

A DIPOLE SCHEME FOR THE ELECTRON STORAGE RING AT THE FUTURE ELECTRON-ION COLLIDER*

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Abstract

The Electron-Ion Collider, which is currently being designed for construction at Brookhaven National Laboratory, will collide polarized electron beams (5–18 GeV) with polarized hadron beams (41–275 GeV) at luminosities up to $10^{34} \text{ cm}^{-2}\text{s}^{-1}$. The electron storage ring will contain about 750 dipoles. These dipoles must fulfill not only complex geometric constraints but also requirements set by spin polarization. 576 dipoles will be located in the arcs and arranged as super-bend triplets, which provide reverse bending at 5 GeV to increase the emittance and damping decrement. The rest will be situated in the interaction region and insertion regions around the ring. Tight orbit tolerances driven by beam-beam effects at the interaction point result in very tight field-ripple requirements. While these could be mitigated by powering all dipoles in series, due to the super-bend configuration the dipoles do not all scale similarly with energy. A novel scheme has been developed using variable-turn coil designs and trim coils to achieve the required fields across the energy range. This contribution presents the unique dipole layout developed for the electron storage ring.

INTRODUCTION

The Electron-Ion Collider (EIC) [1, 2] will collide polarized electrons with polarized hadrons (protons up to heavy ions) for the purpose of investigating the structure and properties of nucleons. It will be built at Brookhaven National Laboratory and utilize the 3.8-kilometer tunnel that currently houses the Relativistic Heavy Ion Collider (RHIC) [3–5], as well as the existing hadron injector chain. Collisions will occur at a range of center-of-mass energies between 29 GeV and 140 GeV, providing luminosities up to $10^{34} \text{ cm}^{-2}\text{s}^{-1}$. In order to achieve the desired range of center-of-mass energies, various combinations of electron and hadron beam energies will be collided. Three values for the electron beam energy are planned: 5, 10, and 18 GeV.

The Electron Storage Ring (ESR) lattice consists of six arcs with insertion regions (IRs) in between, labeled according to the numbers on a clock face. The baseline design for the EIC includes a single interaction point (IP), denoted IP6, where the beams will collide in the ePIC detector at a crossing angle of 25 mrad. A second interaction point and detector in the neighboring IR8 may be included in a fu-

ture upgrade, which would have a crossing angle of 35 mrad. In order to achieve synchronization between electron and hadron bunches [6], the ESR beamline will be located on the outside of the HSR for three arcs and on the inside for the other three arcs, with the paths crossing in IRs 4, 6, 8, and 12. A 200 μrad vertical tilt of the ESR centered on IPs 6 and 8 ensures sufficient vertical separation at IRs 4 and 12 for the ESR and HSR to cross without the need for vertical bending. In IR8 the two rings will be in the same vertical plane and therefore share a vacuum chamber, which requires the path lengths to be set appropriately to ensure that the bunches miss each other for the initial version with just one interaction region.

In order to achieve roughly constant emittance values over the energy range, the arc-cell phase advance is set to 60° at 5 and 10 GeV and 90° at 18 GeV. In addition, super-bend triplets are used for the arc bends to increase the emittance and damping decrement at 5 GeV.

Spin rotators are located on each side of the IP to rotate the beam polarization from the vertical direction in the arcs to the longitudinal direction at the IP [7, 8]. These spin rotators consist of a combination of solenoids and horizontal bends. Two long solenoids and two short solenoids are placed on each side of the IP in order to achieve this rotation for all three energies.

In order to maximize the luminosity, the EIC will operate with large beam-beam parameters up to 0.1 for electrons and 0.015 for protons. These parameters for collisions with flat beams result in very tight tolerances for the beam position and size stability at the IP [9]. These tolerances would translate to very tight power-supply ripple specifications beyond state-of-the-art if the dipoles were powered in families according to their strengths. Powering all dipoles in series would significantly relax the ripple requirements; however, this arrangement is complicated to achieve due to the fact that there are many different strengths of dipoles in the lattice and the strengths do not scale linearly with energy. In order to overcome these challenges, a novel scheme was developed that makes use of variable-turn coils and trim coils to achieve the required fields across the energy range.

This paper describes the dipole arrangement in the ESR and the powering scheme that was developed to meet these requirements. A separate paper describes the ripple specifications for the power supplies derived from the beam-beam limits [9].

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DIPOLE ARRANGEMENT IN THE ESR

The ESR consists of almost 750 normal-conducting dipole magnets. Table 1 shows the key properties of these dipoles at the three energies.

The six arcs of the ESR each contain 16 cells and 32 super-bend triplets [10, 11]. Each super-bend triplet comprises three dipoles: two 2.726 m dipoles (D13) and a shorter, 0.891 m dipole (D2) in the middle, each with 52 mm gap. At 10 and 18 GeV the field in all three dipoles is the same, and the triplet behaves as one long dipole. At 5 GeV the field in the middle dipole is reversed, which provides additional bending that increases the emittance and damping decrement. The total bend angle of the super-bend triplet is maintained at 24.2 mrad for all configurations, excluding the special cases mentioned below. Figure 1 shows the trajectory through the super-bends for the three energies of operation. Due to the reversed bending at 5 GeV, the field in these super-bends does not scale linearly with energy, and in fact the strongest fields in the D2 magnet are at 5 GeV.

