Radiation Resistant Magnets

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Both the ISOL and the fragmentation target area are subjected to extremely fluxes of high-energy neutrons. Magnetic devices are required to operate reliably for the lifetime of the facility since replacing failed magnets will be difficult and expensive. Therefore, the goals of the R&D effort must be on simplicity and effectiveness, rather than on cost savings.

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 [1]. 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. Development of relatively radiation resistant epoxies is underway at a commercial company, Composite Technology Development (CTD), and we are working with them on testing their formulations.

The ISOL magnets are relatively simple in that they only transport low-energy beams, so resistive magnets can be made using the metal-oxide insulated conductor used at LANL and Paul Scherrer Institute (PSI) [2], who potted their coils with solder and KEK who uses an inorganic matrix [3]. The relatively low current density results in large magnets, though. Aluminum conductor that has an insulating anodized layer has been used since the 1950's [4], but the higher resistivity of aluminum and the brittleness of the anodized layer have limited its utility. A potentially higher current density option is to have a thin aluminum layer on the outside of a hollow copper conductor [5]. The single attempt at this met with limited success but was not attempted on a commercial scale. A manufacturer was located, with great difficulty, who tried unsuccessfully to co-extrude aluminum around the hollow copper conductor. Therefore, this approach has been abandoned.

The magnets in the fragmentation front end are much more difficult because they require large apertures and high gradients in the quads and large gaps in the dipoles. The dipole is complicated because of the necessity of placing beam stops for the un-reacted primary beam and the many kilowatts of undesired secondary fragments. The quadrupoles are difficult because the pole tip fields need to be kept low, in a resistive coil option, and the iron warm in a superconducting version. The R&D requires examining both resistive and superconducting options.

The first quad in the fragment separator can be made resistive, with LANL style coils, but there are several problems even with this solution. A preliminary design, shown in Fig. 1, requires approximately sixty parallel water paths to keep the coils cooled. This large number of joints is not consistent with reliability because each joint is a potential leak.

Higher water pressure can be used to reduce the number of joints, but erosion becomes a worry. The maximum current density in this magnet is less than 4 A/mm^2.

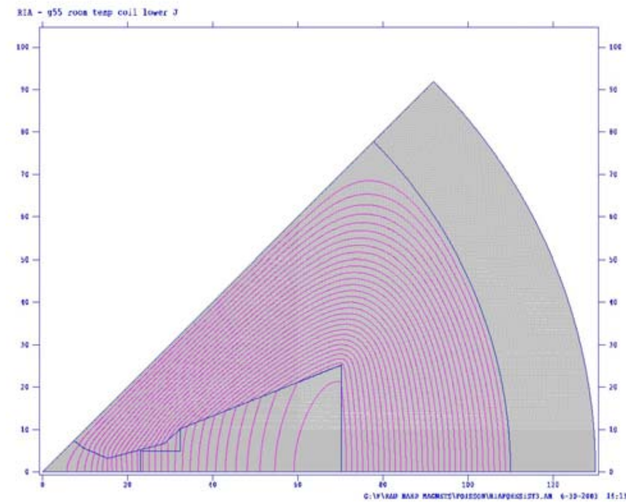

Fig. 1 POISSON calculation for a resistive radiation hard quadrupole for the fragment separator (units of cm).

There are several possible superconducting solutions that allow more than 100 A/mm^2 in the coil package, but none of them is fully developed. Additionally, developing a warm iron solution may be required to keep the refrigeration load (because of neutron heating) at an acceptable level. 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 forces and the magnetic field. Low current density options are cryostable coils or those wound with Cable-In-Conduit-Conductor (CICC). The low current density solutions use intimate contact between the conductor and liquid helium for stability so that large amounts of nuclear heating can be removed without affecting magnet operation.

Presently, the commercial company CTD is working on more radiation resistant epoxies 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.

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. 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 alumina (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 2 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 2: All-inorganic, cryostable test coil.

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.

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 [6]. 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. 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 only 40% was achieved. Normal CICC is typically 70-90%, so the stability had to be tested. The results are shown in figure 3.

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.

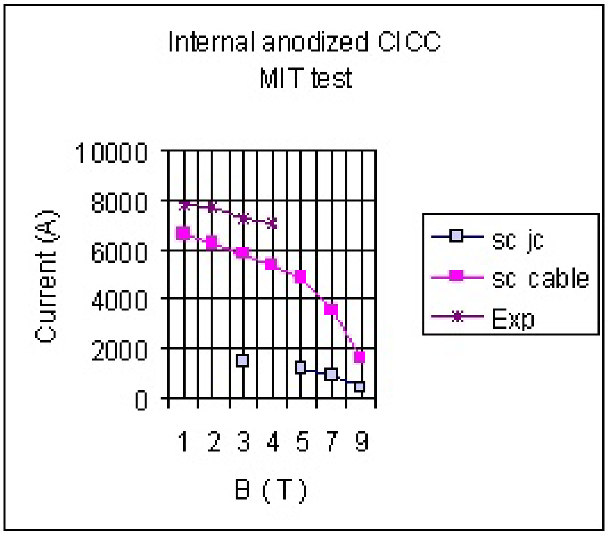

Figure 3: Test results. The curve labeled "sc jc" is the current density in the superconductor in A/mm^2

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.

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. 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 can be used.

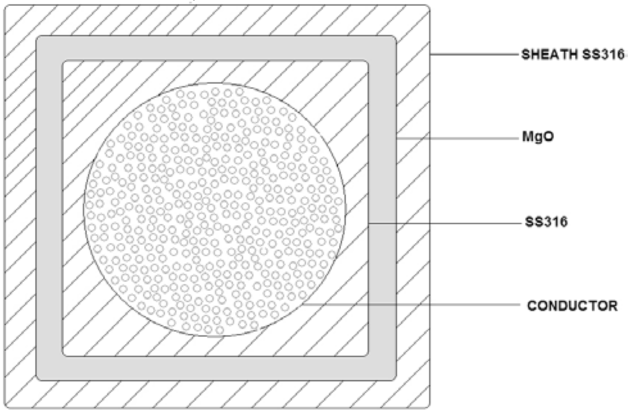

Figure 4: Metal oxide insulated CICC.

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

Specific R&D projects that require significant funding are:

1. Development of reliable joints.
2. Development of various radiation resistant CICC for high current density solutions.
3. Development of warm iron superconducting solutions.
4. Development of protection for large superconducting magnets with high stored energy that are also radiation resistant.
5. Development of radiation resistant magnets that see significant radiation levels, but less than the first three or four quadrupoles, that can be fabricated by industry in an economical way.

This is a multi-year effort that requires a full time postdoctoral level individual with access to testing and irradiation facilities. In addition, funds will be required for conductor procurement and testing.

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