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# ION BUNCH LENGTH EFFECTS ON THE BEAM-BEAM INTERACTION IN A HIGH LUMINOSITY RING-RING ELECTRON-ION COLLIDER WITH HEAD-ON BEAM-BEAM COMPENSATION*

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*Abstract*

The luminosity of a ring-ring electron-ion collider is limited by the beam-beam effect on the electrons. Simulation studies have shown that for short ion bunches this limit can be significantly increased by head-on beam-beam compensation via an electron lens. However, due to the large beam-beam parameter experienced by the electrons, together with an ion bunch length comparable to the beta-function at the IP, electrons perform a sizeable fraction of a betatron oscillation period inside both the long ion bunches and the electron lens. Recent results of our simulation studies of this effect will be presented.

## INTRODUCTION

One of the major luminosity limitations in the eRHIC ring-ring design is the beam-beam effect experienced by the polarized electron beam.

As previous simulation studies [1] have shown, head-on beam-beam compensation allows for significantly higher beam-beam parameters in the limit of vanishing lengths of the proton bunches and the electron lens. In reality, however, both the length of the electron lens and the proton bunches cannot be ignored, and the beam-beam interaction leads to a significant betatron phase advance over the interaction length [2]. This effect is characterized by the disruption parameter [3]

$$\zeta = \frac{2r_0 N \sigma_z}{\sigma_x \sigma_y \gamma_e}, \tag{1}$$

where $\sigma_x$, $\sigma_y$, and $\sigma_z$ denote the rms transverse beam sizes and the rms length of the oncoming proton or electron lens beam, respectively. $N$ is the number of protons per bunch or electrons inside the electron lens at any given time, $r_0$ the classical particle radius, and $\gamma_e$ the relativistic Lorentz factor of the circulating electron beam.

## THE ELECTRON RING MODEL

The electron ring used in the simulation studies is comprised of 50 identical FODO cells which are equipped with chromaticity correction sextupoles [1]. The electron-proton interaction point (IP) and the electron lens are separated by 10 of these FODO cells, while the remaining 40 FODO cells form the rest of the ring, as schematically shown in Figure 1. Ideal dispersion suppressors are located at each end of each of the two arcs, resulting in zero dispersion $D^*$ and zero derivative $D^{*\prime}$ at both the IP and the electron lens. Chromatic matrices provide low-$\beta$ focusing at the IP and the electron lens, with the chromaticity of each of these telescopes set to $-2.5$. The betatron phase advance in the arc between IP and electron lens is adjusted to a multiple of 180 degrees by means of phase rotation matrices. Quantum excitation and synchrotron radiation damping are implemented at the end of each arc, taking into account their different length accordingly. The parameters of the electron ring model are listed in Table 1.

The beam-beam interaction of the electrons with the long proton bunches and the electron lens is implemented by slicing both the proton bunch and the electron lens into 100 slices. At each slice, the nonlinear beam-beam kick is applied according to the beam intensity within that slice, followed by a drift corresponding to the slice thickness. To separate the dynamic focusing effects from the emittance blow-up, the linear part of the beam-beam interaction is included in the linear beam optics of the electron ring. Therefore, the actual $\beta$-function at the IP and the electron lens equals the nominal value, and the linear optics around the ring remains undisturbed by the beam-beam interaction.

## LUMINOSITY AS A FUNCTION OF TUNES

100 particles were tracked over 10000 turns to determine the luminosity as a function of the working point, which was calculated using the average rms electron beam sizes $\sigma_{x,e}$, $\sigma_{y,e}$ over the last 1740 turns in the tracking. Together with the nominal rms proton beam sizes $\sigma_{x,p}$, $\sigma_{y,p}$, we define the geometric luminosity factor as

$$F_{\text{geom}} = \frac{2\sigma_{x,p}\sigma_{y,p}}{\sqrt{(\sigma_{x,p}^2 + \sigma_{x,e}^2)(\sigma_{y,p}^2 + \sigma_{y,e}^2)}}. \tag{2}$$

To determine the optimum working point, we perform tune scans in steps of $\Delta Q_{x,y} = 0.01$, using the phase rotation matrices indicated in Figure 1.

