RADIATION RESISTANT MAGNET R&D AT THE NSCL*

A. F. Zeller#, J. C. DeKamp, NSCL, Michigan State University, E. Lansing, MI 48824 USA

Abstract

Proposed high radiation environment projects like the Rare Isotope (RIA) and the Neutrino Factory (NF) require magnetic elements that are radiation resistant. Development of radiation resistant magnets at the National Superconducting Cyclotron Lab (NSCL) has been underway for several years. The focus has been on superconducting devices, as resistive solutions have been know for two decades, but have relatively small current densities. Higher current density options than can be commercially manufactured have been examined. Several solutions for superconducting versions use radiation resistant epoxies, for medium level hardness, and variations on Cable-in-Conduit-Conductor (CICC) for high-radiation areas. These allow engineering current densities of more than 100 A/mm^2.

INTRODUCTION

Proposed projects like RIA [1] and the NF [2] require strong magnets that must operate in high radiation environments. Because failures result in significant down time, due to the difficulties of working in a radioactive area, magnetic elements must be radiation resistant for the lifetime of the project. It is possible and likely that resistive magnets can be used in various places, but there is a strong desire to use superconducting coils because the engineering current density can be up to ten times higher. This is particularly important for quadrupoles where high gradients and large apertures are required for acceptance of secondary particles.

The most radiation-sensitive part of a magnet is the electrical insulation. Conductors like copper and aluminum are many orders of magnitude more radiation resistant than organic insulators. Even the superconductors, NbTi and Nb_3Sn, are at least twenty-five times more resistant than the common organic epoxies and ten times better than organic insulation [3]. Attempting to invent new radiation resistant organic materials is very expensive and very likely to fail; therefore, development of coils using present materials in new ways has been started.

RESISTIVE OPTIONS

The successful solution used at Los Alamos National Lab and the Paul Scherrer Institute for radiation resistant magnets is to surround standard copper conductor, either hollow or solid, with magnesium oxide (MgO) inside a copper sheath. The coils are then potted with solder [4]. Work at KEK duplicates this except the potting is done with an inorganic matrix [5].

Aluminum conductor that has an insulating anodized layer has been used since the 1950's [6], but the higher resistivity of aluminum and the brittleness of the anodized layer have limited its usefulness. A potentially more productive approach is to have a thin aluminum layer on the outside of a hollow copper conductor [7]. The single attempt at this met with limited success and was not attempted on a commercial scale. A manufacturer was located who tried unsuccessfully to co-extrude aluminum around the hollow copper conductor. Because of the thinness of the anodized layer (~0.01 mm), a more compact coil using hollow aluminum conductor can be fabricated. Unfortunately, for the same temperature rise in the cooling water, this gains about 10% over a copper conductor in the same coil cross section.

SUPERCONDUCTING COILS

Superconducting coil options can be divided up into two groups: low and high current density. High current density superconducting coils use some type of epoxy to constrain the conductor from moving due to the Lorenz Forces. Current densities in the coil (engineering current densities) range from 60 A/mm^2 to well over 500 A/mm^2, depending on the forces and the magnetic field. Low current density options are cryostable coils or those wound with CICC. The low current density solutions use intimate contact between the conductor and liquid helium for stability. It has the big advantage in that large amounts of nuclear heating can be removed without affecting magnet operation.

High current density options

Presently, a commercial company, Composite Technology Development, Inc. (CTD) is working on more radiation resistant epoxies. They have developed several systems that increase the radiation resistance by factors of two or three, relative to standard epoxies. Polyimids, like Kapton® provide excellent radiation resistance and would be used as primary wire insulation. Test windings with CTD-422 epoxy system are underway to determine whether the NSCL's standard wet winding method of coil fabrication is possible. This would lead to significant improvements in coil lifetimes in areas where the expected doses are ~10 MGy per year.

Lower current options

It should be pointed out that lower current is only with respect to potted superconducting technology and that it is 3-10 times higher than resistive technology when the magnets have to exhibit long-term reliability. The absolute need to construct magnets that require no maintenance for 10-20 years tends to lead to lower current density

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#zeller@nscl.msu.edu

solutions. Additionally, quench protection issues also go in the direction of lower current densities. Many cryostable coils have been constructed with G10 as the only insulation. Substituting an inorganic, such as alumna (Al_2O_3), should provide a way to produce a radiation resistant magnet with current densities of 40-60 A/mm^2. Alumna is, however, much more brittle than G10 or other composite materials, so it would require demonstration before using it in a deployed magnet. One possible problem with using a cryostable magnet in a high radiation environment is the coils are not self-protecting in case of a quench. They need some external energy absorption system with an active quench detection circuit. Making these radiation hard may be difficult. Figure 1 shows a test wind of an inorganic cryostable coil. Coil height is approximately 50 mm. A second coil that will be inserted in the bore of a solenoid for stability testing is presently being wound.

Figure 1: All-inorganic, cryostable test coil.

CICC Options

CICC has advantages over cryostable radiation hard magnets:

- Higher current densities are possible.
- Higher helium mass flow is possible for heat removal.
- Less complicated cryostats are required.
- Coil winding easier.

Disadvantages are more costly conductor and the very limited bending of the conductor due to the brittleness of the insulators.

Anodized CICC

Aluminum conduit can be anodized on the inside to leave the outside available for use as a welding surface, so the entire coil is a single, self-supporting structure [8]. Because of the difficulty in getting good conductor fill-fractions, a test loop was constructed for testing at the Plasma Science and Fusion Center at MIT, shown in figure 2. The conduit is first bent to the final shape and then anodized. The 325 strands of 0.25 mm are then forced through the conduit. Since this last step is difficult, a fill-factor of 40% was achieved. Normal CICC is typically 70-90%, so the stability had to be tested.

