STATUS OF THE RAPID CYCLING SYNCHROTRON OPTICS[*]

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Abstract

The spin-preserving Rapid Cycling Synchrotron (RCS) is an integral component of the Electron-Ion Collider (EIC) complex. It will accelerate 750 MeV electrons from the Beam Accumulator Ring (BAR) to 5, 9, or 18 GeV, as required by the Electron Storage Ring (ESR), all while preserving the polarization. We discuss here the design considerations and the current optics solution, including considerations related to dynamic aperture and spin preservation as well as a reduced-cost RCS for operations to 9 GeV.

INTRODUCTION

The Electron-Ion Collider (EIC) is a new collider to be constructed at Brookhaven National Laboratory within the coming decade which will collide electrons with protons or ions in order to probe proton and nuclear structure [1]. In order to meet its science goals, the EIC requires polarized electron beams of 5, 9 and 18 GeV with charges of up to 28 nC. This necessitates the construction of an electron injector chain consisting of a linac, which produces 1.2 nC electron bunches and accelerates them to 750 MeV; the Beam Accumulator Ring (BAR), which combines the electrons from several linac pulses into a bunch of up to 28 nC; and the spin-preserving Rapid Cycling Synchrotron (RCS), which ramps this bunch to the desired collision energy and injects it into the EIC's Electron Storage Ring (ESR) once per second. A schematic of the electron injector as part of the total EIC complex is shown in Fig. 1. In order to save on project costs, the RCS will initially be constructed to only accelerate to 9 GeV, with full 18 GeV capability being added during operations. We discuss here the design considerations for both the full 18 GeV RCS and the upgradable 9 GeV version.

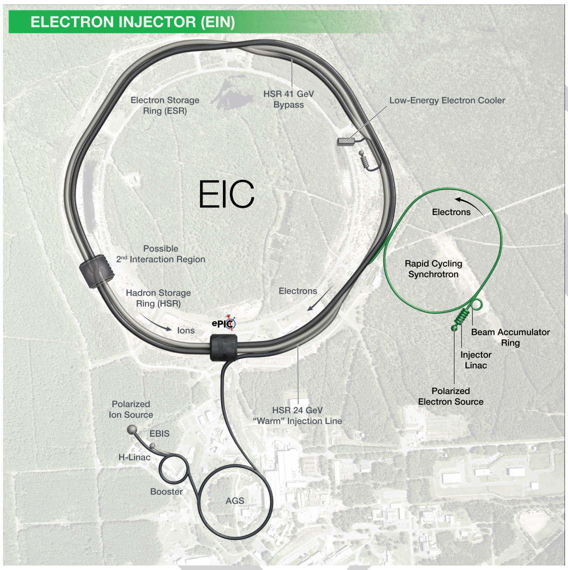

Figure 1: The EIC, with the RCS and electron injection chain highlighted.

RCS LAYOUT

The RCS will be built as a 1507 m racetrack with two straight sections connected by arcs, as can be seen in Fig. 1. One straight section will include injection from the BAR, while the second will house the RF cavities and extraction elements. Intrinsic spin resonances occur when $G\gamma = nP \pm \nu_y$ where G is the electron's anomalous magnetic moment, γ is the relativistic gamma factor, n is an arbitrary integer, P is the lattice periodicity, and ν_y is the vertical tune [2]. If ν_y and $P - \nu_y$ are both larger than $G\gamma$ during the entirety of the ramp, we can guarantee that we will not cross any intrinsic resonances. The racetrack design for the RCS would normally result in a periodicity of 2, which is not sufficient to handle acceleration to 18 GeV, where $G\gamma \approx 40.8$. However, if the straights have a vertical phase advance equal to an integer multiple of 2π, they are invisible from a spin perspective, and so we can recover the desired periodicity condition by having sufficient FODO cells in the arcs [3]. We choose to have 4π phase advance across each straight, a vertical tune of 56.21, and 80 FODO cells per arc. This gives us a periodicity of 160 and an effective arc tune of 52.21 (since we ignore the straights), avoiding all intrinsic resonances which we would encounter on the ramp to 18 GeV. This also avoids the strongest imperfection resonances, which occur when $G\gamma$ is an integer near $nP \pm \nu_y$. However, we still cross weaker imperfection resonances whenever $G\gamma$ takes on an integer value. Strategies for reducing their impact will be discussed in [4]. The bending radius of the RCS dipoles is chosen as 92 m in order to minimize costs; a larger bending radius would increase tunnel length, while making it shorter would increase synchrotron radiation and increase the RF costs. We have chosen to make the horizontal phase advance across each arc an integer multiple of 2π. This automatically results in zero dispersion in the straights, reducing complications with the RF system. In order to provide space for the eight 591 MHz 5-cell RF cavities required to recover

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radiation losses at 18 GeV, the extraction straight is designed with 8 drift lengths of length 6 meters each. To reduce the number of independent power supplies, the injection straight follows an identical layout. We use regular FODO cells in both the arcs and straights, with 4 quadrupoles at the start and end of each straight to allow for matching of the optics functions. Plots of the beta functions and dispersion in both the arcs and straight sections are shown in Fig. 2. We use two sextupole families to bring the chromaticities to 1, which already provides an acceptable dynamic aperture.

