A Radiation Resistant Dipole Using Metal-Oxide Insulated CICC

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***Abstract*—Several proposed accelerator facilities will be capable of providing intense beams on targets that are in close proximity to superconducting magnets. These magnets will have to operate in high-radiation environments. A proposed solution to the manufacture of radiation tolerant coils is to use a metal-oxide insulated version of the standard CICC, which allows the use of welding to provide structural integrity. A small superferric dipole, similar to one previously constructed with conventional epoxy-potted coils, has been fabricated with metal-oxide CICC. The coils have four turns of 10 mm square conductor having 42 strands of 0.5 mm diameter NbTi wire. The calculated field on the conductor is about 2 T at a current of 10 kA. Test results will be reported and extension to larger devices discussed.**

***Index Terms*—CICC, dipole, radiation resistant, superconducting magnet.**

I. Introduction

HIGH intensity accelerators such as the Rare Isotope Accelerator (RIA) [1] and FAIR [2] will need to deal with the problem of operating superconducting magnets in high radiation environments. The problem is composed of two elements: the removal of neutron heating and the long term destruction of either the conductor or the insulator.

To limit neutron heating into the liquid helium system the cold mass should be kept as small as possible. Also, a suitable method of carrying away the heat is necessary. Long-term radiation damage can best be managed by constructing the magnets with materials that are inherently tolerant of radiation. Ideally all materials in the magnet would have radiation tolerances higher than that of the superconductor. We proposed [3] that constructing coils with radiation resistant Cable-in-Conduit-Conductor (CICC) technology would be a solution to these problems. A resistive metal-oxide insulated, water-cooled copper conductor has existed for years at PSI and LANL [4], [5], but this work examines a superconducting version. Using CICC technology allows forced flow liquid helium as a means of carrying away the heat, and also allows easy separation of the cold mass from the warm iron because a helium containment vessel is not required. Due to the high radiation tolerance of ceramics like MgO, the use of MgO as an insulator in the CICC results in a radiation tolerance greater than or equal to that of the superconductor [7].

TABLE I
MAGNET AND WIRE PARAMETERS

System	Parameters
Wire	0.5 mm diameter 2:1 copper to superconductor ratio
Bundle	42 strands (14 x 3) 44% fill factor
Coil Dimensions	4 turns 21 mm x 21 mm cross section 178 mm width, 192 mm length
Magnet	310 mm x 310 mm x 180 mm outer dimensions

II. Magnet Design

A dipole magnet was fabricated and tested to examine the suitability and operating properties of this CICC technology. As irradiation testing of inherently radiation resistant materials is very difficult, only the magnet properties were tested. Since the radiation tolerances of the materials are known, this is the most practical approach. In the interest of cost reduction and time conservation the design was based on a previously existing dipole magnet [8]. The coils have only 4 turns due to space restrictions in the iron and also due to conduit manufacturing limitations. Tyco Thermal Controls, the manufacturer of the conduit, could provide only short (about 4 m) lengths for developmental work.

Our primary concerns in the design of the magnet were current density and radiation tolerance. The use of forced flow liquid helium means large radiation heat loads can be tolerated. The first quadrupole in the proposed fragment separator for RIA has a load of about 150 W in the coil mass [9], which was simulated with the code GANDALF [10]. With an input pressure of 5 atm and 5 g/s flow, and the heat load uniformly distributed along the length of the coil, the temperature rose 1 K.

Magnet, coil, and wire parameters are summarized in Table I. Field lines were calculated using POISSON [6] and appear in Fig. 1. The coils were made from CICC that was composed of a 316 Stainless Steel 4.8 mm diameter inner conduit, surrounded by MgO, with another 10 mm square stainless steel jacket on the outside as shown in Fig. 2.

