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Design, fabrication, and testing of the quadrupole triplet magnet for the HRS project

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Abstract. The Facility for Rare Isotope Beams (FRIB) is a scientific user facility under the U.S. Department of Energy Office of Science (DOE-SC) and an independent scientific user organization of approximately 1,800 researchers. The High Rigidity Spectrometer (HRS) will be the centrepiece experimental tool of the FRIB fast-beam program, enabling experiments with the most exotic, neutron-rich nuclei available at FRIB. A discrete cosine theta quadrupole triplet was designed for the HRS project. This magnet, with a warm bore of 200 mm, 18.5 T/m quadrupole field gradient, and a total length exceeding 2 meters, lacks an iron yoke and thus weighs only one-third of a traditional iron-dominated quadrupole triplet, that can reduce cool down time and reduce the helium requirement by a factor of 3-4. The new designed magnet can improve mechanical behaviour and the operation efficiency by reducing secondary beam tuning time. A new protection circuit was designed to ensure the safe operation of superconducting magnets. This work will introduce the design, full-scale prototype fabrication, and testing of the quadrupole triplet magnet.

1. Introduction

The Facility for Rare Isotope Beams (FRIB) is a scientific user facility under the U.S. Department of Energy Office of Science (DOE-SC), supporting the mission of the Office of Nuclear Physics. It provides intense beams of rare isotopes, which are crucial for scientific research and have broad benefits for other sciences, medicine, materials science, national security, and industry [1,2].

The High Rigidity Spectrometer (HRS) is a key expansion of the FRIB user facility, aimed at improving beam transmission efficiency and delivering rare isotope beams with high magnetic rigidity (up to 8 T·m). Fig. 1 shows the layout of the HRS at FRIB. The HRS project is staged in two phases: the High Transmission Beam Line (HTBL) phase followed by the Spectrometer (SPS) phase. FRIB has now completed the final design of the upstream HTBL, and the project is currently in the construction phase [3].

The HTBL contains four 22.5° bending dipole magnets (DH1 through DH4), eight quadrupole triplets (TH1 through TH8), and three vertical corrector magnets (SH1 through SH3). The eight quadrupole triplets have an identical design, with each triplet consisting of a short-long-short quadrupole configuration. The short and long quadrupoles are hereafter referred to as the QHA and QHB types, respectively. The quadrupole package incorporates nested higher-order correctors, including sextupole and octupole elements.

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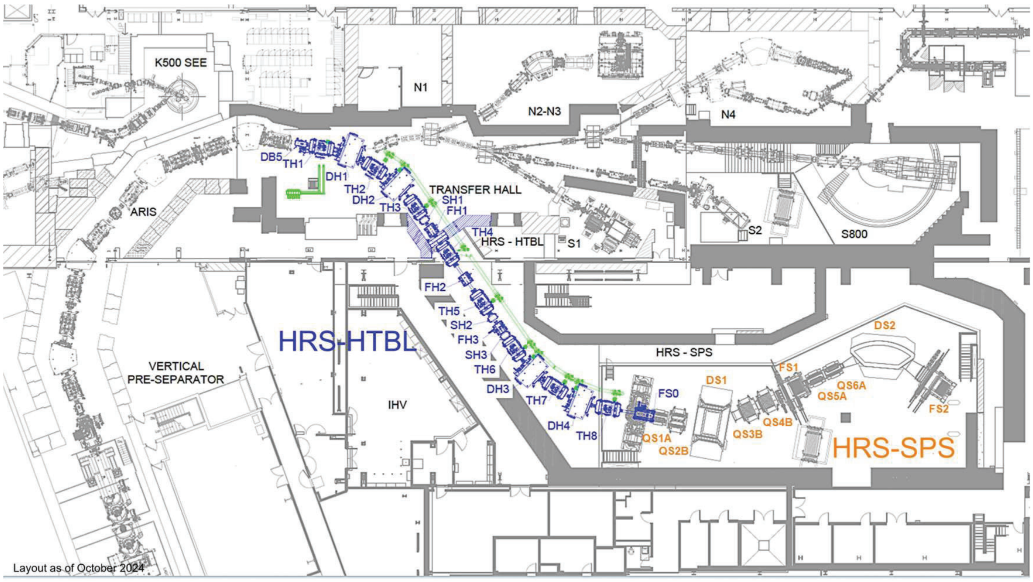

Figure 1. Layout of HRS in FRIB.

