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STATUS OF COIL-DOMINATED DISCRETE-COSINE-THETA QUADRUPOLE PROTOTYPE FOR HIGH RIGIDITY ISOTOPE BEAMS *

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Abstract

Iron-dominated superconducting magnets are one of the most popular and most used design choices for superconducting magnetic quadrupoles for accelerator systems. While the iron yoke and pole tips are economic and effective in shaping the field, the large amount of iron also leads to certain drawbacks, namely, unwanted harmonics from the sextupole correctors nested inside of quadrupole iron pole tips. Additional problems include the nonlinear field profile present in the high-field regime engendered by the presence of steel, the cryogenic design challenges of the entire iron yoke being part of the cold mass, and the mechanical challenges of mounting the sextupole and octupole, which will generate significant forces for apertures of the size being proposed. The Facility for Rare Isotope Beams (FRIB) plans to implement a coil dominated quadrupole as a future upgrade, and the presented work discusses the advantages of using a iron-free quadrupole, along with the methods and choices of the design and the current status of prototype fabrication.

INTRODUCTION

The Facility for Rare Isotope Beams (FRIB) transports secondary isotope beams with high magnetic rigidity, up to 8 Tm. The intensity and beam emitance requires an aperture of 0.2m in the fragment separator and the focusing quads need large iron yokes in order to meet their operating requirements [1–3]. Having iron yokes this scale in the cold mass introduce cooldown times that can span weeks, difficulties with magnetic alignment due to transportation and thermal cycle, and transportation challenges due to their size and weight. An additional issue with the iron-dominated quadrupoles of the fragment separator come from an undesired interaction they have with their sextupole correctors, which generates an unwanted dipole component [4]. There are multiple triplets of this design type in FRIB's Advanced Rare Isotope Separator (ARIS) third stage. The quadrupoles used in these triplets are the Fragment Separator Quadrupole Type C (FSQC) and Type B (FSQB) [5]. Our group has proposed replacing these A1900 triplets with a coil-dominated quadrupole design with similar higher order multipole magnet package, a conceptual triplet design can be seen in an earlier report [4]. The use of a coil-dominated design would eliminate the sextupole induced dipole component, reduce cooling times, and reduce tuning time significantly due to linear behaviour of the magnet. This paper will consist of the prototype design, the prototype fabrication. The quadrupole design is inspired by similar discrete-cosine-theta designs done for GANIL's SPIRAL2 project [6].

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COIL-DOMINATED QUADRUPOLE DESIGN AND FIELD ANALYSIS

Due to the aperture to length ratio requirements of the quadrupole a discrete cosine theta or Walstorm style was adopted for the quadrupole design. This method allows one to generate a cosine theta multipole, but with coil end geometry that helps to minimize higher order harmonics. This can be done through the use of a "shape function", which is a parameterized step function which can generate the contours of the magnet turns [7, 8].

Geometry

The geometry of a discrete-cosine-theta coil set or Walstrom style coils allows one to dictate the winding path through he choice of a shape function, $f(z)$. Through the use of Eq. (1), where z is the axial coordinate, ϕ is the azimuthal angle, m is the multipole order, and N is the total turn number a series of discrete parametric contours can be created which are the fundamental geometry of the winding. Our chosen shape function and more detail is shown in an earlier report of the work [4]. Once the core geometry is created, then additional aspects are added to the winding geometry. These addition are aspects such as the turn-to-turn transitions and quadrant-to-quadrant transitions. These aspects can be seen in Fig. 1, where the coil geometry is plotted in 2D.

$$f(z)\sin(m\phi) = \frac{n-\frac{1}{2}}{N}, n = 1, 2, ..., N \qquad (1)$$

Field Analysis

The field requirements for the magnet will be achieved by stacking concentric layers of quadrupole windings. The field of the designed model was evaluated in MatLab, CST Studio®, and COMSOL with sufficient agreement. A plot of B_r of the coil-dominated magnet and the normalized integrated harmonics can be seen in Fig. 2. Every non-quadrupole component up to $n = 10$ contributed 0.1% of the entire field, which is well within the design criterion of 1% maximum non-uniformity.

