H$^-$ CYCLOTRON MESON FACTORY (*)

R.P. Haddock, J.R. Richardson
and B.T. Wright
University of California, Los Angeles
(Presented by R.P. Haddock)

General Design

The special design requirements of a negative-hydrogen-ion cyclotron are a low gas pressure to reduce ion loss by stripping, and a limited maximum magnetic field to reduce ion loss by electric dissociation. In addition, there is the requirement common to all sector-focused cyclotrons of the selection of a spiral-ridge structure that will provide proper radial and vertical focusing throughout the acceleration. Analysis1) has led to the selection of a vacuum working pressure of 4×10^{-8} torr. At this pressure the total gas stripping loss is estimated to be equivalent, in its effect in activating the machine, to a loss of 2% of the full-energy beam. The engineering objective for which the vacuum system is designed is 1×10^{-8} torr, a factor of four below the working pressure. To meet this objective, a bakable vacuum system pumped primarily by ion pumps is provided.

At 700 MeV a hill field of 5 kG cannot be exceeded without excessive beam loss due to electric dissociation. At this field the total loss due to electric dissociation is 11%, almost all of which occurs above 600 MeV. As a result of these beam loss considerations a definite limit can be placed on the total loss during acceleration of the equivalent of 20 μA of 700 MeV protons. This figure corresponds to an external beam of 150 μA at 700 MeV, with most of the activation due to beam lost by electric dissociation. With 600 MeV external beam, the electric dissociation is negligible and the same activation rate, in this case due almost entirely to gas stripping, corresponds to 900 μA of external beam.

Relative beam loss as a function of energy is shown in Fig. 1. For electric dissociation, the lifetime calculated by Hiskes as reported by Judd2) was used. The gas-stripping cross-section per atom of air was taken as $2 \times 10^{-16} [1/E(\mathrm{MeV})]^{0.77}$ cm^2. This represents an interpolation between measured values at low energy3) and calculated values at higher energy4).

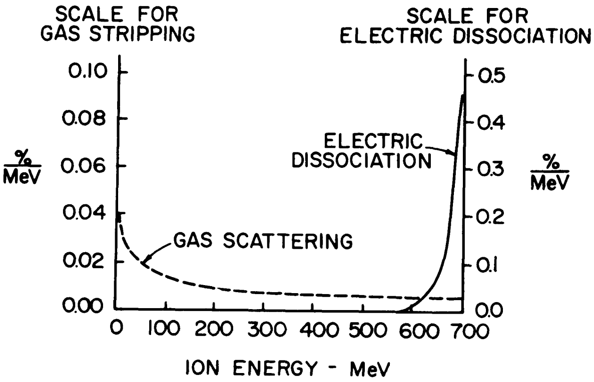


Fig. 1 Beam loss during acceleration at 4×10^{-8} torr.

Design of the magnetic field is based on the large and increasing body of theoretical and practical knowledge of

---

(*) This work was performed under the auspices of USAEC.

sector-focused cyclotrons. Six-fold symmetry is chosen. The hills are made as wide as possible at the maximum radius to reduce the maximum magnetic field to as low a value as possible. Radial hill edges with an included angle of 18° are used to half radius beyond which the spiral angle increases to a maximum of 78° and the width of the hill iron to 47°. A large spiral angle is practical because there is no need to induce a large radial oscillation amplitude to extract the beam. The combination of flutter and spiral angle chosen is expected to result in a vertical oscillation frequency in the conventional range of about two to three tenths of the rotation frequency.

Radiation Considerations

A principal advantage of the negative-ion cyclotron is the small internal beam loss and correspondingly small activation of the machine. The loss which occurs while the machine is producing 150 μA of 700 MeV external beam is estimated to be equivalent to 20 μA at 700 MeV. The ions neutralized by stripping travel outward, tangent to their equilibrium orbit, until they strike the outer wall of the vacuum tank. The high-energy protons will penetrate the tank wall and stop in the magnet yoke or shield iron surrounding the tank.

The protons stopped in the iron shield or yoke produce neutrons which penetrate the remainder of the local shielding around the machine and pass into the shielding walls of the cyclotron vault. The local shielding is iron and heavy concrete opposite the valleys, and iron alone opposite the hills, in either case equivalent to at least 20 ft of ordinary concrete. The vault walls are ordinary concrete 20 ft thick, making the total equivalent thickness 40 ft of ordinary concrete. With 20 μA equivalent beam loss in the cyclotron, and adjusted for the obliquity of the beam with respect to the normal to the shield, the radiation outside the vault is 1.4 neut/cm^2-sec. The corresponding dose rate is about 9 mRem in 40 hrs which is about a factor of ten below the intensity allowable for radiation workers exposed 40hr/wk over a long period.

