HIGHER LUMINOSITY eRHIC RING-RING OPTIONS AND UPGRADE*

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Abstract

Lower risk ring-ring alternatives to the BNL linac-ling [1] eRHIC electron ion collider (EIC) are discussed. The baseline from the Ring-Ring Working Group [2] has a peak proton-electron luminosity of $\approx 1.2\times10^{33}\,\mathrm{cm^{-2}\,s^{-1}}$. An option has final focus quadrupoles starting immediately after the detector at 4.5 m, instead of at 32 m in the baseline. This allows the use of lower β^*s. It also uses more, 720, lower intensity, bunches, giving reduced IBS emittance growth and requiring only low energy pre-cooling. It has a peak luminosity of $\approx 7\times10^{33}\,\mathrm{cm^{-2}\,s^{-1}}$. An upgrade of this option, requiring magnetic, or coherent, electron cooling, has 1440 bunches and peak luminosity of $\approx 15\times10^{33}\,\mathrm{cm^{-2}\,s^{-1}}$.

INTRODUCTION

Brookhaven National Laboratory's eRHIC electron ion collider (EIC) design uses an electron energy recovery linac that intersects an ion beam based on RHIC [1]. A baseline alternative ring-ring design, using 360 bunches, and a peak proton-electron luminosity of $1.2\times10^{33}\,\mathrm{cm^{-2}\,s^{-1}}$ was studied in 2015 and is reported on at this conference [2]. This paper describes an 'option' with final focus quadrupoles starting at 4.5 m, instead of 32 m, from the IP. It uses 720, instead of 320, lower charge bunches, and gives a luminosity of $\approx 7\times10^{33}\,\mathrm{cm^{-2}\,s^{-1}}$. An 'upgrade', using 1440 bunches and coherent electron cooling [3] has a luminosity of $\approx 15\times10^{33}\,\mathrm{cm^{-2}\,s^{-1}}$. The luminosity and IBS times for electron-ion collisions will be similarly improved.

The use of many, but lower charge, bunches in ring-ring designs is integral to high luminosity e^+e^- colliders, and the Jefferson Laboratory's EIC design [4] and was suggested for use at Brookhaven [5]. The constraints used in this study are the same as in the baseline, but it uses somewhat lower normalized proton transverse emittances (1.8 vs. 2.5 µm), shorter (11 vs. 20 cm) bunches, a larger crossing angle (20, vs 15, mrad), flatter beams (σ_x/σ_y upto 5.6, vs. 2.8), and unequal proton/ion emittances (ϵ_x/ϵ_y=2.4 vs. 1.0).

LUMINOSITY

The luminosity of an electron proton collider is:

$$\mathcal{L} = f\frac{N_p N_e}{4\pi\sigma_x\sigma_y} \tag{1}$$

where the σ_x and σ_y beam dimensions at the IP are the same for both protons and electrons and depend on their geometric

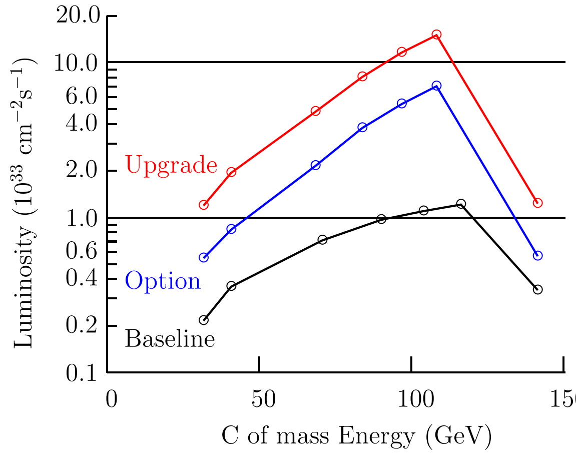

Figure 1: Luminosities vs. center of mass energy

emittances $\epsilon_{x,y}$ and β^*s.

$$\sigma_{p,e,x,y} = \sqrt{\epsilon_{p,e,x,y}\beta_{p,e,x,y}} \tag{2}$$

Limits on the beam powers come from synchrotron radiation and other practical considerations.

