A heavy-ion accelerator facility featuring a separated-sector isochronous cyclotron *

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ABSTRACT

An isochronous cyclotron of modest size with a model TU Tandem Van de Graaff as its injector would have the capability of accelerating the heaviest ions to well above the Coulomb barrier for the heaviest elements. An evaluation of several cyclotron designs has led to an isochronous cyclotron with four separate sectors. As now envisaged the cyclotron will be capable of accelerating heavy ions with a charge-to-mass ratio of 0·15 to an energy of 7·5 MeV/a.m.u. A unique feature of the plan is the use of a source of highly charged ions of the Dubna or LRL type in the terminal of the tandem. For example, to obtain energetic uranium ions, 9+ ions from the terminal ion source are accelerated to 144 MeV (0·605 MeV/a.m.u.), passed through a stripping foil to increase the ion charge to 36+, injected into the cyclotron, and accelerated to 1785 MeV (7.5 MeV/a.m.u.). The cyclotron will also accelerate light particles, for example, protons and α-particles to about 300 MeV, deuterons to 150 MeV, and $^3He^{2+}$ ions to 400 MeV. For this added flexibility a small cyclotron will be provided as the alternate light-ion injector. When the tandem is used separately for experiments requiring its special capabilities, the two cyclotrons can also be used together for independent medium-energy research. When the tandem and large cyclotron are used together for heavy-ion acceleration, the injector cyclotron becomes an independent tool for low-energy nuclear chemistry or isotope production.

1. INTRODUCTION

A new accelerator facility is planned to meet new needs of the various research groups in nuclear chemistry and in nuclear physics at ORNL. This facility couples a powerful tandem electrostatic generator with a large cyclotron to

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provide intense beams of ions to the heaviest elements at energies of at least 7·5 MeV/a.m.u. In addition, it will provide intense beams of very energetic light ions. The maximum proton energy will be 300 MeV, and for non-relativistic particles the maximum energy attainable is 325 q^2/A MeV. A small cyclotron is included as an alternate light-ion injector to permit utilisation of the main cyclotron for medium-energy research whenever the tandem is used separately for experiments requiring its special capabilities. Separate use of the small cyclotron for low-energy nuclear chemistry or isotope production is also planned.

2. ACCELERATION OF VERY HEAVY IONS

In the design of an accelerator for heavy ions, the choice of minimum charge-to-mass ratio, q/A, is very important in determining the accelerator size and cost. For reasonable intensities the q/A of the heaviest ions from an ion source is not expected to exceed 0·05 (12^+ for U ions). A machine to accelerate ions of such low charge-to-mass ratio to useful energies (~ 7·5 MeV/a.m.u.) would be very large, but entirely practicable. For reasons of economy, however, most proposed new heavy ion accelerators would use two accelerator stages with a thin foil or gas stripping cell between them to increase the q/A ratio. The first accelerator may be either a d.c. accelerator or a cyclic accelerator. Since the tandem electrostatic generator injecting into a cyclotron has some attractive features, this system was chosen for the new facility.

3. THE TANDEM INJECTOR

The heavy ion injector proposed for the facility is a tandem Van de Graaff with a rated terminal potential of 16 million volts. To give added flexibility and to eliminate the need for two strippers, we have chosen to provide a source for highly charged ions in the high voltage terminal of the tandem. The terminal has adequate mechanical strength, and at least 30 kW of electric power will be available. The ion source will be of the Dubna[1] or the Berkeley[2] type; both appear capable of large outputs of the heaviest ions with charge states in the 5 to 12 range. Ions with a q/A of 0·0375 (9^+ for U ions) will be produced and accelerated to an energy of about 0·6 MeV/a.m.u. (144 MeV for U ions), passed through a stripping foil to change the ion charge to 36^+, and accelerated to an energy of 7·5 MeV/a.m.u. in the main cyclotron. It is believed that an output of 1 particle microampere of the heaviest ions can be easily achieved with this system.

