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# Magnetic Testing of a Superferric Dipole That Uses Metal-Oxide Insulated CICC

Jonathan DeLauter, Jon C. DeKamp, Al F. Zeller, *Senior Member, IEEE*, Chen-yu Gung, and Joseph V. Minervini

**Abstract**—A small dipole magnet designed for use in high-radiation environments that uses metal-oxide Cable-In-Conduit-Conductor has been constructed and tested for magnetic properties. The conductor consisted of 42 strands of 0.5 mm diameter wires, in a conduit with outer dimension of 10 mm  $\times$  10 mm. The magnet carried about 8 kA. This gives an engineering current density of 80 A/mm<sup>2</sup>. The current density in the cable bundle is approximately 1 kA/mm<sup>2</sup>.

**Index Terms**—CICC, metal-oxide, radiation resistant, superferric dipole.

## I. INTRODUCTION

THE high-radiation environment around the target area in fragment separators, such as that expected at FAIR [1], requires that magnets withstand the nuclear radiation effects. In the short term this means removing the deposited heat and in the long term, having the magnet survive the radiation damage. We have previously proposed [2] that a special Cable-In-Conduit-Conductor (CICC) be used. The standard CICC is radiation resistant, but the insulation between turns and layers is not. Metal-oxide insulated CICC places an insulating layer of aluminum, magnesium or magnesium-aluminum (spinel)-oxide around the inner conduit and then a further layer of stainless steel. This permits welding the turns for structural integrity, as the inner conductor is electrically isolated from the outer.

Because all of the components, stainless steel, metal oxide and NbTi have well established radiation resistance properties, radiation testing is both time-consuming and unnecessary. It only remains to establish the magnetic properties.

Of concern is a low fill factor, <50%, caused by the necessity of having to insert the conductor into the conduit after it has been drawn to the final dimension. Additional concerns are the splices, which are sources of heating, especially when testing without flowing helium.

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Fig. 1. The magnet attached to the 10 kA leads prior to insertion in the Dewar. Note the magnet does not have connections for forced-flow of liquid helium.

## II. INITIAL TESTING

### A. Set Up

A small superferric dipole constructed using magnesium oxide insulated CICC for the coils has been constructed [3]. Previous testing was limited to about 1.2 kA because of power supply and current lead limitations. The magnet was taken to the MIT for testing at the Plasma Science and Fusion Center. Fig. 1 shows the magnet attached to the 10 kA lead assembly prior to insertion in the Dewar.

To reduce the cost of the tests, the magnet was simply inserted into a liquid helium bath. The magnet is designed to operate using forced flow, so there is decreased resistance to disturbance.

The coils were modeled with GANDALF [4] to ensure the safety and to set the protection parameters. The calculations for an 8 kA quench without helium flow are shown in Fig. 2. The calculations show the temperature rise is within acceptable limits.

### B. Results

The initial results at ramp rate of 100 A/s were disappointing, with the magnet quenching at only 2.8 kA. It was observed that a

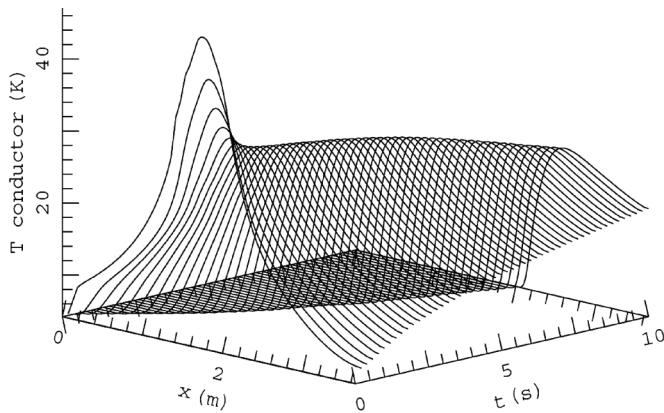


Fig. 2. GANDALF calculation for a quench at 8 kA and no helium flow. X is length along the conductor.