MgO was chosen as the insulator because, as a ceramic, it has greater radiation tolerance than NbTi, and because it is effective as an electrical and thermal insulator [4]. The metal-oxide CICC was tested for voltage breakdown across the insulation, which

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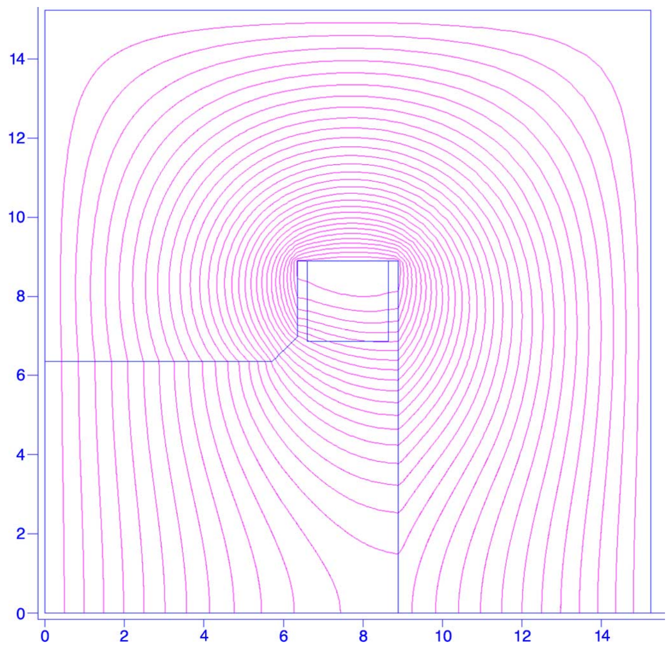

Fig. 1. Field lines and field strength were calculated using POISSON [6]. The maximum field in the conductor was calculated to be 2 T for 10 kA. Dimensions are in cm.

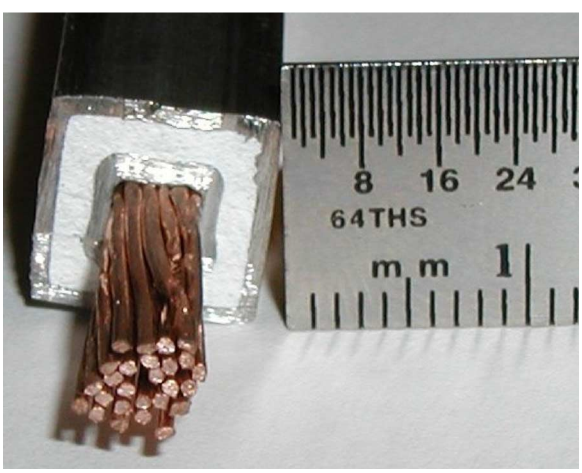

Fig. 2. The CICC outer jacket measures about 10 mm as shown. The conductor is surrounded by a 0.8 mm thick 316 Stainless Steel conduit, followed by 2.3 mm of MgO insulation, and then enclosed by another 0.8 mm stainless steel jacket (316LN).

occurred around 5 kV. The breakdown measured at 5 kV was at the ends of the samples, and there was no indication that it occurred internally through the MgO. The MgO is hygroscopic, so absorbance of water from air, and especially from condensate after cold-shock, can lead to dramatic changes in the breakdown voltage. While this may cause problems in resistive magnets, it does not affect operation at liquid helium temperatures. Since the quench voltages are not expected to be above 1 kV, 5 kV is a safe margin as long as the ends are well insulated. The breakdown voltage was not tested after the coils had been joined together. All high potential tests were done in air, not in liquid helium.

The conductor was inserted into the inner conduit and consisted of 42 strands of 0.5 mm diameter NbTi wire that were twisted into a bundle. The short sample limit of the 42 strands is 12 kA in a 2.5 T field.

III. Magnet Construction

The first step in the construction process was to find the largest amount of conductor that could be reproducibly inserted into the conduit. This was an important factor not only because of the effect on current density, but also because tighter packing would better constrain the conductor strands. However, radiation heat loads are proportional to density, so exchanging helium for conductor results in increased density and thus increased heat load. For this reason, a compromise must be found between current density and heat load.

The 42 strands of conductor were first twisted in to 14 three-stranded bundles and then those were twisted into the whole bundle. The bundle was inserted by running a steel cable down the conduit, attaching it to one end of the bundle, and pulling the bundle through. This process resulted in a fill factor (the cross sectional area ratio of conductor to void) of 44%.

The CICC conduit manufactured by Tyco Thermal Controls had a very dense MgO powder in between the inner and outer steel tubes. The manufacturing process is proprietary, but presumably the volume between the steel tubes was packed with MgO powder and then all were drawn into the smaller conduit seen in Fig. 2.

