BROOKHAVEN
NATIONAL LABORATORY

BNL-81820-2009-CP

Beam-beam interaction study of medium energy eRHIC

Y. Hao, V.N. Litvinenko, V. Ptitsyn

Presented at the Particle Accelerator Conference (PAC09)
Vancouver, B.C., Canada
May 4-8, 2009

Collider-Accelerator Department

Brookhaven National Laboratory
P.O. Box 5000
Upton, NY 11973-5000
www.bnl.gov

DISCLAIMER

Printed on recycled paper

BEAM-BEAM INTERACTION STUDY OF MEDIUM ENERGY ERHIC*

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

Abstract

Medium Energy eRHIC (MeRHIC), the first stage design of eRHIC, includes a multi-pass ERL that provides 4GeV high quality electron beam to collide with the ion beam of RHIC. It delivers a minimum luminosity of 10^{32} cm^{-2}s^{-1}. Beam-beam effects present one of major factors limiting the luminosity of colliders. In this paper, both beam-beam effects on the electron beam and the proton beam in MeRHIC are investigated. The beam-beam interaction can induce a head-tail type instability of the proton beam referred to as the kink instability. Thus, beam stability conditions should be established to avoid proton beam loss. Also, the electron beam transverse disruption by collisions has to be evaluated to ensure that the beam quality is good enough for the energy recovery pass. The relation of proton beam stability, electron disruption and consequential luminosity are carried out after thorough discussion.

INTRODUCTION

Medium Energy eRHIC (MeRHIC) is the initial stage of eRHIC. A three-pass ERL, to be installed in the free space of the interaction region(IR) #2 of the existing RHIC tunnel, can produce up to 4GeV high quality electron beam. The electron beam collides with 250 GeV proton beam at IR 2 with a luminosity greater than 10^{32} cm^{-2}s^{-1}. One scheme is to use the current RHIC proton beam without any modification, which is the 'not-cooled' case. After low-energy cooling is implemented, the 'pre-cooled' case can be achieved (Table 1). There is another scheme, the 'high energy cooling' case, which is not discussed here due to lack of space.

The beam-beam interaction is weaker for MeRHIC than its successor, eRHIC[1], since the beam sizes are larger. However the energy of the electron beam is also 2.5 times lower, and so is the rigidity. It turns out that the beam-beam and the disruption parameter for the electron beam is even larger than in the eRHIC case. Therefore, the electron disruption and the mismatch effects after collision are still essential for preventing beam loss in the ERL. The proton beam kink instability must also be evaluated because the wake field induced by the electron beam is strong.

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

† Email: yhao@bnl.gov

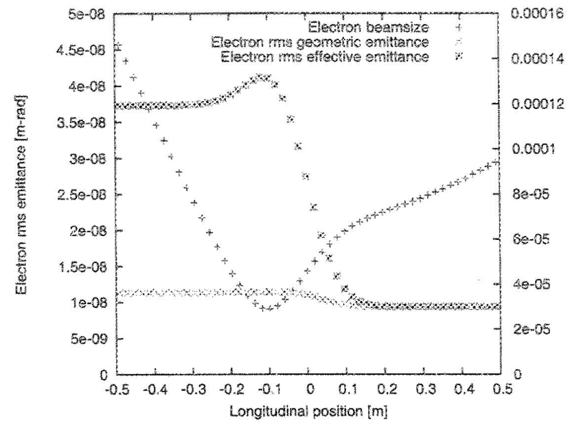

Figure 1: Electron beam evolution during beam-beam interaction.

