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

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*Abstract*

One of the luminosity limits in a ring-ring electron-ion collider is the beam-beam effect on the electrons. In the limit of short ion bunches, simulation studies have shown that this limit can be significantly increased by head-on beam-beam compensation with an electron lens. However, with an ion bunch length comparable to the beta-function at the IP in conjunction with a large beam-beam parameter, the electrons perform a sizeable fraction of a betatron oscillation period inside the long ion bunches. We present recent simulation results on the compensation of this beam-beam interaction with multiple electron lenses.

## INTRODUCTION

The beam-beam effect experienced by the electron beam in a ring-ring electron-ion collider is one of the major luminosity limitations. Previous simulation studies have shown that in the limit of short ion bunches head-on beam-beam compensation allows for significantly higher beam-beam parameters [1]. However, the length of the ion bunch cannot be ignored, leading to a significant betatron phase advance over the interaction length [2]. Here we study how multiple electron lenses can be used for the head-on beam-beam compensation of the electrons. We calculate the luminosity in a tune scan, and evaluate the creation of transverse tails.

## THE SIMULATION MODEL

The electron ring in this simulation model consists of 100 identical FODO cells which are equipped with sextupoles for chromaticity correction. The electron-proton interaction is compensated by three individual electron lenses, as schematically shown in Figure 1. For this purpose, we consider the long proton bunches to be comprised of three slices - one for its head, one for its center, and one for its tail. Furthermore, we consider these three thick slices to be represented by three single beam-beam kicks. The electron lenses therefore need to be located at a betatron phase advance of $k \cdot \pi$, $k$ being an integer, downstream of their respective proton bunch slice. The first electron lens is positioned at a phase advance $k_1 \cdot \pi$ from the thin lens representing the tail slice, the second lens $k_2 \cdot \pi$ from the thin lens approximating the center slice, and the third lens $k_3 \cdot \pi$ from the beam-beam lens for the head slice, with $k_1$, $k_2$, and $k_3$ being integers. In the limit of an infinite number of proton beam slices and corresponding electron lenses, the beam-beam effect of the long proton bunch would therefore be exactly compensated. In the actual tracking, the proton bunch is represented by 60 individual beam-beam kicks, which is a large number compared to the number of electron lenses.

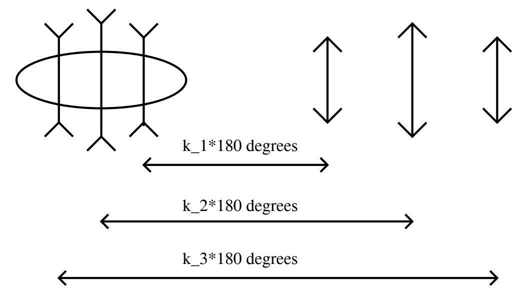


Figure 1: Illustration of the head-on beam-beam compensation scheme with three electron lenses. The long proton bunch (left) is considered to be represented by three short beam-beam lenses, which in turn are each compensated by their corresponding electron lens (right).

The electron-proton interaction point (IP) and the electron lenses are separated by 4 FODO cells each, i.e. the three electron lenses are 4, 8, and 12 FODO cells downstream of the IP. The phase adjustment, as well as the necessary dispersion suppression, is provided by the appropriate transfer matrices at the ends of each arc. Quantum excitation and synchrotron radiation damping are implemented in each arc according to its length. The parameters of the electron ring model are listed in Table 1.

## TUNE SCANS

To determine the luminosity as a function of the electron ring tunes, 100 particles are tracked for 20000 turns, or four transverse radiation damping times. The resulting transverse RMS electron beam sizes $\sigma_{x,e}$ and $\sigma_{y,e}$ were determined by averaging over the last 5000 turns in the tracking. Together with the nominal RMS proton beam sizes $\sigma_{x,p}$ and $\sigma_{y,p}$ we define the geometric luminosity factor as

$$F_{\text{geom}} = \frac{2\sigma_{x,p}\sigma_{y,p}}{\sqrt{(\sigma_{x,p}^2+\sigma_{x,e}^2)(\sigma_{y,p}^2+\sigma_{y,e}^2)}}, \quad (1)$$

which is independent of such quantities as the number of bunches, revolution frequency, or the bunch intensity. $F_{geom}$ is a measure of the electron beam core size increase

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Table 1: Model electron ring parameters. $\beta$-functions and rms beam sizes at the IP and the electron lens are taken from the previous eRHIC ring-ring design [3].

