Advanced Design for the WIQ Magnet with Steering Corrector Function

Xiaoji Du, Yoonhyuck Choi, Mauricio Portillo, David Greene, John Wenstrom, Hai Nguyen, Danlu Zhang, Christopher Jones, Bradley M. Sherrill, and Ting Xu

***Abstract*—The Facility for Rare Isotopes Beams (FRIB) delivers heavy-ion primary beams at energies of up to 300 MeV/u at 10 kW of beam power to generate rare isotope beams for experiments and will eventually operate at beam power of 400 kW. The preseprator of the Advanced Rare Isotope Separator (ARIS) is equipped with six warm-iron quadrupole (WIQ) singlets and two dipoles integrated right after the production target. They have a compact structure and operate in a high radiation vacuum environment within a hot cell having remote handling capabilities for installation and maintenance. Due to asymmetry with respect to the quadrupole poles, nested sextupole excitations in WIQs induce vertical dipoles that offset the centroid trajectory; Magnet misalignments also result in trajectory offsets. Such offsets degrade separator performance but can be minimized by changing the current distribution on sextupole and octupole coils. In this work, we show how modifications to the WIQ coil design can allow superimposed dipole fields to be included to the octupole and sextupole windings, as well as addition of dipole components by splitting coil currents over groups with separator power supplies. Adjusting the group currents can cancel the sextupole-induced vertical dipole component which can be as high as 0.012 Tm. Octupole coil changes may superimpose a horizontal dipole integrated strength as high as 0.0332 Tm. Unwanted higher harmonics induced as a side effect of the new design are kept to a minimum such that separator performance is preserved as much as possible.**

***Index Terms*—Accelerator magnets, Magnet design and analysis techniques, Magnetic field quality.**

I. INTRODUCTION

THE Facility for Rare Isotope Beams (FRIB) delivers heavy-ion primary beams at energies of up to 300 MeV/u for lightest ions [1]. Recent operations sustain up to 10 kW of beam power on-target to generate rare isotope beams for experiments. In July 2024, a Se-82 beam was accelerated to 228 MeV/u at an average power of 21.9 kW [2]. The preseparator front-end of the Advanced Rare Isotope Separator (ARIS) is equipped with six warm-iron quadrupole (WIQ) singlets and two dipoles integrated right after the production target. They have a compact structure and operate in a high radiation vacuum environment within a hot cell having remote handling capabilities for installation and maintenance [3-6].

The asymmetry of the sextupole coil and four iron poles creates a dipole magnetic field that offset the centroid trajectory; Magnet misalignments also result in trajectory offsets. These offsets degrade separator performance, so to meet the power-up requirements it is necessary to minimize them by adding steering correctors. The maximum integral strength of the vertical and horizontal dipole fields that need to be eliminated is 0.016 Tm. However, due to space limitations, we can only make design improvements to the existing WIQ magnets.

In this work, MATLAB was used to analyze the harmonic components of the magnetic field of the magnet. An additional power supply was introduced for the sextupole coil to adjust the current ratio between the six coils. This effectively eliminated the unwanted vertical dipole field and improved beam precision. Adjusting the group currents can cancel the sextupole-induced vertical dipole component which can be as high as 0.012 Tm per magnet. By altering the polarity of individual coils within the original octupole coil arrangement, a horizontal dipole field is generated. It may superimpose a integrated strength as high as 0.0332 Tm.

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II. HARMONIC ANALYSIS OF MAGNET

There are six warm-iron quadrupoles (WIQ) singlets located in the preseparator of ARIS within the target hall. All but the first quadrupole after target have nested multipole coils (sextupole and octupole). The multipole coils correct aberrations of large phase space secondary beams.

