Second Generation HTS Quadrupole for FRIB

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Abstract— **Quadrupoles in the fragment separator region of the Facility for Rare Isotope Beams (FRIB) will be subjected to very large heat loads (over 200 Watts) and an intense level of radiation (~10 MGy per year) into the coils of just the first magnet. Magnets made with High Temperature Superconductors (HTS) are advantageous over conventional superconducting magnets since they can remove these heat loads more efficiently at higher temperatures. The proposed design is based on second generation (2G) HTS which allows operation at ~50 K. 2G has been found to be highly radiation tolerant. The latest test results are summarized. The goal of this R&D program is to evaluate the viability of HTS in a real machine with magnets in a challenging environment where HTS offers a unique solution.**

Index Terms— **High Temperature Superconductors, HTS, 2G YBCO, FRIB, radiation tolerant.**

I. INTRODUCTION

HTS quadrupoles are being developed for the Facility for Rare Isotope Beams (FRIB). FRIB [1] will be built at Michigan State University where it will use several existing components of the National Superconducting Cyclotron Laboratory (NSCL). It will create rare isotopes for research in intensities not available anywhere today. Large quantities of various isotopes will be produced when a high power (400 kW) LINAC with a beam energy of 600 MeV for proton and 200 MeV/amu (or more) for all ions hits the target. The magnets in the fragment separator region will be subjected to large heat and radiation loads [2] since they are located immediately after this target. The use of HTS is attractive [3] since it can remove these high heat loads at 30–50 K rather than at 4–10 K that is needed for conventional low temperature superconductors. Removing these heat loads at higher temperatures (30-50 K) is over an order of magnitude more efficient than removing at lower temperature (4-10 K). Earlier, in the first phase of HTS magnet R&D for Rare Isotope Accelerator (RIA), we had successfully designed, built and tested [4] a 10 T/m, 290 mm aperture quadrupole with ~ 4 mm wide first generation (1G) BSCCO-2223 tape operated at 30 K. The second generation magnet design requires a higher gradient (15 T/m) and is being designed with ~12 mm wide second generation (2G) YBCO tape to operate at even higher temperature – at ~50 K instead of 30 K. Higher operating temperature makes the removal of large amounts of energy even more efficient.

One key design requirement, which is similar to that for the alternate cable-in-conduit NbTi design being developed at NSCL [5], is that these quadrupoles are remotely serviceable such that damaged parts can be replaced without the need for humans to enter the high radiation environment.

TABLE I: DESIGN PARAMETERS OF THE R&D MAGNET

Parameter	Value
Pole Radius	110 mm
Design Gradient	15 T/m
Magnetic Length	600 mm
Coil Overall Length	680 mm
Yoke Length	~550 mm
Yoke Outer Diameter	720 mm
Overall Magnet Length(incl. cryo)	~880 mm
Number of Layers	2 per coil
Coil Width (for each layer)	12.5 mm
Coil Height (small, large)	26 mm, 39 mm
Number of Turns (nominal)	110, 165
Conductor (2G) width, SuperPower	12.1 mm ± 0.1 mm
Conductor thickness, SuperPower	0.1 mm ± 0.015 mm
Cu stabilizer thickness SuperPower	~0.04 mm
Conductor (2G) width, ASC	12.1 mm ± 0.2 mm
Conductor (2G) thickness, ASC	0.28 mm ± 0.02 mm
Cu stabilizer thickness ASC	~0.1 mm
Stainless Steel Insulation Size	12.4 mm X 0.025 mm
Field parallel @design (maximum)	~1.9 T
Field perpendicular @design (max)	~1.6 T
Minimum I_c @2T, 40 K (spec)	400 A (in any direction)
Minimum I_c @2T, 50 K (expected)	280 A (in any direction)
Nominal Operating Current	~280 A
Stored Energy	37 kJ
Inductance	~1 H
Operating Temperature	50 K (nominal)
Design Heat Load on HTS coils	5 kW/m^3

The overall design parameters are given in Table I. The design has evolved in response to increased field gradient requirements on one hand (10 T/m to 15 T/m) and improved conductor performance on other hand. The increased gradient requirements (within the same funding allocation) initially led to lowering the design operating temperature from 50 K to 40 K (hence the conductor specifications at 40 K) but improved conductor performance allowed increasing the operating temperature back to 50 K. The overall design space can accommodate conductors from two vendors (SuperPower, SP [6] and American Superconductor Corporation, ASC [7]) despite a significant difference in the conductor thickness between the two. Some design parameters, however, will be

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different than those listed in Table I. Both vendors agreed to in-field specification at given temperature rather than usual 77 K, self field specification. This is a significant development in planning to use HTS in magnet applications.

