STATUS OF THE HOLIFIELD HEAVY ION RESEARCH FACILITY PHASE II BOOSTER

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Abstract

The first phase of the Holifield Heavy Ion Research Facility will become operational in late 1979. The status of plans for addition of a larger booster accelerator is discussed.

Introduction

At the time of the last Cyclotron Conference, we were in the early stages of beginning the first phase of the Holifield Heavy Ion Research Facility (HHIRF) and were proposing the addition of a second phase based on a room-temperature, separated-sector cyclotron.[1,2] This cyclotron, with an energy constant of K = 300, would have been capable of providing uranium ions with E/A of at least 10 MeV/nucleon when injected with the 25 MV tandem of Phase I. Since that last meeting, good progress has been made on construction of Phase I of our facility. I am sorry to say that despite our efforts Phase II is still not beyond the proposal stage. These last three years have seen as many evolutions in our proposed Phase II booster cyclotron, and this paper is intended to provide a brief historical record of this evolution, some of the reasons for these changes, and the present status of our plans.

HHIRF Phase-I

The present phase of construction is centered around the addition of a 25-MV tandem electrostatic accelerator to our existing cyclotron facility. The new tandem has been designed with particular attention to features such as transport optics, vacuum, and diagnostics that should enhance its ability to accelerate heavy ions. Our existing isochronous cyclotron (ORIC) has been modified to serve as a booster accelerator when injected by the new tandem. The two accelerators are also capable of completely independent operation.

Construction on this phase is proceeding well. The building is essentially finished, the large pressure vessel has been completed and tested successfully, the major modifications to the ORIC have been completed, and installation of the tandem inside the pressure vessel has begun.

A view of the HHIRF building, showing the newly completed tower, which houses the pressure vessel for the 25-MV tandem, is shown in Fig. 1. A cross-section of the facility, illustrating the relationship between the new tandem and the ORIC, is shown in Fig. 2. One feature of the 25-MV tandem,[3] readily apparent from the figure, is the "folded" configuration. This feature has been introduced since the accelerator has become large enough, from electrostatic considerations, that both low- and high-energy accelerating tubes can be accommodated within the same column structure. The tandem is being built, to our specifications, by National Electrostatics Corporation. Performance specifications call for 1 pμA (6×10^{12} ions/sec) for all ions.

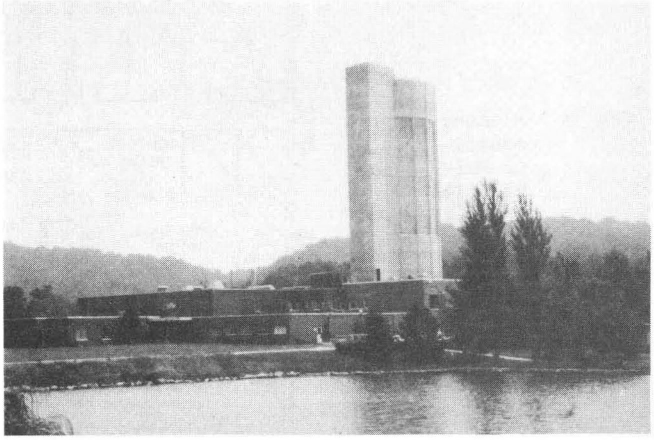

Fig. 1. The Holifield Heavy Ion Research Facility at Oak Ridge

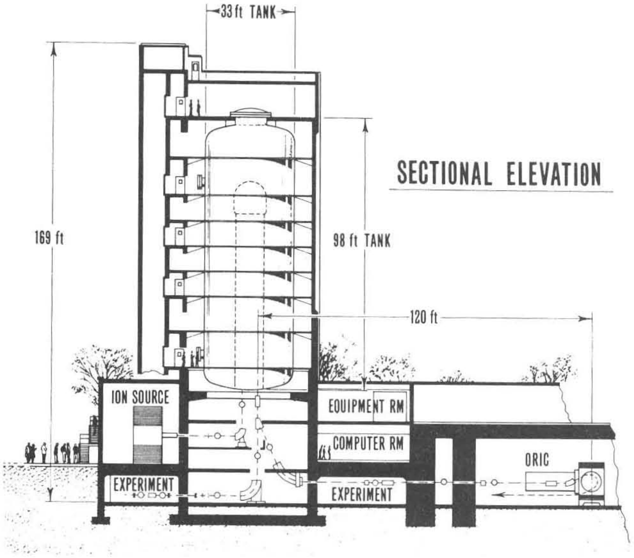

Fig. 2. Vertical section of the HHIRF building

The Phase-I facility is scheduled to be operational in October of next year. A plan view of the facility as it is expected to look during early operation is shown in Fig. 3.