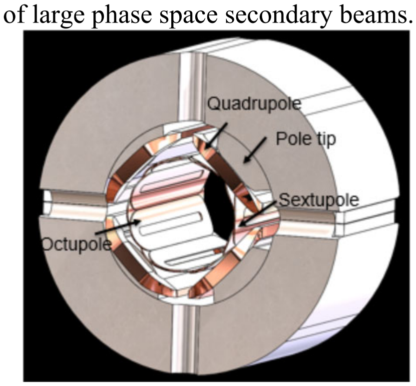

Fig. 1. Structure and layout of the WIQ magnet.

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Xiaoji Du, Yoonhyuck Choi, Mauricio Portillo, David Greene, John Wenstrom, Hai Nguyen, Danlu Zhang, Christopher Jones, Bradley M. Sherrill , and Ting Xu are with the Facility for Rare Isotope Beams, Michigan State University, East Lansing, MI 48824 USA (e-mail: du@frib.msu.edu).

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Figure 1 shows the overall structure and details of the magnets having the largest beam aperture. The sextupole coils in this type magnet are oriented for a vertically bending section. Table 1 shows the parameters of the existing magnet.

TABLE I
PARAMETERS OF THE EXISTING MAGNET

Parameters	Quadrupole	Sextupole	Octupole
Operating Current [A]	361	51	16.5
Aperture radius [m]	0.2	0.2	0.2
Reference radius [m]	0.16	0.16	0.16
Effective length [m]	0.77	0.676	0.7
Field gradient	9.123 T/m	6.437 T/m^2	13.65 T/m^3
Integrated field strength	7.028 T	4.354 T/m	9.544 T/m^2

A. Dipole field induced from sextupole

Due to the asymmetry of the sextupole coil distribution relative to the quadrupole pole tips, a significant dipole component will be generated when the sextupole coils are energized. Field analysis was carried out at 1 mm steps within a range of ± 0.5 meters from the magnet center along the beam axis. Harmonic decompositions are carried out on the radial field component about a circle at reference radius r_0=0.16 meters (i.e. 80% of aperture) at 1° steps.

A harmonic decomposition using the discrete Fourier transforms (DFT) method. The formalism used here is given by the following equations:

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

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

$$\varphi_k = \frac{2\pi k}{N}, \quad k = 0, 1, 2, \cdots, N-1. \quad (3)$$

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 [7, 8].

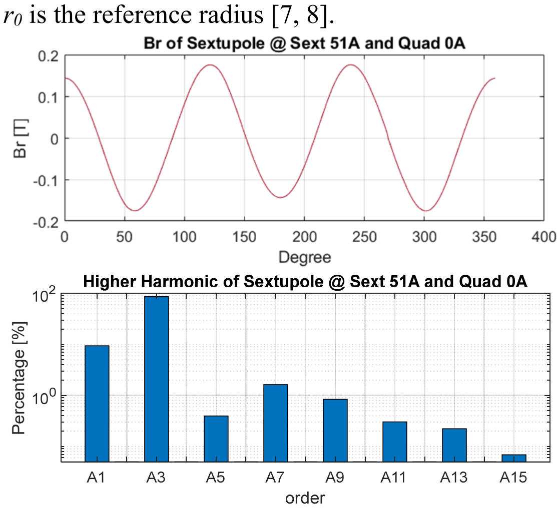

Fig. 2. Radial magnetic field and higher-order harmonics of sextupole with quadrupole pole tips and quadrupole off.

Figure 2 shows plot of Br vs angle at the reference radius at magnet center when only the sextupole coils are energized. Below it are the resulting magnitudes from the harmonic analysis. Bn and the even terms of An are very small, so only the odd terms of An are shown here, with the highest order being A15.

As can be seen from Figure 2, the sextupole coil induces a vertical bending dipole component under the influence of the quadrupole pole tips, accounting for approximately 9.43% of the total Br(r_0).

The sextupole induced harmonics vary with the quadrupole coil excitation as the yoke material saturates. Figure 3 shows the integrated strength and proportion of harmonic components for A1, A5, A7, and A9.