The activation of the machine by the internally lost beam has been estimated by comparison with the beam lost in the 184 in. cyclotron at LRL. The large diameter of the proposed machine spreads the lost beam over a large area. The irradiation intensity at any point is estimated to be about the same as the corresponding value for the 184 in. cyclotron. The gamma field strength inside the vault due to residual activity of the cyclotron is, therefore, estimated to be about the same as that observed near the 184 in. cyclotron, which has the following values one foot outside the vacuum tank: at shutdown, 0.27 R/hr; 12 hr after shutdown, 0.19 R/hr; and 7 days after shutdown, 0.11 R/hr. Within the allowable dose rate of 100 mR/wk, an operator will be able to spend about 20 min/wk inside the cyclotron room if he enters immediately after shutdown and receives no appreciable radiation above normal background at other times. For this reason, no more equipment than necessary is located in the cyclotron room. Remote control is provided for all adjustments and quickchanging features are built into the minor assemblies. Major changes will be made after a cooling period, and rapid but not remotely-operated handling and assembly features will be included.

Most of the equipment requiring frequent servicing or adjustment will not be located in the cyclotron room, but in the basement below a 12 ft thick concrete floor. In this room the neutron level will not be high enough to produce appreciable radioactivity.

The Magnet

The cyclotron magnet (Fig. 2 and 3) is unusual because of its large diameter and its low maximum field. Because of the large size, the conventional design used for most cyclotrons is impractical due to the great quantity of iron that would be required. The magnet design used provides iron only in the hill region, primarily to transmit the the flux in a radial direction.

With this type of cyclotron, a choice exists between winding the coils around the individual hills, around the outer radius of the poles as in a conventional cyclotron, or around the return paths. There are advantages and disadvantages to each of the arrangements. The arrangement selected, circular coils around the outer radius, is

