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SELF-CORRECTION COIL FOR RCS DIPOLE IN ELECTRON ION COLLIDER*

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Abstract

The Rapid Cyclotron Synchrotron (RCS) is an acceleration ring designed for boosting the electron energy from 400 MeV after the LINAC to 1 GeV prepared for injection into the Electron Storage Ring (ESR). Operating in a pulsed mode at 1 Hz, the RCS accelerates four consecutive bunches with dipole magnet ramping rapidly at each injection. Rapid ramping of the magnetic field induces eddy currents, causing delays and high harmonic effects which are detrimental to low-energy electron bunches. To mitigate this, cost-effective multi-turn coils with specific patterns are proposed. These coils, powered by eddy currents from main dipole field ramping, generate counter fields to cancel selected high harmonic components. This paper explores the coil pattern selection process.

INTRODUCTION

The Electron Ion Collider (EIC) stands as a pioneering collider, offering a unique experimental platform for nuclear physics research through high luminosity collisions of polarized electrons and ions. The polarized electron bunches, generated from a DC gun, are accelerated to 400 MeV in the LINAC before being injected into the RCS. Within the RCS, designed to accommodate one batch of four 7 nC bunch trains, these electron bunches merge into one 28 nC bunch and are accelerated to beam energies of up to 18 GeV. The RCS is in the Relativistic Heavy Ion Collider (RHIC) tunnel, same as the electron and hadron storage rings, as shown in Fig. 1.

The beam acceleration process, critical for reaching collision energies required by the electron storage ring (ESR), is achieved within a tight timeframe of 100 ms while preserving the spin polarization from the source. The current lattice design uses a spin resonance free lattice, and the layout fits in the existing RHIC tunnel with 1152 dipoles for bending of the electrons. The dipole field must follow the beam energy from the injection energy to a merging energy and ramp up again after the merge to the top collision energy. The ramping cycle is at a frequency of 1 Hz, with a fast rise from 0.0223 T to 0.247 T in 0.09 s, which corresponds to a ramping rate of 2.5T/s. The eddy current generated on the beam pipe introduces magnetic field to the beam region. The strength of the eddy current magnetic field that correlates to the beam pipe geometry and material may cause beam loss due to the higher order components.

To mitigate these effects, a cost-effective solution involving self-correction coils is proposed, enabling real-time adjustments to counteract higher order components of the eddy current magnetic field. Through detailed analysis and discussion, this paper provides a solution of the eddy current magnet field corrections essential for the successful operation of the EIC RCS.

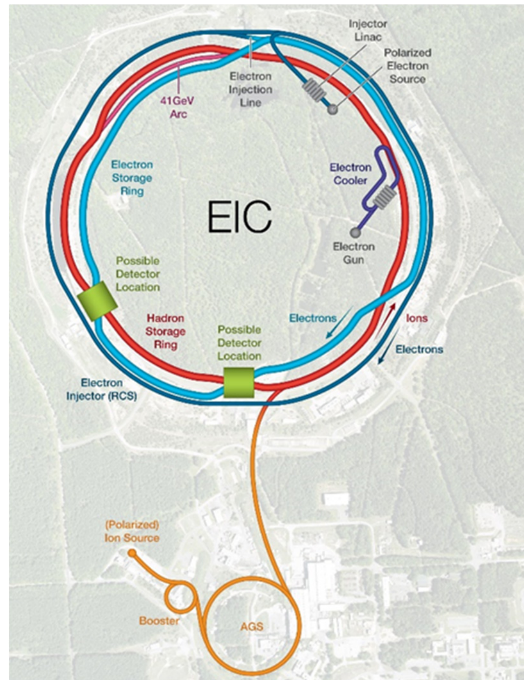

Figure 1: EIC design complex.

HIGHER ORDER MULTIPOLES

In RSC dipoles, the beam pipe is constructed from copper to mitigate the resistive wall heating and high impedance, factors that drive the transient mode coupled instability. However, the high conductivity of copper leads to high magnetic field induced by eddy currents.

When considering only the eddy current effect, the induced magnetic field is pure dipole which serves reducing the main dipole magnet field. Adding the yoke boundary condition as infinite permeability material, the mirror images of the eddy current, thereby introducing higher order harmonics.

Given that the bending of these dipoles occurs in the horizontal direction, the winding design incorporates mirror image in the vertical direction and inverse mirror image in horizontal direction. As a result, all even order harmonics are effectively cancelled, as well as all skew components. Thus, we only need to find a way to cancel the odd normal harmonics.

