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DYNAMIC APERTURE OPTIMIZATION IN THE EIC ELECTRON STORAGE RING WITH TWO INTERACTION POINTS*

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Abstract

In the Electron-Ion Collider (EIC), which is currently being designed for construction at Brookhaven National Laboratory, electrons from the electron storage ring will collide with hadrons, producing luminosities up to $1{\times}10^{34}\,\mathrm{cm^{-2}\,s}$. The baseline design includes only one interaction point (IP), and optics have been found with a suitable dynamic aperture in each dimension. However, the EIC project asks for the option of a second IP. The strong focusing required at the IPs creates a very large natural chromaticity (about -125 in the vertical plane for the ring). Compensating this linear chromaticity while simultaneously controlling the nonlinear chromaticity to high order to achieve a sufficient momentum acceptance of $\pm1\%$ ($10\sigma_\delta$) at 18 GeV is a considerable challenge. A scheme to compensate higher-order chromatic effects from 2 IPs by setting the phase advance between them does not, by itself, provide the required momentum acceptance for the EIC Electron Storage Ring. A thorough design of the nonlinear optics is underway to increase the momentum acceptance using multiple sextupole families, and the latest results are presented here.

INTRODUCTION

The Electron-Ion Collider (EIC) [1, 2] is a new machine currently being designed that 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 in the 3.8-kilometer tunnel that currently houses the Relativistic Heavy Ion Collider (RHIC) [3–5]. Two electron rings will be built: a rapid cycling synchrotron (RCS) for accelerating electrons to collision energies and an electron storage ring (ESR) for colliding electrons with hadrons from a separate storage ring. Collisions will occur at a range of center-of-mass energies between 29 GeV and 140 GeV, providing luminosities up to $1{\times}10^{34}\,\mathrm{cm^{-2}\,s}$. These luminosities are considerably greater than those achieved at HERA [5, 6], an electron/positron-proton collider that operated until 2007 at DESY, and, although the top center-of-mass energy will be less than HERA's 318 GeV, the EIC will be optimized for a much wider range of energies.

The baseline design for the EIC includes a single interaction point (IP), called IP6, where the beams will collide. A detector will be installed in an existing hall at IP6, which currently houses the STAR detector. The option of a second IP and detector is currently being studied. This would be located in the neighboring straight section, IP8, due to the presence of another experimental hall there, which currently houses the sPHENIX detector. Due to beam-beam tune-shift limits, the luminosity would be shared between the two detectors by timing bunches to collide only at one IP per turn. While this reduces the luminosity per detector by a factor two, it allows both to operate simultaneously, leading to the same integrated luminosity as if they would share time successively.

Including a second IP results in a significantly larger natural chromaticity, as the final-focusing quadrupoles (FFQs) are responsible for a large fraction of the total chromaticity. The linear chromaticity must be compensated to a value of +1 in both planes over the whole ring. In addition, nonlinear chromaticity up to many higher orders plays a role in restricting the momentum acceptance. The target momentum acceptance is ten times the rms energy spread in each direction. Similarly, in the transverse planes, 10σ dynamic aperture at the nominal energy is required. These goals are set to maximize the lifetime and therefore limit the charge variation between fills. Each electron bunch is replaced approximately every six minutes to mitigate depolarization; nevertheless, the charge variation between fills must be kept small due to its detrimental effect on the hadron beam by means of transient beam-beam interactions.

In order to achieve the desired range of center-of-mass energies, the electron beam energy will vary from 5 GeV to 18 GeV. The phase advance of the arc FODO cells is set to 60° at lower energies and 90° at the maximum energy of 18 GeV to compensate the increase in horizontal emittance. With this change, the geometric, 1σ emittance varies from 24.0 nm at 10 GeV to 28.3 nm at 18 GeV. Including a second IP further increases the emittance at top energy to 30.1 nm. Increasing the phase advance from 60° to 90° also adds a few units of chromaticity due to the increased focusing. Moreover, the relative energy spread scales with the beam energy. This means that the required momentum acceptance is much greater at 18 GeV, at around 1%, which is very challenging to achieve. A 90° optics also imposes constraints on the phase advance across straight sections, in particular at the IPs, when attempting to cancel the higher-order chromaticity with multiple sextupole families per plane.

Optimization of the dynamic aperture is key to showing the feasibility of EIC operation with two IPs. Whereas the

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requirements have been met in simulations with just one IP, work is ongoing to achieve the stated goals for the lattice with two IPs. This paper provides a summary of some of these recent efforts for the most challenging case of 18 GeV beam energy. In the following section, the cancellation of the off-momentum β-beat between the two IPs by setting an appropriate phase advance is considered. Thereafter comes a section on reducing the tune variation as a function of momentum by optimizing the W-functions [7, 8], which are related to the off-momentum β-beat, followed by a section on synchrobetatron resonances. The baseline lattice version used for the studies presented here is referred to as version 5.3. Figure 1 shows the β- and dispersion functions for this lattice with 2 IPs, and Table 1 provides the main parameters. Further information on the ESR layout and design may be found in [1].