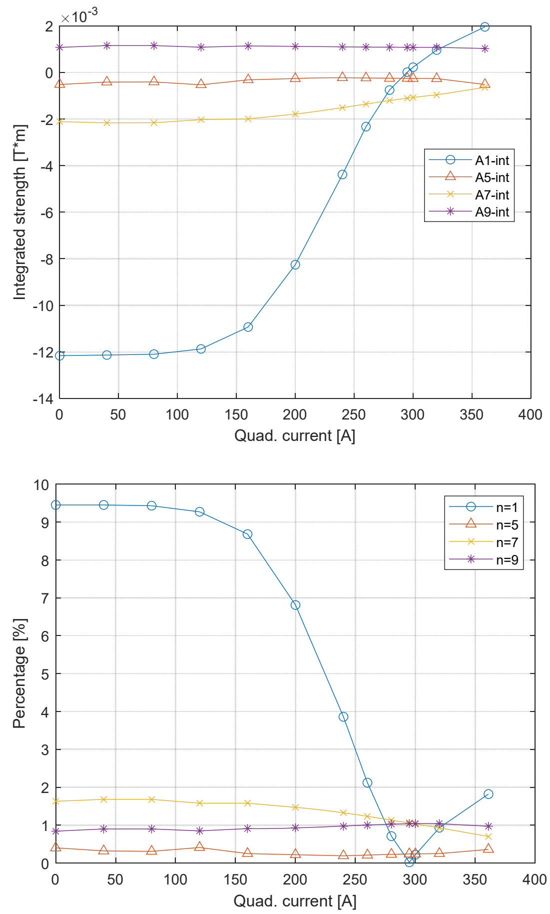

Fig. 3. Integrated strength (left) and relative percentage (right) of multipole field.

The vertical dipole component n=1 will offset the centroid trajectory and needs to be minimized.

B. Dipole field induced from quadrupole misalignment

The effective dipole component on the reference trajectory varies with horizontal and vertical offset from the origin. For a normal quadrupole (A_2 = 0) the field can be expressed as

$$B_x(x,y) = gy\,, \quad B_y(x,y) = gx\,, \quad (4)$$

where g is the quadrupole gradient expressed in T/m [8]. When there is an x_d misalignment in the x-direction of the magnet, the field can be calculated in a displaced coordinate system where $x' = x - x_d$, resulting in

$$B_y(x', y') = gx' + gx_d \;, \tag{5}$$

This constant term gx_d corresponds to a dipole field induced by the displacement of the quadrupole magnet. Similarly, a displacement of the quadrupole coils in the y-direction will induce a constant term $B_x$with a magnitude of gy_d.

III. Method

Due to the compact structure of the Target Hall, there is no space to add additional correctors for the dipole field. Moreover, to save manufacturing time and cost, two novel approaches are proposed in this work. Without altering the original mechanical structure of the magnet, the coil currents in the sextupole and octupole coils are altered in order to adjust or eliminate the unwanted vertical dipole and introduce a horizontal dipole field, respectively.

A. Eliminating vertical dipole field

Figure 4 shows the layout of the sextupole coils. These six coils can be divided into two groups, with each group being supplied with different current. The group with current I_1 includes coils S1, S3, S4 and S6, while the other group with current I_2 includes S2 and S5. Adjusting the group currents (I_1 and I_2) can cancel the sextupole-induced dipole component.

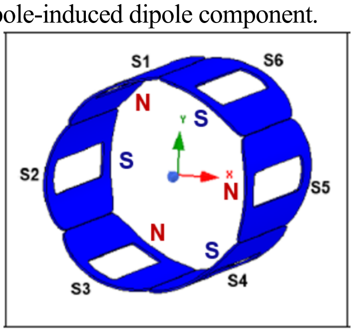

Fig. 4. Layout of the sextupole coil.

Figure 5 shows a feasible power supply circuit. PS1 is the main power supply. Once the current of PS1 is set, adjusting the current of PS2 allows the current ratio between the two groups of coils to vary.

