Design, Construction and Test Results of a Warm Iron HTS Quadrupole for the Facility for Rare Isotope Beams

R. Gupta, M. Anerella, A. Ghosh, J. Schmalzle and W. Sampson

***Abstract*—The first quadrupole in the fragment separator region of the proposed Facility for Rare Isotope Beams would be subjected to extremely high radiation and heat loads (~15 kW in the magnet and 5 kW/m^3 in the coil). As a critical part of this proposal, a radiation resistant quadrupole made with first generation High Temperature Superconductor (HTS) has been built and tested. This paper summarizes design, construction and test results of this magnet that has been designed to operate at ~30 K to remove this heat economically. Of particular interest are the simulated energy deposition experiments that demonstrate the stable operation of this HTS magnet in the presence of these unprecedented loads. The next quadrupole will use second generation HTS and is expected to operate at 50 K or above for even more efficient energy removal.**

***Index Terms*—High Temperature Superconductors, HTS magnets, radiation resistant magnets, Facility for Rare Isotope Beams.**

I. INTRODUCTION

THE Superconducting Magnet Division at Brookhaven National Laboratory (BNL) has designed, built and tested a super-ferric quadrupole magnet made from High Temperature Superconductor [1-4]. It has been developed for the fragment separator of the proposed Facility for Rare Isotope Beams (FRIB), an evolution of the earlier Rare Isotope Accelerator (RIA) proposal [5-7]. A variety of fragments in large quantities are created when up to 400 MeV per nucleon beams (of proton to uranium) having a beam power of up to 400 kW hit the target. The magnets in the fragment separator, which then selects one of these beams, would be subjected to extremely high radiation and heat loads [8]. Conventional magnets with water-cooled copper coils do not allow high capture efficiency. In addition, radiation resistant copper coil magnets were found to be more expensive to build and more expensive to operate than the proposed HTS magnets [8]. HTS allows operation of these magnets at ~30 K (50 K or above with the second generation) where the removal of energy is over an order of magnitude more efficient than that at ~4K in low temperature superconductors.

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R. Gupta, M. Anerella, A. Ghosh, J. Schmalzle and W. Sampson are with Brookhaven National Laboratory, Building 902A, Upton, NY 11973 USA (corresponding author: Ramesh Gupta; phone: 631-344-4805; fax: 631-344-2190; e-mail: gupta@bnl.gov).

Another important consideration is the impact of large radiation doses of mostly, but not limited to, high-energy neutrons, with an estimated dose of 10^{18} n/cm^2 over the lifetime. A significant program is underway [9,10] to carry out radiation damage study on BSCCO and YBCO HTS. Stainless steel insulation has been chosen, as most organic insulations would not survive in such an environment.

TABLE I: DESIGN PARAMETERS OF THE MODEL MAGNET

Parameter	Value
Aperture	290 mm
Design Gradient	10 T/m
Magnetic Length	425 mm (1 meter full length)
Coil Width	500 mm
Coil Length	300 mm (1125 mm full length)
Coil Cross-section	62 mm X 62 mm (nominal)
Number of Layers	12 per coil
Number of Turns per Coil	175 (nominal)
Conductor (Bi-2223) Size	4.2 mm X 0.3 mm
Stainless Steel Insulation Size	4.4 mm X 0.038 mm
Yoke Cross-section	1.3 meter X 1.3 meter
Minimum Bend Radius for HTS	50. 8 mm
Design Current	160 A (125 A full length)
Operating Temperature	30 K (nominal)
Design Heat Load on HTS coils	5 kW/m^3

II. MAGNET DESIGN AND CONSTRUCTION

To reduce the amount of radiation hitting the cold-mass, a warm iron design has been developed. Moreover, use of two rather than four cryostats further reduces the cold volume, particularly at the magnet ends. The design cuts the initial huge ~15 kW heat load to a more manageable ~130 W. However, this is still an unprecedented load in a ~1 meter-long cold structure.

The design philosophy and detailed design calculations have been presented elsewhere [1-4]. However, for reference, major parameters are shown in Table I. Construction of the HTS coil with stainless steel turn-to-turn insulator and construction of the cold-iron magnetic mirror with six coils have been presented elsewhere [1]. Warm iron model magnets (both magnetic mirror and complete model) required a compact cryostat that fits in the limited space around the pole of the magnet (see Fig. 1).