4. THE INJECTOR CYCLOTRON

Since unique capabilities of the tandem are not required for light ions, a small cyclotron serving as an alternate injector is included in the facility. A four-sectored AVF machine is envisaged with an rf tuning range of 15 to 30 MHz. The rf system is synchronised with the main cyclotron while the ion orbit frequencies may be either two-thirds or four-thirds of that in the main cyclotron.

5. THE MAIN CYCLOTRON

The cyclotron is of the separated sector isochronous type with four 47° sectors. The chief characteristics of the cyclotron are listed in Table 1. The arrangement of the principal elements of the accelerator is shown in Fig. 1. Two opposing open spaces between sectors are used for the main rf acceleration cavities that can provide a voltage gain of 1 MV/turn. The other two spaces are used for the ion injection and extraction systems and for smaller auxiliary rf cavities that operate at the second harmonic frequency of the main cavities. The auxiliary cavities effectively flat-top the accelerating voltage to increase the phase acceptance and reduce the energy spread in the beam.

6. MAGNET SYSTEM

The principal characteristics of the magnet system are listed in Table 2. The 47° sectors have good orbit properties for both heavy and light ions. Fig. 2 shows the orbit properties for $f = 0{\cdot}5$ and $f = 0{\cdot}52$ (45° and 47° sectors respectively); it illustrates how the choice of the larger angle avoids passage through the $\nu_z = 1$ imperfection resonance. For heavy ions the focusing frequencies remain relatively constant, and for protons the axial frequency decreases as the radial frequency