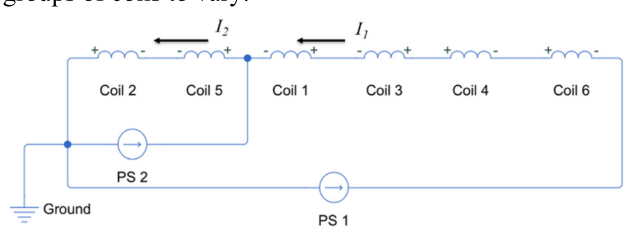

Fig. 5. Power supply circuit for sextupole coil.

For the case in Figure 2, when there is no current in the quadrupole coil, different ratios of I_1/I_2 can be obtained by adjusting the current values of PS1 and PS2, and higher-order harmonic analysis of the magnetic field is performed for each ratio. As seen in Figure 6, when the I_1/I_2 ratio is approximately 0.744, the dipole field component becomes zero.

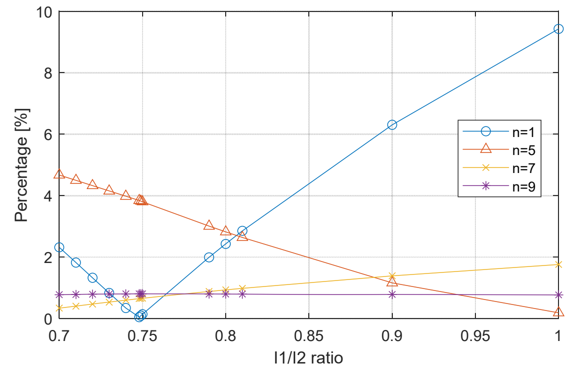

Fig. 6. Plot showing dipole (Order 1) being minimized by adjusting the I_1/I_2 ratio.

Using the same method, the appropriate I_1/I_2 ratio can be determined for varying currents in the quadrupole coil to eliminate the unwanted vertical dipole component. Figure 7 shows the optimized ratio of I_1/I_2 to eliminate the dipole field component at different quadrupole currents. Offseting the ratio can be used for vertical corrections due to beam and magnet misalignments.

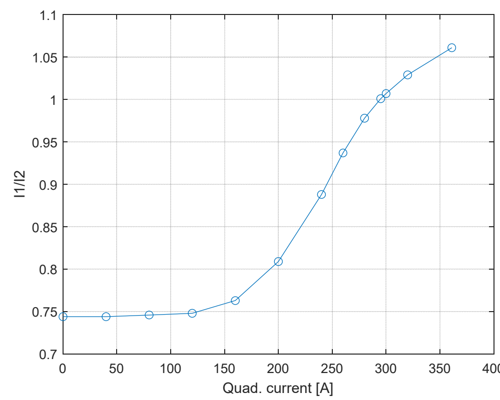

Fig. 7. Optimized ratio of I_1/I_2 to eliminate the dipole field component at varying quadrupole current.

B. Eliminating horizontal dipole field

One or two of the six WIQ magnets can be selected to generate a horizontal dipole field by reversing the polarity of the eight octupole coils in the magnets. Figure 8 shows the reconfiguration of the octupole coils, where coils O1, O2, O3, and O4 are configured as S poles, and O5, O6, O7, and O8 as N poles.

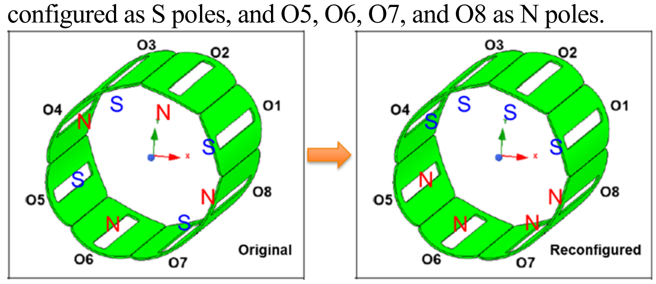

Fig. 8. Reconfigured octupole coils groups to generate a horizontal dipole field.

