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PROGRESS ON THE NORMAL CONDUCTING MAGNETS FOR THE ELECTRON-ION COLLIDER*

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Abstract

The Electron-Ion Collider (EIC) at Brookhaven National Laboratory is designed to deliver a peak luminosity of $1\text{x}10^{34}$ cm^{-2} secs^{-1}. The EIC will take advantage of the existing Relativistic Heavy Ion Collider facility. Two additional rings will be installed: an electron storage ring and a rapid cycling synchrotron. This paper presents an update on the normal conducting magnet designs required for the electron storage ring and rapid cycling synchrotron.

OVERVIEW

The electron storage ring (ESR) will store polarized electron beams up to 18 GeV and utilize dipole superbend magnets to increase the emittance at 5 GeV and generate excess bending to create additional radiation damping to allow a larger beam-beam tune shift. The rapid cycling synchrotron (RCS) will accelerate single bunches of spin-polarized electrons to various energies from 5 GeV to 18 GeV, with a ramp rate of 100 ms and 1 Hz repetition rate. Both new rings require normal conducting dipole, quadrupole, sextupole magnets and correctors with different specifications.

ESR MAGNETS

ESR Dipole Superbend Magnets

The ESR dipole superbend consists of two identical, long, low-field magnets, designated as D1 and D3, and a short, high-field magnet, located between D1 and D3, designated as D2. Magnet parameters for the D1/D3 magnet and the D2 magnet are shown in Table 1.

Table 1: ESR Dipole Superbend Specifications

Parameter	**D1/D3**	**D2**
Yoke length [m]	2.7	0.89
Dipole field, min. [T]	0.07	-0.5
Dipole field, max. [T]	0.25	0.4
Required field quality	$1\text{x}10^{-4}$	$1\text{x}10^{-4}$
Gap height [m]	0.052	0.052
No. of coil turns	5	12
Current density [A/mm^2]	2.31	3.67
Cooling type	Water	Water

The ESR D1/D3 has a mature mechanical design, shown in Figure 1, with completed analyses for:

- 2D harmonics via COMSOL, including tolerance analysis study with varying error profiles on the pole profile within 50 microns.
- 3D harmonics via OPERA, see Figure 2.

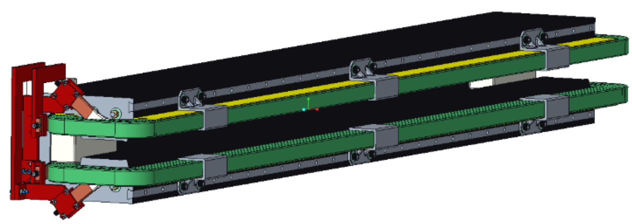

Figure 1: ESR D1/D3 mechanical model.

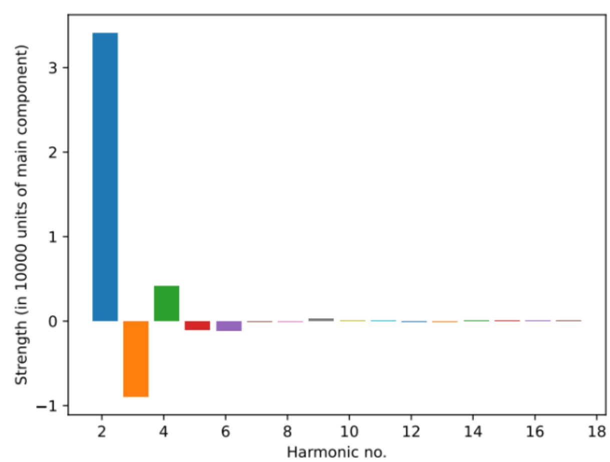

Figure 2: ESR D1/D3 harmonic analysis at reference radius R0.017m via OPERA 3D, n=1 being the dipole.

The ESR D2 has an advanced mechanical design concept, shown in Figure 3. An in-depth analysis of the pole profile for the D2 was performed leading to a proposed optimized design in terms of manufacturing, while still maintaining the physics requirements. There is an on-going effort to support powering all ESR dipoles in series by using split-winding coils with additional trim coils on their own power supply. The split-winding design will allow a different number of coils to be powered for different instances of the magnets, as well as for the different energies since the dipole strengths do not all scale together with energy due to the superbend configuration.

