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WEAK-STRONG BEAM-BEAM SIMULATION FOR eRHIC*

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Abstract

To compensate the geometric luminosity loss due to the crossing angle in eRHIC, crab cavities are to be installed on both sides of the interaction point. When the proton bunch length is comparable to the wavelength of its crab cavities, protons in the bunch head and tail will not be perfectly tilted in the x-z plane. In the article, we employ weak-strong beam-beam interaction model to calculate the proton beam size growth rates and the luminosity degradation rate. The goal of these studies is to optimize the beam-beam related machine and beam parameters of eRHIC.

INTRODUCTION

In the present eRHIC design, a crossing angle of 25 mrad between the proton and electron closed orbits in the interaction region is adopted. To compensate the geometric luminosity loss, crab cavities are to be installed to tilt the proton and electron bunches by 12.5 mrad in the x-z plane so that the two beams collide head-on at the interaction point (IP).

A local crabbing scheme is adopted for both beams. One set of crab cavities are placed on either side of IP. The horizontal phase advance between the crab cavities and IP is exactly $\pi/2$. The total voltage for crab cavities on one side is determined by the particle energy, crossing angle, and the crab cavity frequency. The higher crab cavity frequency is, the lower cavity amplitude is required.

To evaluate the effects of beam-beam interaction with crab cavities, both strong-strong and weak-strong simulation methods are used [1]. In this article, we present the results with weak-strong model. The eRHIC machine and beam parameters v5.1 are used. Table 1 shows the beam-beam interaction related parameters. Figure 1 shows the particle distributions of both beams at IP. Here the proton crab cavity frequency is 394 MHz. The final choice is to be decided.

SIMULATION METHOD

In the weak-strong simulation with the code SimTrack [2], we focus on the long-term stability of the protons. In the code, the proton bunch is represented by 10,000 macro-particles with 6-d Gaussian distribution. The electron bunch is assumed to be a rigid 6-d Gaussian charge distribution and is assumed perfectly crabbed. In the simulation, only 1 interaction point per turn is considered. The proton macro-particles are transported around the ring using a 6×6 uncoupled linear matrix. The betatron tunes will be adjusted each turn according to the particle's relative momentum deviation and the settings of linear chromaticities.

Table 1: Beam-beam Interaction Related Machine and Beam Parameters Used in this Article

quantity	unit	proton	electron
Beam energy	GeV	275	10
Bunch intensity	10^{11}	1.05	3.0
β^* at IP	cm	(90, 5.9)	(63, 10.4)
Beam sizes at IP	μm	(112, 22.5)	
Bunch length	cm	7	1.9
Energy spread	10^{-4}	6.6	5.5
Transverse tunes		(0.31, 0.305)	(0.08, 0.06)
Longitudinal tune		0.01	0.069

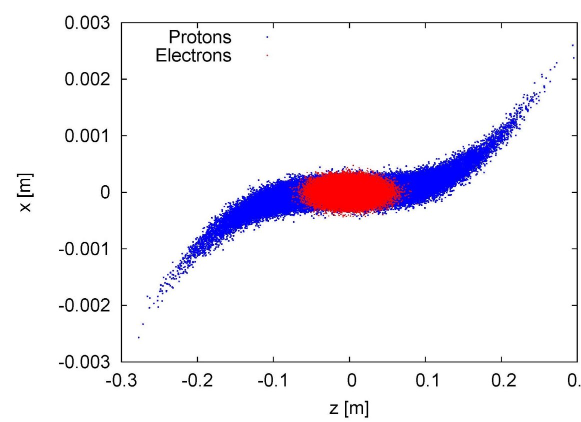

Figure 1: Proton and electron distributions at IP.

So far beam-beam interaction is the only source of nonlinear force in our current weak-strong simulation code. For the beam-beam interaction at IP, we split the electron bunch into 5 slices longitudinally. At IP, each macro-proton interacts with these 5 electron slices one-by-one in a time order. At each encounter, the beam-beam force is calculated with Hirata's synchro-beam mapping [3]. There is no cross-talk between the proton macro-particles.

We track protons up to 2 million turns. On each turn, we calculate the RMS beam sizes of the protons and the luminosity. The luminosity is calculated by overlapping the proton macro-particle onto the transverse Gaussian charge distribution of electron slices. Figure 2 shows one example of calculated turn-by-turn proton RMS beam sizes in 2 million turns. Figure 3 shows the raw data of calculated turn-by-turn luminosity.

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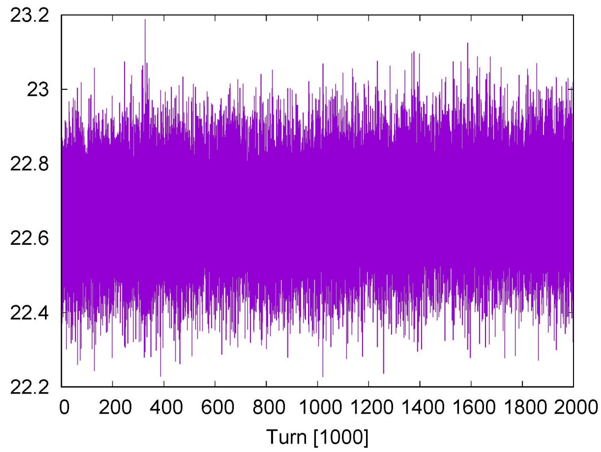

Figure 2: Example: raw data of calculated proton vertical beam size.

