GENERAL DESIGN AND FEATURES OF NEGATIVE ION CYCLOTRONS*

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(Presented by B. T. WRIGHT)

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.

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Due to motion in a magnetic field, an H^- ion in its rest frame experiences an electric field E(MV/cm)=0.3 $\beta\gamma B$(kGs). If the value of E becomes large enough, an appreciable fraction of the ions will undergo «electric stripping» within a few revolutions. Fig. 1 shows the information available on ion lifetime vs. electric field strength in the region of interest. The curves shown represent theoretical calculations of Khoe [1] Khuri [2], Darewych and Neamtam [3], and Hiskes [4]. The recently reported preliminary experimental results of Verba et al. [5] agree in the range of the measurements (2.0—2.4) MV/cm with the theories of Khoe and Khuri. The theoretical lifetimes

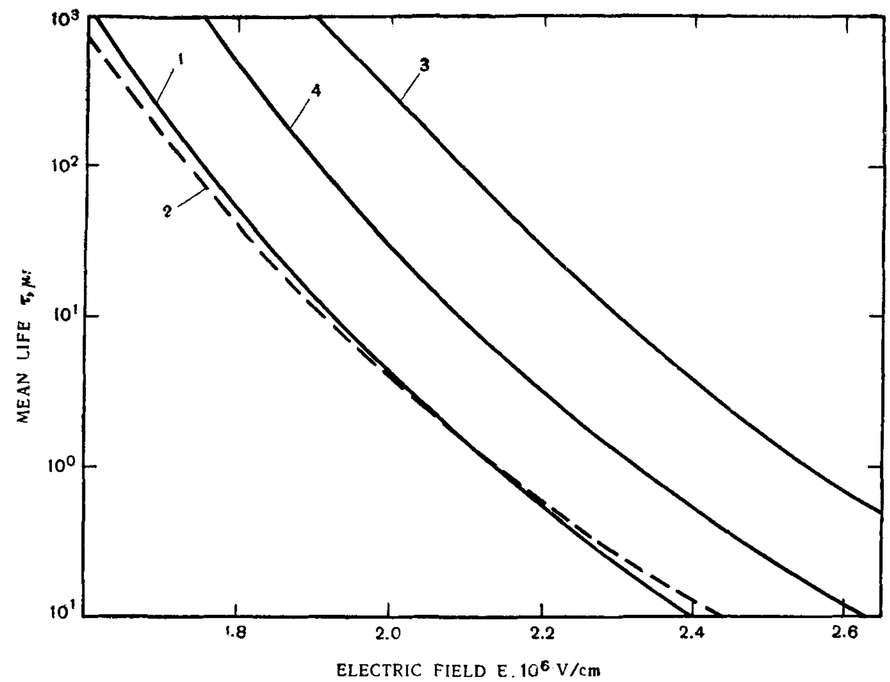

Fig. 1. Lifetime vs. electric field strength according to several theoretical calculations:
1 — Khuri; *2* — Khoe; *3* — Hiskes; *4* — Darewych and Neamtam.

differ by almost two orders of magnitude, and the experimental values are uncertain by about two-thirds of an order of magnitude. The cyclotron study presented in this paper is based on the experimental lifetimes, extrapolated to the region of interest (1.6—2.0 MV/cm) by the theory of Khoe.

paper. The hill field at the final radius is 1.15 times the mean field. The solid curve in Fig. 3 presents the fractional loss as a function of energy.

The basic data required to compute ion loss by gas stripping are shown in Fig. 2. The dashed line, which represents a blending of