One of the two cryostats was specifically designed to perform energy deposition experiments and to study both "direct cooling" and "conduction cooling" methods. In the "direct cooling" mode all twelve coils in the cryostat were

exposed to the helium flow and hence provided "direct cooling". In the "conduction cooling" mode, only the top and bottom plates of the support structure were cooled by helium and then the coils were cooled by conducting heat through copper rods, copper washers and copper foils between the pair of coils and between the top and bottom plates of the support structure. In addition, stainless steel tape heaters were attached to copper foils to help perform simulated energy deposition experiments. Conduction cooling can, in principle, be also provided by cryo-coolers.

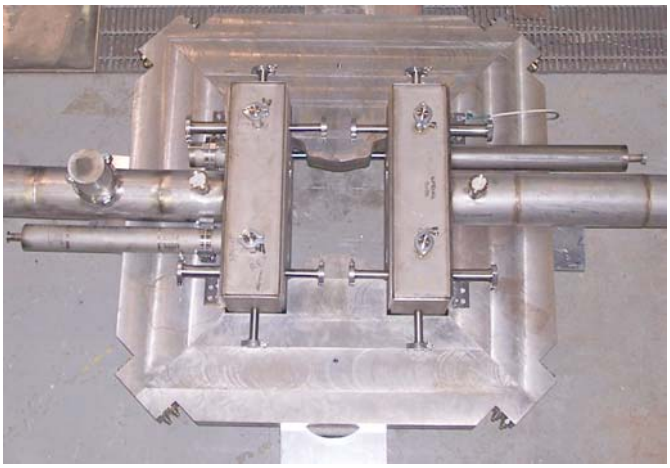

Fig. 1. Warm iron HTS quadrupole with two cryostats.

III. Test Results

In this section, we summarize test results of a variety of coil and magnet configurations. From the very outset, a step-by-step R&D program was envisioned to address various critical issues that were associated with this new design and technology, as well as to match the expected funding profile. The magnet program required a series production of 24 (+1 spare) HTS coils. These coils were tested individually and in a variety of magnet configurations. These configurations included the cold iron magnetic mirror quadrupole [1,2], warm iron magnetic mirror quadrupole, full short length warm iron quadrupole and common coil dipole. Most of these tests were performed over a large range of temperature (as wide as ~4 K to ~90 K).

A. Coil Test Results

Coils for the complete magnet were made in two series. An improvement in conductor performance between the two series resulted in a significant reduction in the amount of conductor required in the second series. Whereas the first thirteen coils (including one spare) of Series I were nominally wound with 175 turns made with 220 meters of conductor, the last twelve coils of Series II were wound with 150 turns made with 180 meters of conductor. Different currents in two coils of this R&D magnet give the same amp-turns. The conductor for both series of coils was purchased from American Superconductor Corporation [11].

Fig. 2 shows the 77 K (liquid nitrogen) performance of individual coils in Series I. I_c is defined as the current where the average voltage gradient (reflection of the resistive onset) over the coil is 0.1 μV/cm. We consider that for accelerator magnet application 0.1 μV/cm is a more appropriate definition than 1 μV/cm that is more common in the HTS community for other applications. In double coil tests, two coils were connected in series with a splice on the innermost conductor. The difference in the critical current between single coil test and double coil test is due to higher self-field in two coils. Fig. 3 shows the 77 K (liquid nitrogen) performance of individual coils in Series II. A small piece of conductor was also tested at 77 K and the performance of the coils tracked fairly well with the performance of the conductor. Reasonably uniform performance in a large series of coils made with commercially available superconductor indicates how far the technology has matured.

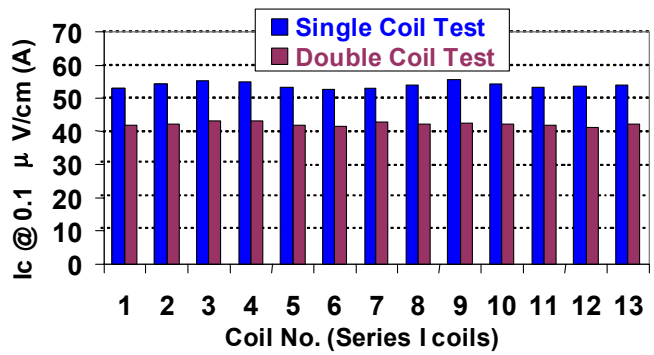

Fig. 2. Performance of coils made in Series I at 77 K. In the double coil test, the lower I_c is due to higher self-field from two coils connected in series.

