TEST RESULTS OF HTS COILS AND AN R&D MAGNET FOR RIA*

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Abstract

This paper presents the successful construction and test results of a magnetic mirror model for the Rare Isotope Accelerator (RIA) that is based on High Temperature Superconductors (HTS). In addition, the performance of thirteen coils (each made with ~220 meters of commercially available HTS tape) is also presented. The proposed HTS magnet is a crucial part of the R&D for the Fragment Separator region where the magnets are subjected to several orders of magnitude more radiation and energy deposition than typical beam line and accelerator magnets receive during their entire lifetime. A preliminary design of an HTS dipole magnet for the Fragment Separator region is also presented.

INTRODUCTION

The Superconducting Magnet Division (SMD) at Brookhaven National Laboratory (BNL), in collaboration with the National Superconducting Cyclotron Laboratory (NSCL), is developing radiation resistant HTS quadrupole magnets [1] for the proposed Rare Isotope Accelerator [2]. These magnets are one of the more challenging elements in the RIA proposal since they appear at the 400 kW (beam power) end of the Fragment Separator region [3]. The proposed super-ferric warm iron design [4] will significantly reduce the energy deposited in the cold structure (15 kW to ~130 W in the first quadrupole alone). Operation at ~30 K offers a factor of ten decrease in the cooling requirements compared to 4 K operation. This large thermodynamic saving in the operating cost for removing the above mentioned enormous heat is the primary motivation for using HTS magnets in RIA. Stainless steel tape is used as a radiation resistant insulation between the turns. To test key critical issues prior to proceeding with a full-length magnet, a magnetic mirror model consisting of six HTS coils has been designed, built and tested [5].

HTS QUADRUPOLE DESIGN

The first quadrupole of the RIA Fragment Separator triplet is 1 meter long and requires a field gradient of 10 T/m in an aperture of 300 mm. It is based on 24 racetrack coils placed in two cryostats. Each coil (see Fig. 1) contains 175 turns of 4.2 mm wide and 0.3 mm thick HTS tape. The design gradient is obtained at ~125 A. The magnetic mirror model (see Fig. 2) is made of 6 coils and it simulates the magnetic field and Lorentz force configuration of the full quadrupole. The coil length in the magnetic mirror model and in the first model magnet has been reduced to 300 mm (from 1125 mm in a full length magnet) to use existing test facilities and to save conductor cost in the R&D phase. The coil width is determined by the magnet design (iron pole) and is kept at 500 mm. The minimum coil bend radius is 50.8 mm. The detailed design of the proposed RIA quadrupole and the magnetic mirror model are described elsewhere [1].

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MAGNET CONSTRUCTION

The magnet is assembled from a series of flat spirals (pancake coils) fabricated by co-winding stainless steel reinforced HTS ribbon (tape) with an additional stainless steel "insulating" tape. Two such coils connected at their inner turns form a "double pancake" and the magnet is built up of such units mounted in an aluminum fixture which supports the magnetic forces (Lorentz forces) and locates the winding on the iron pole piece.

Figure 1: A coil being wound on the new computer controlled winding machine.

Figure 2: Coils in their bolted support structure, with the pole iron (in the middle, inside the structure), magnetic mirrors (two on the upper side with 45 degree angles on either side of the vertical axis) and iron return yoke.

TEST RESULTS OF HTS COILS

Coils wound with BSCCO ribbon conductor do not usually "quench" like their low temperature (LTS) counterparts. As the current *(I)* is ramped up in an HTS magnet, the resistive component of the coil voltage *(V)* will increase and remain at an easily measurable level before it becomes irreversible (a runaway situation where the increase in temperature due to resistive heating is more than the cooling available). Since the resistive voltage is swamped by the much larger inductive component when the current is changing, the *"V-I curve"* of a magnet can only be obtained by stopping the current and reading the voltage at selected intervals. Voltage-current curves for coils look very much like the corresponding curves for samples of conductor measured in a uniform magnetic field and can be used to specify the "critical current", I_c, in a similar way. It is customary in the HTS community to quote this number for a *"short sample"* at a voltage gradient of 1 μV/cm over the sample length. For a winding made of several hundred meters of conductor this gradient is much too high and a more practical criteria is 0.1 μV/cm (10 μV/m). In this paper, the currents quoted for the coils as a function of temperature are at a voltage of 2.2 mV which corresponds to 0.1 μV/cm for the 220 meters of conductor in each module. Obviously the gradient is not uniform along the length of the BSCCO ribbon due to the changing magnetic field and the anisotropy of the conductor itself but experience has shown this criterion leads to a practical current level where the winding will operate satisfactorily.

