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COMBINED STRONG-STRONG AND WEAK-STRONG BEAM-BEAM SIMULATIONS FOR CRABBED COLLISION IN eRHIC*

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Abstract

In the eRHIC design, crab cavities are adopted to compensate the geometric luminosity loss from the crossing angle. In previous simulations, we observed a much larger luminosity degradation rate from strong-strong beam-beam simulation than that from weak-strong simulation. The discrepancy may come from the numerical noises in the strong-strong simulation and/or from the synchro-betatron resonance introduced by crabbed collision. In this article, we combine strong-strong and weak-strong treatments to study the possible sources for proton beam size growth and luminosity degradation.

INTRODUCTION

In the present eRHIC design, collision with a full crossing angle of 25 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 12.5 mrad in the x-z plane at the interaction point (IP) so that the two beams collide head-on in the head-on collision frame.

Ideally, the deflecting electric field of crab cavities should be proportional to the longitudinal position of particles. However, when the proton bunch length is comparable with the wavelength of the crab cavities, the sinusoidal form of the crab-cavity voltage may generate transverse position offsets in the x-z plane especially for protons in the bunch head and tail. This may drive incoherent or even coherent synchro-betatron resonances.

In the early weak-strong simulation, with the current eRHIC design parameters, the calculated relative luminosity degradation rate is about 10^{-10}/ turn in a 2 million turn tracking with 10,000 macro-particles. However, in the strong-strong beam-beam simulation, the calculated change rates of the proton beam sizes and luminosity degradation are about 10^{-8} – 10^{-7}/ turn, which is about 2 orders of magnitude larger than that from weak-strong simulation. The discrepancy between these two simulation methods may be caused by the known numerical noises in the strong-strong beam-beam simulation or a possible coherent synchro-betatron resonance between the proton and electron beams [1, 2].

In this article, we first analyze the turn-by-turn tracking data from strong-strong simulation. Then we perform weak-strong simulation with the electron bunch information extracted from strong-strong beam-beam simulation. The center of rigid electron bunch can be fixed or relaxed in the weak-strong simulations. The goal of this study to determine the effects of incoherent and coherent beam-beam interaction between the two beams.

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Table 1: Bema-Beam Related Parameters Used in the Study

Parameter	unit	proton ring	electron ring
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
(β_x^*, β_y^*)	cm	(94, 4.2)	(62, 7.3)
beam sizes at IP	um	(123,16)	
Bunch length	cm	7	0.43
Energy spread	10^{-4}	6.5	4.7

STRONG-STRONG SIMULATION

In this study, we adopt the eRHIC design parameter version 2.1, where the electron bunch is 0.43 cm and the proton bunch length is 7 cm. Table 1 shows the beam-beam related parameters. Since the electron bunch length is much shorter than the proton bunch length, in the strong-strong simulation we only slice the proton bunch longitudinally into 11 slices and do not slice the electron bunch [3]. At the IP, the electron bunch will interact with those 11 proton slices one by one in a time order. Both the proton and electron bunches are represented by 500,000 macro-particles.

The transverse radiation damping time for the electron beam is 4000 turns. In about two damping periods, the electron beam sizes reached a so-called equilibrium. We observe 'slow' growths in the proton beam sizes and luminosity degradation in 20,00 turns. There is no fast coherent motion or fast instability with a growth time shorter than 1,000 or 10,000 turns.

Figure 1 shows the particle distributions of the proton and electron bunches at IP after 20,000 turns. Clearly the protons in the bunch head and tail are horizontally offset away from the $x = 0$ axis. This is due to the limit wavelength of proton crab cavities. In the simulation, we use 338 MHz crab cavities for the protons. A lower crab cavity frequency will improve this situation but the cavity size will be bigger and the voltage will be higher. The final choice of the frequency is not made yet.

