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DESIGN STATUS OF A SEPARATED-SECTOR CYCLOTRON BOOSTER ACCELERATOR FOR THE HOLIFIELD HEAVY ION RESEARCH FACILITY

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Summary

A separated-sector cyclotron booster accelerator is being designed for the Holifield Heavy Ion Research Facility as a Phase II project to be started in 1978. Phase I of the HHIRF, now under construction, includes a 25 MV tandem electrostatic accelerator, a beam transport and injection system to enable use of the Oak Ridge Isochronous Cyclotron as an energy booster for tandem beams, and some additional experiment areas and associated beam transport systems. The Phase I facility using the ORIC-25 MV tandem combination will provide energies up to about 25 MeV/amu for light ions such as oxygen and more than 5 MeV/amu up to the region of mass 160. The new Phase II separated-sector cyclotron will provide energies up to 100 MeV/amu for light ions and up to 12 MeV/amu for the heaviest ions such as uranium.

Introduction

The basic criteria for the separated-sector cyclotron were developed in 1975[1] and refined in 1976. The present design has an energy rating of 400 q^2/A MeV (q is the charge number and A the mass number of the accelerated ion) to give energies up to 100 MeV/amu for fully stripped light ions and up to 12 MeV/amu for very heavy ions such as uranium. The new design incorporates improvements to provide full-range compatibility with the use of either the 25 MV tandem or the ORIC as injector, greater simplicity, reduced electrical power consumption, and a better vacuum system.

The principal characteristics of the cyclotron are given in Table I. Figure 1 shows the energy-mass characteristics of the cyclotron using the 25 MV tandem as the injector. The facility plan showing the locations of the ORIC, the 25 MV tandem and the Phase II booster cyclotron are shown in Figure 2.

Table I. Principal Cyclotron Characteristics

Energy constant, $K, E=Kq^2/A$	400 MeV
Energy for U^{42+}	12 MeV/amu
Energy for C^{6+}, O^{8+}, Ca^{20+}	100 MeV/amu
$B\rho$	2957 kG-cm
Magnet fraction	0.58 (52° hills)
Energy ratio, E_f/E_i	8-16
Injection mean radius	1.07-0.75 m
Extraction mean radius	3.01 m
RF system frequency range	9-20 MHz

Magnet Design

The magnet design was evaluated with a 0.15-scale model[2], Figure 3. The measurements show that the focusing characteristics were essentially as designed, with ν_r and ν_z away from significant resonances over the full operating range of the accelerator. The only surprises are the significantly larger-than-expected magnetic field between adjacent poles and the amount of correction that would be required to achieve the desired range of isochronous magnetic field contours. The principal characteristics of the magnet system are given in Table II.

The magnetic field between adjacent poles is large enough to require cancellation along the injected beam

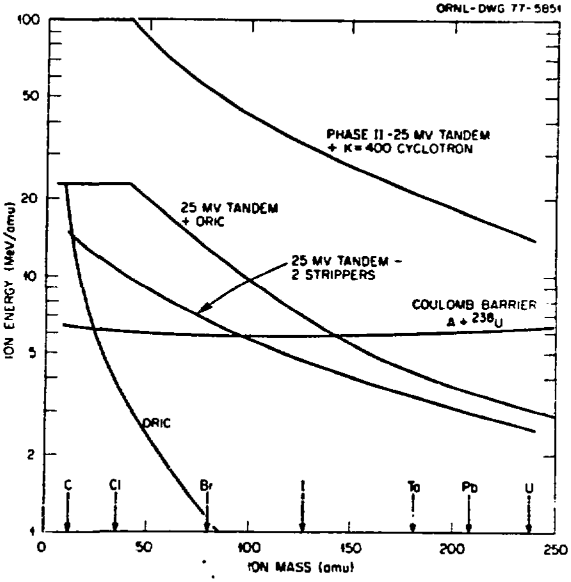

Fig. 1. The ion energy-ion mass characteristics of Oak Ridge Heavy Ion Accelerators. Phase I of the Holifield Heavy Ion Research Facility, the 25 MV tandem, and the transport/injection system to use the ORIC as an energy booster will be completed in 1979. Phase II is proposed for completion in 1983.

