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# BEAM-BEAM RELATED DESIGN PARAMETER OPTIMIZATION FOR THE ELECTRON-ION COLLIDER*

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*Abstract*

The design luminosity for the Electron-Ion Collider (EIC) with 10 GeV electron and 275 GeV proton collision is $1 \times 10^{34}\,\mathrm{cm^{-2}sec^{-1}}$. To achieve such a high luminosity, the EIC design adopts high bunch intensities, flat beams at the interaction point, and a high collision frequency. Crab cavities are used in each ring to restore head-on collision condition to compensate the geometrical luminosity loss due to a large crossing angle 25 mrad at IP. In this article, we will focus on the beam-beam related design parameter optimization. Through intensive beam-beam simulations, we found that beam flatness, electron and proton beam size matching at IP, synchro-betatron resonance, proton and electron's working points play an important role in luminosity degradation and proton's beam size growth. After optimizing those parameters, we chose a set of beam-beam related design parameters with flatness 0.09 and proton's $(\beta_x^*, \beta_y^*)$ = (80,7.2) cm to reach the design luminosity.

## INTRODUCTION

In the Electron-Ion Collider (EIC) design, there are several different collision configurations that have different combinations of electron and ion beam energies [1]. In the following, we will only discuss collisions between 10 GeV electrons and 275 GeV protons, which is the configuration with the highest luminosity, reaching $1 \times 10^{34}\,\mathrm{cm^{-2}sec^{-1}}$. This combination also requires the highest beam-beam parameter for both the proton and electron beams among all configurations.

We set the maximum beam-beam parameters for the electron and proton beams to be $\xi_e = 0.1$ 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. The maximum beam-beam parameter for the proton ring is based on the successful operational experience during RHIC polarized proton runs, where a beam-beam parameter of $\xi_p = 0.015$ was routinely achieved.

In the interaction region (IR), the orbits of proton and electron beams horizontally cross each other at IP with a full crossing angle 25 mrad. To compensate the geometric luminosity loss due to the crossing angle, crab cavities are used to tilt the proton and electron bunches in the $x-z$ plane by half of the full crossing angle to restore head-on collision condition. For EIC, local crabbing scheme is adopted. For each ring, two sets of crab cavities are installed on both side of IP, with an ideal horizontal betatron phase advance $\pi/2$ between IP and crab cavities.

The crab cavity frequencies are 197 MHz for the Hadron Storage Ring (HSR) and 394 MHz for the Electron Storage Ring (ESR). The proton's RMS bunch length is 6 cm at 275 GeV, while the wavelength of 197 MHz crab cavities is 1.5 m. Protons in the bunch head and tail will not be well crabbed in the $x-z$ plane. Those protons will get offset beam-beam kicks from the opposite electron bunch, which leads to synchro-betatron resonance and causes proton emittance growth [2, 3].

Table 1 lists the final beam-beam related design parameters presented in EIC Conceptual Design Report (CDR) for the collision with 10 GeV electrons and 275 GeV protons. During choosing of these beam-beam related design parameters, there are a few constraints and assumptions. Besides the luminosity goal and the maximum beam-beam parameters, the maximum proton and electron beam current can not exceed 1 A and 2.5 A. We originally assumed proton horizontal $\beta_x^*$ 90 cm to reduce the voltage requirement for the crab cavities. The minimum $\beta_y^*$s should be larger than 5 cm, which is required by dynamic aperture and physical apertures of IR magnets. The beam-beam related design parameters need to be verified with beam-beam simulation. In return, beam-beam simulation also provides feedbacks and directions to improve these design parameters.

Table 1: Beam-beam Related Machine and Beam Parameters for 10 GeV Electron and 275 GeV Proton Collision in EIC

| Quantity | Unit | Proton | Electron |
|---|---|---|---|
| Beam energy | GeV | 275 | 10 |
| Bunch intensity | $10^{11}$ | 0.668 | 1.72 |
| $(\beta_x^*, \beta_y^*)$ at IP | cm | (80, 7.2) | (55, 5.6) |
| Beam sizes at IP | μm | (95, 8.5) | |
| Bunch length | cm | 6 | 2 |
| Energy spread | $10^{-4}$ | 6.6 | 5.5 |
| Transverse tunes | | (0.228, 0.210) | (0.08, 0.06) |
| Longitudinal tune | | 0.01 | 0.069 |

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## KEY FACTORS TO BEAM-BEAM PERFORMANCE

we found that beam flatness, electron and proton beam size matching at IP, synchro-betatron resonance, proton and electron's working points play an important role in luminosity degradation and proton's beam size growth. Flatness is defined as the ratio of the vertical to horizontal RMS beam sizes at IP. To obtain a higher luminosity, a flatter beam at IP is required, as shown in Fig. 1. A smaller value of flatness at IP is achieved with a smaller $\beta_y^*$ since the horizontal emittance and $\beta_x^*$ are relatively fixed. However, through beam-beam simulation, we noticed that a smaller flatness will cause a faster proton beam size growth.

