the 0° beam-line and is typical for the others:

<u>Item</u>	<u>Drawing No.</u>
(1) Close Couple Adapter (Chamber SMC-1 to Following Valve)	211-CY-M-1592-B
(2) Beam Valve (BV; 2 in.)	Purchased (Consolidated Vacuum Corporation, VST-23)
(3) Close Couple Adapter (BV to Drift Tube)	211-CY-M-2212-B
(4) Drift Tube	211-CY-M-1515-B
(5) Beam Tube Aperture (A)	CYC-1192-B-1
(6) Energy Degradar	CS-2363
(7) Energy Degradar Support Structure	211-CY-M-1461-C
(8) Quadrupole Doublet (8 in. long; Q-15 and Q-16)	CYC-1148-C-1
(9) Steering Coil (SC-3)	CYC-1145-C-1
(10) Quadrupole Doublet (4 in. long; Q-17 and Q-18)	211-CY-M-1691-D
(11) Quadrupole (Q-15, Q-16, Q-17, and Q-18) Overhead Support	CYC-1140-DD-1
(12) Feedthru (FT)	CYC-1124-D-1
(13) Radiation Plug (RP)	211-CY-M-0996-E
(14) Beam Valve (BV; 2 in.)	Purchased (Vacuum Research Corporation, 2T2EP)
(15) Steering Coil (SC-4)	CYC-1145-C-1
(16) Quadrupole Doublet (4 in. long; Q-19 and Q-20)	211-CY-M-1691-D
(17) Quadrupole (Q-19 and Q-20 Yoke Assembly	211-CY-M-1759-D

3. Switch Magnet SM-1 to Switch Magnet SM-2

<u>Item</u>	<u>Drawing No.</u>
(1) Beam Valve (BV; 2 in.)	Purchased (Consolidated Vacuum Corporation, VST-23)
(2) Drift Tube	Drawing not available
(3) Coupler (2-in. Tube to 2-in. Ladish Flange)	211-CY-M-2214-A
(4) Adapter (2-in. LEAF to 2-in. Ladish)	211-CY-M-1607-B
(5) Dispersive Slit (DS-1)	211-CY-M-1247-E
(6) Bellows (2 in.)	211-CY-M-1588-B
(7) Tee (2 in.)	211-CY-M-1451-C
(8) Drift Tube (2 in.)	211-CY-M-1460-C, Part I
(9) Achromatic Slit (AS-1)	211-CY-M-1237-E
(10) Analyzing Magnet Assembly (AM-A) (40 in. x 120°)	Purchased (Spectromagnetic Industries E-32180-2C)
(11) Analyzing Chamber (AMC-A)	211-CY-M-1319-E
(12) Viewing Chamber (VC-1) (Target and Sliding Screen Assembly)	211-CY-M-1350-E
(13) Beam Valve (BV; 3 in.)	211-CY-M-1525-C (Vacuum Research Corporation, 3T3EP reworked)
(14) Tee (3 in.)	211-CY-M-1664-C
(15) Bellows (3 in.)	211-CY-M-1506-B
(16) Intermediate Slit (IS)	211-CY-M-1737-D
(17) Drift Tube (3 in.)	211-CY-M-1507-B, Part I
(18) Viewing Chamber (VC-2)-- (Sliding Screen Assy.)	211-CY-M-1351-C
(19) Analyzing Magnet Assembly (AM-B) (40 in. x 120°)	Purchased (Spectromagnetic Industries, E-32180-2C)

