

Design of a Radiation Resistant Quadrupole Using CICC

A. F. Zeller, J. DeLauter, J. C. DeKamp and J. Bierwagen

Abstract—High acceptance fragment separators for secondary beam facilities require large aperture quadrupoles close to the production targets. These quadrupoles are exposed to high levels of radiation. We present designs for superferric quadrupoles based on radiation tolerant Cable-In-Conduit-Conductor (CICC) coils that have lifetime limits set by the superconducting materials. CICC coils using both stainless steel and aluminum conduits are described and small-scale coil fabrication presented.

Index Terms—Superconducting, quadrupole, radiation resistant.

I. INTRODUCTION

THE front end of the proposed high-intensity accelerators that will select secondary beams of unstable nuclei from the mass of unwanted fragments and un-reacted primary beam is subjected to very high fluxes of neutrons. Because the fragment magnetic rigidities are high and the desired quadrupole apertures large, using resistive magnets is not an attractive option. The cost of using resistive magnets would be very reduced acceptances and inefficient use of beam time. The calculated neutron-dose rates for the coils in the first quadrupole in the Rare Isotope Accelerator (RIA) are as large as 2 Gy/s [1]. This results in doses of 20 MGy per year of operation. Clearly, organic insulation with end-of-lifetime doses of 10 MGy will not be acceptable. Superconductors, with tolerances of about 500 MGy [2], will be useful as long as an insulation system can be found. There is also much interest in High Temperature Superconductors (HTS) that have a thermodynamic advantage of operation at 30-40 K and can use “insulators” such as stainless steel [3]. At present, though, the tolerance of HTS coils to high-energy neutrons is unknown. Plans are underway to test the materials, but other options need to be considered in case the material is not very radiation tolerant.

Another consideration is the heat generation in the materials that are at liquid helium temperatures. In a superferric quadrupole, the most efficient magnet (in terms of keeping the mass low and the coil small) is obtained by having the iron act

as the coil support structure. This means the iron is at 4 K. Radiation transport calculations indicate the heat deposited in a one-meter long quadrupole would be on the order of 10 kilowatts – a clearly unacceptable refrigeration load [1].

The goal of the project is to design a superferric quadrupole, with warm iron and a radiation tolerant coil that is also capable of removing the large neutron heating.

II. CONDUCTOR

A cable type, Cable-In-Conduit-Conductor (CICC), will be used in several fusion devices. This type of conductor has the advantage of being able to remove large amounts of neutron heating. The cable for ITER is Nb₃Sn [4], but other accelerator or fusion projects propose or make use of NbTi [5] or HTS [6]. None of them, however, is, radiation tolerant when used with some organic insulation, although it may be possible to use the HTS approach. The radiation tolerance of HTS hasn't been demonstrated as of today. The CICC itself is purely inorganic and the lifetime is limited by the superconductor, but some kind of electrical insulation is required. ITER fluxes are low enough that some kinds of organic insulation will survive for the expected life of the machine. In RIA, both the flux and the neutron energies are much higher, and the same approach will yield unacceptably low lifetimes. We propose a design based on Metal Oxide insulated CICC (MOCICC) [7]. The insulation is magnesium oxide, or spinel (an aluminum-magnesium oxide) and coil structure is achieved by welding. The conduit is shown in Fig. 1. Forty-eight strands of 0.5 mm diameter NbTi superconductors are inserted into the conduit.

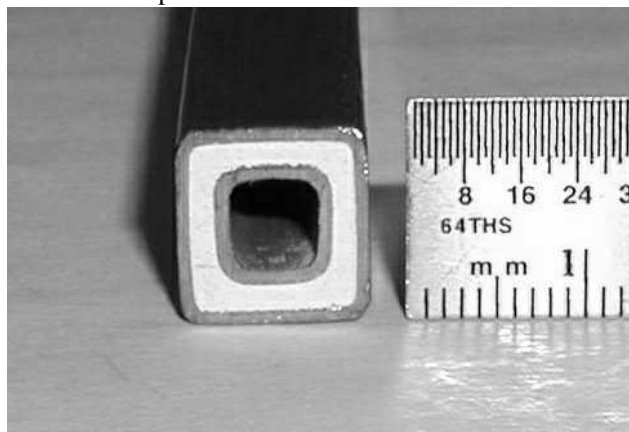


Fig. 1. Metal Oxide insulated conduit for CICC made from 316 Stainless Steel and magnesium oxide insulator by Tyco Thermal Controls.