While the coil-dominated design has a lower ratio of integrated strength per amp-turn, from the comparison shown in

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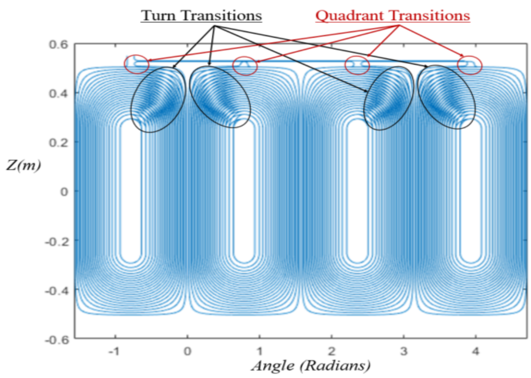


(a)

(b)

Figure 1: (a) 2D plot of coil geometry including turn-to-turn transitions marked in black and quadrant-to-quadrant transitions marked in red. (b) Turn transition area on sub-scaled flat prototype winding. [4]

Table 1: Operation Comparison

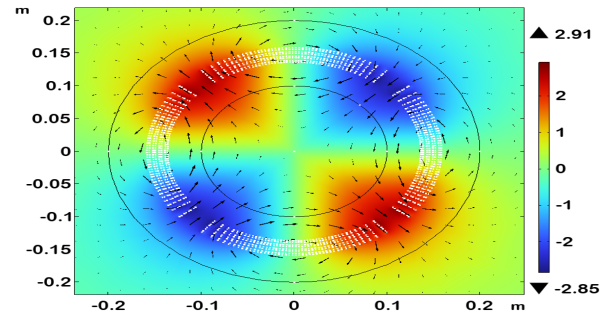
Parameter	FSQC	CD Type C
Operating Current	105 A	450 A
Turns per Coil	2150	176
Amp-Turn	225.75 kA	316.80 kA
Warm Bore Radius	0.1 m	0.1 m
Quad Gradient	18.3 T/m	18.3 T/m
Integrated Strength	14.1 T	14.7 T
Effective Length	0.79 m	0.8 m
Non-Uniformity	1.0 %	0.1 %
Max Field in Coil	3.8 T	2.9 T
Inductance	41 H	1.32 H
Stored Energy	213.3 kJ	134.3 kJ

Table 1, when considering the reduction in inductance and stored energy we consider this an acceptable trade.

FABRICATION

The quadrupole is wound from a four wire NbTi twisted cable. The cable is wound on a cylindrical 6061-T6 aluminum bobbin with machined pathways or grooves for the conductor. Each bobbin consists of four coil quadrants and allows for all the quadrants to be wound in a continuous winding, a picture of the bobbin can be seen in Fig. 3.

Each individual bobbin we call a super-layer. A super-layer consists of two layers of cable winding placed on a bobbin. The entire quadrupole package will consists of four concentric super-layers. We would like to impregnate and



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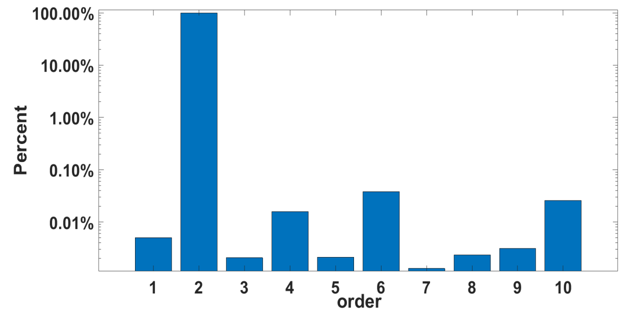
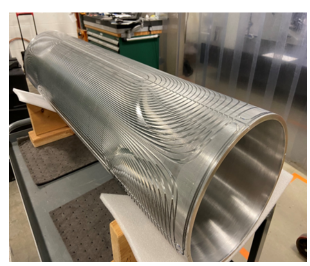
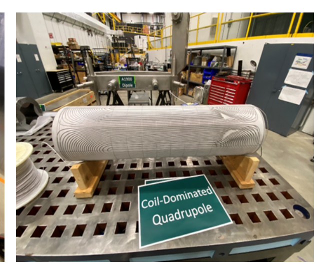


(b)

Figure 2: Field analysis results of coil-dominated electromagnetic (EM) model operating at 450 A. (a) Distribution of the radial component of the magnetic field in the cross section of the magnet. (b) Harmonic decomposition analysis of the coil-dominated model, integrated along beam direction then normalized. Analyzed at 80% warm bore aperture. [4]



(a)



(b)

Figure 3: a) Completed machining of first super-layer bobbin. (b) Bobbin after sand blasting process to treat sharp features.

cold test a single super-layer as a sub-scaled test to verify the performance and field quality aspects of the winding. The following sections will describe the fabrication work done to prepare for this single super-layer testing.