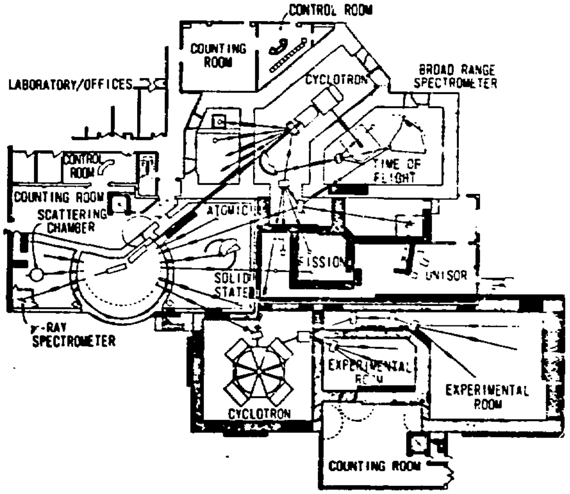

Fig. 2. The Holifield Heavy Ion Research Facility. Phase II is the portion housing the separated sector cyclotron and associated experiment areas.

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*Operated by Union Carbide Corp. for the U.S.E.R.D.A.

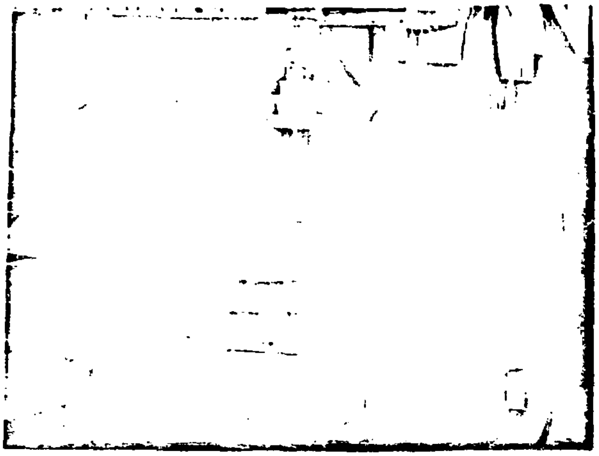

Fig. 3. The 0.15-scale magnet model for the SSC booster cyclotron. Half of one sector is removed.

Table II. Characteristics of Magnet System

Number of sectors	4
Sector angle, degrees	52
Overall height, m	4.9
Overall diameter, m	10.7
Steel weight, metric tons	1700
Main coil copper weight, metric tons	20
Main coil power, kW	320
Number of trimming coil pairs per sector	54
Trimming coil power, kW	80
Gap between poles, cm	10
Gap available for beam, cm	7.5

path if a nearly fixed path is to be used. However, a solution was found using a special magnet outside the cyclotron that accommodates the trajectories of ions of differing rigidities. This is illustrated in Figure 4. which shows the injection magnet that can place beams with a wide range of rigidity from either the tandem or ORIC on an appropriate path into the booster cyclotron.

The radial profile of the average magnetic field is free of significant saturation effects, being constant to within 1/2 percent up to 16 kG, but exhibits a roll-off of several percent near the center and at the outer edge. The correction could be made by trimming coils alone but to do so would require a large amount of power. Because the correction needed was relatively independent of field level it was preferable to provide it by shaping the pole tips and to include in that correction half of the total correction required for the most relativistic ion; that is to make the field shape produced by iron approximately isochronous for 50 MeV/amu. Of the several methods considered for shimming the magnet, the one shown in Figure 5 was most attractive. A constant width shim section is provided along the center of the pole tip. The shim section is contoured to provide the appropriate correction. The result is as illustrated in Figure 6. With the approximate field correction provided by the shim system, the trimming coil power required is only 80 kW rather than the 480 kW required in an earlier design.