FRIB is simultaneously carrying out the design and fabrication of two quadrupole magnet approaches: the traditional iron-dominated quadrupole triplet (IDQT) and the coil-dominated quadrupole triplet (CDQT). The IDQT has a relatively mature design and well-established manufacturing techniques, which helps ensure on-schedule project completion. Compared to the iron-dominated quadrupole triplet (IDQT), the CDQT lacks an iron yoke and thus weighs only one-third of a traditional IDQT, that can reduce cool down time and reduce the helium requirement by a factor of 3-4. The mechanical behaviour is also improved. Due to linear behaviour of the magnet, the CDQT design can improve the operation efficiency by reducing secondary beam tuning time. If successfully developed, it could become a viable alternative to the IDQT.

A discrete cosine-2θ configuration (Walstrom style) was adopted to design the quadrupole coils [4-7]. This approach enables the construction of a coil layout with a cosine-2θ distribution, which generates a high-quality quadrupole field. At the same time, the so-called "shape function" is used to optimize the coil end geometry to minimize higher-order harmonics. By incorporating smooth transitions between adjacent turns in the curved regions, the contour of the coil winding can be accurately defined. The sextupole and octupole correctors use saddle-type, randomly wound racetrack coils, which are nested over the quadrupole coil from inside to outside and finally clamped with aluminium bands to enhance mechanical integrity.

The complete long quadrupole package (including the quadrupole, sextupole, and octupole) and the short quadrupole coils have now been fabricated. The quadrupole coils have successfully passed cold testing. The next step is to assemble the sextupole and octupole correctors with the quadrupole, followed by cold testing of the long quadrupole package assembly. This paper will use the long quadrupole as an example to present the design, fabrication, and testing of the CDQT magnet.

2. Technical requirement and structure

To enable the high-efficiency transmission of fast rare isotope beams produced at optimized magnetic rigidities, the technical requirements for the quadrupole triplet have been defined, as shown in Table 1.

Table 1. Technical requirements for the quadrupole triplets of the HTBL.

Parameter	QHA	QHB
Quantity (in 8 quadrupole triplets)	16	8
Effective field length (m)	0.40	0.79
Warm-bore radius (m)	0.10	0.10
Quadrupole maximum field strength (T/m)	≥ 17.15	≥ 18.19
Quadrupole gradient integral (T)	≥ 6.86	≥ 14.37
Quadrupole good-field region radius (m)	0.10	0.10
Maximum higher-order-field contamination[a] (%)	1	1
Sextupole maximum field strength (T/m^2)	11	11
Octupole maximum field strength (T/m^3)	55	55

[a] Field inhomogeneity is defined as non-quadrupole term fraction relative to the sum of the total terms based on the high order harmonics obtained at the good-field region radius.

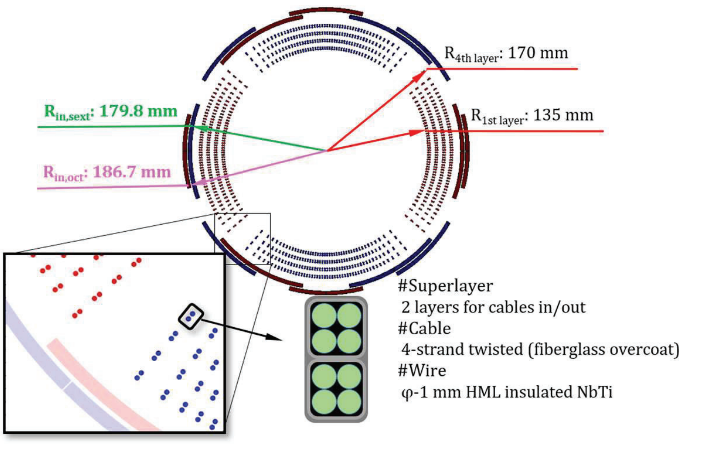

Figure 2. Cross-section view for quadrupole package.