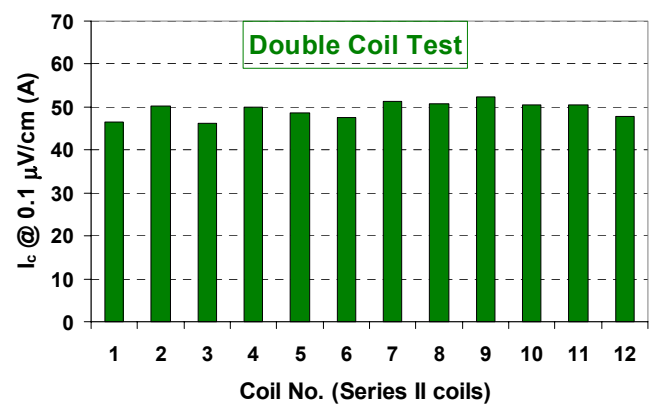

Fig. 3. Performance of coils made in Series II at 77 K.

B. Magnet Test Results

Fig. 4 shows the cumulative results of a large series of magnet tests over a wide range of temperature. This systematic study provides an experimental way to determine a good operating temperature. "Two", "Four" and "Six" coil tests were performed in a "cold iron" magnetic mirror configuration and have been presented earlier [1]. "Twelve" coil tests were performed in "warm iron" configuration, with series I coil performance shown in "mirror" configuration and series II in full magnet configuration. As the number of coils increases, I_c decreases because of higher self-field. The actual I_c in a coil is a complex function of temperature and field, both of which vary over a large range in Fig. 4. There is a relatively smaller decrease in I_c going from "Six" to "Twelve" coils, compared to "Two" to "Four" to "Six" because of a relatively smaller change in the field perpendicular component, in addition to the way I_c changes with field. One

can also notice a significant difference in the relative performance of the "Twelve" Series I coil test (in the mirror model), and the "Twelve" Series II coil test (in the full model). This difference is not associated with the difference in the field on the coils between mirror model and full model (which is rather small), but is attributed to a significant difference in the temperature dependence (usually referred to as the scaling factors) of conductor used in Series I and Series II coils.

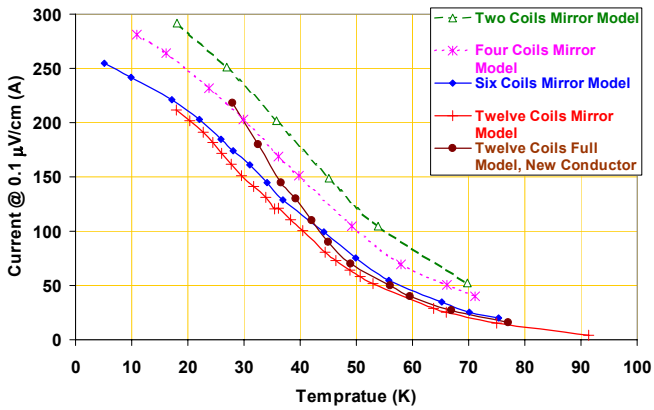

Fig. 4. A summary of a large number of tests involving energizing two, four, six and twelve coils in cold iron magnetic mirror model, warm iron magnetic mirror model, and warm iron full model. The magnets were allowed to warm-up or cool-down by controlling the rate of helium flow which facilitated tests over a large range of temperature.

For reference, the maximum (peak) values of perpendicular and parallel components of fields on the surface of coils are shown in Fig. 5 in case of the full model magnet with 24 coils. The value of field at 100 mm is also shown (to get field gradient in T/m, this value should be multiplied by 10). Large iron saturation, starting at a low current of 30 A, is due to the very small length of the iron (only ~25% of overall coil length) in this short model magnet. Because of this reason, the design gradient of 10 T/m is reached at 160 A instead at 125 A in full-length magnet. However, the computed perpendicular peak field in the coil (which determines the magnet performance) in both short and full-length magnet has nearly the same value at 125 A.

