ERHIC RING-RING DESIGN WITH HEAD-ON BEAM-BEAM COMPENSATION

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Abstract

The luminosity of the eRHIC ring-ring design is limited by the beam-beam effect exerted on the electron beam. Recent simulation studies have shown that the beam-beam limit can be increased by means of an electron lens that compensates the beam-beam effect experienced by the electron beam. This scheme requires proper design of the electron ring, providing the correct betatron phase advance between interaction point and electron lens. We review the performance of the eRHIC ring-ring version and discuss various parameter sets, based on different cooling schemes for the proton/ion beam.

INTRODUCTION

The beam-beam effect experienced by the polarized electron beam in the eRHIC ring-ring design is a major luminosity limitation. When the ion bunch intensity is increased in an effort to maximize the luminosity, the nonlinear beam-beam force results in two effects on the electron beam when the beam-beam limit is approached. The first of these effects is an increase in the core emittance of the electron beam, causing a beam size increase at the interaction point and therefore a reduction in the luminosity. The second beam-beam limit is characterized by the development of a non-Gaussian halo of the electron beam, which needs to be accomodated by the low-β quadrupoles, thus providing a limit on the attainable ion bunch intensity and therefore the luminosity.

In this paper, we investigate the feasibility of head-on beam-beam compensation to increase the beam-beam limit in the ring-ring electron-ion collider eRHIC. We performed weak-strong beam-beam tracking studies with a simplified model of the electron storage ring, with main parameters taken from the eRHIC ring-ring collider design [1]. While the original design assumes a proton bunch intensity of $N_p = 1 \cdot 10^{11}$, corresponding to a vertical beam-beam parameter of $\xi_y = 0.08$, we increase the beam-beam parameter here by quadrupling the proton bunch intensity N_p. The same effect could be achieved by assuming smaller emittances.

THE ELECTRON RING MODEL

The electron ring model used for the simulation studies presented here consists of 50 identical FODO cells, equipped with sextupoles for chromaticity correction. The electron-proton interaction point (IP) and the electron lens are separated by 10 of these FODO cells, forming one arc, while the remaining 40 cells form the other, as schematically shown in Figure 1. At both ends of each arc ideal dispersion suppressors are located, resulting in zero dispersion D^* and zero derivative $D^{*\prime}$ at the IP and the electron lens. Low-β focusing at the IP and the electron lens is realized by chromatic matrices, the chromaticity of each of these telescopes being -2.5. Quantum excitation and synchrotron radiation damping are implemented at the end of each of the two arcs, taking into account the length difference of the two arcs accordingly. Table 1 lists the parameters of the electron ring model.

The presence of the beam-beam lenses at the IP and the electron ring modifies the storage ring lattice significantly; the resulting dynamic focusing effects therefore need to be taken into account. With full head-on beam-beam compensation via the electron lens and a betatron phase advance between the IP and the electron lens of $m \cdot 180°$, however, the dynamic focusing effects cancel at both the IP and the electron lens.

LUMINOSITY AS A FUNCTION OF TUNES

To determine the luminosity as a function of the working point, we track 100 particles over 10000 turns, which corresponds to 5.75 transverse damping times. The equilibrium rms beam sizes of the electron beam, $\sigma_{x,e}$ and $\sigma_{y,e}$, are determined by averaging over the last 1740 turns (one transverse damping time), resulting in a relative statistical error of the equilibrium beam sizes of $1.7 \cdot 10^{-3}$. Using the nominal proton beam sizes $\sigma_{x,p}$, $\sigma_{y,p}$ and the equilibrium electron beam sizes, we define the geometric luminosity factor as

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

In the absence of any beam-beam effects, $F_{\rm geom} = 1$ unless the beam size is affected or beam dynamics is unstable due to lattice resonances. Additionaly, we define the normalized luminosity as

$$L_{\rm norm} = F_{\rm geom} * N_p. \quad (2)$$

To determine the optimum working point, we perform tune scans in steps of $\Delta Q_{x,y} = 0.01$, using the phase rotation matrices schematically indicated in Figure 1. Figure 2 shows contour plots of $F_{\rm geom}$ for tunes below the quarter resonance. Without beam-beam compensation the maximum geometric luminosity factor remains below 0.5,

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Table 1: Model electron ring parameters. β-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 [1].