After the bundle was inserted into the conduit, the CICC was wound into rectangular coils using the bending form and bending arm in Fig. 3. As the turns were wound, they were tack-welded in place occasionally in order to restrain the shape. Once finished, larger sections of weld were placed at the seams of adjacent turns in order to secure the coil's structural integrity. The conduit used had rounder corners than that shown in Fig. 2, and allowed more space for weld without increasing the overall cross section.

The next step was to install the coils into the iron. The coils were shimmed in to prevent overall movement from the Lorentz forces. The leads were then soldered together so the two coils were in series. Over the soldered leads were placed two clamshell halves (a cutaway can be found in Fig. 4) made of stainless steel jacket with an insulating layer of Macor ceramic. The outside of the clamshell was welded on to the CICC and secured to the iron by a post as in Fig. 5. There is some space in the joint that the Macor does not cover, where the only insulation between the conductor and ground is a few millimeters of liquid helium. The dielectric strength of liquid helium at one atmosphere is greater than 10 kV/mm [11], so 3 mm of liquid helium should be sufficient stand off for the 1 kV maximum voltage.

The testing procedure for this magnet was to insert it into a liquid helium bath. In a device designed for actual beamline there would be liquid helium flowing through the splice area. This joint was designed with the capability of forced flow operation. Voids between the square Macor and the round joint bundle allow liquid helium to flow around the soldered joint bundle, as seen in Fig. 4. Forced flow was not used for the test, so the clamshell was simply tack-welded onto the CICC. For forced flow operation the clamshell would need to be larger; a larger joint would handle the flow and provide more space for more

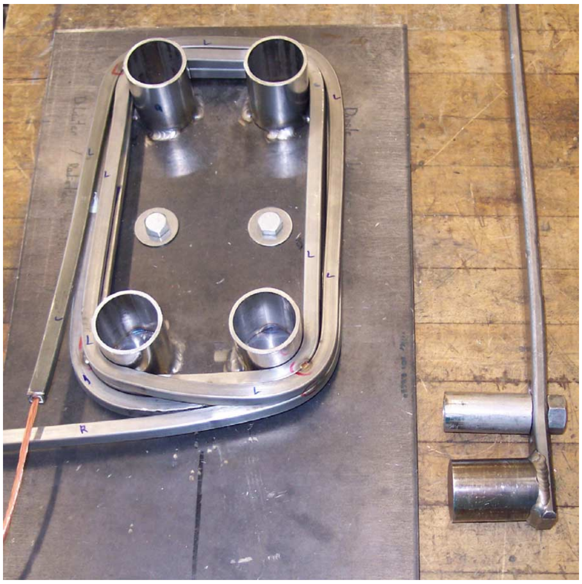

Fig. 3. The coils were wound by inserting the winder arm into a corner socket and then wrapping the CICC around the corner socket. Tack-welds were placed occasionally to maintain the shape of the coil.

Fig. 4. To connect the coils in series they were soldered together. Over the solder joint were welded two clamshell halves made of an insulating layer of Macor and an outer layer of stainless steel.

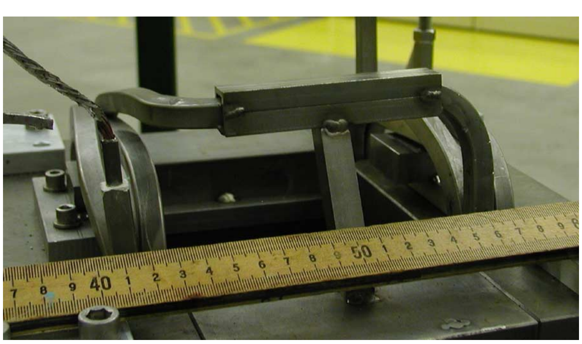

Fig. 5. The solder joint is shown here after the clamshell was welded together. The stainless steel exterior of the joint was secured to the iron by a welded post.

insulation. The Macor would be extended to shield the outer jacket from the conductor.

Optimally, forced flow would enter at the joint. This would provide the best cooling for the resistive joint, and would pump helium in parallel through the coils. This capability has been designed and considered, but not yet implemented.

