DESIGN STUDY FOR THE CONVERSION OF THE OAK RIDGE ISOCHRONOUS CYCLOTRON FROM AN ENERGY CONSTANT OF K=90 to K=300 MeV

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Abstract

A possible method of achieving a K=300 MeV cyclotron by increasing the average magnetic field of the Oak Ridge Isochronous Cyclotron (ORIC) from 18.6 to 33.9 kG with superconducting coils has been investigated.

1. Introduction

The Oak Ridge National Laboratory is presently building a 25 MV tandem electrostatic accelerator. The Oak Ridge Isochronous Cyclotron (ORIC) will be used as a post-accelerator to boost the energy of the tandem beams above the lead Coulomb barrier for heavy ions up to mass A=160. Beams from the tandem will enter the cyclotron through the dee stem and be directed by an inflection-magnet to a stripper-foil on a trajectory suitable for acceleration within ORIC. A second phase is planned that will accelerate uranium above 10 MeV/u. For this second phase, a variety of accelerator concepts are being investigated.

Recent proposals of superconducting cyclotrons[1,2,3]) have resulted in design studies using the 25 MV tandem in conjunction with these machines. There are two main "figures of merit" associated with superconducting cyclotrons, K - the bending strength of the magnet, and K_f - the axial focusing limit of the machine. K is defined by the equation

$$E/u = K(Q/A)^2, \qquad (1)$$

where E/u is the energy per nucleon, Q is the ion charge, and A the atomic mass. K_f is defined by the equation

$$E/u = K_f\ Q/A. \qquad (2)$$

The K_f limit arises due to the saturation of the iron pole-tip in the high-field regime of superconducting cyclotrons. Since the iron contribution to the flutter is constant, the flutter scales as the inverse square of the average field. Hence the characteristic linear dependence on Q/A in limiting the maximum energy/nucleon.

One of the interesting variations proposed and reported in this paper is to modify the existing ORIC to a K=300 MeV cyclotron, with a K_f=75 MeV. Calculation and design studies indicate that a focusing limit of K_f=75 MeV could be achieved with pole-tip and valley coil modification and that beam could be extracted with conventional technology. The energy/nucleon versus charge to mass ratio for the above design is presented in Fig. 1. (Several representative charge to mass ratios

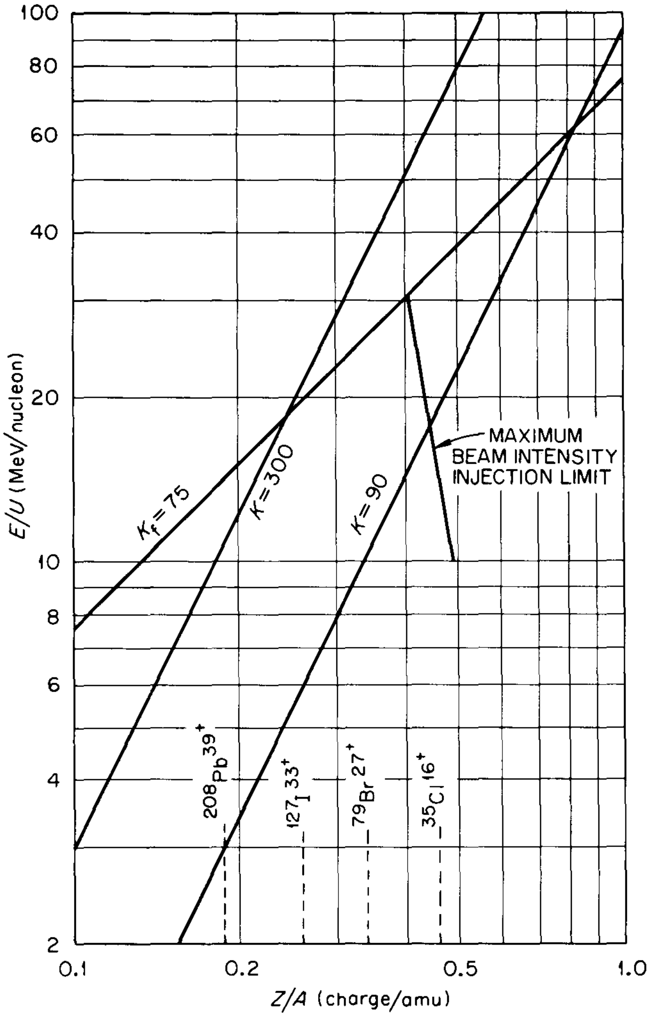

Fig. 1. The ORIC energy performance (MeV/u) for K=90 and 300 MeV versus charge to mass ratio. The focusing limit of K_f=75 MeV will limit the energy for the light masses. Typical charge to mass ratios obtained from gas-stripping in the 25 MV tandem followed by foil-stripping in the ORIC are shown.

