BEAM-BEAM SIMULATIUON WITH CRAB-CAVITIES FOR ERHIC*

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Abstract

To compensate the luminosity loss due to the cross-angle collision, crab cavities are being considered for the electron-ion collider designs at Brookhaven National Laboratory. In this article, we study the effects of crab cavities on the proton beam dynamics without and with beam-beam interactions. Luminosities and dynamic apertures are calculated and compared with different parameters of crab cavities. To minimize the distortion from a single crab cavity, harmonic crab cavities are also considered.

INTRODUCTION

To compensate the luminosity loss due to cross-angle collision, crab cavities are being considered for the electron-ion collider designs at Brookhaven National Laboratory. For the latest FFAG-ERL based linac-ring eRHIC design [1], the full crossing angle between the electron an proton bunches is 10 mrad. Two crab cavities with frequency 140 MHz for the proton ring and 420 MHz for the electron linac are used to tilt the bunches in the $x-z$ plane by 5 mrad.

There are two directions to numerically simulate the beam-beam interaction effects in the eRHIC design: strong-strong and weak-strong beam-beam simulations. For the weak-strong simulation, proton test particles are tracked element-by-element up to 1 million turns. The nonlinearities from the magnets, crab cavities, and beam-beam interaction are included. In this article we will focus on the simulation calculation of proton dynamic aperture.

For the current linac-ring eRHIC design, the electron bunch will be over-focused by the beam-beam force from the proton bunch when it goes through the proton bunch. This effect is called pinch effect and was studied in detailed in Refs. [2,3] for the head-on collision situation. For the proton dynamic aperture calculation, we need to take into account the changes of electron bunch sizes at different longitudinal collision positions.

In the following, we first present the beam and lattice parameters for this study and the methods involved. Then we calculate the electron bunch sizes with a simple one-pass strong-strong beam-beam simulation code. With them, we are ready to calculate the proton long-term dynamic apertures under different crab cavity settings.

PARAMETERS AND METHODS

Table 1 shows the beam parameters for the latest FFAG-ERL based linac-ring nominal design of eRHIC. The luminosity goal is $1.0\times10^{33}cm^{-1}s^{-1}$. The transverse bunch sizes for both beams are matched at the interaction point (IP) without beam-beam effect. With a $\beta^*_{x,y}$ 12.5 cm, the unperturbed beam sizes at IP is 15.3 μm. The proton rms bunch length is 16.5 cm, while the electron bunch length is only 0.3 cm. In the nominal design, there is not cooling. In the ultimate design, with coherent electron cooling [4], the proton bunch length will be reduced by a factor of 3 and the luminosity will reach $14.4\times10^{33}cm^{-2}s^{-1}$.

Table 1: Beam and Optics Parameters (for the latest nominal FFAG-ERL based linac-ring eRHIC design)

Linac-ring Nominal Design		
	Electron	Proton
Energy [GeV]	10	250
Bunch intensity [10^{10}]	1.7	20
$\beta^*_{x,y}$ [cm]	12.5	12.5
Beam size at IP [μm]	15.3	15.3
rms bunch length [cm]	0.3	16.5
Beam-beam parameter	1.2	0.004
Disruption parameter	20	-
Space charge parameter	1.4×10^{-4}	0.006
Polarization [%]	80	70
Peak luminosity	$1.0\times10^{33}cm^{-2}s^{-1}$	

To calculate the electron beam sizes at different longitudinal positions, we carry out a simple one-pass strong-strong beam-beam simulation involving only one electron bunch and one proton bunch. In the linac-ring eRHIC design, one electron bunch only collides with one proton bunch and is dumped thereafter. In the strong-strong simulation code, the proton bunch is represented by 150,000 macro-particles and the electron bunch by 5,000 macro-particles. We first perform Lorenz boost to transfer the coordinates of all these macro-particles from the laboratory laboratory frame to the head-on frame.

In the head-on frame, we slice the proton bunch longitudinally into 200 equal-populated slices and the electron bunch into 5 slices. We either use soft-Gaussian approximation or directly solve Poisson equation with particle-in-cell (PIC) method to calculate the beam-beam forces. We also numerically evaluate the luminosity by mapping macro-particles onto a 2-D rectangle meshes. Numerical calculation of luminosity is suitable for arbitrary particles distribution, various collision scheme, and it takes into account of the beam-beam effect or pinch effect.

The proton dynamic aperture is calculated by tracking test particles element-by-element up to 10^6 turns. Particles are initially launched in 10 equal-distance directions in the first quadrant of the $(x/\sigma_x, y\sigma_y)$ plane. The dynamic aperture is defined as the minimum of survival amplitude among these angles and is given in units of unperturbed rms beam

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

ISBN 978-3-95450-147-2

size σ. Here we adopt a proton ring design introduced in Ref. [5]. The rms momentum deviation $(dp/p_0)_{rms}$ is about 2.0×10^{-4}. Unfortunately the multipole field errors in the interaction region dipoles and quadrupoles are not included. From RHIC's experience, they play a significant role in reduction of dynamic aperture.

