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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 22 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

The key EIC machine parameters identified in the 2015 Long Range Plan [1] are: 1) polarized (70%) electrons, protons, and light nuclei, 2) ion beams from deuterons to the heaviest stable nuclei, 3) variable center of mass energies ~20–100 GeV, upgradable to ~140 GeV, 4) high collision luminosity ~10^{33}–10^{34} cm^{-2}sec^{-1}, and possibly have more than one interaction region. To reach such a high luminosity, both designs of eRHIC at Brookhaven National Laboratory (BNL) and JLEIC at Thomas Jefferson National Accelerator Facility (JLab) aimed to increasing the bunch intensities, reducing the beam sizes at the interaction points (IPs), and increasing the collision frequency, while keeping achievable maximum beam-beam parameters for involved beams [2, 3].

The relative priorities of R&D activities for a next generation EIC were published in the 2016 NP Community EIC Accelerator R&D panel report [4]. The panel evaluated the R&D items needed for each of the current EIC design concepts under considerations by the community. Beam-beam interaction have been identified as one of the most important challenges needed to be addressed to reduce the overall design risk.

We join the expertise from BNL, JLAB, Lawrence Berkeley National Laboratory (LBNL), and Michigan State University (MSU) to address 4 challenging items related to the EIC beam-beam interaction in the two EIC ring-ring designs, namely, 1) beam dynamics study and numerical simulation of crabbed collision with crab cavities, 2) quantitative understanding of the damping decrement to the beam-beam performance, 3) impacts on protons with electron bunch swap-out in eRHIC ring-ring design, and 4) impacts on beam dynamics with gear-changing beam-beam interaction in JLEIC design.

To address the above critical items related to EIC beam-beam interaction, we propose new beam-beam simulation algorithms and methods to the existing strong-strong beam-beam simulation codes, together with a deep physics understanding of the involved beam dynamics. At the completion of this proposal, we should have a clear understanding of the beam-beam interaction in the next generation EIC designs 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. This work would significantly mitigate the technical risks associated with the EIC accelerator designs.

In this article, we will only focus on the simulation challenges related to the eRHIC beam-beam study, or the first three R&D items listed above. They are the common challenges to the eRHIC and JLEIC designs. JLEIC design also have another challenge: impacts on beam dynamics with gear-changing beam-beam interaction, which will not be discussed here.

eRHIC DESIGN PARAMETERS

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 22 mrad. Such a crossing angle scheme is also required by the experiment to avoid separator dipoles in or near the detector, thus minimizing the background in the interaction region (IR). 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 current eRHIC design. Without cooling, the design luminosity is 4.4×10^{33}cm^{-2}s^{-1}. With cooling in the proton ring, it is 1.05×10^{34}cm^{-2}s^{-1}.

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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	22	

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 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 $\pi/2$. The voltage of the crab cavity is

$$\hat{V}_{RF} = -\frac{cE_s}{4\pi f_{RF}\sqrt{\beta^*_x \beta_{cc}}}\theta_c. \tag{1}$$

Here c is the speed of light, E_s is the particle energy in eV, f_{RF} is the crab cavity frequency, and θ_c is the full crossing angle. β^*_x and β_{cc} are the horizontal β functions at the IP and the crab cavity, respectively.

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 folllowing, we assume 338 MHz for the crab cavities in both proton and electron rings. The final choice of the crab cavity frequency is not made yet.

With crabbed collision between the electron and proton bunches, we focus on the emittance growth and luminosity degradation. For this purpose, we 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 evaluate the long-term stability of the protons. In the weak-strong simulation, the equilibrium electron beam sizes from the strong-strong simulation are used.

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 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 in the $x - z$ plane in the head-on collision frame.

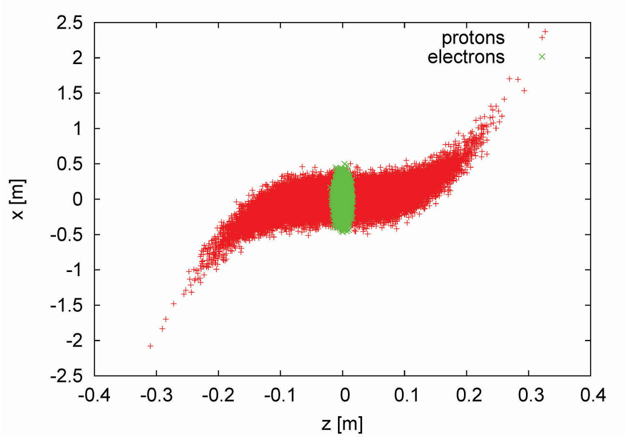

Figure 1: Electron and proton bunch profiles in the head-on frame.

In 2017, supported by the NP proposal award (PI: Yue Hao and Ji Qiang), a special synchro-betatron resonance, which coupled through beam-beam interaction, was found due to the imperfect crab kick, using a strong-strong beam-beam simualtion code [5]. The resonance raises from the beam-beam induced coupling between the transverse motion of the electron beam and the synchrotron motion of the proton beam, and causes luminosity reduction of ~1% per second from the simulation, which depends on the frequency of the crab cavity and the proton synchrotron tunes as shown in Figure 2.