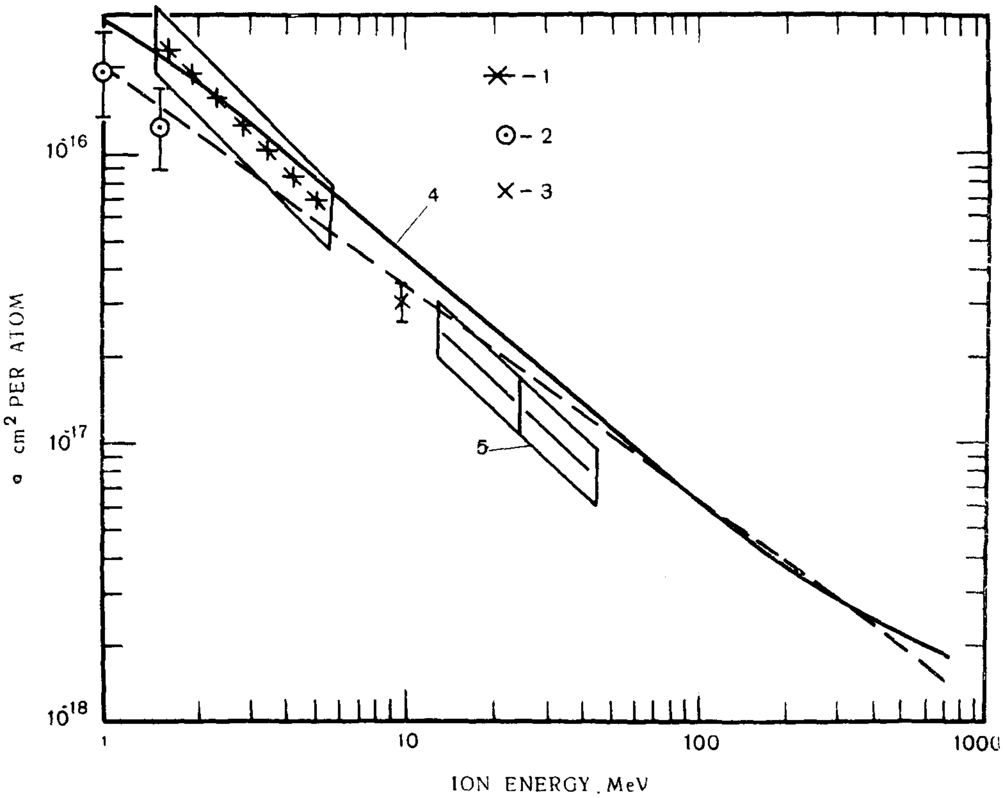

Fig. 2. The cross section $\sigma_{-1,0}$ per atom of air vs. ion energy. The dashed line was used as the basis of desing for the cyclotron herein described:
1 — Fremlin and Spiers; *2* — Allison; *3* — Pyle et al.; *4* — Wright; *5* — Verba et al.

According to a formulation by Richardson [6], the fractional beam loss per unit energy interval (MeV) due to electric dissociation is given by

$$-\frac{1}{N}\frac{dN}{dE}=\frac{\alpha}{1.52\bar{B}\tau\Delta E},$$

where α is the fraction of a sector where the magnetic field is that of the hill=0.58, $\bar{B}$ is the mean field in kGs=4.02 kGs. τ is the negative ion lifetime in microseconds=21 μs and ΔE is the energy gain per turn in MeV= = 0.52 MeV. The numerical values apply to the final radius of the design presented in this

experimental values [7] at low energy with computed values [8] at high energy, was used as a basis for the design presented in this paper. The stripping cross section per atom is given by the empirical relation $\sigma=2\times10^{-16}$ $[1/E$ $(\mathrm{MeV})]^{0.77}\mathrm{cm}^2$. The dashed curve of Fig. 3 gives the per cent loss per MeV at an operating pressure of 10^{-7} Torr for the design presented.

As a result of these beam loss considerations, we find that if 40 μA of beam are accelerated to 625 MeV, insofar as radiation and activation considerations are concerned, the equivalent of 25 μA of 625 MeV protons are lost during the course of the acceleration. The radiation due to lost beam is assumed to be proportional to the energy at which it is lost. Ninety-five microamperes may be accelerated to 600 MeV or 500 μA to 500 MeV and in each case produce the same radiation as for 40 μA accelerated to 625 MeV.

Design of the magnetic field is based on the large and increasing body of theoretical and practical knowledge of sector-focused cyclotrons. Six-fold symmetery was chosen. The hills are made as wide as possible at the maximum radius in order to reduce the maximum magnetic field to as low a value as possible. Radial hill edges with an included angle of 18 degrees are used to half-radius beyond which the spiral angle increases to a maximum of 78 degrees and the width of the hill iron to 47 degrees. 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.