### *Proton bunch length effects in the uncompensated case*

The beam-beam interaction of the electrons with the $0.2\,\mathrm{m}$ long proton bunches results in phase averaging of the beam-beam kicks experienced, which effectively reduces the magnitude of the kicks [5]. This effect is shown

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| | | |
|---|---|---|
| no. of FODO cells | $N_{\mathrm{FODO}}$ | 50 |
| no. of cells between IP and electron lens | $N_{\mathrm{sep}}$ | 10 |
| phase advance/cell (hor./vert.) | $\Delta\Phi_x/\Delta\Phi_y$ | $79.7°/89.0°$ |
| chromaticity (hor./vert.) | $Q'_{x,y} = \Delta Q_{x,y}/\frac{\Delta p}{p}$ | +2/+2 |
| telescope chromaticity | $Q'_{\mathrm{telescope}}$ | $-2.5$ |
| synchrotron tune | $Q_s$ | 0.015 |
| rms electron. bunch length | $\sigma_{s,e}$ | 11.7 mm |
| rms electron momentum spread | $\sigma_p$ | $9.4 \cdot 10^{-4}$ |
| rms proton bunch length | $\sigma_{s,p}$ | 20 cm |
| $\beta$-function at IP and electron lens | $\beta_x/\beta_y$ | 0.19 m, 0.26 m |
| no. of positive charges/bunch | $N_p$ | $3 \cdot 10^{11}$ |
| electron lens intensity/bunch | $N_e$ | $3 \cdot 10^{11}$ |
| rms proton beam emittance | $\epsilon_p$ | 9.5 nm |
| rms electron beam emittance (hor./vert.) | $\epsilon_e$ | 53 nm/9.5 nm |
| rms proton beam size at IP | $\sigma_{x,p}/\sigma_{y,p}$ | 101 $\mu$m/50.5 $\mu$m |
| rms electron lens beam size | $\sigma_{x,e}/\sigma_{y,e}$ | 101 $\mu$m/50.5 $\mu$m |
| Lorentz factor | $\gamma$ | 19560 |
| electron beam-beam parameter | $\xi_x/\xi_y$ | 0.09/0.24 |
| damping times | $\tau_x/\tau_y/\tau_z$ | 1740/1740/870 turns |

Table 1: Model electron ring parameters. $\beta$-functions and rms beam sizes at the IP and the electron lens, as well as damping times, are taken from the eRHIC ring-ring design [4].

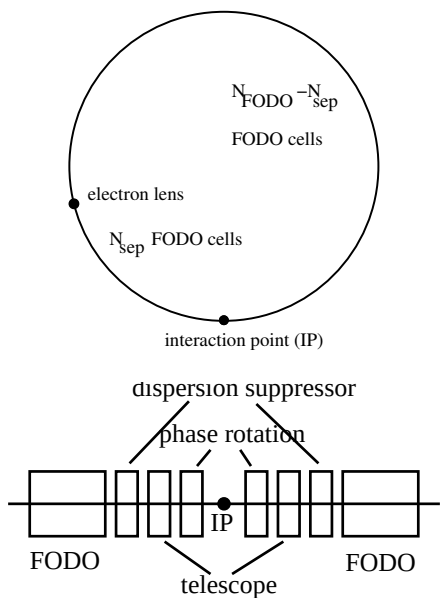


Figure 1: Schematic drawings of the model electron ring (top) with interaction point (IP) and electron lens. The bottom figure depicts a low-$\beta$ insertion with dispersion suppressors, low-$\beta$ telescopes, and phase rotation matrices.

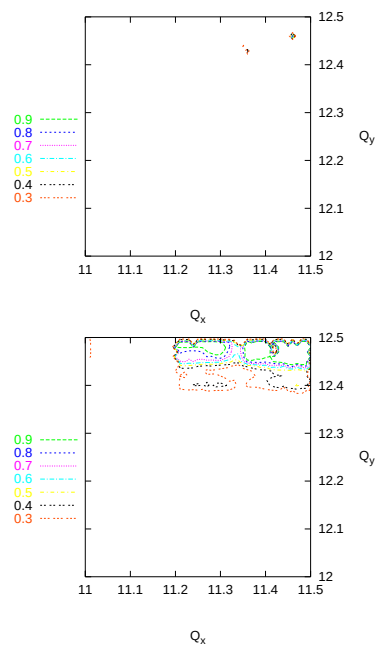


Figure 2: Geometric luminosity factor $F_{\mathrm{geom}}$ as a function of tunes in the uncompensated case, for an rms proton bunch length of $\sigma_{s,p} = 0.5\,\mathrm{mm}$ (top) and 20 cm (bottom). With long bunches, the available tune space increases significantly.

in Figure 2, where we performed tune scans for short ($\sigma_{s,p} = 0.5\,\mathrm{mm}$) and long ($\sigma_{s,p} = 0.2\,\mathrm{m}$) proton bunches.

