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# SUPERCONDUCTING CONVERSION OF THE OAK RIDGE ISOCHRONOUS CYCLOTRON

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## Summary

The superconducting conversion of the Oak Ridge Isochronous Cyclotron (ORIC) will replace the existing aluminum main magnet coils with a NbTi superconducting coil system to provide an increase in magnetic field from 1.9 to 3.3 T. The higher magnetic field will provide a three-fold increase in maximum energy capability of the cyclotron for high mass ions. The conversion will include a new beam extraction system, magnet yoke stiffening to counteract the increased magnetic forces, and minor modifications to the beam transport systems and shielding.

## Introduction

The Oak Ridge Isochronous Cyclotron began operation in 1964, providing maximum beam energies up to approximately 75 $q^2/A^2$ MeV/A. Subsequent modifications of the cyclotron increased the maximum energy to 100 $q^2/A^2$ MeV/A. Although used primarily for light ions in early years, the cyclotron is now used almost exclusively for heavy ion research. With the internal Penning-type ion source, the cyclotron provides beams up to A=40 with energies high enough for nuclear physics.

In 1975 a major expansion of the facility was begun: the addition of the 25 MV tandem, and the ORIC beam injection system. In coupled operation, using the cyclotron as a booster accelerator, ion energies above the nuclear interaction barrier will be available for ions up to A=160. Construction of the new facility is complete and final testing is in progress.[1,2]

The superconducting conversion of the cyclotron will provide an additional large increase in energy capability (Fig. 1). For ions heavier than A=130, the increase in energy is a factor of three, from 100 $q^2/A^2$ MeV/A to 300 $q^2/A^2$ MeV/A. For lighter ions the increase is somewhat less. For $^{16}O^{8+}$, for example, the energy will be increased by a factor of 1.5 from 25 to 37.5 MeV/A.

## Isochronism and Focusing Considerations

### Isochronism

Increasing the energy of the ORIC with superconducting main magnet coils was examined in a preliminary study in 1975.[3] Since that time a complete remapping of the magnetic field has been completed. The new measurements have been Fourier analyzed and the coefficients parameterized in terms of the currents in the main coil, average-field-trimming coils, harmonic correction coils, and valley coils, in a way which takes the variable saturation of the iron into account.[4] This description of the magnetic field is now used in a computer program which provides essentially exact current settings for the various coil systems. We have used this program to predict the magnet characteristics at the K=300 field levels. A close fit to the isochronous magnetic field was obtained by increasing the radius of the main magnet coils and locating them nearer the median plane (Figs. 2 and 3). The magnetic fields of the new geometry were incorporated into the parameterization; orbit code analyses show that the new geometry provides magnetic fields which are a good fit to the isochronous requirements over the required range.

The computer program GFUN-3D[5] which calculates the magnetic field of complex 3-dimensional systems of coils and iron, has been used to compute the ORIC magnetic fields. Comparison of GFUN-3D results with the measurements at 1.85 T, and with the analytical extrapolations at 3.3 T, shows good agreement. These results lend confidence to our predictions of the characteristics of the conversion.

### Focusing

The maximum energy of an isochronous cyclotron may be limited by the bending power of the magnet, $E = K_B\, q^2/A^2$ MeV/A, or by focusing, $E = K_f\, q/A$ MeV/A. The focusing limit occurs at the onset of loss of axial focusing. We have determined through equilibrium orbit code studies, using extrapolated ORIC magnetic fields, that $K_f$ for the conversion is approximately 75 MeV. Figure 1 shows the ion energy characteristics of the conversion, taking into account the focusing and bending limits of the magnetic field and the charge states obtained by injection of tandem beams. The ion energy from the cyclotron is limited by focusing below approximately A=130.