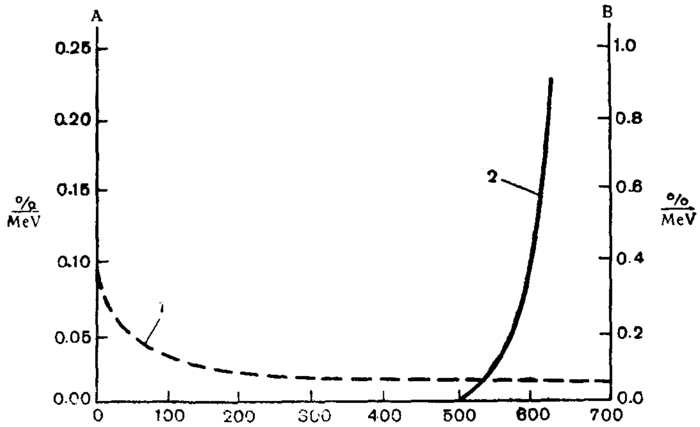

Fig. 3. Computed beam loss due to both gas and electric dissociation for the cyclotron desing herein presented: *A* — scale for gas stripping; *B* — scale for electric dissociation; *1* — gas scattering; *2* — electric dissociation.

RADIATION CONSIDERATIONS*

The activation of the machine by the internally lost beam has been estimated by comparison with the beam lost in the 184-inch cyclotron at Berkeley. Loss due to gas stripping is azimuthally uniform, and that due to electric dissociation is spread uniformly over about 60% of the circumference. Since the circumference is large, the lost beam is spread over a very large area.

The gamma field strength inside the cyclotron vault due to residual activity of the cyclotron is estimated to be about twice that observed near the 184-inch cyclotron, which has the following values one foot outside the vacuum tank: at shutdown, 0.27 R/h; 12 h after shutdown, 0.19 R/h; and 7 days after shutdown, 0.11 R/h. Within the allowable dose rate of 100 mrem per week, an operator could spend only ten minutes per week inside the cyclotron room if he were to enter immediately after shutdown. For this reason, no more equipment than necessary would be located in the cyclotron room. Remote control would be provided for all adjustments and quick-changing features built into the minor assemblies. Most of the equipment requiring frequent servicing or adjustment would not be located in the cyclotron room, but in the basement below a twelve-foot thick concrete floor. In this room the neutron level is not high enough to produce appreciable radioactivity.

The protons stopping in the iron shield or yoke produce neutrons which penetrate the remainder of the local shielding around the machine and 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 feet of ordinary concrete. The vault walls are ordinary concrete 20 feet thick making the total equivalent thickness 40 feet of ordinary concrete.

With 25 μA equivalent beam loss in the cyclotron, and considering the obliquity of the beam with respect to the normal to the shield thickness, the radiation outside the vault is 1.4 neutrons/cm$^2\times$s. The corresponding dose rate is about 9 mrem in 40 h, which is about a factor of ten below the intensity allowable for radiation workers exposed forty hours per week over a long period.

* We are indebted to Dr. Roger Wallace of the Lawrence Radiation Laboratory for much assistance in connection with these considerations.

MAGNET

The cyclotron maget (Figs. 4 and 5) is unusual because of its large diameter and its low maximum field. Because of the large size, the conventional H 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 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 entirely feasible and provides a firm basis for cost estimating. Coils around the individual poles, while individually smaller, introduce a problem in exciting the center of the magnet and appear to be inefficient in the use of ampere turns due to adjacent conductors carrying currents in opposite directions. They do, 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 contain about 100 t of copper and have an outside diameter of 76 feet. They would, of course, have to be wound in place as they are much too large to move through the streets.

The magnetic forces, amounting to a total of about 2300 t 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 t. Mating surfaces and

