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OPTIMIZING THE DESIGN TUNES OF THE ELECTRON STORAGE RING OF THE ELECTRON-ION COLLIDER*

Y. Luo†, J. S. Berg, M. Blaskiewicz, C. Montag, D. Marx, S. Peggs, V. Ptitsyn,
S. Tepikian, F. Willeke, D. Xu, Brookhaven National Laboratory, Upton, NY, USA
Eliana Gianfelice-Wendt, Fermi National Accelerator Laboratory, Batavia, IL, USA
V. Morozov, Oak Ridge National Laboratory, Oak Ridge, TN, USA
T. Satogata, Thomas Jefferson National Accelerator Facility, Newport News, VA, USA
G. Hoffstaetter, Cornell University, Ithaca, NY, USA

Abstract

The Electron-Ion Collider (EIC) to be constructed at Brookhaven National Laboratory will collide polarized high energy electron beams with hadron beams with luminosities up to $1.0 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ in the center-of-mass energy range of 20-140 GeV. Preliminary beam-beam simulations resulted in an optimum working point (0.08, 0.06) for the Electron Storage Ring (ESR) of the EIC. During the ESR polarization simulation study, this working point was found to be less than optimal for the electron polarization. In this article, we present recent beam-beam simulation results in a wide range tune scan to search for a new optimal ESR working point which would be accepted for both beam-beam and electron polarization performances.

INTRODUCTION

The Electron-Ion Collider (EIC) to be constructed at Brookhaven National Laboratory will collide polarized high energy electron beams with proton to heavy ion beams with luminosities up to $1 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ in the center mass energy range of 20-140 GeV [1, 2]. To achieve such a high luminosity, we adopt high bunch intensities for both beams, small transverse beam sizes at the interaction point (IP), a large crossing angle 25 mrad with crab cavities in both rings, and a novel strong hadron cooling in the Hadron Storage Ring (HSR) to counteract the intra-beam scattering (IBS) at store.

For the EIC, high polarization is required for the electron, proton, and light ion beams. Near half-integer tunes have been used for most previous and existing lepton colliders to achieve a higher luminosity. However, since the design spin tune in the Electron Storage Ring (ESR) of the EIC is chosen to be a half integer to overcome the spin resonances, therefore we move the ESR design tunes close to integers.

Beam-beam interaction simulation is used to optimize the beam-beam related design parameters in the EIC [3], such as beam-beam parameters, working points, transverse emittances, β^*s at the IP, and so on. For the EIC, we adopted large beam-beam parameters for both electron and proton beams based on the successful experiences from KEK-B and RHIC. However, such a combination of large beam-beam parameters for both electron and proton beams has never been demonstrated experimentally. Besides the maximum design luminosity, we also must pay attention to the long-term stability of proton beam which does not have synchrotron radiation damping like the electron beam. Based on those considerations and previous simualtion results, we selected (0.08, 0.06) as a possible working point for the ESR.

With recent electron polarization simulation for the ESR, we noticed that with the design tunes (0.08, 0.06) for the ESR, it is difficult to correct and control vertical orbit and the global betatron coupling. For example, to maintain a relatively high electron polarization, the betatron coupling in the ESR has to be tightly controlled. The global coupling coefficient should be less than 0.0002. In this article, we will present our recent new ESR tune scan to search for a new working point which can be accepted for both beam-beam interaction and electron polarization simulation studies.

PREVIOUS TUNE SCAN RESULTS

First we present our previous ESR tune scan results based on both weak-strong and strong-strong beam-beam simulation models. For the following simulation studies, we simulate the collision mode involving 10 GeV electron beam and 275 GeV proton beam. At this mode, both beams reach their maximum beam-beam design parameters in the EIC, 0.1 for the electron beam and 0.015 for the proton beam, and the peak luminosity reaches its maximum design value $1.0 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ in the EIC.

In the weak-strong tune scan, we assume that the proton bunch is rigid and the electron bunch is represented by 50,000 macro-particles. Both the horizontal and vertical electron tunes are scanned from 0.02 to 0.25 with a step size of 0.02. The effects of sychrotron radiation damping and quantum excitation are taken into consideration. Electrons are tracked to 50,000 turns, which is about 12 times longer than the transverse synchrotron radiation damping periods of the electron beam.

Figure 1 shows the final average luminosity in the last 1000 turns in the weak-strong simulation. From the plot, luminosity is slightly higher when the electron beam's horizontal tune is below 0.10, especially with a higher vertical tune than the horizontal tune in the upper-left corner of the shown tune space.

In the strong-strong electron tune scan, both bunches are represented by 500,000 macro-particles and are tracked for

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† yluo@bnl.gov

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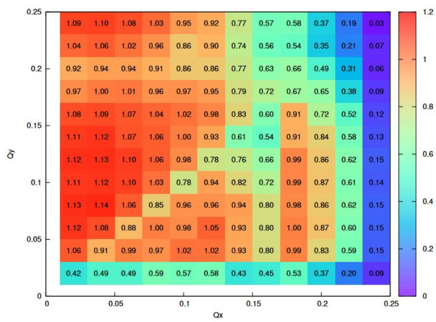

Figure 1: Luminosity averaged over the last 1000 turns of a weak-strong simulation as function of electron tunes. Values are in units of $10^{34}\,\mathrm{cm}^{-2}\mathrm{sec}^{-1}$.