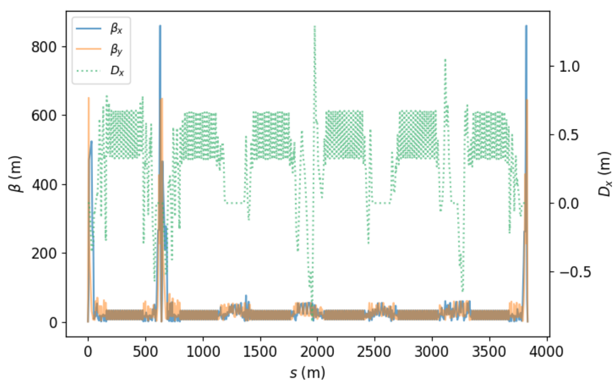

Figure 1: Linear optics functions for the ESR 2-IP lattice. The ring consists of six arcs, separated by straight sections. The beams collide at IP6 ($s = 0$) and IP8 ($s = 641$ m).

Table 1: ESR 2-IP Lattice Parameters

Parameter	Value
Beam energy	18 GeV
Circumference	3 834 m
Emittance	30 nm
Energy spread, σ_δ	9.8×10^{-4}
Synchrotron tune, Q_s	0.056
Betatron tunes, Q_x/Q_y	51.12 / 42.1
Nat. chromaticity, ξ_x/ξ_y	-107 / -125
β^*_x/β^*_y at IP	0.42 / 0.05 m

β-BEAT CANCELLATION BETWEEN INTERACTION POINTS

A large off-momentum β-beat, $b = 1/\beta\ \partial\beta/\partial\delta$, is produced by the strong focusing quadrupoles at the IPs, which contributes greatly to second-order chromaticity in the lattice [7–9]. A strategy for reducing this contribution is to set an appropriate phase advance between the two IPs such that a closed β-bump is formed and the β-beat wave from the two IPs is confined to a section between them with a low contribution in the rest of the ring. This assumes interaction regions with similar chromatic contributions. The optimal phase advance will be close to an odd multiple of 90°, as the β-wave propagates at twice the betatron phase advance.

This scheme was successfully adopted in the HERA electron ring after the luminosity upgrade with the two IPs at opposite ends of the ring, so the β-bump comprised half the ring [5]. Two global families of sextupoles were then used for chromaticity correction. Due to the stronger focusing at the EIC ESR, this is far from sufficient, producing steep "chromaticity walls" at $\pm0.3\%$ momentum deviation, far short of the $\pm1\%$ acceptance required. Figure 2 shows the W-functions, $W = \sqrt{a^2 + b^2}$, and tune as a function of momentum offset, computed using the matrix formalism in MAD-X [10]. Although the β-beat is zero at the IP, $a = \partial\alpha/\partial\delta - \alpha b$ is nonzero, which results in a nonzero W-function at that point.

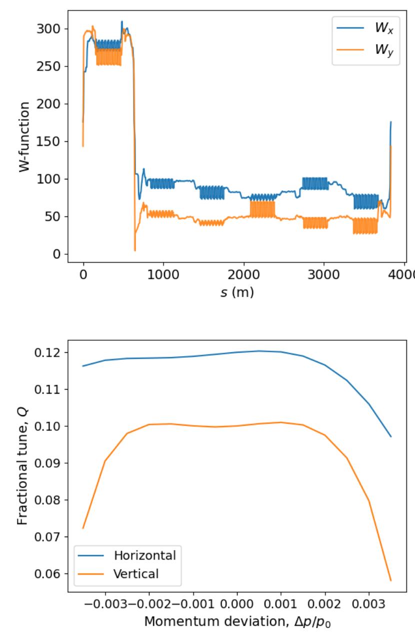

Figure 2: W-functions along the ring and tune as a function of momentum offset using two global sextupole families to correct the linear chromaticity.

INCREASING THE MOMENTUM ACCEPTANCE

Setting the phase advance between IPs as detailed above is effective at reducing the second-order chromaticity; however, higher-order chromaticity components still lead to a small momentum acceptance. Additional sextupole families can be used for a more sophisticated chromaticity correction scheme. Four families of sextupoles (two per plane) provide control of the W-vectors and linear chromaticities indepen-

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dently for a 90° lattice, provided that the phase advance from the IP to the first sextupole in the arc is set suitably.