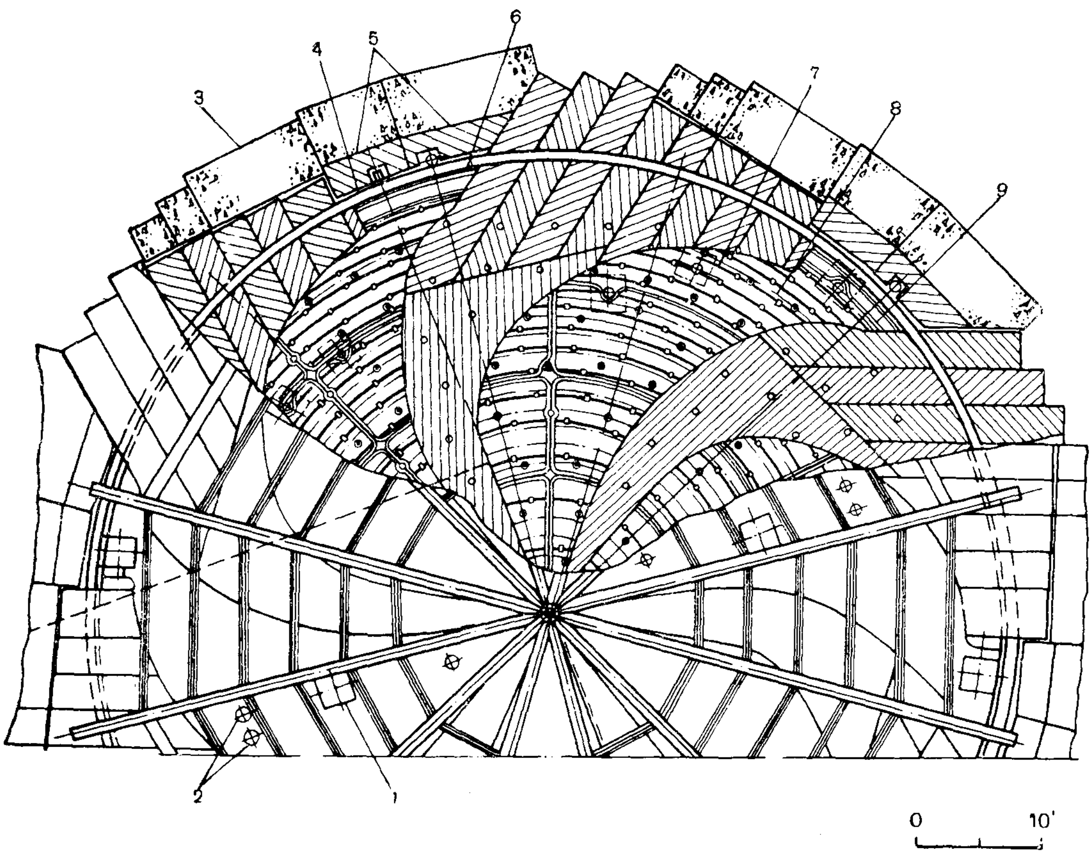

Fig. 4. Plan view, showing spiral shape, tank support frame, main coil, and other indicated details of the design:

1 — ion pump; *2* — resonator tuning actuator; *3* — heavy concrete shielding; *4* — main coil; *5* — steel shielding; *6* —vacuum tank; *7* — profile coil; *8* — heating tube; *9* — harmonic coil.