Figure 2: Test loop in testing support.

The individual wires in the conductor are made from material that is optimized for high-field operation, while the test magnets was intended for short on-times at fields less than 5 T. The results are shown in figure 3.

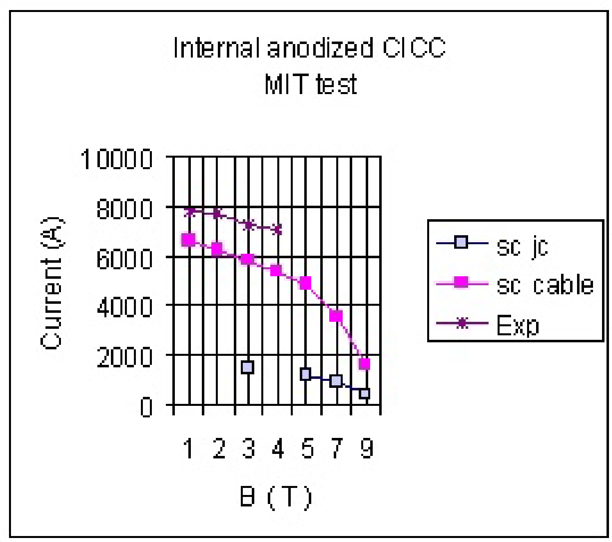

Figure 3: Test results. The curve labeled "sc jc" is the current density in the superconductor in A/mm

The experimental results appear higher than the short sample limit, but the cable short sample is derived by multiplying the individual guaranteed wire critical current by the number of wires. The actual short sample will be higher, and the background field is only accurate to within 10%. It would appear there isn't a problem with stability due to a low fill factor. Since the projected single turn cross section is 1 cm^2, the engineering current density is 70 A/mm^2. The conductor has a copper-to-superconductor ratio of 3:1, so by decreasing it to 1.5:1, we can double the current density. In addition, if we use a conductor optimized for 2-4 T, a further factor of two increase can be obtained. The reduction in copper-to-superconductor may impact the stability, though, so further test are planned. Because the power supply used in the test is limited to 10 kA, smaller conduit is being used, as well as fewer individual conductors.

Even though the anodized layer is brittle, it is still possible to bend it over some radius before it fails. The sulfuric acid process used for the test pieces produce an ~ 18 μm thick layer. This will withstand a 500 V potential. Bending the 9.5 mm diameter conduit to a radius of 250 mm reduced the break down voltage to 100 V. Complete failure occurred at 200 mm.

High magnetic field operation (> 9 T) requires the use of Nb_3Sn as the superconducting material. Because this material is brittle, the coil must be formed first, anodized, the unreacted conductor inserted, then heat treatment to form the superconducting compound. Aluminum melts below the heat treatment temperature, so something like titanium would be needed. Considerable work would need to be done to make this practical.

Metal Oxide Insulated CICC

Magnesium oxide insulated conductor has been used successfully for at least two decades, so a superconducting version would be very desirable. One would simply fill the cooling passage with superconductor, as shown in figure 4.

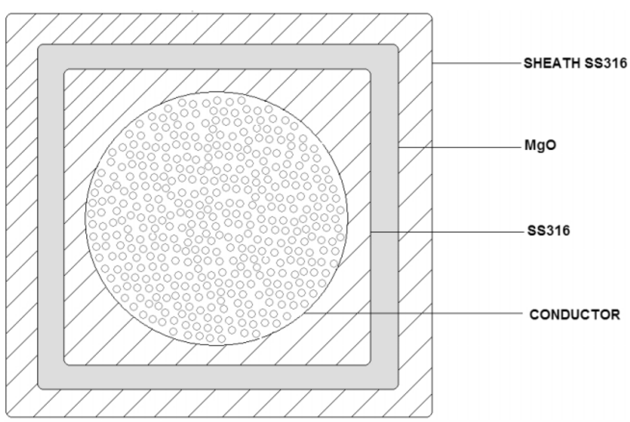

Figure 4: Metal oxide insulated CICC.

The difference between standard CICC is the addition of the sheath around the metal oxide. This reduces the available current density, although some of it can be recovered because the inner conduit can be made thinner because the outer conduit adds to the strength. Taking a nominal 15 mm^2 CICC and adding 1 mm each of metal oxide and stainless steel, reduces the current density by about 20%. There are several advantages to this type of conductor that outweigh any lost current density:

- The conductor is flexible.
- Magnesium oxide, aluminum oxide or spinel can be used for insulation.
- It is likely that Nb_3Sn with wind and react technology may be used.

One problem with the metal oxide insulated conductor when used in resistive magnets is the loss of resistance when the metal oxide absorbs water from the air. The conductor is sealed, but it is difficult to completely eliminate it. For operation at liquid helium temperatures, any trapped moisture or air is frozen out. The three possible metal oxides have different radiation resistances, with spinel (an aluminum and magnesium oxide) being the best. Unfortunately, it is more expensive and it's drawing properties not as good as MgO. All three of the oxides are used in high temperature applications, so they can readily withstand the 700 C heat treatment temperatures used in formation of Nb_3Sn, opening up operation at the high field needed in the NF.

A collaboration with the original manufacturer of the metal oxide insulated conductor, Pyrotenax (now Tyco Thermal Controls) has been started to examine these possibilities.

SUMMARY

Several lines of development are being pursued in the development of radiation resistant coils for use in future accelerators. The most promising are the use of anodization to produce the insulation and other metal oxides for insulation of CICC coils.

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