The magnetic field in the transverse (x, y) plane experienced by the electron beam in the RCS can be expressed as:

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$$B_x(x,y) = |B|\begin{bmatrix} -a_1 + \frac{b_2}{r_0}y - \frac{a_2}{r}x - \frac{a_3}{r^2}(x^2-y^2) + \\ \frac{b_3}{r^2}2xy - \frac{a_4}{r^3}(x^3-3xy^2) + \\ \frac{b_4}{r^3}(3x^2y-y^3) - \cdots \end{bmatrix}$$
$$B_y(x,y) = |B|\begin{bmatrix} b_1 + \frac{a_2}{r}y + \frac{b_2}{r}y + \frac{a_3}{r^2}2xy + \\ \frac{b_3}{r^2}(x^2-y^2) + \frac{a_4}{r^3}(3x^2y-y^3) + \\ \frac{b_4}{r^3}(x^3-3xy^2) + \cdots \end{bmatrix} \quad (1)$$

where $|B|$ is the magnitude of the magnetic field at the location of interest, r is the radius of evaluation location, and a_n, b_n are the coefficients of the nth order component.

The eddy current generated on the outer surface of the beam pipe is

$$I_{eddy} = \frac{d\Phi}{R_0 dt} = 2r_0 L\cos\varphi\frac{dB}{R_0 dt}$$

where r_0 is the outer radius of the beam pipe, L is the length of the magnet, and R_0 is the resistance of the thin loop circulated along the surface of the copper beam pipe with an azimuthal angle of φ.

This eddy current will induce the following magnetic field with respect to the longitudinal position in the magnet [1]:

$$B(z) = \frac{\mu_0 hB' r_0^2}{4g\rho}\left[\frac{\pi^2 r_0}{2g}\left(\tanh^2\left(\frac{\pi z}{2g}\right) + \coth^2\left(\frac{\pi z}{2g}\right) - 2\right) - \left(\frac{2g}{r_0} + \frac{2gr_0}{z^2}\right)\right]$$

Ignore the end effect, the dipole field in the transverse y direction can be expressed into multipole components using Taylor expansion

$$B_y(x, y=0) = \frac{\mu_0 hB' r_0^2}{4g\rho}\left(\frac{2g}{r_0} + \frac{2\pi^2 r_0}{3g} - \frac{2\pi^4 r_0 x^2}{15g^3} + \frac{4\pi^6 r_0 x^4}{189g^5} - \frac{2\pi^8 r_0 x^6}{675g^7} + \frac{4\pi^{10} r_0 x^8}{10395g^9} - \cdots\right) \quad (2)$$

Where μ_0 is the permeability of air, h thickness of the beam pipe, B' is the ramping rate of the main magnet, g is the gap between the poles, and ρ is the resistivity of the copper.

Comparing Equation (1) and (2), the components b_n of each harmonic can be expressed by measurable parameters as shown in the corresponding term in Equation (2).

A 2D simulation of the dipole magnet, including the yoke and outer frame, as shown in Fig. 2, provides a more precise characterization of the magnetic field. The strengths of the higher order multipoles are compared with the theoretical calculations derived from Equation (2) in Table 1. The discrepancy of the multipoles between the simulation and the theoretical calculation is less than 6%. This validates the theoretical method of calculating the multipole components b_n, which is subsequently used in the optimization of the eddy current magnetic field cancellation simulation.

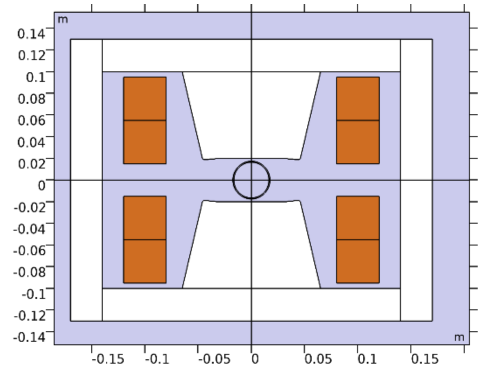

Figure 2: Cross section view of the RCS dipole magnet.

Table 1: Multipole Comparison Betwen 2D Simulation and Theoretical Calculation in Units of 10^{-4}

	2D simulation	**Equation (2)**
b_3	120.00	121.73
b_5	-25.35	-26.82
b_7	4.95	5.21

SELF-CORRECTION COIL

In the Booster ring of the Alternating Gradient Synchrotron (AGS) at Brookhaven National Laboratory, beam loss resulting from eddy currents on the Inconel beam pipe during the ramping process has been a notable issue. To address this, passive coils were wound onto the beam pipe to counteract the eddy current sextupole field with minimal effort [2], as shown in Fig. 3.

Each AGS Booster dipole is equipped with a pick-up coil, which is connected in series with a set of thin self-correction coils traversing longitudinally through the entire magnet. The change in the main dipole field dB/dt induces current in the pick-up coil, subsequently powering the correction coils. Through precisely designed winding, these Booster self-correction coils effectively counteract the sextupole component induced by beam pipe eddy currents, thereby minimizing beam loss to an acceptable level. Since these correction coils wound directly onto the beam pipe, these coils inherently address imperfections in the beam pipe's transverse profile.