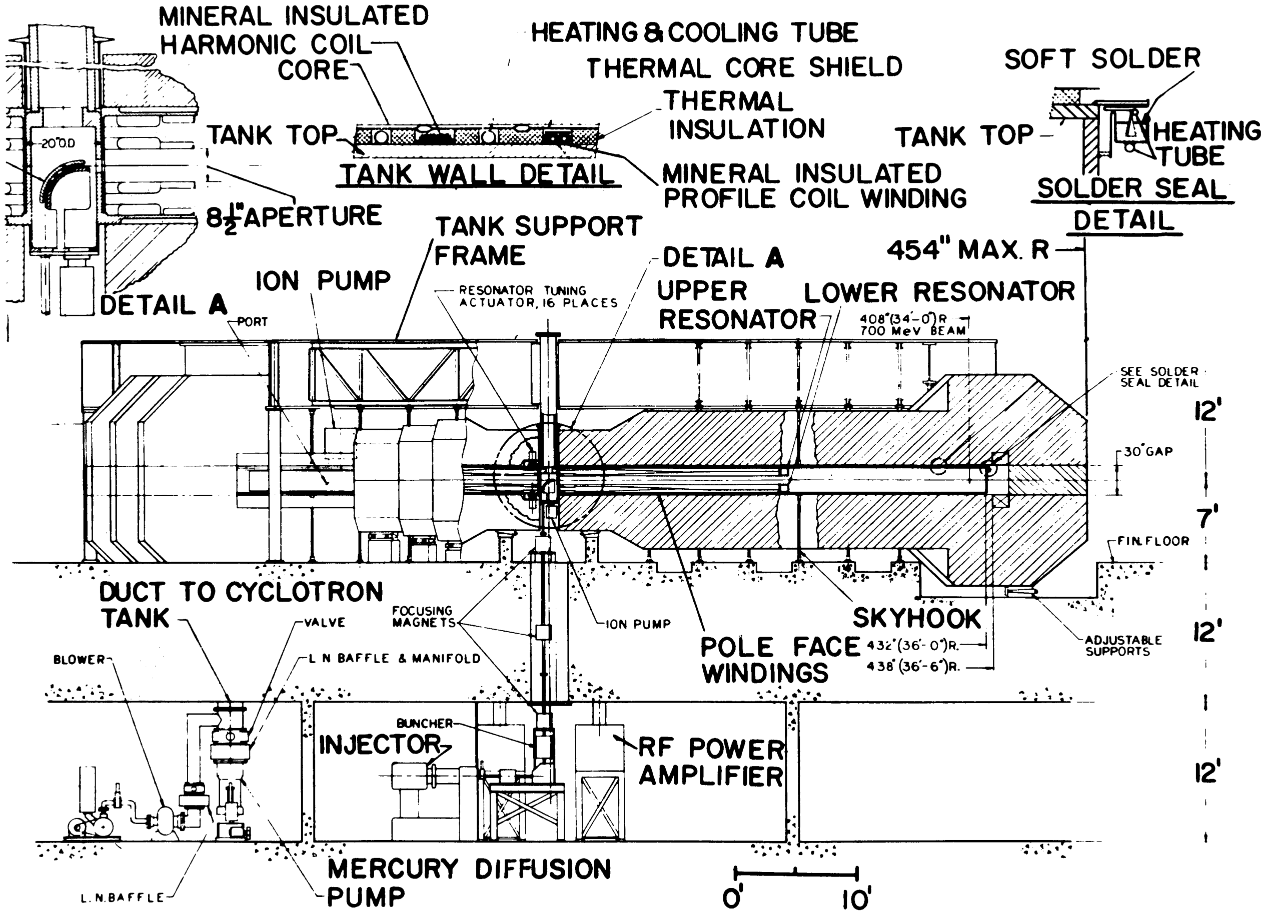


Fig. 2 Elevation and section, with detailed sections of the central region, tank wall, and vacuum-tank solder seal.

entirely feasible and provides a firm basis for cost estimates. Coils around the individual poles, while individually smaller, introduce a problem in exciting the center of the magnet and also appear to be inefficient in the use of ampere turns due to adjacent conductors carrying currents in opposite directions. This does, however, increase the flutter over that which can be obtained with the circular coils and would have to be considered if the flutter amplitude were insufficient. The circular coils now planned will contain about 100 tons of copper and have an outside diameter of 76 ft. They will, of course, have to be wound in place as they are much too large to move through the streets. Adequate space and crane capacity is provided for the winding operation.

The magnetic forces, amounting to a total of about 2300 tons between the poles, are resisted by a central support and by the return yokes outside the coils. The magnet is made in pieces weighing up to 150 tons. Mating surfaces and the surfaces facing the gap and valleys are machined; other surfaces are flame cut. The magnet design provides for assembly by setting one piece on top of another, bolting each in place