| | | |
|---|---|---|
| no. of FODO cells | $N_{\mathrm{FODO}}$ | 100 |
| no. of cells between IP and electron lenses | $N_{\mathrm{sep}}$ | 4/8/12 |
| 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 |
| electron RMS bunch length | $\sigma_{s,e}$ | 11.7 mm |
| electron RMS momentum spread | $\sigma_p$ | $9.4 \cdot 10^{-4}$ |
| $\beta$-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 | $N_e$ | $1 \cdot 10^{11}$ |
| proton RMS beam emittance | $\epsilon_p$ | 9.5 nm |
| electron RMS 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 |
| electron Lorentz factor | $\gamma$ | 19560 |
| electron beam-beam parameter | $\xi_x/\xi_y$ | 0.09/0.24 |
| damping times | $\tau_x/\tau_y/\tau_z$ | 5000/5000/2500 turns |

due to the beam-beam interaction. Tune scans are performed in steps of $\Delta Q_{x,y} = 0.01$ to determine the optimum working point.

As a first step, we study the effect of the proton bunch length on the available tune space in the uncompensated case without electron lenses. For this purpose, we perform tune scans for short ($\sigma_s = 100\,\mu$m) and long ($\sigma_s = 0.1$ m) proton bunches. As expected, the significant betatron phase advance during the interaction with the long proton bunch leads to significant phase averaging of the individual beam-beam kicks, which in turn opens up the available tune space, as shown in Figure 2. For tunes close enough to the integer the dynamic focusing effect of the proton bunches results in geometric luminosity factors $F_{\mathrm{geom}}$ slightly greater than one.

Adding three electron lenses at a proton bunch length of $\sigma_s = 0.1$ m opens up nearly the entire tune space over which the tune scan is performed, with the exception of areas near low-order resonances, see Figure 3. Due to the head-on beam-beam compensation the dynamic focusing effect of the proton bunch is cancelled, which limits the geometric luminosity factor to $F_{\mathrm{geom}} \leq 1$.

## TRANSVERSE TAILS

Besides increasing the core emittance and therefore diminishing the luminosity, beam-beam effects may also lead to an enhanced population of the transverse beam tails. These enhanced tails result in poor beam lifetime if not accounted for in the design aperture of the machine. We therefore determine the transverse electron distribution in working points with good luminosity performance ($F_{\mathrm{geom}} > 0.9$), both with and without head-on beam-beam compensation, using the algorithm described in Ref. [4].

As Figure 4 shows, long transverse tails get populated in the uncompensated case with short ($\sigma_s = 100\,\mu$m) proton bunches, especially in the vertical plane where the beam-beam parameter is largest. With $\sigma_s = 0.1$ m long proton bunches these tails are significantly reduced due to the phase averaging effect. When head-on beam-beam compensation with three electron lenses is added in the case of $\sigma_s = 0.1$ m long proton bunches, significant tails appear again in the vertical plane, though not as heavily populated as in the uncompensated case with short proton bunches.

## SUMMARY

For the parameter set used in the studies presented in this paper, lengthening the proton bunches increases the tune region of high luminosity, and at the same time reduces the transverse non-Gaussian tails populated by the beam-beam interaction significantly. When head-on beam-beam compensation with three electron lenses is introduced in the case of long proton bunches, the entire tune space with the exception of the vicinity of low-order resonances becomes available. However, this compensation also enhances the transverse beam tails significantly, to a level in-between the uncompensated cases presented for short and long proton bunches.

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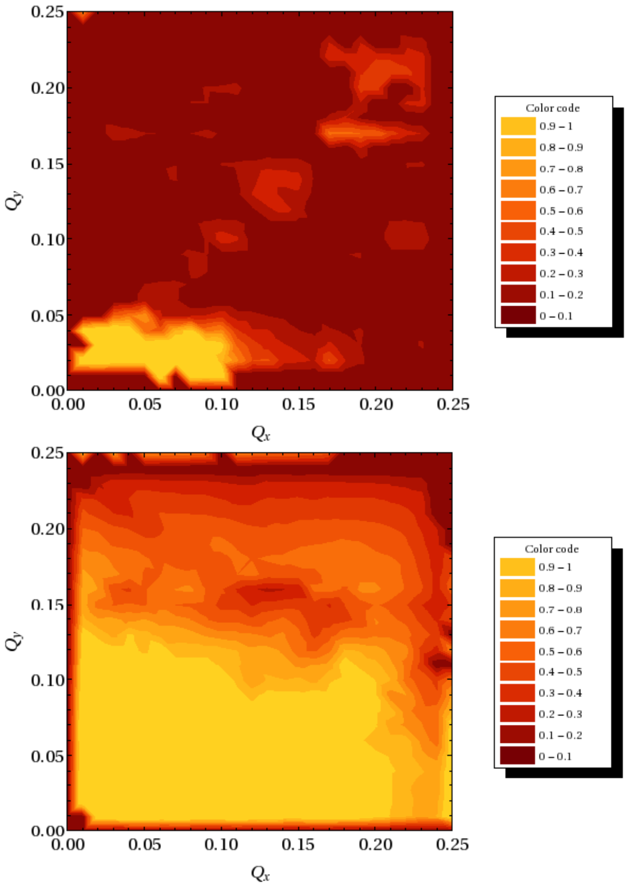


