Proposed Midwest tandem cyclotron (MTC)*

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ABSTRACT

The proposed accelerator system consists of two major components, a modified TU tandem Van de Graaff and a 6-open-sector cyclotron. For the acceleration of heavy ions to high energies, the tandem must serve as an injector for the cyclotron. Alternatively, the tandem can be used by itself to supply heavy ions of moderate energy, and then by employing a small $N = 4$ cyclotron as an injector for the $N = 6$ machine, very high energy light ions can be obtained. Energies in MeV per nucleon and external yields in units of 10^{12} particles per s (shown in parentheses) range from 350 (60) for protons to 10 (0·1) for uranium.

The cyclotron is a variable energy $N = 6$ design with a 3-phase rf system including energy flat topping. The vacuum system is to operate at about 10^{-7} torr to minimise heavy ion charge exchange losses. The design aim for energy resolution is to be better than 1 in 10^3.

1. INTRODUCTION

The criteria for the proposed machine[1] are that it should accelerate ions in all regions of the periodic table, with variable energy, high intensity, and good energy resolution. It must reliably produce uranium ions of at least 9 MeV/nucleon and protons of 350 MeV (well above the meson threshold) and at minimum cost. The complex consists of two major components: (a) a TU tandem Van de Graaff with negative ion source and pulser, a gas stripper and mass analyser in the 16 MV terminal, additional gas pumping along the acceleration tube, and a foil stripper at the output, and (b) a variable energy ring cyclotron of $N = 6$ sectors. These components are used with heavy ions, the TU serving as injector. For light particles, the injector for the $N = 6$ cyclotron is a small $N = 4$ machine with a 3 MV Van de Graaff as pre-injector; the TU may then be used independently for other research.

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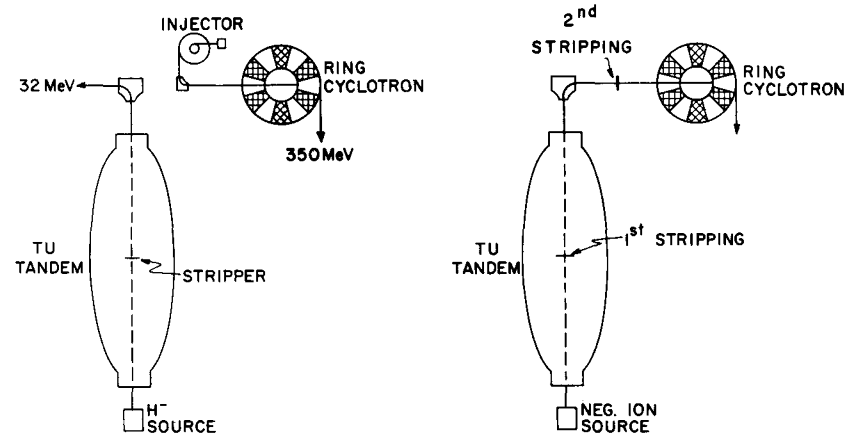

PROTON ACCELERATION HEAVY-ION ACCELERATION

Fig. 1. The three modes of operation of the complex

2. BEAM CHARACTERISTICS

2.1. *Energy and intensity*

The design reliably satisfies both the heavy-ion and light-ion requirements. The maximum value of the field rigidity Bρ with conventional copper coils is 1160 kG-in (2946 kG-cm), corresponding to an energy of 350 MeV for protons and 10 MeV/nucleon for uranium (charge 37+) obtained with the TU operated at the guaranteed terminal potential of 16 MV. The energy is variable over a range of 7:1. With the exception of the protons, the lowest energy of the light ions slightly overlaps or approaches the maximum energy provided by the tandem.

Fig. 2 illustrates the maximum energy per nucleon achievable by the cyclotron as a function of the final charge-to-mass ratio q/A of the projectile.