The R&D structure has significantly more flexibility and diagnostics than what would be in a production structure. It allows the coils in each of the four quadrants to be tested independently.

II. MAGNET DESIGN

The magnetic model of one quadrant of the cross section is shown in Fig. 1. The complete 3-d model is shown in Fig. 2. The overall design is based on the same general principle as the design for the RIA [4] quadrupole for fragment separator. The yoke is warm since it is isolated from the cooler coils to minimize the heat load to be removed at lower temperatures.

A significant design effort has been made to minimize the space for coils and cryo-mechanical structure to increase the magnetic efficiency of the design. In such quadrupoles, the loss in transfer function due to iron saturation occurs primarily in neck region (Fig. 1). The compact structure with nested coils (Fig. 2) allows maximizing the width and minimizing height of the pole. It also reduces the height of pole region. Optimization in the cryo-mechanical structure allowed the warm pole radius to be reduced to 110 mm from an earlier value of 135 mm.

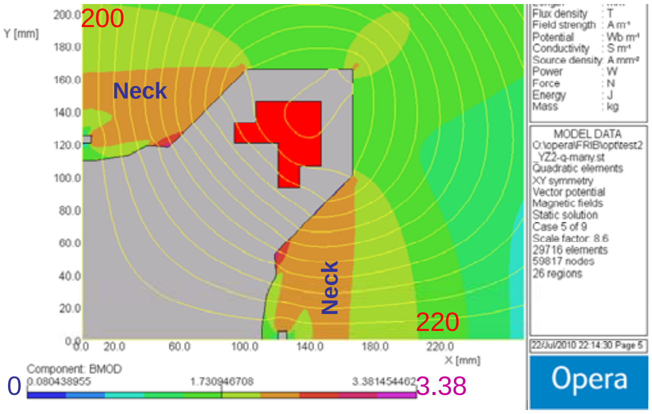

Fig. 1. Magnetic model of one quadrant of the cross-section. Significant effort is made in the design to maximize the iron width in "neck" region of the pole. Field lines and magnitude of the field contour (T) in the yoke are also displayed.

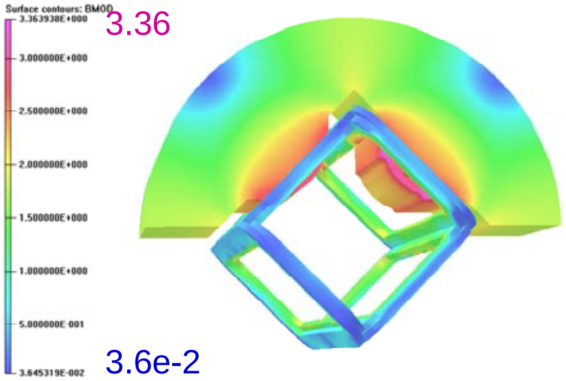

Fig. 2. OPERA 3-d magnetic model with all coils and the upper half of the yoke. The magnitude of the field (T) is superimposed on the surface of yoke and coil. Coils of two heights (26 mm and 39 mm) are nested to maintain the quadrupole symmetry in the cross-section (Fig. 1).

III. CRYO-MECHANICAL STRUCTURE AND ANALYSIS

The magnet is designed to be cooled by helium from the FRIB "exit gas" which is planned to be available at ~40 to ~50 K. The helium flows through distribution tubes into conductive cooling blocks within the coil clamps. Cooling blocks are provided for each of the four straight section coil quadrants and also each of the four coil end region clamps at both ends. Exiting helium is also provided to the cold end of vapor cooled current leads. In addition to containing the cooling blocks the coil clamps also serve to restrain the coils against radial and axial Lorentz forces with acceptable deflections. ANSYS analysis of the structure with Aluminum clamp shows that the deformation in coils <25 microns both in cross-section (Fig. 3) and in ends (Fig. 4).