THE DISRUPTION AND THE MISMATCH EFFECTS OF THE E-BEAM

Using simulation code EPIC (Electron Proton Interaction Code)[2], we can study two effects during the evolution of the electron beam when colliding with the opposing beam. First, the nonlinear beam-beam field deforms the initial electron distribution, which is called the disruption effect. Second, the field causes an additional phase advance, which is not included in the optics design. These two effects make the electron beam emittance vary during interaction. To distinguish them from each other, we define two emittances. One is the geometric emittance, which is calculated from the electron beam distribution. The other is the effective emittance, that measures the average of the Courant-Snyder invariance based on the design optics. The geometric emittance describes only the nonlinearity of the field, while the effective emittance reflects both nonlinearity and mismatch. In figure 1, the electron beam travels from right to left, with initial Gaussian distribution with a 4-σ cut-off. Before collision, two emittances are identical because of the absence of any mismatch.

Figure 1 shows that the beam geometric emittance increases roughly by 10% due to the field nonlinearity. However, after taking the mismatch into account, the rms effective emittance blows up enormously. This suggests to match the electron optics after the collision to the beam distribution instead of ignoring the strong focusing force.

The electron beam distribution after collision depends on its initial emittance and the design optics. We can vary these parameters to investigate the dependence. The ini-

Table 1: MeRHIC Parameter Table and Comparison with eRHIC

	MeRHIC (Not-Cooled)		MeRHIC (Pre-Cooled)		eRHIC (High Energy)	
	p	e	p	e	p	e
Energy (GeV)	250	4	250	4	250	10
Bunch intensity ($\times 10^{11}$)	2.0	0.31	2.0	0.31	2.0	1.2
rms Emittance (nm)	9.4	9.4	9.4	9.4	3.8	5.0
β^*(cm)	50	50	50	50	26	20
Beam-beam/Disruption(Electron only) parameter	0.0015	0.61/3.1	0.0037	1.5/7.7	0.015	0.46/5.8
rms bunch length (cm)	20	0.2	20	0.2	20	0.7
Peak Luminosity ($cm^{-2}s^{-1}$)	0.93×10^{32}		2.3×10^{32}		2.6×10^{33}	

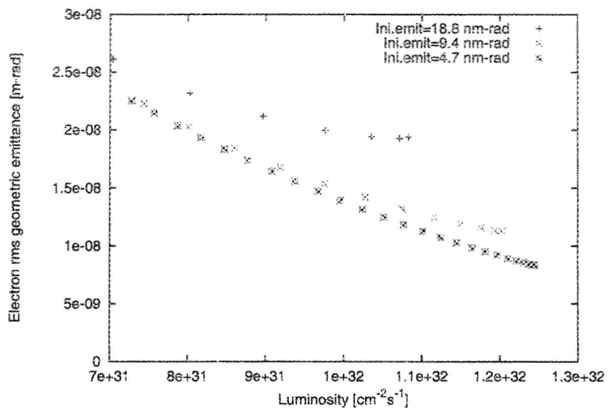

Figure 2: rms geometric emittance after collision as a function of the final luminosity. Each point corresponds to one initial electron emittance and design optics.

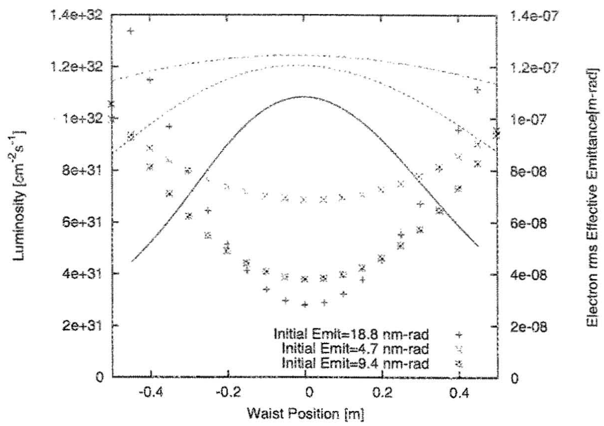

Figure 3: Luminosity and rms effective emittance as a function of the electron beam waist position.

