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INTERACTION REGION EFFECTS ON THE EIC'S ELECTRON STORAGE RING'S DYNAMIC APERTURE *

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Abstract

The Electron-Ion Collider, to be constructed at Brookhaven National Laboratory, requires a large dynamic aperture (DA) of the electron storage ring (ESR) for stable operation of 10 beam sigma for the transverse aperture and 10 times the RMS momentum spread in the longitudinal plane. In particular for operations at the top energy of 18 GeV this has not been easy to achieve, and the DA has proven sensitive to small changes. Nevertheless, a chromaticity-correction scheme has been developed for the bare lattice. There are several important effects in the interaction region that are potentially damaging to the ESR's DA, including the beam-beam interaction, crab cavity kicks, the detector solenoid field, and skew quadrupoles for coupling compensation. In this contribution, these effects are modelled to evaluate their impact on the dynamic aperture of the ESR at 18GeV.

INTRODUCTION

The Electron-Ion Collider (EIC) requires a dynamic aperture (DA) for the electron storage ring (ESR) of 10 beam sigma in the transverse and 10 times the RMS momentum spread in the longitudinal plane. This goal must be reached for the possible running energies of 5, 10 and 18 GeV, as well as for the one and two interaction point (IP) configurations [1]. The basic strategy for increasing the DA for the 18 GeV lattice has been to adjust the phases between the six arcs and use sextupole families in the arcs (typically four per arc) to correct the W-function [2] and chromaticity with additional single sextupoles used for correcting the second order dispersion.

The 2-IP configuration at 18 GeV has proven to be particularly difficult in optimizing towards the momentum aperture goal. The goal has been met for a baseline lattice (version 5.6) where certain features in the interaction region (IR) have not yet been included [3]. These features include crab cavities, the detector solenoid and its compensation, and the beam-beam interaction. In the following sections, the models for these features are described and their impact on the ESR's DA is shown. The DA calculations were done using Bmad and its related programs [4].

CRAB CAVITIES

In order to regain the luminosity loss from the crossing angle of 25 mrad, the EIC makes use of a local crabbing scheme at both IPs. The crab cavities are modelled as sinusoidal kicks to the horizontal momentum of the form

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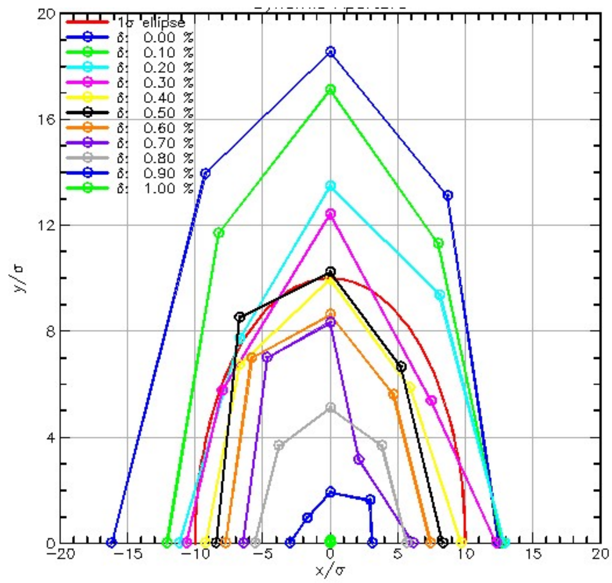

Figure 1: Dynamic aperture of ESR in 2-IP configuration, including crab cavities, detector solenoid and correction, and beam-beam

$$\Delta p_x = \frac{V}{cP_0} \sin \frac{2\pi f t}{c}, \quad (1)$$

where V is the cavity voltage, P_0 is the particle momentum, and f is the cavity's frequency. For the ESR, the cavity frequency is 394 MHz.

On their own, the crab cavities in the ESR do not reduce the dynamic aperture, only doing so when paired with another effect. The solenoid without coupling compensation interacts negatively with the crab cavities, but this case is not considered as the coupling will always be corrected.