$$P_{p,e} \propto f N_{\mathrm{bunches}} N_{p,e}\gamma_{p,e} \tag{3}$$

The numbers of particles per bunch $N_{p,e}$ are constrained by the beam-beam tune shifts $\xi_{x,y,e,p}$ (also known as beam-beam parameters) induced by each beam on the other. Their strength is given by:

$$\xi_{p,e,x,y} = \frac{r_{p,e}}{2\pi}\frac{N_{e,p}}{\epsilon_{p,e}\gamma_{p,e}}\frac{1}{1+\sigma_{y,x}/\sigma_{x,y}} \tag{4}$$

Combining equations 1, 2, and 3, eliminating the emittances, gives:

$$\mathcal{L} \propto \sqrt{P_e P_p(1+K)(1+1/K)}\left(\frac{\xi_{x,p}\xi_{y,p}\xi_{x,e}\xi_{y,e}}{\beta_{x,p}\beta^*_{y,p}\beta^*_{x,e}\beta_{y,e}}\right)^{1/4} \tag{5}$$

where $K = \sigma_y/\sigma_x$. The ξ_ps for the protons are bounded by beam stability considerations at $\approx$ 0.015. In a ring-ring EIC the ξ_es are bounded by stability at $\approx$ 0.1, higher because of the strong synchrotron damping. In a linac-ring EIC the ξ_es of the electrons can be much higher because the electrons will soon be discarded and can suffer significant emittance growth. But this advantage is offset by practical limits on the electron current, and thus on P_e. An electron ring, like PEP II, can store and collide currents of 3 A, while the BNL linac-ring design is limited to 50 mA.

Luminosity, for given beam powers, is maximized with very flat beams ($K = \sigma_y/\sigma_x \ll 1$) and low β^*s. The β^*s

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are constrained by the angular acceptance of the focusing quadrupoles, that limit the beam divergences $\sigma'_{p,e,x,y}$:

$$\sigma'_{p,e,x,y} = \sqrt{\frac{\epsilon_{p,e,x,y}}{\beta_{p,e,x,y}}} \quad (6)$$

So low βs require low transverse emittances, and, in order to avoid excessive hour glass effects, they also require short bunches. The lower emittances, from the ξ constaints, require lower N_e and N_p, and these, for the same average powers P_e and P_p allow more bunches and higher luminosity.

PARAMETERS

Table 1 gives selected parameters for three ring-ring EIC cases:

1. The baseline with final focusing starting at 32 m, magnetic electron cooling at 50 and 100 GeV, relatively short IBS times, and a peak luminosity of 1.2×10^{33} cm^{-2} s^{-1}.
2. An option, with final focusing starting at 4.5 m, as in the linac-ring, allowing lower β^*s. It uses more, but smaller, bunches, and was optimized, individually, at each energy, for both luminosity and IBS lifetime. It has flatter beams with unequal x-y emittances for both protons, using rf noise, and for electrons using reduced x-y coupling. The IBS emittance growth times are all above 8 hours, and needs only non-magnetic pre-cooling. Its peak luminosity is 7×10^{33} cm^{-2} s^{-1}.
3. An upgrade scaled from the option with half the β^*s, σ_zs, and emittances $\epsilon_{x,y}$, and double the number of bunches. It needs magnetic electron cooling, or Coherent Electron Cooling, and achieves a peak luminosity of 1.5×10^{34} cm^{-2} s^{-1}.

For the latter cases, the higher numbers of bunches would be formed by binary splitting the baseline's 320 bunches after injection into RHIC. Figure 1 shows the luminosities as a function of center of mass energies.

The lower horizontal electron emittances electron ring lattice with shorter or low emittance cells are required. The larger electron ratios of ϵ_x/ϵ_y imply less x-y coupling.

Crab cavities for the option need 12 MV at 336 MHz, plus harmonic correction at 672 MHz. The upgrade needs 13 MV at double the frequencies.

