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STUDY OF CRABBED COLLISION IN eRHIC WITH A COMBINATION OF STRONG-STRONG AND WEAK-STRONG SIMULATIONS*

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Abstract

In the present design of the future electron-ion collider eRHIC at the Brookhaven National Laboratory, a crossing angle of 22 mrad between the electron and proton orbits at the interaction region is adopted. To compensate the geometric luminosity loss, a local compensation scheme with two sets of crab cavities for each beam is considered. In this article, we first carry out strong-strong beam-beam simulation to study possible coherent beam-beam instability. Under the assumption of no coherent beam-beam motion, we then carry out a weak-strong beam-beam simulation to determine the long-term stability of the proton beam with the equilibrium electron beam sizes extracted from the strong-strong beam-beam simulation.

INTRODUCTION

In the present design of eRHIC [1], collision with a full crossing angle of 22 mrad is adopted. To compensate the geometric luminosity loss due to the crossing angle, crab cavities are to be installed to tilt the proton and electron bunches by 11 mrad in the x-z plane at the interaction point (IP) so that the two beams collide head-on. The crab cavities provide a horizontal deflecting force to the particles in a bunch. Ideally, the deflecting electric field should be proportional to the longitudinal position of particles.

A higher frequency of crab cavities requires a lower crab cavity voltage. However, due to the sineous wave shape of the crab cavity voltage, particles in the bunch tail may not be perfectly crabbed. In the following study, we assume 112 MHz and 338 MHz for the crab cavities in the proton and electron rings respectively. The final choice of the crab cavity frequency is not made yet.

With crabbed collision between the electron and proton bunches, we will focus on the emittance growth and luminosity degradation with current design machine and beam parameters. For this purpose, we suggest to combine strong-strong and weak-strong beam-beam simulation methods. The strong-strong beam-beam simulation is used to reveal any possible coherent beam-beam instability in a few electron damping periods. If there is no clear coherent beam-beam motion from the strong-strong beam-beam simulation, then a weak-strong beam-beam simulation is to be used to study the long-term stability of the proton beam. In the weak-strong simulation, the equilibrium electron beam sizes are used.

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Table 1: Machine and Beam Parameters Used in the Study

Parameter	unit	proton ring	electron ring
Circumference	m	3833.8451	
Energy	GeV	275	10
Bunch Intensity	10^{11}	1.11	3.05
Working point	-	(31.31, 32.305)	(34.08, 31.06)
synchro. tune	-	0.01	0.069
$\beta^*_{x,y}$	cm	(94,4.2)	(62, 7.3)
rms emittance	nm	(16.0,6.1)	(24.4,3.5)
Bunch length	cm	7	0.43
Energy spread	10^{-4}	6.5	4.7
Crossing angle	mrad	22	
crab freqency	MHz	112	336

In this article, the following machine and beam parameters defined in the erhic design parameters v2.1 are used. Table 1 shows some key parameters to be used in this study.

STRONG-STRONG SIMULATION

Two strong-strong beam-beam simulation codes, Beam-Beam3D [2] by Dr. Qiang and BBSS [3] by Dr. Ohmi have been used for the eRHIC study. The results from those two codes were benchmarked and agreed well with each other. In the following we only show the results from BBSS.

Figure 1 shows the evolution of luminosity under different collision conditions. For crabbed crossing collision, we used three crab cavity frequencies 112 MHz, 224 MHz, and 336 MHz for the proton ring. 336 MHz crab cavities are used for the electron ring. We tracked particles up to 20 k turns or 5 radiation damping times of the electron beam. After 20 k turns, the luminosity reductions with respect to the head-on case are 5.6%, 6.6%, and 9.0% with 112 MHz, 224 MHz, and 336 MHz proton crab cavities, respectively.

Figure 2 show the evolution of horizontal proton rms beam size for all four collision conditions. Under 20 k turns, there is no obvious beam size growth with head-on collision and crabbed crossing collision with 112 MHz crab cavities. There are clear horizontal proton beam size growth with crabbed crossing collision with 224 MHz and 336 MHz crab cavities. In the study, the rms beam sizes are calculated with $\sqrt{<x^2> - <\bar{x}>^2}$.

Figure 3 shows the spectrum of the horizontal proton centeroid motion in the above strong-strong beam-beam simulation. The vertical axis is the amplitude with a log scale. In the spectrum, the highest peak at about 0.31 is contributed by the proton horizontal tune. The second highest peak around 0.1 may be contributed by the electron horizontal motion with an unperturbed tune around 0.08. There are

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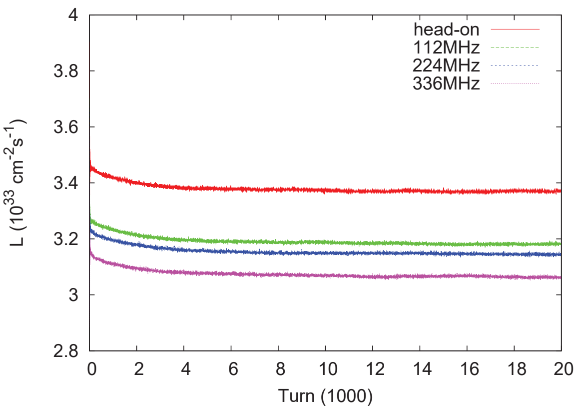

Figure 1: Evolution of luminosity without and with crabbed crossing collision.