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produced by gas-stripping from the 25 MV tandem followed by foil-stripping in ORIC are also shown.) The K=90 MeV curve is the present ORIC limit. An injection limitation for maximum beam intensity is also shown. In the following section modifications and calculations for the K=300 MeV ORIC are discussed.

2. ORIC Modifications

The characteristics of the ORIC have been reported previously[4,5,6]. The purpose of this study is to identify the minimum modifications to the cyclotron which would produce a K=300 MeV machine, that would be compatible for use with the 25 MV electrostatic accelerator as an injector[7,8]. Further, these minimum modifications avoid use of technology that requires significant developmental research.

The indications of this study are that ORIC could be upgraded to K=300 MeV by substituting superconducting main coils for the existing water-cooled coils, by adding additional iron to the yoke to help reduce the stray field, by increasing the number of pole and core bolts, by modification of the pole-tip to increase the spiral, and by the modification of the harmonic coils and valley coils to provide sufficient axial focusing and trim coils to achieve isochronism.

The beam separation at the ORIC extraction radius would be larger than the separation obtained for the present high energy protons. The greater rigidity of the K=300 MeV heavy ions requires that the present extraction system be modified by replacing the electrostatic deflector by a septum magnet. Calculations using the magnetic field obtained with a conventional magnetic extractor show that the high rigidity beams would be extracted.

The post-accelerator beam-transport system would require larger magnet power supplies and some magnet redesign to bend and focus the higher rigidity beams.

3. Superconducting Coils

The superconducting coils would be approximately 1/4 the cross section of the existing coils (Fig. 2). Coil and pole forces, as measured on a 1/9 scale model of the original ORIC gemoetry[5], are shown in Fig. 3. By linear extrapolation the forces on the superconducting coils, poles and cores range from 1000-1500 tons. The forces are initially toward the yoke, then as the field is increased they reverse and are toward the gap and are much greater. The existing coils operate only

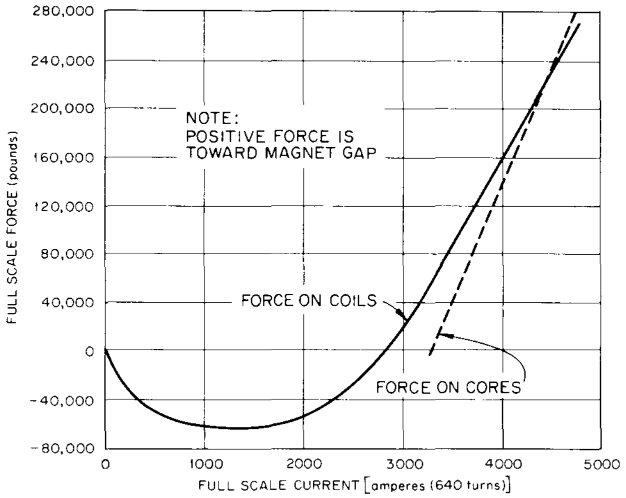

Fig. 3. The measured forces on the coils and magnet core from a 1/9 scale model of ORIC versus the coil current. A linear extrapolation of these forces to the superconducting current of a K=300 MeV cyclotron, yields forces on the coils and magnet of 1000-1500 tons toward the median plane.