Taking into account field quality, coil fabrication, and magnet operation, the quadrupole package adopts a nested configuration. The innermost part consists of four superlayers of

Walstrom-style quadrupole coils, followed outward by the saddle-type, randomly wound racetrack sextupole and octupole coils, and finally clamped with aluminum bands to enhance mechanical integrity.

The quadrupole coil uses a braided cable composed of four Heavy Polyimide Insulated (HML) NbTi conductors. Considering the target operating current of 450 A for the quadrupole coil, the parameters of the selected conductor are listed in Table 2. Under 4.2 K conditions, the corresponding operating margin is calculated to be 56%. The sextupole and octupole coils use NbTi superconducting wire with a bare wire diameter of 0.55 mm and a copper-to-superconductor ratio of 4.5. This ensures a 60% safety margin when operating at a current of 36A.

Table 2. Technical requirements for the quadrupole triplets of the HTBL.

Magnet Type	Bare Wire Diameter (mm)	Insulated wire diameter (mm)	Filaments	Cu:SC Ratio	Wire Insulation
Quad.	0.95	1.0	54	1.3	HML
Sext. & Oct	0.55	0.6	30	4.5	HML

3. Magnet design

A discrete cosine-2θ configuration (Walstrom style) was adopted to design the quadrupole coils [4-7]. The current density distribution of a quadrupole coil over the cylindrical surface can be mathematically expressed as follows:

$$\psi_n(\theta, x) = \cos(2\theta) \cdot F(x) \tag{1}$$

where F(z) is the shape function,

$$F(z) = \begin{cases} 0, & x < -L \\ k_2(L + x)), & -L < x < -L_1 \\ 1 - k_1(x + L_2)^2, & -L_1 < x < -L_2 \\ 1, & -L_2 < x < L_2 \\ 1 - k_1(x - L_2)^2, & L_2 < x < L_1 \\ k_2(L - x), & L_1 < x < L \\ 0, & x > L \end{cases} \tag{2}$$

which is plotted in Fig. 3 (a).

After discretizing the current density according to the number of coil turns, the path of each individual turn is obtained, with each forming a closed loop. To create a continuous winding path for the conductor, transitions between adjacent turns and between different quadrants are introduced (see Fig. 3(b)).

Harmonic decomposition is performed using the discrete Fourier transform (DFT) method to calculate the harmonic terms. The formalism used here is given by the following equations:

$$A_n \approx \frac{2}{N} \sum_{k=0}^{N-1} B_r(r_0, \varphi_k) \cos n\varphi_k , \tag{3}$$

$$B_n \approx \frac{2}{N}\sum_{k=0}^{N-1} B_r(r_0, \varphi_k)\sin n\varphi_k, \tag{4}$$

$$\varphi_k = \frac{2\pi k}{N}, \quad k = 0, 1, 2, \cdots, N-1. \tag{5}$$

where B_n are the normal harmonic terms, A_n are the skew harmonic terms, N is the total number of angular data points, φ_k is the angular interval between adjacent points on the circle, and r_0 is the reference radius [8].

Using the above method, the four superlayers short quadrupole (QHA) and long quadrupole (QHB) were designed. Figure 3 shows the shape function, the planar layout of the wire path of the first-superlayer coil, the axial distribution of the gradient strength, and the percentage content of each harmonic component of the QHB. Table 3 presents the design parameters and calculation results of the QHB. All performance meet or exceed the functional requirements, and the field quality is significantly better than required.

