STUDY OF BEAM-BEAM EFFECTS IN eRHIC*

Y. Hao†, V. Litvinenko and V. Ptitsyn, BNL, Upton, NY 11973, U.S.A.

Abstract

Beam-beam effects in eRHIC have a number of unique features, which distinguish them from both hadron and lepton colliders. Due to beam-beam interaction, both electron and hadron beams would suffer quality degradation or beam loss from without proper treatments. Those features need novel study and dedicate countermeasures. We study the beam dynamics and resulting luminosity of the characteristics, including mismatch, disruption and pinch effects on electron beam, in additional to their consequences on the opposing beam as a wake field and other incoherent effects of hadron beam. We also carry out countermeasures to prevent beam quality degrade and coherent instability.

INTRODUCTION

In energy recovery linac (ERL) based electron ion collider (EIC), the energies and the rest masses of the ion beam and electron beam usually does not equal. Especially, the beam-beam parameters of the opposing beams differ by two orders of magnitude. The electron beam collides with the ion beam only once so that the beam-beam parameter of it can exceed the usual limitation in an electron collider ring and reaches and the resulting luminosity gets one order of magnitude increase, compared to a ring-ring scheme collider.

This asymmetry brings designers not only the benefits to take advantages of but also the challenges to overcome. There are many factors that require special studies. In this paper, we focus on two effects. First, we revisit our study in electron beam mismatch effect and propose a new parameter to quantified this effect. Second, a special electron beam feedback system is discussed to suppress the ion beam coherent emittance growth.

We take eRHIC with Coherent Electron Cooling [1] (CEC) parameters as the example (in Table 1) and focus our attention to proton beam instead of other ion species, because it provides the worst cases in those listed challenges. The principles and treatment we present here can obviously be migrated to other ERL based EIC proposals.

* Work supported by Brookhaven Science Associates, LLC under Contract No. DE-AC02-98CH10886 with the U.S. Department of Energy.

† yhao@bnl.gov

Table 1: ERL based eRHIC parameters

	p	e
Energy (GeV)	250	10
Number of bunches	166	
Bunch intensity ($\times 10^{11}$)	2.0	0.22
Beam current (mA)	420	260
95% normalized emittance for p/ rms normalize emittance fore e	1	13
rms Emittance (nm)	0.66	0.66
β^*(cm)	25	25
Beam-beam parameter ξ for p/ Disruption parameter d for e	0.015	7.2
rms bunch length (cm)	4.1	0.7
Peak luminosity ($\text{cm}^{-2}\text{s}^{-1}$)	2.7×10^{33}	

THE MISMATCH PARAMETER OF THE ELECTRON BEAM

The electron beam undergoes large nonlinear beam-beam force. For a round transverse Gaussian distribution ion beam, the force has the form:

$$\vec{F}_r = \frac{n(z)e^2}{\pi\varepsilon_0 r^2}\left[1-\exp\left(-\frac{r^2}{2\sigma^2}\right)\right]\vec{r} \tag{1}$$

By taken a linear approximation of the beam-beam force generated by the proton beam, the focal length of the linear force is

$$\frac{1}{f_e} = \frac{N_p r_e}{\sigma_p^2 \gamma_e} \tag{2}$$

where σ is the transverse rms beam size, N is the number of particle per bunch, r is the classical radius of the particle and γ is the lorentz factor. The subscript p and e denote electron and proton beams respectively. The beam-beam parameter and disruption parameter are calculated from the focal length as $\xi_e = \beta_e/(4\pi f_e)$ and $d_e = \sigma_{pz}/f_e$. Here, β_e is the beta function of the electron beam at the collision point, σ_{pz} is the rms bunch length of the pronton beam.

The disruption parameter d, revealed in [2][3], represents the oscillation of the electron beam inside the long proton bunch. The oscillation wave number is given by

$$n = \frac{1}{2\pi}\int_{-\infty}^{\infty} k(s)\,ds \approx \frac{\sqrt{d_e}}{4} \tag{3}$$

when the longitudinal distribution of the proton beam is Gaussian. Here $k(s)$ is the beam-beam focusing strength that appears in Hill's equation.

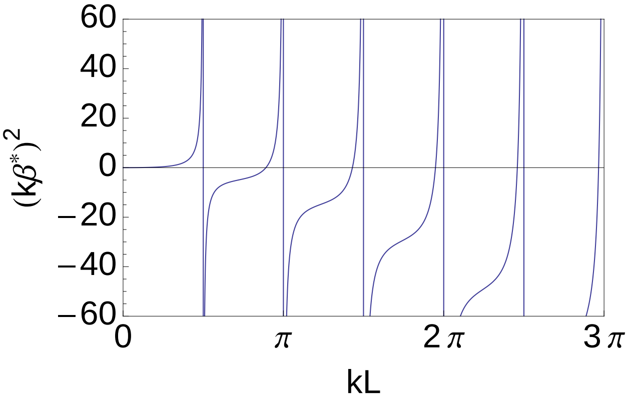

Figure 1: The solution of equation 4.