tial electron beam emittance range is set to be between half and twice of design values. The design optics can be altered by changing the waist beta function β^* and the waist position s. $s = 0$ m corresponds to a design waist at the IP. To make the discussion simpler, we limit the number of parameters by matching the design waist beam size of two beams ($\sigma_p = \sigma_e$), causing the product of β^* and initial emittance to be constant. An important feature in figure 2 is that the initial emittance difference will be smeared out by the nonlinear field. At $10^{32}cm^{-2}s^{-1}$, the difference of the final rms geometric emittance is about 10% between the initial electron emittance 4.7 nm-rad and the design value 9.4 nm-rad. The smaller initial emittance (large β^*) leads to an increase in luminosity, which is the same in eRHIC because of the pinch effect. Here, the pinch effect is not as dangerous, due to the sufficiently small design beam-beam parameter for the proton beam.

The geometric emittance after collision is useful only when we can match the electron optics after collision to the beam distribution. If this condition cannot be fulfilled, the effective emittance becomes the quantity we need to be concerned with. Figure 3 gives another view on the luminosity and the rms effective emittance after collision. It shows clearly the dependence on the waist position. The waist position at the IP is obviously the best candidate in this case. However, just as in the eRHIC case, the final electron beam effective emittance is reversely related to the initial emittance. The design value of the initial rms emittance of 9.4 nm-rad compromises between the high luminosity and a small final effective emittance and becomes a decent choice.

To minimize the beam loss in the energy recovery path after the beam-beam collision, we also have to consider the 100% emittance. A Strong nonlinear force will form a longer tail in the electron beam. To evaluate the effect of long tails, we study the required aperture for zero beam loss at various places including the lowest energy recovery path (750 MeV), the pre-acceleration linac (100 MeV) and the beam dump (10 MeV). The initial electron beam distribution just before collision determines the final answers. Usually, at the exit of the electron gun, a 'Beer-Can' distribution is assumed. Due to errors and synchrotron radiation, the electron distribution will stabilize itself in a Gaussian distribution after the damping time, which is in order of milli-seconds. In the ERL, the travel time for the electron beam is far less than the damping time. Besides, we also consider a 'Water-Bag' distribution, which is used to

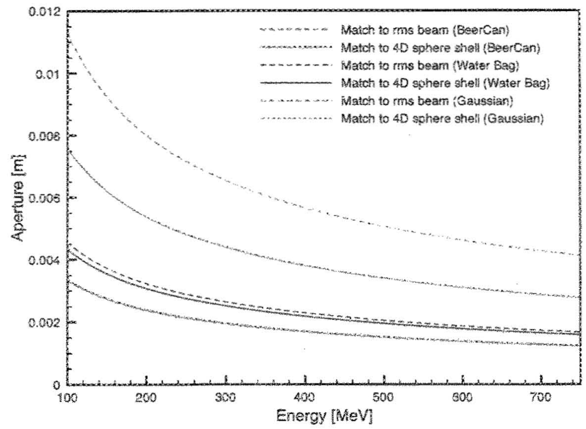

Figure 4: Apertures for zero beam loss at 100MeV to 750 MeV. Apertures of other energies can be scaled by inverse square root of the energy.

represent the transit stage before reaching the equilibrium distribution.

We match the electron optics to the beam distribution after collision. Since the beam-beam force is nonlinear, the phase advance depends on the betatron oscillation amplitude. One option is to match the beam rms quantities. The other is to match the 4-D phase space sphere edge shell to minimize the 100% emittance and required aperture. In figure 4, we can see that the Gaussian distribution case requires the largest aperture; while the Beer-Can case demands the least. We believe that the Water-Bag distribution is the most effective choice for electron beam before collision. It requires a 2mm aperture at 750MeV and a 1.8cm aperture at the beam dump (scaled by the energy from the figure), which are both tolerable.