IBS AND COOLING

From a fit to simulations [6] of RHIC, over the relevant parameters, gives IBS times, with ϵs and σ_zs in mwhere:

$$\tau_{\parallel} \approx 4.78 \times 10^{25} \frac{\gamma^{2.65}\epsilon^{1.15}\sigma_z\delta^{2.5}}{N_p} \text{ (minutes)} \quad (7)$$

$$\tau_{\perp} \approx 4.60 \times 10^{27} \frac{\gamma^{2.65}\epsilon^{2.2}\sigma_z\delta^{0.5}}{N_p} \text{ (minutes)} \quad (8)$$

Table 1: Parameters

	Base		Option		Upgrade	
	e	p	e	p	e	p
Bunches	360		720		1440	
Max ϵ_x/ϵ_y	5.6	1	10.9	2.4	11	2.4
Max ϵ_x (nm)	119	47	79	89	45	39
Min ϵ_x (nm)	53	9.5	40	16	20	8
Min ϵ_y (nm)	9.5	9.5	3.8	6.6	1.9	3.3
Min β (cm)	27	27	9.7	5.5	4.8	2.7
Min σ_z (cm)	≈1	20	≈1	11	1	6.1
Min $\epsilon_{\parallel}$ (eVs)		0.3		0.6		0.3
Max currents (A)	.95	1.35	2.8	1.35	2.8	1.35
Max $N(10^{11})$	2.1	3.0	3.1	1.5	1.6	0.7
rf freq (MHz)		197		395		788
Max rf (MV)		2.3		6.1		14
Min $\tau_{\rm IBS}$ (hr)		1.0		8.0		2.2
Max $\mathcal{L}$ (10^{33})	1.2		7.0		15	

The cooling time constants for magnetic or conventional electron cooling, from Parkhomchuk [7], are approximately:

$$\tau_{\rm cool} \propto \frac{\gamma^5\epsilon^{2.5}\sigma_z\beta_{\rm cool}^{-0.5}}{N_e L_{cool}} \quad (9)$$

where $\beta_{\rm cool}$ is the β in the cooling length $L_{\rm cool}$. The required charges Q to control IBS emittance growth are thus:

$$(QL_{\rm cool})_{\parallel} \propto N_p \frac{\gamma^{2.35}\epsilon^{1.25}}{\beta_{\rm cool}^{0.5}\delta^{2.5}} \quad (10)$$

$$(QL_{\rm cool})_{\perp} \propto N_p \frac{\gamma^{2.35}\epsilon^{0.3}}{\beta_{\rm cool}^{0.5}\delta^{0.5}} \quad (11)$$

If, as in the option, all the IBS growth times are long compared with the turnaround time ($t_{\rm turn} \approx 1$ hr.), then hadron cooling is only needed to reduce the initial emittances and can then be done at 24 GeV after RHIC injection, where, since $QL_{\rm cool} \propto \gamma^{2.35}$, from equations 10 & 11, it is relatively easy. Whereas, in the baseline, at 50 and 100 GeV, where the IBS growth is not $\gg t_{\rm turn}$, cooling is required to maintain emittances against IBS growth, and the required QL_{cool} becomes impracticable above 50, or at most 100, GeV. At 100 GeV, the cooling length times charge is $(100/24)^{2.35} = 29$ times greater than at 24 GeV and becomes a significant risk.

The longer IBS times in the option come in part from the lower N_ps. Larger momentum spreads also helps longitudinally. With the baseline's very large βs in the final focus ($\propto L^{*2}$) with $L^* = 32$ m, a conservative $\sigma_p/p = 5.3 \times 10^{-4}$ was chosen. With the option's $L^* = 4.5$ m, the βs are much less, and $\sigma_p/p = 14 \times 10^{-4}$ was chosen at 50 GeV, where the β^* is 22 cm, falling to 5.8×10^{-4} at 250 GeV where β^* is 5.5 cm and dynamic aperture may be more of a problem. In the linac-ring at 50 GeV $\sigma_p/p = 25 \times 10^{-4}$ — even higher.

Magnetic Electron Cooling, or Coherent Electron Cooling (CEC) [3] should be able to control IBS growth at all energies and emittances, allowing shorter bunches, lower emittances, and higher luminosities as in the 'upgrade' case.