<u>Item</u>	<u>Drawing No.</u>
(20) Analyzing Chamber (AMC-B)	211-CY-M-1319-E
(21) Achromatic Slit (AS-2)	211-CY-M-1306-E
(22) Adapter (Slit to BV)	211-CY-M-1508-B
(23) Beam Valve (BV; 2 in.)	211-CY-M-1528-B (Vacuum Research Corporation, 2T2EP reworked)
(24) Bellows (2 in.)	211-CY-M-1510-B
(25) Drift Tube (2 in.)	211-CY-M-1460-C Part II
(26) Dispersive Slit (DS-2)	211-CY-M-1247-E
(27) Bellows (2 in.)	211-CY-M-1500-B
(28) Quadrupole Doublet (8 in. long; Q-3 and Q-4)	CYC-1148-C-1
(29) Quadrupole Tube	211-CY-M-1460-C Part III
(30) Switch Magnet (SM-2)	Purchased (Pacific Electric Motor Company, PEM-1225-D)
(31) Switch Magnet Chamber (SMC-2)	211-CY-M-1164-D
(32) Support Structure No. 1-- CYC Transport System	211-CY-M-1452-D
(33) Achromatic Slit (AS-1) Shelf and Cradle Subassembly	211-CY-M-1764-C
(34) Analyzing Magnet (AM-A) Support Structure	211-CY-M-1430-D
(35) Support Structure No. 2-- CYC Transport System	211-CY-M-1495-D
(36) Analyzing Magnet (AM-B) Support Structure	211-CY-M-1430-D
(37) Achromatic Slit (AS-2) Shelf and Cradle Subassembly	211-CY-M-1764-C
(38) Support Structure No. 3A-- CYC Transport System	211-CY-M-1711-D
(39) Support Structure No. 3B-- CYC Transport System	211-CY-M-1683-C
(40) Switch Magnet (SM-2) Support Structure	211-CY-M-1267-C

4. Switch Magnet SM-2 to Tunnel No. 2

The following listing of transport hardware is for the 20° beam-line and is typical for the others:

<u>Item</u>	<u>Drawing No.</u>
(1) Close Couple Adapter (SMC-2 to following valve)	211-CY-M-1592-B
(2) Beam Valve (BV; 2 in.)	Purchased (Vacuum Research Corporation, 2T2EP)
(3) Close Couple Adapter (BV to SC-2)	211-CY-M-2023-B
(4) Steering Coil (SC-2)	CYC-1145-C-1 and CYC-1120-A
(5) Beam Envelope Locator (BEL-1)	211-CY-M-1801-D
(6) Quadrupole Doublet (4 in. long; Q-5 and Q-6)	211-CY-M-1691-D
(7) Quadrupole Tube	211-CY-M-1515-B
(8) Coupler (2-in. Tube to 2-in. Ladish)	211-CY-M-1551-B
(9) Feedthru (FT)	211-CY-M-1181-D
(10) Radiation Plug (RP)	211-CY-M-0996-E
(11) Tee (2 in.)	211-CY-M-1933-B
(12) Beam Valve (BV; 2 in.)	Purchased (Vacuum Research Corporation, 2T2EP)
(13) Quadrupole Doublet (4 in. long; Q-7 and Q-8)	211-CY-M-1691-D
(14) Quadrupole Tube	211-CY-M-1515-B
(15) Beam Envelope Locator (BEL-2)	211-CY-M-1801-D
(16) Tee (2 in.)	211-CY-M-1933-B
(17) Same as No. 7 above	
(18) Quadrupole Doublet (8 in. long; Q-9 and Q-10)	CYC-1148-C-1
(19) Beam Envelope Locator (BEL-3)	211-CY-M-1801-D

<u>Item</u>	<u>Drawing No.</u>
(20) Collimating Systems	Drawings not available
(21) 60-in. Scattering Chamber	ANL-5890
(22) Support Structure No. 4-- CYC Transport System	211-CY-M-2041-A
(23) Quadrupole (Q-5 and Q-6) Yoke Assembly	211-CY-M-1759-D
(24) Quadrupole (Q-5 and Q-6) Cart	211-CY-M-2044-B
(25) Quadrupole (Q-7 and Q-8) Support Structure	211-CY-M-1848-C
(26) Quadrupole (Q-7 and Q-8) Yoke Assembly	211-CY-M-1759-D
(27) Quadrupole (Q-9 and Q-10) Yoke Assembly	211-CY-M-1759-D

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