

ENGINEERING DESIGN OF HTS QUADRUPOLE FOR FRIB*

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Abstract

The coils of the first quadrupole in the fragment separator region of the Facility for Rare Isotope Beams (FRIB) must withstand an intense level of radiation and accommodate a very high heat load. Magnets produced with High Temperature Superconductors (HTS) are especially suitable in such an environment. The proposed design employs second generation (2G) HTS, permitting operation at ~50K. The engineering considerations this design are summarized. The goal has been to engineer a compact, readily producible magnet with a warm bore and yoke, made from radiation-resistant materials, capable of operating within the heat load limit, whose four double-layered coils will be adequately restrained under high radial Lorentz forces. Results of ANSYS finite element thermal and structural analyses of the coil clamping system are presented. Coil winding, lead routing and splicing, magnet assembly as well as remote tunnel installation/removal considerations are factored into this design and will also be discussed.

INTRODUCTION

The HTS quadrupole magnet for FRIB [1] is designed to operate under high heat and radiation loads in the Fragment Separator Region. HTS is employed [2] since it can remove these high heat loads at 30–50K instead of 4–10K required for conventional low temperature superconductors (LTS). These higher temperatures make heat removal over ten times more efficient than removing it at 4-10K. This new second generation magnet [3] employs ~12 mm wide second generation (2G) YBCO tape enabling it to operate at a higher gradient (15 T/m) compared to the previous first generation versions [4]. The first generation magnet operated at a gradient of 10 T/m at 30K and was made with ~4mm wide first generation (1G) Bi2223 tape. The new HTS will operate stably at ~50K thereby rendering it the best performer in its class.

An important design requirement - that these magnets be remotely serviceable such that damaged parts can be replaced without requiring personnel to enter the high radiation environment – is reflected in that of the cryostatted coil assembly. This component, the heart of the magnet, with the warm bore tube, can be simply removed from the lower half-yoke, to which it is physically registered, and a replacement coil put in its

place. This can be accomplished without the need for tedious repositioning or survey of the magnet afterwards, because the position of lower half-yoke remains undisturbed throughout the entire service operation. The goal here is to perform such service remotely and robotically for reasons of radiation safety.

The basic design parameters of the BNL FRIB R&D Prototype Magnet made with second generation HTS tape from SuperPower (SP) and American Superconductor Corporation (ASC) are summarized in Table 1.

Table 1: Design Parameters of the HTS Quadrupole Magnet for FRIB

| Parameter | Value |
|---|--------------------------|
| Pole Radius | 110 mm |
| Design Gradient | 15 T/m |
| Magnetic Length | 600 mm |
| Coil Overall Length | 680 mm |
| Yoke Length | 546 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) | 27 mm(SP) 40 mm(ASC) |
| Number of Turns (nominal) | 220(SP), 125(ASC) |
| 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 | ~140 A(SP) ~370A(ASC) |
| Stored Energy | 37 kJ |
| Inductance | ~1 H |
| Operating Temperature | 50 K (nominal) |
| Design Heat Load on HTS coils | 5 kW/m ³ |

The BNL R&D magnet is an ambitious design resulting from earlier successful HTS R&D endeavours at BNL [5]. It is a full-size prototype designed for an actual machine rather than a scaled model but will have enhanced flexibility and diagnostic capability relative to the corresponding accelerator model in three primary areas:

- Each of the eight coils will be instrumented with at least ten voltage taps between turns at regular intervals. Voltage tap leads will be routed such that the noise in pickup loops is minimized

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- Quench protection is very important in HTS coils so strip heaters will be fitted between each of the four spliced coil pairs. They will cover the inner side surfaces of the coils completely.
- Each spliced coil pair's two leads will exit the cryostat separately through two dedicated high-current feed-throughs, thus allowing it to be powered and tested independently of the others.

ENGINEERING DESIGN

Cryo-Mechanical Structure

Given the magnetic design for a warm iron HTS quadrupole [3], with nested flat-patterned coils, much effort has gone into packaging this arrangement into a stiff yet compact mechanical structure with low heat load and high radiation resistance (Figure 1). The coils are cooled by helium gas at temperatures between 40 and 50K. A network of bores, end plate drillings, flex hoses, and stainless steel tubing forms a serial path for the helium to remove heat from the coils in the straight section and in the ends. This cooling circuit will be efficient, easy to set up and unobtrusive during subsequent assembly operations. The stainless steel coil straight-section clamps are designed to hold each coil quadrant firmly and uniformly. Its bolts will be torqued gradually and evenly in order to draw together its two halves to a metal-to-metal stop for precise coil positioning and uniform coil preloading (Figure 2). These clamps also serve as part of the coil assembly's axial support structure by tying both 25mm thick lead and non-lead end plates together, forming a frame with a stiffness adequate to resist the axial Lorentz forces induced at full operating power.