Figure 2: Geometric luminosity factor $F_{\rm geom}$ as a function of tunes in the uncompensated case without electron lenses, for an RMS proton bunch length of $\sigma_s = 100\,\mu$m (top) and $\sigma_s = 0.1$ m (bottom).

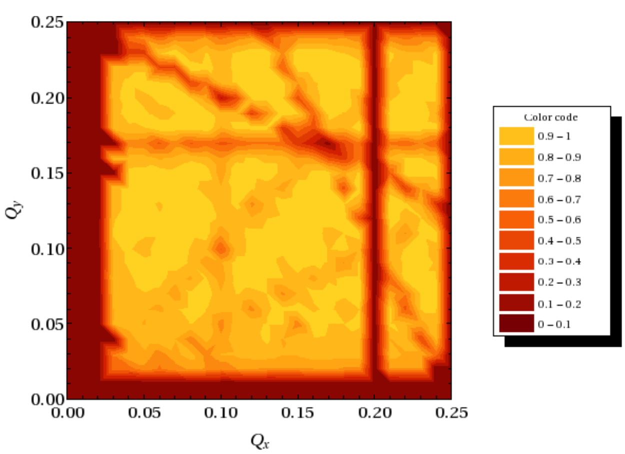


Figure 3: Geometric luminosity factor $F_{\rm geom}$ as a function of tunes in the compensated case with three electron lenses, for a proton bunch length of $\sigma_s = 0.1$ m.

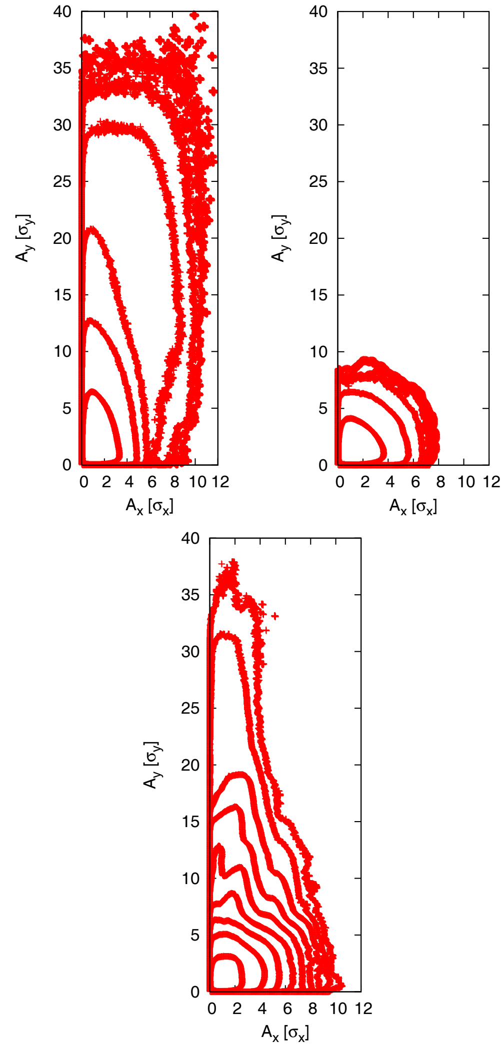


Figure 4: Transverse electron distributions in the uncompensated case, for a proton bunch length of $\sigma_s = 100\,\mu$m (upper left) and $\sigma_s = 0.1$ m (upper right). The bottom plot depicts the transverse electron distribution in the compensated case with three electron lenses and $\sigma_s = 0.1$ m long proton bunches. Tunes are set to $(Q_x, Q_y) = (.04, .03)$ for short and to $(.02, .05)$ for long bunches in the uncompensated case, and to $(.05, .11)$ in the compensated case, which in all cases is in the tune region of highest luminosity.

## ACKNOWLEDGMENTS

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