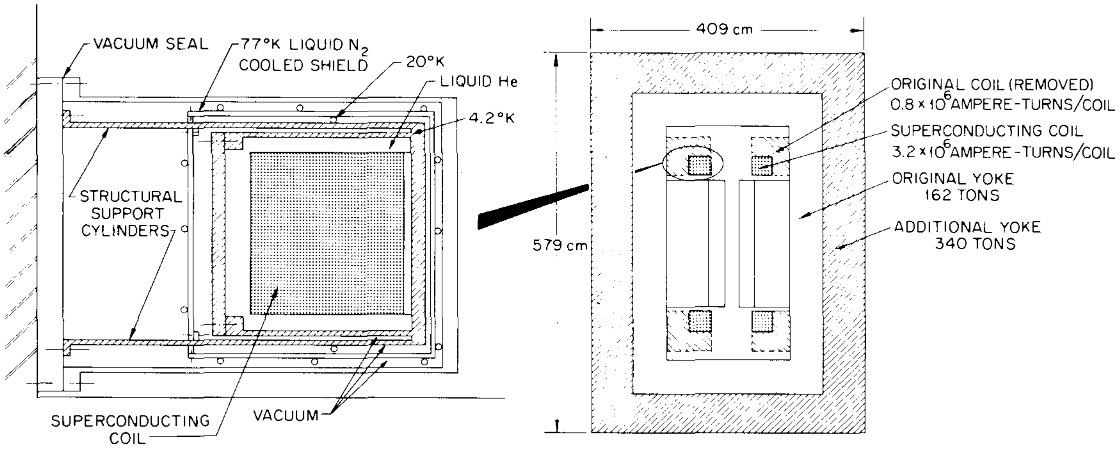

Fig. 2. A cross sectional view of ORIC showing the additional iron to be added to the existing yoke, and details of proposed superconducting main coils. The forces on the coils are transmitted to the yoke through concentric stainless steel cylinders bolted to the yoke.

in the regime where the forces are away from the gap. The forces on the superconducting coils would be transferred to the yokes by 2 concentric stainless steel cylinders for each coil. These cylinders must also carry the temperature gradient from 4.2°K to 300°K and have fixed intermediate temperature points of 20°K and 77°K. The total heat load for the refrigerator is approximately 15 watts/coil.

4. Orbit Calculations

4.1. Magnetic Field Synthesis

The following procedure was followed to obtain the 33.9 kG magnetic field for the calculations. (1) The existing ORIC field synthesis program[9], was used to generate an 18.6 kG (K=90 MeV) field from measured field data. (2) The field produced by the iron pole-tip was extracted from these data by subtracting the field due to the conventional main-coil air-core contribution. (3) A superconducting air-core coil magnetic field was added to the (saturated) iron pole-tips field to obtain the desired 33.9 kG (K=300 MeV) average field. (4) Since the resultant higher-level field had inadequate flutter, the flutter was restored to a level comparable to the ORIC K=90 MeV case using the formula

$$B_{NEW}(r,\theta) = B_{OLD}(r,\theta) + A[B_{OLD}(r,\theta) - B_{OLD}^{AVG}(r)] \qquad (3)$$

where r,θ are the usual polar coordinates, $B_{OLD}^{AVG}(r)$ indicates an azimuthal average, and A is a "flutter adjustment factor" taken to be 0.75 (i.e., a 75% increase in the flutter amplitude). The resulting $B_{NEW}(r,\theta)$ were then normalized to the old average field at each radius. Modifying the field in this manner produces a smooth azimuthal correction to the data and preserves the average field profile as a function of radius, while enhancing the flutter.

The axial focusing frequency range obtained with the above procedure ($.08 < \nu_z < .28$) is slightly less than the K = 90 MeV case but adequate.

4.2. Injection

The calculations shown here are for heavy-ions with atomic mass range of A=158 to 238. Below A=158, calculations show that the ORIC (K=90 MeV) with beams injected from the 25 MV tandem, will produce final heavy ion energies above the Coulomb barrier for lead[10,11]. Fig. 4 shows various injection trajectories to best-centered orbits suitable for acceleration within a K=300 MeV ORIC, with the dee operated at 100 kV. The ORIC pole-tip, dee-stem, and extractor are indicated schematically on the figure. The stripper-foil position is indicated by a star.

The ORIC injection system will include a movable stripper-foil arm, and an inflection-magnet with quadrupole for placing the injected heavy ion beams into the proper injection orbits. The stripper-foil arm must be outside of the dee, and is limited mechanically to the quadrant above the ORIC horizontal center-line. The radial motion of the inflection-magnet is limited by the ORIC dee-stem geometry. The required range of foil-angles and inflection-magnet settings are comfortably within design limits for the K=90 MeV injection system now under design for the 25 MV tandem[6,7].

All finite-size beam calculations are based on a phase-space area from the tandem of 19 π mm mrad (MeV)$^{1/2}$, with a beam-spot size at the ORIC stripper foil of 1 mm x 5 mm (radial by axial dimensions). For finite-emittance studies, the perimeter of an appropriate phase-space area was outlined by a "packet" of particles or rays with differing initial conditions. The evolution in time of this packet of particles allowed the study of finite-size beams of heavy ions.

