HIGHER LUMINOSITY eRHIC RING-RING OPTIONS AND UPGRADE*

R. B. Palmer, J. S. Berg, M. Blaskiewicz, A. Fedotov, C. Montag, B. Parker, S. Peggs, s. Tepikian H. Witte
Brookhaven National Laboratory, Upton, NY 11973-5000, USA

Abstract

Lower risk ring-ring alternatives to the BNL linac-ring [1] eRHIC electron ion collider (EIC) are discussed. The baseline from the Ring-Ring Working Group [2] has a peak proton-electron luminosity of $\approx 1.2 \times 10^{33}\,\mathrm{cm^{-2}\,s^{-1}}$. An initial option 1 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 uses more, 720, lower intensity, bunches, giving reduced IBS emittance growth, requires no cooling and has a peak luminosity of $\approx 2.1 \times 10^{33}\,\mathrm{cm^{-2}\,s^{-1}}$. A first upgrade (option 2) with only non-magnetic electron pre-cooling has a peak luminosity of $\approx 3.8 \times 10^{33}\,\mathrm{cm^{-2}\,s^{-1}}$. A second upgrade (option 3) with more bunches, requiring active magnetic, or coherent, electron cooling, has a peak luminosity of $\approx 14.7 \times 10^{33}\,\mathrm{cm^{-2}\,s^{-1}}$.

CONTENTS

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 was studied in 2015 and presented at IPAC16 [2]. In this study the hadron focusing starts at 32 m from the IP, and has a peak proton-electron luminosity of $\approx 1.2 \times 10^{33}\,\mathrm{cm^{-2}\,s^{-1}}$.

The three options discussed here have more, but lower charged, bunches: 720 for in options 1 & 2, and 1420 for option 3. The use of many, but lower charge, bunches in ring-ring designs has been integral to high luminosity e^+e^- colliders. It is also part of the Jefferson Laboratory's EIC design [3], and was suggested for use at Brookhaven [4].

All three options use much the same constraints as the Ring-ring baseline, but have their hadron final focus elements starting immediately after the detector at 4.5 m, instead of at 32 m. An inevitable consequence is that the crossing angle must be greater. The increase is minimized by limiting the horizontal divergences of both hadron and electron beams, and using actively shielded hadron focus quadrupoles and dipole: quadrupoles and dipole contained within anti-quadrupoles or dipole that cancel all outside fields.

The larger crossing angle ($\approx$ 22 vs. 15 mrad) might be expected to make the crab cavities more difficult. But the increase in crossing angle is compensated by their being at high frequency keeps their voltage much the same.

The three options are:

1. An initial option using no hadron cooling, 720, lower charge, bunches, and gives a peak luminosity of $\approx 2.1 \times 10^{33}\,\mathrm{cm^{-2}\,s^{-1}}$.

2. A first upgrade using the same number of bunches, but with some pre-cooling, probably with non-magnetic electron cooling has a luminosity of $\approx 3.8 \times 10^{33}\,\mathrm{cm^{-2}\,s^{-1}}$.

3. The second more major upgrade using 1420 bunches, higher frequency rf, and magnetic electron [5] (or coherent electron cooling [6]), has a luminosity of $\approx 14.4 \times 10^{33}\,\mathrm{cm^{-2}\,s^{-1}}$. The luminosities for electron-ion collisions would be similarly improved.

* This manuscript has been authored by employees of Brookhaven Science Associates, LLC under Contract No. DE-SC0012704 with the U.S. Department of Energy.

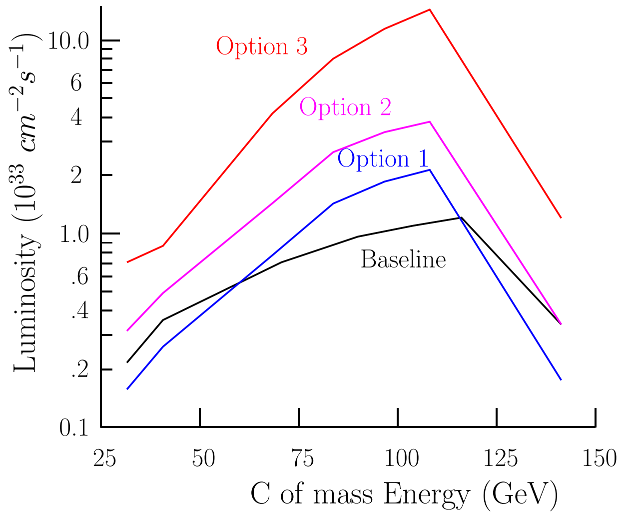

Figure 1: Luminosities vs. center of mass energy

Unlike the baseline, all the options have IR β^*s that vary with energy, and use hadron emittances that are not the same in x and y planes. The larger horizontal emittances would be generated by introducing noise in deflection cavities, something done routinely at CERN [7].

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 emittances $\epsilon_{x,y}$ and $\beta^*_{x,y}$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. For this study, the maximum proton current limited to 1.35 Amps, and that of the electrons to 2.8 Amps, based on the PEP II [8] achievement of 3.0 Amps.

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

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 to 4, eliminating the emittances, gives:

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

Table 1: Constrains on ξs

	Ring-Ring	Linac-Ring	
I_p(A)	1.35	1.35	
I_e(A)	3	.05	Ring-Ring best
ξ_p	0.015	0.015	
ξ_e	0.1	large	Linac-Ring best

Where $K = \sigma_x/\sigma_y$, E_p & E_e are the energies, I_e & I_p are their currents, ξ are the beam-beam tune shifts of e or p in x and y, and β^* are their focus parameters at the IR. Equation 5 can also be written as:

$$\mathcal{L} \propto \sqrt{(1+K)(1+1/K)}\ \bar{E}\ \bar{I}\ \frac{\bar{\xi}}{\bar{\beta}^*} \tag{6}$$

where $\hat{E}$ and $\hat{I}$ are geometrical averages over electrons and protons, and $\hat{\xi}$ and $\hat{\beta}$ are geometric averages over e and p, as well as x and y.

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 than for protons because of the electron 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 for linac-rings is offset by practical limits on the electron currents I. An electron ring, like PEP II [8], can store and collide currents of 3 A, while the BNL linac-ring [2] designs are limited to only 50 mA. These constraints are summarized in Table 1.

Luminosity, for given beam powers, is maximized with flat beams ($K = \sigma_y/\sigma_x \ll 1$), high ξs and low β^*s. How small the β^*s can be is set by several considerations:

1. Beam stability driven by high chromaticity associated with highe βs in the focus systems generating the low β^*s.

2. The length of the bunches σ_z that, if too small compared with the β^* will lower the luminosity from the "hour glass effect".

3. The angular acceptance of the focusing quadrupoles, that limit the beam divergences $\sigma'_{p,e,x,y}$.

These divergences are given by:

$$\sigma'_{p,e,x,y} = \sqrt{\frac{\epsilon_{p,e,x,y}}{\beta_{p,e,x,y}}} \tag{7}$$

Combining equations 4 and 7 gives, leaving out the σ_x/σ_y terms, gives, generically:

$$\beta^* \propto \frac{N}{\xi\ (\sigma')^2\ \gamma} \tag{8}$$

We see this dependence on the energy in the optimized parameters of the options.

Table 2: Beam divergence from the IP, and two other, constraints

$P_p\ \sigma'_{x,p}$	100 (MeV/c)
$\sigma'_{y,p}$	0.4 (mrad)
$\sigma'_{x,e}$	0.12(mrad
$\sigma'_{y,e}$	0.23(mrad
Space charge tune shift	0.08
Synchrotron Power	10 (MW)

The constraints on these divergences are given in Table 2 and will be discussed in section . For these beam divergences, low βs require low transverse emittances, and, in order to avoid excessive hour glass effects, they also require short bunches. For short bunches and given momentum spread constraints, low longitudinal emittance is also needed. For the electrons, lower emittances will be obtained in appropriate ring lattices with lower βs where there is bending. For example in lattices with more, but shorter, cells. For the protons or ions, cooling may be required either to reduce the initaial emittances, or to restrain emittance growth due primarily to Intra-Beam Scattering (IBS) which is discussed in section .

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. The logic here is the same as that for $e^+\ e^-$ colliders: luminosity is maximized by using low emittances, low betas, low charges per bunch, but many bunches. There is however a significant difference in the EICs: Lower emittances of the protons/ions require, in general, hadron cooling.

