A SEPARATED-SECTOR CYCLOTRON POST-ACCELERATOR FOR THE OAK RIDGE HEAVY ION LABORATORY

S. W. Mosko, E. D. Hudson, R. S. Lord, M. L. Mallory, J. E. Mann, J. A. Martin, G. S. McNeilly, J. B. Ball, K. N. Fischer, L. L. Riedinger, R. L. Robinson

Oak Ridge National Laboratory*, Oak Ridge, Tennessee, U.S.A.

Abstract

A separated sector cyclotron post-accelerator is proposed for the Oak Ridge Heavy Ion Laboratory. The SSC accepts beams from either ORIC or the 25 MV tandem electrostatic accelerator and extends the maximum particle energy to 75 MeV/u for A less than 40 and to at least 10 MeV/u for A greater than 40. The SSC has a field-radius product of 2540 kG-cm, a 4-sector configuration, and azimuthal pole width of 52°. RF acceleration of up to 1 MV per turn is obtained with two resonators in opposite valleys. An RF tuning range of 6 to 14 MHz accommodates acceleration on harmonics 2 through 11. Concentric second harmonic resonators are provided for optimizing phase acceptance.

1. Introduction

In 1969 a new accelerator facility was proposed at Oak Ridge for accelerating all heavy ion species to a minimum energy of 7.5 MeV/u using a separated sector cyclotron with a 16 MV tandem electrostatic injector accelerator and a compact cyclotron as an alternate injector[1]. Later, the minimum energy was raised to 10 MeV/u, the existing ORIC cyclotron became the alternate injector cyclotron, and desired tandem potential was increased to 20 MV[2,3]. Finally, in 1974, construction was authorized for a 25 MV tandem electrostatic accelerator at the ORIC facility[4]. The new tandem will operate in both a stand-alone mode, and as an injector accelerator for ORIC.

The tandem-ORIC facility is still short of the goal of 10 MeV/u for ions beyond mass 100. Therefore, a separated sector cyclotron, SSC, post accelerator is now planned which extends the maximum ion energy as illustrated in Fig. 1. The heaviest ions through uranium will be accelerated to about 10 MeV/u, and lighter ions through mass 40 will be accelerated to about 75 MeV/u. The new SSC configuration is similar to that described in 1972[2]), but it is somewhat more compact due to higher ion injection energy and subsequent higher charge state. Fig. 2 shows a layout of the heavy ion laboratory as it will appear when the tandem accelerator is completed. Fig. 3 shows how the laboratory will look when the SSC is added. Beams from the tandem can be injected into ORIC, the SSC, or used directly. Beams from ORIC can be used directly or injected into the SSC.

2. The Cyclotron

A plan view of the cyclotron is shown in Fig. 4. It is a 4 pole separated sector configuration with an effective pole width of 52 degrees.

*Work supported by the U.S. ERDA under contract with the Union Carbide Corp.

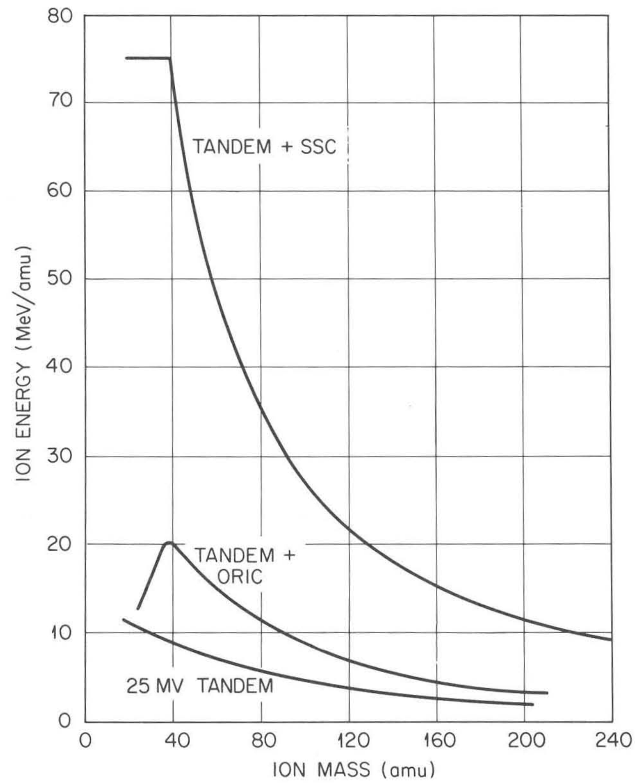

Fig. 1. Maximum ion energy as a function of ion mass. The ion beams are stripped to optimum charge state prior to acceleration in the final stage.