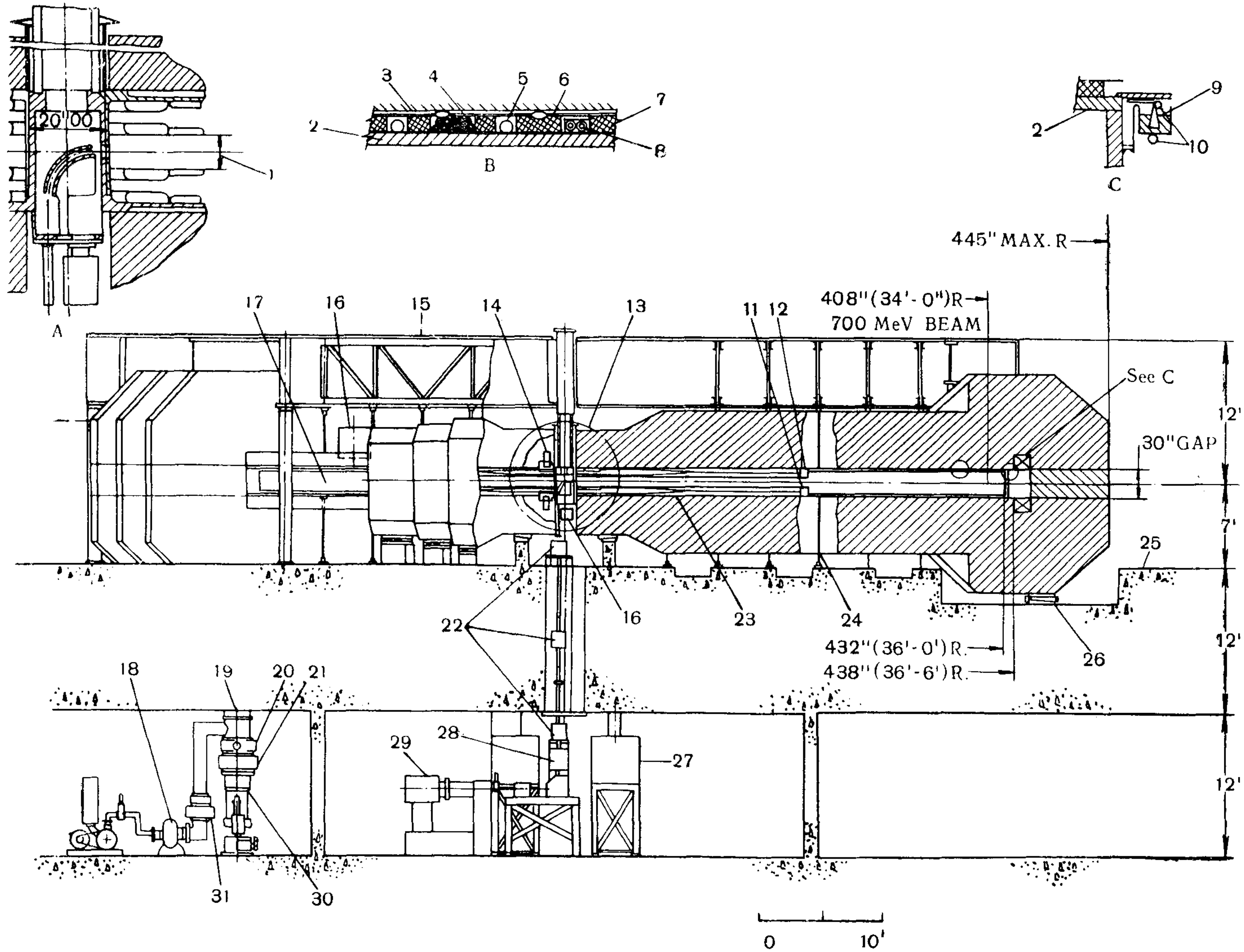

Fig. 5. Horizontal section, showing return yoke, shielding, resonators, and other indicated details of the design: *A* — detail A; *B* — tank wall detail; *C* — solder seal detail; *1*—8.5'' aperture; *2* — tank top; *3* — core; *4* — mineral insulated harmonic coil; *5* — heating and cooling tube ;*6* — thermal core shield; *7* — thermal insulation; *8* — mineral insulated profile coil winding; *9* — soft solder; *10* — heating tube; *11* — lover resonator; *12* — upper resonator; *13* — detail A; *14* — resonator tuning actuator. 16 places; *15* — tank support frame; *16* — ion pump; *17* — port; *18* — blower; *19* — duct to cyclotron tank; *20* — valve; *21* — L. N. Baffle and Manyfold; *22* — focusing magnets; *23* — pole face windings; *24* — skyhook; *25* — fin. floor; *26* — adjustable supports; *27* — RF power amplifier; *28* — buncher; *29* — injector; *30* — mercury diffusion pump; *31* — L. N. Baffle.

the surfaces facing the gap and valley would be machined while other surfaces would be flame-cut. The magnet design provides for assembly by setting one piece on top of another, bolting each in place 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. 5, 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.

In addition to the main exciting coils, trimming coils to adjust the shape of the field are provided. These 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 are provided, each consisting of four turns of mineral-insulated cable, two turns on each side of the ap. They are capable of correcting for a radial gradient of 0.1 percent per foot. For this purpose, a conductor current of 500 A is required. The twenty-four pairs of harmonic coils require 10 A and are 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 3000 kW. The required trim coil power is about 500 kW.

VACUUM SYSTEM

The requirement of a tank 22 m in diameter by 76 cm high to contain a vacuum of 10^{-7} 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 tank to 200° C while it is installed in the magnet. Atmospheric pressure produces a load of about 3900 t on each cover of the tank. This load is 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 fabricated of 2.2 cm stainless steel plate. This thickness corresponds to a skyhook spacing on 1.2-meter centers. The tank would probably be shop-welded in sections and the sections welded together at the site. The principal vacuum seal is around the periphery of the tank. This is planned as a solder seal that will be melted by controlled heating when it 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 bakeout and a few days'pumping. The mercury pumps will handle the outgassing of the ion pumps when they are first started and will assist in the pumpdown before the ion pumps are started. Baking the tank is accomplished by the use of pressurized water 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.