PARAMETERS

Table 10 and 11 give all, and Table 3 give some selected, parameters for the four ring-ring EIC cases. Figure 1 shows the luminosities as a function of center of mass energies.

Baseline

The baseline [2] uses transverse proton emittances of 2.5 μm already available from RHIC without cooling. It used same final focus β^*, in both x and y, (2.17 and 0.27 m) for all energies. To minimize the crossing angle, it has final focusing starting beyond the proton chicane at 32 m resulting in large βs in the IR region ($\beta(max) \geq L*^2/\beta^* \approx 3.8$ Km). This, in turn, limits the acceptable proton momentum spread, requiring the relatively small longitudinal emittance of 0.3 eVsec, compared with the 1.5 eVsec in RHIC, and short IBS time constants of .5 and 1.2 hours at 50 and 100 GeV (see section). To get this inital emittance and maintain it, requires both inital and active magnetic electron cooling. Its peak luminosity of 1.2×10^{33} cm^{-2} s^{-1}, which cannot be easily upgraded without a completely new IR region with focusing closer to the IP, which is made more difficult by the .37 mrad horizontal electron divergence requiring ± 5.5 mrad open aperture.

Option 1: Initial Configuration

This option uses no cooling, so transverse proton emittance is 2.5 μm from RHIC. It uses more (720 vs.320), but smaller, bunches, and was optimized, individually, at each energy, for both luminosity and IBS lifetime. The β_ys are approximately inversely proportional to the energy as suggested by equation 8. The β_xs follow the same trend, but not as strongly.

The final focusing starts at 4.5 m, as in the linac-ring, allowing, at the full energy, a β^* of 6.1 cm. Even at this small β^* the maximum β is only 900 m. Its beams are flatter, with σ_x/σ_y rising to 13. This is made possible, in part, by the use of unequal emittances in x and y for both protons, using rf noise, and for electrons, using reduced x-y coupling. The IBS emittance growth times are all above 10 hours, thus needing no active cooling. Since the maximum βs are modest, especially at the lower energies, the momentum spreads can be higher than in the baseline (rms dp/p = 14, vs. 5.3 10^{-4}). This allow shorter bunches for the same longitudinal emittance (0.75 eVsec), which itself has been halved (from 1.5 eVsec) when the bunches were adiabatically divided to double their number. Its peak calculated luminosity is 2.1×10^{33} cm^{-2} s^{-1}. This, being well over the initial requirement of 1.0×10^{33} cm^{-2} s^{-1} leaves a healthy margin for errors or other goals not met. For instance if less than 2.8 A of electron current is achieved.

Option 2: Early Upgrade

This option uses pre-cooling to modestly lower transverse proton emittance from 2.5 to 1.8 μm. As in the initial configuration, it uses 720 bunches, and uses the same physical hadron ring and IR, but with the IR tuned to give β^*= 72% of that in the initial option. With the transverse emittance and βs decreased by the same amount, the divergences remain the same, except that the IR is tuned to reach the same maximum β of 900 m. Figures 5, 6 & 7, and Table 7, show this configuration.

The β^* at full energy is now 4.4 cm. The IBS emittance growth times are shorter than in the initial option, but still all above 8 hours, thus not needing active cooling. Some longitudinal pre-cooling allows somewhat shorter bunches and lesser hour glass effects. The needed pre-cooling appears to be doable with non-magnetic electron cooling. Its peak luminosity is 3.8×10^{33} cm^{-2} s^{-1}.

Option 3: Later Upgrade

This upgrade is largely scaled from the initial upgrade, with half the β^*s, σs, and emittances $\epsilon_{x,y}$, and double the number of bunches. It needs not only pre-cooling in both longitudinal and transverse directions, but also dynamic magnetic electron cooling, or Coherent Electron Cooling, at all energies, and achieves a peak luminosity of 1.44×10^{34} cm^{-2} s^{-1}.

For the latter cases, the higher numbers of bunches would be formed by adiabatic binary splitting of the baseline's 320

Table 3: summary of key parameters

	Base	Op 1	Op 2	Op 3
Bunches	360	720	720	1440
Max p current (A)	1.35	1.35	1.35	1.35
Max e current (A)	.95	2.8	2.8	2.8
Max $N_p(10^{11})$	3.0	1.5	1.5	0.75
Max $N_e(10^{11})$	2.1	3.1	3.1	1.6
max σ_x/σ_y	2.8	13	13	30
Min p ϵ_{Ny} (μm)	2.6	2.5	1.8	0.2
Min p β_y (cm)	27	6.1	4.4	2.2
Min p $\sigma_{z,p}$ (cm)	20	16.6	11	5.5
Min p$\epsilon_\parallel$ (eVs)	0.3	0.75	0.6	0.3
θ_{cross} (mrad)	15	20-22	20-22	20-22
Crab freq. (MHz)	168	336	336	672
Crab Volts (MV)	7.4	7.1-7.8	7.1-7.8	4.7-5.2
rf freq (MHz)	197	395	395	788
Max rf (MV)	3.0		6.1	28
Max p dp/p (10^{-4})	5.3	19	14	14
Max p β (Km)	≥3.8	0.9	0.9	0.9
Min $\tau_{\rm IBS}$ (hr)	0.5	16	8.0	0.6
Max $Q_{100\ m}$ (nC)	200	0	0	60
Max $\mathcal{L}$ (10^{33})	1.2	0	3.8	14.4

Table 4: Electron cloud parameters

			cold		warm	
	N_p 10^{11}	t_{sep} ns	r cm	n	r cm	n
LHC	1.15	25	2.0	0.16		
FCC hh	1.0	25	1.3	0.19		
Base	1.5	36	3.5	0.26	6	
Option 2	1.5	18	3.5	0.52	6	1.5
Option 3	0.75	9	3.5	2.08	6	6.1
Option 4	0.375	4.5	3.5	8.32	6	17.6

Table 5: rf Parameters vs. energy

E_p GeV	f_{rf} MHz	V_{rf} MV	$\epsilon_\parallel$ eVsec	dp/p 10^{-4}	f_{crab} MHz	V_{crab} MV
50	394	4.0	0.6	14	336	4.14
100	394	5.1	0.7	9.5	336	5.8
150	394	8.2	0.8	8.1	336	7.2
200	394	9.0	0.8	6.6	336	8.3
250	394	13.9	0.8	6.5	336	8.3

bunches after injection into RHIC. The lower horizontal electron emittances require a ring lattice with shorter or low emittance cells. The larger electron ratios of ϵ_x/ϵ_y imply less x-y coupling.

ELECTRON CLOUD CONSIDERATIONS

If the secondary emission yield SEY is low enough, electron cloud generation may not be a problem, but even local higher SEYs any electons can be amplified by their cross the beam pipe and being accelerated by the space charge of the hadron bunches. The likely hood of of such multiplication can be shown to depend on a parameter n, given by:

$$n = \frac{r^2}{r_e N_p L_{sep}}$$

where r is the beam pipe radius, N_p is the protons per bunch, L_{sep} is the bunch to bunch separation, and r_e is the classical electron radius.

If $n << 1$ then electrons will be absorbed on the walls between bunches. If $n >> 1$ then the beam charge is essentially uniform and electrons arrive at the other side with their initial zero energy and do not generate secondary emission. Only if $n \approx 1$ do electrons get accelerated by a bunch's space charge, but not equally decelerated because the bunch is passing and the field is less. They can then hit the opposite wall with enough energy to be multiplied and accelerated back by the field from the following bunch.

With our new baseline parameters, in cold pipes of radius 3.5 cm, $n \approx 0.26$ similar to, but greater than LHC with $n \approx 0.16$. It the increase was serious enough, we could increase the bunch charge and emittance by 1.3 to bring n down to 0.2. In warm sections, the beam pipe has a greater radius ≈ 6 cm, and $n \approx 0.76$ which could be dangerous.

But with double the number of bunches (upgrade 1), $n \approx 0.56$ in cold pipes and 1.64 in warm locations which are both dangerous (it may well have been wise to fall back to 360 bunches).

For upgrade 2 (old option 3) with 1440 bunches spaced only 2.5 m, and half the charge per bunch, $n \approx 2.3$ cold and 6.6 warm which still looks scary, but on the other side.

