STUDIES OF BEAM DYNAMICS FOR ERHIC*

G. Wang[#], M. Blaskiewicz, A. Fedotov, Y. Hao, J. Kewisch, V. N. Litvinenko, E. Pozdeyev, V. Ptitsyn, BNL, Upton, NY 11973, U.S.A.

Abstract

We present our studies on various aspects of the beam dynamics in 'racetrack' design of the first stage electron-ion collider at RHIC (eRHIC), including transverse beam break up instabilities, electron beam emittance growth and energy loss due to synchrotron radiation, electron beam losses due to Touschek effects and residue gas scattering, beam-beam effects at the interaction region and emittance growth of ion beam due to electron bunch to bunch noises. For all effects considered above, no showstopper has been found.

INTRODUCTION

The linac-ring design of the future electron ion collider at RHIC (eRHIC) uses staged approach[1]. For the first stage, the polarized 4GeV electron beam collides with 250 GeV polarized proton beam or 100 GeV/u heavy ion beam. The beam dynamic studies that we show here are based on the so called 'racetrack' design as shown in Figure 1. Injected with 100MeV, the electron beam passes through two linacs for 3 times gaining 650MeV energy in each linac per passage, collides with the ion beam at 4GeV in the interaction region and then passes through the two linacs for another 3 times to return its energy. The beta functions of linac optics design with constant gradient quadrupoles are shown in Figure 2. The electron beam has 5nC charge per bunch and the rms bunch length is 2mm with 107ns spacing between two adjacent bunches.

In the following sections, we present the evaluation of various beam dynamic issues for the 'racetrack' design of the first stage eRHIC.

MULTIPASS BEAM BREAKUP

In energy recovery linac (ERL), the voltages of high order modes (HOM) induced by the re-circulating electron bunches can add up constructively and cause instabilities. For a single dipole mode in a single cavity, the threshold of the beam breakup instability can be solved analytically from the dispersion relation[2]. However, for multi-cavities with multi-modes, the threshold usually has to be found from simulation. Figure 3 shows the simulation result using generic beam breakup codes (GBBU) developed by E. Pozdeyev[3]. The dipole modes used in the simulation are input from Microwave-

* Work supported by Brookhaven Science Associates, LLC under Contract No.DE-AC02-98CH10886 with the U.S. Department of Energy.
#gawang@bnl.gov

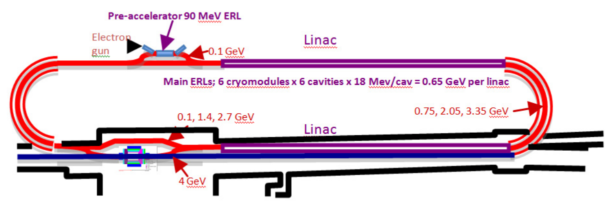


Figure 1: Schematic drawing of the 'Racetrack' design for the first stage eRHIC.

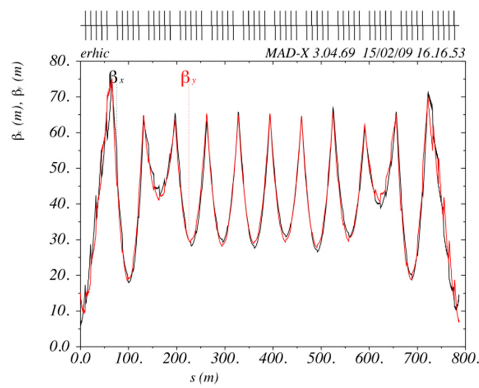


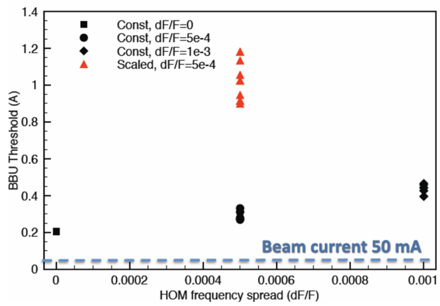
Figure 2: Beta function inside linac with constant gradient quadrupoles. The beta functions of arcs are not shown.

studio calculations and measurements. As shown in Figure 3 (a), the lowest threshold for zero resonant frequency spread is 200mA, which is 4 times larger than the designed electron current. Figure 3 (b) shows the maximal quality factor, Q_{max}, allowed for each modes in order to avoid beam breakup, which can be conveniently used as the design requirements for the HOM damper.

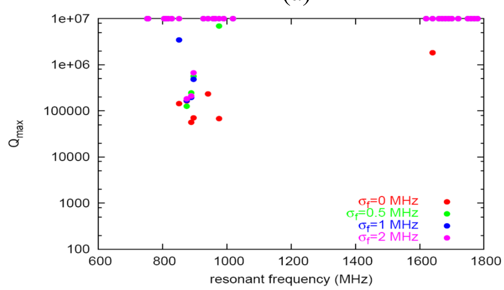
BEAM LOSSES DUE TO SCATTERING

Both electron-electron scattering and electron-residue gas scattering can cause beam losses in the ERL.