HHIRF Phase-II/77

The ion energy performance that will be available from the 25-MV tandem and the Phase-I facility is shown in Fig. 4. Since the use of ORIC as a booster accelerator will provide ions only up to mass 160 with energies above the Coulomb barrier, the facility has been designed with an eye towards later addition of a larger booster accelerator to make available the full range of ion masses. The proposed booster accelerator discussed at the 1975 cyclotron conference was a separated-sector cyclotron with an energy constant $K_B = 300$. This

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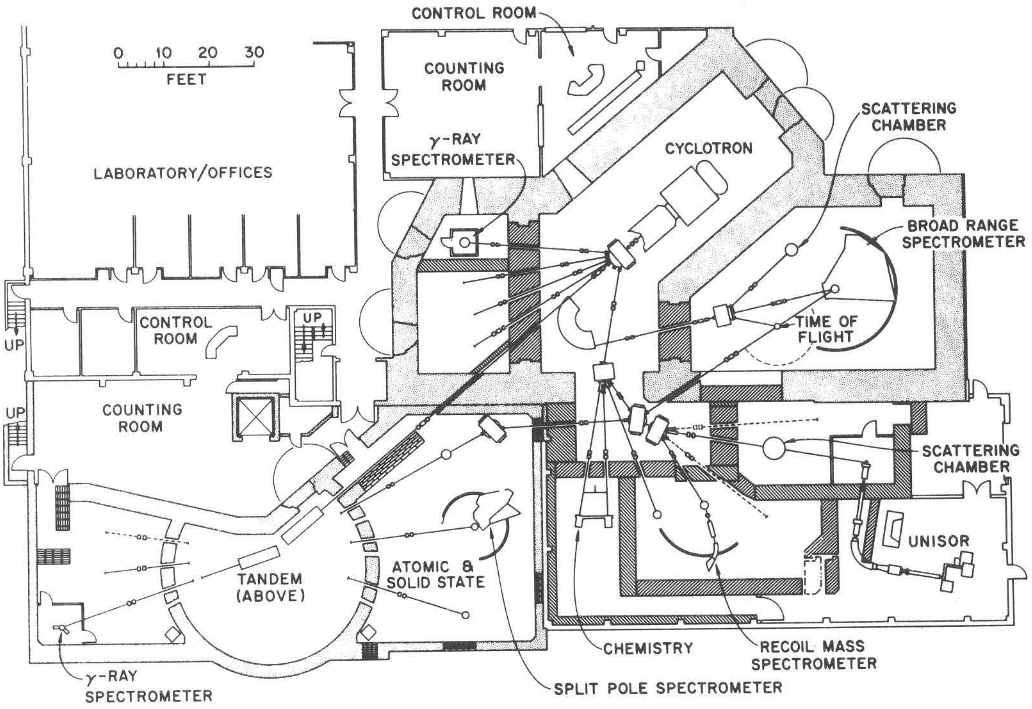