ACCELERATING SYSTEM

The radio frequency accelerating system uses two dees resonating at 11.04 MHz, the third harmonic of the ion frequency. The peak voltage is 130 kV to ground [9]. The frequency was chosen to permit location of the dees entirely inside the circular vacuum tank. As is shown in Fig. 6 each «dee» consists of eight subassemblies, each of which is a separate resonant circuit. What corresponds to the top of one dee and the adjacent liner, for example, is four resonators side by side. 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 while 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. In order 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 at this point. The optimum depth of beams and capacity loading to minimize flexibility and RF power is still to be determined. The present design dissipates 1900 kW in copper loss and has a static deflection, uncorrec-

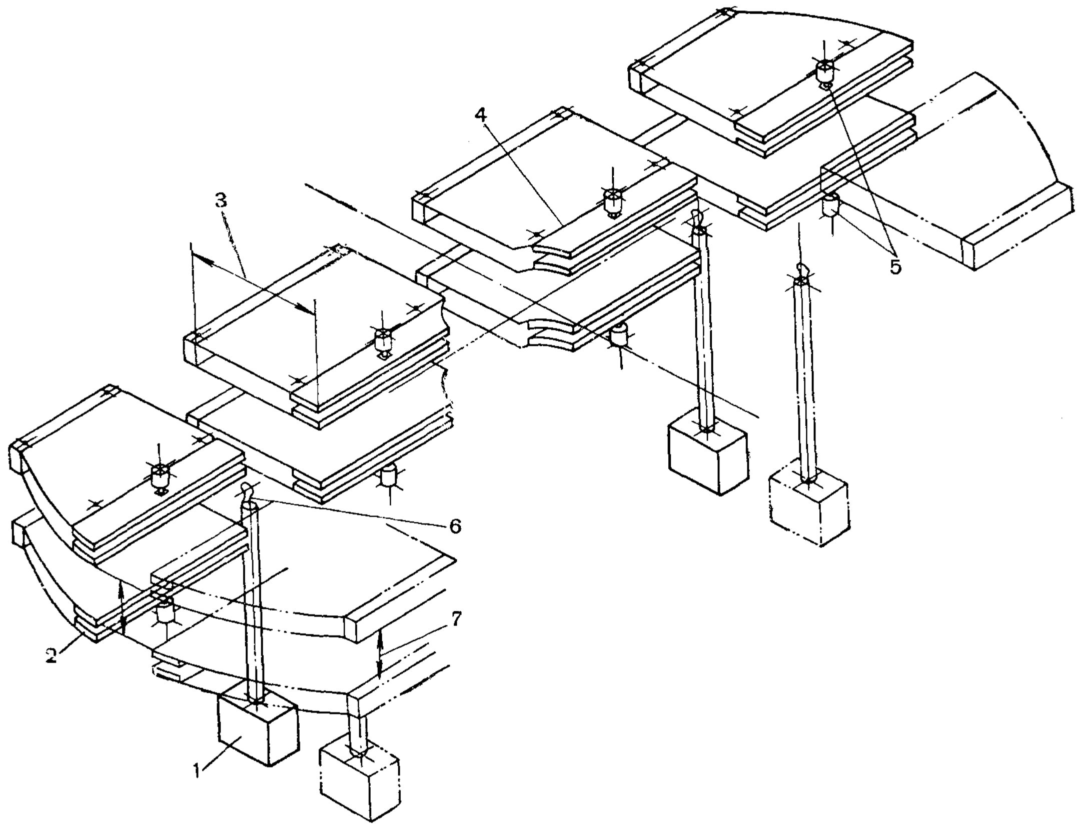

Fig. 6. Perspective drawing of the accelerating electrodes:
1 — power amplifier; *2* — loading capacitor; *3* — approx. $\lambda/4$; *4* — hinge; *5* — dee tuning servo actuator; *6* — coupling loop; *7* — aperture.

ted, of three inches in its 18-foot length. As the resonators would be shaped to deflect into a horizontal position when installed, the calculated deflection is primarily a measure of stiffness.

