Final Report on Radiation Resistant Magnets II
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INTRODUCTION

The development of magnet designs capable of reasonable life times in high-radiation environments and having reasonable performance is of paramount importance for RIA as well as other high-intensity projects under consideration, such as the Neutrino Factory and FAIR project at GSI.

Several approaches were evaluated for radiation resistant superconducting magnets. One approach was to simply use a more radiation resistant epoxy for the coil fabrication. Another approach for cryostable magnets, like the S800 Spectrograph dipole, is the use of all-inorganic materials. The final approach was the development of radiation resistant Cable-In-Conduit-Conductor (CICC) like that used in fusion magnets; though these are not radiation resistant because an organic insulator is used. Simulations have shown that the nuclear radiation heating of the first quadrupoles in the RIA Fragment Separator will be so large that cold mass minimization will be necessary with the magnet iron being at room temperature.

RADIATION TOLERANT EPOXIES

Fabrication of standard superconducting coils using either wet-winding or vacuum impregnation requires a primary insulation on the wire and an epoxy to restrain the wire motion. Polyimid, of which Kapton is the best-known example has good radiation resistance [1] and serves well as a primary insulation. Composite Technology Development (CTD) has developed "epoxies" based on cyanate esters that demonstrate good radiation tolerances [2]. We have used one of their esters, CTD-422 to fabricate coils that have polyimid primary insulation. Coils were wet-wound and installed in dipole configuration using all-inorganic materials for any parts that provide significant support for the magnet. The magnet assembly was installed in a Dewar for testing. It is shown in Fig. 1. The magnet was ramped up until it quenched. The quench history of the magnet is shown in Fig. 2 as a percentage of the manufacturer's guaranteed short sample limit. (The current exceeded the manufacture's guarantee by about 5%, but the guaranteed current usually is lower than the expected current.) The conductor field reached 3 T.

Fig. 1. Radiation tolerant dipole ready for testing.

Quench calculations showed the transverse quench propagation velocity and thermal conductivity for the material is lower than standard epoxies. However, CTD feels it can make esters with better thermal properties mitigating these issues. The coils should have a lifetime dose of about 10 MGy. This is not sufficient for use in the first few quadrupoles in the Fragment Separator because this would result in magnet lifetimes of less than 5 years. More information is available in [3].