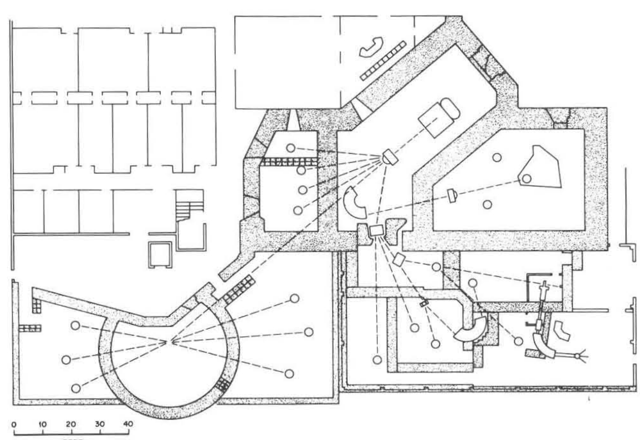

Fig. 2. A plan drawing of the heavy ion laboratory showing the ORIC, the tandem electrostatic accelerator beam lines, experimental areas, and the beam transport system. The tandem is of a vertical design, and located above the beam lines on lower left.

Proc. 7th Int. Conf. on Cyclotrons and their Applications (Birkhäuser, Basel, 1975), p. 600-603

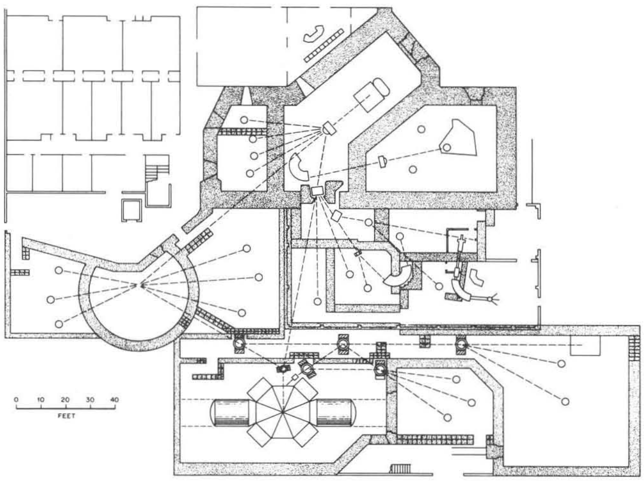

Fig. 3. A plan section drawing of the heavy ion laboratory showing the ORIC, the tandem electrostatic accelerator, experimental areas, the beam transport system, and the new SSC with required additional beam transport system, and new experimental area.

Two of the valleys contain RF cavities, and the others contain injection and extraction components, the injection beam line, and beam diagnostics instrumentation. The machine dimensions from edge to edge are 10 m on the magnet yokes, and 17 m on the RF cavities. Cyclotron characteristics are listed in Table 1. The variable injection radius and respective range for energy ratio are due to unique combinations of injection energy, ion charge, and RF synchronization with ORIC.

Table 1. Cyclotron Characteristics

Maximum Energy, MeV/u	
Uranium ($^{238}U^{43+}$)	10
Carbon ($^{12}C^{6+}$)	75
Maximum Bρ, kG-cm	2540
Energy Constant, K, ($E = Kq^2/A$)	310
Orbit Frequency, MHz	
10 MeV/u ions	2.46
75 MeV/u ions	6.49
Maximum Magnetic Field, kG	15
Orbital Magnet Fraction	0.60
Number of Sectors	4
Energy Ratio, E_f/E_i	15-7
Radius Ratio	3.88-2.65
Injection Radius, Path/2π, cm	73-107
Extraction Radius, Path/2π, cm	283

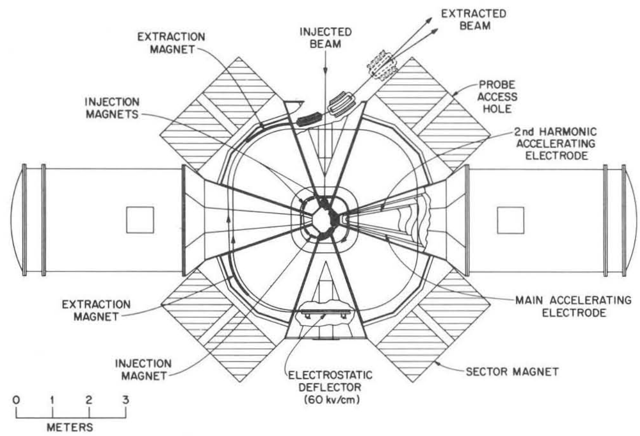

Fig. 4. Plan view of the cyclotron.