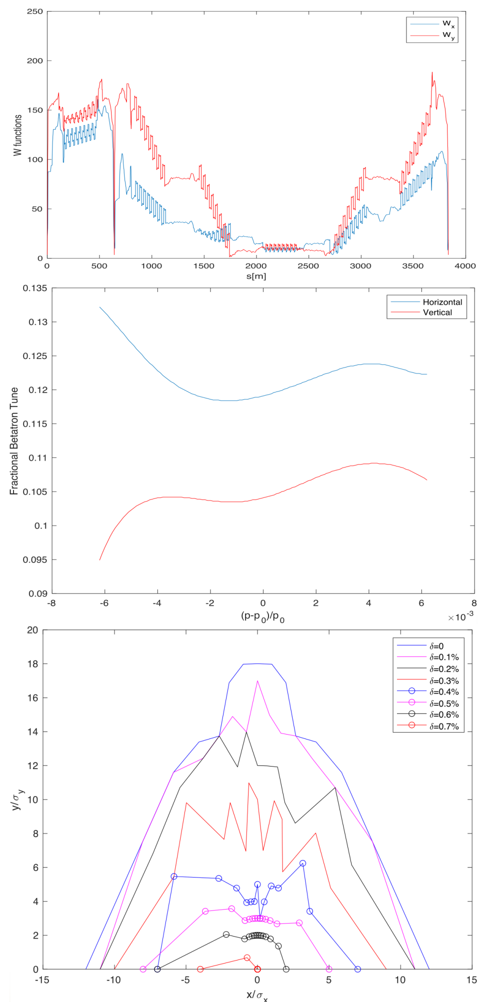

Figure 3: W-functions along the ring (top), tune as a function of momentum offset (middle), and dynamic aperture (bottom) using fourteen sextupole families over the ring. The dynamic aperture is computed in LEGO [11] with RF on and without synchrotron radiation.

In this scheme, sextupoles are used to match the W-functions (i.e. both b and a) to zero at the IPs. A β-bump is contained between the FFQs downstream of IP6 and those upstream of IP8. The W-functions rise sharply at the other two FFQs (upstream of IP6 and downstream of IP8) and are then brought down over the course of two arcs adjacent to each IP. Artificial phase trombones have been inserted at every straight section to achieve the optimal orientation of the W-vectors; these will need to be incorporated into the lattice using the existing quadrupoles in due course. Fourteen independent families of sextupoles in total are used over the six arcs of the lattice. This solution was obtained through a combination of numerical optimization and manual adjustment. Optimizing the contributions to linear chromaticity in each arc was found to be very important. Figure 3 shows the W-functions and tune as a function of momentum offset, computed using the matrix formalism in LEGO [11]. This yields a momentum acceptance of $\pm 0.7\%$ when tracking, a great improvement with respect to the two-family solution but still somewhat short of the $\pm 1\%$ target.

SYNCHROBETATRON RESONANCES

Further efforts were made to limit the tune deviation at large momentum offsets. However, despite achieving flatter tune functions and increased momentum acceptance with RF off, no significant increase in the momentum acceptance with RF on was observed. This apparent limit in the momentum acceptance was investigated, and it appeared to be caused by the tune crossing a synchrobetatron resonance line. In particular, the nominal tunes (see Table 1) make the $Q_y - 2Q_s = p$ (integer) resonance especially problematic, as shown in Fig. 4. The nominal transverse tunes are selected by considerations relating to beam-beam and polarization effects. Shifting the transverse tunes by small amounts away from this resonance helps to increase the momentum acceptance.

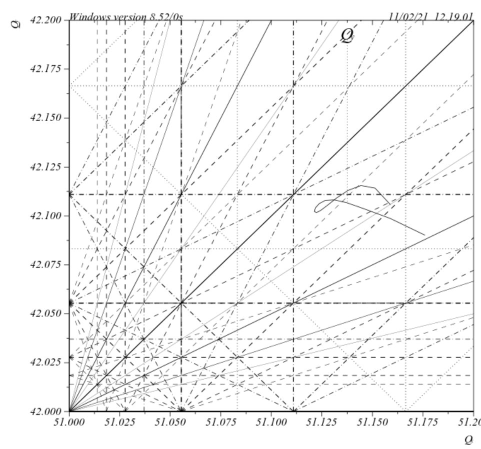

Figure 4: Resonance diagram (Q_x, Q_y) with an example of a tune footprint superimposed.

CONCLUSION AND OUTLOOK

The EIC ESR lattice version with two IPs at 18 GeV presents a great challenge in terms of achieving the required dynamic aperture and momentum acceptance. Significant progress has been made in extending the momentum acceptance, although it still falls short of the $\pm 1\%$ desired.

Significant changes to the layout of the interaction regions are currently being implemented, which will have an effect on the chromatic properties of the lattice. One problem identified was the presence of dispersion in the solenoid spin rotators, and efforts are underway to limit this. New solutions for optimizing the dynamic aperture in the new lattice will have to be found, using the extensive knowledge and experience acquired so far. Further work on avoiding synchrobetatron resonances may be necessary, as the current working point seems particularly problematic. Finally, the results presented in this paper do not take into account errors, misalignments and beam-beam-interactions, and these will have to be considered.

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