Fig. 3. Planned experimental layout of HHIRF before addition of Phase-II

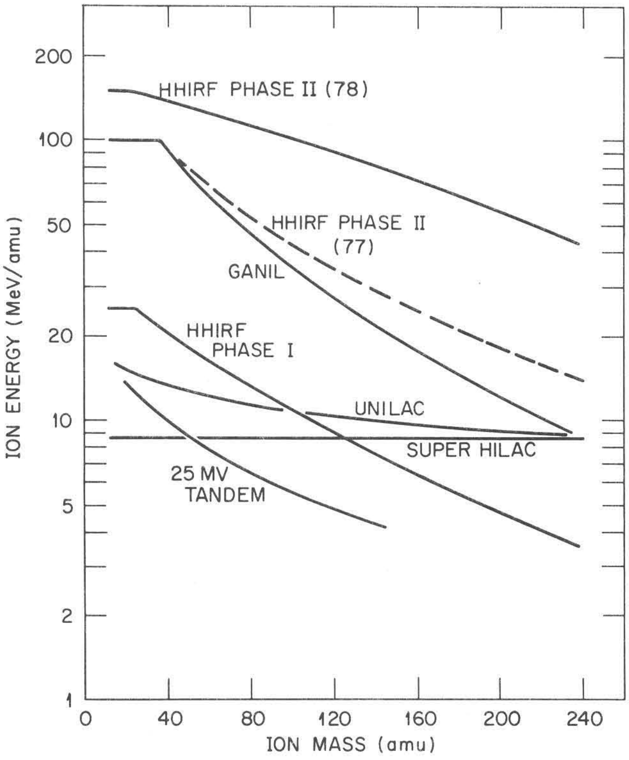

Fig. 4. Comparison of ion energy performance capabilities for various accelerator facilities

size machine was essentially a compromise between minimizing costs and still providing at least 10 MeV/nucleon for uranium ions.

The following year we returned to the machine size, K_B=400, of our original NHL proposal. Along with this we made several refinements of our design concept for this type of machine. The facility addition that was proposed is shown in Fig. 5, with the performance capability shown by the dashed line in Fig. 4. The philosophy here is very similar to that of our previous proposal with the use of either the 25-MV tandem or the ORIC as the injector and minimim disturbance of the Phase-I areas. There were, however, some detailed changes in design. The injection line is slightly more complicated in order to accommodate the effect of the valley field, as determined from our model measurements, on the range of magnetic rigidities of particles to be injected.[4] A decision was made to adopt a vertical resonator design in place of the previous radial structures. The vertical half-wave resonators offered a significant reduction in power consumption as well as an increased frequency range. The new design eliminated the flat-topping electrodes of the previous design which added to the potential power savings. This decision was based on our judgement that the required beam quality could be attained by improved buncher performance. The prototype double-drift harmonic buncher[5] developed for injection of ORIC from the 25-MV tandem has tested very satisfactorily and could equally well provide the required bunch timing for the K = 400 separated-sector machine.

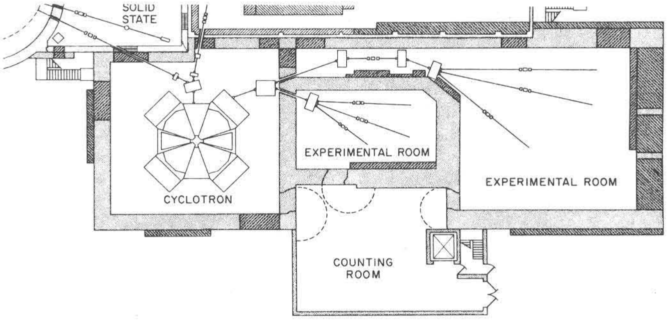

Fig. 5. Layout of addition proposed for Phase-II/77

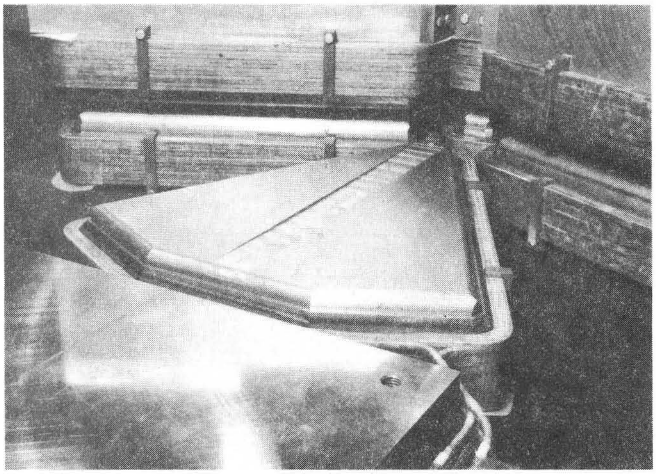

Fig. 6. Contoured slot to adjust the magnetic field contour shown on the lower pole of one sector of the 0.15-scale model

Another change proposed for the separated-sector machine is illustrated in Fig. 6. Contoured slots on the bisector of each sector magnet pole face provide an average field contour for isochronizing particles to half the full energy capability--in this case, 50 MeV/nucleon. This means that the trim coils, instead of adding to a flat base field, add or subtract from the intermediate field. Required maximum currents are thus reduced by a factor of 2 and electrical power reduced by a factor of 4.