The maximum RMS current density of about 80 A per inch can 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.

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 [10].

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 dc 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 dc accelerator will remove most of hydrogen gas introduced through the ion source, so that no appreciable quantity of gas will enter the main vacuum tank. The principal design specifications of the cyclotron are shown in Table 1.

Table 1

Principal design specifications for the design study herein presented

Particle	H^-
Max. energy	625 MeV
Current	40 μA at 625 MeV 95 μA at 600 MeV 500 μA at 500 MeV
Max. orbit radius	10.4 m
Magnet	
Sectors, Number	6
Pole tip diameter	22.3 m
Gap	76.2 cm
Ampere turns	595,000
Wt. iron	7000 t
Wt. copper	106 t
Power	3000 kW
Profile coil pairs	17
Harmonic coil pairs	24
Dee volts, peak	130 kV
Max. energy/turn	520 keV
Ion frequency	3.68 MHz
Dee frequency	11.04 MHz
RF power	2750 kW
Operating vacuum	10^{-7} Torr
Baking temperature	200° C
Injection energy	150 keV
Injected current	10 mA
Extracted beam energy range	200 to 625 MeV
Shielding in median plane (equivalent)	40 ft. concrete

EXTERNAL BEAMS

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 causing them to reverse their direction of curvature in the magnetic field. The resulting outward curvature brings the ions quickly out of the cyclotron field. Carbon foils three to five microns thick are used for the stripping targets. Power dissipation in the targets is of the order of 200 mW.

By introducing the target from the top or bottom of the beam, it is possible to extract only a portion of the beam at a given energy and allow the rest to proceed. This technique permits the simultaneous production of several external beams. Several experimental groups may use the machine at the same time.

At 10 MeV for nitrogen, Pyle et al. [11] have determined that $\sigma_{1,0}$: $\sigma_{0,1}$:$\sigma_{1,1}$ = 1.0 : 0.38 : 0.055. If we assume that these same ratios apply at higher energy and for a carbon target, we may compute the per cent of neutrals vs. target thickness for an incident negative ion

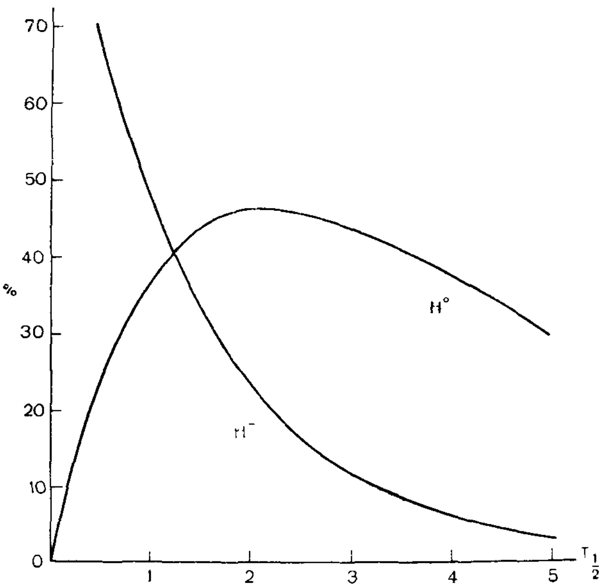

Fig. 7. Percent of neutral ions vs. target thickness for an initially pure negative hydrogen ion beam $\sigma_{-1,0}$: $\sigma_{0,1}$: $\sigma_{-1,1}$ = 1.0 : 0.38 : 0.055.

beam. The result, shown in Fig. 7, indicates that almost half the particles are neutrals for the proper target thickness.

Fig. 8 shows a means of producing a beam of continuously variable energy along a given external trajectory through the use of extracted neutral particles. The neutrals pass through a second stripper foil which is placed in a magnet as shown in Fig. 8. By imagining that a particle of any energy in the indicated range has a reversed trajectory and a reversed sequence of charge changes, it will become clear that the combination magnet can be so energized that the neutral beam line will be tangent to an equilibrium orbit of the same energy. By moving a stripping foil along the locus of such tangents, and at the same time properly adjusting the excitation of the combination magnet, a variable energy external beam is obtained.

