ELECTRON PINCH EFFECT IN BEAM-BEAM INTERACTION OF ERL BASED ERHIC*

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Abstract

Beam-beam effects present one of major factors limiting the luminosity of colliders. In the linac-ring option of the eRHIC design, an electron beam accelerated in a superconducting energy recovery linac(ERL) collides with a proton beam circulating in the RHIC ring. Some specific features of beam-beam interactions should be carefully evaluated for the linac-ring configuration. One of the most important effects on the ion beam stability originates from a strongly focused electron beam because of the beam-beam force. This electron pinch effect makes the beam-beam parameter of the ion beam several times larger than the design value, and leads to a fast emittance growth of the ion beam. The electron pinch effect can be controlled by adjustments of the electron lattice and the incident emittance. We present results of simulations optimizing the ion beam parameters in the presence of this pinch effect.

INTRODUCTION

One of the key features of the linac-ring type electron-ion collider is the strong focusing effect on the electron beam, named pinch effect, due to strong beam-beam interaction. This nonlinear interaction also causes the electron beam emittance growth during collision and the head-tail type instability of the ion beam[1]. In this paper, we will focus on the electron pinch effect, including the formation, effects on the opposing beam and possible cures.

In the ERL based eRHIC, the focusing force on the electron beam is enormous, because the electron beam is pushed to the beam-beam limit in order to achieve the desired luminosity. One side effect is the creation of a tiny electron beam size inside the proton beam. Therefore, the local beam-beam force for proton beam may cause severe beam quality degradation including:

- A large beam-beam parameter will produce a large tune spread such that one cannot find a proper working point to avoid nonlinear resonances. Nonlinear diffusion will destroy the beam quickly.
- The proton beam exerts different beam-beam parameters within one proton bunch. The longitudinal oscillation will guide every proton in the bunch pass through the 'pinch' position which will induce synchro-betatron oscillation.

* Work supported by Brookhaven Science Associates, LLC under Contract No. DE-AC02-98CH10886 with the U.S. Department of Energy.
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Table 1: ERL Based eRHIC Parameter Table

	p	e
Energy (GeV)	250	10
Bunch intensity ($\times 10^{11}$)	2.0	1.2
RMS emittance (nm)	3.8	5.0
β^*(cm)	26	20
Beam-beam parameter	0.015	0.46
RMS bunch length (cm)	20	0.7
Peak luminosity ($\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	2.6×10^{33}	

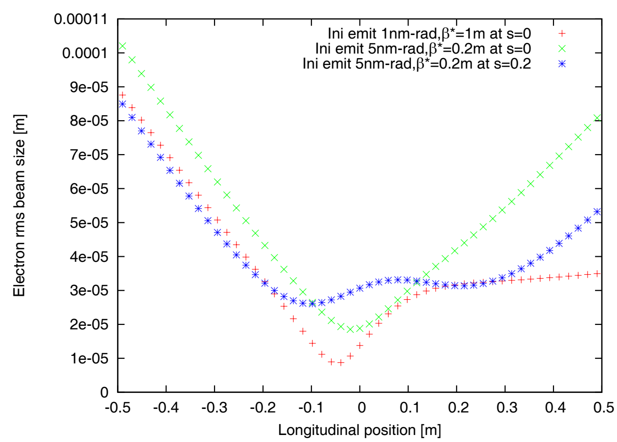

Figure 1: Electron pinch effect with different initial electron parameter. Red curve: design $\beta^* = 1$ m at IP; Green curve: design $\beta^* = 0.2$ m at IP; Blue curve: design $\beta^* = 0.2$ m at $s = 0.2$ m upstream. In all cases, the electron beam size at the waist matches the proton beam waist size at IP.