HHIRF Phase-II/78

Despite our optimism and enthusiasm over the proposal for the K = 400 separated-sector cyclotron booster, it failed to receive support in the 1979 budget. The consequent delay in beginning a booster accelerator for this facility has resulted in a decision to make a major change in our proposal.

Looking toward what type facility would best serve experimental programs of the last half of the next decade, the desire for increased energy capability stands out most clearly. Unfortunately, there seems to be no way to significantly increase the energy performance of the separated-sector cyclotron booster within reasonable bounds of project cost. The emergence of the concept for a high field isochronous cyclotron,[6,7,8,9] utilizing superconducting main field coils, offers the possibility of providing the increase in ion energy performance while at the same time offering a savings in both construction and operating costs.

A design prepared for consideration in the 1980 budget is illustrated in Fig. 7. Based on a 2.1-meter 3-sector cyclotron, with superconducting main coils to provide a maximum average field of 5 Tesla, this layout departs significantly from our previous proposals. Preliminary characteristics of the accelerator are listed in Table 1. A schematic plan view section of the cyclotron pole is shown in Fig. 8 along with a view of the proposed resonator illustrating the idea of utilizing a twin dee stem configuration. A vertical section of the magnet is illustrated in Fig. 9. The maximum bending constant of K_B=1200 along with focusing limitations for lighter ions yields the performance curve shown in Fig. 4.

The higher fields of this accelerator and the higher rf frequencies are no longer compatible with use of the ORIC as an alternate injector. The higher frequencies also require tighter bunching of the injected beam and would necessitate addition of a terminal buncher to the 25-MV tandem. The layout of Fig. 7 illustrates the proposed rearrangement of the existing ORIC areas including utilization of the ORIC vault for experimental area. A feature of this layout that we think will be an essential component of all future facilities is the provision for beam sharing. The "beam splitter" consists of a 1.25-m-long set of rf deflection plates and a 4 1/2-degree septum magnet. Two conventional bending magnets follow the septum magnet and small steering magnets precede and follow