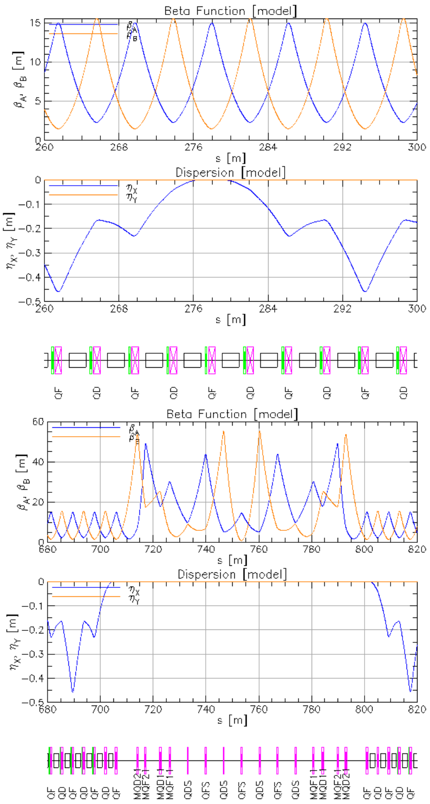

Figure 2: Optics for the 18 GeV RCS lattice in a portion of an arc (top) and a full straight section (bottom).

To test the performance of this lattice, we introduce a suite of static magnet errors and misalignments, then apply a simple correction scheme. Specifically, we give all magnets Gaussian random horizontal and vertical offsets with an RMS value of 100 µm, rolls with an RMS of 400 µrad, systematic multipole errors of RMS relative size 6×10^{-4} for the non-forbidden multipoles, and random multipole errors of RMS relative size 2×10^{-4}. Kickers have systematic and random multipoles of RMS size 10^{-2}. Systematic multipoles are the same for all magnets of a given type and are due to the inability to design a perfect dipole, quadrupole, etc., while random errors vary from magnet to magnet due to manufacturing tolerances. The relative multipole strengths are evaluated 15 mm off-axis. All Gaussian random errors have a 2.5-sigma cutoff. Corrections are performed by using the kickers to bring the orbit to zero at the BPMs, which are assumed offset by a Gaussian random 100 µm from each quadrupole, followed by using the arc quadrupoles to fix the tunes and two sextupole families to bring the chromaticities to 1. The dynamic apertures (DAs) for the ideal lattice along with 10 random seeds are shown in Fig. 3.

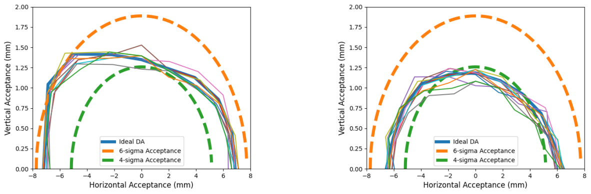

Figure 3: Dynamic apertures for electrons injected into the 18 GeV RCS with 0% (left) and 1% (right) energy offsets. The ten thin curves are ten different random seeds with errors and corrections. The physical beampipe aperture is included. We see all DAs at or beyond the 4-sigma bound, as desired.

As a final test, we use BMAD's long-term-tracking module [5] to track injected electron bunches up the ramp for the lattices with errors and corrections applied as described above. We also include power supply errors with 100 ppm ripple and between 332 ppm and 7900 ppm offset in the baseline value, depending on magnet type. Injecting a bunch with 114 nm horizontal emittance, 5 nm vertical emittance, 37 mm bunch length, and 10^{-3} energy spread, we find that essentially 100% of the electrons survive the ramp, but the end-of-ramp polarization ranges between 48% and 82%, far below the 95% desired by the ESR. Further spin tuning is necessary, as discussed in [4]. This is a consequence of stronger spin resonances at higher energies; if we instead extract the beam at 9 GeV, the polarization transmission is 99% or better.

UPGRADABLE 9 GeV RCS

In order to reduce project costs, we will initially install a version of the RCS which would only reach 9 GeV. Since $G\gamma$ becomes only half as large, we cut the number of FODO cells in the arcs in half while maintaining the same tunnel geometry. In order to minimize the cost of the build-out to the full 18 GeV RCS, we wish to place the magnet girders for the 9 GeV RCS in the same places where they would be for the full 18 GeV case. One solution would be to remove the odd numbered magnet girders in the arcs, while keeping the even-numbered ones, with twice the bend angle in the dipoles. However, it can be seen that this shifts the geometry: trivially, the first dipole in the 9 GeV lattice would need to be shifted to accept beam coming out of the straight, and the errors compound throughout the arc to result in the magnets near the arc center needing to shift by several meters. To address this issue, we retain the first dipole of the 18 GeV solution with its bending angle unchanged, sending the beam smoothly to the second dipole. This dipole bends with 1.5 times the 18 GeV bend angle, so as to bypass the third dipole and send the beam to the location of the fourth. Subsequent dipoles have twice the 18 GeV bend angle to accept the beam from the previous and send beam to the subsequent even numbered dipole. The final dipole in the arc has 1.5

times the 18 GeV bend angle to send the beam into the next straight. This concept is illustrated schematically in Fig. 4.