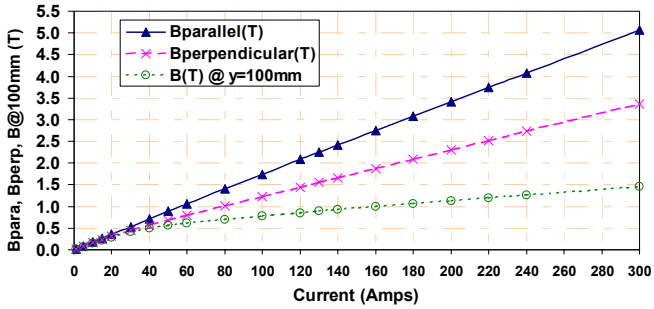

Fig. 5. Computed maximum values of parallel and perpendicular component of field on the surface of coil as a function of current. The magnitude of field inside the aperture at 100 mm radius is also shown.

C. *Energy Deposition Experiments*

The primary motivation of using HTS in these magnets is its major cryogenic advantage so that magnets can have stable operation in the presence of large heat loads. In actual operation, these heat loads in coils would come from the energy deposited by various isotopes. In the simulated experiments, these heat loads are created by passing a small current in thin stainless steel tape heaters (put on copper sheets). To carry out a detailed study, temperature sensors were installed at several places (at the surface of coils and at the outside surface of the cold structure). Several controlled experiments were performed to determine the performance of the HTS coils and of the cryo-system under various scenarios.

The first series of experiments was performed during the regular cool-down when the helium flow rate was 135 standard cubic feet per hour. To vary the total amount of heat load, the current in all heaters was changed. The chosen flow rate was more than adequate to remove a heat load of 19.4 Watts (see Fig. 6 which shows that the temperature continues to decrease) but not 29.4 Watts (as temperature start increasing). The computed equilibrium heat load at this flow rate is about 26 W. Therefore, it is expected that at a flow rate of 135 standard cubic feet per hour and a heat load of 26 W, the temperature would remain constant as indicated in Fig. 6.

A series of experiments were performed where only one or a few heaters were powered and the influence of other coils was observed. We also carried out experiments where the above tests were performed in "conduction cooling" (cooling only top and bottom plates with no helium in contact with coils) and in "direct cooling" mode (helium flowing in direct contact with coils). Based on these experiments, it is very encouraging to conclude that in all cases stable magnet operation can be found and that HTS magnets can withstand such heat loads. It is important to point out that during such experiments the HTS coils were able to operate near a temperature that is expected from the plots shown in Fig. 4.

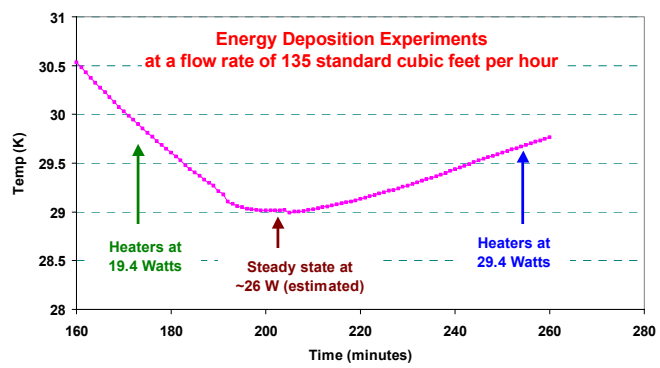

Fig. 6. Energy deposition experiments during cool-down at a constant flow rate of helium. The plot shows the value of temperature on one of several sensors when all heaters were uniformly energized.

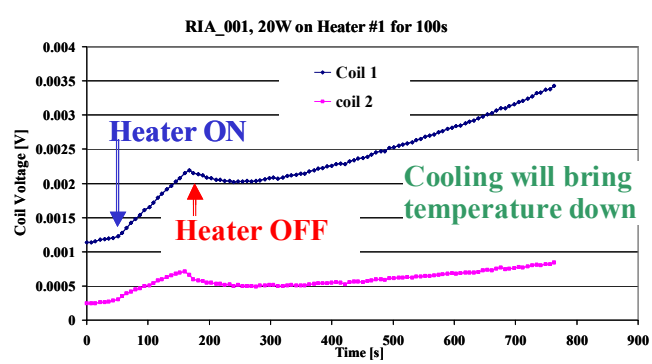

Fig. 7. Energy deposition experiments during natural warm-up (no helium flow). Voltages on two coils were observed while one heater was briefly energized.