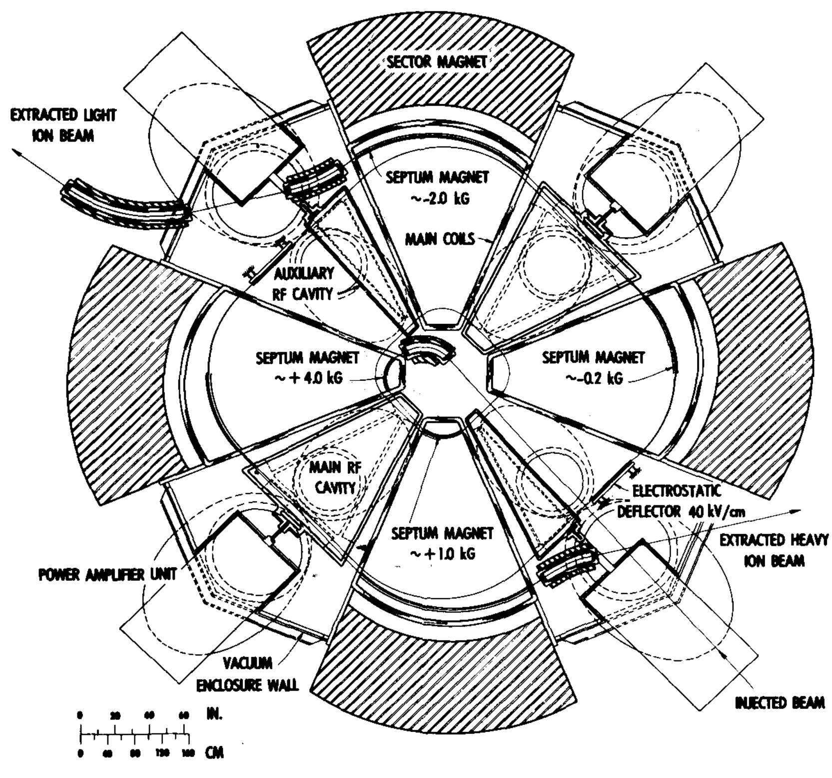

Fig. 1. Plan of the heavy ion cyclotron

Table 1. CHARACTERISTICS OF SEPARATE SECTOR CYCLOTRON

	Heavy Ions		*Protons*
Injection charge-to-mass ratio	0·15		1·0
Injection voltage (MV)	16·0		
Injection energy (MeV/a.m.u.)	0·605		16·6
Final energy (MeV/a.m.u.)	7·5		300·0
Maximum magnetic field (kG)	15·0		15·5
Magnet fraction, f		0·52	
$B\rho_{max}$ (kG-cm)	2612		2700
No. of sectors		4	
Inner beam radius, $\bar{r}_i$ (cm)		90·4	
Outer beam radius, $\bar{r}_f$ (cm)		318·0	
Ion frequency (MHz)	1·891		9·781
Acceleration harmonic No.	5		3
Rf system frequency (MHz)	10		30
Magnet weight (tons)		~1900	
Outer diam. of cyclotron (m)		10·7	

Table 2. MAGNET CHARACTERISTICS

Number of magnet sectors	4
Sector angle (°)	~47
Height (m)	5·0
Diameter, overall (m)	11·1
Main coil power (kW)	500
Number of trimming coils	25
Trimming coil power (kW)	350
Magnet gap, steel (cm)	7·5
Magnet gap, available for beam (cm)	5

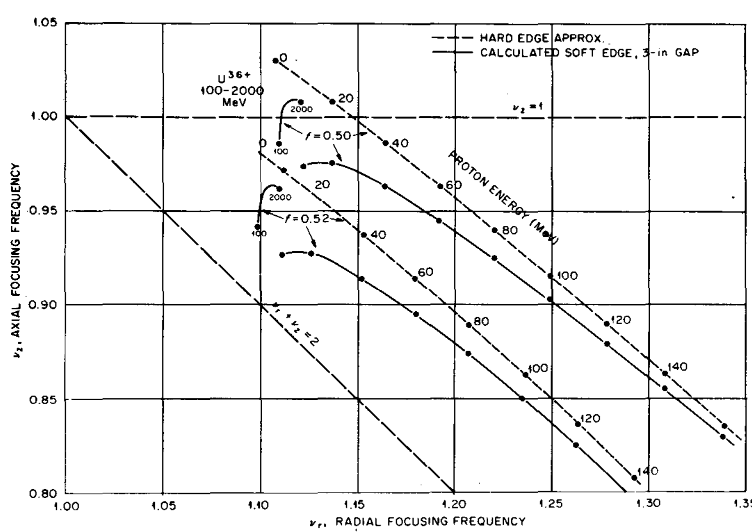

Fig. 2. Orbit properties of the cyclotron for protons and for U^{36+} *ions*

increases. Two resonances are crossed during proton acceleration, ν_r = four-thirds intrinsic resonance at 170 MeV and the $\nu_r - 2\nu_z = 0$ coupling resonance at about 230 MeV. Neither of these resonances is expected to be troublesome for well-centred beams.

Model magnet measurements have been made and computer studies show that the soft-edge orbit dynamics properties are, as expected, in good agreement with the measured magnetic field orbit properties. The measured magnetic field data is being used in tracing orbits to study the effects of resonances and to verify analytical calculations.