Clearly simulation is needed here, but we can still discuss options that would avoid problems if they appear. Suppose we double the number of bunches to 2880, and halve their charge again, then $n \approx 8.3$ cold, and 24 warm, which is probably safe. If we make no other changes, the luminosity would drop a factor of two, and not reach the specified 10^33-10^{34} target.

Ideal scaling would double the luminosity, but requires, besides doubling the number of bunches and halving their charge, also halving the bunch lengths, emittances and β^*s. Halving the β^* and bunch length looks very hard, but halving the the emittance may not be so hard. The IBS times would get shorter, but the electron bunch charges needed to control IBS growth (equations 12 and 13) actually fall with the emittances. With only that, we would recover the same luminosity, but keep $n \approx 8.3$, and the peak luminosity above 10^{34}.

The question remains whether one could not, perhaps in a subsequent upgrade 3, lower the betas and bunch lengths further and double the luminosity. That might well be possible if the quads were inside the detector, as in The JLAB EIC.

RF SYSTEMS

Table 5

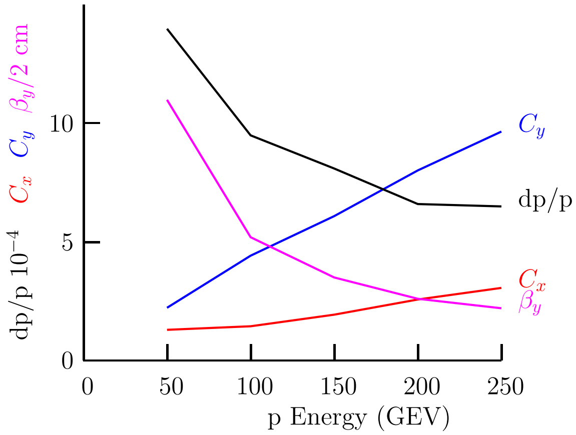

Figure 2: Momentum spread dp/p, IR chromaticities per side in x and y, and β_y^*, vs. proton energy (GeV).

IBS AND COOLING

Approximate IBS time constants

The following approximate estimates of IBS time constants and needed electron cooling parameters are intended only give to a qualitative understanding of the relative needs and of the different approaches. They are not intended to give actual parameters.

Figure **??** shows some simulations [9] of IBS times in RHIC, over the relevant parameters. These simulations assumed good mixing between x and y. A fit to these data gives approximate IBS times:

$$\tau_{\parallel} \approx 4.78 \times 10^{25} \frac{\gamma^{2.65} \epsilon^{1.15} \sigma_z \delta^{2.5}}{N_p} \text{ (minutes)} \qquad (9)$$

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

The ϵs and σ_zs are in m.

The cooling time constants for magnetic or conventional electron cooling, from Parkhomchuk [10], are approximately:

$$\tau_{\text{cool}} \propto \frac{\gamma^5 \epsilon^{2.5} \sigma_z \beta_{\text{cool}}^{-0.5}}{N_e L_{cool}} \qquad (11)$$

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

$$(Q L_{\text{cool}})_{\parallel} \propto N_p \frac{\gamma^{2.35} \epsilon^{1.25}}{\beta_{\text{cool}}^{0.5} \delta^{2.5}} \qquad (12)$$

$$(Q L_{\text{cool}})_{\perp} \propto N_p \frac{\gamma^{2.35} \epsilon^{0.3}}{\beta_{\text{cool}}^{0.5} \delta^{0.5}} \qquad (13)$$

How to make unequal x,y proton emittances

- All options require some electron cooling to reduce longitudinal phase spaces from ≈ 1.5 eV sec to:
  0.3 eV sec for option 0
  0.5 eV sec for option 1
  0.3 eV sec for option 2
- This cooling will also reduce the transverse emittances by similar factors
- In all options this must be opposed by some noise sources in x and y
- For Options 0 and 1 this noise would be equal in x and y
- In Option 2 there would be more noise applied in x

Can coupling be small enough to keep this asymmetry ?

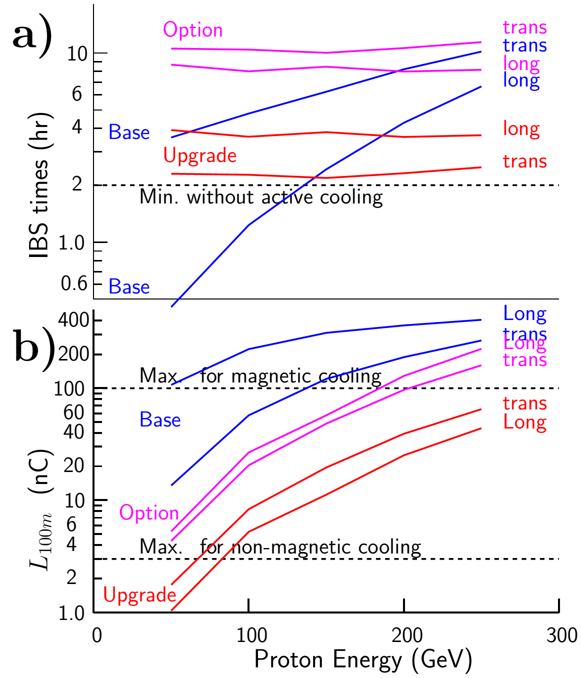

Figure 3: IBS parameters for the three cases: baseline (blue), option (magenta), and upgrade (red); a) Approximate IBS time constants, (longitudinal and transverse) vs. proton energy, A minimum acceptable time constant is indicated in a dashed line; b) Approximate required electron charges for 100 m of cooling $Q_{100m\ magnetic}$ for longitudinal and transverse emittance stabilization. Maximum plausible values are indicated in dashed lines for magnetic electric cooling (above) and non-magnetic electron cooling (below).

IBS with protons un-coupled in x,y

From Jie Wei *Evolution of Hadron Beams under Intrabeam scattering*

For $\gamma \gg \gamma_T$, significant vertical amplitudes, and bunched beams, then:

$$\begin{bmatrix} \frac{1}{\sigma_p}\frac{d\sigma_p}{dt} \\ \frac{1}{\sigma_x}\frac{d\sigma_x}{dt} \\ \frac{1}{\sigma_y}\frac{d\sigma_y}{dt} \end{bmatrix} \approx \frac{Z^4 N}{A^2}\frac{\pi {r_o}^2 m_o c^2 L_c}{16\beta^4\gamma_T\epsilon_x\epsilon_y S}\begin{bmatrix} \frac{(1-d^2)}{d} \\ \frac{d}{n_c} \\ \frac{(n_c-1)d}{n_c} \end{bmatrix}$$

$$\text{where} \quad d = \frac{D_p\sigma_p}{(\sigma_x + {D_p}^2{\sigma_p}^2)^{1/2}}$$

$$C = 2\beta\sigma_p\left[\frac{\sigma_y(1-d^2)}{r_o}\right]^{1/2}$$

$$S = \frac{\pi m_o c^2\gamma\sigma_s\sigma_p}{\beta^3 cA}$$

for uncoupled xy $n_c = 1$ giving negligible heating in y

for coupled xy $n_c = 2$ giving half heating in x and y

At first I thought the un-coupled situation is worse, e.g. Having 1.5 hour time constant in x, but no growth in y, sounds worse than 3 hours time constants in both. Surely the run is stopped after the worst time constant is approached.

But what cuts off a run is dictated by the fall in luminosity. Assuming the electron IP cross section can follow that of the protons, then the luminosity is determined by the inverse of the IP beam cross section: $\pi\sigma_x\sigma_y$, which falls at the same rate whether coupled or not.

But the situations are really not the same. Our vertical beam focus is more constrained by beam-beam parameters than the horizontal. In the un-coupled case we can, to some extent, decrease the horizontal β^* to correct for the increase in horizontal emittance, while that is far harder in the vertical case. I find better parameters with unequal emittances: $\epsilon_x > \epsilon_y$ which is just the asymmetry that develops naturally from IBS in the un-coupled case.

Perhaps another way of thinking of it is that un-coupled IBS makes the proton emittances more like the electron ones, larger horizontally than vertically, that makes it easier to match the two.

So it is all more complicated than I thought but exploration of asymmetric p emittances remains worth looking at.