Four triplets in the arcs closest to IP6 and IP8 are set to different angles in order to create the crossing angle at the IP. For IP6, 2 mrad less bending is provided in four triplets in the upstream arc 5, and this is compensated by additional bending in four triplets in the downstream arc 7. For IP8, 2.75 mrad additional bending is provided in four triplets in the upstream arc 7, and this is compensated by decreased bending in four triplets in downstream arc 9. This bending is included in the lattice, even though the interaction region at IP8 will not be initially installed.

Specific bending angles are required to rotate the spin in the spin rotators on each side of the IP [7, 8]. The 97.81 mrad bending angle required between the two solenoid modules will be achieved using special dipoles with lengths between 3.5 and 3.8 m being considered, which will have relatively high fields of 0.3–0.33 T at top energy. A 38.79 mrad total bending angle between the solenoids and the IP is also required on each side. Furthermore, there are various constraints on the local geometry in this section. Not only is the position of the IP fixed, but sufficient separation between elements in the various beamlines is required, as well as between the beamline and the tunnel walls. Furthermore, there are numerous locations in the interaction region where synchrotron radiation must be minimized, for example at

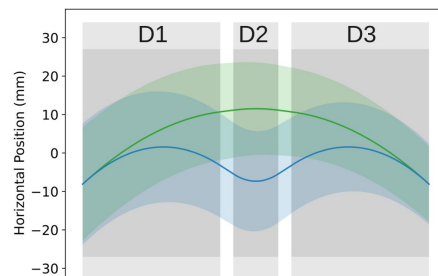


Figure 1: Trajectory through a super-bend triplet in the arcs. D1 and D3 are the same magnet type, which is referred to as D13. The trajectory at 10 and 18 GeV is shown in green, and the trajectory at 5 GeV is shown in blue. The colored shaded areas are the 15σ beam envelopes.

Table 1: Dipole quantities and powering schemes based on v6.3.1 of the ESR lattice. Some changes are expected in the future. The fields and currents between 10 and 18 GeV will scale linearly with energy. The main-bus current will be 391.4 A at 18 GeV, 214.5 A at 10 GeV, and 556.0 A at 5 GeV. The trim coils will each have 20 turns.

Name	Quantity	Bending angle (mrad)			Field (T)			No. main bus turns		Trim current (A)		
		18/10 GeV	5 GeV	18 GeV	10 GeV	5 GeV	18/10 GeV	5 GeV	18 GeV	10 GeV	5 GeV	
D2ER (5.5 m)	1	-20.0	-20.0	-0.216	-0.119	-0.061	24	5	4.1	2.2	4.5	
D13 (2.726 m)	2	1.5	1.5	0.033	0.018	0.009	2	0	5.3	2.9	9.6	
	8	9.2	18.3	0.201	0.110	0.113	11	4	7.1	3.9	5.9	
	8	9.5	18.9	0.208	0.114	0.117	11	4	0.2	0.1	10.0	
	352	10.4	20.6	0.227	0.124	0.128	12	5	0.0	0.0	6.9	
	8	11.3	22.3	0.246	0.135	0.138	13	5	0.2	0.1	4.0	
	144	11.4	11.4	0.249	0.136	0.071	13	3	2.8	1.5	10.4	
	8	11.6	22.9	0.253	0.139	0.142	13	5	7.1	3.9	8.1	
	4	12.2	12.2	0.267	0.147	0.076	14	3	2.7	1.5	4.9	
	2	-12.3	-12.3	-0.270	-0.148	-0.077	14	3	5.0	2.7	4.2	
	5	12.4	12.4	0.271	0.148	0.077	14	3	5.9	3.3	3.9	
1	13.0	13.0	0.284	0.156	0.081	15	3	0.2	0.1	0.0		
D2 (0.891 m)	1	-1.5	-1.5	-0.100	-0.055	-0.028	5	1	5.8	3.2	1.6	
	4	3.0	-15.1	0.201	0.110	-0.286	11	11	7.0	3.9	10.1	
	4	3.1	-15.6	0.208	0.114	-0.296	11	11	0.2	0.1	0.2	
	1	-3.2	-3.2	-0.211	-0.116	-0.060	11	2	3.5	1.9	6.5	
	176	3.4	-17.0	0.227	0.124	-0.322	12	12	0.1	0.1	0.0	
	4	3.7	-18.4	0.246	0.135	-0.349	13	13	0.0	0.0	0.2	
4	3.8	-18.9	0.253	0.139	-0.359	13	13	7.2	4.0	10.1		
DBSR (3.8 m)	10	19.6	19.6	0.306	0.168	0.087	16	3	3.9	2.1	6.6	

the photon detectors for the luminosity monitor and Compton polarimeter. As a result, there are a number of dipoles between the solenoids and the IP with specific bend angles, including some with negative bend angles, to satisfy all these constraints. The same two dipole types used in the arc will also be used here. There are also additional large-aperture dipoles with a gap of about 110 mm. These dipoles (D2ER) are the first dipoles downstream of the IP and serve to bend the electron beam away from the beam of Bethe-Heitler photons coming from the IP, which will proceed to a detector for luminosity measurement. The exact lengths of these dipoles and the division of bending angle between them will be set to limit the synchrotron radiation at the photon detector.