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This is about a 40% fill factor. It is possible to insert a few more strands into pieces that are less than 3 meters, but difficult in longer lengths. An attempt was made to insert the strands into conduit that was intermediate in size and draw the whole assembly down to the final size, as is done for ITER; however, it appears the strands may have been damaged. The test piece is presently at Brookhaven National Lab for testing. It is likely this would lead to larger fill factors, but requires more cable development. The peak field on the conductor is about 3 T and the manufacturer's guaranteed current at this field is about 175 A. This will achieve a pole tip field of 2.0 T, and a gradient of 13 T/m in the test quadrupole, which requires 8500 A in each CICC turn.

III. COIL DESIGN

The project has two stages: The first stage is to construct a dipole with MOCICC. Because it uses less conductor and is easier to build we will use an available 200 mm long dipole. The coils will consist of four turns that are welded for structural integrity. A single four-meter length of conductor will be needed for each half. Once the magnet has been tested, the quadrupole will be built.

The coils will consist of fourteen MOCICCs (10 mm x 10 mm), arranged as two double pancakes of four and three each conductors per layer. The arrangement is shown in Fig. 2. It is possible to add another single pancake of three turns, but the added cost is not justified.

Another way to reduce the heat deposition in the cold mass is to substitute aluminum for stainless steel in the conduit and to use aluminum stabilized superconductor [8]. This reduces the heating of the coil. For the RIA case, the neutron induced

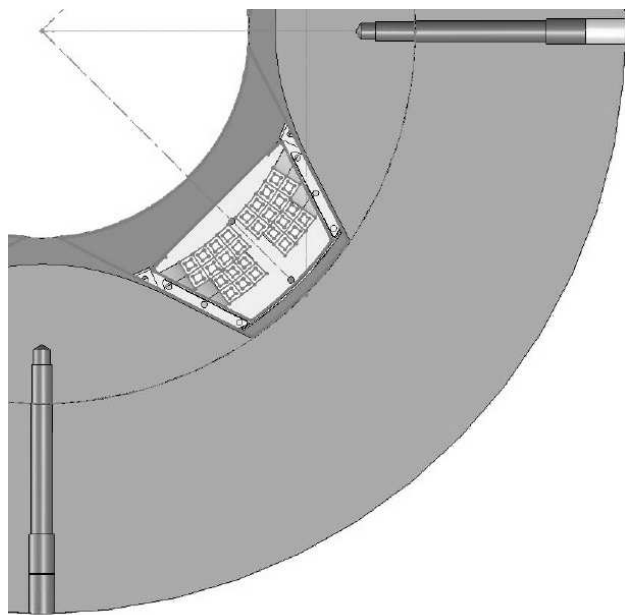


Fig. 2. Quarter section of the quadrupole showing the coils, pole tips and return yoke.



Fig. 3. Test weld on aluminum conduit.

heating in the coil is reduced from 150 W to about 65 W. The major concern about the aluminum conduit is the ability to weld the coil into a tight package. Test welds on the stainless steel conduit indicate that small welds are easy to achieve, with negligible heating of the superconductor. This not the case for the aluminum conduit, where the rise in temperature is 175° C [1]. While the temperature rise is still acceptable, a bigger concern is the size of the weld. The sample weld piece is shown in Fig. 3. Obviously, more work on welding or more room for the coils is required.

IV. MAGNET DESIGN

A schematic drawing of the four coils is shown in Fig. 4. Because the conduit in the present conductor is thick and forces on the coil relatively low, little in the way of a bobbin is needed to restrain the radial forces. The inter-coil axial forces are taken up by a stainless steel (or aluminum) spacer. The conduit manufacturer, Tyco Thermal Controls, believes they can produce a conduit that has much thinner walls (0.5 mm), which would increase the current density, but reduce the stiffness. If the thinner wall is used, then a reinforcing strongback will be used to counteract the radial forces.

The magnet iron is shown in Fig. 5. The length of the steel is 324 mm and the effective length is 400 mm. This magnet iron is the same as the ones used in the A1900 fragment separator, so the magnetic fields can be compared with the conventional superferric design.

After the coils are wound on a separate winding fixture, they will be placed in the cryostat and assembled with the pole tips in pockets in the cryostat, as shown in Fig. 6. This whole assembly can be inserted into the yoke. For simplicity, the connections between the pancakes and the separate coils have been omitted. Also omitted are the spacers between the coils and the warm-to-cold support links. The links will support the coils from the ends. During assembly, spacers will be placed in the radial direction to locate the coils. These will be removed before the cryostat is closed.