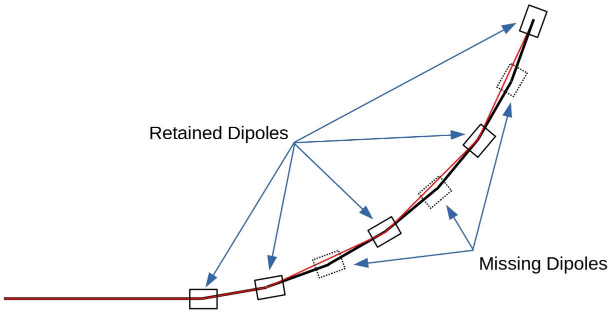

Figure 4: Comparison of the dipole layout in the first portion of the arc for the 18 GeV (black) and 9 GeV (red) lattices. Dipoles indicated by dashed lines are only present in the full 18 GeV RCS.

For the design of the optics for the 9 GeV lattice, we had initially attempted to use the same trick as in the 18 GeV case, with an integer horizontal phase advance across each arc guaranteeing zero dispersion in the straights. However, with fewer magnet girders, the dipoles bend at a steeper angle and we have more space between quadrupoles, generating increased horizontal dispersion with less ability to control it. This results in the projected physical aperture for off-momentum particles being unacceptably low. We therefore power the first and last 8 quadrupoles in each arc on independent power supplies to perform dispersion suppression. The optics for this solution are shown in Fig. 5 and a comparison of its parameters with those of the 18 GeV solution is provided in Table 1.

Table 1: RCS Lattice Parameters

Parameter	**18 GeV RCS**	**9 GeV RCS**
Circumference [m]	1507	1507
Arc periodicity	160	80
Horizontal tune	43.13	28.20
Vertical tune	56.21	27.44
Equilibrium horizontal emittance [nm]		
at 5 GeV	3.0	16.9
at 9 GeV	9.6	54.8
at 18 GeV	39.1	–

We have studied the effects of errors in the same manner as for the 18 GeV RCS. The DAs for the 9 GeV RCS are shown in Fig. 6. These appear quite good out to 1% energy error. We have also performed tracking studies to 9 GeV, finding that this solution has negligible losses and delivers $\geq 96\%$ polarization transmission across 10 random seeds.

CONCLUSION

We have developed an RCS lattice capable of accelerating electrons from 750 MeV to 18 GeV with negligible losses. Polarization transmission to 9 GeV is very good, but suffers during ramps to the highest energy due to the stronger imperfection resonances; we need to improve our method of correcting the lattice errors in order to address this issue. We have also identified a version of the RCS which uses half the arc magnets to accelerate to 9 GeV, finding good DA and spin transmission with reasonable magnet errors.

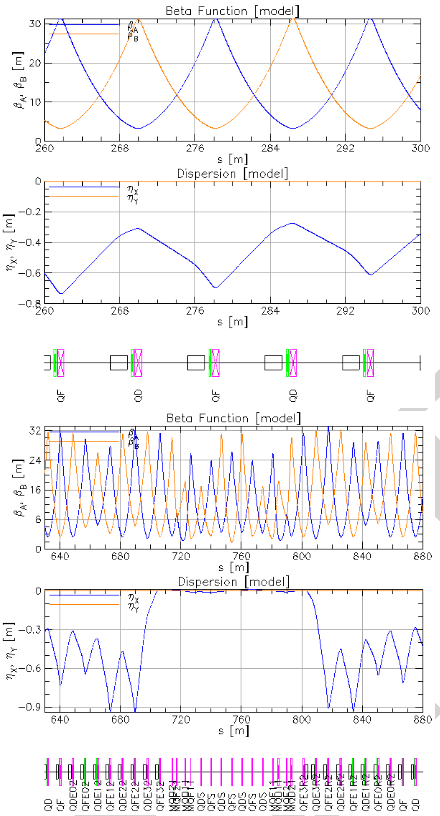

Figure 5: Optics for the 9 GeV RCS lattice in a portion of an arc (top) and a full straight section (bottom).

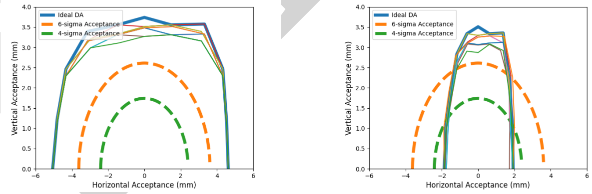

Figure 6: Dynamic apertures for electrons injected into the 9 GeV RCS lattice with 0% (left) and 1% (right) energy offsets. The ten thin curves are ten different random seeds with errors and corrections. The physical beampipe aperture is included. In the worst case, the DAs are only slightly inside the 4-sigma bound.

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