With short proton bunches, a maximum geometric luminosity factor of $F_{\mathrm{geom}} = 1$ is achieved in a tiny tune spot only, while $F_{\mathrm{geom}}$ approaches unity over a large range of working points.

## *Effect of the electron lens length*

In the full 6-dimensional study of head-on beam-beam compensation, the electron lens length is an additional parameter for optimization. As Figure 3 shows, the optimum length of the DC electron lens in our case is around 30 cm. Comparing these luminosity contour plots with the uncompensated case depicted in Figure 2 shows some enlargement of the "good" tune space where geometric luminosity factors $F_{\mathrm{geom}}$ greater than 0.9 are reached. However, the improvement is by far not as striking as in the case of short proton bunches [1].

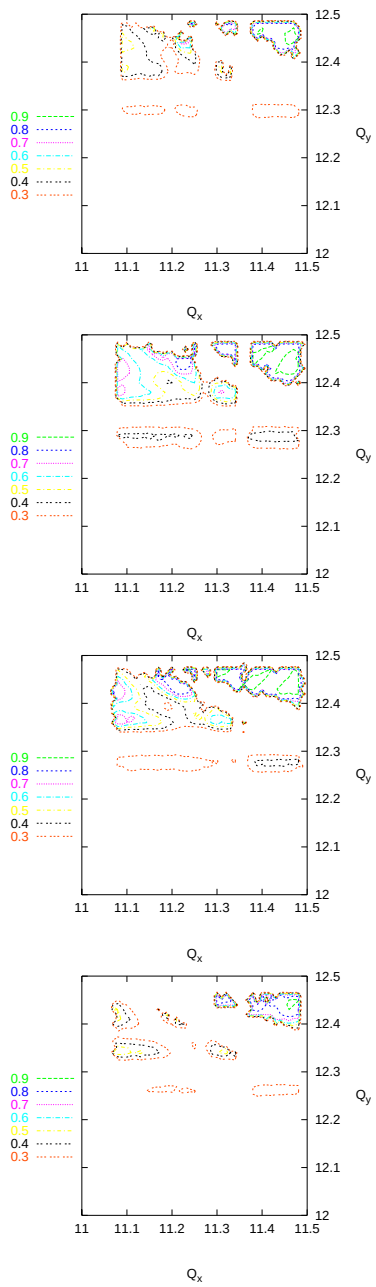


Figure 3: Geometric luminosity factor $F_{\mathrm{geom}}$ as a function of tunes in the compensated case, for an electron lens length of (top to bottom) 20 cm, 28 cm, 34 cm, and 42 cm, and an rms proton bunch length of $\sigma_{s,p} = 20\,\mathrm{cm}$. The tune space of highest luminosity reaches its maximum for an electron lens length between 28 and 34 cm.

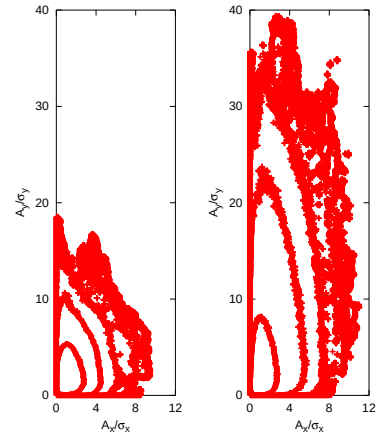


Figure 4: Transverse electron distributions in the uncompensated (left) and the compensated (right) case, for an rms proton bunch length of $\sigma_{s,p} = 20\,\mathrm{cm}$ and an electron lens length of 34 cm. Full head-on beam-beam compensation increases the transverse tail population.

## TRANSVERSE TAILS

To further study the effect of head-on beam-beam compensation, we determined the transverse electron distribution in "good" working points where $F_{\mathrm{geom}} \geq 0.9$, both with and without head-on beam-beam compensation, using the algorithm described in Ref. [6]. As Figure 4 shows, head-on beam-beam compensation enhances the population in the transverse tails significantly.

## SUMMARY

In the parameter range studied so far, no benefit of full head-on beam-beam compensation could be observed. The main effect of the electron lens is a significant enhancement of the transverse tails. In future simulations, we are planning to study the effect of partial beam-beam compensation, as well as that of a pulsed electron lens with a Gaussian longitudinal bunch profile instead of the DC lens with its uniform longitudinal electron density used the simulations presented in this paper.

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