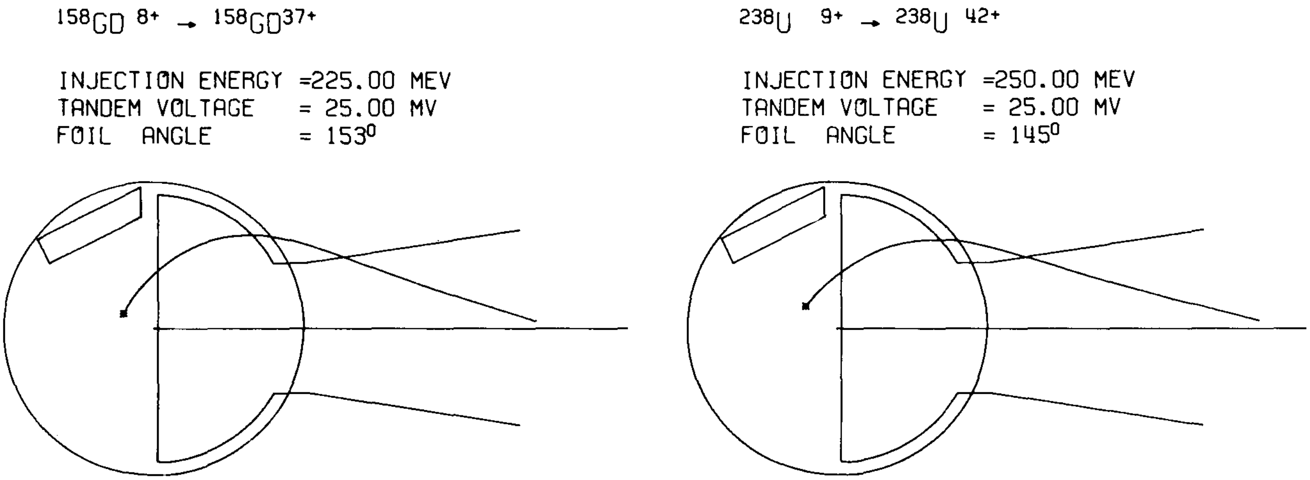

Fig. 4. Various heavy ion trajectories for injection to best-centered orbits for acceleration within the ORIC. The ORIC pole-tip, dee, and extractor are indicated schematically. The trajectories are obtained by integrating the equations of motion backwards from the stripper-foil (indicated by a star) out through the fringe-field of the cyclotron.

Table I. Tabulated Beam Widths

Injected Beam	Radial Width After Inflection-Magnet (cm)	Axial Width After Inflection Magnet (cm)	Maximum Axial Width within Dee Walls (cm)	Turn Separation at Foil-Stripper (cm)
^{158}Gd $8^+ \to 37^+$	1.62	.208	.557	2.60
^{181}Ta $8^+ \to 38^+$	1.26	.111	.555	2.81
^{208}Pb $8^+ \to 40^+$	1.82	.197	.552	3.09
^{238}U $9^+ \to 42^+$	1.78	.216	.542	3.16

Table I gives the radial (i.e., bending plane) widths of various beams just after exit from the inflection-magnet on an injection path into the ORIC.

Similarly, Table I gives the axial widths of the beams after exit from the inflection-magnet, and the maximum axial widths within the dee walls (the walls are 2.4 cm apart). Beam-transport studies from the 25 MV tandem through the ORIC inflection-magnet have been performed for the ORIC K=90 MeV system[12]. Those calculations, which include more difficult beams than are required for this K=300 MeV study, indicate successful beam-transport from the tandem to the ORIC stripper-foil. Fig. 5 and Table I indicate the various turn-separations at the ORIC stripper-foil.

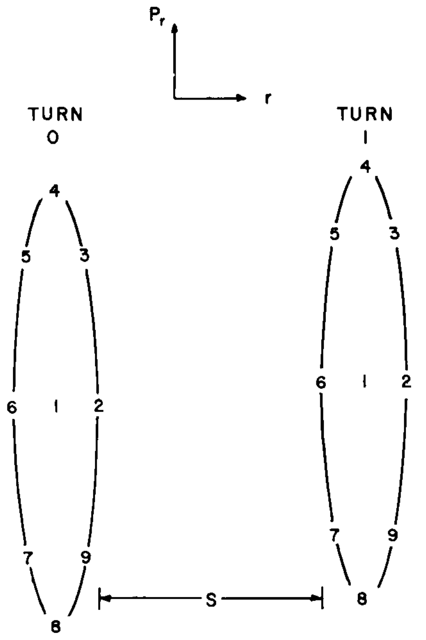

Fig. 5. Phase-space area for the first two turns of ^{158}Gd^{37+} at the ORIC stripper-foil. (See Table I for various turn separations). This calculation was performed by following a "packet" of nine particles with differing initial conditions which outlined the phase space area.

5. Conclusions

The modification of the ORIC to a K=300 MeV cyclotron appears to be possible using "conventional" superconducting technology. Beam extraction using normal magnet technology is also possible. The modified ORIC would not have the energy range or versatility, particularly for lighter heavy ions, that is obtained by the separated-sector cyclotron design[13]. However, since this design makes maximum use of existing machine and experimental facilities, it would have a significantly lower capital cost.

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