Cooling Requirements

Intra-Beam Scattering causes transverse and longitudinal emittances to rise. In the transverse cases this increases beam sizes as $\sqrt{t/\tau}$ and decreases luminosity as $(t/\tau)^{-1}$. If the beam size and momentum spread increases are limited to 30%, runs must be less than 0.5 $\tau_\perp$, and a reasonable minimum $\tau_\perp$ is 2 × the turnaround time of approximately 1 hour. This would give an average luminosity 42% of its initial value. $\tau/t_{turn} = 8$ would give an average luminosity 63%.

The increase in longitudinal emittance does not explicitly decrease luminosity but it increases the bunch length hurting the crab correction, and momentum spread that could hurt stability. Again a limit of $\tau_\|/t_{turn} = 2$ seems reasonable, with longer times much preferred.

If the time constants are below ≈ 2 hours, then active cooling is required. For non-magnetic electron cooling the cooling electrons must have emittances less than, or of the order of, the cooled hadrons. This appears practical for electron bunch charges less than a few nC, and in this case the required electron charge is about 1/3 of that needed for magnetic electron cooling. For cooling lengths of 100 m, the required charge Q_{100m} needs to be below approximately 1 nC, or the calculated $Q_{100m\ magnetic}$=3 nC.

For magnetic electron cooling, the electron emittances can be larger and it appears practical to get electron bunches with charges up to the order of 100 nC. For cooling lengths of 100 m, over which very accurately aligned solenoids are required, the product $Q_{100m\ magnetic}$ should be below 100 nC.

IBS parameters for the cases

Using the parameters for the baseline, initial option, and upgrades, the IBS time constants from equations 9 and 10, are plotted in Figure **??**a, and using equations 12 and **??**, normalized from magnetic cooling calculations for the liac ring, the $Q_{100m\ magnetic}$= electron cooling charge times for 100 m are plotted on Figure **??**b.

Baseline For the baseline, the longitudinal time constants are below approximately 150 GeV. At 50 GeV the $Q_{100m\ magnetic\|} \approx 100$ nC which appears to be at the limit of what we know hoe to generate. But at 100 GeV where we also need active cooling, the required $Q_{100m\ magnetic\|} \approx$ 200 nC which appears to be beyond what we know how to generate.

Option 1, with no cooling For the Initial Option 1 the longitudinal (1.5 eV sec per half RHIC bunch) and transverse (2.5 μm) are as now available from RHIC, so no Pre-cooling is required. And all the IBS time constants are longer than 10 hours so no active cooling is not required.

The longer IBS times in this, and the following option, come in part from the lower N_ps, but more from larger momentum spreads ($\sigma_p/p = 14 \times 10^{-4}$) at the low energies. These momentum spreads are kept much lower ($\sigma_p/p = 5.3 \times 10^{-4}$) in the baseline for stability with its maximum $\beta = L^{*2}/\beta^*$= 3.8 Km, even with its relatively long β^*= 27 cm, with the option's IR starting much closer to the IP, the maximum β is only 900 m (see section), so this concern may not be so strong. In the linac-ring, also with IR focusing starting near the IP, $\sigma_p/p = 25 \times 10^{-4}$ at 50 GeV - even higher.

Option 2, with only pre-cooling For the option 2, an early upgrade, the time constants τ are all above 8 hours and thus do not appear to require any active cooling. But hadron cooling used to reduce the initial emittances from 2.5 to 1.8 μm. This could, in principal be done at 50 GeV with relatively easy magnetic cooling: $Q_{100m\ magnetic} = 5$

nC: e.g. with 30 m and 15 nC. But since $QL_{\text{cool}} \propto \gamma^{2.35}$, it should be possible to initially cool with non-magnetic e cooling at the injection energy of 24 GeV.

Option 3, later upgrade to 10^{34} For the option 3, a later upgrade, with lower emittances, the time constants are shorter, although they do all fall above our defined minimum of 2 hours. Active magnetic electron cooling does, however, appear possible over the full energy range. Coherent Electron Cooling (CEC) [6]) could be easier, but does nor appear essential to reach peak luminosities above $10^{34}\ cm^{-2}s^{-1}$.

IR DESIGN

For higher luminosity it is necessary to have a smaller β^*, but for stability and dynamic aperture reasons, a high maximum β should be avoided. Since as a distance from the IR of L^*, without other elements,

$$\beta^* \approx \frac{L^{*2}}{\beta^*}$$

The free distance L^* must also be minimized. In the baseline ring-ring design, $L^* = 32$ m, giving, for its β_y^* of 27 cm, a maximum β of al least 3.8 km, which is already large and risks instabilities. With a lower β^* for higher luminosity this will be worse.

For this reason we need to start the IR focus as soon as possible, as in the linac-ring designs [1], immediately after the detector at 4.5 m. The challenge is to design the early focus quadrupoles and dipole without disturbing the electron beam nearby without requiring a too large cross angle θ_{cross}. In the linac-ring the electron beam has a low emittance and is relatively narrow. It is planed to pass the beam through small 'sweet spots' in the quadrupole field returns and allows a crossing angle of 14 mrad. For the much larger electron beams in ring-ring cases, a wider field free region is required, and designing a large enough field free 'sweet spot' in the magnet returns is probably impractical. In the baseline, the problem is solved by pushing the final focus magnets back till after the beam has been displaced the hadron from the electron beam by the chicane. Even with this the crossing angle is still 15 mrad.

Quadrupoles with active shielding

In these optional designs with the focus starting at 4.5 m from the IP, both quadrupoles and dipole use active shielding. Each qudrupole/dipole is surrounded by a weaker anti-quadrupole/dipole that exactly cancels all fields. A prototype of such a magnet has been designed [11]a and built [11]b for the ILC. All its coils were made by automated 'direct' winding [12]. In our case, where the fields are higher, it is proposed to wind the primary coils using two layers of Rutherford cable, while the anti-coils, with lower currents but more acute placement requirements, would use direct winding (see Figure 4c).

No real design of these magnets has yet been completed, so the minimum needed outside radius remains uncertain.

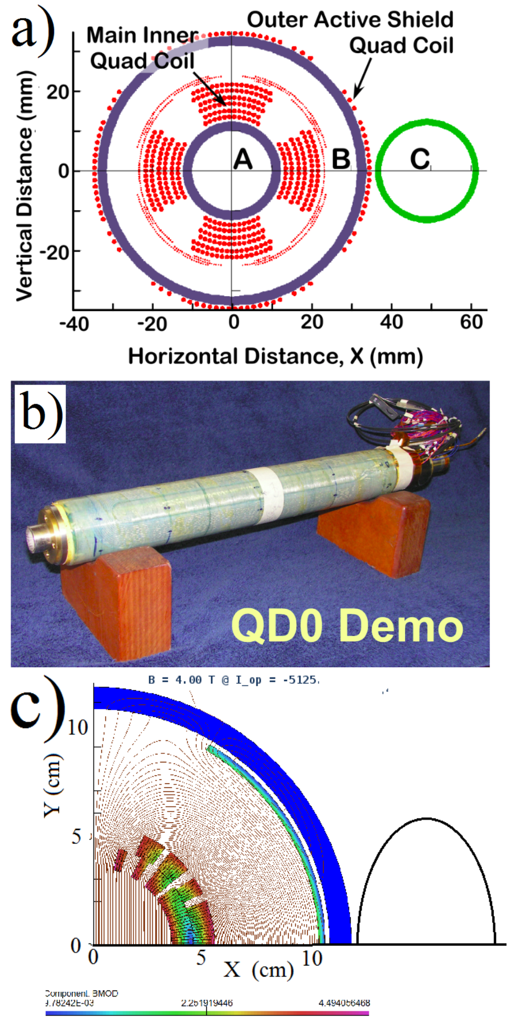

Figure 4: Quadrupoles with anti-quad coils to cancel exterior fields: a) Section of Quad-ant-quad as built for ILC protype; b)The prototype; c) Conceptual design of quadrupole with anti-quad outside for Ring-ring IR application.

With some optimistic assumptions it would appear that the first quadrupole (Q1) could have a field free region starting at 8 cm, allowing a crossing angle of 22 mrad as shown in figures **??** and magnets specified in table 7.

The use of elliptical actively shielded quadrupoles could be made part of a later upgrade that could greatly increase the acceptance of larger transverse momentum forward particles. Adding a weak initial dipole before the first focus quadrupole will also be studied.