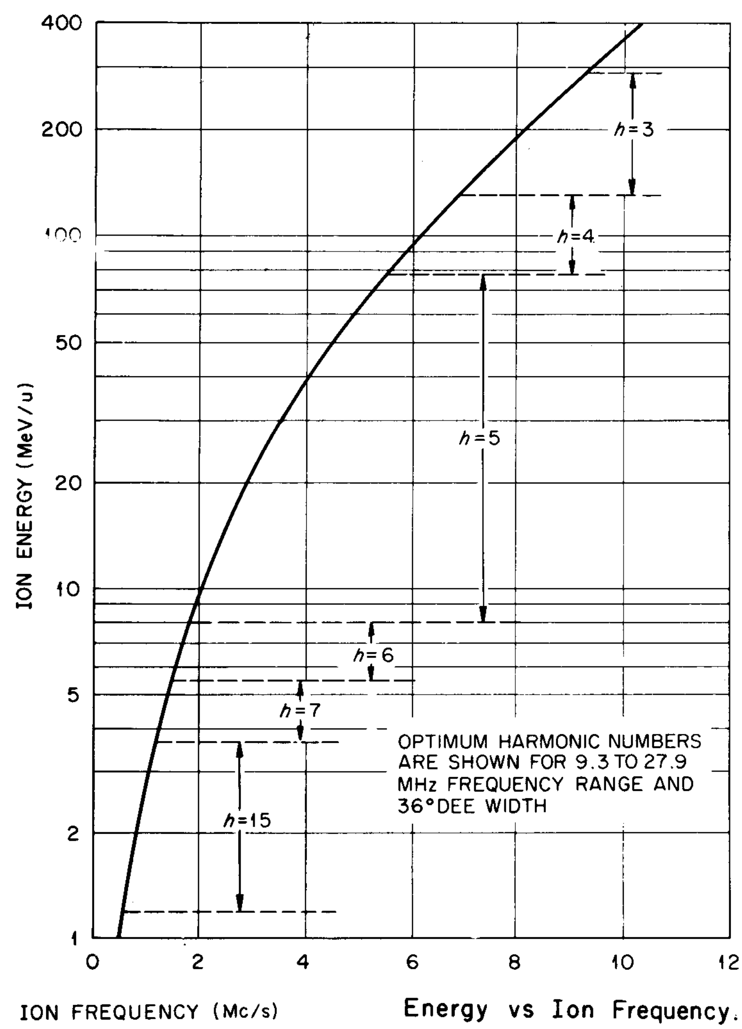

Fig. 3. Ion energy and optimum acceleration harmonics, h, *as a function of orbit frequency*

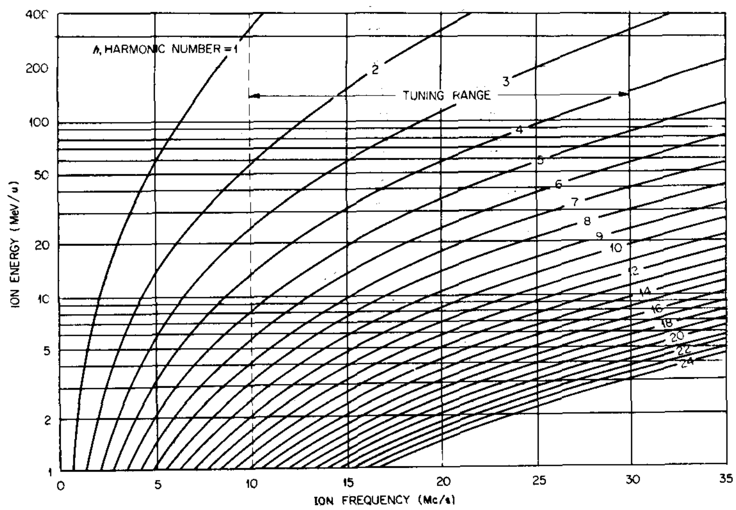

Fig. 4. Ion energy range as a function of harmonic number

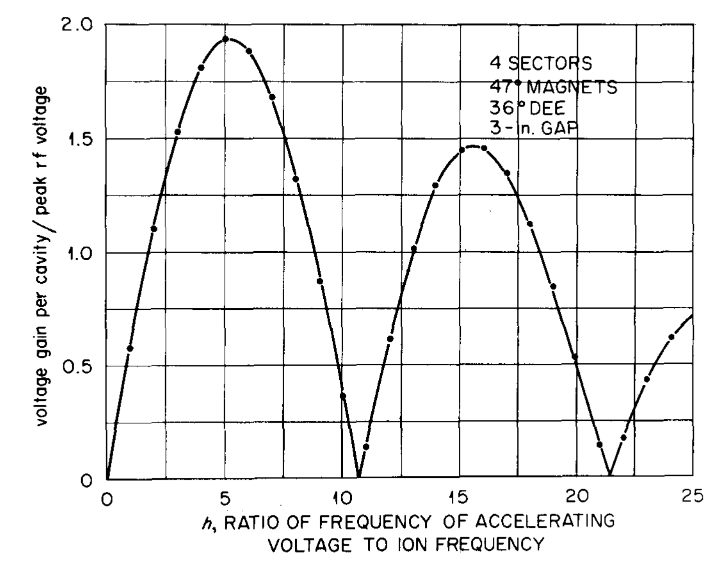

Fig. 5. Ratio of voltage gain per rf cavity to peak rf voltage as a function of harmonic number, or ratio of radio frequency to orbit frequency