DETECTOR SOLENOID COMPENSATION

A solenoid is inserted at each IP, introducing coupling and vertical dispersion, which are corrected by the use of skew quadrupoles in the IR. The coupling is corrected from the start of the IR to the IP and from the IP to the end of IR. In addition, the solenoid affects both the crabbing at the IP and the ability for the second crab cavity to undo the crabbing kick because it couples the horizontal crab kick into the vertical. In order to correct this the following matrix equations in the transverse phase space must be satisfied:

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$$\begin{bmatrix} M_{11} & M_{12} & M_{13} & M_{14} \\ M_{21} & 0 & M_{23} & M_{24} \\ M_{31} & 0 & M_{33} & M_{34} \\ M_{41} & 0 & M_{43} & M_{44} \end{bmatrix}_{crab1\rightarrow IP} \begin{bmatrix} 0 \\ \Delta x' z \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} \theta_{crab} z \\ 0 \\ 0 \\ 0 \end{bmatrix} \tag{2}$$

$$\begin{bmatrix} M_{11} & 0 & M_{13} & M_{14} \\ M_{21} & M_{22} & M_{23} & M_{24} \\ M_{31} & 0 & M_{33} & M_{34} \\ M_{41} & 0 & M_{43} & M_{44} \end{bmatrix}_{crab1\rightarrow crab2} \begin{bmatrix} 0 \\ \Delta x' z \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ \Delta x' z \\ 0 \\ 0 \end{bmatrix} \tag{3}$$

where $\Delta x'$ is the crabbing kick, θ_{crab} is the desired crabbing angle (half of the crossing angle), and z is the longitudinal position from the bunch center. Unfortunately, there is insufficient space between the crab cavities and IP to fully decouple, meaning these conditions are in addition to the general decoupling at the ends of the IRs. In addition to correcting the coupling, the optical functions are kept constant at the ends of the IRs and at the IPs. $\beta_x = 150$ m and $\alpha_x = 0$ are also kept fixed at the crab cavities.

Without special placement of quadrupoles, these conditions would require 8 skew quadrupoles on each side of each IP, four for decoupling, two for the crabbing plane, and two for η_y and η'_y. In order to provide flexibility in avoiding undesirable solutions, this correction was done with 9 skew quadrupoles on each side of the two IPs, giving 36 in total for the 2-IP configuration. The placement of the skew quadrupoles were fixed, with them superimposed on the non-skew quadrupoles in the IR.

This compensation was done for a 4m long, 3 T solenoid, as this was considered the upper bound of solenoid strength.

BEAM-BEAM

The beam-beam interaction was implemented using a weak-strong model. Due to the crossing angle, crabbing, and detector solenoid, the interaction is not well described by a single thin lens model, and instead is represented by many equal charge slices, where each slice is a thin lens. This is due to the crab cavity giving a longitudinal dependence to the beam centroid. The opposing strong, proton beam has a longitudinally dependent centroid defined by the crab cavities, and at the IP is represented by a polynomial

$$x_c(z) = crab_{x1} z + crab_{x2} z^2 + crab_{x3} z^3 \tag{4}$$

The first order term is the main crab kick, the second order term is zero due to the crab cavities' sinusoidal form, and the third order term is also zero due to the HSR's harmonic crab cavities. It was found that higher order terms had no effect on the DA. The effect of the detector solenoid on the opposing beam was ignored for specifying the centroid. The particles of the weak, electron beam track through the sinusoidal kick of the crab cavities, so this treatment is only needed for the strong beam.

Equal charge slices were placed along the polynomial, each modelled as a Gaussian thin lens beam-beam interaction using the Bessetti-Erskine formula [5]. While tracking through the beam-beam interaction, the particles experience the solenoid field between slices. This slice-by-slice tracking method is available as a parameter in the Bmad beam-beam element [4], with the results here being obtained with 100 slices.

In the 2-IP configuration, each bunch only interacts at one IP, so both were checked, and it was observed that the beam-beam interaction produced the same results at both IPs.

DYNAMIC APERTURE RESULTS

These features were inserted into both 1-IP and 2-IP configurations at 18 GeV, giving the results shown in Table 1. For all configurations and combinations of features, the crab cavities did not reduce the energy aperture, so all numbers are given with their inclusion. The 1-IP configuration performs well with the detector solenoid and beam-beam, dropping just 0.1% below the goal of 1% with both included. The 2-IP configuration performs significantly worse, with the momentum aperture dropping by around half when either detector solenoid or beam-beam was included. In both configurations the on-momentum transverse aperture remained above 10σ.

Table 1: Momentum Aperture With Crabbing

1-IP configuration baseline = 1.1%		
Solenoid	**BB**	**Solenoid and BB**
1.0%	1.0%	0.9%
2-IP configuration baseline = 0.9%		
Solenoid Only at IP6		
Solenoid	**BB**	**Solenoid and BB**
0.5%	0.5%	0.3%
Solenoid Only at IP8		
Solenoid	**BB**	**Solenoid and BB**
0.6%	0.5%	0.4%
Solenoid at Both IPs		
Solenoid	**BB**	**Solenoid and BB**
0.4%	0.5%	0.3%

The drop in energy aperture from 0.9% to 0.4% in the 2-IP configuration when the solenoid and correction was added was unexpected given the performance of the 1-IP configuration with solenoid. In order to determine a cause, the DA was also obtained with the solenoid at only one IP at a time to determine if one of the two IPs was the main cause in the drop. The results, seen in Table 1, show that the two IPs see similar drops, with IP6 performing marginally worse.

