CONF-810835--9

DESIGN STUDY FOR SUPERCONDUCTING MAIN FIELD COILS FOR THE OAK RIDGE ISOCHRONOUS CYCLOTRON*

S. W. Schwenterly, P. S. Litherland, J. K. Ballou, R. L. Brown, W. A. Fietz, W. H. Gray, E. D. Hudson, R. S. Lord, M. S. Lubell, J. A. Martin, J. R. Moore, R. E. Stamps, and P. L. Walstrom.

Oak Ridge National Laboratory
P. O. Box Y
Oak Ridge, Tennessee 37830

INTRODUCTION

The Oak Ridge Isochronous Cyclotron (ORIC) has recently been modified for coupled operation as a booster accelerator for the new tandem electrostatic accelerator in the Holifield Heavy Ion Research Facility. The existing ORIC main field coils produce 1.9 T, and the resulting low bending power limits available beam energies, especially for high masses. This paper summarizes a design study to replace the ORIC main field coils with 3.2-T, superconducting NbTi coils, in order to allow acceleration of ions up to a mass of 238 into the nuclear reaction region. An important benefit is the lower electric power requirement and operating cost of such coils.

A number of superconducting cyclotrons are in various stages of planning or completion, both in the United States and abroad.[1-4] The conversion of a conventional cyclotron raises problems not encountered in these superconducting machines, but many aspects of their designs have been useful in the ORIC study. Table I shows the major parameters of superconducting coils proposed for ORIC. The winding pack dimensions, ampere-turn requirements, and forces

*Research sponsored by the Office of Fusion Energy, U. S. Department of Energy, under contract W-7405-eng-26 with the Union Carbide Corporation.

were determined from computer calculations. Details of the proposed design will be given in other sections of this paper.

Table I. Major Coil Parameters

Field - 3.26 T in gap, 3.62 T in windings
Winding dimensions - 2.52-m ID x 3.12-m OD x 0.25-m width
Overall current density - 3161 A/cm^2
Stored energy - 53 MJ
Mass per coil - 7730 kg (17,000 lb)
Axial force - 3.9 MN (880,000 lb) toward midplane — full current
0.3 MN (76,000 lb) away from midplane — 17% current
Allowable deflections - Coil axial suspension — 0.5 mm (0.02 in.)
Coil alignment tolerances - 1.0 mm (0.04 in.) in all degrees of freedom

MECHANICAL DESIGN

The overall magnet configuration is shown in Figs. 1-3. The coil case serves as the winding bobbin, helium containment vessel, and winding support structure. Axial magnetic loads are reacted through 24 epoxy-fiberglass support links equally spaced around the outer and inner diameter of the coil case (see Fig. 2). Each link is pinned between a pair of gussets on the coil case and a clevis on the end of a 9-cm schedule 40 stainless steel support tube. The 77-K radiation shield is also supported and heatsunk at this point. The other end of each tube is welded to a 5-cm-thick backplate that is bolted directly to the existing yoke side pieces, using the existing coil mounting holes. The mounting holes in the backplate are drilled oversize to allow final adjustment of the coil radial position. Extra stiffening structure will be added to the sides of the cyclotron yoke to support the large axial forces.

The radial forces (principally gravity loads) are supported by an octagonal array of 1.9-cm-diam 122-cm-long stainless steel rods (see Fig. 3), which are pinned to the coil at the four 90° positions and to the cold ends of four of the stainless steel axial support posts near the 45° positions. The location of the cyclotron in a Zone 2 seismic area requires a 7% increase in the static design loads. The chosen diameter permits a tensile safety factor of at least 3 under full gravity and thermal contraction loads. All radial and axial supports are attached with spherical ball bearings to allow for small misalignments and adjustments and to minimize bending loads.

A 77-K liquid-nitrogen-filled radiation shield surrounds the coil case. The cold shield extends into the bus duct and terminates around the vapor-cooled lead dewar. Surrounding the outside of the

ORNL–DWG 81-3271 FED

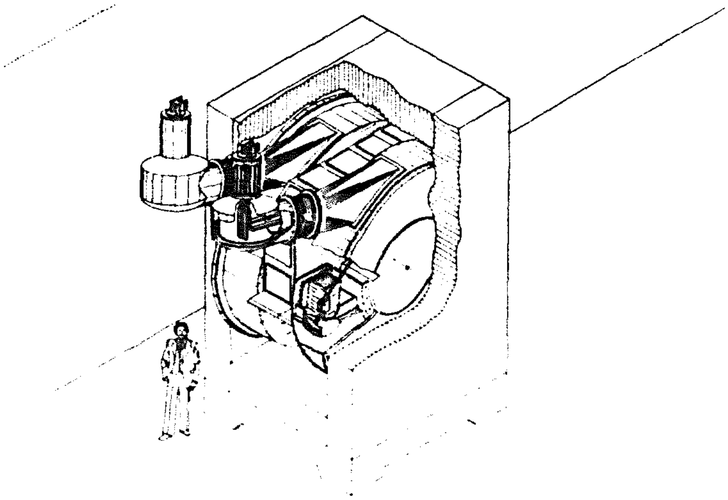

Fig. 1. Isometric view of overall assembly.