If superconducting main coils are adopted, as is being considered, the field rigidity for heavy ions will be increased to about 1290 kG-in, but the maximum energy of the proton and other somewhat relativistic projectiles would remain unchanged.

The yield of extracted ions, in particles per second, ranges from 60×10^{12} for protons to $0{\cdot}1 \times 10^{12}$ for uranium.

2.2. *Energy spread*

For a field stability of 1 in 10^5 and injected beam pulses as short as 0·5 ns (1% duty factor), the 350 MeV protons will have an energy spread of about 1 in 10^3 when acceleration is performed by the 3 dees. This same resolution can be had with 5·0 ns pulses (10% duty factor) if the energy gain per turn is 'flat-topped'. This will be accomplished with 3 auxiliary dees, probably located in the otherwise unoccupied valleys, and driven at twice the frequency of the main dees.

Extremely high resolution (e.g. 20 keV for 350 MeV protons) will be obtained

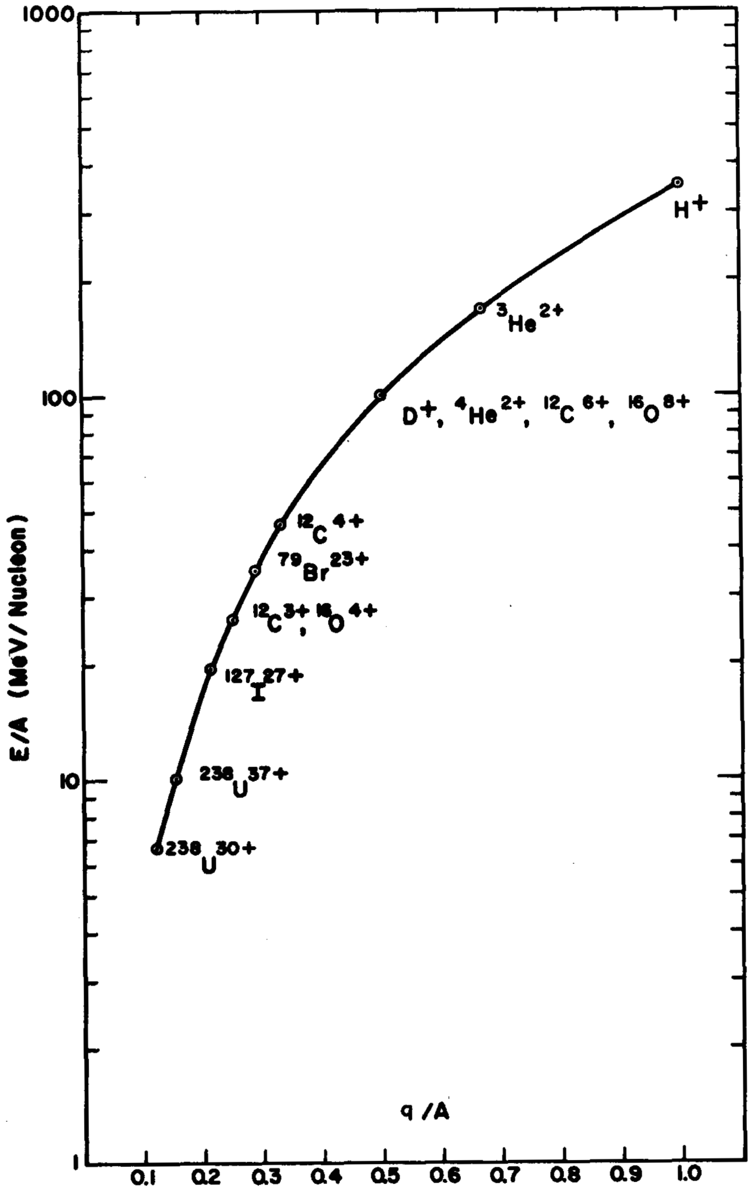

Fig. 2. Energy per nucleon vs *charge-to-mass ratio in the* N = *6 cyclotron*

by a pair of opposed, flat field, double focusing, 120° magnets of 12·4 ft (378 cm) radius.