Ion energy capability is further illustrated in Fig. 5. Ion energy and respective orbit frequency are shown as a function of average magnetic field and mass to charge ratio. The maximum average magnetic field is a result of the 15 kG maximum hill field and the 0.6 orbital magnet fraction. The latter term is defined as that fraction of an orbit path which lies within the magnet sector. The span of orbit frequencies covered by the RF system for harmonic numbers 2 through 7 is also noted.

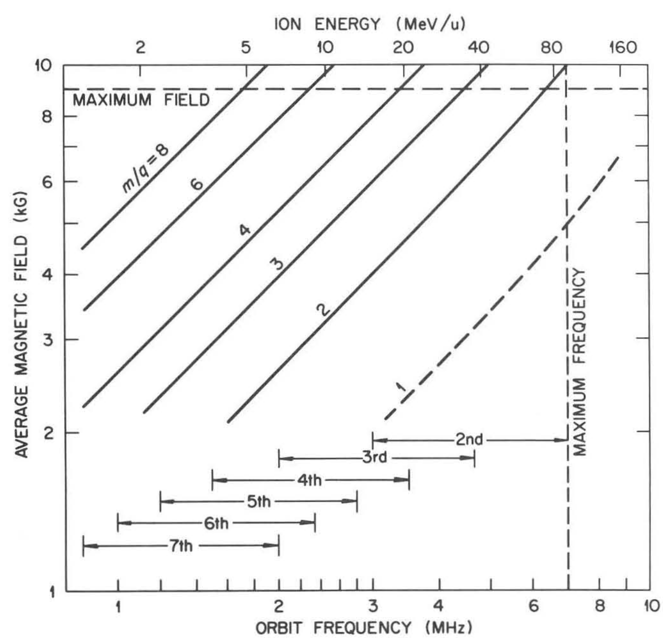

Fig. 5. Final ion energy from the SSC as related to orbit frequency and as a function of magnetic field and mass to charge ratio. The span of the RF tuning range is shown with respect to orbit frequency for several values of harmonic number.

2.1 Magnet System

The effective sector angle of 52° was chosen to provide strong axial and radial focusing of the ion beam without encountering resonances due to magnet periodicity or field imperfections. The relation of axial and radial oscillation, ν_z vs ν_r, is shown in Fig. 6 for a 10 MeV/u uranium ($^{238}U^{43+}$) and a 75 MeV/u carbon ($^{12}C^{6+}$) beam using a 15 kG hill field. These data were derived from model magnet measurements as described elsewhere in these proceedings by Hudson, et al.[5] The open valleys provide sufficient space for the accelerating (RF) system so that the pole tip aperture needs to be only large enough for ion beam transmission. The magnet system characteristics are listed in Table 2.

Table 2. Magnet System Characteristics

Number of Sectors	4
Sector Angle, degrees	52
Overall Height, cm	488
Overall Diameter, cm	1000
Steel Weight, metric tons	1450
Main Coil Copper Weight, metric tons	20
Main Coil Excitation Power, kW	300
Number of Trimming Coil Pairs per Sector	30
Trimming Coil Excitation Power, kW	300
Gap Between Poles, cm	10
Gap Available for Beams, cm	7

2.2 The RF System

The RF system is designed to provide a high rate of energy gain and a large ion beam pulse width concurrent with good ion beam quality. The high rate of energy gain is required for reducing charge exchange losses and for providing good orbit separation at both injection and extraction radii. The large beam pulse width is obtained with 2nd harmonic flat-topping of the RF acceleration wave form. The RF system tuning range is approximately 6 to 14 MHz. Referring to Fig. 5, it can be seen that operation in the 5th harmonic mode covers the energy range of about 2 through 12 MeV/u. Higher energy, as is possible with light ions, requires 2nd, 3rd and 4th harmonics. When ORIC serves as the injector, only odd harmonics are usable.