ORNL–DWG 81-3272 FED

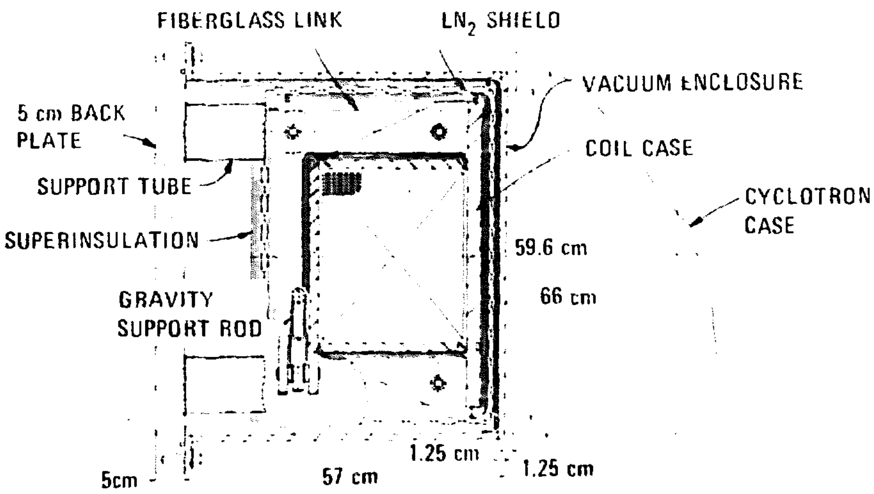

Fig. 2. Detailed assembly cross section.

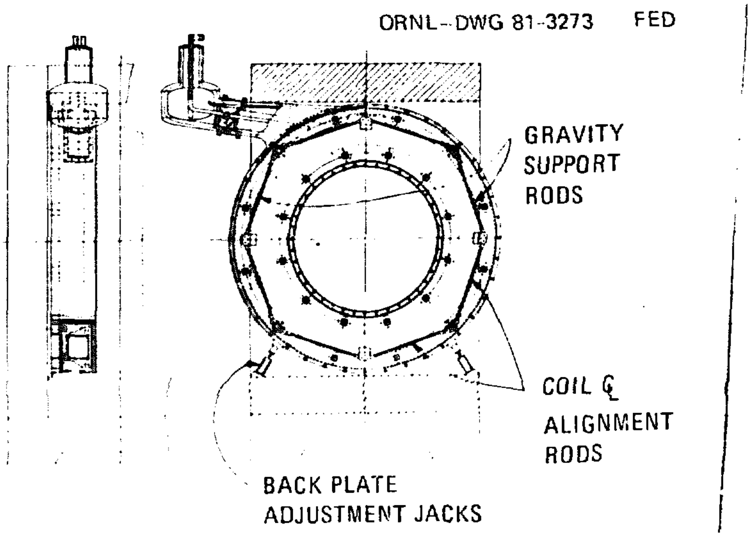

Fig. 3. Assembly side view.

coil case and both sides of the LN_2 shield are 10 layers of super insulation. A common vacuum envelope extends around the coil case, bus duct, and vapor-cooled lead dewar.

The total heat leak of the 24 epoxy-fiberglass links is limited to 6.3 W, as explained later, and the full-load deflection must be much less than 0.50 mm. When a support link must operate between two temperatures with limited deflection and heat leak, one well-known figure of merit for choice of the material is $E/\bar{k}$, the ratio of the Young's modulus to the average thermal conductivity over the temperature interval. Uniaxial fiberglass in a NASA-Resin-2 matrix[5] has been chosen for the suspension links because it has a particularly high value of this parameter. The design configuration is shown in Fig. 4. The link is fabricated by winding uniaxial fiberglass tape to form a band. After curing, the bands are potted into stainless steel end caps which transfer compressive loads from the bearings to the fiberglass.