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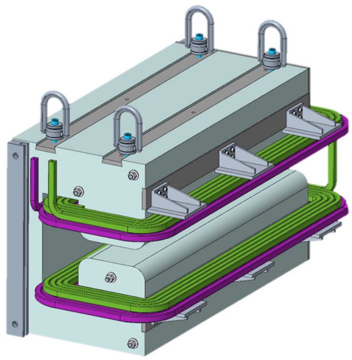

Figure 3: ESR D2 mechanical model.

ESR Quadrupole and Sextupole Magnets

Brookhaven National Laboratory has received quadrupole and sextupole magnets from Argonne National Laboratory's (ANL) recently decommissioned Advanced Proton Source (APS) to be used in the ESR [1]. Multipoles for the APS quadrupole magnets were measured and are being used in ESR dynamic aperture studies. Modifications to several of the quadrupole magnets are needed due to the space constraints within the existing Relativistic Heavy Ion Collider tunnel. At the time of writing, there has not been an identified need to modify the APS sextupole magnets. The main magnet parameters for the APS quadrupole and sextupole magnets are shown in Table 2 and Table 3, respectively.

Table 2: APS Quadrupole Specifications

Parameter	**Value**
Effective length [m]	0.6
Strength at 7.0 GeV [T/m]	18.9
Pole tip radius [m]	0.04
No. of coil turns	32
Current density [A/mm^2]	2.6
Cooling type	Water

Table 3: APS Sextupole Specifications

Parameter	**Value**
Effective length [m]	0.241
Max. gradient [T/m^2]	405
Field at R0.015m [T]	0.046
Pole tip radius [m]	0.049
No. of coil turns	42
Current density [A/mm^2]	3.1
Cooling type	Water

RCS MAGNETS

The RCS will be ramped, with the RCS magnets following a 1 Hz cycle as shown in Figure 4. The magnets will be powered at low current for 320 ms for beam injection, then ramped to peak current in 90 ms. The magnets will be powered at a constant peak current for 10 ms for beam transfer before ramping down in 90 ms to zero current. Only peak current is shown in the RCS magnet specification tables in this paper.

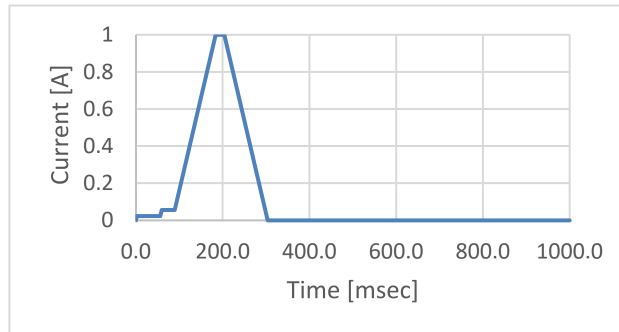

Figure 4: Normalized RCS ramp cycle.

Dipole Magnets

The RCS dipole is being designed by Thomas Jefferson National Accelerator Facility (TJNAF) and Fermi National Accelerator Laboratory (FNAL). The RCS dipole pole profile was optimized to obtain the best field homogeneity in the gap by varying the pole width, pole shim height and the corners of the pole. The FNAL RCS dipole concept is shown in Figure 5.

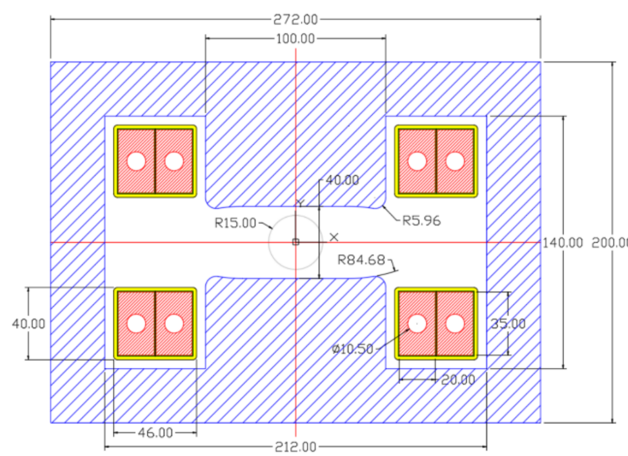

Figure 5: RCS dipole concept 2D design.

Design efforts on the RCS dipole continue, with focus on the effects of eddy current induced by the beampipe as well as magnetic field reproducibility due to the low field at injection. The main magnet parameters for the RCS dipole are shown in Table 4.