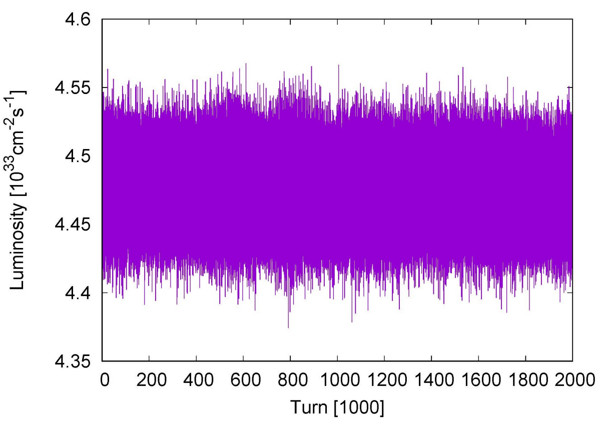

Figure 3: Example: raw data of turn-by-turn luminosity.

To determine the change rates of proton beam sizes and luminosity, we normally use the raw data from the second half tracking turns. We fit the recorded turn-by-turn beam sizes or luminosities with a linear function, say $y = ax + b$, where b is the initial value, and a/b the relative change rate per turn. For eRHIC, the relative change rate of $a/b = 1.0 \times 10^{-10}$ corresponds to 2.8%/hour. To reduce the uncertainty in the change rate calculations, we only take into account the macro-particles initially within $3\sigma_l$. More seeds of initial distributions are used too.

We benchmarked our weak-strong simulation results with the 250 GeV RHIC proton operation. During the RHIC operation, the observed transverse emittance growth was less than 10% in a 7-8 hour-long store. This emittance growth can be largely reproduced by the intrabeam scattering. From our weak-strong simulation code, the calculated proton beam size growth for the same RHIC parameters is less than 0.01%/hour, which is probably the noise level of the simulation method.

Table 2: Calculated Change Rates with Head-on and Crabbed Collisions

Case	$\frac{\Delta\sigma_x}{\sigma_x}$	$\frac{\Delta\sigma_y}{\sigma_y}$	$\frac{\Delta L}{L}$
head-on:			
0 mrad	0.14%/h	-0.26%/h	0.03%/h
25 mrad:			
394 MHz	9.0%/h	18.0%/h	-6.7%/h
197 MHz	-2.0%/h	27.7%/h	-7.6%/h

Table 3: Calculated Change Rates with 394 and 197 MHz Crab Cavity Frequency

Case	$\frac{\Delta\sigma_x}{\sigma_x}$	$\frac{\Delta\sigma_y}{\sigma_y}$	$\frac{\Delta L}{L}$
197MHz:			
(.310, 0.305)	-2.0%/h	27.7%/h	-7.6%/h
(.228, 0.224)	0.4%/h	2.0%/h	-0.6%/h
(0.180, 0.175)	1.4%/h	6.8%/h	-1.0%/h

SIMULATION RESULTS

Head-on and Crabbed Collisions

First we calculate and compare the proton beam size growth rates and the luminosity degradation rate with head-on and crabbed crossing angle collisions. Without beam-beam interaction, the proton's transverse tunes are set to (0.310, 0.305). Both 394 MHz and 197 MHz proton crab cavities are simulated. Table 2 shows the results.

From the table, with head-on collision, the calculated beam size growth rates and the luminosity degradation rate are less than 0.3%/hour, which may come from the numerical noises in the simulations and can be ignored. Any large beam size growth in the following with crabbed crossing collision should be related to how the proton bunch is crabbed.

With 394 MHz proton crab cavities, the calculated horizontal and vertical beam size growth rates are 9%/hour and 18%/hour respectively. With 197 MHz proton crab cavities, the calculated horizontal beam size growth rate is -2%/hour. There is more vertical beam size growth than that with 394 MHz proton crab cavities.

From the simulations, with crabbed crossing collision, the vertical beam size growth rate is larger than the horizontal beam size even though the crossing angle is in the horizontal plane. The reason is being studied. It may be caused by non-linear beam-beam interaction, flat beam at IP, mis-matched beam sizes around IP, and the proton working points, and so on.

Proton Tune Scan

The proton working point for the routine RHIC polarized proton operation is between 2/3 and 7/10. For eRHIC, considering that collisions are between protons and electrons, we chose the proton working point (0.310, 0.305) which are the mirrored tunes of the RHIC tunes below the half integer.