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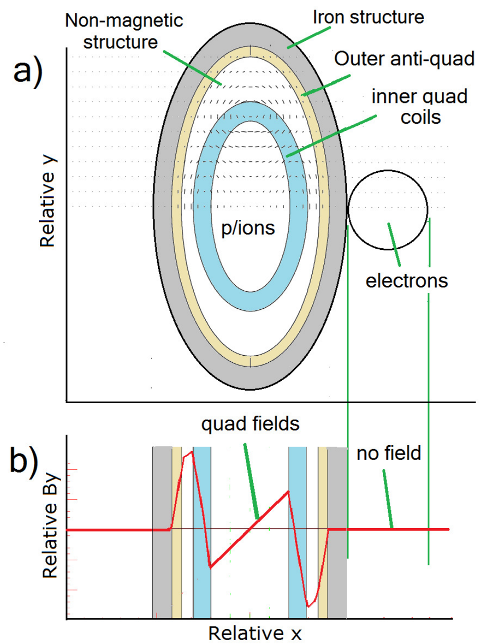

Figure 2: Elliptical quadrupole (blue) with outer cancelling anti-quadrupole (yellow), the grey area is an iron shield; a) cross section of coils with location of electron beam; b) vertical fields vs. horizontal position on the mid plane showing field cancellation.

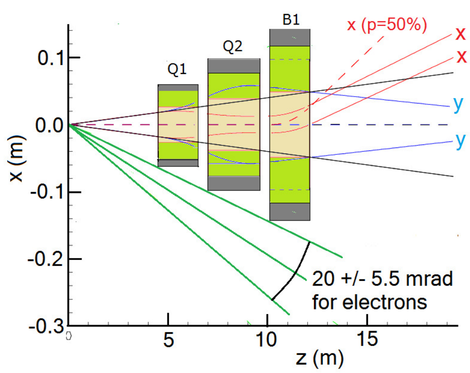

Figure 3: IR design.

IR DESIGN

To operate with smaller β^*s the hadron focus quadrupoles should, as in the linac-ring designs, start immediately after the detector at 4.5 m. The quadrupoles must, as in that case, have minimal stray fields where the electrons pass close by. In the linac-ring this is achieved by relatively small 'sweet spots' in the quadrupole field returns, but for the much larger electron beams in ring-ring cases, a wider field free region is required. The use of a 'sweet spot' is now impractical, but anti-quadrupole coils outside a stronger quadrupole coils can achieve this.

With the first focus in the horizontal direction, the beam cross section is an upright ellipse. For the field free region to be as close as possible to the beam, the quadrupoles shoiuld also be elliptical. Figure 2a shows the cross section of such an elliptical quadrupole with its outer cancelling anti-quadrupole. The iron shorts local error fields and provides support. Figure 2b shows simulated vertical fields on the horizontal mid plane. This example has a larger ellipticity than needed for the beam, and would give neutrons and forward protons a 4×8 mrad elliptical acceptance, without further increasing the crossing angle.

Figure 3 shows 10 σ proton beam profiles, 15 σ electron beam profiles, and magnet extents for such a design with a crossing angle of 20 mrad.

An alternative IR design, with a similar layout, a crossing angle of 22 mrad, and somewhat modified parameters, uses round quadrupoles.

CONCLUSION

Assuming, for electron bunch replacement, an RLA, or fast ramped synchrotron, is used, then the baseline ring-ring design [2] has significantly fewer risks than the linac-ring [1]. It needs no FFAG, no main energy recovery linac, and no 50 mA polarized electron gun, has no HOM challenges, and does not need Coherent electron cooling (CEC). It does, however, require quite challenging magnetic electron cooling, crab cavities, and has a limited luminosity.

The option avoids the same list of risks, needs only low energy non-magnetic cooling, and gives a 6 times higher luminosity. It does, however, require a more challenging IR region, a larger crossing angle, and stronger crab cavities. Their frequency, however, are higher and more similar to the LHC crab cavities already prototyped.

With coherent electron cooling, the upgrade would allow a peak luminosity of 1.5×10^{34} cm^{-2} s^{-1}, and with continuous cooling maintaining this luminosity would give an additional increase in average luminosity.

These options have not, however, been looked at even as much as the baseline ring-ring, let alone the linac-ring. They urgently need more study.

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