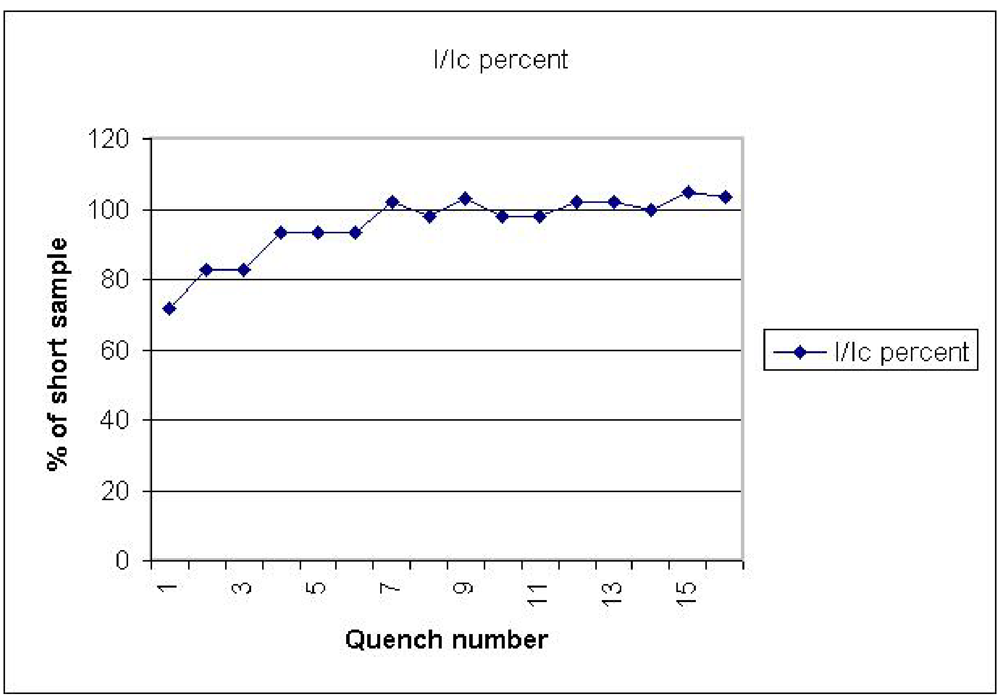

Fig. 2. Quench history of radiation tolerant dipole.

CRYOSTABLE INORGANIC COILS

The advantage of a cryostable coil is that it can absorb a large amount of radiation heating and still function. The disadvantage is the reduced current density, about 4 kA/cm^2, relative to a potted coil (20 kA/cm^2). The S800 Spectrograph dipoles were wound with bare conductor placed in grooves machined in G10. This is not a radiation tolerant coil, since G10 fails at about 10 to 20 MGy and the boron captures neutrons, leading to high energy deposition in the coil. Substituting an inorganic material for G10 will produce the necessary radiation resistance. A test coil using S800 conductor in alumna plates has been fabricated and tested. The test coil, shown in Fig. 3, was inserted into a solenoid that produced a background of 3 T. The coil reached the short sample limit after one quench.

The disadvantage of this type of coil is the very labor intensive winding. The alumna grooves are very fragile and frequently break off. For winding a coil with a continual positive curvature, like a solenoid, this does not cause much problem. The winding tension keeps the conductor from moving far enough to cause a turn-to-turn short, but for magnets with long, straight sides or negative curvatures, this is a significant problem. Overall, the technique works, but should only be considered as a last resort.

Fig. 3. Cryostable test coil made with alumna insulation. Sample alumna piece is at the right.

CICC

The majority of the effort has gone into producing radiation resistant CICC. Metal oxide (magnesium oxide) insulated copper conductor has been used to produce radiation resistant resistive magnets used at LANL and PSI. The major problems are the very low current density possible for any large device, on the order of 100 A/cm^2, and the certainty of water leaks for systems with many parallel lines. Dipoles usually have large coil areas available, so the penalty for low current density is not high, but large aperture, high gradient quadrupoles are a major problem. Adapting the metal oxide insulation system to a superconducting conductor involves replacing the copper with stainless steel or aluminum. A sample conductor is shown in Fig. 4. The inner and out copper jackets have been replaced with 316 stainless and a mixture of superconducting and standard copper wires inserted into the hollow conduit. For this test, only six of the 24 conductors were superconductors. This was done to reduce the critical current. Obviously, to maximize the current density, all conductor will need to be superconducting.

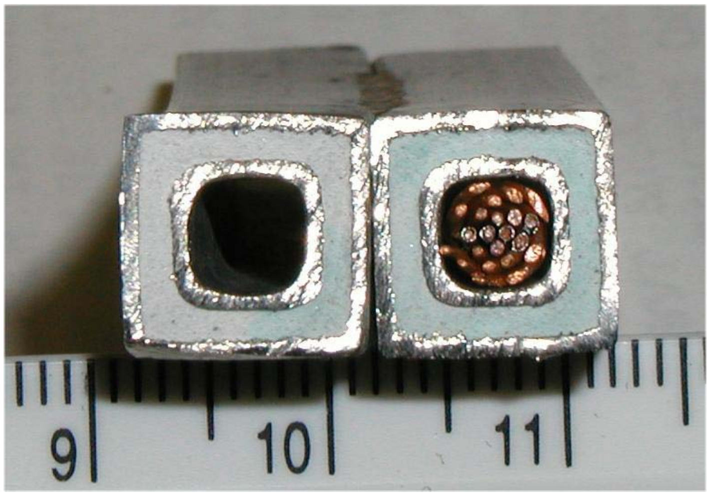

Fig. 4. Sample of metal oxide insulated CICC.