3. THE CHOICE OF THE NUMBER OF SECTORS

Both four-sector and six-sector designs of the large cyclotron were seriously considered. The four-sector machine is somewhat less expensive, since it has fewer major components. However, orbit calculations show that a six-sector machine is vastly superior in every other respect—in freedom from resonance instabilities for both light and heavy ions, higher energy for light ions, superior performance in beam extraction, lower rf power, ease of construction with non-spiralled magnets and less stringent tolerance in placement.

After several trial calculations, the magnet sectors' effective angular width $\theta = 20^\circ$ has been found to be most suitable for the attainment of 350 MeV protons. The ν_z *vs* ν_x plots for protons and uranium are shown in Fig. 3 for ideal hard and realistic soft edges. Only three resonances need be crossed by protons and none of these are serious; very heavy ions cross none at all.

A 4-poled magnet with 35° sectors is adequate for the injector cyclotron; at its low energy (13·7 MeV for protons) no resonances are crossed at all.

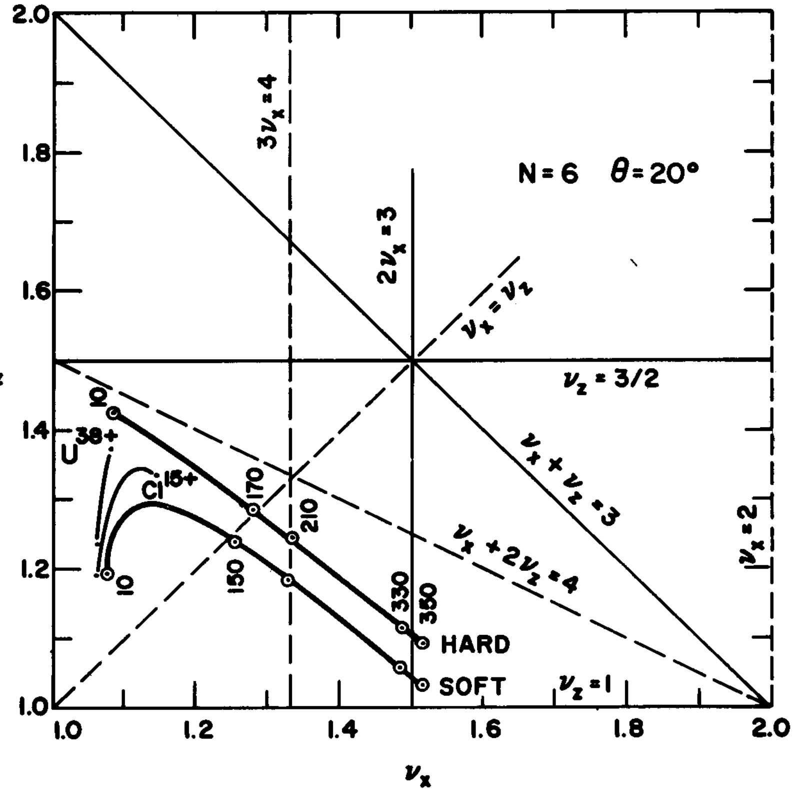

Fig. 3. Resonance patterns for N = 6

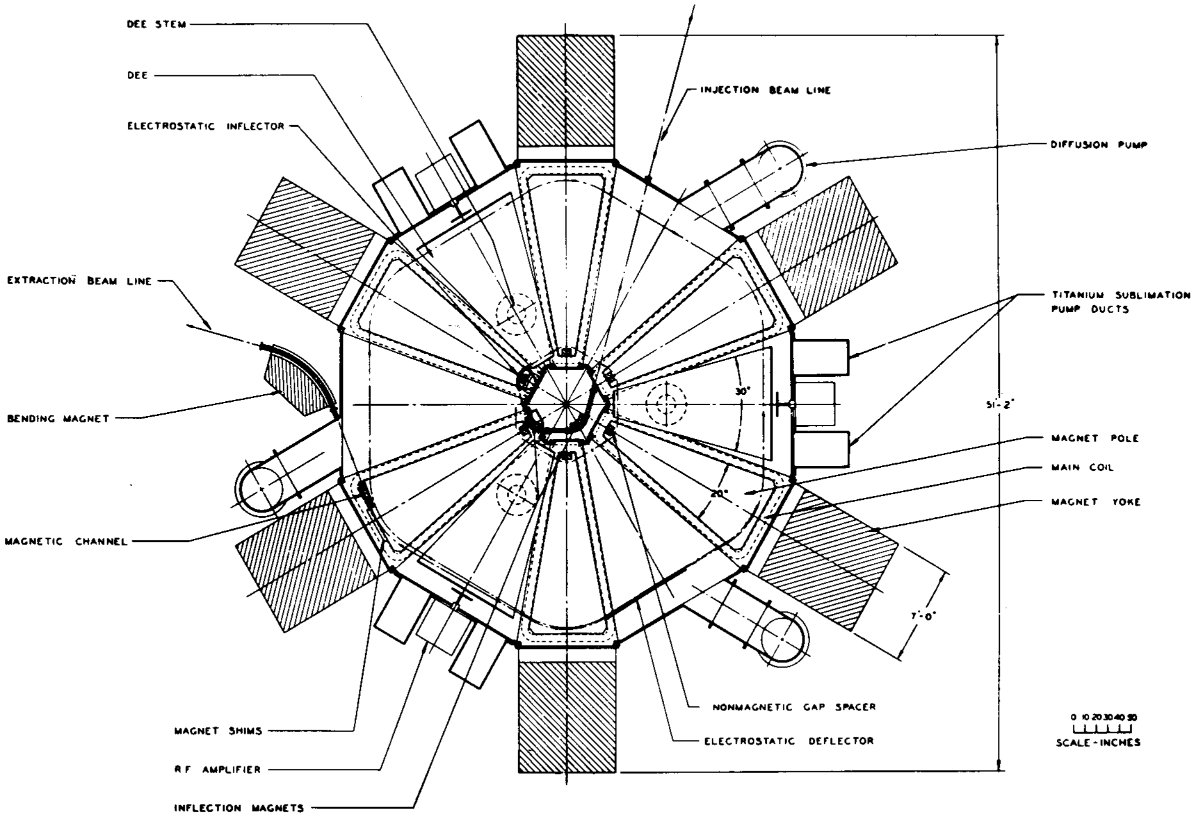

Fig. 4. Plan of N = 6 *cyclotron. If the auxiliary dees (not shown here) are not nested inside the main dees, the injection beam line will be carried over or under the cyclotron*