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Table 4: RCS Dipole Specifications

Parameter	Value
Effective length [m]	1.923
Dipole field, min [T]	0.005
Dipole field, max [T]	0.256
Required field quality	1×10^{-3}
Gap height [m]	0.040
No. of coil turns	2
Peak Current density [A/mm^2]	5.42
Cooling type	Water

RCS Quadrupole Magnets

The RCS quadrupole is being designed in collaboration with ANL. The RCS quadrupole design efforts are continuing, with focus on the effects of eddy currents induced by the beampipe and overall optimization of the mechanical design. The main magnet parameters for the RCS quadrupole are shown in Table 5.

Table 5: RCS Quadrupole Specifications

Parameter	Value
Yoke length [m]	0.4
Quad gradient [T/m]	22.2
Pole tip radius [m]	0.02
No. of coil turns	5
Peak Current density [A/mm^2]	4.94
Cooling type	Water

RCS Sextupole Magnets

The RCS sextupole has a mature mechanical design, shown in Figure 6. The main magnet parameters are shown in Table 6. Analyses completed for the RCS sextupole include:

- 2D harmonics via COMSOL, including tolerance analysis study with varying error profiles on the pole profile within 50 microns.
- 3D harmonics via OPERA.
- Thermal study on coil heating with ramped cycle, via COMSOL.

Recent analyses have been performed to determine the suitability of using convective cooling for the RCS sextupole. A bidirectionally coupled model was solved for the temperature field, along with several magnetic field interfaces, one for each significant frequency component of the input signal. The temperature field results, using the input ramped cycle signal for the RCS, is shown in Figure 7.

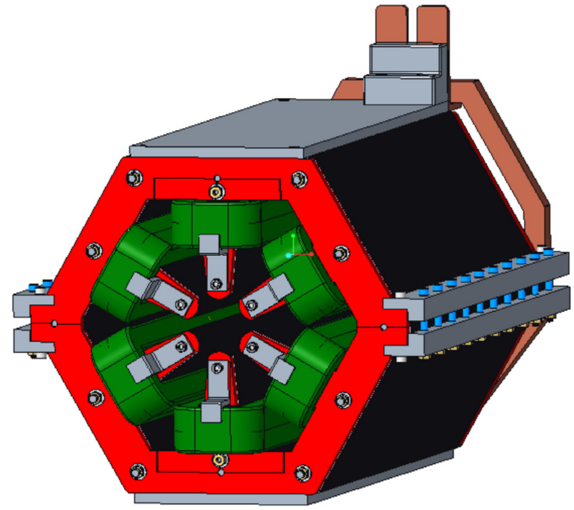

Figure 6: RCS sextupole mechanical model.

Table 6: RCS Sextupole Specifications

Parameter	Value
Yoke length [m]	0.6
Max. gradient [T/m^2]	560
Field at R0.015m [T]	0.063
Pole tip radius [m]	0.025
No. of coil turns	2
Peak Current density [A/mm^2]	1.46
Cooling type	TBD

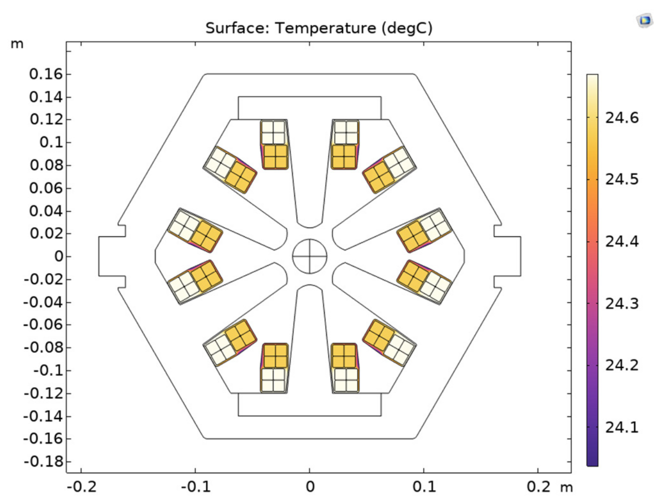

Figure 7: Maximum temperature in the coils is shown to be 24.7°C for the RCS sextupole using the ramp cycle identified at the time of writing.

REFERENCES

[1] C. Montag *et al.*, "Recycling Magnets for the EIC Electron Storage Ring", presented at IPAC'24, Nashville, TN, USA, May 2024, this conference.