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SIMULATION CHALLENGES FOR eRHIC BEAM-BEAM STUDY*

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Abstract

The 2015 Nuclear Science Advisory Committee Long Rang Plan identified the need for an electron-ion collider (EIC) facility as a gluon microscope with capabilities beyond those of any existing accelerator complex. To reach the required high energy, high luminosity, and high polarization, the eRHIC design, based on the existing heavy ion and polarized proton collider RHIC adopts a very small β-function at the interaction points, a high collision repetition rate, and a novel hadron cooling scheme. A full crossing angle of 25 mrad and crab cavities for both electron and proton rings are required. In this article, we will present the high priority R&D items related to the beam-beam interaction studies for the current eRHIC design, the simulation challenges, and our plans and methods to address them.

INTRODUCTION

For the present eRHIC design, the maximum beam-beam parameters for the electron and proton beams are $\xi_e = 0.1$ and $\xi_p = 0.015$, respectively. The choice of the beam-beam parameter of $\xi_e = 0.1$ for the electron beam is based on the successful operational experience of KEKB, where it was achieved with a transverse radiation damping time of 4000 turns. The choice of the beam-beam parameter for the proton ring is based on the successful operational experience of RHIC polarized proton runs, where a beam-beam parameter of $\xi_p = 0.015$ was routinely achieved.

To avoid long-range collisions, a crossing-angle collision scheme is adopted. For the present design, the proton and electron beams collide with a total horizontal crossing angle of 25 mrad. To compensate the luminosity loss by the crossing angle collision, crab cavities are to be used to tilt the proton and electron bunches such that they collide head-on at the IP. Table 1 shows key beam-beam interaction related parameters of the eRHIC design [1].

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 IPs 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. For the local crabbing scheme, the horizontal betatron phase advances between the crab cavities and IP are $\pi/2$.

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Table 1: Machine and Beam Parameters for eRHIC Design

Parameter	unit	proton ring	electron ring
Circumference	m	3833.8451	
Energy	GeV	275	10
Bunch Intensity	10^{11}	1.05	3.0
Working point	-	(29.31, 30.305)	(51.08, 48.06)
synchro. tune	-	0.01	0.069
$\beta^*_{x,y}$	cm	(90,5.9)	(63, 10.4)
rms emittance	nm	(13.9,8.5)	(20,4.9)
Bunch length	cm	7	1.9
Energy spread	10^{-4}	6.6	5.5
Crossing angle	mrad	25	

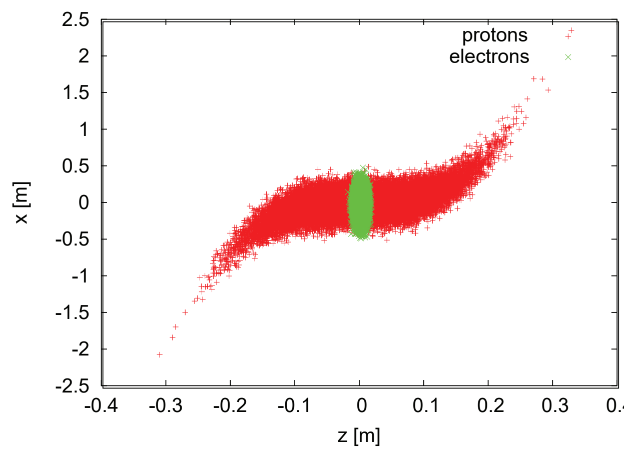

Figure 1: Electron and proton bunch profiles in the head-on frame.

SIMULATION CHALLENGES

Dynamics Study and Numerical Simulation of Crabbing Collision with Crab Cavities

For collision with a crossing angle and crab cavities, when the bunch length is comparable with the wavelength of the crab cavity, the sinusoidal form of the crab-cavity voltage may lead to the transverse deviation of particles at the bunch head and tail as the function of the longitudinal position of the particles. As an example, Figure 1 shows the proton and electron bunch profiles at IP in the $x-z$ plane in the head-on collision frame.

With weak-strong simulation, the calculated relative luminosity degradation rate in a 2 million turn tracking with 10,000 macro-protons is about 10^{-10}/ turn with the eRHIC design parameters. However, with strong-strong beam-beam simulation, the change rates of the proton beam sizes and luminosity degradation are at 10^{-8} – 10^{-7}/ turn. The discrepancy between these two simulation methods may be

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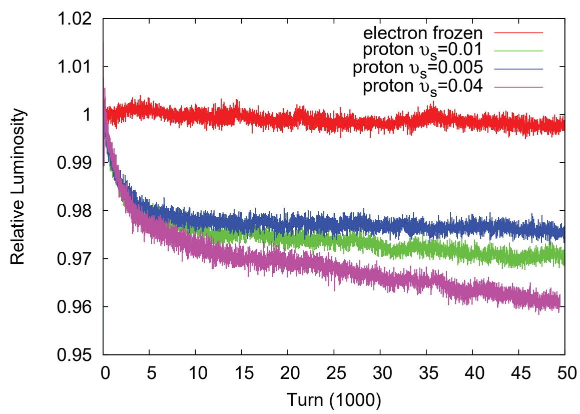