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Table 4: Calculated Change Rates with Different Proton Tunes

Case	$\frac{\Delta\sigma_x}{\sigma_x}$	$\frac{\Delta\sigma_y}{\sigma_y}$	$\frac{\Delta L}{L}$
(0.310, 0.305):			
394	(9.0+/-10.3)%/h	(18.0+/-11.0)%/h	(-6.7+/-3.2)%/h
394/788	(173.1+/-27.3)%/h	(1607.2+/-81.6)%/h	(-333.1+/-13.0)%/h
394/788/1182	(2.0+/-10.0)%/h	(69.8+/-17.)%/h1	(-17.2+/-3.2)%/h
394/788/1182/1576	(-1.5+/-3.3)%/h	(8.3+/-4.4)%/h	(-1.0+/-1.1)%/h
197	(-2.0+/-3.2)%/h	(27.7+/-9.1)%/h	(-7.6+/-3.9)%/h
197/394	(2.1+/-5.4)%/h	(2.4+/-6.3)%/h	(-0.2+/-1.9)%/h
(0.228, 0.224):			
394	(23.1+/-13.3)%/h	(66.0+/-19.7)%/h	(-9.3+/-3.0)%/h
394/788	(31.9+/-17.8)%/h	(47.8+/-7.2)%/h	(-6.3+/-2.8)%/h
394/788/1182	(-1.8+/-2.5)%/h	(3.8+/-1.8)%/h	(-0.5+/-0.7)%/h
394/788/1182/1576	(0.24+/-1.4)%/h	(-0.32+/-1.2)%/h	(0.08+/-0.6)%/h
197	(0.4/-1.6)%/h	(2.0+/-3.8)%/h	(-0.6+/-0.9)%/h
197/394	(-0.6+/-3.4)%/h	(1.3+/-5.4)%/h	(0.1+/-0.5)%/h
(0.180, 0.175):			
394	(1.3+/-4.8)%/h	(136.1+/-38.0)%/h	(-15.1+/-3.0)%/h
394/788	(14.7+/-9.7)%/h	(140.4+/-18.6)%/h	(-18.1+/-2.4)%/h
394/788/1182	(2.0+/-1.7)%/h	(42.8+/-15.4)%/h	(-4.7+/-1.3)%/h
394/788/1182/1576	(-0.4+/-4.0)%/h	(14.2+/-11.5)%/h	(-1.6+/-0.5)%/h
197	(1.4+/-2.1)%/h	(6.8+/-5.7)%/h	(-1.0+/-0.7)%/h
197/394	(-1.0+/-1.9)%/h	(6.7+/-7.2)%/h	(0.2+/-0.5)%/h

A good working point of the protons should provide a good beam-beam lifetime and a good polarization lifetime.

In the proton tune scan, we tested (0.228, 0.224), which are the tunes for the RHIC heavy ion operation. And we also tested (0.180, 0.175), which are close to the initial RHIC design tunes (0.19, 0.18) for the polarized proton operation. Table 3 shows the simulation results. The crabbing frequency for the proton bunch is 197 MHz. From the table, with these two proton tunes (0.228, 0.224) and (0.180, 0.175), the calculated vertical beam size growth rates are reduced by about a factor of 4 and the luminosity lifetime is improved by a factor of 7. Strong-strong beam-beam simulation also confirmed that (0.228, 0.224) and (0.180, 0.175) deliver a better beam-beam lifetime than (0.310, 0.305). We will continue searching for good working points for both protons and electrons for eRHIC.

Combinations of Harmonic Crab Cavities

Above weak-strong simulations show that a lower crab cavity frequency gives smaller proton beam size growth rates and lower luminosity degradation rate. From the physics view, we prefer 197 MHz crab cavities for the proton ring over 394 MHz crab cavities. However, from the technical view, 394MHz crab cavity is preferred.

In the following, we study how to combine harmonic crab cavities of 394 MHz to create a linear crabbing kick and evaluate theire beam-beam performances. In these tests, we focus on the protons between +/-3σ_l area. We tested different optimization algorithms to find the optimum kick strengths of harmonic cavities to create a linear kick between +/-3σ_l area. In one of these algorithms, we minimize the area between the proton bunch center and $x = 0$ axis in the $z - x$ plane for each combination.

Table 4 shows the weak-strong simulation results with these combinations. Here 788 MHz, 1182 MHz, and 1576 MHz are the second, third, and fourth harmonics of 394 MHz. From the table, to be comparable to the beam size growth rates and the luminosity degradation rates with 197 MHz proton crab cavities, we need to combine all 394, 788, 1182, and 1576 MHz crab cavities together. However, having so many high frequency harmonic crab cavities also poses a big technical challenge. At this point, the final choice of proton crabbing frequency has not been decided yet.

SUMMARY

In this article, with a weak-strong beam-beam interaction model, we calculated the proton beam size growth rates and luminosity degradation rate for eRHIC. We found that large growth rates of beam sizes are related to the choice of proton crab cavity frequency. By choosing a lower frequency such as 197 MHz or using a high frequency harmonic cavities, these change rates can be greatly reduced. The final choice of crab cavity frequency will be decided soon. We also studied the effects of different proton tunes.

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