Crab Cavities

In both linac-ring and ring-ring designs, crab cavities are needed to align the bunches as they interact and thus avoid luminosity loss. The required voltage is given by:

$$V_{crab} = \frac{\theta_{crab} E[eV]\ c}{2\pi\ f_{crab}\ \sqrt{\beta_{crab}\ \beta^*}}$$

Parameters for the ring-ring baseline, options 1&2 and for the upgrade option 3 are given in table 6. The now

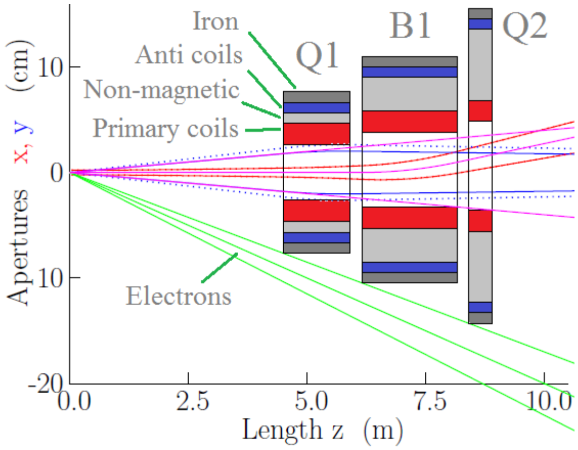

Figure 5: Detail of IR Apertures and first 3 magnets

Table 6: Parameters for crab cavities in three ring-ring cases, all with $E = 250\ 10^9$ eV.

		Base	Opt. 1&2	Opt. 3
θ_{cross}	mrad	15	20-22	20-22
f_{crab}	MHz	168	336	672
β_x^*	m	2.17	2.77	1.51
β_{cool}	m	2400	900	900
Half aperture	cm	10.1	4.2	3.1
Volts	MV	7.4	7.1-7.8	4.7-5.2

larger crossing angles, 20-22 instead of 15 mrad, and much lower β_{crab} (900 vs. 2400 m) act to increase the required voltage, but the higher frequency used for the now shorter bunches, and larger β_x^* compensate these, giving a slightly lower voltage. In all cases a second harmonic cavity is used to correct non-linearities. Table 6 also gives the horizontal beam size at the cavity which defines the cavity's deflection gap and thus the internal peak voltage. This is less than half that for the baseline. In both cases the β_{crab} at the cavities is reduced at lower energies to avoid the otherwise larger beam size. The cavity voltage is not thereby increased because it is also proportional to the energy.

It is noted that the option's frequencies of 336 and 672 MHz are more similar to that of the 420 MHz test cavity already tested, thus reducing the risks involved.

IR LAYOUT

Figure **??** shows β_x (red) and β_y (blue) from the IR to 40 m. The lines are those present at 250 GeV, the dashes are for 50 GeV. In both cases the betas are essentially constant between 25 and 35 m where the crab cavities are located. At 250 GeV this is 900 m as given in table 6, but it is only ≈ 200 m at 50 GeV. The reduction is achieved by powering Q2 and adjusting Q3. This is done to keep the beam size less than or equal to that at 250 GeV, so as not to increase the required crab cavity gap. Since the crab voltage is $\propto E/\sqrt{\beta_x}$ the voltage is still lower at 50 GeV.

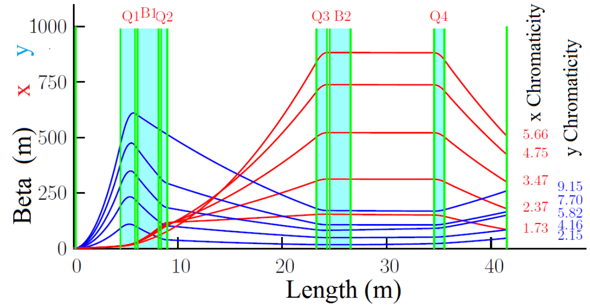

Figure 6: betas vs. distance from IR for two hadron momenta, for Option 2, given for energies 250 GeV at the top and steps of 50 Gev going down.

Table 7: IR Coil dimensions & fields for 250 GeV Option 2

	p GeV/c	L1 m	L m	IR cm	OR cm	B T	Grad T/m
Q1	50	5.91	1.41	2.64	8.55	0.21[1]	-8.00
B1	50	8.16	2.00	3.54	11.7	0.80	0.00
Q2	50	8.91	0.50	4.20	16.0	0.51[1]	12.02
Q3	50	24.31	1.00	4.43		0.01[1]	0.36
B2	50	26.56	2.00	4.47		-0.80	0.00
Q4	50	35.55	0.99	4.00		0.05[1]	1.27
Q1	250	5.91	1.41	2.64	8.55	3.62	-137.50
B1	250	8.16	2.00	3.54	11.7	4.00	0.00
Q2	250	8.91	0.50	4.20	16.0	0.00	0.00
Q3	250	24.31	1.00	4.43		1.77	39.95
B2	250	26.56	2.00	4.47		-4.00	0.00
Q4	250	35.55	0.99	4.00		1.27	31.67

Note 1: Pole tip fields

Figure 7 shows 10 σ proton beam extents in x in red and in y in blue. The magnet extents and apertures in x are also shown. Again the lines are those present at 250 GeV, the dashes are for 50 GeV. These are all given for the design with a crossing angle of 20 mrad. The magenta lines define the outline of the 4 mrad cone in which neutrons can propagate from the IP to the shown neutron detector. The dotted blue lines indicate the envelope of charged tracks from the IP with initial angles up to 5.2 mrad including forward outgoing protons from 250 GeV proton interactions with transverse momenta in y up to 1.3 GeV. These could be detected using 'Roman pots' in the free space between Q2 and Q3. It is these protons that define the inside radius of Q1 and thus the crossing angle. This radius is ≈ 15 % larger than that otherwise defined by the neutron cone. The use of elliptical quads here would capture even higher transverse momentum protons while reducing the required aperture in x.

ELECTRON RING AND INJECTOR

The electron ring lattice must be adjustable to have the equilibrium emittances given in table 8. For the options 1 & 2, they are about a factor of two lower than in the baseline, and a factor of 2.5 lower for option 3. These will require

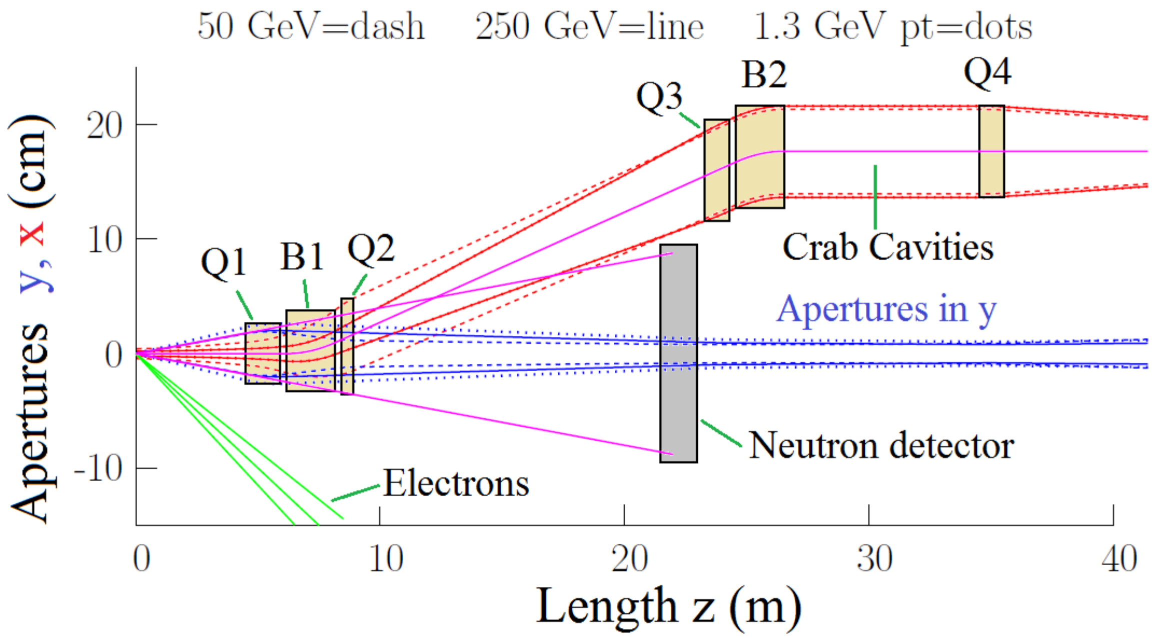

Figure 7: IR Apertures in x and y vs. z for option 2.