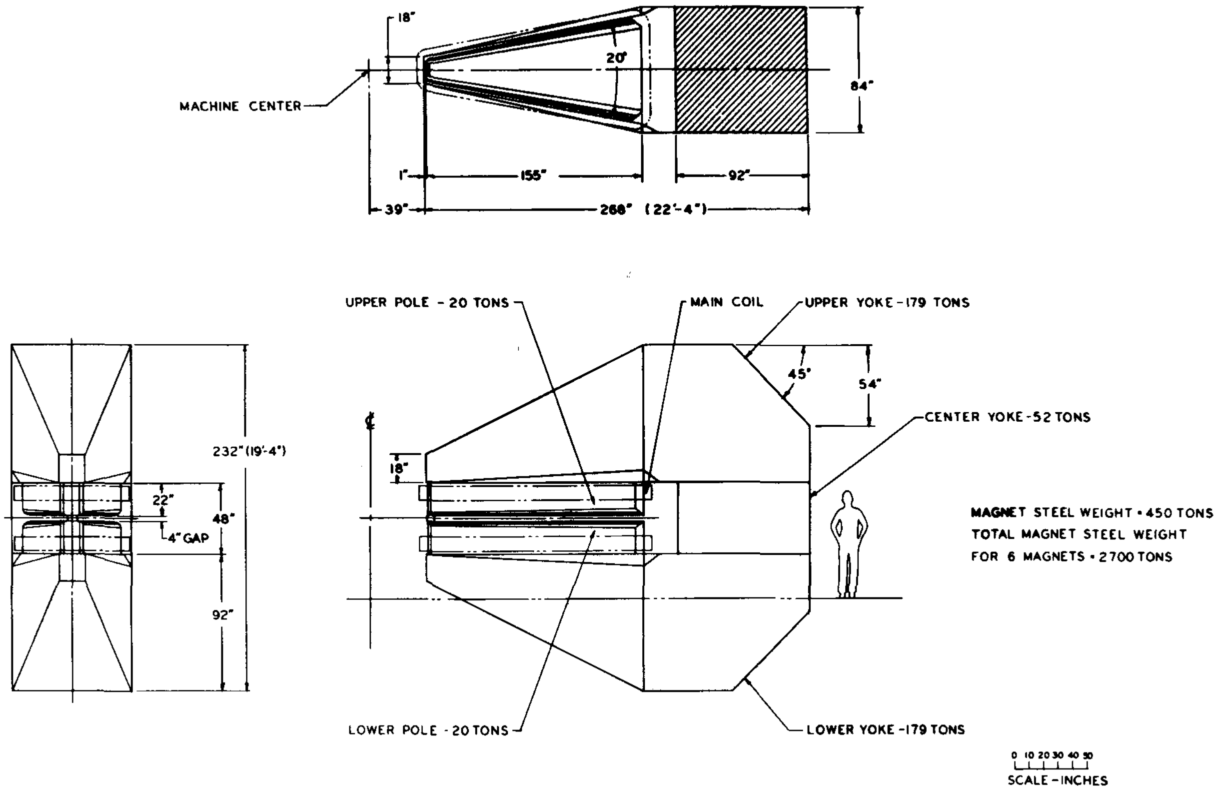

Fig. 5. Magnet sector details of N = *6 machine*

4. MAGNET SECTORS

A plan view of the $N = 6$ cyclotron magnet is shown in Fig. 4, the dimensions of a sector being given in Fig. 5. The maximum magnetic field in the gap has been set at 18 kG. The radial edges of the poles will be contoured to minimise the change in the effective width of the azimuthal field with a change in field intensity. Parameters of the magnets were selected on the basis of a cost-optimisation study.

Two main coils are required for each magnet sector; $9{\cdot}9 \times 10^4$ NI per pole, i.e. 60 turns and 1650 A. Current excitation will be controlled to ~1 in 10^5.

The field for the 350-MeV protons is the most difficult to isochronise because its increase with radius (by a factor of 1·373) is greater than for any other projectile. A current gradient of about 120 A-turns/in will be provided at the inner radius, increasing to 1080 A-turns/in at the outer radius. This requires 32 trim-coil pairs per sector, at 900 A regulated to 1 part in 3×10^4. The d.c. power will then be 470 kW in the trim coils and 360 kW in the main coils; uranium acceleration will require a total of 970 kW. At this time, it is believed that the best design will be one in which all 32 trim coils on one pole are completely 'canned' in a vacuum-tight, welded, non-magnetic stainless steel jacket.

Further magnet studies are required to optimise the combined use of iron and trim coils. For example, it is quite reasonable to plan that the gap should decrease and the field increase toward larger radii. The trim coils would then be used to superimpose a positive or negative gradient as the particle requires. On the basis of orbit calculations, it has been decided that all the trim coils can be made as circular arcs centred on the mechanical centre of the cyclotron rather than that each coil should describe an arc about an appropriate one of the many orbit centres.