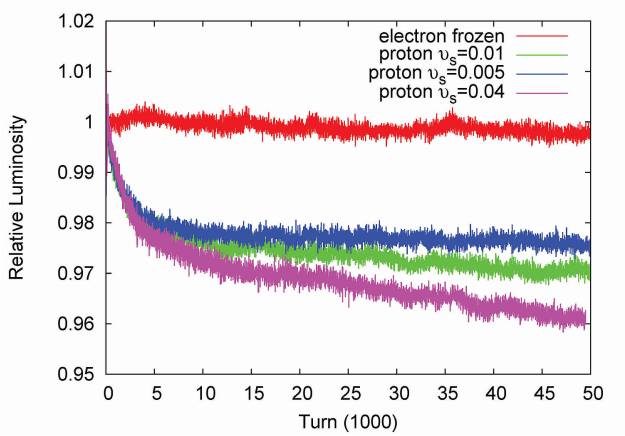

Figure 2: Luminosity degradation as function of proton synchrotron tune.

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. Currently, the computational method used in those simulations is based on a particle-in-cell method with Green's function to calculate the beam-beam force self-consistently.

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.

At present, the only crab crossing scheme is accomplished by KEKB [6]. The beam-beam induced synchro-betatron resonance can be suppressed by the synchrotron radiation damping of both colliding beams. The situation is quite different in an EIC, since the ion beam does not have fast damping. Therefore, to achieve a more reliable prediction, it is desired to develop special codes and/or simulation methods, which exclude or largely reduce the artificial numerical noise in the beam-beam simulation.

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, super-bends are being considered for the electron ring lattice design in eRHIC. 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 [7]. Figure 3 shows the evolution of the horizontal beam size of the electron beam with different radiation damping times.

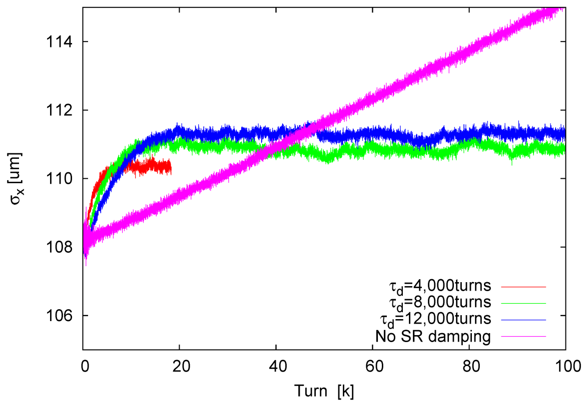

Figure 3: Equilibrium electron horizontal beam size as a fucntion of the radiation damping time.

In these simulation studies, we did not observe coherent beam-beam motion with the different damping times as shown in Fig. 3. Simulation results show that with a longer damping time, it takes a longer time to reach the electron equilibrium beam size. However, 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 current EIC ring-ring designs.

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 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 replace with 5 electron bunches from the RCS. The bunch intensity from the RCS is about 10 nC. The time interval between the injected RCS bunches is 1 second, or 7800 turns. To maintain high electron polarization in the electron storage ring, we will replace one electron bunch in 1 second and replace all electron bunches in 5 minutes.

With zero dispersion throughout the detector and the upstream beamline, 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 [8]. 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 horizontal and vertical emittance evolution over the course of 100 electron bunch replacements from the above weak-strong code. Since each 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.

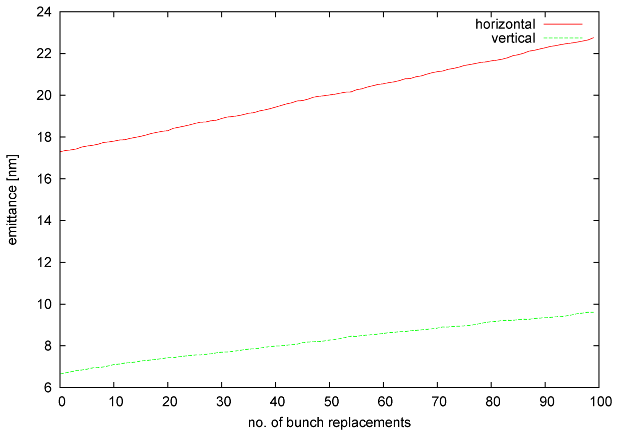

Figure 4: The simulated emittance evolution of the proton bunch during 100 electron bunch replacement.

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 size 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.

PROPOSED RESEARCH AND METHODS

Both strong-strong and weak-strong beam-beam simulation codes are to be used to address the above simualtion challenges in the eRHIC beam-beam studies. We choose Dr. Qiang's code BeamBeam3D [9] for the strong-strong beam-beam simulations, and Dr. Luo's code SimTrack [10] for the weak-strong beam-beam simulations. To meet the needs for the required EIC beam-beam simulations, we will make several modifications to these existing codes.