The stainless steel vacuum vessel (cryostat) consists of the warm bore tube, 10 mm thick rear support plates, the 2mm thick sheet metal straight section, and the 2mm thick end cans and cover plates. It is a multi-faceted weldment designed to be assembled around a completed and fully insulated coil assembly with end plates and helium cooling pipes installed. Its pieces are slowly systematically seam-welded with great care to prevent damage from overheating to the insulation just behind it.

The cryostatted coil is aligned with the iron upper yoke at four indexing pads (two at each end) located on the rear surfaces of the cryostat's back plates. The upper yoke is indexed to the lower yoke at installation, completing the magnetic geometry.

Coil thermal shrinkage relative to the cryostat is accounted for through the use of four ceramic thermally isolated slides engaging the lead and non-lead end plates. They are locked to the cryostat at the lead end yet are free to allow movement of the cold mass (coils and end plate) at the non-lead end - the majority of which is longitudinal.

Coils are paired side-by-side and their first turns spliced together at the non-lead end by means of a cross-over jumper soldered with indium. At the lead end, HTS lead routing is kept as simple as possible. Each of the eight exiting leads makes a single 90 degree bend. The

routing of the exiting HTS leads takes into account a minimum bend radius of 50mm (Figure 3).

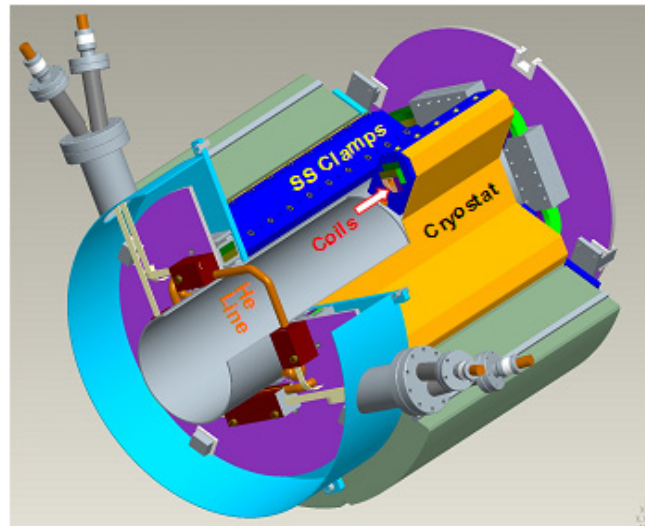


Figure 1: BNL FRIB R&D Magnet Cut-Away View.

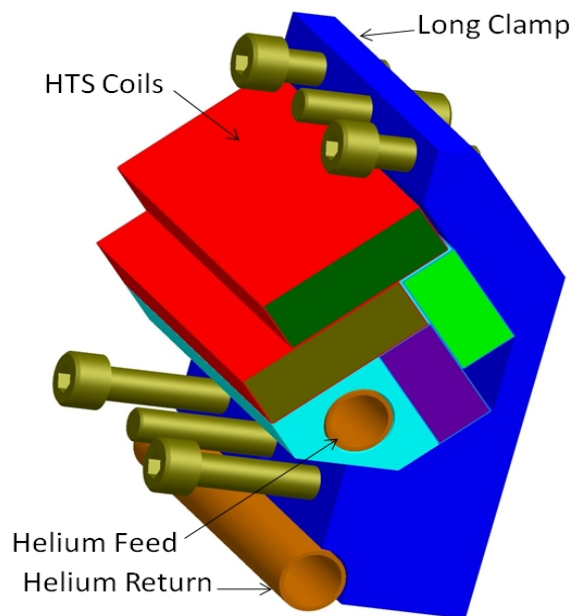


Figure 2: Partial view of Clamped Coil Straight Section.

Radiation Resistant Features

All components used in this magnet must withstand radiation exposure as high as 10 MGy per year. Any resulting material degradation must be limited and sustainable. Stainless steel coil insulation is used rather than the usual polyimide insulation (kapton). The thin coat of V40-815 epoxy applied to the sides of the coil after winding is for handling purposes and is not intended to have any other structural or insulating value in the magnet, so, considering its minimal thickness, its disintegration will be of no consequence. Nomex 410 aramid paper is used for coil-to-coil and coil-to-ground insulation. In addition to being radiation resistant, this material has good dielectric properties, high strength, and

high abrasion resistance, making it suitable for this application.