One pair of harmonic coils (3000 NI/sector at 550 W) will be provided per sector to compensate for mechanical and magnetic imperfections. These coils will be connected in a three-phase configuration such that a first-harmonic corrective field can be introduced at any azimuth without altering the average field strength around the orbit.

5. RF SYSTEM

Main acceleration in the large cyclotron will be provided by 3 dees in three-phase operation (2 dees will be used for the injector machine). Though more expensive to build than 2 dees, this system requires only two-thirds the voltage and two-thirds the power for the same energy gain per turn (1 MeV for singly charged ions).

Each main dee will be the centre portion of a $\lambda/2$ coaxial resonator whose length can be changed to a fixed smaller value by closing two annular shorts; intermediate frequencies will be obtained by movable panels above and below each dee. The frequency bands will be 22–13·8 and 14–9 MHz. For the auxiliary dees, with a somewhat similar tuning method, the bands will be 44–27·6 and 28–18 MHz.

Harmonic acceleration will be used, with $h = 3, 4$, and 5 for protons from 350 to 50 MeV. Intermediate ions will employ $h = 4, 5$, and 6, while uranium will need $h = 6, 7$, and 8. The use of lower harmonic numbers for heavy ions has been considered (implying a larger rf structure). Calculations show that it will be no more difficult to achieve the required tolerances in the magnetic