Assuming an active length of 20.3 cm and an E value of 69 GPa[6] for uniaxial fiberglass, the 6.3-W heat leak criterion leads to a combined cross-sectional area of 17.2 cm^2, or a band cross section 2.86-cm-square. The calculated tensile yield and compressive buckling safety factors for the link are 7 and 45 respectively. Reported test results[7] indicate excellent long-term dimensional stability for a member similar to the proposed design.

ORNL-DWG 81-3274 FED

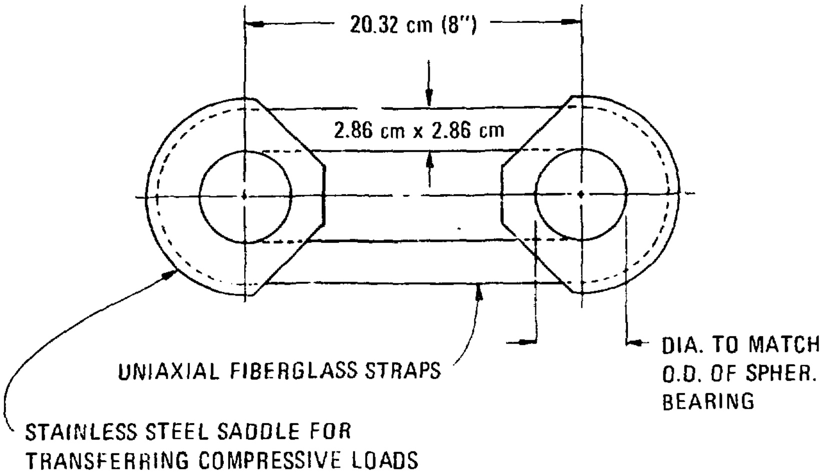

Fig. 4. Fiberglass support link.

CONDUCTOR AND WINDING SCHEME

For maximum magnet stability, a fully cryostable pool-boiling design has been chosen. The Joule heat flux is about 0.26 W/cm^2 for a normal zone in the conductor. The cooling passages occupy 15% of the winding-pack volume and one-half of the conductor surface is exposed to helium. The conductor area and current are maximized, subject to the 5000-A limit on the existing bus work to the cyclotron. This lowers the number of turns and inductance, which in turn reduces the coil dump voltage and allows faster routine charging and discharging of the coils. Coil fabrication is also simplified with the larger conductor.

With the above concerns and a consideration of the winding pack dimensions, the available standard insulation thicknesses, and the ampere-turn requirement, a set of conductor and coil parameters has been chosen as shown in Table II.

Basically, the conductor will consist of a solid copper stabilizer bar, with a superconducting insert soldered into a 3-7-mm-wide groove in one face. The insert will contain twisted filaments of niobium 46.5 wt % titanium alloy, no greater than 60 μm in diameter. The critical current will be between 7000 and 7500 A at 4.6 K and 4 T, and the overall Cu:Sc ratio will be about 40:1. The insulation

Table II. Conductor Parameters

Conductor dimensions	1.97 x 0.52 cm (0.78 x 0.20 in.)
Pancake insulation	0.16 cm (0.063 in.) thick
Turn insulation	0.12 cm (0.047 in.) thick
Coil width x height	12 x 47 turns
Turns per coil	564
Current	4255 A
Heat Flux	0.26 W/cm^2

will be composed of perforated sheets of G-10 fiberglass composite between adjacent turns and pancakes. Fig. 5 shows a detail of the

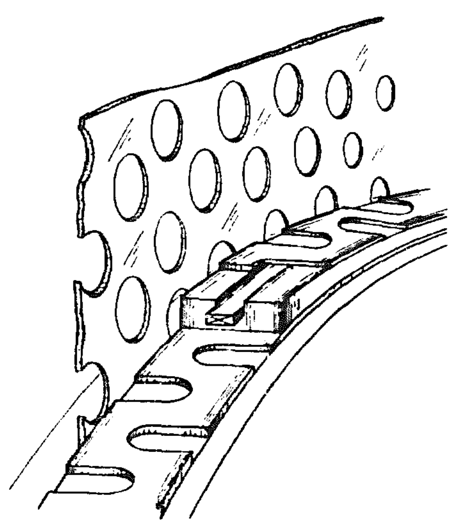

Fig. 5. Conductor and insulation scheme.

proposed conductor and insulation scheme. The coils are wound in continuous double pancakes with no internal joints, as determined from consideration of several ORIC coil design factors. Among these are better transmission of radial forces, reduced conductor motion, better cooling, and more efficient packing of the available winding space.