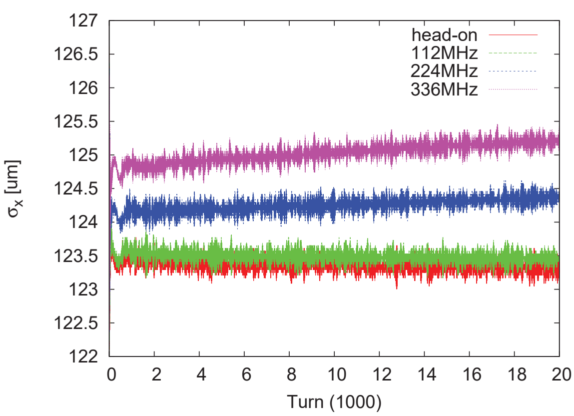

Figure 2: Evolution of proton beam size without and with crabbed crossing collision.

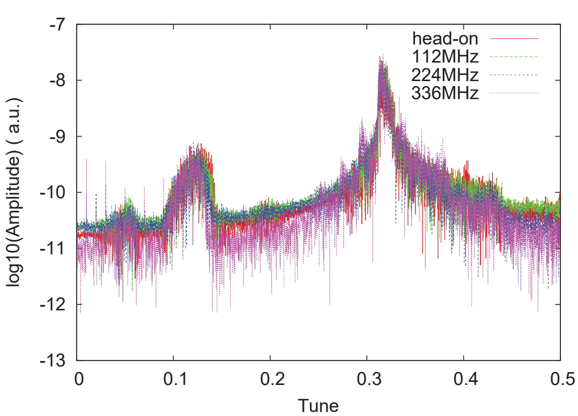

Figure 3: Spectrum of horizontal centroid of proton bunch without and with crab crossing collision.

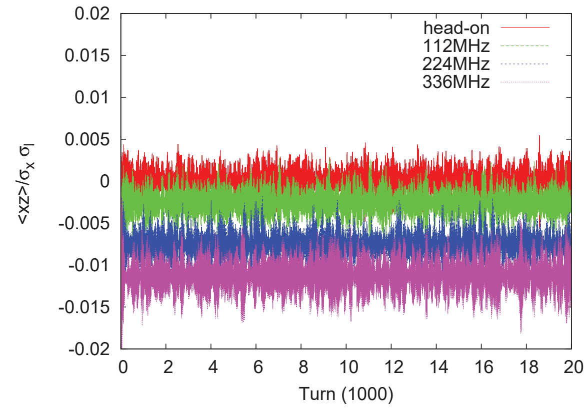

Figure 4: Evolution of $< xz >$ of proton bunch without and with crab crossing collision.

lines with multiples of proton synchrotron tune with crabbed crossing collision, especially with 224 MHz and 336 MHz crab cavity frequencies. However, there is no such peaks in the head-on collision case.

Figure 4 shows the evolution of $< xz >$ of the proton centroid under different collision conditions. There is not clear beating in the $< xz >$ evolution or an obvious growth in $< xz >$ in 20 k turns. With crossing collision, $< xz >$ is usually used to identify possible synchro-betatron instability.

In Ref [4], in an extended 200 k turn strong-strong beam-beam simulation with BeamBeam3D, luminosity degradation is observed with crabbed crossing collision with the same beam parameters. And the luminosity decay rate varies with the proton synchrotron tunes. To understand the luminosity degradation in a long term strong-strong beam-beam simulation, we need to further improve the codes to minimize the numeric noise and to investigate the beam dynamics with crabbed crossing collision.

WEAK-STRONG SIMULATION

As mentioned above, if there is no clear coherent beam-beam motion from the strong-strong beam-beam simulation, a weak-strong beam-beam simulation is used to study the long-term stability of the proton beam. In the following, we focus on the crabbed collision case with 112 MHz proton crab cavities.

SimTrack [5] by Dr. Luo is used for the eRHIC weak-strong beam-beam simulation, where the strong beam is represented by a rigid Gaussian charge distribution. SimTrack had been extensively used for dynamic aperture calculation and head-on beam-beam compensation simulation in RHIC. To extract the electron beam sizes, a strong-strong code based on SimTrack is also used. The result of strong-strong beam-beam simulation from SimTrack are benchmarked with BBSS and agreed well.