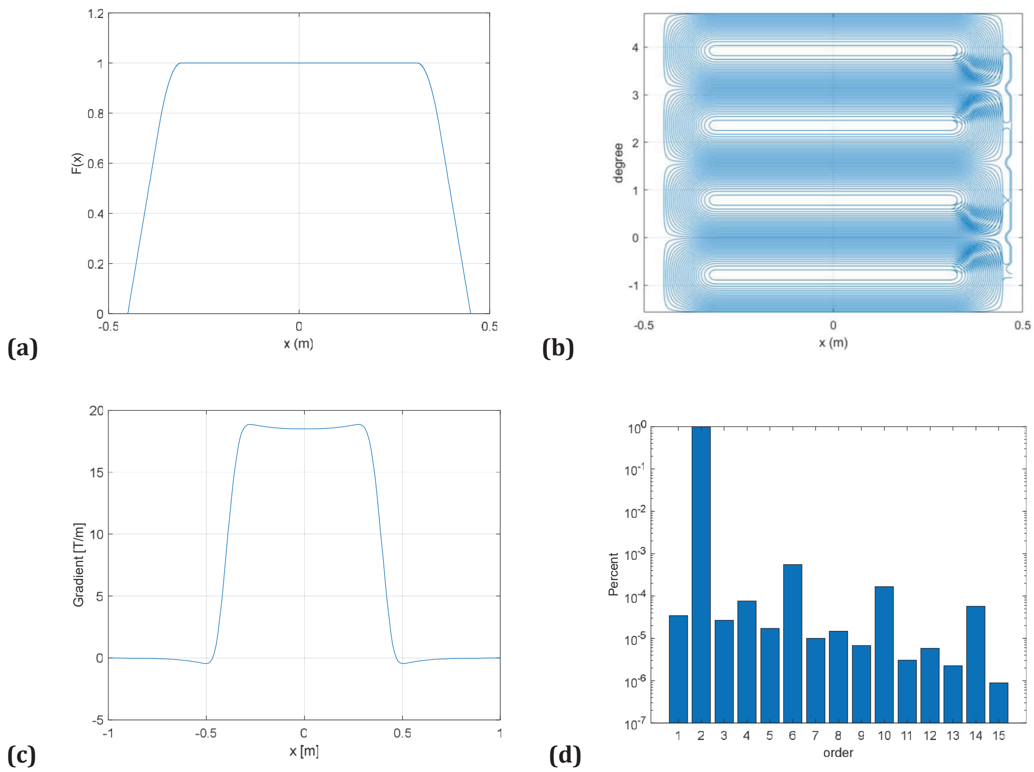

Figure 3. Coil design and field quality of QHB: (a) the shape function, (b) the planar layout of the wire path of the first-superlayer coil, (c) the axial distribution of the gradient strength, (d) the percentage content of each harmonic component.

Table 3. Design parameters and calculation results of the quadrupole coil.

Parameter	Value	Parameter	Value
Number of super-layers	4	Quad Gradient [T/m]	18.50
Number of turns	22, 23, 24, 25	Integrated Strength [T]	14.50
Min wire spacing in straights [mm]	4.4	Effective Length [mm]	783.9
Min wire spacing in arc [mm]	3.1	Non-Uniformity	0.09%
Total length [mm]	900	B_max [T]	2.8049
Length of cable [m]	1338.8	Energy [kJ]	144.3
Operating Current [A]	450	Inductance [H]	1.4252
Number of super-layers	4	Quad Gradient [T/m]	18.50

The sextupole and octupole coils use saddle-type, randomly wound racetrack coils, which are nested over the quadrupole coil from inside to outside. Calculation results show that the field non-uniformity of the sextupole and octupole coils remains below 1% .

Table 4. Design parameters and calculation results of the sextupole and octupole coils.

Parameter	Sext.	Oct.	Parameter	Sext.	Oct.
Operating Current [A]	36	36	Start angle [degree]	0.0797	0.0755
Diameter of wire [mm]	0.6	0.6	End angle [degree]	20.1077	14.9935
Inner Radius [m]	0.1798	0.1892	Coil angle [degree]	20.028	14.918
Outer Radius [m]	0.1874	0.1975	Max field on wire [T]	0.657	0.664
Number of Turns	969	819	Reference radius [m]	0.1	0.1
Racial Thickness [mm]	7.6	8.3	Field Gradient	11.16	55.89
Packing factor	0.562	0.554	Effective length [mm]	802.06	818.03
Total length [mm]	880	880	Non_uniformity	0.068%	0.073%

4. Magnet fabrication

A single superlayer prototype quadrupole coil has been fabricated in-house at FRIB. Grooves were machined into an aluminium cylinder to accommodate the coil wires. This cylinder was then sandblasted and anodized for electrical insulation. The coil wire, which itself is wrapped in a layer of fiberglass insulation, is then wound into the grooves to form the superconducting coils. The assembly was then wrapped with G10 bands to contain the coil wires within the grooves, fiberglass to provide a structure to reinforce the epoxy, and Kapton for electrical insulation. An aluminium shell is then added to form the outermost layer. Finally, a vacuum pressure epoxy impregnation process completes the magnet assembly. Cold testing of the single superlayer magnet prototype has been completed. The full scale four superlayer magnets have been fabricated by vendors. Currently, two long and six short magnet assemblies have been completed. The multipole coils for the long quadrupole magnet have also been fabricated.

