BEAM-BEAM SIMULATIONS FOR THE ERHIC ELECTRON RING [*]

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Abstract

To study collisions between polarized electrons and heavy ions or polarized protons at high energy, adding a 10 GeV electron storage ring to the existing RHIC facility is currently under consideration. To achieve high luminosities of several $10^{33}\,\mathrm{cm}^{-2}\mathrm{sec}^{-1}$ range, a vertical beam-beam tuneshift parameter of $\xi_y = 0.08$ is required for the electron beam. Simulation studies are being performed to study the feasibility of this high tuneshift parameter and explore the potential for even higher tuneshifts. Recent results of these studies are presented.

INTRODUCTION

The electron-ion collider eRHIC [1], currently under study at BNL, consists of a $10\,\mathrm{GeV}$ electron ring added to the existing RHIC accelerator complex to study collisions of polarized electrons and relativistic heavy ions or polarized protons. The circumference of this electron ring is one third of the RHIC circumference. Some machine parameters of this facility are listed in Table 1.

A beam-beam tuneshift parameter of $\xi_y = 0.08$ is required for the electron beam to achieve a luminosity of several $10^{32}\,\mathrm{cm}^{-2}\mathrm{sec}^{-1}$. These high tuneshift parameters require careful simulation studies to ensure the feasibility of attaining the projected luminosity. Additionally, the unequal circumferences of the two rings lead to additional resonances that must be avoided when choosing the working point of the machine.

UNEQUAL CIRCUMFERENCES

Colliders comprised of storage rings of different circumference require careful choice of the working point of both rings to ensure stable beam operation [2]. The resonance condition is

$$Q_1 - \frac{C_1}{C_2} Q_2 = n, \quad n \text{ integer}, \tag{1}$$

where Q_1 and Q_2 are the fractional tunes of the two machines and C_1 and C_2 denote their respective circumferences. The actual width of these resonances is most easily studied by simulations. In the case of eRHIC, $C_1/C_2 = 3$, so each electron bunch collides with three different hadron bunches.

The simulation is performed by describing both beams as rigid Gaussian bunches. One electron bunch and three hadron bunches are simulated. The beam-beam interaction is modelled as a mutual weak-strong kick, while the accelerator is described by a linear one-turn matrix. To seed the possible resonance, the electron bunch starts with an offset of $1\,\mu\mathrm{m}$ at the interaction point (IP), small compared to the rms beam size of $\sigma_x = 100\,\mu\mathrm{m}$ and $\sigma_y = 50\,\mu\mathrm{m}$. Bunches are tracked for $3 \cdot 10^4$ electron beam turns, corresponding to 10^4 hadron beam turns in RHIC. Stability is defined as no increase of the electron beam amplitude during tracking.

electrons:	
ring circumference [m]	1278
number of bunches	120
geometric emittance hor./vert. [nm]	53/9.5
β functions hor./vert. [m]	0.19/0.27
bunch length [mm]	11.7
synchrotron tune	0.04
particles/bunch	$1.0 \cdot 10^{11}$
beam-beam tune shift hor./vert.	0.027/0.08
damping times hor./vert./long. [turns]	1740/1740/870
hadrons:	
ring circumference [m]	3834
number of bun ches	360
geometric emittance hor./vert. [nm]	9.5/9.5
β functions hor./vert. [m]	1.08/0.27
particles/bunch	$1.0 \cdot 10^{11}$ (p), $1.0 \cdot 10^{9}$ (Au)
beam-beam tune shift hor./vert.	0.007/0.0035
beam spot size hor.vert. [μm]	100/50
luminosity [$\mathrm{cm}^{-2}\mathrm{sec}^{-1}$]	$4.4 \cdot 10^{32}$

Table 1: Interaction region parameters of the electron-ion collider eRHIC.

Taking into account both planes and setting the ion beam tunes to the current RHIC working point $Q_{p,x} = .21$, $Q_{p,y} = .23$, a sufficiently large region of the electron beam tune space $.06 < Q_{e,x} < .34$, $.05 < Q_{e,y} < .28$ leads to stable motion, as shown in Figure 1.