7. THE RADIO FREQUENCY SYSTEM

In each of the two main rf resonators a dee of 36° azimuthal width is mounted at the midpoint of a vertical $\lambda/2$ line. Tuning over the 10–30 MHz frequency range is accomplished by a system of movable panels.[3] To span the ~1 to 300 MeV/a.m.u. energy range, the system is operated at various harmonics of the ion frequency as shown in Figs 3 and 4. On these harmonics, a voltage gain per turn of 750 kV to 1000 kV is obtained with a peak rf potential of 250 kV on each of the main dees. Fig. 5 shows the relative voltage gain per turn available with each harmonic. The rf power required is about 400 kW per resonator.

Two auxiliary resonators operated on the second harmonic of the main rf system are used to effectively flatten the top of the accelerating waveform with the purpose of increasing the phase acceptance and decreasing the energy spread of the beam. These resonators are similar to the main units but half scale in azimuth and overall height. The energy spread depends on the phase width of the beam microstructure pulses, with and without the addition of second harmonic, as shown in Fig. 6; clearly, accurate phase control of the second harmonic voltage with respect to the fundamental voltage is necessary if the benefits of the harmonic resonators are to be realised. The usable phase width is also dependent on the amplitude of the second harmonic voltage. The data in Fig. 6 are based on a near-optimum second harmonic-to-fundamental voltage ratio of 0·25.