Figure 2: Luminosity degradation as function of proton synchrotron tune.

caused by the numerical noise in the strong-strong beam-beam simualtion or a possible coherent synchro-betatron resoance between the proton and electron beams [2]. We also found that the luminosity degradation rate depends on the frequency of the crab cavity, the proton synchrotron tunes, the proton bunch length, and the bunch intensities, and so on. One example is as shown in Figure 2.

As we know, numerical noise in the self-consistent strong-strong beam-beam simulation can cause artificial emittance growth and may block the true physics driven emittance growth. To verify the small emittance growth observed from the strong-strong simulations, the most challenging task is to separate the beam degradation due to the nonlinear resonance from the artificial emittance growth induced by the numerical noise in the strong-strong beam-beam simulation code. The numerical noise reduction is an essential step for the further understanding of the EIC crab crossing scheme.

In the most of existing beam-beam strong-strong beam-beam simulation codes, the particle-in-cell and Green's function methods are used to solve the 2-dimensional Poisson equation to obtain the electro-magnetic fields from one slice of one bunch [3]. To reduce the numerical noises, we propose to use a spectral method that uses a finite number of global basis functions to approximate the charge density distribution. Such a spectral method helps smooth the numerical noise associated with a finite small number of macro-particles and mitigate the numerical noise driven emittance growth. The early result with this approach shows much smaller emittance growth due to numerical noise can be achieved in the 4-d beam-beam interaction situation.

Quantitative Understanding of the Damping Decrement to the Beam-Beam Performance

To reach the beam-beam parameter 0.1 for the electron rings of eRHIC and JLEIC, based on the experience at KEKB, it requires a radiation damping decrement of 1/4000, or a radiation damping time of 4000 turns, in the transverse plane. To achieve the same radiation damping decrement at the low electron beam energies of eRHIC, super-bends are being considered for the electron ring lattice design. The purpose of these complicated three-segment super-bends is to be able to radiate additional synchrotron radiation energy at low electron energies to increase the radiation damping rate.

Since the connection between the damping decrement and the achievable beam-beam parameter is empirical, we carried out beam-beam simulations to study the beam-beam performance with different radiation damping decrements with strong-strong beam-beam simulation codes [4]. Figure 3 shows the evolution of the horizontal beam size of the electron beam with different radiation damping times. In these simulation studies, we did not observe coherent beam-beam motion with the different damping times. Simulations show that there are not significant differences in equilibrium beam sizes and luminosities even when the radiation damping time is up to 12,000 turns, or 3 times the design value.

Lepton beams can tolerate beam-beam tune shift parameters 0.1 that are about ten times larger than corresponding values for collisions between hadron beams. The common understanding of these facts is the presence of radiation damping in lepton beams and the absence of damping in the hadron beam. It is of great importance for EIC running with low electron energies. Therefore, further investigations with dedicated simulation methodology and computer codes are required to study the effects of damping decrement to the beam-beam performance, and establish the connections between the damping decrement and the maximum beam-beam parameter at various collision energies for the eRHIC design.

To fully understand the effects of synchrotron damping time on the beam-beam performance, the lattice nonlinearity should be included into the strong-strong beam-beam simulation. Both the beam-beam and the lattice nonlinearities generate diffusion. The beam-beam force decreases like 1/r while the nonlinear magnetic force increases like polynomials with the particle amplitude. The simulation shows that without the lattice non-linearities, the diffusion solely due to beam-beam interaction is weak. Therefore, in the simulation code we plan to 1) replace the linear ring lattice with a nonlinear map up to a certain order, 2) include high order nonlinear field errors from the interaction region, and 3) use the real RF cavities instead of linear synchrotron oscillation in the simulation.

Impacts on Protons with Electron Bunch Swap-Out in eRHIC Ring-Ring Design

In the current eRHIC ring-ring design, a rapid cycling synchrotron (RCS) is chosen as the baseline injector to the main electron storage ring. The RCS will be accommodated in the existing RHIC tunnel. It will be capable of accelerating the electron beam from a few hundred MeV up to 18 GeV and maintaining the electron polarization during acceleration.