The drop in momentum aperture is then likely caused by the interaction of the two IPs in a way disruptive to the DA correction scheme, and not a particular problem with one

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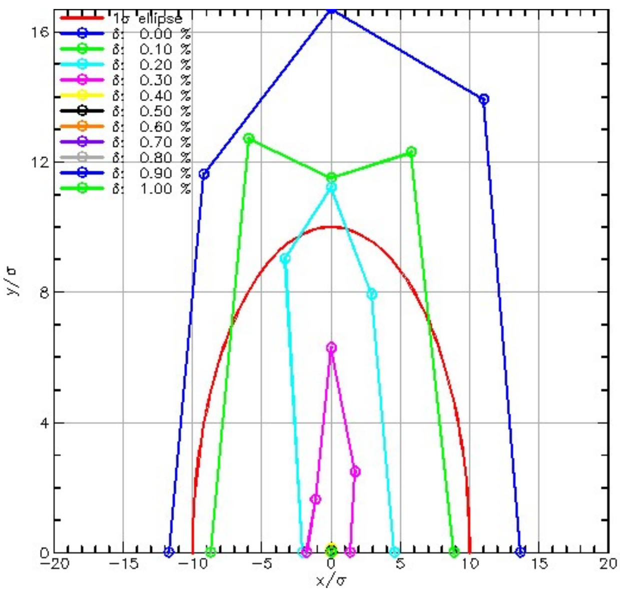
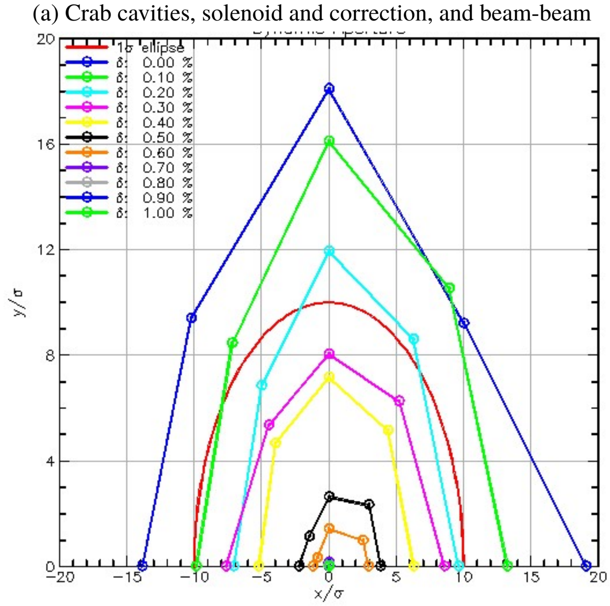


(a) Crab cavities, solenoid and correction, and beam-beam



(b) Crab cavities, solenoid and correction, and beam-beam. After adjusting phases

Figure 2: Dynamic aperture for the 2-IP configuration, compared before and after adjusting phase advances near the IRs.

of them. This was confirmed by inspecting the W-function and second order dispersion before and after the solenoids were inserted. A significant change in both was observed, although the vertical W-function and second order dispersion performed particularly bad when compared to the 1-IP case. This was then partially corrected by inserting a phase trombone before and after each IR, choosing the phases to reduce the W-function and second order dispersion while keeping the fractional tune constant at $Q_x = 0.12$ and $Q_y = 0.1$. This had the result of increasing the energy aperture from 0.3% with crab cavities, solenoids, and beam-beam to 0.6% as seen in Fig. 2. This increase from adjusting the phases, suggests that increasing the momentum aperture back to the original 0.9% through the adjusting of the full DA correction scheme is likely.

In addition to re-optimizing the sextupoles and phase advances after the insertion of the detector solenoid and correction, it may be possible to compensate for the solenoid in a way less disruptive to the baseline lattice. By carefully choosing the the skew-quadrupole positions, it may be possible to reduce their strengths [6].

CONCLUSION

In the case of the 1-IP configuration, the addition of these features reduced the energy aperture; however, the already larger-than-needed aperture provided enough of a buffer to keep the aperture to 0.9% after all features were included.

The 2-IP configuration did not perform as well. Starting already below the goal at 0.9%, it was reduced to 0.3% after all features were included. This loss in aperture could be reduced if the phase advances on each side of the IRs were adjusted, bringing the momentum aperture to 0.6%. This increase suggests that the effects considered here need to be included in the optimization of dynamic aperture for the 2-IP lattice.

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