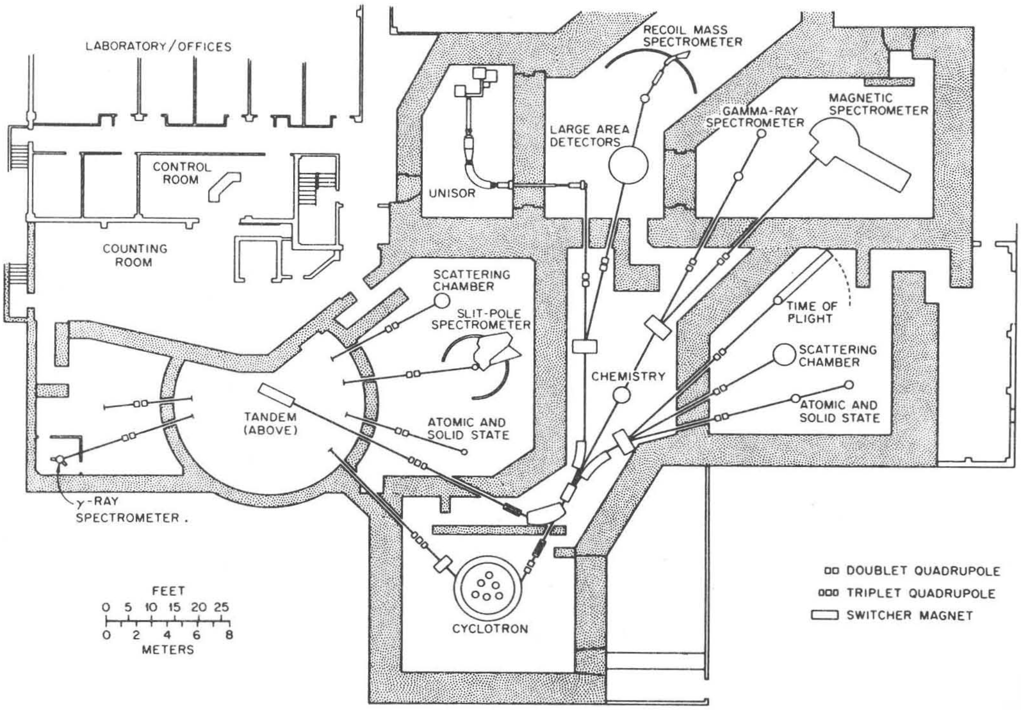

Fig. 7. Proposed layout for Phase-II/78

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Table 1. Phase II/78 Cyclotron Characteristics

Energy constant, bending, K_B,† MeV/A	1200
Energy constant, focusing, K_f,† MeV/A	300
$B\rho_{max}$, Tesla-meters	5.08
Average beam radius, extraction, meters	1.02
Number of sectors	3
Flutter, $1/2\ F^2$, typical	0.015
Magnetic field spiral, degrees, r-meters	θ=173.2 r
Injection radius, cm, min, max	16-32
Energy gain raio, E_f/E_i, min, max	10-40
Frequency range, MHz	30-72
Harmonic range	3-7
Dee angle, degrees	45
RF power, kW/dee, max at 75 MHz	75
Magnet weight, U.S. tons	∿530
Magnet height, ft, in.	13'10"
Magnet diameter, ft, in.	15' 0"

†The achievable energy is limited either by bending according to $E = K_B \frac{q^2}{A^2}$ or by focusing as $E = K_f\ q/A$. The crossover occurs at $q/A = K_f/K_B$ or, for this cyclotron-tandem combination, at about A = 150.

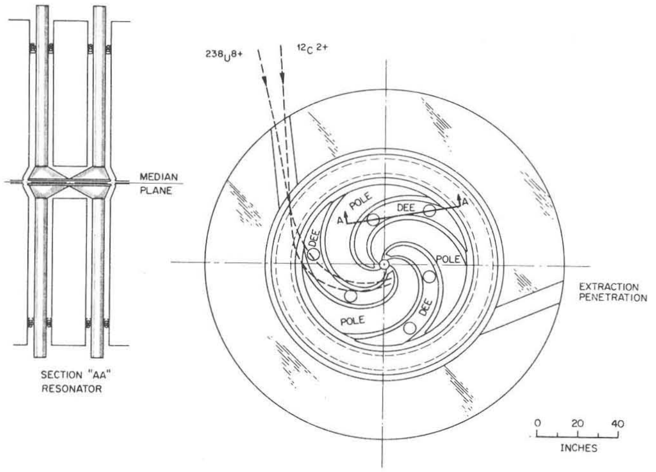

Fig. 8. Plan view and section of the Phase-II/78 cyclotron

the deflection plates. By operating the deflector plates on a subharmonic of the orbit frequency, beam pulses can be alternated between any two of the principal beam lines or shared among all three. For operation in a single beam line, the deflector plates are not used and displacement is provided by the steering magnets. A duplicate deflector system on the beam line from the 25-MV tandem allows similar sharing of the direct tandem beam. This system, then, provides the capability of accommodating up to three simultaneous experiments.

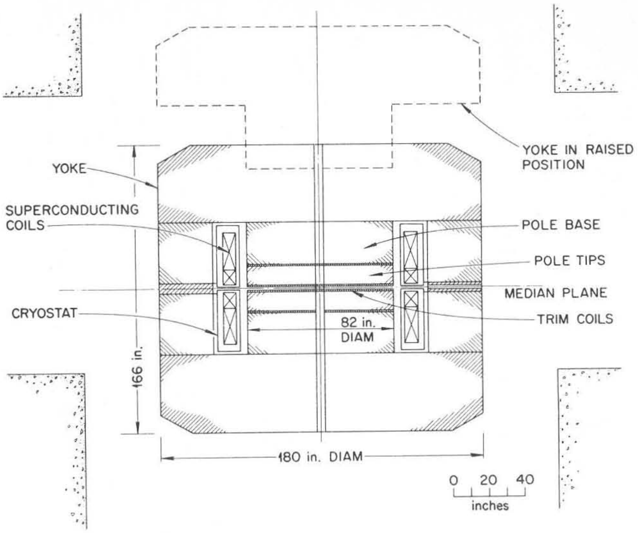

Fig. 9. Elevation section of Phase-II/78 cyclotron

Although this proposal did not receive the endorsement of the NUSAC Facilities Subcommittee for inclusion in the 1980 budget, it was recommended that the proposal be further developed with consideration given to possibilities of providing ever higher ion energies. The possible variations that we have examined, to date, are all based on the basic layout shown in Fig. 7.