After connecting them in series and applying the same current, the resulting higher-order harmonic components of the magnetic field on a circle with a reference radius of 0.16m are shown in Figure 9 (a). In addition to the n=1 dipole field component, there are also significant n=3 and n=5 field components. By keeping the number of turns n in coils O2, O3, O6, and O7 unchanged and adjusting the number of turns n' in coils O1, O4, O5, and O8, a higher-quality horizontal dipole field can be achieved. Figure 9(b) shows the proportion of each field component when n'/n is 0.4. This may superimpose a horizontal dipole integrated strength as high as 0.0332 Tm.

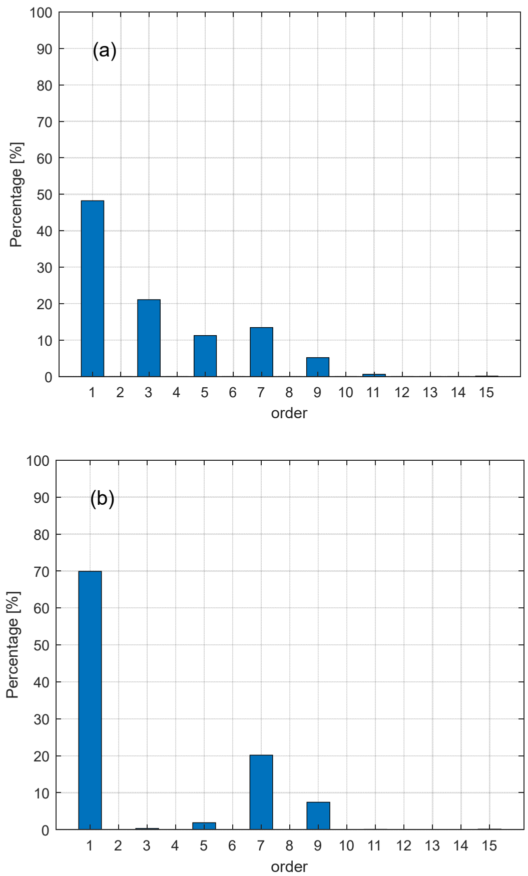

Fig. 9. Harmonic analysis results of reconfigured octupole excitations before (a) and after (b) adjusting turns in coils as explained in the text.

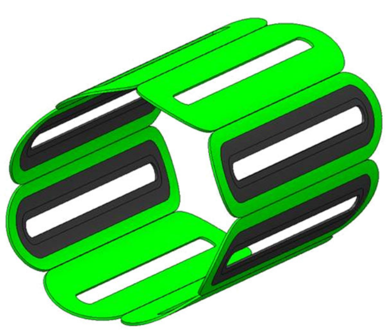

Fig. 10. Coil winding with dead wire.

When winding coils O1, O4, O5, and O8, the original coil winding former can still be used. A portion of dead wire can be wound first before winding the superconducting wire, or the superconducting wire can be co-wound with appropriately sized insulated wire. This results in the same geometric dimensions as the original coil. Figure 10 shows the coils with dead wire. The magnet structure and assembly tooling will remain the same as the existing WIQ magnet.

V. Conclusion

The design of existing Warm-iron Quadrupole (WIQ) magnets in the FRIB accelerator system was enhanced. An additional power supply was introduced for the sextupole coil to change the current configuration in the sextupole coils, which effectively eliminates an unwanted vertical dipole component. The current ratio was scaled based on the simulation results to account for quadrupole excitation effects. Operating currents of octupole coils were reconfigured to add horizontal dipole excitation needed for steering corrections. The number of turns of the octuplet coils are optimized to get higher-quality dipole field. Unwanted higher harmonics induced as a side effect of the new design are kept to a minimum such that separator performance is preserved as much as possible. The changes to the coil excitations should improve the quality of beam transport in the separator system.

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