no. of FODO cells	N_{FODO}	50
no. of cells between IP and electron lens	N_{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 bunch length	σ_s	11.7 mm
rms momentum spread	σ_p	$9.4 \cdot 10^{-4}$
β-function at IP and electron lens	β_x/β_y	0.19 m, 0.26 m
no. of positive charges/bunch	N_p	$4 \cdot 10^{11}$
electron lens intensity/bunch	N_e	$4 \cdot 10^{11}$
rms proton beam emittance	ϵ_p	$9.5\,\mathrm{nm}$
rms electron beam emittance (hor./vert.)	ϵ_e	$53\,\mathrm{nm}/9.5\,\mathrm{nm}$
rms proton beam size at IP	$\sigma_{x,p}/\sigma_{y,p}$	$101\,\mu\mathrm{m}/50.5\,\mu\mathrm{m}$
rms electron lens beam size	$\sigma_{x,e}/\sigma_{y,e}$	$101\,\mu\mathrm{m}/50.5\,\mu\mathrm{m}$
Lorentz factor	γ	19560
electron beam-beam parameter	ξ_x/ξ_y	0.11/0.32
damping times	$\tau_x/\tau_y/\tau_z$	1740/1740/870 turns

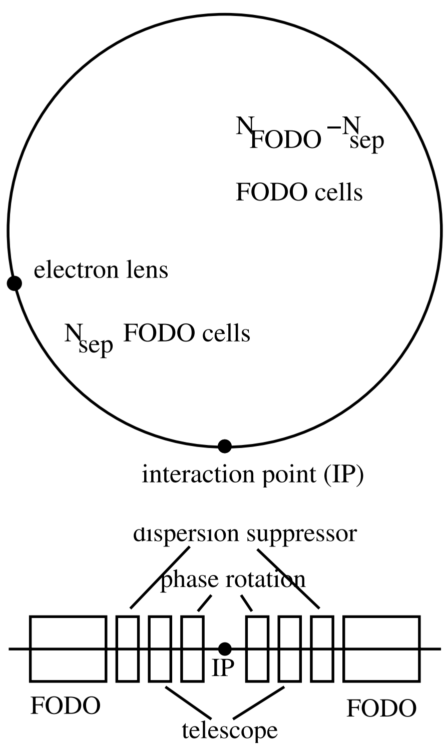

Figure 1: Schematic drawings of the model electron ring (top) with interaction point (IP) and electron lens. The bottom figure depicts a low-β insertion with dispersion suppressors, low-β telescopes, and phase rotation matrices.

while with full beam-beam compensation ($N_e = N_p$) it reaches almost 0.7. Furthermore, beam-beam compensation greatly reduces the tune dependence of the luminosity.

TRANSVERSE TAILS

Development of long, non-Gaussian transverse tails is often referred to as the second beam-beam limit in e^+e^- colliders. A simulation code has been developed to study the transverse electron distribution, based on techniques developed by Shatilov [2].
As Figure 3 shows, the beam dynamics is dominated by this second beam-beam limit. Head-on beam-beam compensation significantly reduces the transverse electron beam tails.

ROBUSTNESS TO PARAMETER VARIATIONS

We have studied the sensitivity of head-on beam-beam compensation to small changes of parameters such as proton beam size, proton beam intensity, and deviations of the betatron phase advance between IP and electron lens from the ideal value of $k \cdot \pi$. The resulting luminosity is rather insensitive to proton beam size and intensity fluctuations, as long as the electron lens does not overcompensate the beam-beam effect imposed by the proton beam. In fact, our results indicate that half compensation, where the electron lens has only half the strength required to completely compensate the proton beam, results in the highest luminosities.
The betatron phase advance between IP and electron lens