Figure 2 shows the turn-by-turn centriod positions of the proton bunch. Figure 3 shows the turn-by-turn and averaged centroid positions of the electron bunch. The horizontal axis is the longitudinal positions of the 11 beam-beam encoun-

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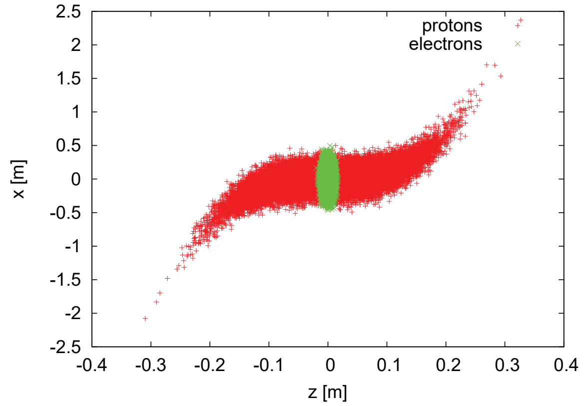

Figure 1: Proton and electron distributions at IP.

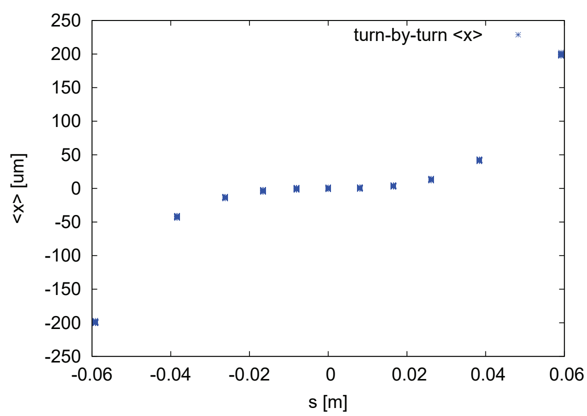

Figure 2: Turn-by-turn proton centroid position.

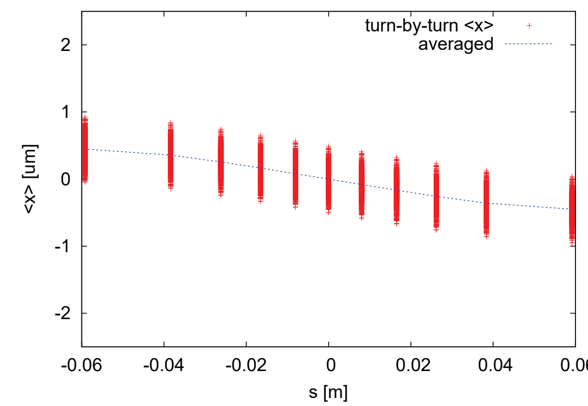

Figure 3: Turn-by-turn electron centroid position.

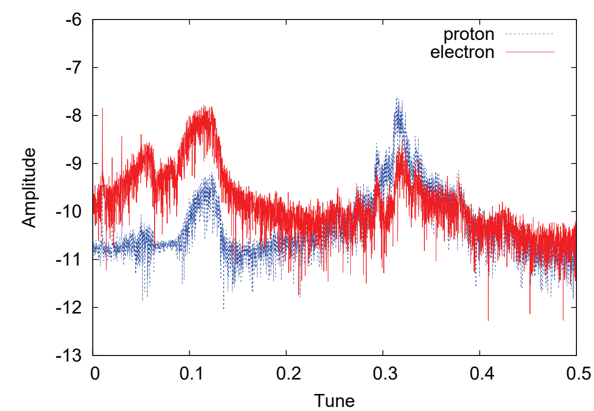

Figure 4: Spectrum of both beams' horizontal motion.

ters. The horizontal position offsets of the proton bunch are comparable to the beam size at IP and are much larger than that of the electron bunch. Both the average positions and oscillation amplitudes of the electron bunch center are less than 1 μm.