While multiple small-angle scattering within charged particle beam usually results in emittance degradation, depending on the momentum aperture, large-angle Moller scattering among electrons can cause instant beam losses, which is called Touschek effect. Figure 4 shows analytical estimation of beam losses due to Touschek effect for a round electron beam. As shown in Figure 4, for 6MeV energy deviation acceptance, the total beam losses due to Touschek effect are 200pA.



(a)



(b)

Figure 3: Multi-pass beam breakup simulation using GBBU[3]. (a) Current threshold for various HOM frequency spread. The red triangles are for linac lattice design with scaled gradient quadrupoles. (b) Quality factor threshold, Q_{max}, of major dipole modes for onset of multi-pass beam breakup.

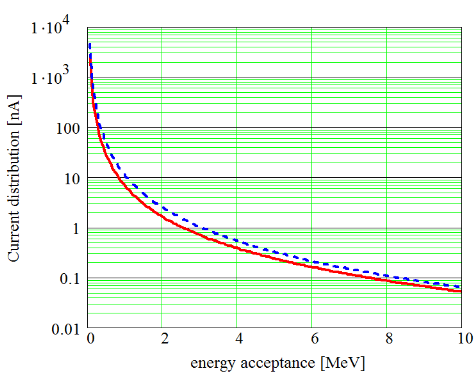
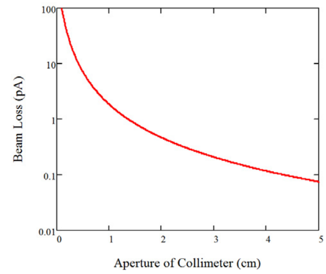
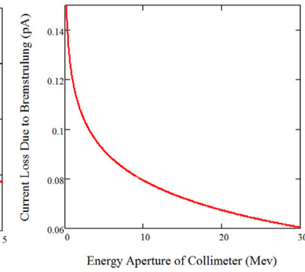


Figure 4: Analytical calculation of beam loss due to Touschek effect. The red solid curve is the beam losses in arcs only. The blue dash curve is the beam losses in arcs and linac.

Another mechanism for beam losses is electron scattering off the nuclei of residue gases. We considered beam losses caused by elastic scattering and bremsstrahlung. Due to adiabatic damping (anti-damping) during the accelerating (decelerating), the kick angle from the elastic scattering in the high energy passes results in a much larger angular deviation in the low energy passes and thus the beam losses tends to take places in the low energy passes. Assuming the vacuum level is 0.01 nTorr in the linac, 1 nTorr in arcs, the species are H^-, and the collimator sits at the very end of ERL, Figure 5(a) shows analytic estimate of beam losses due to elastic



(a)



(b)

Figure 5: Beam losses caused by electron scattering off the nuclei of residue gases. (a) Losses due to angular kick in elastic scattering; (b) Losses due to electron energy loss in bremsstrahlung.

scattering as a function of collimator aperture. Similar to the angular kick, the energy kick due to bremsstrahlung can cause electron energy exceed the energy acceptance. Figure 5(b) shows the integrated beam losses as a function of the energy acceptance, assuming the minimum energy acceptance is located at the end of ERL.

From the estimates shown in Figure (4) and (5), the dominant mechanism of beam losses is Touschek effect. The overall beam losses are negligible and the induced beam halo can be cleared with proper collimation.

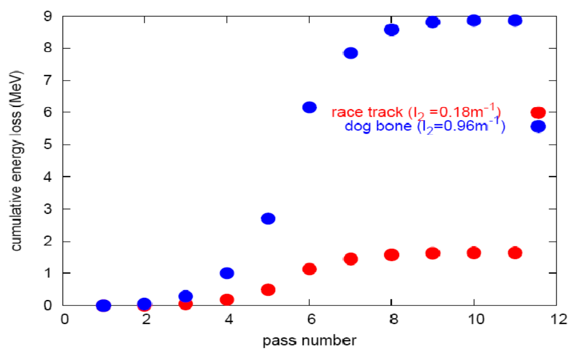
COHERENT SYNCHROTRON RADIATION

When passing through a bending magnet, the head of the electron bunch can interact with the radiation field emitted by the tail of the bunch. This self interaction can constructively add up the radiation field, which causes beam energy loss and increases the energy spread of the bunch. Meanwhile, the shielding effects from the metallic wall of the beam pipe can substantially reduce the radiation power. Without consideration of shielding effect, analytic estimate shows that coherent synchrotron radiation (CSR) causes 8MeV of total energy loss and 5.7MeV of rms energy spread increase for electron bunch with 2mm rms bunch length. When the shielding effect with 2cm wall height is taken into account, theoretical calculation shows that the average energy loss reduces to 21eV.

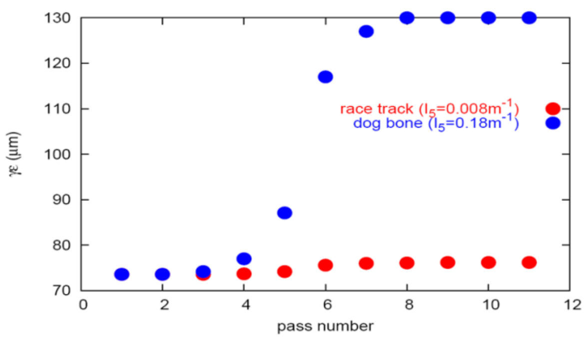
In order to verify the suppression effect of shielding on CSR induced total energy loss and energy spread increase, experiment has been set up at BNL accelerator test facility (ATF) recently. Measurements and data analysis are presently in progress.