ONE-PASS SIMULATION RESULTS

Figure 1 shows the electron and proton bunch profiles in the head-on frame without crab cavities. The horizontal and vertical axis are the z and x coordinates of particles. Due to the large crossing angle and the long proton bunch length, only a small amount of protons in the bunch center will collide with the electron bunch. The calculated luminosity without crab cavities is only 2.5

Figure 2 show the electron and proton bunch profiles with the main harmonics of crab cavities for proton rings and electron linac. One crab cavity is place on either side of IP with a horizontal betatron phase advance $\pi/2$ from IP. The design crab cavity frequencies are 140 MHz for the proton ring and 420 MHz for the electron linac.

From Figure 2, with crab cavities, there are more proton particles interacting with the electron bunch. The calculated luminosity is $0.79 \times 10^{33} cm^{-2} s^{-1}$, which is about 69% of the luminosity without crossing angle. From the plot, there are still a large portion of proton particles on the bunch tails not interacting with the electron bunch. This is due to a limited range of linear deflecting field from the crab cavity. A shorter proton bunch will help, too.

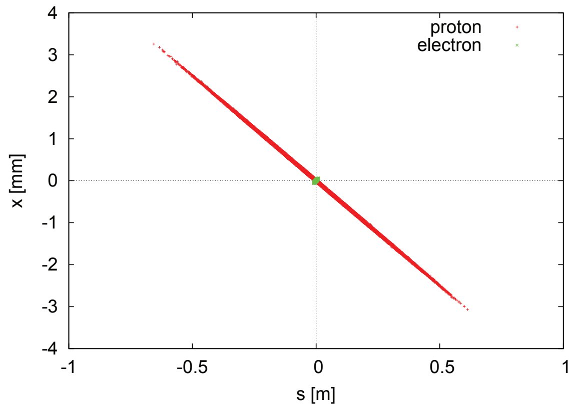

Figure 1: Electron and proton bunch profiles in the head-on frame without crab cavities.

Next we add two third harmonic crab cavities to the proton ring at the same locations of the main crab cavities. To maximize the region with a linear deflecting field, we let the main crab cavity deflects the proton bunch by 1.16×5 mrad and the third harmonic crab cavity by -0.16×5 mrad [6]. Figure 3 shows the electron and proton bunch profiles with the additional third harmonic crab cavities. The calculated luminosity with harmonic crab cavities are $1.05 \times 10^{33} cm^{-2} s^{-1}$ which is about 91% of the luminosity without crossing angle.

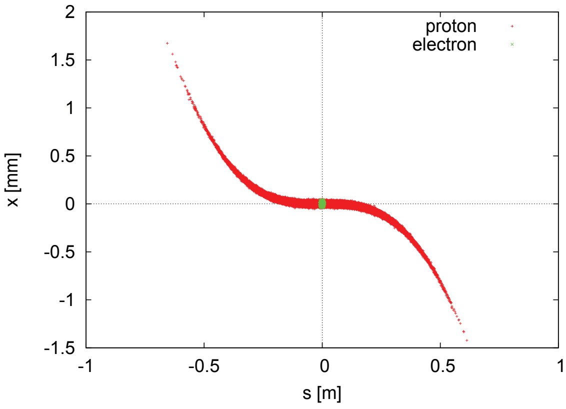

Figure 2: Electron and proton bunch profiles in the head-on frame with the main harmonic crab cavities.

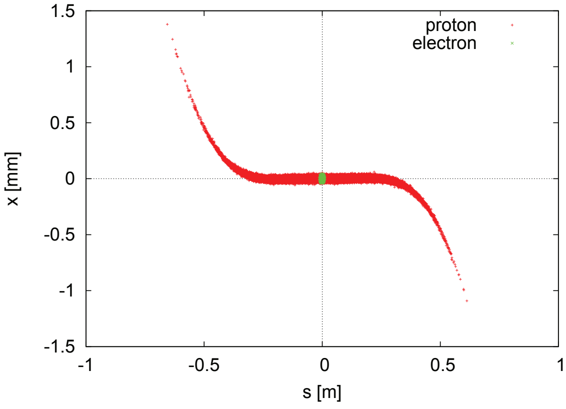

Figure 3: Electron and proton bunch profiles in the head-on frame with the main and third order harmonic crab cavities.

PROTON DYNAMIC APERTURE CALCULATION

With strong-strong beam-beam simulation, we are able to calculate the electron bunch's beam sizes at different longitudinal positions. At each position, we calculate the rms transverse electron bunch sizes. In the following, we only show the results with soft-Gaussian approach. The results from soft-Gaussian and PIC methods agreed very well.