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 necessity to introduce low order symmetries in the magnetic field to excite a resonance extraction scheme. Estimates

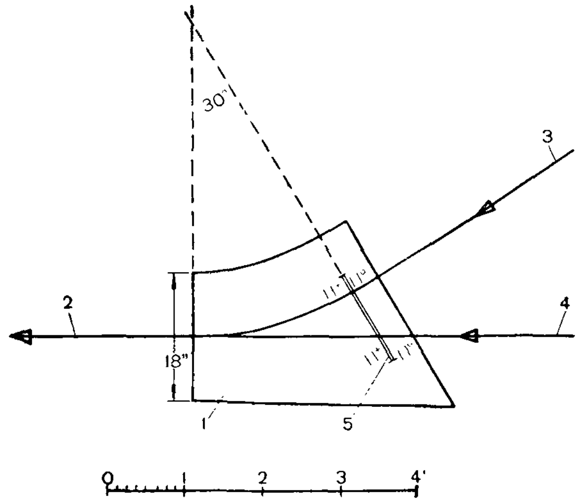

Fig. 8. Showing a means of production of an external beam of continuously variable energy by the use of extracted neutral particles:

1 — combination magnet; *2* — 100—625 MeV beam trajectory; *3* —100 MeV H^0 beam line; *4*—625 MeV H^0 beam line; *5* — second stripper foil.

which have been made of the emittance provide values which compare favorably with the emittance expected of a linear accelerator of the same energy.

DUTY FACTOR

Because of the use of an inflector to introduce ions from an external source, if one wanted to take sufficient care in the adjustment of the magnetic field, microstructure duty factors approaching 50% could be achieved. In practice, however, one would probably be limited a microstructure duty factor of 25% during most of the course of the acceleration. The work of Gordon [12] indicates that as the target is approached, the phase spread (through the use of a non-isochronous magnetic field, for example) may be increased to a maximum of 32%. If the target is radially thin, so that half the beam is intercepted and half passes it, the microstructure duty factor may be increased to 64% by producing additional phase slip which causes the passed ions to decelerate and return to the target on the energyloss portion of the radiofrequency cycle.

Control of the beam injected at the center of the machine leads to great flexibility in the macrostructure duty factor. Also, by control of the range of phase acceptance of the injected beam through the use of narrow slits on the first few turns, and by careful control of tuning conditions and the accelerating voltage, it will be possible to reduce the microstructure duty factor to a few per cent. Pulses of a few nanoseconds duration will result.

ACKNOWLEDGEMENTS

W. M. Brobeck and Associates have made a number of contributions to the design presented in this paper.

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DISCUSSION

A. S. Temkin

What is the rating and type of the accelerator tube?

B. T. Wright

One-half megawatt.

V. V. Kol'ga

Is the 6/4 resonance which occurs in the given device at 400 MeV dangerous?

B. T. Wright

Being guided by the successful crossing of a similar resonance on Oak Ridge Analogue II, we do not consider the 6/4 resonance to be dangerous.

V. P. Dmitrievskiĭ

1. Were the results of the effect of free oscillations on the isochronism considered?

2. What is the thought that went into the selection of the maximum intensity of the internal accelerator beam?

B. T. Wright

1. Due to the control on starting conditions which we obtain through the use of an external injector, the amplitude of the free ascillations will be small and their effect on the isochronous motion small.

2. We do not wish to use extensive remote handling techniques to service the machine. Our internal beam losses are estimated to produce a radiation level near the machine which is twice that near the 187″ cyclotron at Berkeley.

R. S. Livingston

Comment of Dmitrievsky's question on influence of free oscillation on large number of turns.

(1) Large number of turns have been observed satisfactorily isochronous in the electron analogue in Oak Ridge, up to 2600 turn.

(2) The oscillation amplitude can be made very small by high quality injection.

B. I. Zamolodchikov

How do you ensure the strength and rigidity of the internal resonator plates?

B. T. Wright

These planes are a ribbed structure, with the depth of the ribs being a maximum at the ground end.

V. P. Dzhelepov

A remark on the report of B. T. Wright. It seems to me that the current of 40 mA which was specified by you for an energy of about 450 MeV is insufficient for a "meson factory." This is due to the fact that the beam intensity of the secondary particles in such conditions will only be a few times greater than the intensity of the beams from the internal targets of the synchrocyclotron as a result of the single passage of the emerging beam of protons from the external target.