Future Options

Two possibilities beyond the accelerator discussed in the previous section have been explored. These options have been developed in response to two questions: (1) What type of facility would be required to provide energies of at least 100 MeV/nucleon for all ions? (2) What is the practical limit to the size of a superconducting cyclotron booster?

To produce uranium ions of 100 MeV/A, a single booster following the 25-MV tandem would need an energy constant $K \geq 3000$. Since this appears, *a priori* larger than practical, a more effective way to achieve this energy seems to be multistage acceleration. Performance of one possible solution is shown in Fig. 10. Here, the 25-MV tandem would be followed successively by K = 600 and K = 900 cyclotrons with stripping between each stage of acceleration. The ion energy from the first booster cyclotron is chosen to produce a stripping ratio of 2:1 between cyclotrons. The tandem terminal voltage required to produce the correct charge state for the first cyclotron is also indicated in the figure. Although it might seem more practical to design two cyclotrons of the same size (the same performance could be achieved with two K = 850 cyclotrons) the injection conditions for the 25-MV tandem are better satisfied with the sizes shown.

Of course the three-stage facility does introduce the additional complexity of two injection and two extraction systems but the major drawback is the additional loss of intensity introduced by the second stripping. Energies shown in Fig. 4 are achievable with intensities of 10^{11} particles/sec. Intensities for Fig. 10 are of the order of 10^{10} part/sec. Even so, intensities from the three-stage facility would be two orders of magnitude above other proposals for facilities covering this energy range.

Our most recent studies of a large single booster cyclotron have been influenced by the recent closing of the Space Radiation Effects Laboratory and the possibility that the large yoke of the SREL synchro-

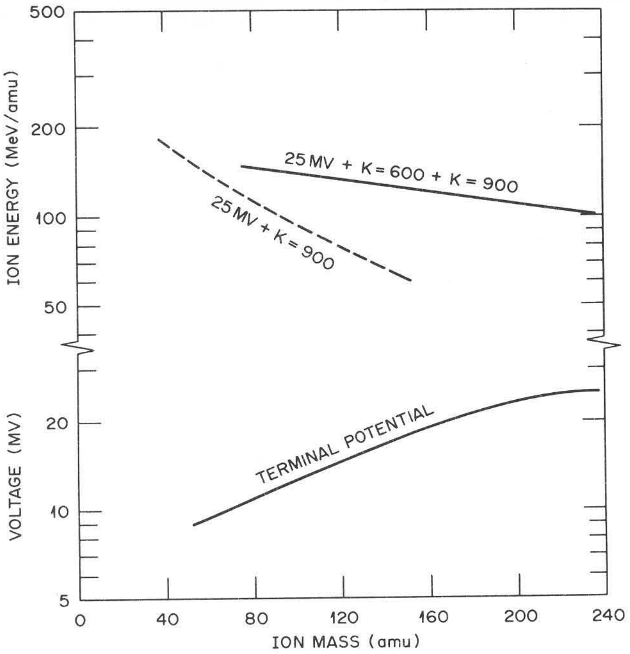

Fig. 10. Ion energy performance for a double cyclotron booster injected by the 25-MV tandem. The dashed line shows energy performance without the intermediate booster. The terminal voltage requirement for three-stage operation is also shown.

cyclotron might be available for conversion to another accelerator. What type of booster cyclotron might be built utilizing this magnet?

One possibility of a large high-field machine utilizing the SREL yoke is shown schematically in Fig. 11. A pole diameter of 3.9 m is selected to operate at average field levels up to about 3.5 Tesla while maintaining fields in the yoke at about 2.0 Tesla. The effective energy constant K_B for this cyclotron would be 1500. Coupled to the 25 MV tandem, this would yield uranium ions with energies in excess of 50 MeV/nucleon. Some parameters of this accelerator are listed in Table 2.