Similar method can be used for the RCS dipoles to correct for the eddy current induced magnetic field. The beam pipe of RCS is constructed with copper tubes, which has a resistivity of 1% of the AGS Booster Inconel beam pipe, and there are over 1152 dipole magnets in the RCS lattice design.

To efficiently cancel the eddy current, a coil design optimizer code has been developed using Julia [3], and 6 independent coils were looped on the top half of the beam pipe with a mirror image set of coils on the bottom half. The optimizer was set with conditions to cancel eddy

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current harmonics from b_3 to b_7. The higher harmonics induced by these coils were calculated from both Equation (2) and a 2D simulation to compare with the eddy current induced field.

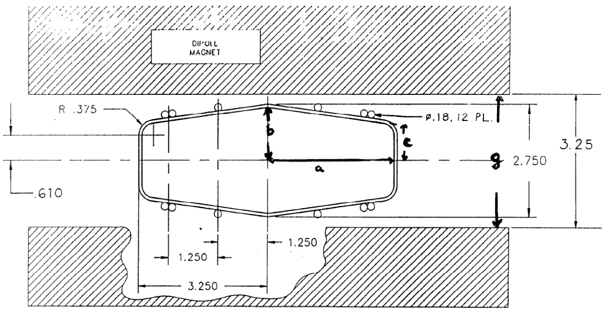

Figure 3: AGS Booster beam pipe self-correction coil design [4].

The self-correction system with 6 coils as shown in Fig. 4 is optimized with parameters listed in Table 2. The location of each coil is described by the cable azimuthal angle in the first quadrant in the cross section of the magnet beam pipe, and all coils distributed symmetrically around the pipe.

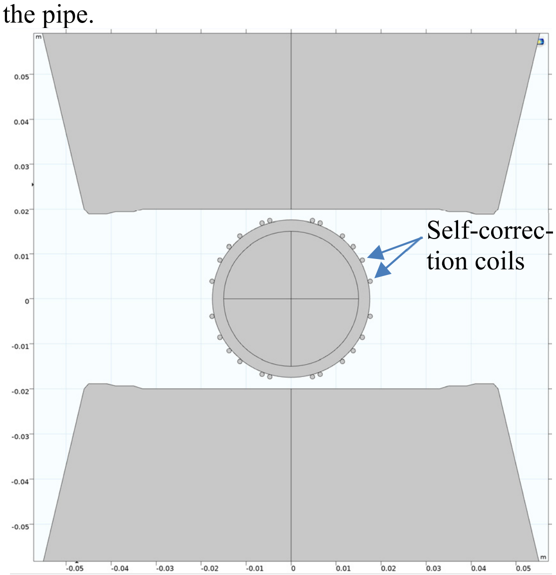

Figure 4: RCS beam pipe cross-section view with self-correction coil design, 6-coil version

Table 2: Self Correction Coil Location

	Azimuthal angle [deg]	**Current [A]**
Coil 1	12.5	-1.74
Coil 2	28.4	-0.41
Coil 3	40.0	1.03
Coil 4	50.7	2.01
Coil 5	69.0	1.06
Coil 6	74.7	1.66

The currents in each coil are independently defined. This can be changed by adding a constraint of connecting the coils in series to share the same current flow. However, this will lead to a reduction in the cancelling effect or require adding more coils to the system.

Table 3: Harmonic Cancellation from Optimized Self-correction Coils for RCS

Harmonic component	**Eddy Current Induced**	**Line current induced**	**2D simulation with 1 mm diameter coil**
b_1	1134.53	-49.94	-44.68
b_3	26.82	-26.82	-25.33
b_5	-121.52	121.75	115.12
b_7	-5.20	5.20	5.25
b_9	0.94	-15.03	-11.89
b_{11}	-0.16	-2.11	-1.4
b_{13}	0.03	4.22	2.86
b_{15}	0	-12.49	-7.92

The current optimization method for 6 coils can reach a good cancellation effect to the eddy current induced magnetic field components b3, b5, and b7 at the same time, as shown in Table 3. However, the low number of compensating coils will increase the higher order terms (n>7).

At the meantime, the eddy current induced dipole field will reduce the main magnetic dipole field by nature. This will introduce a delay in the ramping of the magnet. The self-correction coil induced dipole can only regain 4% of the field reduction.

The optimization considered the coils are line currents, which will induce error in the results by ~5%. The winding can be adjusted with real time measurements to compensate for these errors.

SUMMARY

The self-correction coil system adopted from the AGS Booster dipole magnets can be used to cancel the eddy current magnetic field harmonics. With simple winding and good control of the coil location and current, full cancellation can be achieved up to the 7th order multipole. However, the higher order components might be enhanced at the same time. Transient beam tracking simulations should be provided to set threshold for these components for beam stability.

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