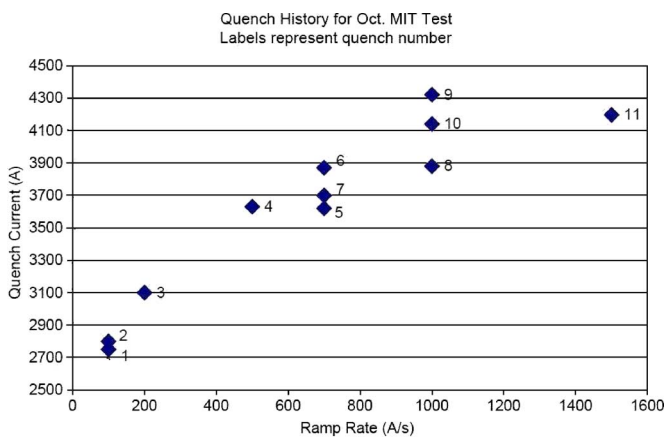


Fig. 3. Test results. The quench current is plotted versus ramp rate.

voltage signal appeared on the positive current voltage tap prior to the start of the quench. This indicated the quenches were initiated external to the coils. The voltage taps across the leads did not show anything unusual. Therefore the ramp rate was increased try to achieve higher currents before the heat generated in the connection to the external lead diffused into the coils. The results are shown in Fig. 3. There is an obvious ramp-rate dependency. The maximum currents were obtained at 1 to 1.5 kA/s. At this point the tests were suspended, as it did not appear that more progress would be obtained.

The magnet was removed from the Dewar to fix the problem at the positive lead connection. It was discovered there was an excessive amount of conductor between the coil and the lead that was not well supported. This is shown circled in Fig. 4.

### III. SECOND TEST RESULTS

After reinforcing the connections between the coils and the current leads on both sides the magnet was retested. This time there were no voltage signals from the leads prior to a quench. The quench history is shown in Fig. 5. Note, the first shot was not a quench, just a test of the protection circuit. The magnet exhibited some training, starting about 5 kA and going to about 8 kA. No ramp-rate dependence was observed. It should be noted that a variety of ramp rates were tried. After about shot number 20, we tried different ways to increase the quench

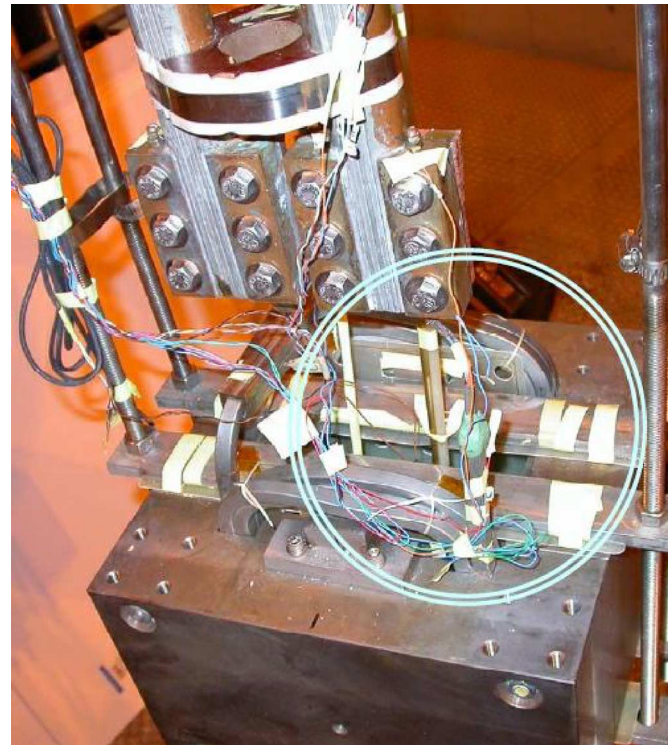


Fig. 4. Poorly supported lead connection is shown in the circle.

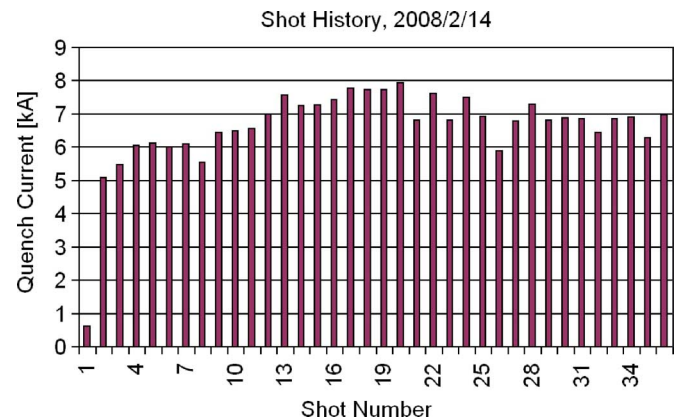


Fig. 5. Quench history for the second series of tests. The first shot was not a quench, but a safety system test.

current. In addition to varying the ramp rate, the magnet was ramped to a plateau below the maximum and held there before going higher. None of these tests was particularly useful in increasing the quench current.