Another series of experiments was performed during the warm-up cycle when cooling is discontinued by stopping the helium flow. Note that when the combination of current, temperature and field is such that the conductor is close to I_c, the coil voltage becomes very sensitive to a change in any parameter. Fig. 7 shows the behavior of two coils, as measured through the voltage across them, when one heater on one side of the coil was energized at 20 W during the above warm-up. The accelerated increase in coil voltage means that the coil is approaching I_c faster. The coil voltage (implying coil temperature) goes down in the beginning after the heater is turned off because rest of the magnet was cooler. If the cooling had not been stopped, the temperature would have come down depending on the flow rate and heat load.

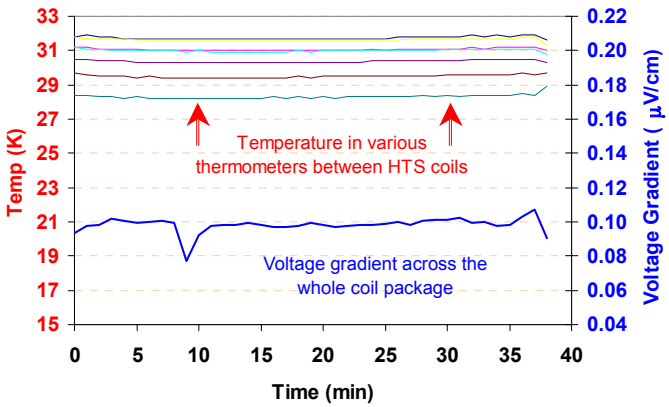

Fig. 8. Monitoring of thermometers between various coils and over-all voltage -gradient on all twelve coils in the presence of ~25 Watts of heat load distributed between the coil. The helium flow-rate and current in the coil was kept constant. A stable operation demonstrates that the HTS magnet developed here can safely remove the expected heat loads and meets the machine requirements.

The last series of experiments was to demonstrate stable operation of the quadrupole at the design gradient (10 T/m), design temperature (~30 K) and at design heat load in the coils (5 kW/m^3). The expected total heat load in the HTS coils of a full-length magnet of 130 Watts, translates to ~25 Watts in one coil of the present short length R&D quadrupole. Fig. 8 shows a 40 minute cycle of stable operation during which the helium flow was kept constant and a distributed heat load of ~25 Watts was generated by the stainless steel tape heaters. The plot shows the reading of various temperature sensors placed between the coils. The difference in temperature, as displayed by various thermometers, may be partly real and may be partly artificial because of the calibration mis-match of various sensors. As such the HTS coils can tolerate a temperature variation of several degrees and operate safely. In this respect superconducting magnets made with HTS are significantly different from the magnets made with conventional low temperature superconductors where temperature is usually regulated to a few tenth of a degrees. In HTS magnets, I_c decreases only a few percent per degree increase in temperature (see Fig. 4 at ~30 K).

During the period of above energy deposition experiment, the current in quadrupole was kept constant current at 140 A, well above the design current of 125 A. One can see (Fig. 8) that temperature in all sensors remains fairly constant, indicating a stable operation. The most sensitive parameter to monitor stable operation is the coil voltage, with a value of ~2.5 mV corresponding to the 0.1 μV/cm definition of I_c.

IV. Future Plans

Three coils are being wound with the second generation HTS (YBCO). Conductor for two coils has been purchased from American Superconductor Corporation [11] and conductor for one coil from SuperPower [12]. The second generation HTS is not only expected to reduce the cost of construction, but is also expected to further reduce the cost of operation by allowing further increase in operating temperature (30 K to 50 K or above). We will test these coils over a large range of temperature (~5 K to ~80 K).

V. Conclusion

The first phase of a unique R&D program of design, construction and test of an HTS quadrupole has been successfully completed. Moreover, it has been demonstrated that the HTS magnet can operate in a stable fashion while removing an unprecedented amount of energy (5 kW/m^3 of heat loads in coils) at 30 K. The program not only provides a solution for one of the most critical items in the design of the Facility for Radioisotope Beams, but also opens the way for a large number of future applications. The next phase of the program with the second generation superconductor makes this design and technology even more attractive.

Acknowledgment

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