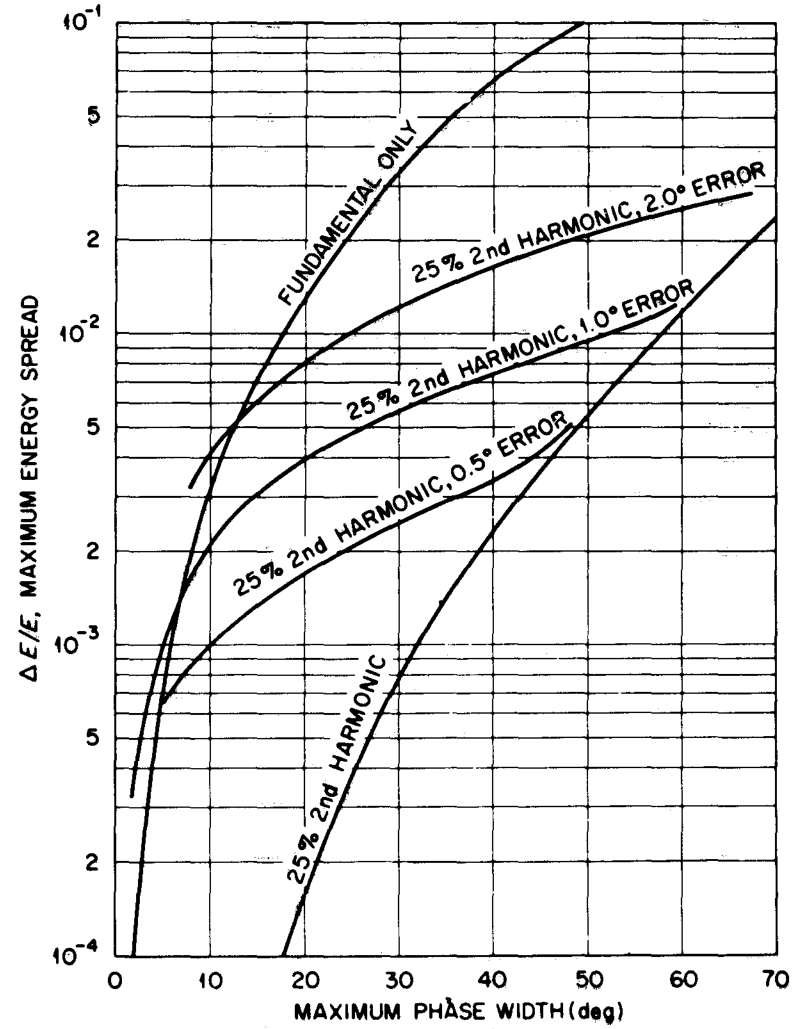

Fig. 6. The energy deviation as a function of the phase width for 25% second harmonic amplitude and for several values of phase error

8. VACUUM SYSTEM

The lifetime for multi-charged heavy ions is given[2] by

$$N = N_0\, e^{-Pt/10^{-10}},$$

where P is in torr, t in seconds, N is ion population. For the acceleration of U^{36+} to 7·5 MeV/a.m.u., t is ~29 × 10^{-6} second; then, N/N_0 is 0·73 for $P = 1 \times 10^{-6}$ torr and 0·86 for $P = 5 \times 10^{-7}$ torr. Therefore, a conventional vacuum pumping system with diffusion pumps is adequate.

9. ION INJECTION AND EXTRACTION

The ion injection system uses three magnets, as shown in Fig. 1. The first, a 78° 15-kG unit, brings the beam nearly to the correct radius and angle for injection. This large magnet is followed by two smaller septum magnets (with thin walls radial to the beam) in successive sectors; they add 4 and 1-kG respectively to the base magnetic field. Injection is eased by the large orbit radius gain per turn; 2·5 cm for protons and 11·6 cm for 7·5 MeV/a.m.u. ions.

The ion extraction system uses both electrostatic and magnetic elements.[4] Extraction begins in the middle of a valley with an electrostatic deflector operating at low gradient. An electrostatic deflector, 1-m long and with a 40 kV/cm gradient will deflect full-energy protons about 3 mm. It is followed in successive sectors by a 22·5° (−200 gauss) septum magnet, and a 45° (−2 kG) septum magnet. Finally, a 23° (−12 kG) magnet bends the beam to clear the magnet yoke. Two essentially identical beam extraction systems will deliver heavy ions and protons to separate research areas.

Highly efficient beam extraction is anticipated. For the highest energy protons, the turn spacing will be about 2 mm and the electrostatic septum thickness need be no more than a small fraction of a millimetre. We confidently expect the extraction efficiency to be well over 50% for high energy protons and to approach 100% for heavy ions, which will have ~2 cm turn spacing at extraction.

DISCUSSION

Speaker addressed: S. W. Mosko (ORNL).

Question by J. R. Richardson (UCLA): I am concerned about the pressure required in the Oak Ridge design—my calculations would indicate that 10^{-6} mm Hg is very optimistic. What data did you use in calculating the beam loss of 36+ uranium ions in your machine?
Answer: Our data is based upon the work done at L.R.L. for the Omnitron proposal. Our design goal is an operating pressure of 10^{-7} torr. For a pressure of 10^{-6} about 75% of the beam will survive acceleration to 7·5 MeV/nucleon. This latter figure is marginal.

J. R. Richardson (UCLA): I would like to point out that the TRIUMF group has put a major engineering effort into evaluating the use of a cryopumping system in their H^- cyclotron. It seems to me that this technique is the answer to the vacuum problem of heavy ion cyclotrons.

J. A. Martin (ORNL): In further answer to Prof. Richardson's question, I would like to add that the number of turns for uranium is only 50 in the Oak Ridge design.

J. R. Richardson (UCLA): I had assumed 80 turns in my estimates for beam loss.

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4. Hudson, E. D., McDaniel, F. E., A Magnetically Self-Septum for Beam Deflection, Proceedings of this Conference, p. 180.