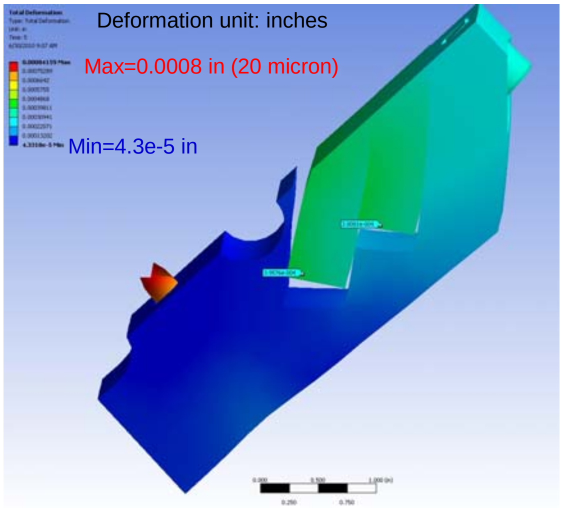

Fig. 3. Total deformation of coils in Aluminum clamp is <25 μm (0.001").

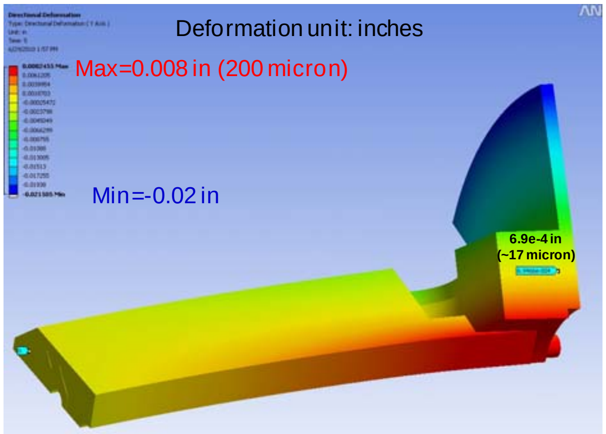

Fig. 4. Axial deformation of the support structure. The maximum deformation in the region of coil end is <25 μm (0.001") in the case of Aluminum clamp.

The 300 K magnetic yoke is located only in the straight section of the magnet, installed around the outer cryostat. The cryostat is enlarged in the end regions beyond the yoke to permit installation of low heat leak structural supports between coil and cryostat, and also the necessary helium and electrical connections. The design of the yoke and magnet allows for the upper yoke and cryostatted coils to be removed for repair when needed with the lower yoke permanently surveyed into position, with repeatable accurate positions when the coils and upper yoke are replaced.

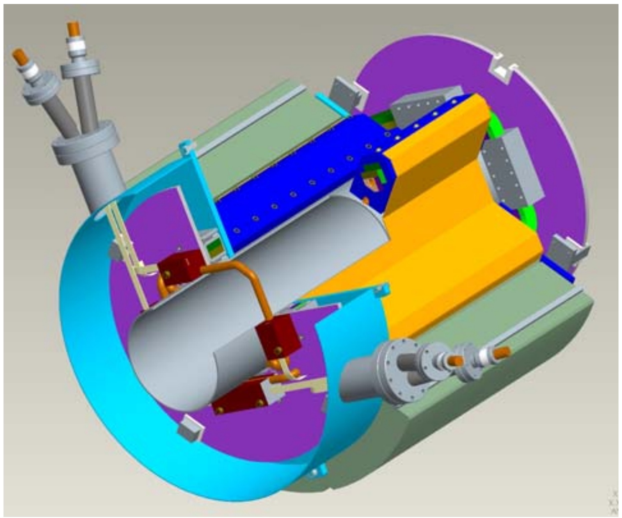

Fig. 5. Cut-away isometric view of the assembled magnet. Note in yellow the outside straight section cryostat, in blue the straight section coil clamps and in brown (foreground) and grey (background) the end coil clamps with connecting helium lines.

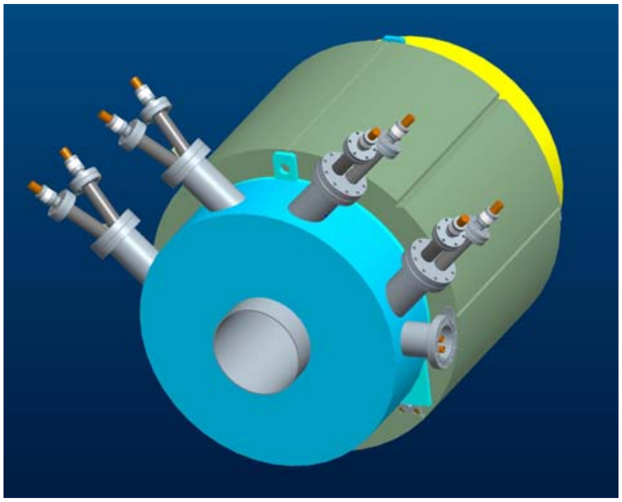

Fig. 6. End isometric view of the assembled magnet showing 300 K yoke, end cryostat and exiting power leads and helium lines. Note that for R&D purposes each HTS coil is planned to be tested individually as can be seen by the eight exiting leads. Production magnets are envisaged to utilize internal coil splices and as such will have only two exiting leads.