Table 8: Equilibrium emittances in nm vs. energy

Energy (GeV)	5	20
Baseline	119	53
Option 1	47	53
Option 2	53	24
Option 3	40	20

significantly shorter cells in the electron ring than those in the baseline.

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 challenging magnetic electron cooling. Also, because of the 32 m drift before the first hadron focus magnet, it has a very high $\beta \approx 4$ Km in the IR. And it offers no easy way to an upgrade. The baseline has the specified initial luminosities of 0.1 to 1.0 $10^{3}3\ cm^{-2}s^{-1}$.

The option 1 avoids the same list of risks, and needs no cooling. By bringing the focus elements nearer to the IP, it has significantly lower maximum βs (0.9 vs 3.8 Km). It has a peak luminosity double that of the baseline, though somewhat less at the energy extremes. It does have a more challenging IR region, though no more so than that proposed for the linac-ring options. It has a somewhat larger crossing angle (≈22 vs. 15 mrad) than the baseline, that would require higher voltage crab cavities if it were not for their higher frequency that lowers it to about the same value. The higher frequency also makes them more similar to the LHC crab cavities already prototyped. It has good luminosity upgrade possibilities. Like all the other designs, JLAB EIC, High Luminosity LHC, Linac-ring, and these options, it requires crab cavities, and their use in a hadron machine remains to be demonstrated. This is probably its greatest risk.

The first upgrade, option 2, only adds low energy non-magnetic cooling, and gives a peak luminosity 4 times the baseline. No other changes are needed.

The later upgrade, option 3, would require higher frequency main hadron, crab and electron rf, and active cooling for all energies. Magnetic electron cooling should be able to provide this, as would Coherent Electron Cooling. This upgrade would give 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 of:

1. Incorporation of this IR into the full ring and determine dynamic apertures for both low energy (50 GeV) with large dp/p

2. (14 10^{-4}) but moderate β_y^* (22 cm), and high energy (250 GeV) with smaller dp/p (5.8 10^{-4}) but small β^* (4.2 cm).
3. The electron ring with lower emittance;
4. Polarization preservation in the electron ring
5. More detailed design of the actively shielded IR quads and dipoles;
6. Betacool simulation of IBS in all options
7. More detailed study of cooling for options 2 and 3
8. Simulation of the bunch dividing to get the increased numbers of bunches
9. And many more details common to all proposals

REFERENCES

[1] E.C. Aschenauer et al, "Linac-Ring eRHIC Design Study: An Electron-Ion Collider at BNL", arXiv 1409.1633 (2014).

[2] C. Montag et al, "The 2015 Ring-Ring Design", WEPOY057, at this conference (IPAC2016); "Ring-Ring Working Group", BNL eRHIC/46; Oct. 13 (2015).

[3] JLEIC "MEIC Design Summary", Jan 20, (2015).

[4] Yhong Zhang, "An alternate Ring-Ring Design for eRHIC", arXiv:1502.07721v1; Feb 26 (2015).

[5] *** magnetic electron cooling

[6] Vladimir N. Litvinenko, Yaroslav S. Derbenev, "Coherent Electron Cooling", Phys. Rev. Let. 102, 114801 (2009).

[7] Frank Zimmermann, private communication

[8] PEP II

[9] I. Meshkov, "Physics Guide of BETACOOL Code";BNL C-A/AP#262, Nov. (2006).

[10] V. V.Parkhomchuk, "New insights in the theory of electron cooling", Nuclear Instruments and Methods in Physics Research A 441 (2000) 9-17.

[11] Brett Parker, active shielding

[12] Direct winding

Table 9: rf

a) baseline

γ	N_b	freq	Volts	ϵ_{xN}	ϵ_{yN}	σ_z	dp/p	evsec	N_p	$\tau_\parallel$	$\tau_\perp$	Q_{100m}	f_{crab1}	V_1	f_{crab2}	V_2	HG	Lum	eff	lum*eff
		MHz	MV	μm	μm	cm	10^{-4}	eV sec	10^{11}	hr.	hr.	nC	MHz	MV	MHz	MV	%	10^{33}	%	10^{33}
54	360	197	0.48	2.55	2.55	20	5.3	0.3	1.8	0.8	5.9	64[2]	168	1.48	336	0.00	94	0.22	30[4]	0.06
54	360	197	0.48	2.55	2.55	20	5.3	0.3	2.9	0.5	3.6	107[2]	168	1.48	336	0.00	94	0.36	21[4]	0.08
108	360	197	1.14	2.55	2.55	20	5.3	0.7	3.0	1.2	4.8	223[3]	168	2.95	336	0.00	91	0.71	36	0.25
161	360	197	1.75	2.55	2.55	20	5.3	1.0	2.8	2.4	6.3	312[3]	168	4.43	336	0.00	90	0.97	45	0.43
215	360	197	2.36	2.55	2.55	20	5.3	1.4	2.4	4.3	8.2	363[3]	168	5.91	336	0.00	88	1.10	52	0.57
269	360	197	2.96	2.55	2.55	20	5.3	1.7	2.1	6.7	10.2	407[3]	168	7.38	336	0.00	87	1.21	57	0.69
269	360	197	2.96	2.55	2.55	20	5.3	1.7	3.0	4.7	7.2	574[3]	168	7.38	336	0.00	87	0.34	52	0.18

b) Option 1 (file Ibs12m)

γ	N_b	freq	Volts	ϵ_{xN}	ϵ_{yN}	σ_z	dp/p	evsec	N_p	$\tau_\parallel$	$\tau_\perp$	Q_{100m}	f_{crab1}	V_1	f_{crab2}	V_2	HG	Lum	eff	lum*eff
		MHz	MV	μm	μm	cm	10^{-4}	eV sec	10^{11}	hr.	hr.	nC	MHz	MV	MHz	MV	%	10^{33}	%	10^{33}
54	720	394	2.33	6.48	2.45	17	14.0	0.77	0.9	23.8	43.0	5.3[1]	336	0.91	672	0.00	89	0.16	75[4]	0.12
54	720	394	2.33	6.48	2.45	17	14.0	0.77	1.5	14.3	25.8	8.8[1]	336	0.91	672	0.00	89	0.26	69[4]	0.18
108	720	394	5.07	6.48	2.45	12	9.5	0.74	1.5	10.6	20.5	47[2]	336	1.81	672	0.00	94	0.79	66[4]	0.52
161	720	394	8.19	6.48	2.45	10	8.1	0.79	1.5	10.8	18.9	107[2]	336	2.73	672	0.00	94	1.45	65[4]	0.95
215	720	394	9.03	6.48	2.45	9	6.6	0.77	1.3	10.0	19.7	214[3]	336	3.65	672	0.00	92	1.96	65	1.27
269	720	394	11.09	6.61	2.50	8	5.8	0.75	1.3	9.3	19.4	373[3]	336	4.07	672	0.00	90	2.30	64	1.48
269	720	394	11.09	6.48	2.45	8	5.8	0.75	1.5	8.1	16.5	409[3]	336	4.07	672	0.00	91	0.20	62	0.12

c) Option 2 (file ibs12n)