The way the geometry is arranged is that the same bending angle in IR6 (summing to 273 mrad) is repeated in the other five IRs. 24 dipoles, each with a bending angle of 11.4 mrad, make up this bending angle in the non-colliding IRs (8, 10, 12, 2 and 4). These dipoles will have the same yoke design as the 2.726 m dipoles used in the arcs. Furthermore, at IRs 4, 8 and 12, additional dipoles of the same type will be used to provide additional bending for cross-over. These dipoles will all have the same 11.4 mrad bending angle, though some will bend in the opposite direction.

POWERING SCHEME

As explained in detail in [9], it is essential that all dipoles in the ring are connected to a single main power supply in series in order to relax the ripple tolerances to realistic values. There are two major complications to achieving this. First, as outlined in the previous section, while there are just a few different types of magnets, there are about 25 different sets of field strengths, ranging from extremely weak dipoles with fields of less than 0.01 T at their lowest energy to strong dipoles with peak fields of over 0.3 T. In order to connect these all together on one circuit, the number of coil-turns must vary between the magnets. Since specific bend angles are required due to the unique geometry of this lattice, changing the number of coil-turns alone is not sufficient to achieve these specific strength values. For this reason, the dipoles will require additional trim coils to make up the difference in Ampere-turns required between the discretization of the main coil-turns. On top of this, the fields in the super-bend dipoles in the arcs do not scale linearly with energy between 5 GeV and higher energies, while the fields in all dipoles outside of the arcs do scale linearly with energy. Therefore, the field ratios between the dipoles are far from constant with energy. Not only must the number of coil-turns vary between the dipoles, but each dipole magnet must also be designed such that its number of coil-turns can be varied as the operational energy changes between 5 GeV and higher energies (the coil configuration does not change between 10 and 18 GeV since the dipole fields scale linearly). Given that the operational energy is only expected to change between runs, there is no requirement to be able to change this configuration quickly or remotely.

As a result of these considerations, a variable-turn coil design with integrated trim coils has been adopted for these dipoles [12]. The D13 dipoles will have up to 15 coil-turns and the D2 dipoles up to 13 turns with the ability to manually change between the required number of turns by using jumpers between bus connections. A rendering showing this for the D13 dipole is presented in Fig. 2. Whereas all D13 dipoles require a different number of turns between 5 GeV and higher energies, only a couple of D2 magnets have this requirement, due to the way the main-bus currents have been defined. At 10 and 18 GeV the main-bus current is defined by the current required for the 352 D13 dipoles, which is the largest set with the same field, assuming exactly 12 turns. These dipoles will not require a trim supply at these energies. The main-bus current is set to 391.4 A at 18 GeV and 214.5 A at 10 GeV. At 5 GeV the main-bus current is set to 556.0 A, defined by the current required for exactly 12 turns for the 176 D2 magnets with the same strength. Since the number of turns required for the D2 dipoles in the arcs is set to be the same for all energies, only the two D2 dipoles in the interaction region will require different turn numbers for different energies. The trim coils in the D13 and D2 dipoles will each have 20 turns to achieve reasonable current and voltage values.

Similar considerations must be made for the other magnet types, though these have not yet been designed. Information on number of turns and currents is summarized in Table 1.

CONCLUSION

The ESR has a complex lattice design, which calls for a large number of dipoles with varying strengths to satisfy the geometric and spin-polarization requirements. The design is further complicated by the use of super-bend dipoles in the arcs, which means that the dipoles do not all scale linearly with energy. Recently, a new powering scheme for the dipoles was conceived to mitigate the effect of the tight beam-beam requirements on the power-supply ripple tolerances. A scheme using variable-turn coils and trim supplies has been developed to achieve the required field strengths in the dipoles at all three operating energies while connecting all dipoles to the same main-bus supply. While the configuration for the vast majority of dipole magnets has now been finalized, there are a small number of dipoles that still need to be designed to fit into this scheme, which will be the focus of upcoming work.

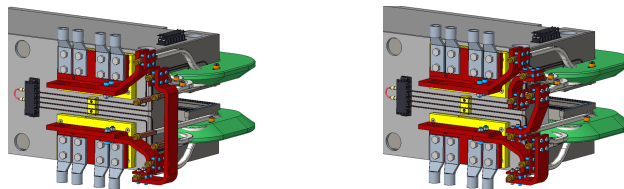


Figure 2: A view of the D13 dipole showing the configuration with 5 active turns (left) and 12 active turns (right).

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