The intermediate heat shield will be placed around the coil, as shown in Fig. 7. In an application such as RIA, the cooling would be done with excess helium boil-off because of concerns about Oxygen Deficiency Hazards in an underground

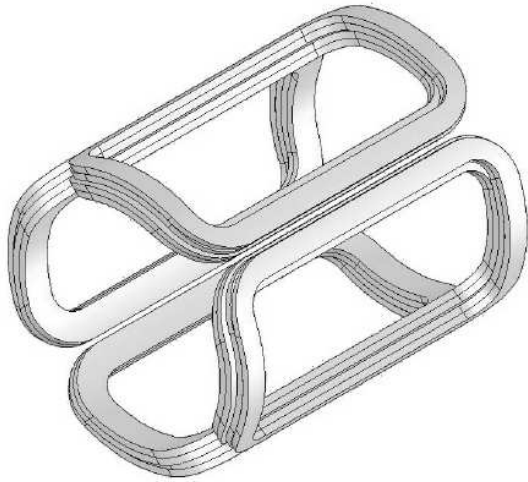


Fig. 4. The coils consist of two double pancakes of four and 3 turns for a total of 14 turns per coil.

installation associated with cold nitrogen gas. For this test we will use liquid nitrogen.

Because the high-radiation environment prohibits the use of organic materials, we cannot use superinsulation between the 77 K surfaces and the room temperature ones or any between 4 K and 77 K. It would be possible to use a Kapton® based superinsulation, but the expected lifetime would only be one year of operation. Since we cannot use it for the actual application, we will forgo it in the prototype. When the beam in the fragment separator is on, the neutron induced heating is 100-150 W. If we assume the emissivity of the 77 K and the 4 K surfaces are one, then the added infrared radiation is only 2 W/m^2 – a small change in the heat load. Of course, when the beam is off, this will be the dominant heat load; although it is still small compared to the lead requirements.

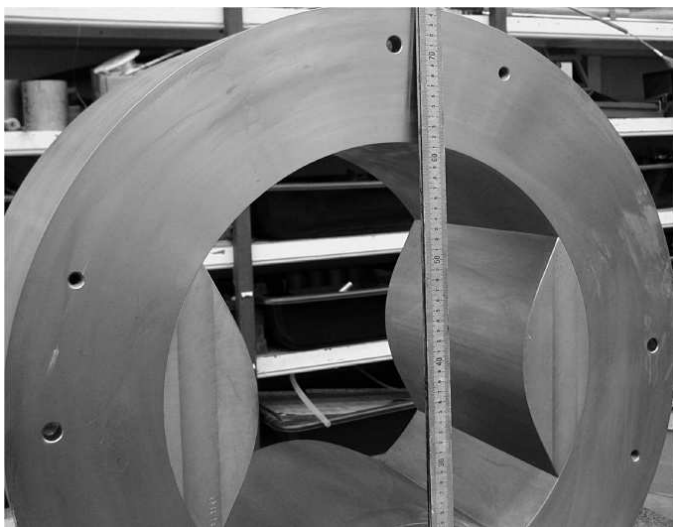


Fig. 5. Quadrupole iron assembly, with one pole tip removed. The steel is 324 mm long.

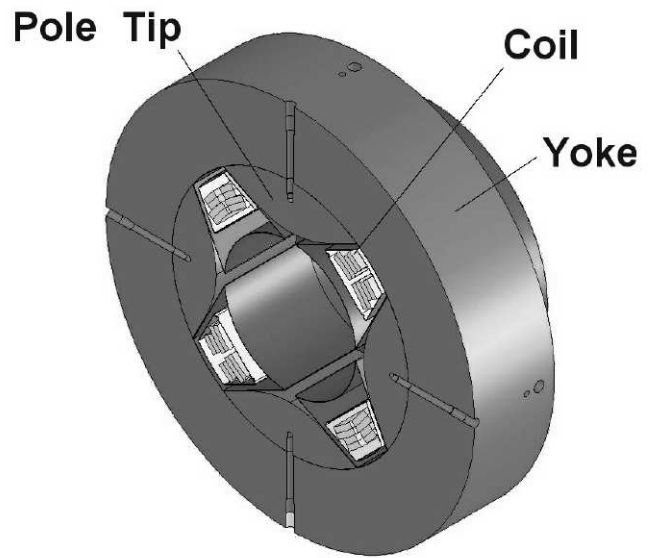


Fig. 6. Coils assembled around pole tips.

The complete quadrupole, minus the cross connects and the lead ends, is shown in Fig. 8. The lead ends and buss ring will be in a box, located where the section of cryostat is missing in the figure. The ends can be compact because the CICC can be bent with a radius of twice the width of the CICC without damage to the superconductor. Because the bend-radius for this conductor is only 20 mm, the most appropriate coil fabrication is to insert the superconductor into the conduit while the conduit is still straight or has a large radius (It comes from the factory on a one-meter diameter spool.) The entire cold mass of the coil is only 30 kg, plus an equal amount of support pieces. If aluminum conduit is used, then the mass is even smaller.