Beam Dynamics Study and Numerical Simulation of Crabbed Collision With Crab Cavities

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 Possion equation to obtain the electro-magnetic fields from one slice of one bunch. To reduce the numerical noises in the strong-strong beam-beam simulations, 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 (in comparison to the real number of particles in a bunch) and mitigate the numerical noise driven emittance growth.

Figure 5 compares the emittance growth evolution by using the standard Green's function method and the spectral method in a single slice beam-beam force model [11]. It is seen that the spectral method yields much less numerical noise driven emittance growth than Green's function method. This example shown here is the nominal LHC parameters without crossing angle and with a single interaction point. For those parameters, it is expected that there should be little emittance growth under the stable operational condition. In our plan, we would like to extend the above spectral method to multi-slice beam-beam interaction model. We also plan to implement this method on the massive parallel computers using a hybrid parallel programming model.

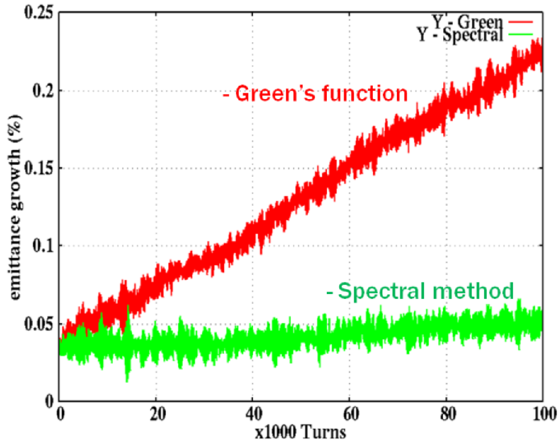

Figure 5: Comparison of calculated emittance growth with Green's fucntion and spectral method.

With the new code development, we will try to find the scaling behavior of the luminosity degradation due to the sychro-betatron resonance as function of the beam-beam parameters of both beams, as well as the crab cavity frequency and the crossing angle. we also will evaluate if the non-zero dispersion function or the non-$\pi/2$ phase advance at the location of crab cavities will lead to beam quality degradation. The effects of the noises in the voltage and phase of crab cavities will be evaluated too.

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

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. The equilibrium emittances are decided by the ratio of the radiation damping and the nonlinear lattice caused diffusion. 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 nonlinearities, the diffusion solely due to beam-beam interaction is weak.

For most of the existing strong-strong beam-beam simulation codes, the ring is simply represented by a 6×6 linear matrix to save the computing time involved in the beam-beam interaction calculation. However, from single particle element-by-element weak-strong beam-beam simulations, we learned that the interplay between the beam-beam interaction and the lattice non-linearities plays a crucial role to the dynamic aperture.

To include the lattice non-linearities without time-consuming element-by-element particle tracking in the strong-strong beam-beam simulation code, we propose the following methods: 1) Replace the linear ring map by a nonlinear map to up to a certain order. The nonlinear map should be symplectic in order to avoid artificial diffusion. To shorten the tracking time, a low order map, for example up to the 5th order, is planned during the first test. A higher order map can be implemented later as necessary. 2) Implement high order nonlinear field errors in the interaction region. According to the RHIC experiences, these high order field errors play an important role in the dynamic aperture reduction. 3) In the longitudinal plane, we plan to use the real RF cavities instead of linear synchrotron oscillation.

With the proposed lattice nonlinear in the strong-strong beam simualtion codes, we will be able to study the effects of the damping decrement to the beam-beam performance. We will establish the connection between the damping decrement and the maximum beam-beam parameter for eRHIC.

Impacts on Protons with Electron bunch Swap-out in eRHIC Ring-ring Design

Instead of early 4-d weak-strong simulation method, we propose to use the self-consistent 6-d strong-strong beam-beam code BeamBeam3D to simulate the electron bunch replacement in the eRHIC ring-ring design. To be suitable for this study, some modifications to BeamBeam3D are needed.

In the eRHIC ring-ring design, one electron bunch in the storage ring will be knocked out every 5 mins. 5 RCS bunches with a smaller bunch charge will be injected in the same bucket in the longitudinal phase space. The interval between these 5 injections is 1 second. In the code, we will first simulate the interaction between an electron bunch and a proton bunch up to several electron damping times to reach the equilibrium. After the 5 RCS bunches are injected, we also need to continue to track the beam-beam interaction between the newly injected electron bunch and the proton bunches up to a few damping times.

With these code modifications, we will evaluate the emittance growth during the electron bunch replacement. We will record the proton bunch emittance's change during the electron bunch kick-off, each RCS bunch injection, and the final equilibrium. The emittance blow-up will be compared with the analytical estimate based upon a linear beam-beam force assumption and that from the previous weak-strong beam-beam simulation. We also will study the effects of any errors or noises during the electron bunch replacement, for example, the injection jitters, the fluctuation in the RCS bunch intensities, and so on.

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 EIC accelerator designs, we joined beam-beam simualtion expertises from 3 labroatories 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 next generation EIC designs 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.

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