SYNCHROTRON RADIATION EFFECTS

Synchrotron radiation can cause beam energy losses and emittance growth. Uncorrected energy losses introduce energy difference of electron bunch during its accelerating pass and decelerating pass of linac and thus jeopardize the energy recovery of linac. As shown in Figure 6(a), the cumulative energy loss for the racetrack design presented here is below 2MeV for number of



(a)



(b)

Figure 6: Analytical evaluation of energy losses and emittance growth due to synchrotron radiation for various number of passes. The blue dot is for the old 'dog bone' design and the red dot is for the 'racetrack' design. (a) The energy losses due to synchrotrn radiation; (b) Normalized electron bunch emittance in various passes starting from 70 $mm \cdot mrad$.

passes below 11. The 2% energy deviation at 100MeV pass can be corrected with 2nd harmonic cavities if necessary. Due to random kicks from photon emissions, the emittance of the electron beam can be degraded. Figure 6(b) shows the analytical calculation of synchrotron radiation induced emittance growth. For the 'racetrack' design, the emittance growth is less than 10 $mm \cdot mrad$.

ION DEGRADATION DUE TO ELECTRON BUNCH FLUCTUATION

Fluctuation of electron bunch charge and emittance can cause modulation of beam-beam tune shift, which leads to ion beam emittance growth. Assuming the ion beam emittance growth is small compared with its initial emittance, the expectation value of the ion emittance after the nth interaction with electron bunches reads,

$$\langle J(\theta)\rangle = J(0)\exp\left[2\langle u_n(\theta)\rangle\right], \quad (1)$$

where θ is time like variable,

$$\langle u_n(\theta)\rangle = n\sum_{m=-\infty}^{\infty}\frac{1}{4}\cos(4\pi Qm)\langle\delta\varepsilon_k\delta\varepsilon_{m+k}\rangle, \quad (2)$$

Q is the betatron tune and $\langle\delta\varepsilon_k\delta\varepsilon_{m+k}\rangle$ is the correlation between two beam-beam kicks received from electron bunches. Assuming the correlation function takes the following form,

$$\langle\delta\varepsilon_k\delta\varepsilon_{m+k}\rangle = \sigma_\varepsilon^2\exp(-\alpha|m|), \quad (3)$$

equation (2) becomes

$$\langle u_n(\theta)\rangle = n\frac{\sigma_\varepsilon^2}{4}\frac{1-e^{-2\alpha}}{1+e^{-2\alpha}-2\cos(4\pi Q)e^{-\alpha}}. \quad (4)$$

For completely uncorrelated kicks, $\alpha\to\infty$ and equation (4) reduces to formula derived for fluctuations with spectrum of white noise[4].

Along with bunch charge and emittance modulation, the steering error modulation of the electron bunch also contributes to the ion beam emittance growth. Assuming the correlation of the steering error has form

$$\langle y_l y_{m+l}\rangle = \sigma_y^2\exp(-\alpha|m|), \quad (5)$$

the ion emittance after kth beam-beam interaction with electron bunches reads

$$\varepsilon_{rms,k} = \varepsilon_{rms,0} + k\frac{(\varepsilon\sigma_y)^2}{2\beta^*}\frac{1-e^{-2\alpha}}{1+e^{-2\alpha}-2\cos(2\pi Q)e^{-\alpha}}, \quad (6)$$

where $\varepsilon/4\pi$ is the beam beam tune shift and β^* is the beta function at interaction point.

More accurate estimate requires knowledge of the fluctuation spectrum.

BEAM BEAM EFFECTS

The electron-ion beam beam interaction can cause kink instability to the ion beam and beam disruption to the electron beam. Detailed study can be found in Refs. [4] and [5].

SUMMARY

For all beam dynamic effects presented here, no show-stopper has been found.

Further improvements of beam dynamic studies include investigating ion trapping in the ERL and its countermeasures, completing study of CSR shielding and measuring the spectrum of electron bunch noise.

REFERENCES

[1] V. Ptitsyn, J. Beebe-Wang, I. Ben-Zvi, et al., in *PAC09* (Vancouver, BC, Canada, 2009), WE6PFP062.

[2] G. H. Hoffstaetter and I. V. Bazarov, Physical Review Special Topics - Accelerators and Beams **7**, 054401 (2003).

[3] E. Pozdeyev, Phys. Rev. ST Accel. Beams, 054401 (2005).

[4] Y. Hao, V. N. Litvinenko, C. Montag, et al., in *PAC07* (Albuquerque, New Mexico, 2007), p. 1865.

[5] Y. Hao, V. N. Litvinenko, and V. Ptitsyn, in *IPAC'10* (Kyoto, Japan, 2010), TUPEB041.