First we extract the electron beam sizes from the above 20 k turn strong-strong beam-beam simulation after a so-called equilibrium is reached. The macro-particles from the strong-strong beam-beam simulation are re-used. We

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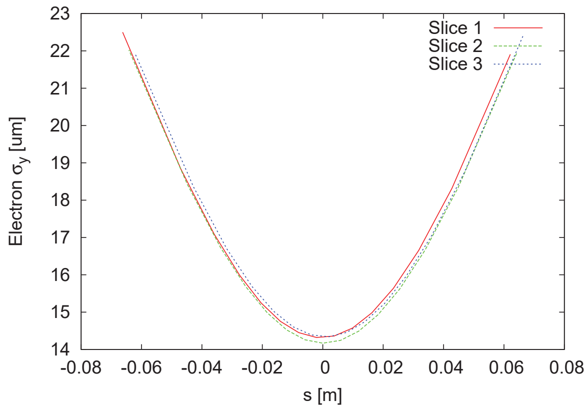

Figure 5: Vertical beam sizes of different electron slices as function of collision location s from IP at turn 20,000.

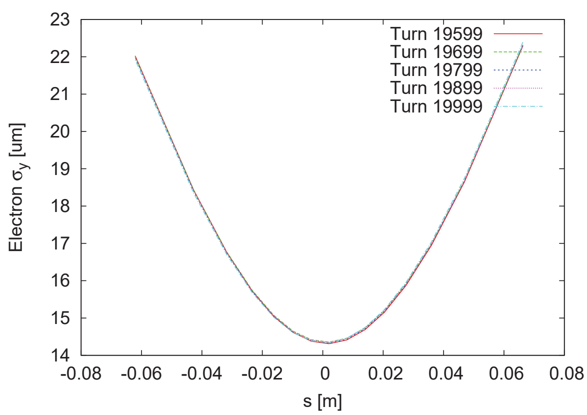

Figure 6: Vertical beam sizes of the central electron slice as function of collision location s from IP in the last 500 turns.

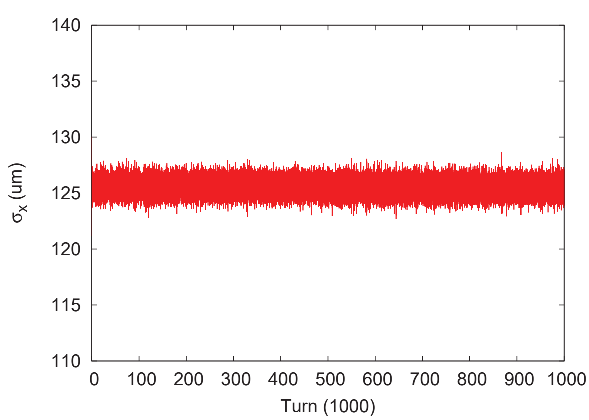

Figure 7: Evolution of the horizontal proton beam size up to 1 M turn in the weak-strong simulation.

slice the proton bunch into 15 slices and the electron bunch into 3 slices. By re-simulating the one-pass beam-beam interaction, we calculate and record the transverse beam sizes of each electron slices at all collision locations.

Figure 5 shows the vertical electron beam sizes of each slice of the electron bunch at different locations from IP in the end of 20 k turn strong-strong beam-beam simulation. As shown in the plot, the variation of the electron beam sizes between different electron slices are small. The reason is that the electron bunch is much shorter than the proton bunch for the parameters we used here.

Figure 6 shows the vertical beam sizes of the center electron slice over the final 500 turns in the 20 k turn strong-strong beam-beam simulation. We can see that the electron beam size change in 500 turns is negligible. This justifies our use of weak-strong beam-beam code to study the proton long-term stability.

Next, we carry out weak-strong simulation with the above electron beam sizes extracted from the strong-strong beam-beam simulaiton. In the study, the electron bunch is assumed rigid. For the first test, we assume the electron bunch is represented by 1 slice since the elctron bunch is short and the difference in beam sizes between difference slices is small. The proton bunch is represented by 10 k proton macro-particles which are sampled from the 500 k macro-particles used in the strong-strong simulation.

Figure 7 shows the horizontal proton size evolution during 1 M turn weak-strong simulation. There is not significant proton beam size change in the simulation. The variation of the horizontal proton beam size between the first and the last 1000 turn is less than +0.083%.

SUMMARY

In this article, to study the possible emittance growth and luminosity degradation with crabbed crossing collision in eRHIC, we combined both strong-strong and weak-strong beam-beam simulation. In the 20 k turn strong-strong beam-beam simulation, there is no clear coherent beam-beam instability. With the extracted electron beam sizes from the strong-strong simulation, a weak-strong simulation shows that there is not proton beam size growth and luminosity degradation up to 1 M turn.

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