Previous CICC research using aluminum conduit that was anodized on the inside, although successful [4,5], showed the difficulty of threading cable through the conduit when it had been formed into shapes required for either testing or coil fabrication. While it is possible to get a few meters of cable into the conduit and commercial manufacturers state they can get long lengths in, we have not pursued its development. Certainly, small magnets can be built with this technology, but there are potentially significant difficulties applying the technology to large-scale magnets.

What makes the metal oxide insulated cable radiation resistant is that structural strength is obtained by welding the coils together. Similarly, the radiation resistance of the resistive coils is obtained by potting the coil in solder. However, unlike the resistive conductor, the amount of stainless steel in both the inner and out sheaths needs to be minimized to give the maximum current density. In addition, it’s known that synthetic spinel (Mg-Al oxide) is more radiation resistant than magnesium oxide or aluminum oxide. Therefore, we have also tried to change the insulation in the CICC.

Tyco Thermal Controls (Pyrotenax), who provides the standard metal oxide insulated copper conductor, has been working with us to provide the conduit. They have attempted to fabricate the conduit insulation with spinel, but have been unable to get the raw material in the appropriate particle size. The best they have been able to do is to get a 30% spinel – 70% magnesium oxide mixture. This has helped one problem. The magnesium oxide is hygroscopic so it needs to be heated before sealing the end to keep the resistance high. The addition of the spinel has increased the resistance, either because it is less hygroscopic or the material compacts better. Cold-shocking in liquid nitrogen did not decrease the resistance or open up shorts.

The advantage of using stainless steel conduit is both the ability to weld to make the structural integrity and that it is useful at high temperatures. This allows the use of Nb_3Sn in a wind-and-react method. Aluminum conduit, though it absorbs significantly less radiation than copper or stainless, melts below the reaction temperature for producing Nb_3Sn. Besides the high-field advantage of Nb_3Sn relative to NbTi, Nb_3Sn also has a higher transition temperature that would allow a higher temperature rise in the forced-flow helium used to cool the CICC.

A test loop of the CICC that contained 22 strands of 0.7 mm diameter Nb3Sn unreacted wire was fabricated and sent to BNL for testing. The conductor was reacted according to the manufacturer's schedule and tested. The results are given in Fig. 5 and in [6]. The conductor did not reach the short sample limit, reaching about 80% at 7 T. It was felt that the reason the conductor performed poorly was because there wasn't good contact between strands so that current sharing was affected. Going to smaller conductor size and a tighter winding will likely cure the problem. The strand winding is done here in the lab where we do not have good facilities for cabling. A commercial cabler would have made a much tighter and more circular cable, but was too expensive. Two things should be pointed out: The conductor is not designed for low field operation and, hence, looks better at higher fields. Since the conductor cross section is 10 mm by 10 mm, this gives an engineering current density (current density in the winding) of 5.5 kA/cm^2 at 7 T and about 8 kA/cm^2 at 2 T. This is because the conductor includes the insulation and, so, the CICC current density is also the engineering current density.

The major advantage of a CICC coil is the ability to remove large quantities of neutron-induced heating. This is the solution used in fusion reactors like ITER. Then magnet life becomes limited by the lifetime of the superconductor. This is then the ultimate limitation of using superconducting coils in high-radiation environments.