In linear field approximation, only the mismatch between the beam distribution and the design optics contribute the emittance growth. It is possible [3] to adjust β^*, hence the phase advance at IR without beam-beam interaction, to match the phase shift with beam-beam effect. For a uniform longitudinal distribution of the proton beam, the exactly matched solution can be found analytically. If the proton beam has constant longitudinal profile within $[-2L, 2L]$, the proton rms beam size is $2L/\sqrt{3}$. Then, we can calculate the exact matching solution as:

$$\beta^* = \frac{\sqrt{1 - k^2L^2 + kL\left[\tan\left(kL\right) - \cot\left(kL\right)\right]}}{k} \tag{4}$$

where k is a constant now. When kL falls in the region $[0, \pi/2]$, the matching solution always exists, $(k\beta^*)^2 > 0$. Equivalently, this requires that the disruption parameter D less than $\pi^2/\sqrt{3} = 5.7$. There are also other regions that has solution for β^*, however, the regions shrinks as the beam-beam force getting stronger, as shown in figure 1.

Taking nonlinearity into account, we will find that the perfect matching can not be satisfied for all electrons, since the beam-beam phase advance now depends on the betatron oscillation amplitude. The electron distribution after collision is determined by the simulation code EPIC [3]. Since the proton beam is much more rigid than the electron beam, a strong (the proton beam)-weak (the electron beam) approximation is suitable. After beam-beam interaction, the electron macro-particle will be traced back to IP. From the distribution, the optics functions can be calculated. We define a match parameter m as:

$$m = \left(\beta\gamma^* - 2\alpha\alpha^* + \beta^*\gamma\right)/2 \tag{5}$$

where the optics functions with and without asterisks represent the design optics and the values from the distribution respectively. The smallest value of m is 1, which means two ellipses of the optics functions are identical. The larger m is, the larger mismatch is observed.

Figure 2 through 4 illustrate the luminosity, effective emittance and average electron rms size as function of the match parameter, when we scan the design parameter as we

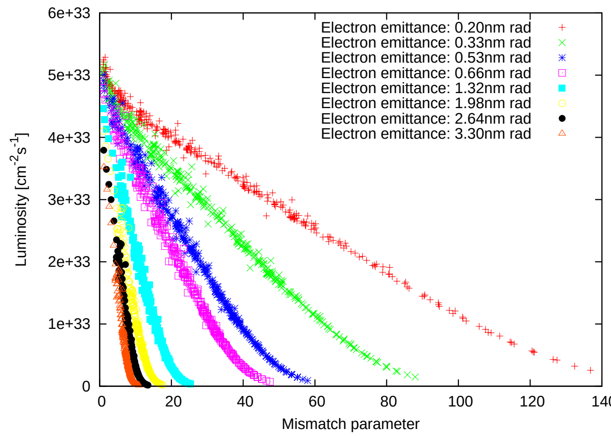

Figure 2: The luminosity as function of the mismatch parameter.

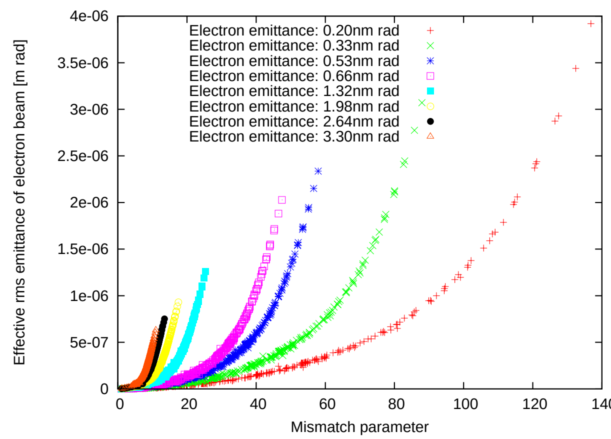

Figure 3: The final rms effective emittance as function of the mismatch parameter.

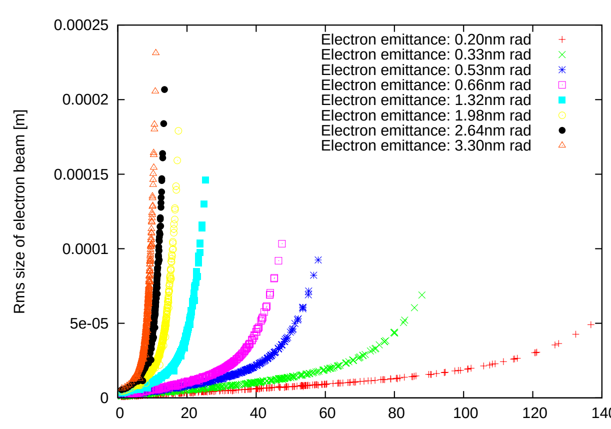

Figure 4: The average rms electron beam size as function of the mismatch parameter.