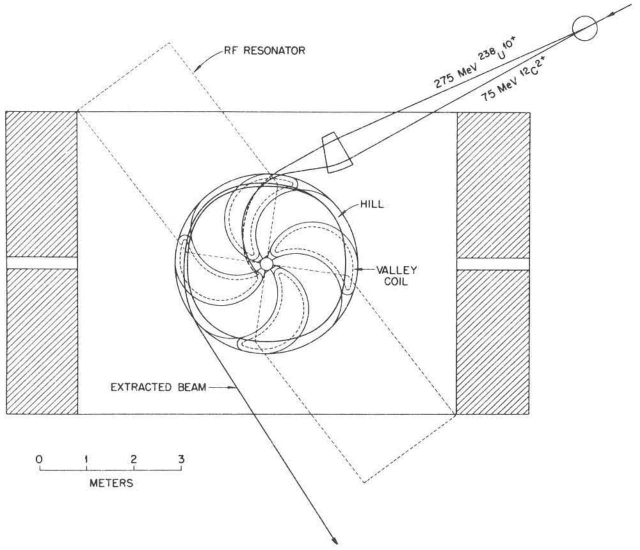

Fig. 11. Plan view of booster cyclotron utilizing the SREL cyclotron yoke

Table 2. Characteristics of Booster Cyclotron Utilizing SREL Magnet Yoke

Energy constant, bending, K_B, MeV/A	1500
Energy constant, focusing, K_f, MeV/A	600
$B\rho_{max}$, Tesla-meters	5.6
Average beam radius, extraction, meters	1.7
Number of sectors	4
Magnetic field spiral, θ-degrees, r-meters	$\theta=\mathrm{Sin}^{-1}\left(\frac{r}{1.7}\right)$
Energy gain ratio, E_f/E_i, max	50
Frequency range, MHz	9-18
Harmonic range	1,2,3
Dee angle, degrees	90
Magnet weight, U.S. tons	2360

The machine concept discussed here differs in a number of important aspects from other large ($K \geq 800$) superconducting cyclotrons presently under consideration. Since the upper energy limit for a machine at these field levels utilizing only iron pole tips to provide flutter appears to be about 200 MeV/nucleon, to go significantly beyond this requires the introduction of valley coils. It also becomes advantageous to use a four-sector geometry and to ease the path constraints on the injection trajectories by relaxing the spiral angle somewhat. Valley coils introduce a new dimension in the design of such machines by allowing some flexibility in the control of injection conditions.

Shown in Fig. 11 are injection loci computed for two calculated fields. One to accelerate uranium ions to 50 MeV/nucleon and the other to accelerate carbon ions to 300 MeV/nucleon. The uranium case does not require any field contribution from the valley coils, while the carbon case requires a 1.0-Tesla contribution. Focusing frequencies for these two cases are shown in Fig. 12. In the case of the lighter heavy ions

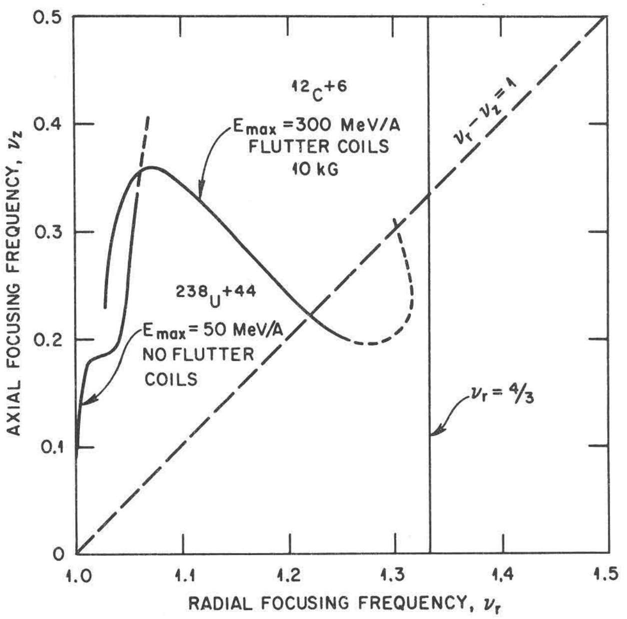

Fig. 12. Focusing frequencies calculated using computed fields for two cases

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accelerated to high energy, the valley coils are needed not only to provide sufficient flutter to obtain focusing but also to reduce fields along the injection path in order to match the magnetic rigidity of the beams provided by the 25-MV tandem.