THE KINK INSTABILITY OF THE P-BEAM

The proton bunch length is much longer than that of the electron. When the electron beam travels in the opposing beam, the deformation formed by the head part of the proton beam will affect the tail part. In the whole beam-beam process, the electron beam acts as a wake field. In previous works[2], we analyzed the wake field strength from both analytical formulas and simulations. Using the 2-particle model[2], we estimated the threshold of the stability criterion for the proton beam as:

$$\frac{\sigma_{pz}\beta_p^*}{16 f_p f_e \nu_s} = \frac{\pi^2 \xi_p \xi_e \sigma_{pz}}{\beta_e^* \nu_s} < 1 \qquad (1)$$

The subscripts p and e represent the parameters for proton and electron beam respectively. σ_{pz} denotes the proton beam length and ν_s is the synchrotron tune of RHIC. f and ξ are the focal length and the beam-beam parameter with linear approximation of the beam-beam force.

For the MeRHIC 'not-cooled' case, the parameter is 2.6 times larger than the threshold; for the 'pre-cooled' case the parameter is 15 times larger. Proper tune spread in the proton beam can suppress the proton beam emittance growth due to the instability. In simulation we use 0.0014 as the RHIC synchrotron tune and 5×10^{-4} for the rms energy spread. The tune spread is provided by the chromaticity in simulation.

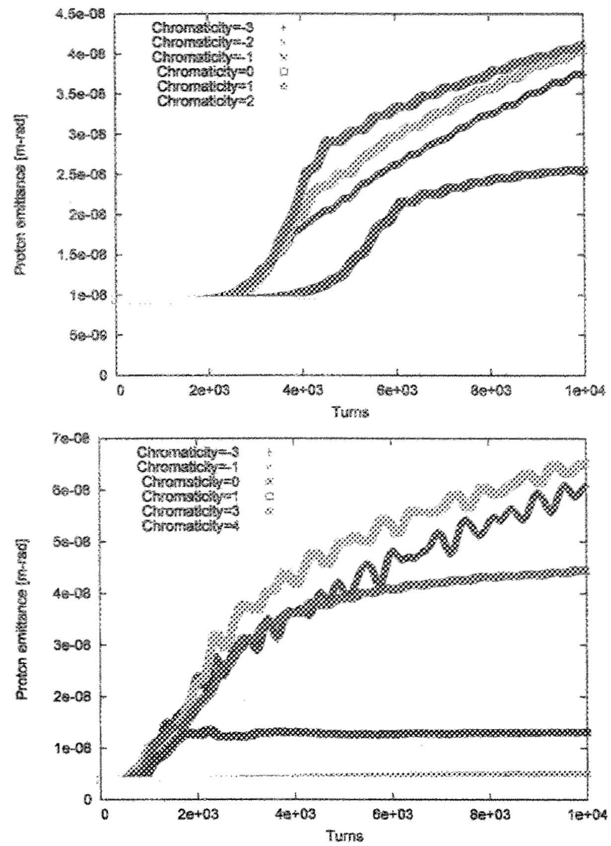

Figure 5: Proton emittance growth and suppression with chromaticity. Top: 'not-cooled case'; bottom: 'pre-cooled case'.

As shown in figure 5, we confirm that the emittance growth can be suppressed by a proper tune spread. For the 'not-cooled' case, an extra tune spread of 5×10^{-4} rms tune spread, in addition to the native tune spread of the beam-beam interaction, can effectively reduce the emittance blowup to a negligible level. One needs a larger tune spread for the 'pre-cooled' case, due to more severe beam-beam interaction. From the figure, we need at least 2×10^{-3} rms tune spread for the proton beam. For both cases, a reasonable linear chromaticity can prevent the proton emittance growth due to the kink instability.

REFERENCES

[1] Y.Hao et al, "Study of electron-proton beam-beam interaction in eRHIC", PAC07, Albuquerque, NM, 2007

[2] Y. Hao, "Beam-Beam Interaction in ERL based eRHIC", PhD thesis, Indiana University, 2008