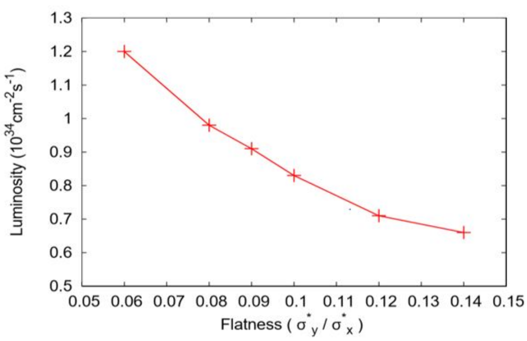


Figure 1: Luminosity as function of flatness at IP. Luminosity are calculated with strong-strong simulation.

Due to the synchrotron radiation (SR) damping and quantum fluctuation of the electron beam, we normally have un-matched transverse electron and proton beam sizes at IP with beam-beam interaction. The electron beam's equilibrium beam sizes are decided by the interplay between SR process and beam-beam interaction. In our current beam-beam simulation, the lattice nonlinearities have not been included. We noticed that having a matched beam sizes of electron and proton beams at IP is important for the proton emittance growth. We should avoid the situation when the electron beam size is smaller than the proton's.

Synchro-betatron resonance is another key factor to affect the proton beam emittance growth. Synchro-betatron resonance in the HSR is introduced by a large crossing angle and nonlinear crabbing with RF crab cavities. Two kinds of synchro-betatron resonances are observed in EIC with the help of Frequency Map Analysis (FMA). The first kind synchro-betatron resonance is $mQ_x + kQ_z$. The second one is coupled synchro-betatron resonance $2Qx - 2Qy + lQ_z$. Both are visible in Fig. 2.

Synchro-betatron resonance can be minimized with a shorter bunch length, a smaller synchronous tune, a smaller beam-beam parameter. But the practical methods are tune optimization and using second harmonic cavities. We moved the proton's original design working point (0.310,0.305) down to (0.228, 0.224) to minimize the synchro-betatron resonance $mQ_x + lQ_z$. Later on we moved it a little bit away from the diagonal line to (0.228, 0.210) to minimize the coupled synchro-betatron resonance $2Qx - 2Qy + lQ_z$. Second harmonic crab cavities is also under consideration, which is not included in the following simulation studies.

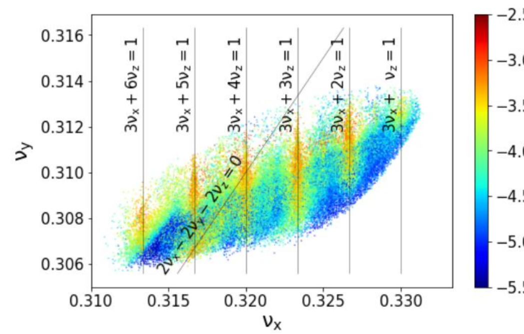


Figure 2: FMA of proton bunch with crossing collision and crab cavities. Synchro-betatron resonances are visible.

## BEAM SIZE GROWTH RATE

In the following, we study the dependence between proton's beam size growth rate and flatness at IP. Three simulation methods are used.

### *Strong-Strong Simulation*

Here both proton and electron bunches are represented with half million macro-particles. The proton and electron are split into 15 and 5 longitudinal slices. The beam-beam force is calculated by solving the 2-D Poisson equation with Fast Fourier Transformation (FFT) [4]. We track particles to 50,000 turns. We linearly fit the proton beam sizes in the second half of tracking turns after electron beam has reached its equilibrium. Then we extrapolate the growth rate from %/turn to %/hour.

Strong-strong beam-beam simulation is subject to numeric noises. The calculated beam size growth rate depends on the number of macro-particles, the number of longitudinal slices, the grid sizes, and the beam-beam parameter, and so on. Here we only use those calculated proton beam size growth rates for a qualitative comparison. Figure 3 shows the normalized growth rates for proton bunch's horizontal and vertical beam sizes as function of flatness at IP. The flatness is scanned from 0.14 down to 0.06.

From the plot, the proton's horizontal beam size growth rate changes very small in the study range of flatness. However, the vertical growth rate begins to increase when the flatness is larger than 0.09. For the extreme case with flatness 0.06, the proton's vertical beam size growth rate is more than doubled than the base line with a larger flatness.