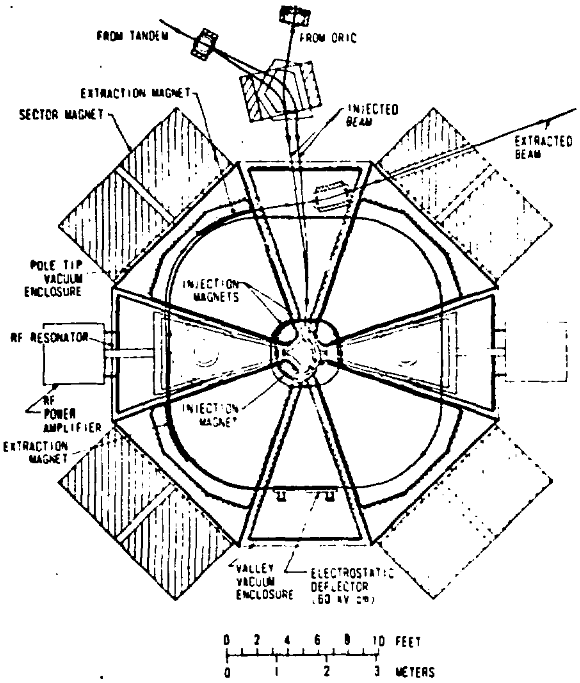

Fig. 4. Plan view drawing of the cyclotron. The injected beam is seen at the top of the figure entering the injection magnet.

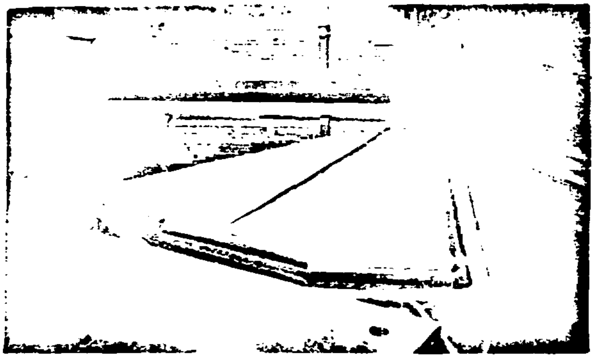

Fig. 5. The contoured shim to adjust the magnetic field contour fits in a slot in the middle of the face of the pole tip.

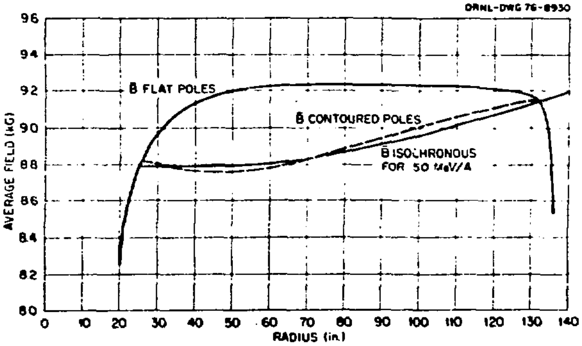

Fig. 6. The average magnetic field produced by the contoured poles approximates the isochronous magnetic field for 50 MeV/A.

Radio Frequency System

The new emphasis on high energy light-ion performance and the increase in maximum energy to 100 MeV/amu necessitated a redesign of the RF system. The previous design using radial 1/4-wave resonators was tuneable over the frequency range 7-14 MHz. With this range it is not possible to use the ORIC as the injector above about 45 MeV/amu. Above that energy the SSC must operate on the second harmonic but the ORIC cannot accelerate on even numbered harmonics because of the 180° dee design. Eliminating this basic incompatibility required that the cyclotron RF system range be extended to 20 MHz.

The new system, see Figure 7, uses vertical half-wave resonators to achieve a frequency range of 9 to 20 MHz. With this design the third harmonic can be used to 100 MeV/amu, thus providing complete compatibility with both the 25 MV tandem and the ORIC. For example, 100 MeV/amu oxygen ions can be obtained by accelerating 0^{4+} ions in the ORIC to 5.6 MeV/amu stripping to 0^{8+} and accelerating in the separated sector cyclotron to 100 MeV/amu. The RF system was further simplified by eliminating the second-harmonic flat-topping resonators. Acceleration of 6°-wide beam pulses without flattopping resonators gives the same resolution, $\Delta E/E \sim 10^{-3}$, that is achieved with 20° phase width with flattopping. An efficiency of more than 50% for 6° bunches is predicted for the two-gap bunching system being developed for the 25 MV tandem.[3] The small bunching efficiency gain that might be achieved for 20° bunching does not seem to support the added complexity of the RF system.