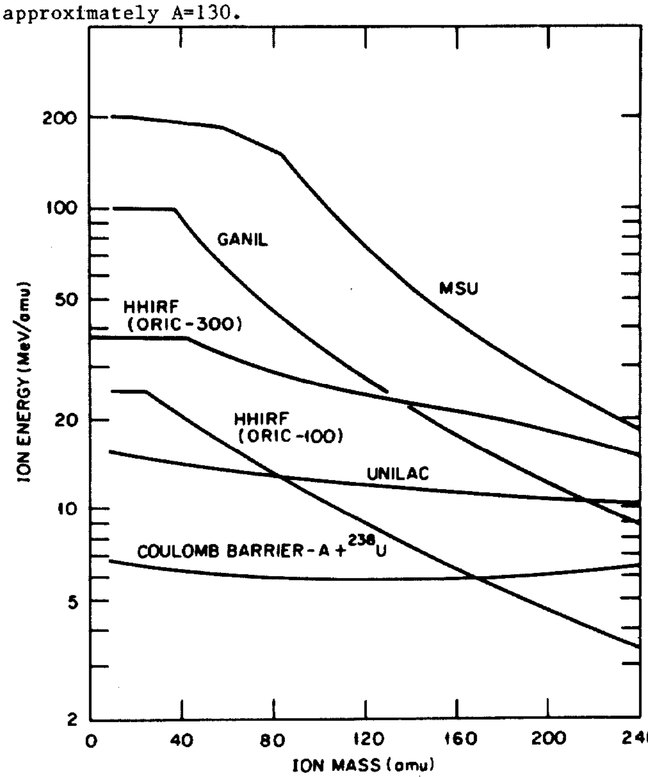


Fig. 1. Energy vs. mass characteristics for the ORIC in present coupled operation with the 25 MV tandem (ORIC-100), and for the conversion (ORIC-300), for beam intensities of $10^{11}$ particles/sec. Energy characteristics of other large facilities are shown.

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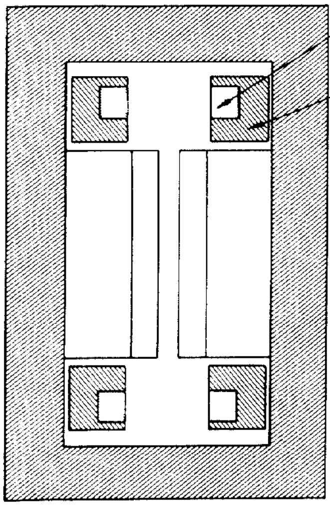


Fig. 2. The superconducting coils will have a smaller cross-section than the present coils and are effectively nearer the median plane and of larger radius.

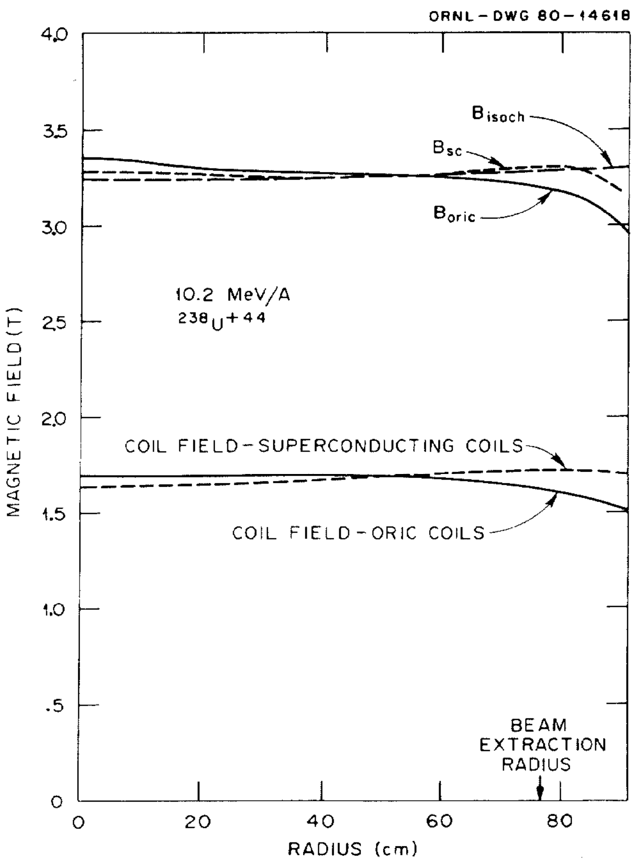


Fig. 3. Radial profile of average magnetic field for the conversion showing the improvement in shape obtained with optimized coil geometry.

## The Superconducting Coil System

The new coil system (Fig. 4) is designed to replace the existing coil system exactly; the cryostats for the superconducting coils will bolt onto the cyclotron yoke using the same mounting holes. A yoke stiffening system (not shown in the figure) will be provided to accommodate the increased magnet forces.