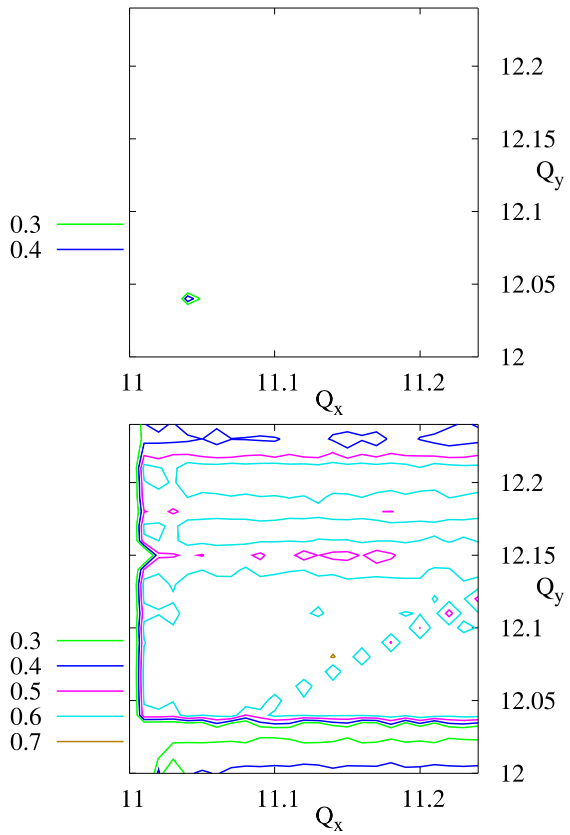

Figure 2: Geometric luminosity factor F_{geom} as a function of tunes, without (top) and with (bottom) full head-on beam-beam compensation.

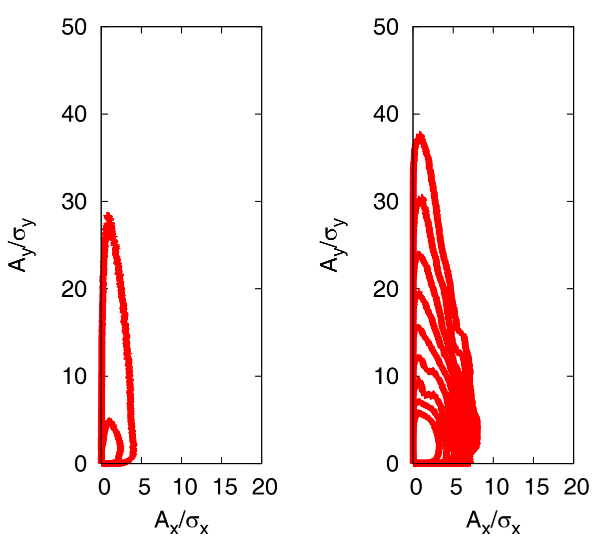

Figure 3: Transverse electron distributions for uncompensated (left) and fully compensated (right) head-on beam-beam interaction, for a proton bunch intensity of $N_p = 4 \cdot 10^{11}$ protons per bunch. The contour lines are spaced by a factor 10.

Table 2: Updated eRHIC ring-ring parameters

	no cooling	pre-cooling
ϵ_p [nm]	9.5	3.8
ϵ_e (x/y) [nm]	53/9.5	21/3.8
N_b	166	166
f_{rev}	78 kHz	78 kHz
E_p	250 GeV	250 GeV
E_e	10 GeV	10 GeV
N_e	$2.3 \cdot 10^{11}$	$0.9 \cdot 10^{11}$
N_p	$2 \cdot 10^{11}$	$1.6 \cdot 10^{11}$
β_p^*	1.08/0.27	0.43/0.11
β_e^*	0.19/0.27	0.08/0.11
ξ_p (x/y)	0.015/0.008	0.015/0.008
ξ_e (x/y)	0.06/0.16	0.12/0.32
L	$9.5 \cdot 10^{32}$	$1.8 \cdot 10^{33}$

was found to be the most sensitive parameter. This phase advance has to be accurate within about $\delta\phi = 2°$.

UPDATED ERHIC RING-RING PARAMETERS

Based on the results of these simulation studies, which suggest the feasibility of an electron beam-beam parameter as high as $\xi_e = 0.3$ the design parameters for the ring-ring electron-ion collider eRHIC have been modified. Table 2 lists the updated parameters, taking into account the present RHIC beam emittances as well as pre-cooling of the proton beam beam at injection. In both scenarios, the proton bunch intensity is assumed to be limited to $N_p = 2 \cdot 10^{11}$ protons/bunch, the currently achieved maximum.

SUMMARY

Weak-strong beam-beam simulations indicate that head-on beam-beam compensation is capable of raising the beam-beam limit in the eRHIC electron ring significantly, to roughly $\xi = 0.3$. This results in an attainable luminosity of almost $1 \cdot 10^{33}\,\text{cm}^{-2}\text{sec}^{-1}$ even for currently achieved proton beam emittances and intensities, and significantly higher values if cooling of the proton beam is assumed.
It is worth mentioning that, although the studies presented here were carried out with an electron beam circulating in the model storage ring, similar luminosities can be expected for a stored (polarized) positron beam.

ACKNOWLEDGMENTS

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