### *Weak-Strong Simulation*

Here the electron bunch is rigid and its beam-beam force is analytically calculated [5]. For each tracking job, we track 10,000 macro-particles up to 2 million turns. We fit the beam size data from the second half of tracking turns. To reduce statistic errors, we use several seeds of proton's initial

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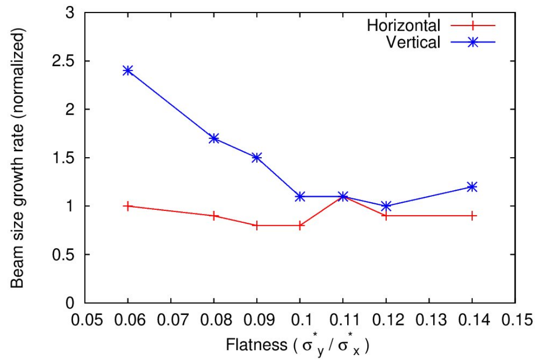


Figure 3: Normalized proton beam size growth rates as function of flatness at IP.

Table 2: Calculated Proton Beam Size Growth Rates in Weak-strong Simulation

| **Flatness** | ($\beta_x^*$, $\beta_y^*$) cm | **Proton H Size Growth Rate (%/hour)** | **Proton V Size Growth Rate (%/hour)** |
|---|---|---|---|
| 0.06 | (90,5.4) | -0.68+/-1.10 | 14.57+/-7.1 |
| 0.08 | (90,7.2) | -0.52+/-0.37 | 2.6 +/-1.9 |
| 0.09 | (90,8.1) | 0.16+/-0.94 | 2.7+/-3.1 |
| 0.10 | (90,9.0) | 0.09+/-0.86 | 1.2+/-2.6 |
| 0.12 | (90,10.9) | 0.05 | 0.87 |
| 0.14 | (90,12.6) | -1.2+/-2.5 | 0.27+/-8.9 |
| 0.09 | (80,7.2) | 0.11+/-0.75 | 3.3+/-3.2 |

distribution. Table 2 lists the calculated proton beam size growth rates as function of flatness at IP.

From the table, with flatness from 0.14 down to 0.06, the proton's horizontal growth rate keeps less than 1.5%/hour for all cases. This agrees with the strong-strong beam-beam simulation. The vertical growth rates are less than 3%/hour except the extreme case with flatness 0.06, which gives about 15%/hour growth rate. The last case in the table is with flatness 0.09 and ($\beta_x^*$, $\beta_y^*$) = (80,7.2) cm, which is the set of design parameters presented in CDR with the design luminosity $1 \times 10^{34}$ cm$^{-2}$sec$^{-1}$.

### *Combined W-S and S-S Simulation*

Weak-strong simulation has a much smaller numeric noise level than strong-strong simulation. However, it ignores the electron's pinch effect due to beam-beam interaction and the actual equilibrium electron distribution. To include those information in weak-strong, we developed a new simulation model. After the electron beam reaches its equilibrium with beam-beam interaction in strong-strong simulation, we freeze the electron bunch's charge distribution and its space charge potentials. Then we carry out an extended weak-strong simulation with the frozen electron distribution.

Table 3 shows the calculated proton emittance growth rates with this method. The calculated proton emittance growth rates are between strong-strong and weak-strong simulation, but much closer to those from weak-strong. Qualitatively, we still can draw a similar conclusion: flatness 0.06 has a much higher beam size growth rate than other smaller flatness cases.

Table 3: Calculated Proton Beam Size Growth Rates in Combined Weak-strong and Strong-strong Simulation

| **Flatness** | ($\beta_x^*$, $\beta_y^*$) (cm) | **Proton H Size Growth Rate (%/hour)** | **Proton V Size Growth Rate (%/hour)** |
|---|---|---|---|
| 0.06 | (90,5.4) | 8.8 | 301 |
| 0.08 | (90,7.2) | 4.8 | 66 |
| 0.09 | (90,8.1) | 19 | 78 |
| 0.10 | (90,9.8) | 9.4 | 43 |
| 0.12 | (90,11 ) | 14 | 74 |
| 0.09 | (90,0.72) | 8 | 76 |

Based on above studies, together with dynamic aperture calculation with preliminary lattice design, we chose flatness 0.09 and proton ($\beta_x^*$, $\beta_y^*$) = (80,7.2) cm as the base design parameters for EIC 10 GeV electron and 275 GeV proton collision. With them, the design luminosity $1\times10^{34}$ cm$^{-2}$sec$^{-1}$ is reached with a relatively low proton emittance growth rate.

## SUMMARY

In this article, we presented the beam-beam challenges for the 10 GeV electron and 275 GeV proton collision in EIC. We noticed that beam flatness, beam size matching at IP, synchro-betatron resonance, both electron and proton's working points are important to proton bunch's vertical emittance growth. The design luminosity $1 \times 10^{34}$ cm$^{-2}$sec$^{-1}$ for e-p collision can be reached with a relatively low proton beam size growth. Based on beam-beam simulation, we chose flatness = 0.09 and proton ($\beta_x^*$, $\beta_y^*$) = (80,7.2) cm as our base design parameters. We will continue optimizing the beam-beam design parameters and studying the physics behind crossing collision with crab cavities in EIC.

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