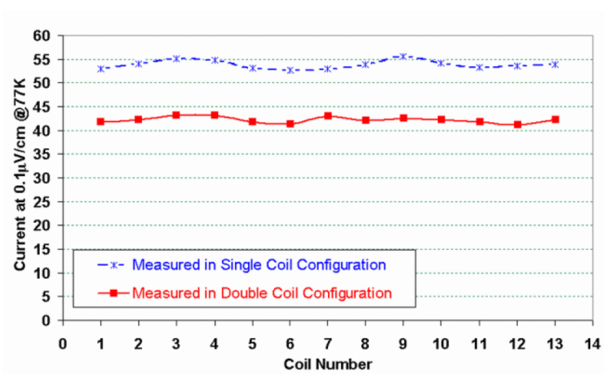

Figure 3: The current at an average voltage gradient of 0.1 μV/cm (10 μV/meter) over the total length of the coils measured at 77 K for the first thirteen pancake coils powered individually and in pairs.

At the time of writing thirteen of the modular coils have been fabricated, twelve for use in the magnetic mirror test and one spare. As the modules became available, they were tested individually and as "double pancakes" in liquid nitrogen. Fig 3 shows the remarkable uniformity of these coils when operated at 77K in their own self-field. Typical "V-I curves" for coils powered as a double pancake, are illustrated in Fig. 4. The nominal critical current is where the curves intersect the 0.1 μV/cm level.

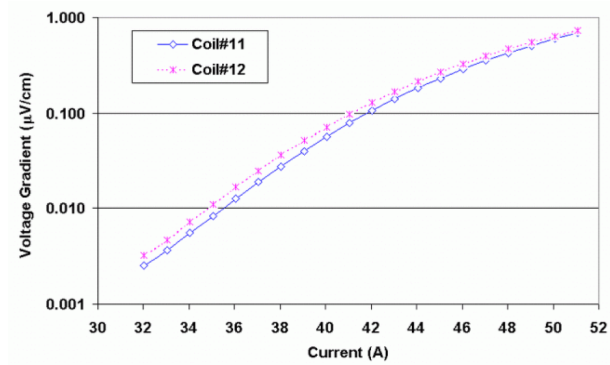

Figure 4: Typical voltage gradient vs. current curves for a pair of coils operated in series in liquid nitrogen bath.

TEST RESULTS OF MIRROR MODEL

The magnetic mirror model consisted of six coils. One of the major purposes of this test, apart from validating the technology, was to measure the current carrying capacity of the coil pack as a function of temperature. This was determined by cooling the coils with helium to ~5 K and measuring them as they slowly warmed up. When mounted on the magnetic mirror iron core and suspended in a deep cryostat, the combination of large thermal mass and low heat leak allowed measurements to be made over several days without additional cooling.

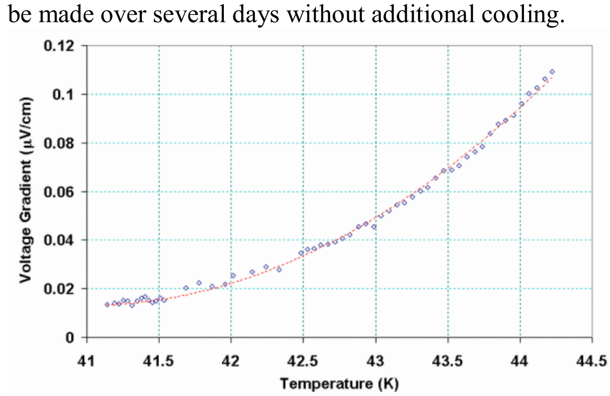

Figure 5: A plot of the voltage gradient as a function of temperature for the magnetic mirror model at a constant current of 100 A. The temperature at which the gradient is 0.1 μV/cm (10 μV/meter) is seen to be 44.1 K.

When an array of coils are connected in series, voltage first shows up on the end coil since the perpendicular field component is greatest there and the current carrying capacity of the ribbon is significantly lower when the field is perpendicular to the wide face of the ribbon.