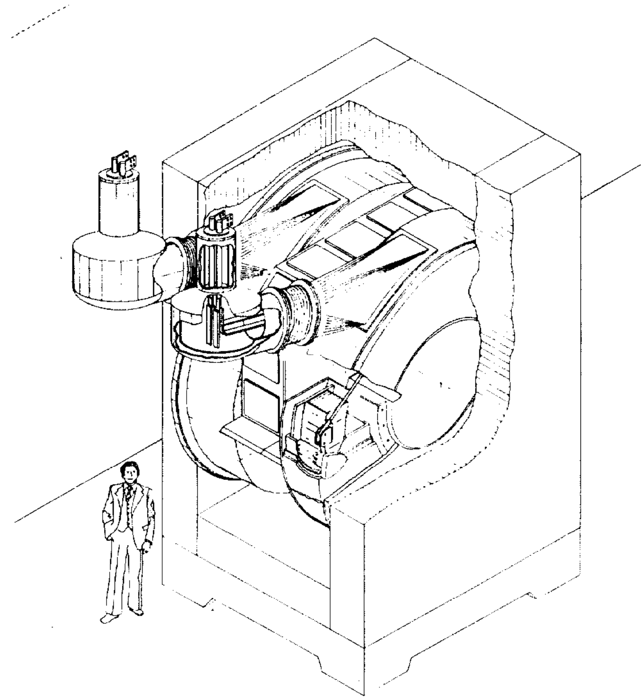

Fig. 4. The superconducting coils are in separate cryostats which occupy the same space used by the present aluminum coils.

## Coil Design

The two windings have inner and outer diameters of 2.5 m and 3.1 m and are 0.25 m wide. Each winding contains 564 turns of NbTi conductor wound in six double pancakes. G-10 epoxy fiberglass insulation will be used: 0.12-cm-thick slotted material between turns, and 0.16-cm perforated sheet between pancakes. The maximum operating current is approximately 4300 A. The conductors will be cooled by pool-boiling 4.5 K helium from a liquefier. The conductor is designed to be fully cryostable. With a copper stabilizer bar 2.0 cm wide and 0.5 cm thick the quench heat flux is 0.26 $w/cm^2$. The overall current density is 3200 $A/cm^2$. The stored energy in the system is 55 MJ.

To ensure safe and reliable operation, all features of the coil design incorporate substantial safety factors. The critical current of the conductor is 7000 A at 4 T. The peak dump voltage is only 150 V and the maximum conductor temperature reached in a dump is estimated to be 104 K. The peak pressure in the cryostat during a quench is approximately 7 atmospheres.

Mechanical stresses in the winding have been computed using the computer code STANSOL.[6] Stresses from winding preload, cooldown, and energization were considered. A winding preload of about 49 MPa (7000 psi) was sufficient to prevent the windings from lifting off the bobbin. The maximum tensile stress in the conductor at full field was 80.5 MPa (11,500 psi).

## Suspension and Cryostat Design

The mechanical suspension for the coils must support the attractive force of 3.9 MN (880,000 lb) between the coils with acceptably low heat leakage and deflection, and maintain the coils concentric and coplanar with the median plane to within ± 0.5 mm. The coil forces must be supported from the yoke through the cryostat. The design adopted (Figs. 5 and 6) incorporates epoxy-fiberglass links between the 4 K coils and the 77 K liquid nitrogen shield. This shield is mounted on short tubular stainless-steel supports from the baseplate at 300 K. Stainless steel transverse support rods, cantilevered from the tubes, support the 76 kN (17,000 lb) gravity load and the coil decentering forces which are calculated to be a maximum of 46.6 kN/cm (26,600 lb/in). The safety factors of this design are approximately seven for the epoxy-fiberglass, and three for the stainless steel components. The two coils will consume about 25 liters/hr of liquid helium and an equal amount of liquid nitrogen.

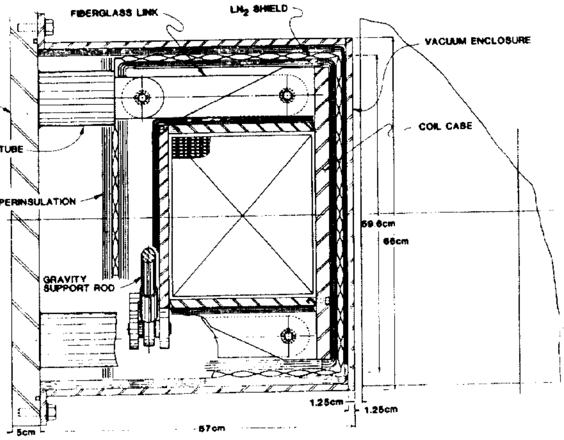


Fig. 5. Cross-section of the cryostat/coil assembly.