ELECTRON BEAM EVOLUTION

From previous studies[1], we learned that the electron beam is focused by the strong beam-beam force in the interaction region(IR). As an immediate result, the electron beam has a very small rms beam size at a certain position within the IR, usually referred as 'pinch effect'. We carried out strong-weak simulations based on the parameter table 1 to get the electron beam size evolution at the interaction region. The initial electron transverse distribution is Gaussian.

Figure 1 shows that the proton beam pinches the electron beam via the beam-beam force. The electron beam travels from the right side to the left. The resulting electron beam envelope depends on the electron lattice design. Accord-

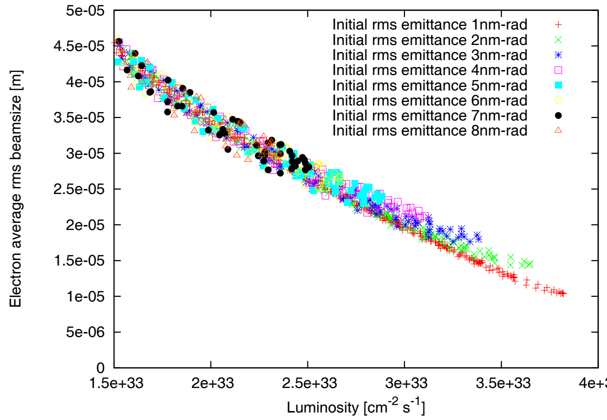

Figure 2: Average electron rms beam size as a function of luminosity.

ing to the graph, we can conclude that a large β^* enhances the electron pinch effect. The design electron waist beam size is 31.6 μm. However, in the red curve ($\beta^* = 1$ m), the pinched minimum beam size is reduced to 8.7 μm at $s = -0.04$ m, which corresponds to 13 times local enhancement in beam-beam parameter compared with table 1. The average beam size throughout the interaction region is also reduced to 14 μm, so the average beam-beam parameter for the proton beam is as high as 0.067!

An improvement is easily achieved by decreasing the waist beta function to 0.2 m (green curve). The minimum and average electron beam size changes to 18 μm and 23 μm, and the maximum and the average beam-beam parameter for proton beam read 0.043 and 0.026 respectively. In blue curve, another improvement was done by shifting the electron beam waist position 0.2m upstream, such that the electron beam diffracts when it meets the opposing beam. By implementing the waist position shift, we can cancel most of the pinched beam size and get the minimum beam size very close to the design value of 31.6 μm.

From previous discussion in this section, we conclude that the pinch effect can be reduced by proper electron optics($\beta^* = 0.2$ m at $s = 0.2$ m). In addition we can vary the initial electron beam parameters to investigate the resulting average electron rms beam size. We plot the average beam size as a function of luminosity in figure 2. The figure reveals a surprise fact that no matter what the initial electron beam emittance and optics are, the average electron rms beam size during collision is nearly a linear function of the luminosity. In other words, if we know the luminosity during collision, we will know the approximate average electron beam size and hence the average beam-beam parameter of the proton beam.

Figure 2 also indicates that if we reduce the electron pinch effect, the luminosity also decreases. But it is worthwhile to do so. For a 1 m waist beta function, the resulting luminosity is $3.4 \times 10^{33}\text{cm}^{-2}\text{s}^{-1}$[2], 1.3 times greater than the design luminosity due to the pinch effect. But the price