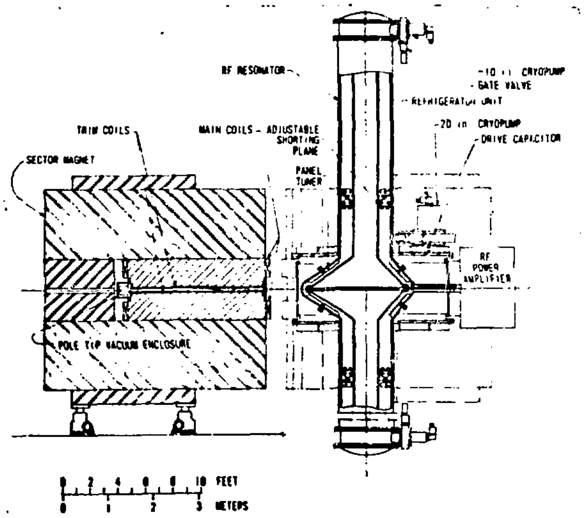

Fig. 7. Elevation-section of the cyclotron showing the vertical stem half-way resonator.

The radio frequency power amplifier systems use high-gain tetrodes driven directly by broad band solid-state amplifiers to achieve a maximum power output of 250 kW with noise and ripple 80 dB below the maximum output level. Table III lists the principal characteristics of the RF system.

Mechanical Design

To minimize beam loss by charge-changing collisions with the background gas, heavy ion cyclotrons require lower operating pressures than light-ion cyclotrons. For the heaviest ions with a charge-change cross-section of $\sim 10^{-16}$ cm^2, a pressure of 10^{-7} torr is required to keep beam losses less than 10%. The present design uses cryogenic pumps and blower mechanical pumps. Each RF cavity has two 10-in. cryopumps which give a total pumping speed of about 2000 ℓ/sec for air and 14,000 ℓ/sec for water vapor. Each of the two vacuum chambers in the spaces used for injection and extraction are equipped with two 20-in. pumps providing 20,000 ℓ/sec speed for air and 50,000 ℓ/sec for water vapor. The system can be pumped from atmospheric pressure to 10^{-7} torr in approximately 15 hr.

To reduce residual gas loads and to improve reliability, elastomer seals have been eliminated wherever possible. Thin metal welded seals are used between the magnet poles and pole tip vacuum chamber and between the pole tip chambers and the valley vacuum chambers. Soft metal (indium) seals are used between the valley vacuum chambers and the RF resonator assemblies.

Table III. Characteristics of Radiofrequency System

Resonator tuning range, MHz	9-20
Coarse tuning	Shorting plane & panels
Fine tuning	Trimmer capacitors
Minimum gap, cm	7.5
Peak RF voltage, kV	250
Approx. cavity height, m	9
Approx. cavity diameter, m	1.25
Power amplifier tube	RCA 4648
Driver amplifier power, W	1200
Plate input power cavity, KW	420
RF power/cavity at 60% eff. KW	250

Conclusion

The new separated sector cyclotron proposed for the Holifield Heavy Ion Research Facility at Oak Ridge will provide heavy ion beams in a range of energies and masses not presently available. The latest design provides improvements in the magnet system, the radio frequency system, the vacuum system, and the mechanical design. These improvements have provided a significant reduction in electrical power consumption and improved performance, especially in the ability to use the ORIC as the injector over the full range of ion mass and energy.

References

[1] S. W. Mosko, et al., "A Separated-Sector Cyclotron Post-Accelerator for the Oak Ridge Heavy Ion Laboratory," Proceedings of the Seventh International Conference on Cyclotrons and Their Applications, Birkhaüser, Basel (1975), p. 600.

[2] E. D. Hudson, et al., "Magnet Model Studies for Separated-Sector Heavy Ion Cyclotrons," Proceedings of the Seventh International Conference on Cyclotrons and Their Applications, Birkhaüser, Basel (1975), p. 197.

[3] W. T. Milner, et al., "Transport of DC and Bunched Beams Through a 25 MV Folded Tandem Accelerator," IEEE Trans. Nucl. Sci. NS-22, No. 3 (1975) 1697.