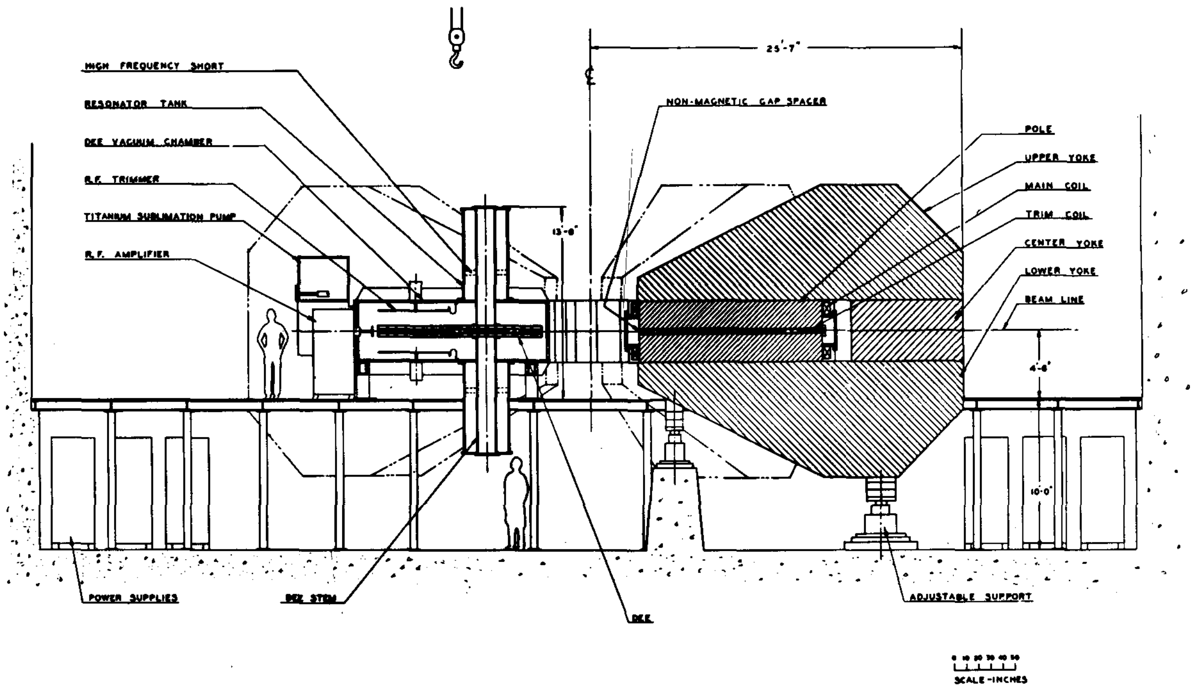

Fig. 6. Section of rf structure and magnet, N = 6

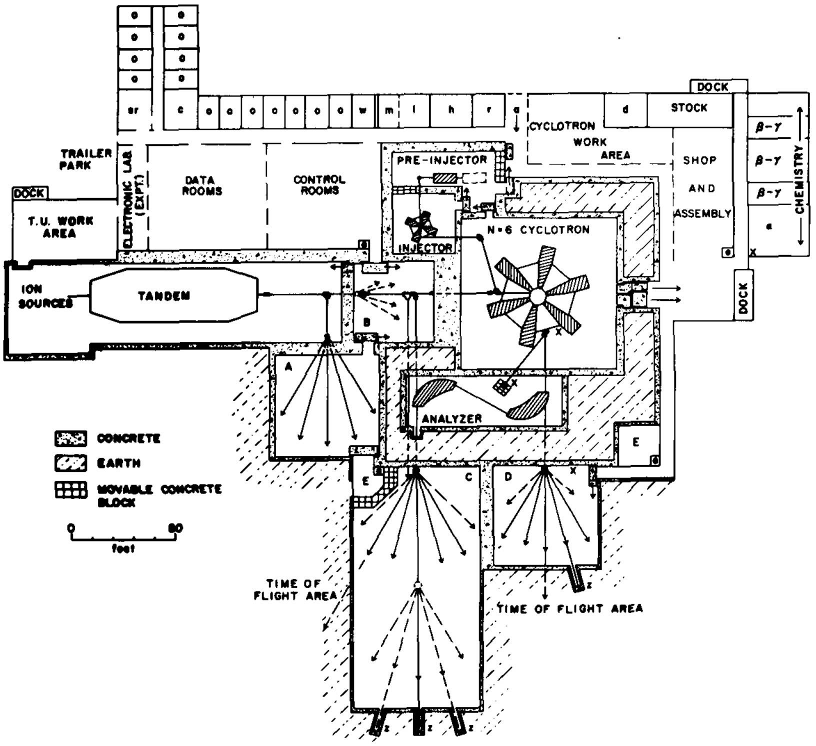

Fig. 7. Plan of accelerator complex

fields for accelerating heavy ions than to come within the tolerances required for accelerating protons to 350 MeV ($h = 3$). Hence, the proposed structure is adequately large and any further size increase to lower the frequency would entail unnecessary costs.

The primary rf signal for the main or auxiliary dee systems will be generated from a precision variable-frequency oscillator. This signal is coupled to a wide band phase splitter from which the three-phase rf voltage signals are obtained. Each of these voltages is amplified by an identical amplifier chain and is capacitively coupled into the dee resonator. The main power amplifier in each chain uses an RCA A2872A tetrode, capable of delivering 250 kW of rf power. It is conservatively designed and will operate at a maximum level of 180 kW for a dee-to-ground voltage of 250 kV. To conserve power, the voltage on a main dee is allowed to droop from a maximum value V (250 kV) at the extraction radius to a minimum of about 0·6 V at lower radii. Calculations show that this does not jeopardise the effective flat topping effect of the auxiliary dee.

Each dee system has three feedback loops: (a) to control the resonant frequency of the structure, (b) to stabilise the amplitude of the voltage (1 in 10^4), and (c) to control the relative phase of its voltage with respect to other dee voltages (0·16°).

General parameters are given in Table 1.