It should be remembered that we did not have helium flow through the coils, except from natural convection. When a hold plateau was reached, heat was generated in the splices (one in each half) and any bubbles were not rapidly removed. It was felt that lack of helium flow contributed to the quench limitations.

### IV. DISCUSSION

The overall conductor size, including inner and outer conduits and the magnesium oxide insulation is 10 mm × 10 mm. Because the turns are welded together, no further insulation is required. This yields an engineering current density of 80 A/mm<sup>2</sup>.



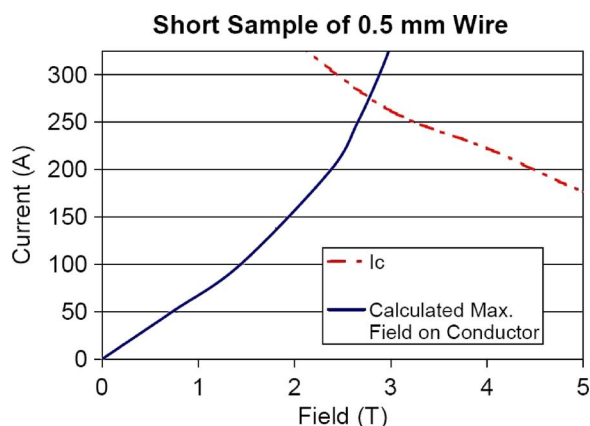


Fig. 6. Field on the conductor and critical current for each strand.

The actual conductor consists of 42 strands of 0.5 mm diameter NbTi wire, with a 2:1 Cu:SC ratio. The current density in the conductor bundle is about  $1 \text{ kA/mm}^2$ . For comparison, the current density in the ITER Toroidal Field Coils conductor bundle is  $425 \text{ A/mm}^2$  [5]. The strand short sample versus magnetic field and the conductor magnetic field is shown in Fig. 6. Since there are 42 strands, the 8 kA corresponds to 190 A per strand.

The peak current is about 60% of the short sample limit. This is likely the result of the 44% fill factor. The conductor is too free to move around under the large Lorenz Forces. In absence of any helium flow, the heat generated cannot be removed. It's not clear that even with significant mass flow, higher current could be achieved. Fortunately, current densities of  $40 \text{ A/mm}^2$  are sufficient for producing workable devices.

## V. FUTURE DIRECTIONS

In order to get higher current densities, there are two possible paths: Decrease the copper-to-superconductor ratio or increase the fill factor. Decreasing the Cu:SC by itself may not solve the problem if the poor fill factor is the cause of the inability to approach the short sample limit and it introduces protection problems. The obvious approach is to try to increase the number of strands in the bundle.

After two years of work, the conduit manufacturer, Tyco Thermal Controls LLC has successfully produced conduit that uses pure synthetic spinel as the insulating material. Spinel has better radiation tolerance [6] than magnesium oxide. Additionally, they have succeeded in producing longer lengths (up to 13 m), reducing the number of splices required in larger magnets. The outer conduit has also been produced with more rounded corners. This makes welding the turns easier because there is more room so the weld does not increase the coil size by projecting above the surface (see Fig. 7).

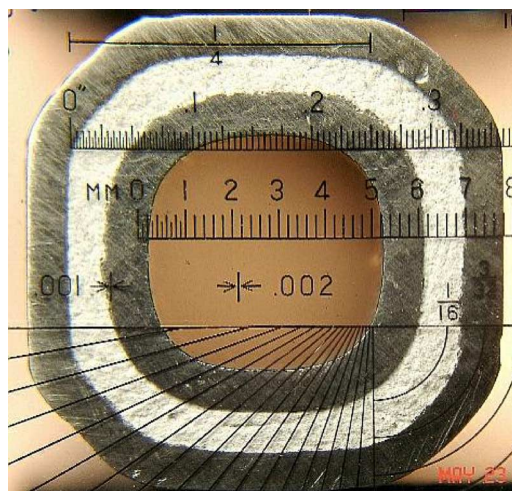


Fig. 7. New conductor cross section.

The construction of a quadrupole is presently underway, funded by the DOE. This magnet is significantly larger than the test dipole and requires single piece lengths of up to 13 m. We have worked on improving the fill factor by increasing the number of strands that can be pulled through the conduit. The conduit is first carefully straightened to remove any kinks before attempting to insert the strands. So far, 66 strands, plus two insulated copper ones for the protection circuit, have been inserted. This gives a fill factor of 62%.

## VI. CONCLUSION

The successful testing of a superferric magnet with low-fill factor provides optimism that CICC with more strands will be useful for practical devices in a high-radiation environment. It is likely that the 50% increase in the number of strands will yield a correspondingly higher engineering current density.

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