γ	N_b	freq	Volts	ϵ_{xN}	ϵ_{yN}	σ_z	dp/p	evsec	N_p	$\tau_\parallel$	$\tau_\perp$	Q_{100m}	f_{crab1}	V_1	f_{crab2}	V_2	HG	Lum	eff	lum*eff
		MHz	MV	μm	μm	cm	10^{-4}	eV sec	10^{11}	hr.	hr.	nC	MHz	MV	MHz	MV	%	10^{33}	%	10^{33}
54	720	394	3.99	4.67	1.77	13	14.0	0.6	0.9	12.5	16.0	3.4[1]	336	1.07	672	0.00	94	0.31	65[4]	0.20
54	720	394	3.99	4.67	1.77	13	14.0	0.6	1.5	7.5	9.6	5.6[1]	336	1.07	672	0.00	94	0.52	57[4]	0.30
108	720	394	5.07	4.67	1.77	12	9.5	0.7	1.5	7.3	10.0	30[2]	336	2.13	672	0.00	91	1.48	57[4]	0.85
161	720	394	8.19	4.67	1.77	10	8.1	0.8	1.5	7.4	9.2	69[2]	336	3.22	672	0.00	90	2.70	57[4]	1.53
215	720	394	9.03	4.67	1.77	9	6.6	0.8	1.3	6.8	9.6	137[3]	336	4.30	672	0.00	87	3.58	57	2.03
269	720	394	11.09	4.76	1.80	8	5.8	0.8	1.3	6.4	9.4	239[3]	336	4.80	672	0.00	85	4.18	56	2.35
269	720	394	11.09	4.67	1.77	8	5.8	0.8	1.5	5.5	8.0	263[3]	336	4.80	672	0.00	86	0.36	54	0.19

d) Options 3

γ	N_b	freq	Volts	ϵ_{xN}	ϵ_{yN}	σ_z	dp/p	evsec	N_p	$\tau_\parallel$	$\tau_\perp$	Q_{100m}	f_{crab1}	V_1	f_{crab2}	V_2	HG	Lum	eff	lum*eff
		MHz	MV	μm	μm	cm	10^{-4}	eV sec	10^{11}	hr.	hr.	nC	MHz	MV	MHz	MV	%	10^{33}	%	10^{33}
54	1440	394	9.33	2.24	0.40	9	14.0	0.4	0.3	6.4	2.5	0.7[1]	336	1.51	672	0.00	96	0.70	40[4]	0.28
54	1440	394	9.33	2.24	0.41	9	14.0	0.4	0.4	5.2	2.1	0.9[1]	336	1.51	672	0.00	96	0.86	37[4]	0.32
108	1440	394	17.29	2.33	0.44	7	9.5	0.4	0.7	2.5	1.1	7.8[1]	336	3.02	672	0.00	94	4.19	25[4]	1.06
161	1440	394	19.38	2.45	0.36	7	8.1	0.5	0.7	2.8	1.1	19[2]	336	4.55	672	0.00	88	7.78	25[4]	1.91
215	1440	394	20.33	2.45	0.29	6	6.6	0.5	0.7	2.2	0.9	34[2]	336	5.90	672	0.00	83	11.25	21[4]	2.36
269	1440	394	19.71	2.57	0.21	6	5.8	0.6	0.7	2.0	0.7	54[2]	336	6.50	672	0.00	77	14.44	17[4]	2.41
269	1440	394	19.71	2.57	0.21	6	5.8	0.6	0.7	1.7	0.6	61[2]	336	6.50	672	0.00	78	1.21	15[4]	0.18

Note 1: Non magnetic cooling possible with ≈1/3 charge
Note 2: Magnetic cooling possible
Note 3: Only Coherent Electron Cooling possible

Table 10: Parameters for : a) Baseline ; b) Option 1 (no cooling).

a)

	E GeV	N 10^{10}	Nb	$\epsilon_x(\epsilon_{Nx})$ μm(nm)	$\epsilon_y(\epsilon_{Ny})$ μm(nm)	ϵ_x/ϵ_y	β_x cm	β_y cm	σ_x μm	σ_y μm	σ_x/σ_y	σ'_x mrad	σ'_y mrad	ξ_x	ξ_y	Elke MeV	ΔQ	σ_s cm	I A	SR/m kW/m	SR MW	HG %	lum 10^{33}
com	31.6																						
p	50	17.7	360	47.5(2.6)	47.5(2.6)	1.0	217.0	27.0	321	113	2.8	0.15	0.42	.015	.005	74	.022	20.0	0.80	0.0	0.0	94	0.22
e	5.0	21.1	360	119.1(1168)	21.33(209)	5.6	87.0	61.0	322	114	2.8	0.37	0.19	.050	.098		.000	1.0	0.95	0.1	0.2		
com	40.7																						
p	50	29.4	360	47.5(2.6)	47.5(2.6)	1.0	217.0	27.0	321	113	2.8	0.15	0.42	.015	.005	74	.037	20.0	1.33	0.0	0.0	94	0.36
e	8.3	21.1	360	119.1(1939)	21.33(347)	5.6	87.0	61.0	322	114	2.8	0.37	0.19	.050	.098		.000	1.0	0.95	0.7	1.3		
com	70.7																						
p	100	30.0	360	23.8(2.6)	23.8(2.6)	1.0	217.0	27.0	227	80	2.8	0.10	0.30	.015	.005	105	.009	20.0	1.35	0.0	0.0	91	0.71
e	12.5	21.1	360	84.2(2065)	15.08(370)	5.6	61.5	43.1	228	81	2.8	0.37	0.19	.048	.094		.000	1.0	0.95	3.6	6.8		
com	90.0																						
p	150	27.6	360	15.8(2.6)	15.8(2.6)	1.0	217.0	27.0	185	65	2.8	0.09	0.24	.015	.005	128	.004	20.0	1.24	0.0	0.0	90	0.97
e	13.5	21.1	360	68.8(1821)	12.31(326)	5.6	50.2	35.2	186	66	2.8	0.37	0.19	.050	.098		.000	1.0	0.95	4.9	9.3		
com	103.9																						
p	200	23.9	360	11.9(2.6)	11.9(2.6)	1.0	217.0	27.0	161	57	2.8	0.07	0.21	.015	.005	148	.002	20.0	1.08	0.0	0.0	88	1.10
e	13.5	21.1	360	59.6(1577)	10.66(282)	5.6	43.5	30.5	161	57	2.8	0.37	0.19	.050	.098		.000	1.0	0.95	4.9	9.3		
com	116.2																						
p	250	21.3	360	9.5(2.6)	9.5(2.6)	1.0	217.0	27.0	144	51	2.8	0.07	0.19	.015	.005	165	.001	20.0	0.96	0.0	0.0	87	1.21
e	13.5	21.1	360	53.3(1410)	9.54(252)	5.6	38.9	27.3	144	51	2.8	0.37	0.19	.050	.098		.000	1.0	0.95	4.9	9.3		
com	141.4																						
p	250	30.0	360	9.5(2.6)	9.5(2.6)	1.0	217.0	27.0	144	51	2.8	0.07	0.19	.003	.001	165	.002	20.0	1.35	0.0	0.0	87	0.34
e	20.0	4.2	360	53.3(2089)	9.54(374)	5.6	38.9	27.3	144	51	2.8	0.37	0.19	.047	.093		.000	1.0	0.19	4.7	8.9		

b)

	E GeV	N 10^{10}	Nb	$\epsilon_x(\epsilon_{Nx})$ μm(nm)	$\epsilon_y(\epsilon_{Ny})$ μm(nm)	ϵ_x/ϵ_y	β_x cm	β_y cm	σ_x μm	σ_y μm	σ_x/σ_y	σ'_x mrad	σ'_y mrad	ξ_x	ξ_y	Elke MeV	ΔQ	σ_s cm	I A	SR/m kW/m	SR MW	HG %	lum 10^{33}
com	31.6																						
p	50	9.0	720	120.5(6.5)	45.6(2.5)	2.6	308.8	30.5	610	118	5.2	0.20	0.39	.010	.005	99	.014	16.5	0.81	0.0	0.0	90	0.16
e	4.4	30.9	720	73.7(723)	14.89(146)	5.0	507.8	94.8	612	119	5.2	0.12	0.13	.047	.045		.000	0.8	2.79	0.2	0.3		
com	40.7																						
p	50	15.0	720	120.5(6.5)	45.6(2.5)	2.6	308.8	30.5	610	118	5.2	0.20	0.39	.010	.005	99	.024	16.6	1.35	0.0	0.0	90	0.26
e	7.3	30.9	720	73.7(1200)	14.89(242)	5.0	507.8	94.8	612	119	5.2	0.12	0.13	.047	.045		.000	0.8	2.79	1.2	2.3		
com	68.4																						
p	100	15.0	720	60.3(6.5)	22.8(2.5)	2.6	310.4	14.4	432	57	7.5	0.14	0.40	.010	.004	139	.007	13.1	1.35	0.0	0.0	92	0.77
e	10.2	31.1	720	52.1(1196)	8.00(184)	6.5	360.9	41.7	434	58	7.5	0.12	0.14	.049	.043		.000	0.8	2.80	4.8	9.0		
com	83.8																						
p	150	15.0	720	40.2(6.5)	15.2(2.5)	2.6	307.7	9.7	352	38	9.2	0.11	0.40	.011	.003	171	.004	10.8	1.35	0.0	0.0	92	1.43
e	10.2	31.1	720	42.6(976)	6.53(150)	6.5	292.1	22.8	353	39	9.1	0.12	0.17	.062	.044		.000	0.8	2.80	4.8	9.0		
com	96.7																						
p	200	13.4	720	30.1(6.5)	11.4(2.5)	2.6	305.7	7.3	304	29	10.5	0.10	0.40	.011	.003	199	.002	11.1	1.20	0.0	0.0	87	1.86
e	10.2	31.1	720	36.9(846)	5.88(135)	6.3	251.4	14.3	304	29	10.5	0.12	0.20	.064	.038		.000	0.8	2.80	4.8	9.0		
com	108.2																						
p	250	13.1	720	24.6(6.6)	9.3(2.5)	2.6	383.6	5.8	307	23	13.2	0.08	0.40	.011	.002	200	.001	10.8	1.18	0.0	0.0	84	2.14
e	10.2	31.1	720	33.6(771)	5.37(123)	6.3	282.1	10.3	308	23	13.1	0.11	0.23	.070	.033		.000	0.8	2.80	4.8	9.0		
com	141.4																						
p	250	14.7	720	24.1(6.5)	9.1(2.5)	2.6	384.3	6.1	304	24	12.9	0.08	0.39	.001	.000	198	.001	12.2	1.33	0.0	0.0	81	0.18
e	20.0	2.3	720	33.0(1293)	5.26(206)	6.3	282.6	10.7	305	24	12.8	0.11	0.22	.047	.023		.000	0.8	0.21	5.3	10.0		