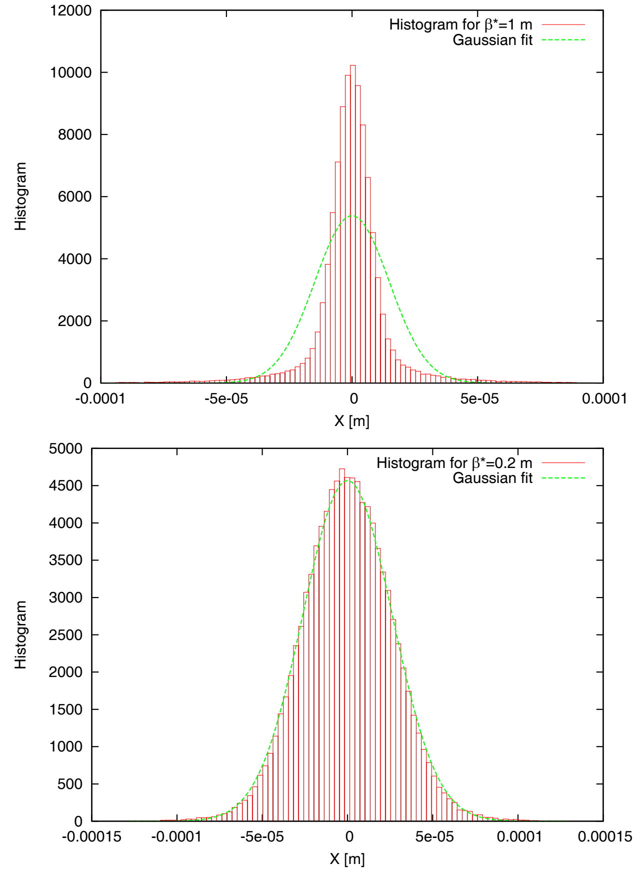

Figure 3: Electron position histogram after Beam-Beam collision. Green curve corresponds to the Gaussian function fit based on electron beam rms size and histogram data. The initial rms emittances are 1 nm-rad and 5 nm-rad for top and bottom figures respectively.

is too high to pay, as it causes the local proton beam-beam parameter to grow by a factor of 13. This shows that it is not a smart way to gain excess luminosity from the pinch effect. To keep the proton beam stable, the pinch effect must be suppressed.

Besides the shrinking of the electron beam size, the distribution of the electron beam also changes. The deformation can be modeled simply. The initial electron transverse distribution is written in a bi-Gaussian form:

$$f(x, x') \propto \exp\left(-\frac{x^2 + \beta^2 x'^2}{\sigma_x^2}\right) \quad (1)$$

Here f is the phase space distribution function, β is the beta function and σ_x is the rms beam size. The beam-beam kick from the opposing bunch, which is also Gaussian, is simplified using a thin length approximation:

$$\begin{aligned} x_n &= x \\ x'_n &= x' - \tfrac{2\sigma_x^2}{f_x x_n}\left[1 - \exp\left(-\tfrac{x_n^2}{2\sigma_x^2}\right)\right] \end{aligned} \quad (2)$$

The subscript n represents the new coordinate after kick. f_x is the focal length of the beam-beam force. After the beam-beam kick, the distribution reads:

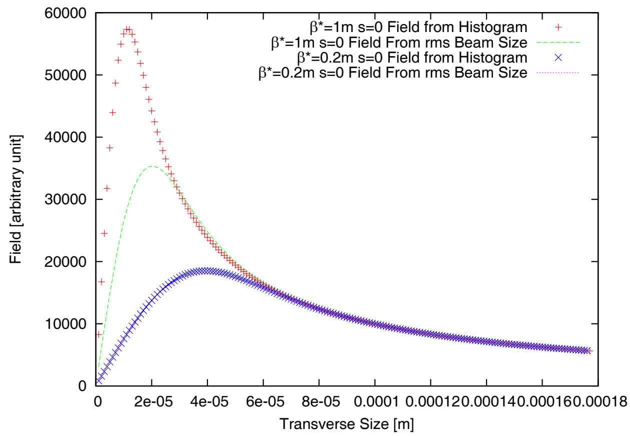

Figure 4: The beam-beam field calculated from the Gauss's Law and from the equation 4