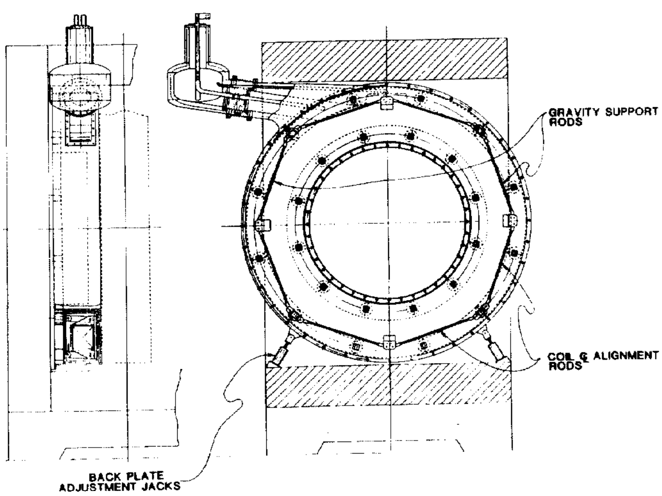


Fig. 6. Side-view of the cryostat/coil assembly showing the coil centering supports, alignment system, and coil leads.

## Beam Extraction System

The beam extraction system for the conversion (Fig. 7) will consist of an electrostatic deflector operating at a gradient of 120 kV/cm, followed by two -0.5 T room temperature coaxial magnetic channels[7] and a -2.4 T superconducting coil channel.

Two concepts are being evaluated for the -2.4 T magnetic channel. One is based on the use of a cosine current distribution in an inner (main) winding, and a similar outer (compensating) winding with current of

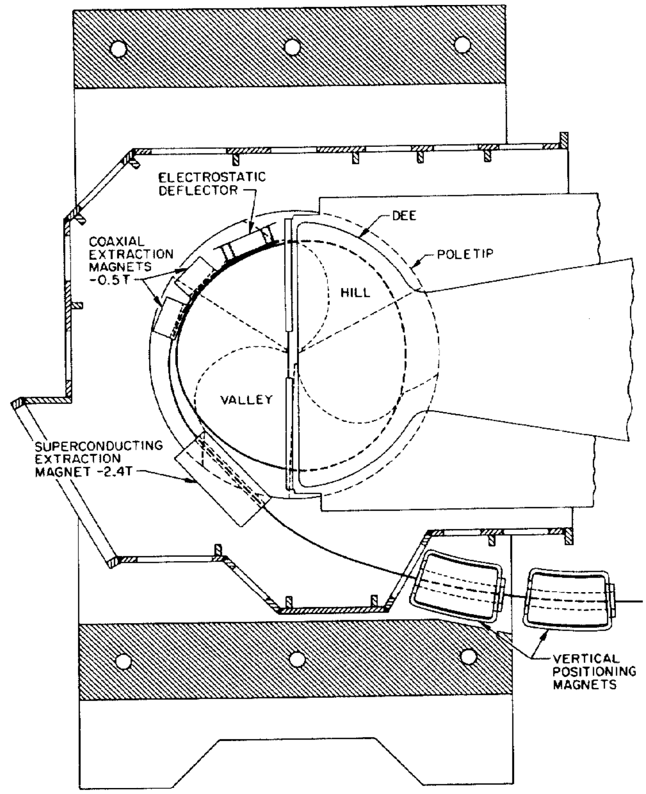


Fig. 7. The beam extraction system for the conversion. The two vertical positioning magnets are to be provided with coils to compensate the effect of the stray field on the iron yokes.

opposite sign to cancel the external magnetic field. The alternate design includes a set of main conductors to produce the channel field and a distributed array of compensating conductors.

The channel location and strength were chosen to produce a nearly linear path so that a straight channel element may be used with consequent ease of construction.

## Beam Transport and Shielding Modifications

Only minor modifications of the beam transport system are required to serve all existing and planned experimental stations with the higher energy ion beams of the conversion. A small amount of additional radiation shielding will be required.

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