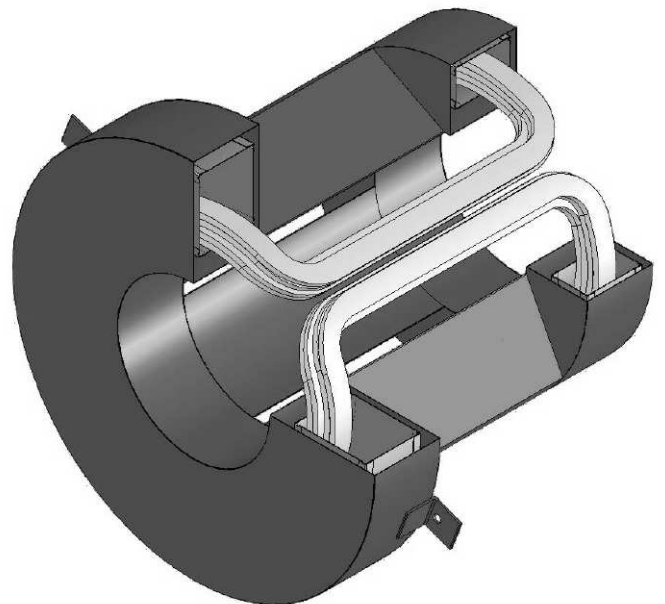


Fig. 7. Quadrupole coil in heat shield and cryostat without the iron assembly.

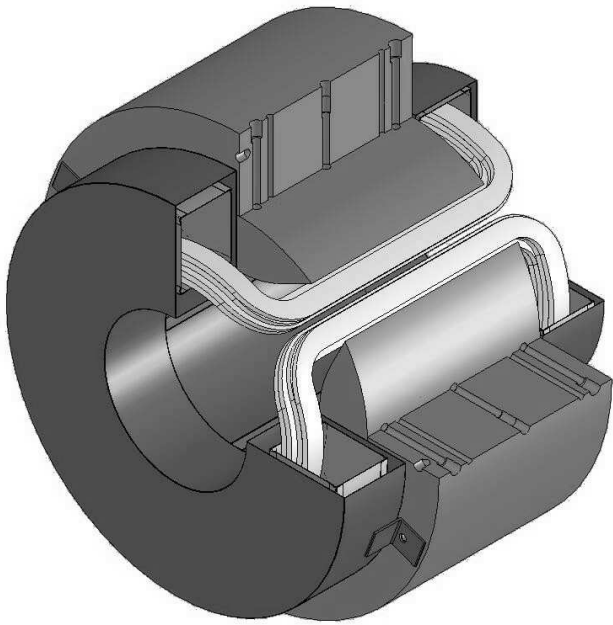


Fig. 8. Complete quadrupole assembly with one quarter removed to show the interior.

V. DISCUSSION

As long as high fields and large apertures are required in the first few quadrupoles of the proposed fragment separators, then superconducting magnets are the only option. Of course, one could make the magnets from less radiation tolerant materials and make frequent changes when they suffer irreversible damage. Because the magnets will be in an area that will become so radioactive that remote handling is required, this is even less attractive than using resistive magnets and a smaller acceptance. That leaves only two options: The MOCICC version, with warm iron; or a warm iron version using HTS. In either case, the design presented here will be useful. The HTS version has the attractive feature of not operating at about 10 kA, but has to overcome an aversion to new technology.

Several technologies still need to be developed. The most important are the terminations and the connections to the current leads. Because the individual conductor lengths are longer than those required for a single double-pancake, no splices are required in the coils. Connections between the pancakes and the coils are made on the buss ring. As the

magnetic fields on the ends are well below one Tesla, the forces are small and simple piping will suffice for the connections. The end terminations relatively easy because all we require is that the inner conduit is not shorted to the outer conduit. The outer conduit has to be leak tight, but that is not required for the inner conduit. The insulation is dense and very little helium gets into it. What little that does doesn't affect the dielectric strength because high voltage is only present when the coil is cold. The initial conductor tests simply involve putting the CICC in a liquid helium bath, without trying to keep it out of the insulator. No problems during either testing or subsequent warm-up were encountered. The leads have not been examined, but we intend to use ones similar to those developed for other CICC-based magnets.

The initial test dipole will be constructed with stainless steel conduit. If the aluminum conduit can be developed and the welding problem overcome, then it would be the preferred option for constructing the quadrupole because of the lower neutron induced heating.

ACKNOWLEDGMENT

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