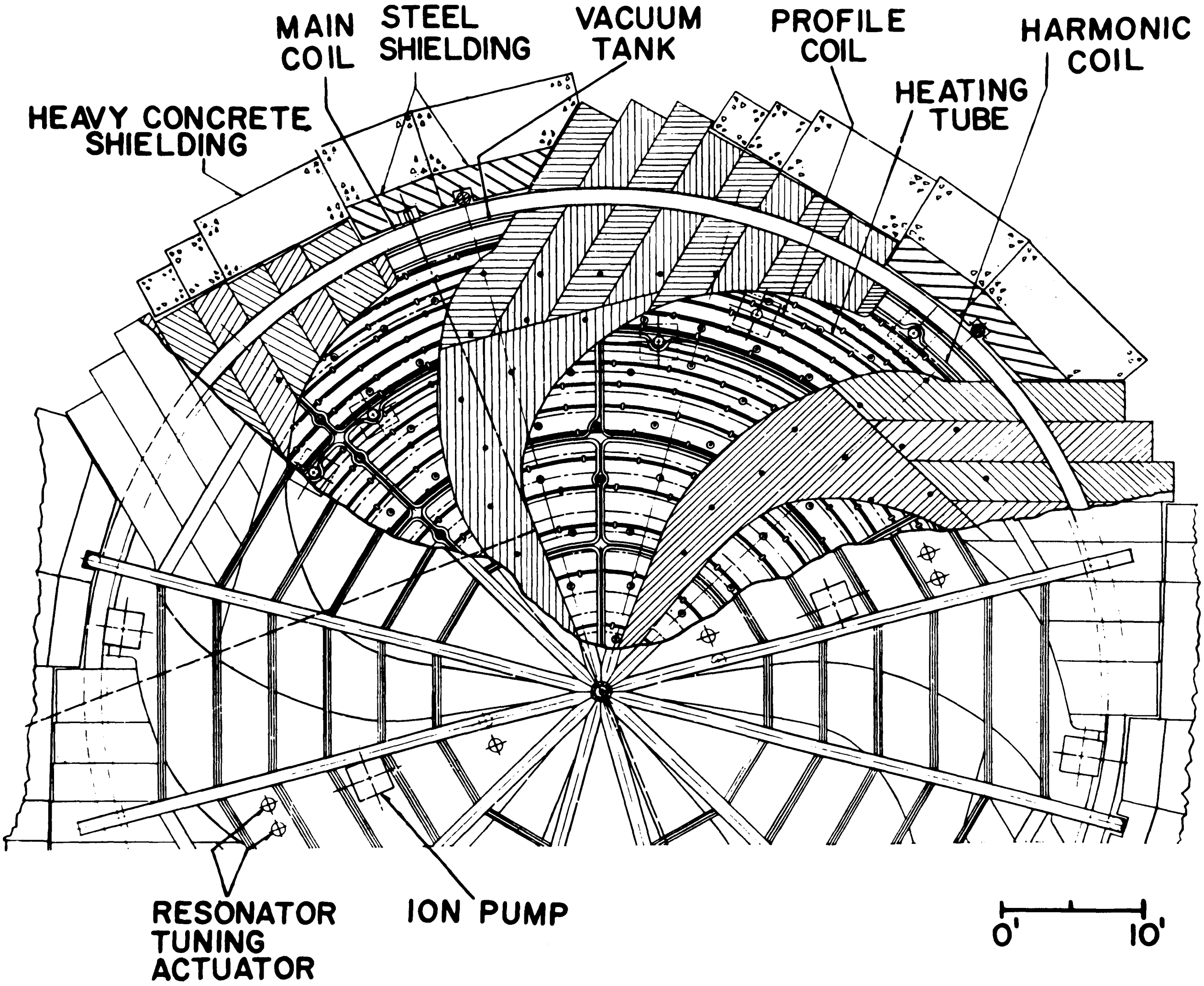


Fig. 3 Plan view, showing spiral shape, tank support frame, main coil, and other indicated details of the design.

before the next is added. The top half of the magnet core is installed after the coils and vacuum tank are in place.

The central column (Fig. 2, detail A) is made in two concentric tubes so that atmospheric pressure on the vacuum tank does not affect the magnet. This permits making magnetic field measurements in air without correction for deflection of the magnet due to vacuum. Magnet iron will be forged low-carbon steel.

In addition to the main exciting coils, trimming coils to adjust the shape of the field will be provided. These will consist of profile coils concentric with the magnet axis and harmonic coils to correct the first and second harmonics in amplitude and phase. Seventeen pairs of profile coils will be provided, each consisting of four turns of mineral-insulated cable, two turns on each side of the gap. They are capable of correcting for a radial gradient 0.1%/ft. For this purpose, a conductor current of 500 A is required. The 24 pairs of harmonic coils require 10 A and will be wound of 12 turns of mineral-insulated cable. Additional field corrections may be made by changing the width of the valleys by attaching iron shims to the sides of the poles adjacent to the gap. The required magnet power is 3.5 MW5). The required trim-coil power is about 500 kW.

The Vacuum System

The requirement of a tank 72 ft in diameter by 2.5 ft high to contain a vacuum of 10^{-8} torr is unusual, but within the present state of the art of vacuum technology. To ensure reaching the design pressure, provision is made for heating the installed tank to 200°C.

Atmospheric pressure produces a load of about 4300 tons on each cover of the tank. This load is to be supported by several hundred "skyhooks". The top skyhooks are in turn supported by a structural steel frame resting on a central column at the center, and on the magnet return yokes at the periphery. The lower skyhooks are attached to sockets in the concrete floor. The central column is concentric with and independent of the column that supports the magnet as previously described. Provision is made for radial expansion of the tank during heating.

The tank is to be fabricated of 7/8 in. stainless-steel plate. This thickness corresponds to a skyhook spacing on 4 ft centers. The tank would probably be shop-welded in sections and the sections welded together at the site. The principal vacuum seal will be around the periphery of the tank. This is planned as a solder seal that will be melted by controlled heating when the seal is made or broken.

Pumping is accomplished by a combination of ion and mercury-diffusion pumps. The ion pumps should bring the system below 10^{-8} torr after bake-out and a few days of pumping. The mercury pumps will handle the outgassing of the ion pumps when first started and will assist in the pumpdown before the ion pumps are started.

Pressurized water will be used to bake the tank to permit close temperature control and slow temperature change to reduce thermal stresses. A water-cooled heat shield is used between the tank and the magnet to prevent thermal distortion of the magnet.

The Accelerating System

The radio frequency accelerating system uses two dees resonating at 11.3 Mc/s, the third harmonic of the ion frequency. The peak voltage is 100 kV to ground$^{6)}$. The frequency was chosen to permit location of the dees entirely inside the circular vacuum tank. As is shown in Fig. 2 and 4, each "dee" consists of eight subassemblies, each of which is a separate resonant circuit. For example, four resonators side by side correspond to the top of one dee and the adjacent liner. The coupling between the resonators is very close due to the capacity between the high voltage ends and the magnetic flux which links all of the eight resonators forming one dee.

One side of each resonator is attached to the vacuum tank through adjustable supports at three or more points, the second side is supported from the first as a cantilever. The resonator sides are stiffened by beams tapering from their maximum depth at the ground end. To reduce the length of the resonators, the capacity between the two resonator sides may be increased at the high voltage end by reducing the gap