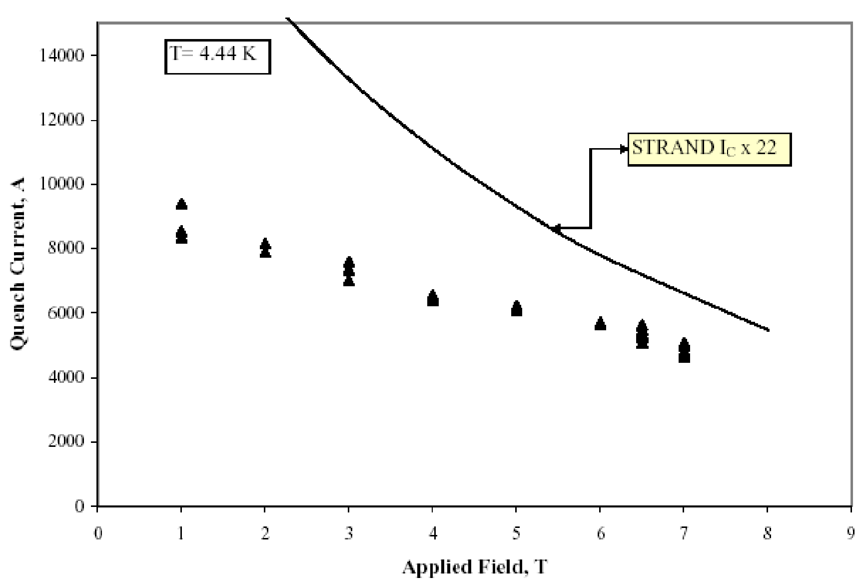

Fig. 5. Quench current of Nb_3Sn CICC tested at BNL.

SUMMARY

Three different types of conductor for radiation resistant superconducting magnets have been built and successfully tested. The cyanate ester potted coils will work nicely for magnets where the lifetime dose is a factor of 20 less than the end of life of the superconductor and the rate of energy deposition is below the heat-removal limit of the coil. The all-inorganic cryostable coil and the metal oxide insulated CICC will provide conductor that will work up to the life of the superconductor and have the ability to remove large quantities of nuclear heating. Obviously, more work needs to be done on the CICC to increase the current density and to develop different insulations; and on the cyanate esters to increase the heat transfer.

REFERENCES

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[2] K. Bittner-Rohrhofer, et al, *Adv. Cryo Eng* **48A**, (2002) 261.
[3] A.F. Zeller, J.C. DeKamp and J. DeLauter, *IEEE Trans Applied Superconductivty* **15**, (2005) 1181.
[4] A. F. Zeller, *Adv. Cryo Eng* **48A**, (2002) 255.
[5] A.F. Zeller and J.C. DeKamp, Proc PAC 2003, 161.
[6] A. Ghosh, Superconducting Cable Test Report, Cool-down # 4601, Test date 3/10/05, CICC-MSU-001, BNL (unpublished).

Appendix 1

Talks presented or to be presented on work partially supported by this grant:
[1] "Radiation Resistant Magnet R&D at the NSCL", A. Zeller and J.C. DeKamp, PAC 2003
[2] "Superconducting Magnets for RIA", A.F. Zeller, CEC/ICMC 2003. INVITED
[3] "A radiation Resistant Dipole Magnet", A.F. Zeller, ASC, Oct 10, 2004. INVITED
[4] "Radiation Resistant Magnets for the RIA Fragment Separator", A. Zeller, V. Blideanu, R. Ronningen, B. Sherrill and R. Gupta, PAC 2005.
[5] "Inorganic Insulation for Use in High Radiation Environments", A.F. Zeller, Topical Meeting on Insulation and Impregnation Techniques for Magnets, CERN, 22-23 March 2005.
[6] "Metal Oxide CICC for Radiation Resistant Magnets", A.F. Zeller, J.C. DeKamp, J. DeLauter and A. Ghosh, to be presented at CEC/ICMC 2005
[7] "Design of a Radiation Resistant Quadrupole Using CICC**"**, A. Zeller, J. DeLauter, to be presented at MT-19 2005

Papers published for work partially supported by this grant:
[1] A.F. Zeller, *Adv. Cryo Eng* **48A**, (2002) 255.
[2] A.F. Zeller and J.C. DeKamp, Proc PAC 2003, 161
[3] A.F. Zeller, J.C. DeKamp and J. DeLauter, *IEEE Trans Applied Superconductivty* **15**, (2005) 1181
[4] A.F. Zeller, *Adv. In Cryo. Engr*. **49A**, 758 (2004)