50,000 turns. The proton tunes are fixed at (0.228, 0.210). Both the horizontal and vertical tunes of the electron beam are scanned from 0.02 through 0.20 with a step size of 0.02. Figure 2 shows the final average luminosity in the last 1000 turns. From the plot, the luminosity is significantly reduced when the horizontal tune is higher than 0.1.

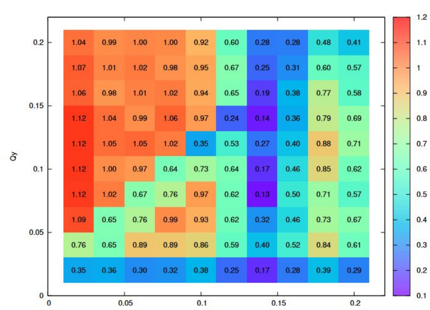

Figure 2: Luminosity averaged over the last 1000 turns of a strong-strong simulation as function of electron tunes. Values are in units of $10^{34}\,\mathrm{cm}^{-2}\mathrm{sec}^{-1}$.

Figures 3 shows the horizontal dipole motion of both proton and electron bunches from the same strong-strong beam-beam simulation. From it, the coherent beam-beam instability happens when the electron horizontal tune is between 0.1 and 0.14. This instability had been studied in details and it can be explained by the sum coupling resonance between the electron beam mode and the proton beam mode [4].

For the EIC, besides the maximum design luminosity, we also pay attention to the long-term stability of the proton beam. We chose the fractional tunes (0.08, 0.06) for the ESR in Ref. [1]. One reason for this choice is that this working point is able to provide the maximum design luminosity $1.0 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{sec}^{-1}$. Another more important reason is that the proton bunch's vertical emittance growth with this working point is lower than those working points with a higher vertical tune than the horizontal tune.

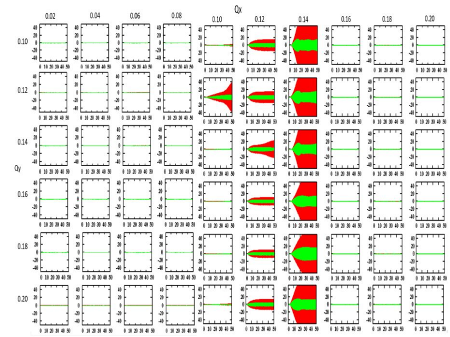

Figure 3: Evolution of horizontal center motion for both beams in above strong-strong ESR tune scan.

Table 1: Beam-beam Related Beam and Optics Parameters for the New ESR Tune Scan

quantity	unit	proton	electron
Beam energy	GeV	275	10
Bunch intensity	10^{11}	0.668	1.72
(β_x^*, β_y^*) at IP	cm	(80, 7.2)	(55, 5.6)
Beam sizes at IP	µm	(95, 8.5)	
Bunch length	cm	6	0.7
Energy spread	10^{-4}	6.8	5.8
Transverse tunes		(0.228, 0.210)	to be scanned
Longitudinal tune		0.01	0.069

NEW 2-D ESR TUNE SCAN

In this section we will present the results from our recent ESR tune scan with a strong-strong beam-beam simulaton code SimTrack [5]. Table 1 lists some beam-beam related beam and optics parameters used here. For this study, we limited our tune scan region to the upper-left corner in Figs. 1 and 2 since we would like to explore a larger tune split between the horizontal and vertical tunes. As we showed above, a higher horizontal tune than 0.1 will cause coherent instability. A better option is to increase the vertical design tune. A higher vertical tune will benefit the global vertical orbit correction and a large tune split will benefit the global betatron coupling compensation, too. In the new tune scan, we scan the horizontal tune from 0.06 to 0.12 and the vertical tune from 0.1 to 0.2 with a smaller step size 0.01.

To decide which working point is considered optimal, we applied two criteria: 1) the quasi-equilibrium luminosity after 5 electron damping periods should be close to the maximum design luminosity $1.0 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{sec}^{-1}$, 2) the simulated proton beam size growth rates in both transverse planes should be better or close to those from the old design tunes (0.08, 0.06). Figure 4 shows the scan area and the optimal values of the ESR tunes we found.

In this study, we notice that when the horizontal tune is higher than 0.1, the proton's horizontal beam size growth rate quickly increases. On the other hand, when the ESR horizontal tune is less than 0.06, the proton's emittance growth rates increase too due to the pinch effect for the

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electron beam. For the electron's vertical tune, we need to keep it away from the fifth resonance line at 0.2.