Characteristics of the RF system are listed in Table 3. The cavities are quarter wave coaxial structures extending radially from the cyclotron as shown in Fig. 4. The dees and respective ground planes are cone shaped. Each 15 degree azimuthally wide harmonic dee is located concentrically within a 30 degree azimuthally wide fundamental dee. Electrode clearances are sufficient to hold about 250 kV on the fundamental dee. Half as much clearance is used on the harmonic dee to obtain transit time factors in the harmonic accelerating gaps which are equal to those in the respective fundamental gaps. RF voltage profiles for the

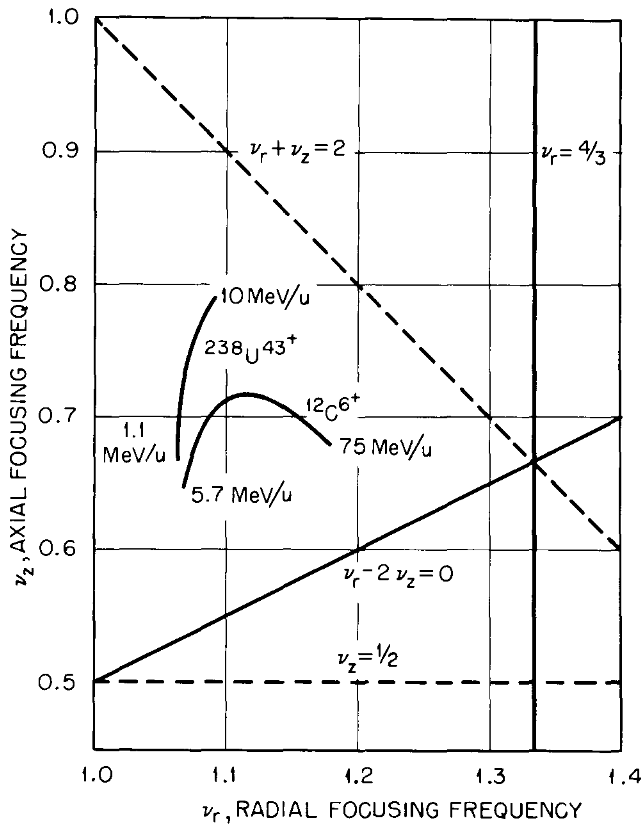

Fig. 6. Focusing characteristics of the SSC magnet as calculated from model data. The data were taken from a 0.15 scale model magnet and smoothed.

dees are shown in Fig. 7. As is typical with radial resonators, the RF voltage decreases with increasing radius; however, this effect is minimized through transmission line shaping. The voltage on the harmonic dee falls off more

Table 3. RF System Characteristics

	Fundamental Frequency	2nd Harmonic
Number of Cavities	2	2
Width of Dee, degrees	30	15
Tuning Range, MHz	6-14	12-28
Coarse Tuning	Shorting Plane	
Fine Tuning	Trimmer Capacitors	
Minimum Electrode Clearance, cm	7.6	3.8
RF Voltage, peak, kV	250	100
RF Excitation Power per Cavity, kW	200	50
Amplitude Stability	1 pp 10^4	
Phase Stability, degrees	± 0.1	

severely than that on the fundamental dee, but the net RF potential (fundamental potential minus the harmonic potential) is nearly constant with respect to radius. When transit time factors are also considered, Fig. 8, the actual potential gained per turn by the ion beam tends to increase substantially with respect to radius. Consequently, the accelerating system will cause a slight beam pulse phase contraction rather than an expansion as one might otherwise expect with a radial RF system.