IV. YBCO Coil R&D For FRIB

There was an intermediate period when the RIA R&D was completed and the FRIB site and program were yet to be established. During this period, coils with YBCO tape (based on earlier geometry for the RIA quad design [4]) were built and tested to make an initial evaluation of 2G HTS. These coils were fabricated with the same construction techniques and parameters used earlier [4]. One such coil is shown in Fig. 7. The performance of two coils as a function of temperature is shown in Fig. 8 (temperature adjusted by varying the flow rate of helium gas). These tests demonstrate that coils with 2G HTS can be reliably built and operated in the context of this application. These tests are performed in self-field of the coil, which is higher at lower temperature as the current achieved is higher. It may be pointed out that these coils were made with the conductor obtained in the early part of the program and performance has significantly improved since then.

Fig. 7. FRIB R&D coil made with 2G HTS.

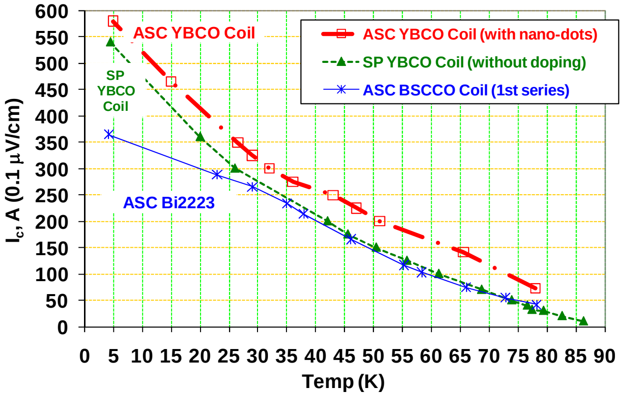

Fig. 8. Critical current performance of 2G HTS coils made with earlier conductor from SuperPower and ASC as a function of temperature. For reference the performance of coils made with 1G HTS is also plotted.

Fig. 9. A cryo-mechanical structure during fabrication that will test six 2G HTS coils. One can see two cryo-heads in the lower-right of the picture and coils in the bolted support structure on the upper-side.

For the same current, the engineering current density in 2G coils is higher because of lower tape thickness (~0.1 mm in SuperPower and ~0.3 mm in ASC) as compared to ~0.4 mm in 1G HTS. One concern is that 2G HTS has a smaller amount of copper stabilizer compared to the silver in 1G. However, it should be sufficient in this application since the operating current will be half of what these coils were successfully tested to and the conductor width about three times higher, making current density in the stabilizer about five or more times less at quench (or runaway). The current density in copper at the design current when the conductor goes normal would be ~578 A/mm^2 for tape from SuperPower (with 40 micron thick copper) and ~224 A/mm^2 for tape from American Superconductor (100 micron thick copper). Both are considered to be adequate for protection and to allow conductor to recover.

Six racetrack coils have been fabricated, four with conductor from ASC and two from SuperPower. They have been assembled in a structure which will be conduction-cooled by cryo-coolers. Fig. 9 shows the final preparation of this test with an intended test range of 40 K and above.

V. RADIATION DAMAGE STUDIES OF YBCO

All components (including the conductor) used in FRIB magnets must be tolerant against high radiation doses (up to 10 MGy per year). An important part of this comprehensive R&D program is to assure that any damage caused by radiation to various magnet components remains within acceptable limits. Stainless steel insulation (rather than organic insulation such as Kapton or epoxy) is used since stainless steel, being metal, is highly radiation tolerant.

An experimental program was started to study the radiation damage to conductor (YBCO), as no prior data were available. The samples of the YBCO tapes from ASC and SuperPower were irradiated at the Brookhaven Linear Isotope Production (BLIP) facility with a 142 MeV proton beam. The experimental results of radiation damage measurements at 77 K but with no applied field were reported earlier [8]. Recently the same samples were studied with 0.25 to 1.25 T applied field. Since the critical current in HTS tape is anisotropic with respect to the field angle, radiation damage studies on critical current are performed as a function of both field and field angle.