To protect the coils in case of an unanticipated quench, an external air-cooled dump resistor will be connected in parallel with the coil. The dump resistor is sized to limit conductor temperatures to about 100 K in a quench. Assuming all current transfers to the copper matrix, a computer calculation is made of the temperature rise versus time, using the temperature-dependent resistivities and heat capacities of the conductor materials. The program also considers the effects on the inductive coil time constant due to the iron in the cyclotron yoke. No cooling by the surrounding helium is assumed. The dump resistor is varied until the desired temperature is reached. With the conductor dimensions and current given previously, the computer solution of the heat-up equations leads to resistance and peak voltage of 35 mΩ and 150 V, which is below the Paschen minimum voltage for helium breakdown. A protection circuit time delay of 0.1 s is assumed. The current and stored energy are reduced to safe levels within about 10 min and the peak temperature is 104 K.

Radial and axial stresses must be considered in the design of the winding pack, to prevent excessive deflection of the coil cases and to maintain compressive stresses between all layers of conductor and insulation. These two concerns may be satisfied by the design of a sufficiently rigid bobbin and coil case and by the use of appropriate pretension on the conductor during winding.

A computer program called STANSOL[8] is used to predict the mechanical stresses in the bobbin and windings during preload, cooldown, and energization. The program considers all loads resulting from pretension, internal pressure, thermal contraction, and Lorentz forces and incorporates all the desired material properties and magnetic field distributions. A winding pretension is first assumed; then, STANSOL is used to determine the radial and tangential stresses in the various layers of the coil. The preload and bobbin thickness are adjusted until it is verified that a compressive radial stress of over 0.7 MPa exists at the inner bobbin-conductor insulation interface over the whole range of coil excitation. For the assumed design, a 1.6-cm bobbin thickness and a 3780-N pretension force have been found to be appropriate. No external banding is required. The calculated hoop stresses versus radius under full coil excitation are well within safe operating limits. The radial pressure at the bobbin is 0.74 MPa and is compressive as desired.

THERMAL ANALYSIS

The principal heat loads are thermal radiation, conduction and Joule heating in the current leads, conduction through the mechanical suspension, and parasitic losses in the coil lead dewars, main liquid storage dewar, and transfer lines. Minimum heat load is obtained when the total radiation plus conduction heat leak to the coil just balances the "self-sufficient" heat load of the vapor-cooled leads, in this case 7.2 W per coil at 4.6 K and 4255 A. Radiation is calculated to supply 0.3 W per coil, and the radial suspension rods contribute another 0.6 W. The dimensions of the fiberglass links are chosen to pass the remaining 6.3 W and their deflection is calculated to be 0.28 mm at full field. The remaining 0.22 mm of axial deflection is allocated to the stainless steel support tubes, which are sized accordingly.

The total radiation and conduction heat loads amount to 14.4 W at 4.6 K and 1176 W at 77 K. The equivalent liquid requirements are 25 ℓ/h of liquid helium and 26 ℓ/h of liquid nitrogen. In order to handle the parasitic and other unforeseen losses, it is good practice to size the helium refrigerator for roughly twice the coil heat load. With a standard commercial refrigerator-liquefier of 100 W or 40 ℓ/h capacity a cooldown time of 160 h is estimated. The refrigerator will draw a maximum of 200 kW of electrical power, as compared to the 1.75 MW consumption of the existing coils.

CONCLUSION

The design study described here demonstrates the feasibility of replacing the existing ORIC coils with superconducting magnets. The design is quite conservative, requires no unusual technology, and should result in a coil system with good reliability and durability. The operating regime of ORIC will be considerably extended, and running costs should be reduced. A proposal to continue with detailed design and coil fabrication is currently under review and has been submitted to the Nuclear Science Advisory Committee.

REFERENCES

1. H. G. Blosser, IEEE Trans. Nucl. Sci. NS-26: 2040 (1979).
2. H. G. Blosser and F. Resmini, IEEE Trans. Nucl. Sci. NS-26: 3653 (1979).
3. J. H. Ormrod et al., IEEE Trans. Nucl. Sci. NS-26: 2034 (1979).
4. E. Acerbi et al., IEEE Trans. Nucl. Sci. NS-26: 2048 (1979).
5. L. M. Soffer and R. Molho, NASA CR-72114 (1967).
6. M. B. Kasen, Cryogenics 15: 331 (1975).
7. V. Buchanan, D. Dassner, and I. Polk, IEEE Trans. Nucl. Sci. NS-26: 4039 (1979).
8. N. E. Johnson, W. H. Gray, and R. A. Weed, Proc. 6th Symp. Eng. Problems of Fusion Research, 243 (1976).