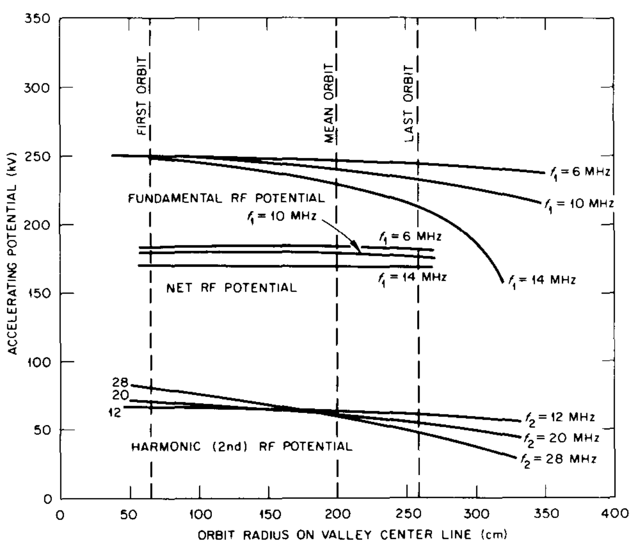

Fig. 7. The RF accelerating potential profile for each accelerating gap.

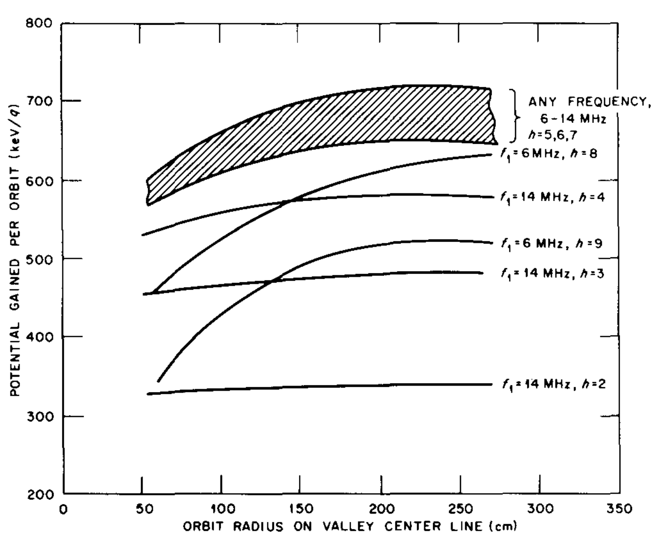

Fig. 8. Voltage gained per orbit (kV) for various orbit harmonic numbers. The data from Fig. 7, net RF gap potential, is multiplied by 4 and corrected for transit time effects. Higher energy gain per turn with reduced beam pulse phase width is available when the second harmonic cavities are turned off.

2.3 Vacuum System

The vacuum system characteristics are listed in Table 4. The base operating pressure, 1×10^{-7} Torr, is sufficient to avoid significant beam loss through charge exchange processes as determined from cross section estimates[6,7]. The system volume includes pole tip vacuum tanks, valley vacuum tanks, and the RF cavities. In order to achieve the required pressure within a reasonable time with a rather large variety of residual gases, a combination of oil diffusion pumps and helium cooled cryopumps is used. Fore pumping is accomplished with a combination of Roots blowers, and oil-sealed mechanical pumps. The system is pumped down to a pressure of 1×10^{-3} Torr in approximately one hour prior to starting up the diffusion pumps and cryopumps.

Table 4. Vacuum System Characteristics

Operating Pressure		1.0×10^{-7} Torr
System Surface Area		7.0×10^{6} cm^2
System Volume		95,000 ℓ
Pumping Speed:	Air	140,000 ℓ/sec
	Water vapor	1,000,000 ℓ/sec
Pumpdown Time		< 15 hr

References

1. J. A. Martin, et al., Fifth International Isochronous Cyclotron Proceedings, Butterworths (1971), p. 41.

2. J. A. Martin, et al., Sixth International Cyclotron Conference Proceedings, American Institute of Physics (1972) p. 54.

3. E. D. Hudson, et al., IEEE Trans. Nucl. Sci. NS-20, No. 3 (1973), p. 168.

4. R. S. Lord, et al., "The Oak Ridge Isochronous Cyclotron as a Booster for a 25 MV Tandem," Proceedings of this Conference.

5. E. D. Hudson, et al., "Magnet Model Studies for Separated Sector Heavy Ion Cyclotrons," Proceedings of this Conference.

6. The Omnitron, UCRL 16828, July (1966).

7. Ch. Schmelzer, 1968 Proton Linear Accelerator Conference Proceedings, Brookhaven National Laboratory report BNL-50120 (1968), p. 735.

DISCUSSION

D. CLARK: Was your choice of K = 300 based on optimum performance or economics?

J.A. MARTIN: It reflects the requirements for an energy of ∿10 MeV/A for the heaviest ions using the 25 MV tandem as an injector.