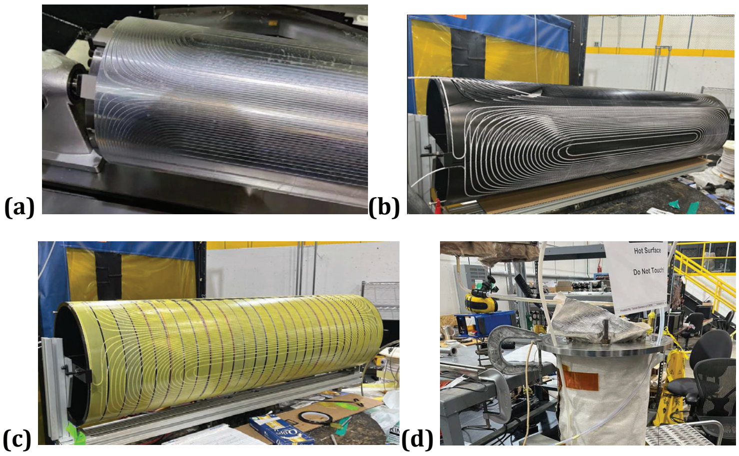

Figure 4. Quadrupole fabrication: (a) Bobbin grooving, (b) Coil winding, (c) G-10 pieces overbanding, (d) Vacuum Pressure Impregnation.

5. Quadrupole coil testing

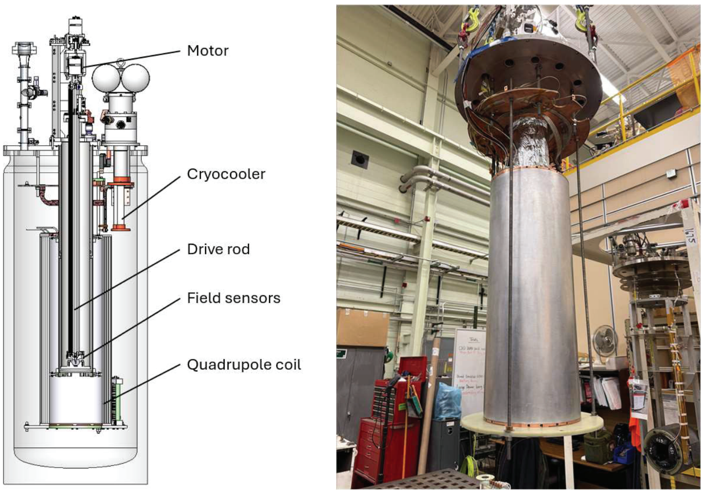

Figure 5. Quadrupole coil liquid helium test setup.

Figure 5 shows the test setup for the quadrupole coil. The quadrupole coil is placed in a liquid helium cryostat for testing.

The cryostat has a central warm bore that allows for measurement of the magnetic field distribution of the coil. Now one long and two short coils have successfully passed cold testing. The current was ramped up to ±480 A (the design current is 450 A) at a rate of 1.5 A/s, without any quench training. The magnetic field on the inner surface of the coil was measured, confirming that the field strength is consistent with the design results. As the next step, a mapper will be used to perform a detailed measurement of the coil's magnetic field distribution in order to verify the field quality.

6. Summary

A discrete cosine theta quadrupole triplet was designed for HRS project. The complete long quadrupole package (including the quadrupole, sextupole, and octupole) and the short quadrupole coils have now been fabricated. The quadrupole coils have successfully passed cold testing. The next step is to assemble the sextupole and octupole correctors with the quadrupole, followed by cold testing of the long quadrupole package assembly.

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