DYNAMIC FOCUSING

With a beam-beam tuneshift parameter as high as $\xi_y = 0.08$, the beam-beam interaction has a significant effect on the entire electron beam dynamics and cannot be treated as a small perturbation. For instance, the resulting small amplitude tune Q is expressed as

$$\cos(2\pi Q) = \cos(2\pi Q_0) - 2\pi\xi \sin(2\pi Q_0). \tag{2}$$

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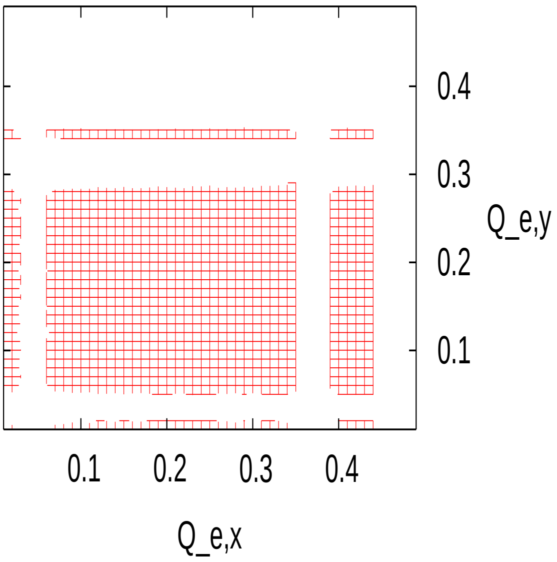

Figure 1: Electron beam tune diagram, $Q_{e,y}$ vs. $Q_{e,x}$, for a hadron working point of $Q_{p,x} = .21$, $Q_{p,y} = .23$. The checkered areas indicate stable tune regions.

Likewise, the strong beam-beam lens at the IP significantly modifies the β-function at the IP, resulting in a tune-dependent β-function,

$$\beta = \frac{\beta_0}{\sqrt{1 + 4\pi\xi\cot(2\pi Q_0) - 4\pi^2\xi^2}}. \qquad (3)$$

The resulting β-function at the IP is therefore significantly reduced for tunes just above the integer, which provides additional focusing.

The presence of this strong beam-beam lens also modifies the entire machine optics and therefore the equilibrium beam emittance, which depends on the "curly H" function

$$\mathcal{H}(s) = \beta(s)D'^2(s) + 2\alpha(s)D(s)D'(s) + \gamma(s)D^2(s), \qquad (4)$$

where $\alpha(s)$, $\beta(s)$, and $\gamma(s)$ are the Twiss parameters at location s, $D(s)$ is the dispersion in the same location, and $D'(s) = \mathrm{d}D(s)/\mathrm{d}s$. The resulting dynamic emittance ϵ can be approximated as [3]

$$\epsilon \approx \frac{1 + 2\pi\xi\cot(2\pi Q_0)}{\sqrt{1 + 4\pi\xi\cot(2\pi Q_0) - 4\pi^2\xi^2}}\epsilon_0, \qquad (5)$$

where ϵ_0 refers to the equilibrium emittance of the unperturbed lattice, but in fact depends rather strongly on the machine lattice [4]. For the simulation, the resulting equilibrium emittance is therefore calculated with the respective actual dynamic machine lattice for each working point.

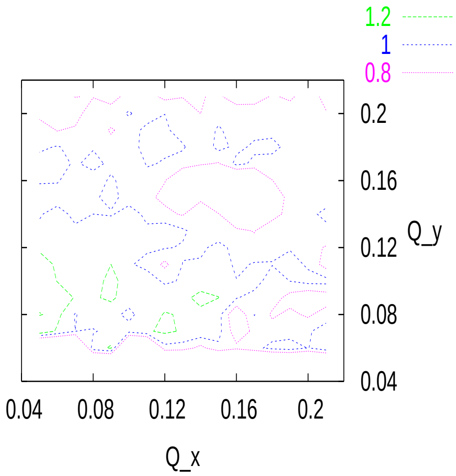

Figure 2: Contour plot of the resulting normalized luminosity $\mathcal{L}/\mathcal{L}_0$ vs. horizontal and vertical electron beam tune. $\mathcal{L}_0$ denotes the geometric design luminosity according to Table 1.

SIMULATION RESULTS

The nonlinear eRHIC electron ring lattice [1] is optimized for a working point of $Q_x = .10$, $Q_y = .14$ and zero chromaticity in both planes. Tracking studies were performed to find the best working point for this machine, scanning tunes in the range between the integer and the quarter resonance by adjusting the main quadrupoles accordingly. For each working point the chromaticities are readjusted to zero.

The beam is represented by 100 macroparticles with a rms momentum deviation of $\sigma_p = 0.007$ and a synchrotron tune of $Q_s = 0.04$. These particles are tracked for ten radiation damping times, including quantum excitation and radiation damping. The horizontal equilibrium emittance is adjusted according to the radiation integrals that correspond to each individual working point. The vertical equilibrium emittance is assumed to be unaffected by the machine tune. The resulting equilibrium luminosity is calculated according to the obtained rms beam sizes σ_x and σ_y after tracking for ten damping times. Figure 2 shows a contour plot of the resulting luminosity in units of the nominal geometric luminosity, as a function of the working point (Q_x, Q_y).