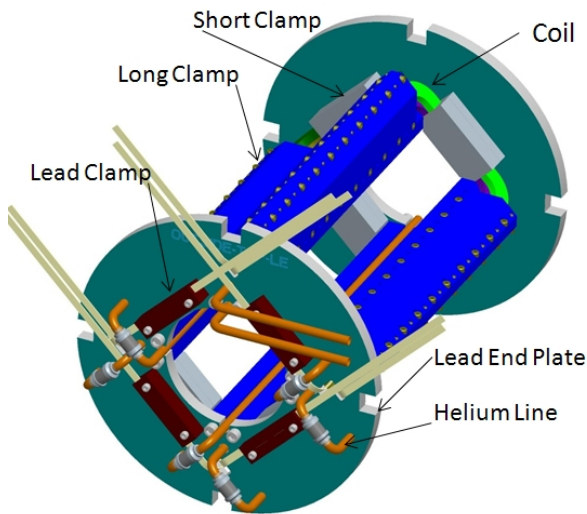


Figure 3: Coil Assembly with Clamps and End plates.

The ~13 layers of cryogenic insulation consist of thin aluminum reflective sheet and ceramic based cloth serving as the separator. The traditional materials (aluminized mylar and spun polyester cloth separator ‘Reemay’) do not offer adequate radiation resistance.

Warm-to-cold insulating structural supports are traditionally made of phenolics such as G-10, G-11, or similar composite plastics. Such epoxy-based materials cannot be used here, so in cases where such insulating support is needed, ceramic parts are employed. Examples of ceramic parts are the axial coil thermal slides, and the coil mid-section-to-cryostat radial supports.

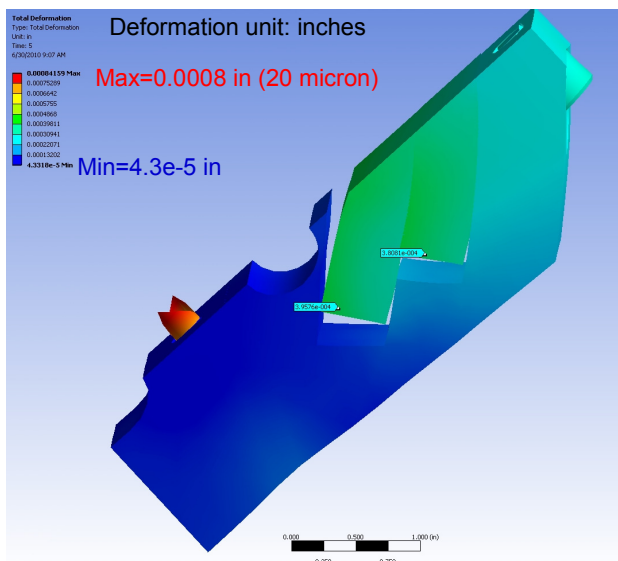


Figure 4: ANSYS analysis of long clamp CS with Coils.

Analyses

The ability of the clamping system to withstand radial and axial Lorentz forces has been studied. Bolts joining the clamps together and attaching the clamps to the end plates have been sized and arranged to maintain stress and deflection within acceptable limits. Analysis results indicate that deformation in the coils does not exceed 25 microns anywhere (Figures 4 & 5).

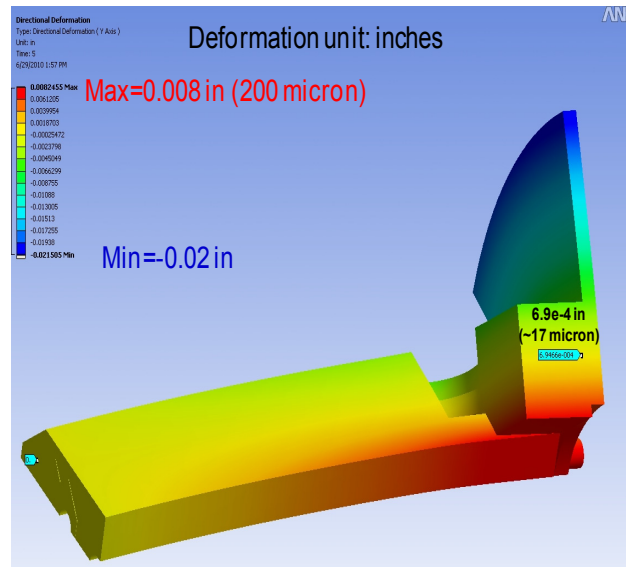


Figure 5: ANSYS analysis of coil axial deformation.

CONCLUSION

BNL’s newly designed FRIB Quadrupole R&D magnet has the features necessary to operate in a harsh accelerator environment. When completed later this year, extensive cold testing will validate the design and confirm its usefulness as a stable and long-lasting HTS accelerator magnet.

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