Figure 4 shows the center positions of the electron bunch center during one pass through the proton bunch. The vertical position of the electron bunch center is supposed to be zero. The non-zero value shown in this plot comes from the computation noise and therefore should not be applied in the proton dynamic aperture calculation. The maximum horizontal position of the electron bunch center is about 7.5 μm, which is caused by offset collisions between the electron bunch and the proton particles in the bunch tail.

Figure 5 shows the electron rms transverse beam sizes at different longitudinal positions. Collisions happen earlier at positive s locations. The electron beam sizes without beam-beam interaction is 15.3 μm at IP. From the plot, the minimum electron beam size reaches 5 μm with beam-beam

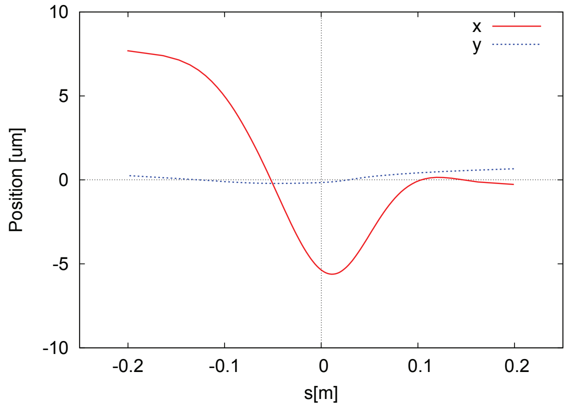

Figure 4: Electron bunch center position during one pass from a strong-strong beam-beam simulation.

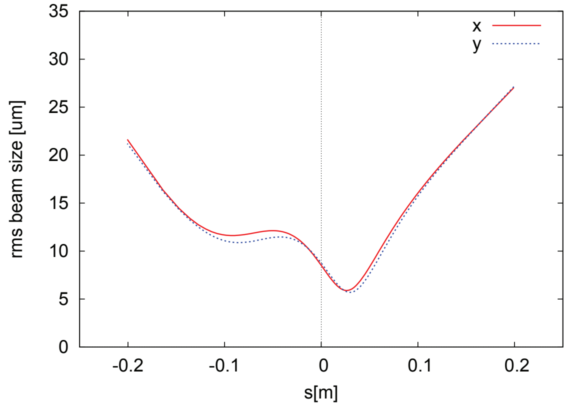

Figure 5: Electron rms bunch sizes during one pass from a strong-strong beam-beam simulation.

effect. This phenomenon is called pinch effect. There is a small difference between the horizontal and vertical electron beam sizes.

In the proton dynamic aperture calculation, we first transfer the proton coordinates into the head-on frame. Then we determine where the proton particle meets the electron bunch. According to the data shown in Figures 4 and 5, we interpolated the electron bunch's center positions and transverse beam sizes at the collision location. The beam-beam force to the proton is calculated with the analytical beam-beam fields with a double Gaussian transverse particle distribution.

Figure 6 shows the calculated proton dynamic apertures for three cases: 1) without crab cavities and without beam-beam interaction, 2) with crab cavities but without beam-beam interaction, 3) with crab cavities and beam-beam interaction. The third harmonic crab cavities are included in this study. From the plot, the proton dynamic aperture with crab cavities drops less than 2.5 σ compared with the case without crab cavity. Further with beam-beam interaction,

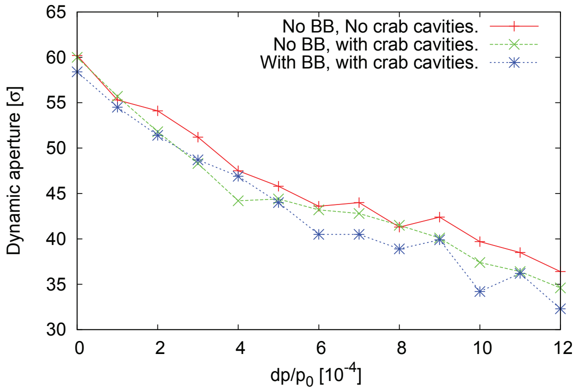

Figure 6: Calculated proton dynamic apertures with different crab cavity and beam-beam conditions.

the maximum dynamic aperture drop less than 5.0 σ compared with that without beam-beam interaction. Without nonlinearities from the multipole field errors in the interaction region magnets, the difference in the proton dynamic aperture is negligible for all three cases.

SUMMARY

In the article, we calculated and compared the luminosities and proton dynamic apertures without and with crab cavities for the latest FFAG-ERL based eRHIC design at Brookhaven National Laboratory. With third harmonic crab cavities, the luminosity is recovered to 91% of that without crossing angle collision. We plan to continue this study with a realistic interaction region design and multipole field errors of magnets in the interaction region.

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