Figure 4 shows both beams' spectrum of horizontal centroid motion. Besides the betatron tunes of both beams, peaks of low multiples of proton synchrotron tunes are also visible in both spectrum. So far we are not sure how important roles of the incoherent and coherent synchro-betatron motions introduced by the offset beam-beam interaction. From simulation, the luminosity degradation rate depends on the proton transverse and longitudinal tunes, electron bunch intensities, and the frequency of crab cavities.

WEAK-STRONG SIMULATION

In the weak-strong simulation, to study the long-term stability of the proton beam, we assume the electron bunch is rigid. For a fair comparison of the calculated growth rates from strong-strong simulation, we first also slice the proton bunch longitudinally into 11 slices. Differently, we use the averaged electron centroid positions and beam sizes extracted from the above strong-strong simulation. We track 10,000 macro-protons up to 2 million turns.

To reduce the numerical noises due to limited proton slices, we next do weak-strong without slicing the proton bunch. To extract the electron bunch information in a larger range of longitudinal displacement from IP, we preform another one-pass strong-strong beam-beam simulation with the final particle distributions from above strong-strong simulation. In this calculation, we slice the proton into 101 equal-distant slices. Figure 5 shows the electron bunch centroid position between +/-0.2 m from IP. The red dots are these with 11 proton slices. Figure 6 shows the electron bunch's horizontal beam sizes. Without proton slicing, the electron information at the encounter point will be extrapolated.

Table 2 compares the results with and without proton slicing. WS stands for tracking 11 proton slices, others weak-strong simulations without slicing. WS1 means tracking with the static averaged electron bunch's horizontal offsets and beam sizes, WS2 with zeroed electron bunch's offsets, WS3 with 0.5 μm turn-by-turn random offsets, WS4 with 0.5 μm turn-by-turn modulating offset with a modulating tune 0.12. With 11 slices, there is no much differences in the calculated change rates between the weak-strong and strong-strong simulations. Comparing WS and WS1, the calculated luminosity degradation rates are much smaller without proton slicing. Comparing WS1 and WS2, the ef-

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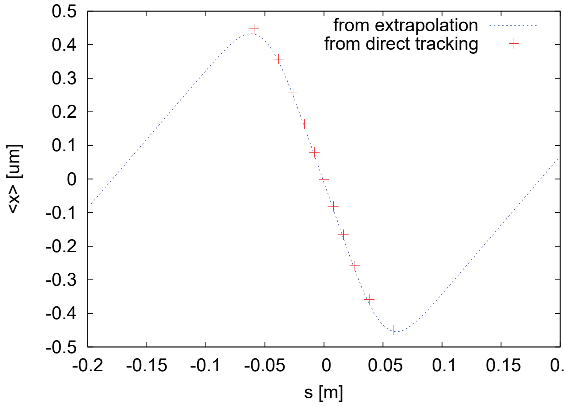

Figure 5: Electron bunch offsets in a larger range.

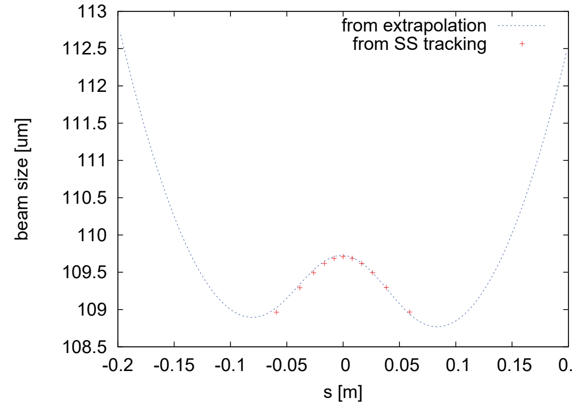

Figure 6: Electron bunch sizes in a larger range.

fects of turn-by-turn averaged electron bunch offsets are negligible. 0.5μm random electron bunch offset does change proton beam sizes and luminosity lifetime. However, the effects of 0.5μm modulating offset of electron bunch center is negligible.