Table 1. PARAMETERS OF THE MAIN AND INJECTOR CYCLOTRONS

	Main Cyclotron		*Injector Cyclotron*	
No. of sectors, N	6		4	
Injector	$N = 4$ cyclotron or tandem		3-MV dc pre-injector	
Overall diameter	51 ft (1555 cm)		15 ft (457 cm)	
Magnet				
Sector width	20°		35°	
Magnet gap, cm	10·16		5·08	
Total weight of iron, tons	2700		72	
Power, operating max, kW (kVA)	970 (1270)		66 (87)	
Radius of final orbit ρ_{max}, cm	164·0		49·0	
Radius of initial orbit ρ_{min}, cm	40·6		23·1	
Final orbit length/$2\pi = R_{max}$, cm	471·2		116·8	
Initial orbit length/$2\pi = R_{min}$, cm	116·8		54·9	
Max field at final orbit B_{max}, kG	18·0		14·8	
Max final rigidity $B_{max}\ \rho_{max}$, kG-cm	2946		724	
Max average field $\langle B \rangle_{max}$, kG	6·25		6·20	
RF	*Main*	*Auxiliary*	*Main*	*Auxiliary*
No. of Dees	3-3 phase	3-3 phase	2	2
Resonance Mode	$\lambda/2$	$\lambda/2$	$\lambda/2$	$\lambda/2$
Azimuthal Width	30°	15°	40°	20°
Maximum Voltage, kV	250	80	100	33
Frequency Range, MHz	22–9	44–18	22–13·8	44–27·6
Frequency Tuning	Tuning Panels and Shorts			
RF Power, kW (kVA)	560 (1250)	45 (100)	32 (85)	6 (13)
RF Power Capability	750 (1650)	63 (140)	45 (115)	8 (18)
Dee Voltage Stability	$\sim$1 in 10^4	$\sim$1 in 10^4	$\sim$1 in 10^3	$\sim$1 in 10^3
RF Phase Control	$0{\cdot}16^\circ$	$0{\cdot}16^\circ$	$\sim 1{\cdot}5^\circ$	$\sim 1{\cdot}5^\circ$
Dee Aperture, cm	5·7	5·7	2·5	2·5
Dee to Ground, cm	8	4	4	2
Energy Resolution	Better than 1 in 10^3		Only 1 in 300 required	
Emittance of external beam at 1160 kG-in.	$1{\cdot}5\pi$ mm-mrad.		$8{\cdot}2\pi$ mm-mrad. required	

6. INJECTION AND EXTRACTION

Injection into the six-sectored cyclotron will require two 75°, 18 kG (max) bending magnets in the open central region, followed by an electrostatic inflector about 44 cm long in the first magnet sector of the cyclotron. This sector will be shimmed at the location of the injected beam to increase the field by about 5·5%. (The separation of initial turns is adequate to permit this.) For the most difficult particles (protons destined for 350 MeV) the inflector field need be only about 66 kV/cm.

Extraction can be aided by controlled use of the $2\ \nu_x = 3$ resonance to enhance the separation of the final orbits. Two electric deflectors, each 70 cm long at 60 kV/cm will flank both sides of an auxiliary dee. The appropriate regions of the following two magnet sectors will be shimmed to give correct focusing and a magnetic channel will lie in the latter third of the second sector. A final bending magnet of about 54° and 15 kG (max) in the next valley will complete the extraction.

7. VACUUM

For the heavy ions, cyclotron transmission exceeding 80% will require a gas pressure of $\sim 1 \times 10^{-7}$ torr. In the beam transport system from the tandem to the cyclotron, 100% transmission will be attained with 3×10^{-7} torr. In the tandem, an efficiency greater than 60% will be achieved if the acceleration tubes are maintained at 2×10^{-6} torr or less.

For the large cyclotron, three oil diffusion pumps (totalling 75 000 l/s, net) will be used to achieve 2 to 3×10^{-6} torr for operation with light ions. For the heavier species, 3 sublimation pumps (totalling 140 000 l/s, net) will be activated to achieve 10^{-7} torr.

REFERENCE

1. 'Midwest Tandem Cyclotron Proposal', **ANL-7582,** Argonne Nat. Lab. (June 1969).