While the luminosity generally increases with lower tunes, the coupling resonance is clearly visible in this plot, as is the 6th order resonance in both planes. At very low tunes synchrotron sidebands enhance the width of the integer resonance. However, to ensure proper matching of beam sizes of the hadron and electron beam at the IP, both planes have to be checked separately. Figures 3 and 4 depict the result-

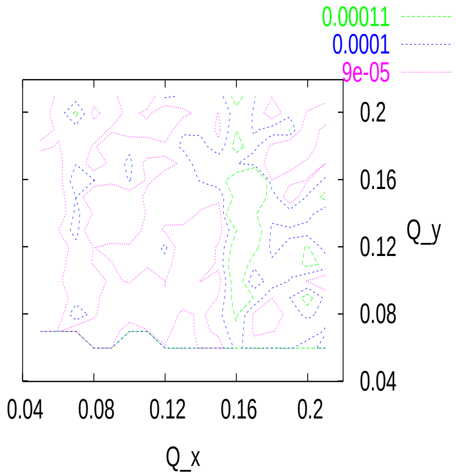

Figure 3: Contour plot of the horizontal rms electron beam size σ_x (in meters) vs. electron beam working point (Q_x, Q_y).

ing rms beam sizes in the two planes as a function of the working point. In the horizontal plane, a significant beam size increase occurs mostly along the 6th order resonance line. The situation in the vertical plane is more complex due to the larger beam-beam parameter.

CONCLUSION

Simulation studies show that even with beam-beam tuneshift parameters of up to $\xi = 0.08$, sufficiently large areas in the working diagram can be found that support the projected luminosity performance of eRHIC. These simulations also indicate that a luminosity significantly higher than the geometrical one could be achieved by moving the electron beam tunes very close to the integer, thus taking advantage of dynamic focusing effects. However, this results in a beam size mismatch of the two beams, which may cause emittance deterioration of the ion beam.

Based on these simulations three possible working points have been identified that promise to deliver the design luminosity without a significant beam size mismatch in either plane. These working points are around $(Q_x, Q_y) = (.05, .07), (.10, .14)$, and $(.14, .07)$. These working points are further investigated in terms of non-Gaussian tails resulting from the beam-beam interaction in conjunction with quantum excitation and radiation damping [5].

According to simulations, unequal circumferences of the two rings are not much of a concern in terms of barycenter motion of the two beams, as long as certain additional resonances are avoided. The remaining stable tune space is sufficiently large to ensure stable operation of the electron-ion collider eRHIC. The location of the stable area within the tune diagram depends on the working point chosen for the ion ring. For the present RHIC working point, stable electron tunes are consistent with those found necessary to achieve design luminosity.

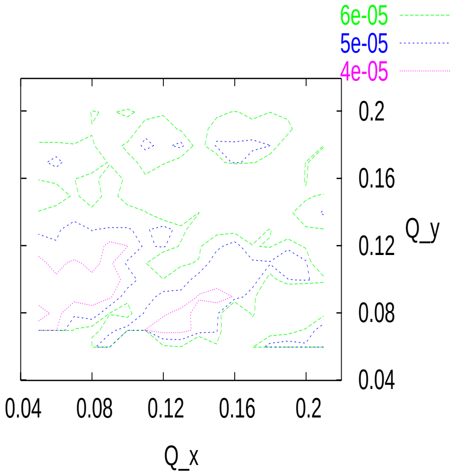

Figure 4: Contour plot of the vertical rms electron beam size σ_y (in meters) vs. electron beam working point (Q_x, Q_y).

REFERENCES

[1] eRHIC Zeroth-Order Design Report, BNL note C-A/AP/142

[2] K. Hirata and E. Keil, “Barycenter motion of beams due to beam-beam interaction in asymmetric colliders”, Nucl. Instr. and Meth. A 292 (1990) 156-168

[3] K. Hirata, “Beam-beam effects”, in: A. W. Chao and M. Tigner (eds.), Handbook of Accelerator Physics and Engineering, World Scientific, Singapore (1999)

[4] A. V. Otboyev and E. A. Perevendentsev, “Self-consistent β functions and emittances of round colliding beams”, Phys. Rev. ST Accel. Beams 2, 104401 (1999)

[5] C. Montag, “Simulation of resonance streaming at the eRHIC electron storage ring”, these proceedings