The valley field contribution produced by room temperature coils would be limited to about 0.5 Tesla for acceptable power levels. The top energy for the light heavy ions would be about 250 MeV/nucleon for this configuration. For valley fields above 0.5 Tesla, superconducting coils would be required.

The magnet as shown here would have a rather wide median plane gap, the total opening between pole tips being 23 cm. The laminated structure of the SREL cyclotron yoke does not lend itself to a vertical dee structure and two 90-deg radial resonators are shown. The gap size is chosen to accommodate these accelerating electrodes and a circular trim coil platter on each pole face. This structure implies limited penetration across the median plane by the cryostat. This may require a cryostat design that takes most of the load forces back to the yoke.

The beam extraction path shown in Fig. 11 could be accomplished using two 80-deg electrostatic deflectors operating at 160 kV/cm, by two septum magnets of the same length operating with fields of -0.08 Tesla or by a combination of these elements. These initial elements would be followed by a 0.9-Tesla magnetic channel.

A possible structure for the 90-deg resonators is sketched in Fig. 13. The resonator structure has a rectangular cross-section with a 2.5-cm aperture and nominal 5-cm spacing dee-to-ground. Design voltage is 150 kV. The structure has some increase in height beyond the pole but is still limited by the cryostat. Beyond the cryostat the height is increased to provide space for support structure and vacuum pumping. A movable shorting plane tunes the resonator over a 9- to 18-MHz range.

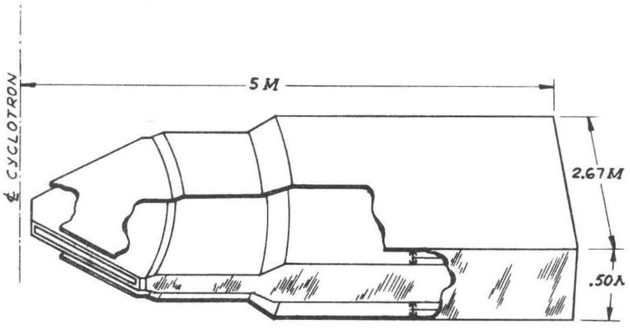

Fig. 13. Possible design for accelerating electrode

Certainly the availability of the SREL yoke presents some interesting possibilities, one of which has been outlined here. At this writing, the chance for such a conversion is uncertain. The construction of a high-field cyclotron of this size does not need to depend on such a conversion. However, starting with a new yoke would likely lead to a new configuration.

Summary

We are at the present time actively pursuing design studies for several options of a booster cyclotron for Phase II of the HHIRF. It seems most likely that the final choice will be for a single-stage booster in the range of K = 1200 to 1500. We look forward to being closer to the realization of such an addition to our facility by the time of the next cyclotron conference.

References

1. R.S. Lord et al., Seventh Internat. Conf. on Cyclotrons and Their Applications, Zurich, Switzerland, Aug. 1975, Birkhäuser, pp. 622.
2. S.W. Mosko, et al., ibid., p. 600.
3. J.K. Bair, et al., IEEE Trans. Nucl. Sci. NS-22, No. 3, 1655 (1975).
4. J.A. Martin et al., IEEE Trans. Nucl. Sci. NS-24, No. 3, 1165 (1977).
5. W.T. Milner, et al., IEEE Trans. Nucl. Sci. NS-22, No. 3, 1697 (1975).
6. J.H. Ormrod et al., IEEE Trans. Nucl. Sci. NS-24 No. 3, 1093 (1977).
7. H.G. Blosser, Seventh Internat. Conf. on Cyclotrons and Their Applications, Zurich, Aug. 1975, Birkhäuser, p. 584.
8. J.H. Ormrod et al., Ibid., p. 595.
9. E. Acerbi et al., IEEE Trans. Nucl. Sci. NS-24, No. 3, 1109 (1977).