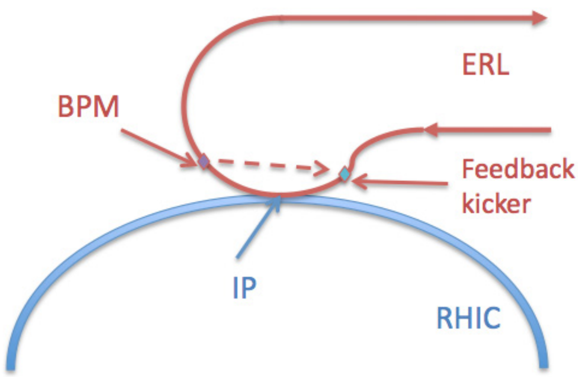

Figure 5: The schematic drawing of feedback system for mitigating kink instability in EIC

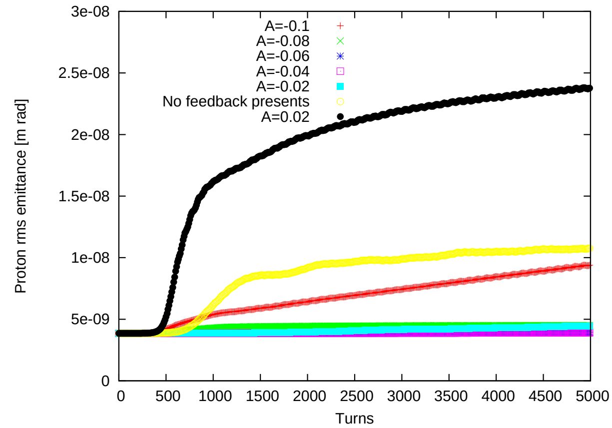

Figure 6: The state-of-art simulation for the feedback system.

did in [3]. In all 3 graphs, each point represents a different design optics and initial emittance of the electron beam.

The advantage of this parameter m is that all important parameters have a simple relation with it with specific initial electron emittance. Therefore the optimization of the whole electron disruption process is simplified by properly searching the best value of mismatch parameter m. The disadvantage of this parameter is also obvious. It cannot be calculated from the parameter table, instead, must be derived from the simulation.

FEEDBACK SCHEME FOR THE KINK INSTABILITY

The kink instability is a head-tail type instability that arise from the beam-beam interaction. A simple 2-particle model gives the threshold of it as:

$$d_e\xi_p < \frac{4\nu_s}{\pi} \approx \nu_s \tag{6}$$

where ν_s is the synchrotron tune. For RHIC, the tune now has the order of 10^{-3}, therefore the current eRHIC parameters are much larger than the threshold.

We already demonstrated that a large tune spread could induce landau damping to suppress this instability. However, a large chromaticity $d\nu/d\delta$ (at least 5 units) is necessary to generate such tune spread. Previous experience of RHIC operation indicates that it is unpleasant to tune the machine to such high number, because of the longitudinal aperture and other limitations.

We carry out a feedback system to mitigate the kink instability, taking advantage of the fact that the electron beam is used only once. The scheme is shown in figure 5. After the collision with the proton beam, the electron bunch's offset is picked up by BPM and the information is sent to the feedback kicker. The kicker will apply an angular or position kick to the next electron bunch that collides with same proton bunch. The amplitude is proportional to the offset.

Mathematically, the electron beam centroid can be calculated from proton beam center fluctuation:

$$\bar{x}_e(s) = k\int_s^{L/2} \bar{x}_p(s', z = 2s') \sin[k(s-s')]\, ds' \tag{7}$$

if we assume the proton beam has a uniform longitudinal distribution with bunch length L and the initial condition (x_0, x_0') of the electron beam are all zero. Coordinate s is the longitudinal position and z is the relative position inside proton beam.

The feedback scheme introduce non-zero initial condition and the equation (7) has two extra terms:

$$x_0 \cos[k(L/2-s)] + x_0' \sin[k(L/2-s)] \tag{8}$$

To make the discussion simpler, we set the feedback system only introduce a position kick, which writes:

$$x_0 = Ak\int_{-L/2}^{L/2} \bar{x}_p(s'-C, z = 2s') \sin[k(s-s')]\, ds' \tag{9}$$

Here, A is the amplification factor. Figure 6 shows the application of feedback system on the eRHIC without CEC. The disruption parameter is 5.8, close to the value with CEC. And it shows the effectiveness of this method. With proper amplification factor, the initial condition (9) cancels the resonance term in equation (7). If the factor has incorrect sign, the instability is enhanced. The detail studies are in progress.

REFERENCES

[1] V. N. Litvinenko and Y. S. Derbenev, Phys. Rev. Lett. 102, 114801 (2009).

[2] S. A. Heifets, G. A. Krafft, and M. Fripp, NIM A 295, 286 (1990)

[3] Y. Hao and V. Ptitsyn, "Effect of Electron Disruption in the ERL based eRHIC", submitted to PRSTAB