Four power leads were used so that each of the three double pancakes could be studied individually in addition to all the coils in series. Due to the gradient introduced by the iron core, almost all of the voltage appearing across the magnet shows up on the coil closest to the pole tip. Because the magnet warms up slowly, curves of voltage vs. temperature can be measured at constant current. This has the advantage that no inductive voltage is present so

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that the resistive component can be read off directly. A voltage vs. temperature curve is shown in Fig. 5 with all six coils powered at 100A. Using this technique the temperature dependence of the current was mapped out for configurations of two, four and all six coils over the temperature range 5 K to 75 K. The results are summarized in Fig. 6. It should be noted that the peak field in the magnet changes as a function of the number of coils and in this model the field, to first order, is simply proportional to the current and number of coils (which in turn is proportional to Amp-turns).

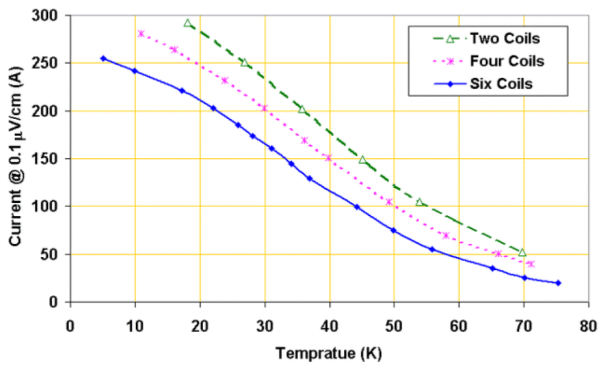

Figure 6: A summary of the temperature dependence of the current in two, four and six coils in the magnetic mirror model. In each case voltage appears on the coil is closest to the pole tip. Note that the magnetic field is approximately three times as great for six coils as it is for four coils.

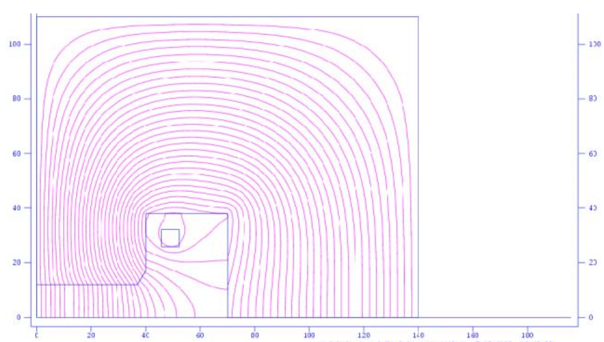

Figure 7: A preliminary magnetic design of an HTS dipole for the Fragment Separator region of RIA.

HTS DIPOLE DESIGN

The 32-degree Fragment Separator Dipole, the magnet just after the first quadrupole triplet in the Fragment Separator of the RIA, faces similar radiation and heat deposition conditions as the quadrupoles. Therefore, it is natural to use HTS technology in this dipole as well. A preliminary magnetic design for this dipole is shown in Fig. 7. This is adapted from the parameter set developed for a design based on conventional technology [6]. At a beam rigidity of 10 T-m, the effective length of this dipole is 2.94 m for a central field of 1.9 T. The magnet has a vertical gap of 240 mm (half gap 120 mm), and a maximum pole width of 800 mm. An interesting and useful coincidence is that the width of the coil is the same as the length of the 1-meter long quadrupole magnet coil. Moreover, it is found that those coils also generate the required field strength. This saves significant developmental cost since the full-length coils of the quadrupole model magnet can be used in the first short dipole model.

SUMMARY

A magnetic mirror model built with commercially available high temperature superconductor has achieved the desired performance (~150 A at ~30 K). It meets the RIA requirements with some margin. The measured magnet performance is also in line with what was expected from the conductor. Stainless steel tape between the turns has provided the necessary insulation. The successful test of this magnet is the first significant step towards demonstrating that HTS-based magnets can provide a good technical solution for one of the most critical items of the RIA proposal. HTS magnets reduce the effective heat load by a factor of ten and bring an enormous savings in the operating cost of the 400 kW end of the RIA's Fragment Separator. At present, no accelerator or beam line magnet has been made with HTS. The challenging magnet requirements of the Fragment Separator region of RIA and the recent advances in HTS offered a unique opportunity to seriously evaluate this solution. The results presented here offer the first proof that, despite its brittle nature, the technology to build magnets with HTS can be developed.

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