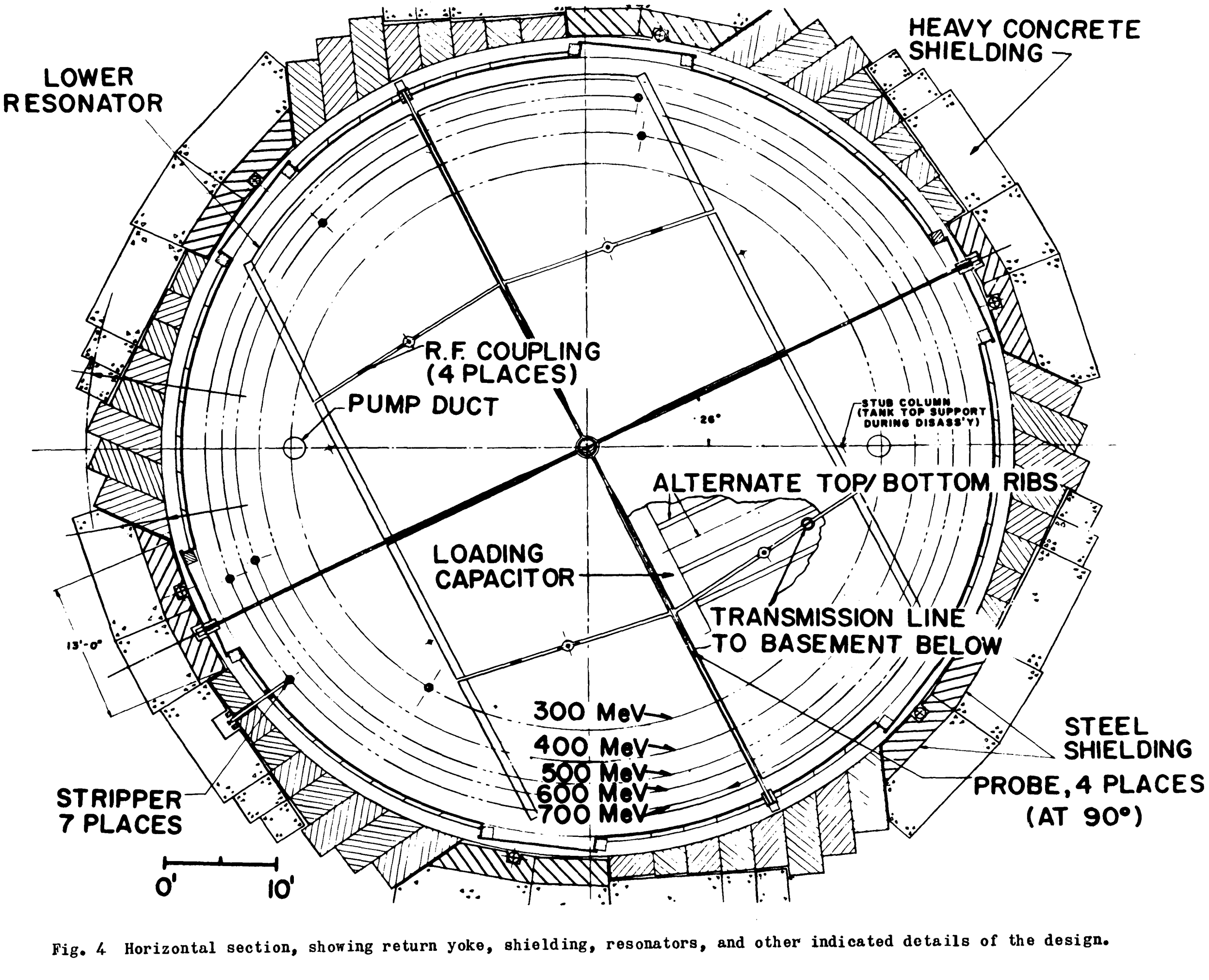


Fig. 4 Horizontal section, showing return yoke, shielding, resonators, and other indicated details of the design.

at this point. The optimum depth of beams and capacity loading to minimize flexibility and RF power is still to be studied. The present design dissipates 1.1 MW in copper loss and has a static deflection, uncorrected, of 3 in. in its 18 ft length. As the resonators would be shaped to deflect into a horizontal direction when installed, the calculated deflection is primarily a measure of stiffness.

The maximum RMS current density of about 60 A/in. can easily be handled by water-cooling tubes attached to the dee surfaces. Adjustment of the tuning of the individual resonators may be required to keep them all at the same voltage. This will be done by varying the clearances at their high voltage ends by servo drives through the tank walls. No electrical insulation problem exists, as the adjusting mechanisms are outside the resonators.

The Injector

A feature of this cyclotron is the external injector. External injection, while commonly used in proton synchrotrons, is unconventional for cyclotrons. The reason for this is that external injection is difficult in small machines due to the lack of available space for the focusing and inflecting elements. However, it has been used on the Birmingham cyclotron for injection of deuterons with good results$^{7)}$.

Negative hydrogen ions are produced in an ion source at 150 kV to ground, accelerated to ground potential, analyzed and guided parallel to the cyclotron axis to the entrance of an electrostatic inflector, and inflected into the horizontal plane where they enter the accelerating field of the dees. In the present design, the injected beam passes through an opening in the central column into the RF field of the dees. Alternatively, inflection could take place entirely outside of the column.