Based on the new ESR tune scan, we recommend a new ESR design working point (0.08, 0.14) for further dynamic aperture and electron polarization simulation studies. Note that there is still some safe tune space around (0.08, 0.14). For example, we could make slight changes to the new ESR design tunes to avoid some resonances, such as the synchro-betatron resonances.

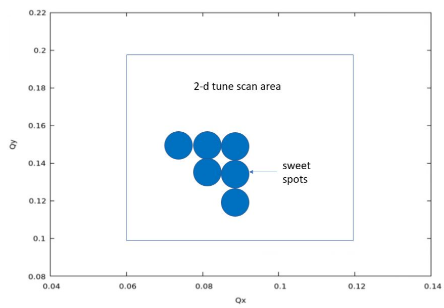

Figure 4: The tune scan area and the sweet spots found in the new ESR tune scan.

After fixing the design tunes for the ESR, we move forward to fine adjust the beam-beam related design parameters. Based on our previous experiences, a slightly larger electron beam sizes than the proton's at the IP will result in a smaller proton beam size growth rate, especially in the vertical plane. To adjust the electron bunch's beam sizes at IP, we normally adjust its β^*s at IP and/or the design electron emittances. Here we only adjusted the electron beam's β^*s. Figures 5 - 7 show the evolution of luminosity, horizontal, and vertical beam sizes after re-matching the electron and proton transverse beam sizes at the IP.

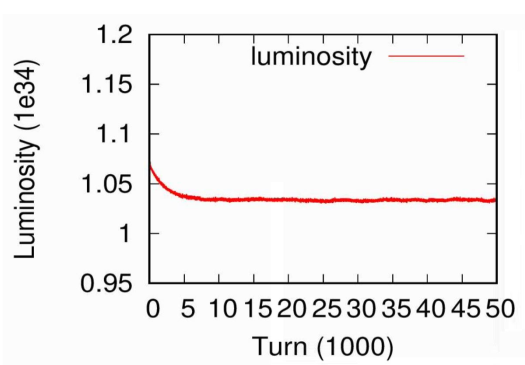

Figure 5: Evolution of luminosity in a strong-strong beam-beam simulation with the new ESR design tunes (0.08, 0.14).

We also test the new ESR design tunes (0.08, 0.14) with the collision mode involving 18 GeV electrons and 275 GeV protons. The beam sizes of both beams are re-matched at IP too. The beam-beam performance with the new tunes is also acceptable for this collision mode. Table 2 lists the zero-amplitude tunes without and with beam-beam inter-

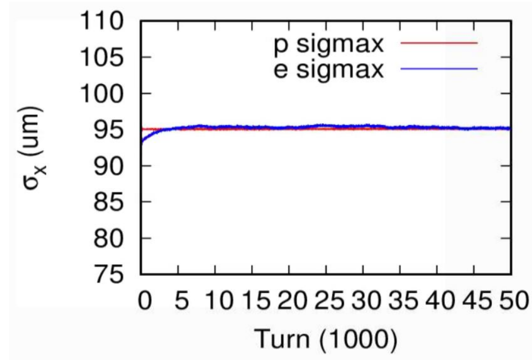

Figure 6: Evolution of horizontal beam sizes with the new ESR design tunes (0.08, 0.14).

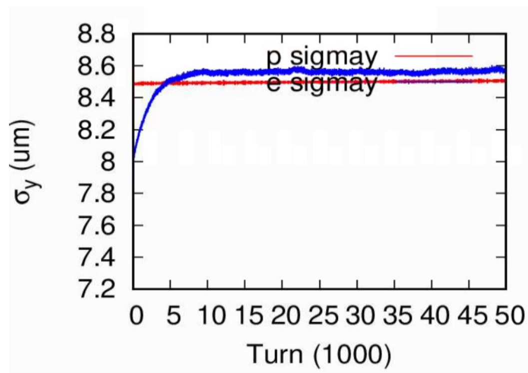

Figure 7: Evolution of vertical beam sizes with the new ESR design tunes (0.08, 0.14).

Table 2: ESR Design Parameters with the New ESR Design Tunes (0.08,0.14)

collision	(275GeV, 10GeV)	(275GeV, 18GeV)
lattice tunes	(0.08, 0.14)	
tunes with BB	(0.146, 0.226)	(0.158. 0.225)
$\beta^*_{x,y}$ (cm)	(55, 6.5)	(70, 5.7)
emittances (nm)	(20, 1.3)	(24, 2)

action, together with β^*s and emittances in the ESR after re-matching electron-proton beam sizes at the IP.

SUMMARY

In this article, we reviewed the previous weak-strong and strong-strong beam-beam simulation results in the ESR tune scan. To improve the vertical closed orbit correction and the global betatron coupling compensation, we launched a new 2-d strong-strong electron tune scan with a higher vertical tune than the horizontal tune. Based on the simulation results, we recommend a new design working point (0.08, 0.14) for the ESR. We re-matched the beam sizes of electron and proton beam sizes at IP and also tested the new working point with other collision mode. Studies are ongoing to evaluate the effect of the new working point on electron polarization and dynamic aperture.

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