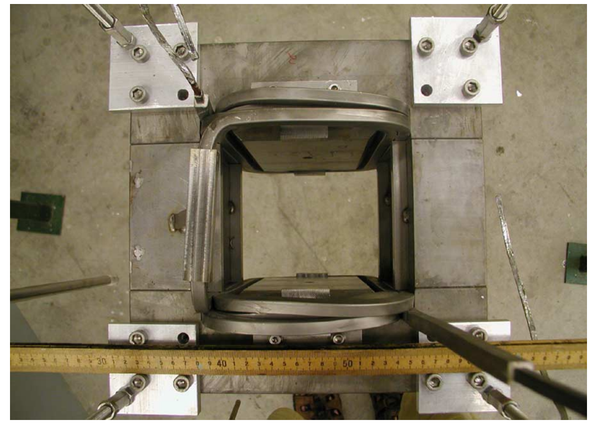

Fig. 6. The dipole magnet hangs from the Dewar lid, ready to be installed and tested. The magnet is seen from above and the splice is on the left.

IV. Results

The magnet coils were connected to leads and the complete dipole shown in Fig. 6 was placed in a Dewar. The Dewar was then filled with liquid helium; however, the helium was not forced through the coils.

The power supply used had an upper limit of about 1.2 kA. During the test the current into the magnet, liquid helium level, and voltage drop across the leads were monitored. The magnet was ramped quickly to 1.2 kA in two tests. The second ramp occurred in less than one minute. At 10 kA the calculated stored energy is only 6 kJ, resulting in an asymptotic inductance of 0.04 mH, so the ramping voltage is minimal. Both tests resulted in stable operation at slightly more than 1.2 kA. Using the code POISSON [6] the maximum field in the coil was calculated to be 0.24 T at 1.2 kA. Measurement of the inductance during testing was impractical due to the high ramp-rate required because the current leads were only rated for 1 kA.

The maximum field in the coil was calculated to be 2 T for the case of the operating current: 10 kA. The forces on the coil at that field at 10 kA were calculated to be $6.19\mathrm{E}+03\ \mathrm{N/m}$ in the x-direction, $3.76\mathrm{E}+04\ \mathrm{N/m}$ in the y-direction (the x and y direction are defined by the x and y axes of Fig. 1). The welding supports these forces in the coil.

V. Discussion

The operation of the CICC dipole at 1.2 kA demonstrates the first step in producing a CICC magnet within the constraints of radiation tolerance. While this is only a fraction of the nominal operating current, it is significant as a proof-of-concept for this new technology. The test established the capability of this technology to carry an effective current density of at least $12\ \mathrm{A/mm^2}$, which is significantly higher than resistive, metal-oxide insulated coils [4], [5]. The importance of the result is that the technology is scalable to larger devices needed for operation in high radiation environments. Everything in the magnet fabrication process can be scaled up to meter-long magnets, which is not possible for other technologies of equivalent radiation resistance. Small coils, for example, can be built by insulating the turns with sheets of ceramic and clamping them together; however, this fails when the coils become large enough to overcome the shear-strength of the ceramic.

In this 10-mm metal oxide CICC, the steel and MgO occupy a significant fraction of the total cross section, which reduces the effective current density. If larger current densities are desired the CICC size can be increased. In a larger cross section the size of the steel and MgO would not increase; the fraction of the cross section that belonged to conductor would increase as the overall size increased. Much higher effective current densities can be obtained this way, but at the cost of higher absorbed radiation heating, and higher operating current.

The next step will be to test the magnet up to its nominal maximum current: 10 kA. This test is in preparation and will also be done in a liquid helium bath. This test will provide insight into the operating limits and protection at higher field.

In order to establish the viability of a radiation resistant high field fragment separator, a large quadrupole is being developed at NSCL using the same CICC technology. This will also establish design and full-scale construction of complex coils with warm-iron. Construction of reliable joints is part of this stage of R&D.

Further research will be done into improving current density and reducing the cold mass. The use of Spinel $(\mathrm{MgAl_2O_4})$ as an insulator will also be investigated. It appears to be less hygroscopic and so breaks down at a higher voltage than MgO and has better radiation tolerance.

VI. Summary

Metal-oxide insulated CICC was used to fabricate a small superferric dipole magnet. The magnet was tested at a fraction of its nominal current as proof-of-concept. The test demonstrated that radiation resistant metal-oxide CICC coils can be built and can carry a current density of at least 12 A/mm2. It further shows the potential for scaling to larger devices. Further testing will establish the operating limits and behavior of the CICC in higher magnetic fields (up to 2 T).

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