The high voltage d.c. accelerator is located in the basement room below the cyclotron. It is not pressurized so that a minimum restriction is placed on the design and accessibility of the ion source. Vacuum pumps at the ground end of the d.c. accelerator will remove most of the hydrogen gas introduced through the ion source, so that no appreciable quantity of gas will enter the main vacuum tank.

Strippers and Probes

A major advantage of the negative ion cyclotron is its ability to produce many external beams over a wide range of energies. Extraction of the negative ions requires only that they pass through a thin foil which removes their two electrons, they then reverse their direction of curvature in the magnetic field. The resulting outward curvature brings the ions quickly out of the cyclotron field where they are collected by beam-transport magnets. Carbon foils three to five microns thick are used for the stripping targets. Power dissipation in the targets will be of the order of 200 mW, which is easily dissipated by radiation.

By introducing the target from above or below the beam, it will be possible to extract only a portion of the beam at a given energy and to allow the rest to proceed.

This technique will permit the simultaneous production of several external beams and permit several experimental groups to use the machine at the same time.

Four probes will be provided for use in tuning and investigating the performance of the machine. The probes will be mounted on carts and will travel on tracks along four radial lines parallel and perpendicular to the dee gap. The probes will be provided with instrumentation to permit observing the position, magnitude, and phase of the beam pulses striking them. The principal design specifications of the cyclotron are shown in Table I.

Table I

Design Specifications

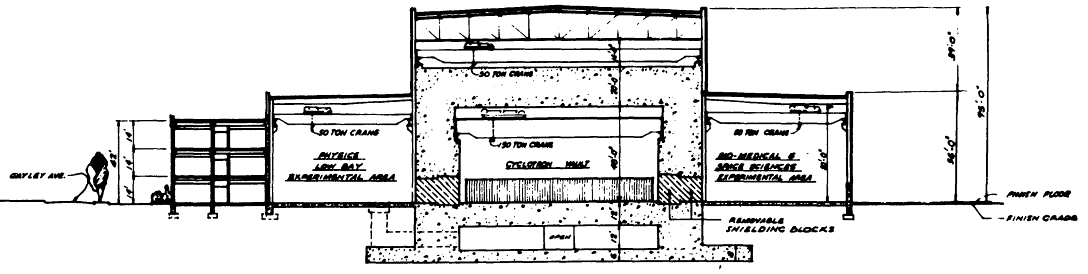
Particle	H^-	Dee volts, peak	100 kV
Max. energy	700 MeV	Max. energy/turn	400 keV
Current	150µA at 700 MeV 500µA at 500 MeV	Ion frequency	3.77 Mc/s
		Dee frequency	11.31 Mc/s
Max. orbit radius magnet	408 in.	RF power	1780 kW
Sectors, number	6	Design vac.	10^{-8} torr
Pole tip dia.	73 feet	Operating vac.	4×10^{-8} torr
Gap	30 in.	Baking temp.	200°C
Ampere turns	640,000	Injection energy	150 keV
Wt. iron	7000 tons	Injected current	10 mA
Wt. copper	106 tons	Extracted beam energy range	300 to 700 MeV
Power	3500 kW	No. extracted beams	7
Profile coil pairs	17	Cyclotron power	7700 kW
Harmonic coil pairs	24	Shielding in median plane (equivalent)	40 ft concrete

Experiment Area Structure

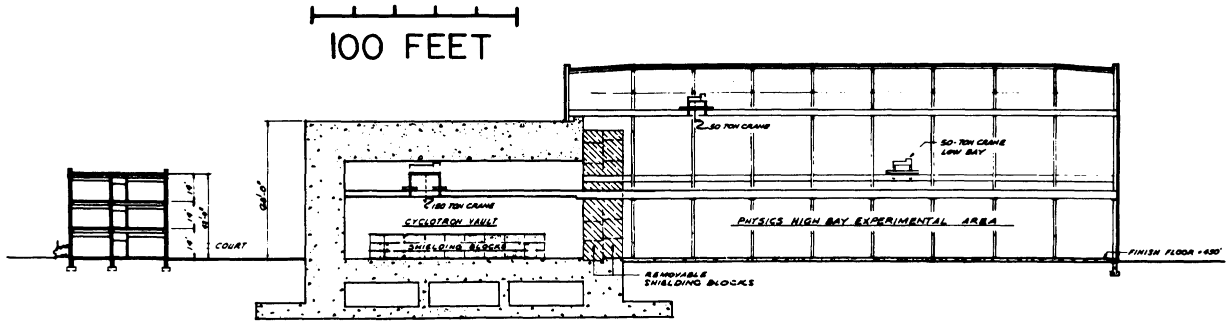
The experiment area structure, approximately 114,450 square feet in area, is composed of three adjoining structures of standard, steel-mill construction, as shown in Fig. 5. The central high-bay structure is approximately 150 by 245 ft, and 95 ft high, with the cyclotron vault located at the west end. The two adjoining low-bay structures are each 70 by 400 ft and 56 ft high.