To estimate the effect of coherent beam-beam interaction, in the following we allow the electron bunch's centroid move when the electron bunch goes through the proton bunch. We calculate and apply the kicks from the protons to the electron bunch center. We sum all the beam-beam kicks the rigid electron bunch gives to the macro-protons, and multiply a negative scaling factor before applying back to electron bunch center. Outside of IP, the electron bunch center will be transferred with one turn linear matrix same as in strong-strong simulation, and the radiation damping will be applied too. We call this treatment modified weak-strong (MWS) simulation.

During the MWS tracking, to avoid the numerical noise to the electron bunch center motion, we have to use a large number of macron-proton particles. In our case, we use 500,000 macro-particles and track them up to 40,000 turns. To save the computing time, we do not sort protons longitudinally. Table 3 shows the results with MWS method. With crabbed collision, MWS method gives a luminosity degradation rate between the SS and WS methods but more close to SS simulation. Head-on collision is also studies for comparison. The luminosity degradation rate from WS1 method is about two order of magnitudes smaller than that from SS method. The results from the MWS are also more closer to the SS method than the WS1 method.

Table 2: Comparison of Calculated Change Rates with Crabbed Collision

Method	$\frac{\Delta\sigma_x}{\sigma_x}$/turn	$\frac{\Delta\sigma_y}{\sigma_y}$/turn	$\frac{\Delta L}{L}$/turn
11 slices:			
SS	1.1×10^{-7}	2.3×10^{-7}	-1.5×10^{-7}
WS	8.1×10^{-8}	6.3×10^{-7}	-2.7×10^{-7}
no slicing:			
WS1	4.8×10^{-9}	5.1×10^{-8}	-7.7×10^{-9}
WS2	2.8×10^{-9}	4.6×10^{-8}	-7.2×10^{-9}
WS3	2.9×10^{-8}	7.5×10^{-8}	-3.6×10^{-8}
WS4	5.3×10^{-9}	5.0×10^{-8}	-6.2×10^{-9}

Table 3: Calculated Change Rates with Modified Weak-Strong Method

Method	$\frac{\Delta\sigma_x}{\sigma_x}$/turn	$\frac{\Delta\sigma_y}{\sigma_y}$/turn	$\frac{\Delta L}{L}$/turn
crabbed:			
SS	1.1×10^{-7}	2.3×10^{-7}	-1.5×10^{-7}
WS1	4.8×10^{-9}	5.1×10^{-8}	-7.7×10^{-9}
MWS	-3.0×10^{-8}	1.4×10^{-7}	-5.3×10^{-8}
head-on:			
SS	-5.8×10^{-9}	1.4×10^{-7}	-6.6×10^{-8}
WS1	2.6×10^{-10}	3.0×10^{-9}	-4.3×10^{-10}
MWS	-3.0×10^{-8}	8.7×10^{-8}	-1.3×10^{-8}

SUMMARY

In this article, we calculated and compared the growth rates of proton beam sizes and luminosity degradation rate with different beam-beam simulation methods. From strong-strong simulation, we extracted turn-by-turn averaged electron bunch center offsets and beam sizes during beam-beam interaction. We applied them to various weak-strong simulations. Weak-strong simulation gives a luminosity degradation rate about two order magnitude smaller than that from strong-strong simulation. The effects of small electron bunch center offsets less than 0.5μm is negligible. Same amplitude of random offset of electron bunch center is more harmful than modulating offset. We also tested modified weak-strong method, which we plan to continue exploring in the future.

REFERENCES

[1] Y. Luo *et al.*, in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 105–107. doi:10.18429/JACoW-IPAC2018-MOPMF012

[2] Y. Hao *et al.*, in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 368–370. doi:10.18429/JACoW-IPAC2018-MOPMK010

[3] Y. Luo, *Nucl. Instrum. and Methods* A 801, pp. 95-103, 2015.