The required electron bunch intensity of up to 50 nC in the eRHIC electron storage ring exceeds the capabilities of

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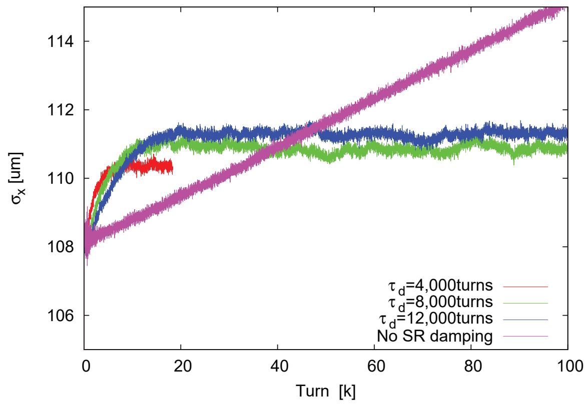

Figure 3: Equilibrium electron horizontal beam size as fucntion of the radiation damping time.

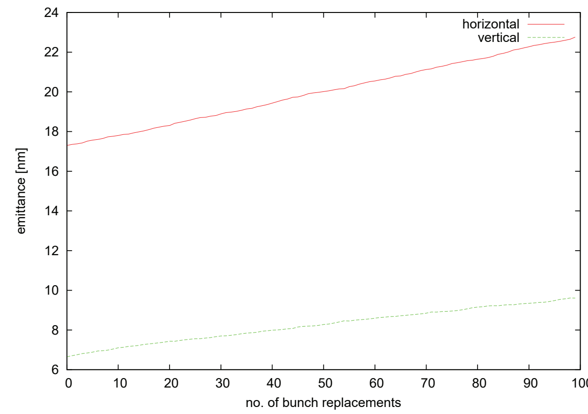

Figure 4: The simulated emittance evolution of the proton bunch during 100 electron bunch replacement.

the electron gun, and such a high bunch intensity would also lead to instabilities at an injection energy in the RCS. These limitations necessitate accumulation of electrons in the electron storage ring.

To minimize detector background during the injection process, an accumulation in the longitudinal phase space is being proposed. After one electron bunch in the electron storage ring is kicked off, it will be replaced with 5 electron bunches from the RCS. The bunch intensity from the RCS is about 10 nC. To maintain high electron polarization in the electron storage ring, we will replace one electron bunch in one second and replace all electron bunches in 5 minutes.

With zero dispersion throughout the detector and the upstream beam line, the newly injected bunches travel on the same closed orbit in the region as the stored beam. However, the beam-beam effect of the injected electron bunches from the RCS on the stored proton beam needs to be studied. The beam-beam parameter for the corresponding proton bunch changes during the electron bunch replacement.

A weak-strong study simulation code was developed to study the proton bunch emittance blow-up during the electron bunch replacement [5]. In the code, the proton bunch is represented by macro-particles and the electron bunches are represented by rigid charge distribution. The 4-d beam-beam kick is used. The effect of radiation damping is simply included by adjusting the position and the energy deviation of the rigid electron bunches. Figure 4 shows the calculated emittance evolution over the course of 100 electron bunch replacements from the above weak-strong code. Since one bunch is replaced every 5 minutes, the time for 100 bunch replacements is about 9 hours. From the plot, the emittance growth from the beam-beam interaction during the electron bunch replacement is less than 4%/hour.

The above 4-d weak-strong simulation to study the electron bunch replacement in the eRHIC ring-ring design is not self-consistent. The injected electron bunch may not have a 4-d Gaussian charge distribution. During the period of the electron bunch passing through the proton bunch, its beam sizes can be altered by the beam-beam force too. And the electron bunch does not always collide with the proton bunch at IP. A self-consistent 6-d strong-strong beam-beam simulation code is needed to study the beam-beam effects during the electron bunch replacement.

SUMMARY

In this article, we have presented the high priority R&D items related to the beam-beam interaction for the current eRHIC design. To mitigate the technical risks associated with the eRHIC design, we joined beam-beam simulation expertise from 3 laboratories and 1 university. We outlined the new beam-beam simulation algorithms and methods to the existing strong-strong beam-beam simulation codes. At the completion of this proposal, we should have a clear understanding of the beam-beam interaction in the eRHIC design and be able to provide robust counter-measures to possible beam-beam interaction related beam lifetime reduction, beam emittance growth, beam instabilities, and luminosity degradation.

REFERENCES

[1] C. Montag and V. Ptitsyn, *Beam Dynamics Newsletter*, No.74, August, 2018.

[2] Y. Hao, *et al.*, presented at IPAC18, Vancouver, Canada, Apr.-May 2018, paper MOPMK010.

[3] J. Qiang, M. Furman, R. Ryne, Strong-strong beam-beam simulation using a Green function approach, *PRST-AB*, v5, 104402 (2002).

[4] Y. Luo, *Additional beam-beam challenges*, presented in the EIC collaboration meeting, Oct. 1-3, 2017, Brookhaven National Laboratory, New York, USA.

[5] C. Montag, unpublished, 2017.