The experimental Area

Provisional development of the experimental area is shown in Fig. 6. Equipment is provided for the simultaneous extraction of five primary beams of five different energies. Some of the primary beams can produce several secondary beams simultaneously. To avoid unnecessary loss of beam intensity, with an accompanying increase in background and induced radioactivity, dispersionless magnet systems are employed to transport the



TRANSVERSE SECTION



LONGITUDINAL SECTION

Fig. 5 Sectional drawings of the facility.

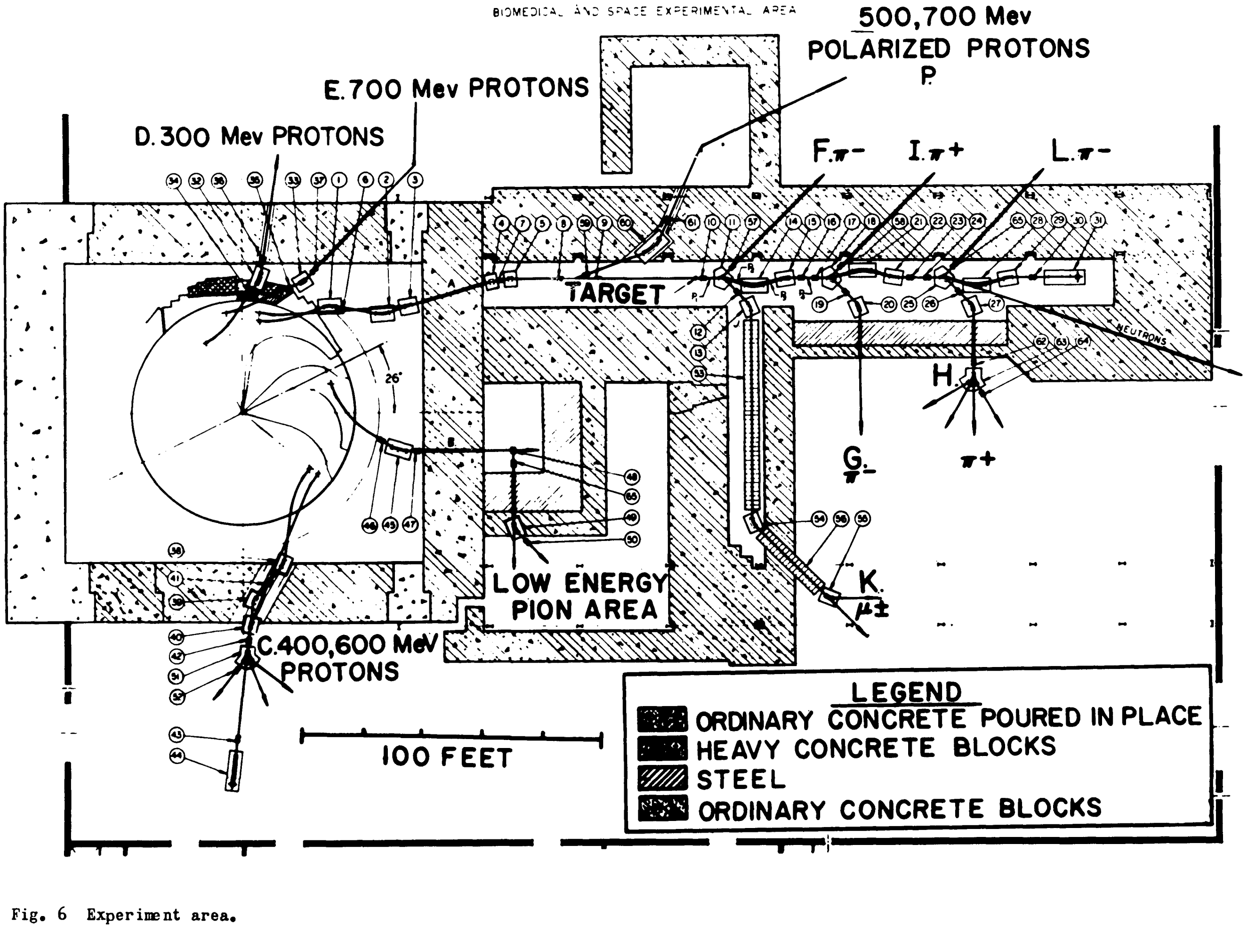


Fig. 6 Experiment area.

high-intensity primary beams. Beyond the last target along a given primary beam line, the beam is deflected 90° downward into a beam stop sunk at least 60 ft into the earth.