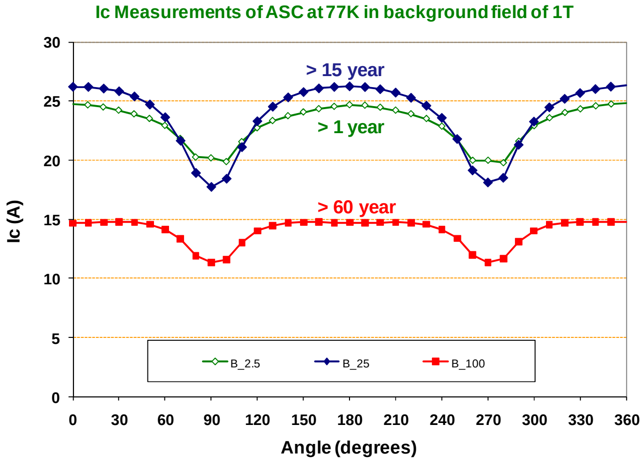

Fig. 10. Measured critical current (I_c) as function of field angle (with respect to c-axis) in ASC tapes for several integrated values of irradiation. Critical current curve of non-irradiated sample was close to that of 1 year curve.

A summary of these measurements at 77 K with 1 T applied is shown in Fig. 10 for ASC tapes and in Fig. 11 for SuperPower tapes. They will be reported in more detail elsewhere. B_2.5, B_25 and B_100 indicate, 2.5, 25 and 100 μA-hrs of integrated dose in the middle of the sample. B_25 (or 10^{17} protons/cm^2) is equivalent to >15 years of FRIB operation [9]. Whereas the radiation damage was similar for tapes from ASC and SuperPower in the absence of field [8], they are significantly different in the presence of field. The reason behind this different behavior is not well understood. The conductor satisfies the machine requirements based on these measurements. The next step is to measure the critical current of these samples at 40-50 K and in applied field up to 3 T. They will be performed in an HTS solenoid (being built under separate funding) which will be modified to split-pair solenoid for this purpose.

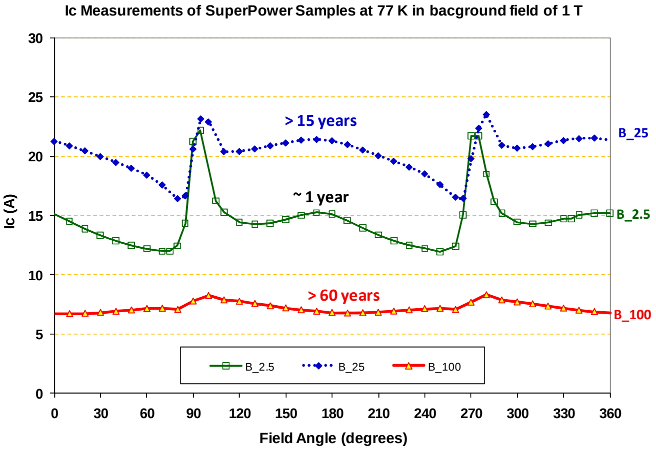

Fig. 11. Measured critical current (I_c) as function of field angle (with respect to c-axis) in SuperPower tapes for several integrated values of irradiation. Critical current curve of non-irradiated sample was close to that of 1 year curve.

VI. QUENCH PROTECTION

Quench protection remains a major issue in HTS magnets in light of slow quench propagation velocity. The challenge is larger in 2G HTS as compared to 1G HTS because of the lower amount of stabilizer. The system should keep the hot spot less than 200 K or so. The current density in copper at quench (or thermal runaway) is kept low in the FRIB design, which is very helpful. An R&D program to find an engineering solution has been started to assure that coils remain well protected. Coils will be segmented with many voltage taps to detect voltage in small sections. Very low signal noise levels will be achieved to help detect a small normal zone. Voltage taps will be routed such that the noise in pickup loops is minimized. A very high resolution converter will be used to digitize the voltage and current signals. The quench switch will be a semiconductor switch as such devices are very reliable. The power Supply will have short term stability of the order of a few parts per million. The current ramp will be very smooth to minimize voltage spikes across the magnet. Power supply will have a small voltage ripple.

VII. SUMMARY

HTS offer a unique solution to deal with the demanding requirements of the high radiation and large energy deposition environment of fragment separator region of FRIB. The R&D program presented is systematically addressing these issues.

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