Winding

Initially the bobbin is practice wound in order to determine if there are any final problems that arise during winding due to issues with machining. After a satisfactory practice winding the surface of the bobbin is then electrically insulated through an electrodeposition of zinc phosphate, this process is known as E-coating. This E-coating is the black

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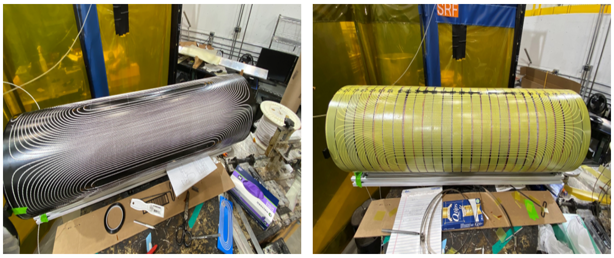


(a) (b)

Figure 4: a) One completely wound super-layer. (b) Over banding preparation of wound super-layer.

coating that can be seen in Fig. 4 that is not present in Fig. 3. After surface treatment is complete the bobbin is now wound with the intended cable. After winding the bobbin is then wrapped in G10 strips to ensure wire submersion into the groove to prevent any damage from later preparations for vacuum impregnation.

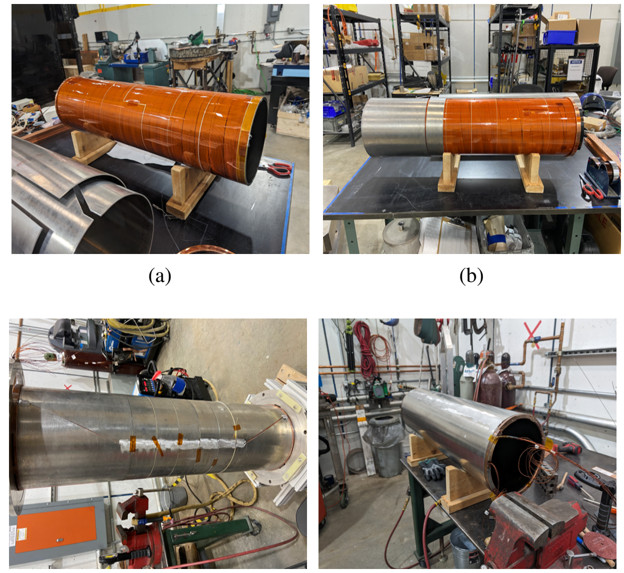
Vacuum Impregnation

Once winding tasks are complete the cable splice procedure is then done. After splicing is complete the bobbin is then wrapped in fiberglass cloth and kapton. The structure that will serve both as the radial force pre-load and vacuum vessel for impregnation is then test fitted. This structure consists of one layer of 1/4 inch thick aluminum bands followed by a second layer consisting of one 1/4 inch thick aluminum cylinder which spans the axial length of the coil. Each layer is fitted by cutting a portion out of the band and then fitting it to the bobbin with clamps. Once each band is clamped the gap is then welded shut such that each band provides radial force pre-load to the bobbin. This structure and the preparation can be seen in Fig. 5. Once both layers are welded shut the ends of the banding are then sealed through a Silicon calk to the end flanges of the magnet, such that a vacuum can be pulled on the coil space through the end flanges. After this the structure is prepared for epoxy flow.

The vacuum impregnation was done using CTD 101K epoxy. When all components were mixed according to their instructions, the epoxy was filled into the inlet tank and degassed at 60°C. The epoxy was then flowed through our tubing into 3 inlet ports on the bottom of the coil. The epoxy then flowed through the coil space up to an outlet port connected to the outlet tank. Once a sufficient amount of epoxy was pushed through the form it is then held at 80°C for 24 hours and then finally held at 135°C for an hour to finish the curing process. This process can be seen in progress in Fig. 6.

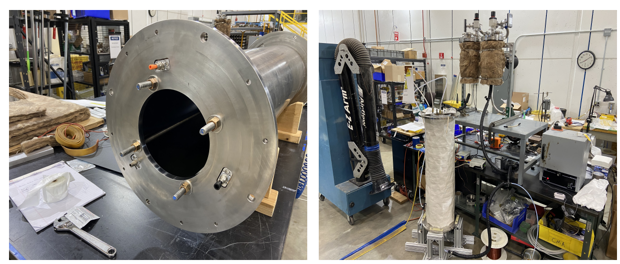
CONCLUSION

Here, is presented a coil-dominated quad design which performs to the same field specifications as FSQC. Coil-dominated would drastically lower the weight of a triplet, reduce cool down time, and reduce the LHe inventory. The proposed coil-dominated design would theoretically require



(a) (b) (c) (d)

Figure 5: a) Coil after being wrapped in fiberglass and kapton. (b) Test Fitting of bands for impregnation form. c) Completed welding of first layer bands. d) Completed welding of second layer shell.



(a) (b)

Figure 6: a) Bottom of the coil with the 3 inlet ports shown. b) Picture of impregnation in progress with supply and return tanks at the top and flow lines connected for filling the coil space.

fewer training quenches than FSQC. It eliminates unwanted dipole component from sextupole interaction with quad steel. Finally linear behaviour allows significant reduction in tuning time. The future work left for demonstrating the performance of this prototype is the cold testing and mapping of the quadrupole, which will take place in the coming months.

ACKNOWLEDGEMENTS

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