The beam extracted from a negative-ion cyclotron is expected to be of high quality. No loss in the quality of the circulating beam results from the introduction of low-order symmetries in the magnetic field to excite a resonance extraction scheme. Estimates which have been made of the emittance give values which compare favorably with the emittance expected of a 700 MeV linear accelerator.

The shielding in the entire experimental area is movable. The only obstructions are two columns at the right-hand side of the cyclotron vault. It is felt that the flexibility acquired by the use of movable shielding is well worth its additional cost.

Acknowledgments

A comprehensive report of this facility entitled, "700 MeV Negative Hydrogen Ion Cyclotron Facility", is available on request. William M. Brobeck and Associates developed the cost estimates for the accelerator and made a number of valuable contributions to the design. The Ralph M. Parsons Co. developed the building plans.

K.R. MacKenzie, whose work on the acceleration system appears as a separate contribution of this Conference, contributed valuable suggestions to the design. A.C. Paul assisted in the development of the beam transport design. We are indebted to Roger Wallace of the Lawrence Radiation Laboratory for much assistance in connection with the radiation considerations.

References

1. J.R. Richardson, Technical Report UCLA-52, (September 1962).
2. D.L. Judd, Nucl. Instr. and Meth., 18-19, 70 (1962).
3. S.K. Allison, Rev. Mod. Phys., 30, 1137 (1958).
4. B.T. Wright, Arch.f.Mat. og Naturvidenskab, B.Liv. Nr 2, 1 (1957).
5. J.R. Richardson, and M.V. Smith, Technical Report UCLA-P55 (1963).
6. K.R. MacKenzie, see paper VIII-6.
7. A.J. Cox, et al., Nucl. Instr. and Meth., 18-19, 25 (1962).

DISCUSSION

KERST : I was surprised to see how serious the Lorentz dissociation is at 700 MeV. Since this dissociation becomes easier as the quantum number for internal excitation of the accelerated entity increases, I would like to ask if your estimate is for the ground state, or if it attempts to include possible excited states for ions in the beam?

HADDOCK : No, the curve of Fig. 1 was obtained by using Hisky's so-called C curve, i.e. the central value. In the event that this curve is wrong, this will reduce the maximum energy at which these qualities can be obtained. Measurements are in progress to determine this curve exactly.

LAPOSTOLLE : What of the possibility of stripping negative ions and the facilities neutrals might provide?

WRIGHT : Based on cross-sections recently measured by Pyle, Berkner and Kaplan (LRL) at 10 MeV, it is possible to estimate the fraction of a circulating H^- beam which may be extracted as neutrals. Fig. 7 shows the cross-section ratios for nitrogen stripping.

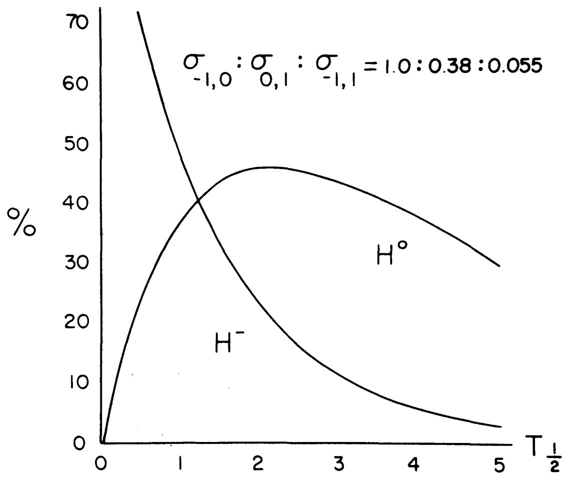


Fig. 7 Stripping data, presented by Wright in discussion.

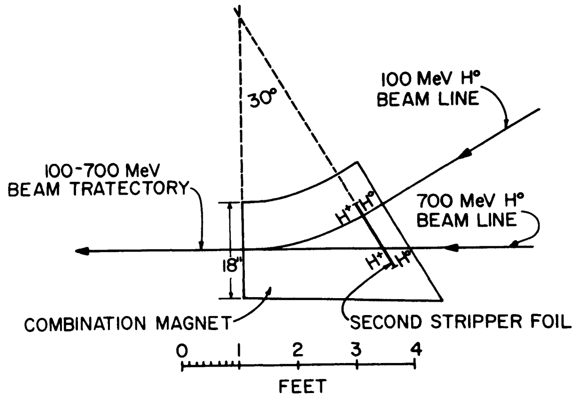


Fig. 8 An application for neutral beam, presented by Wright in discussion.

At two half thicknesses about 45% of the initial beam emerges as neutrals. The absolute cross-sections are such that solid targets can be made sufficiently thin to attain this fraction of neutrals for energies only above about 150 MeV. Fig. 8 shows how, with a "combination" magnet, neutral beams can be used to produce an external beam with continuously variable energy along a constant beam line.