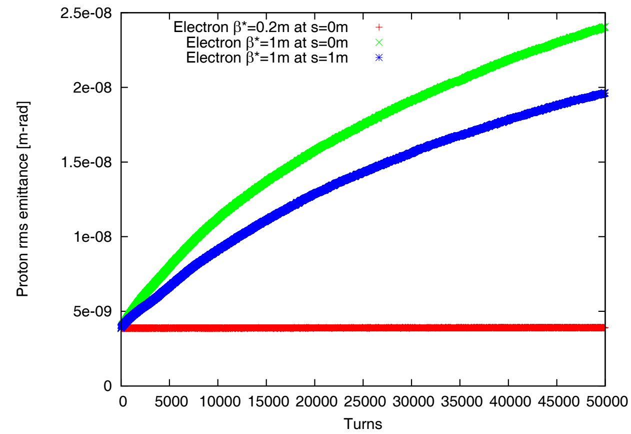

Figure 5: Proton rms emittance comparison among different electron design optics.

$$f\left(x,x'\right)\propto\exp\left[-\frac{x^2}{\sigma_x^2}-\frac{\beta^2}{\sigma_x^2}\left(x'_n+\frac{x_n}{f_x}-\frac{x_n^3}{4\sigma_x^2 f_x}+\cdots\right)^2\right] \tag{3}$$

Here we expand the exponential term in the vicinity of zero. The distribution of the angular divergence x' is not Gaussian any more. As the beam propagates forward, the phase space distribution will totally deviate from the initial bi-Gaussian form. The deformation is proportional to the quadratic term of the beta function.

Simulation results can provide the precise electron beam phase space distribution after beam-beam interactions. Figure 3 shows the histogram of the electron coordinate and deviation from a Gaussian distribution with design beta waist 1 m and 0.2 m (initial electron rms emittance 1nm-rad and 5nm-rad respectively).

The simple model is confirmed by our simulation. It indicates that for small initial rms emittances and large waist beta functions, the distribution has a denser core and longer tail if compared to a Gaussian distribution with the same rms size. When β^* is reduced to 0.2m, the final electron distribution does not deviate much from a Gaussian distribution.

Since there is a chance that the electron beam deviates from the initial Gaussian distribution, we can compare the beam-beam EM field from the distribution using Gauss's Law and from the well-known equation 4 for round Gaussian beam in figure 4.

$$\vec{E}=\frac{ne}{2\pi\epsilon_0 r^2}\exp\left(1-\frac{r^2}{2\sigma_r^2}\right)\vec{r} \tag{4}$$

For the large β^* case (1 m), there is a huge difference between two methods. The beam-beam field near axis is much larger than the prediction using equation 4. If comparing the field slope near axis, the field including beam deformation is about 2.5 times larger. So the real beam-beam parameter is 2.5 times greater than the value we expected from a round Gaussian beam. On the contrary, the difference is tiny for the low β^* case (0.2 m). This is another strong reason why large beta functions should be avoided.

EFFECT ON PROTON BEAM

Under different design optics for the electron beam, the proton beam has a distinct life time due to the pinch effect. We simulate the proton beam emittance evolution when colliding with fresh electron beam each turn. Kink instability and electron beam noise are not included.

Figure 5 confirms the harm of a large proton beam-beam parameter. As we showed before, the large $\beta^*(1\text{m})$ example (green curve) yields an unacceptable average proton beam-beam parameter of 0.067, when the electron distribution deformation is excluded. In this case, the emittance growth becomes very fast (green curve). On the contrary, the small $\beta^*(0.2\text{ m})$ case (red curve) does not show an obvious emittance change. In addition, according to figure 2, we should compare two cases with similar luminosity, i.e. similar average electron rms beam size. If the waist position with $\beta^*=1$m case shifts back from the IP to $s=1$ m, the luminosity will drop to 2.8×10^{33} cm^{-2}s^{-1}, even less than the $\beta^*=0.2$m case (3.0×10^{33} cm^{-2}s^{-1})[2],. Due to the distribution deformation the emittance growth for this case (blue curve) is still huge and unacceptable.

This confirms the importance of avoiding a large distribution deformation and of the control of the electron rms beam size due to the pinch effect. And it indicates that a small beta waist is definitely preferable.

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