Table 11: Parameters for : a) Option 2 (initial upgrade) ; b) Option 2 (Upgrade to 10^{34}.

a)

	E GeV	N 10^{10}	Nb	$\epsilon_x(\epsilon_{Nx})$ μm(nm)	$\epsilon_y(\epsilon_{Ny})$ μm(nm)	ϵ_x/ϵ_y	β_x cm	β_y cm	σ_x μm	σ_y μm	σ_x/σ_y	σ'_x mrad	σ'_y mrad	ξ_x	ξ_y	Elke MeV	ΔQ	σ_s cm	I A	SR/m kW/m	SR MW	HG %	lum 10^{33}
com	31.6																						
p	50	9.0	720	86.8(4.7)	32.8(1.8)	2.6	222.3	22.0	439	85	5.2	0.20	0.39	.014	.007	99	.025	13.0	0.81	0.0	0.0	94	0.31
e	4.4	30.9	720	53.1(520)	10.72(105)	5.0	365.6	68.2	441	86	5.2	0.12	0.13	.065	.062		.000	0.8	2.79	0.2	0.3		
com	40.7																						
p	50	15.0	720	86.8(4.7)	32.8(1.8)	2.6	222.3	22.0	439	85	5.2	0.20	0.39	.014	.007	99	.034	15.9	1.35	0.0	0.0	89	0.49
e	7.3	30.9	720	53.1(864)	10.72(175)	5.0	365.6	68.2	441	86	5.2	0.12	0.13	.065	.062		.000	0.8	2.79	1.2	2.3		
com	68.4																						
p	100	15.0	720	43.4(4.7)	16.4(1.8)	2.6	223.5	10.4	311	41	7.5	0.14	0.40	.014	.005	139	.010	13.1	1.35	0.0	0.0	88	1.44
e	10.2	31.1	720	37.5(861)	5.76(132)	6.5	259.9	30.0	312	42	7.5	0.12	0.14	.069	.059		.000	0.8	2.80	4.8	9.0		
com	83.8																						
p	150	15.0	720	28.9(4.7)	10.9(1.8)	2.6	221.5	7.0	253	28	9.2	0.11	0.40	.015	.004	171	.006	10.8	1.35	0.0	0.0	88	2.64
e	10.2	31.1	720	30.6(703)	4.70(108)	6.5	210.3	16.4	254	28	9.1	0.12	0.17	.086	.061		.000	0.8	2.80	4.8	9.0		
com	96.7																						
p	200	13.4	720	21.7(4.7)	8.2(1.8)	2.6	220.1	5.2	219	21	10.5	0.10	0.40	.015	.004	199	.003	11.1	1.20	0.0	0.0	82	3.35
e	10.2	31.1	720	26.5(609)	4.24(97)	6.3	181.0	10.3	219	21	10.5	0.12	0.20	.089	.053		.000	0.8	2.80	4.8	9.0		
com	108.2																						
p	250	13.1	720	17.7(4.8)	6.7(1.8)	2.6	276.2	4.2	221	17	13.2	0.08	0.40	.015	.003	200	.002	10.8	1.18	0.0	0.0	77	3.79
e	10.2	31.1	720	24.2(555)	3.86(89)	6.3	203.1	7.4	222	17	13.1	0.11	0.23	.097	.046		.000	0.8	2.80	4.8	9.0		
com	141.4																						
p	250	14.7	720	17.4(4.7)	6.6(1.8)	2.6	276.7	4.4	219	17	12.9	0.08	0.39	.001	.000	198	.002	12.2	1.33	0.0	0.0	74	0.31
e	20.0	2.3	720	23.7(931)	3.79(149)	6.3	203.5	7.7	220	17	12.8	0.11	0.22	.065	.032		.000	0.8	0.21	5.3	10.0		

b)

	E GeV	N 10^{10}	Nb	$\epsilon_x(\epsilon_{Nx})$ μm(nm)	$\epsilon_y(\epsilon_{Ny})$ μm(nm)	ϵ_x/ϵ_y	β_x cm	β_y cm	σ_x μm	σ_y μm	σ_x/σ_y	σ'_x mrad	σ'_y mrad	ξ_x	ξ_y	Elke MeV	ΔQ	σ_s cm	I A	SR/m kW/m	SR MW	HG %	lum 10^{33}
com	31.6																						
p	50	3.2	1440	41.7(2.2)	7.39(0.4)	5.6	111.2	11.0	215	28	7.6	0.19	0.26	.015	.011	97	.080	6.5	0.58	0.0	0.0	98	0.71
e	4.4	15.5	1440	40.1(393)	2.41(24)	16.6	116.1	34.1	216	29	7.5	0.19	0.08	.032	.070		.000	0.4	2.79	0.2	0.3		
com	40.7																						
p	50	4.0	1440	41.7(2.2)	7.72(0.4)	5.4	111.2	11.0	215	29	7.4	0.19	0.27	.015	.011	97	.078	8.0	0.73	0.0	0.0	97	0.86
e	7.3	15.5	1440	40.1(653)	2.52(41)	15.9	116.1	34.1	216	29	7.4	0.19	0.09	.024	.052		.000	0.4	2.79	1.2	2.3		
com	68.4																						
p	100	7.3	1440	21.7(2.3)	4.10(0.4)	5.3	111.7	5.2	156	15	10.7	0.14	0.28	.015	.007	139	.040	6.6	1.31	0.0	0.0	94	4.18
e	10.2	15.6	1440	29.5(678)	1.44(33)	20.5	82.5	15.0	156	15	10.6	0.19	0.10	.044	.084		.000	0.4	2.80	4.8	9.0		
com	83.8																						
p	150	7.3	1440	15.2(2.4)	2.24(0.4)	6.8	110.8	3.5	130	9	14.7	0.12	0.25	.014	.007	176	.027	5.4	1.31	0.0	0.0	91	8.03
e	10.2	15.6	1440	25.3(581)	0.96(22)	26.3	66.8	8.2	130	9	14.6	0.19	0.11	.052	.093		.000	0.4	2.80	4.8	9.0		
com	96.7																						
p	200	6.7	1440	11.4(2.4)	1.35(0.3)	8.4	116.8	2.6	115	6	19.4	0.10	0.23	.015	.006	197	.017	5.6	1.20	0.0	0.0	85	11.46
e	10.2	15.6	1440	21.9(503)	0.70(16)	31.4	61.0	5.1	116	6	19.3	0.19	0.12	.056	.091		.000	0.4	2.80	4.8	9.0		
com	108.2																						
p	250	6.5	1440	9.5(2.6)	0.79(0.2)	12.1	150.6	2.1	120	4	29.8	0.08	0.20	.014	.006	199	.015	5.4	1.18	0.0	0.0	79	14.91
e	10.2	15.6	1440	20.5(471)	0.45(10)	45.2	70.4	3.6	120	4	29.6	0.17	0.11	.060	.091		.000	0.4	2.80	4.8	9.0		
com	141.4																						
p	250	7.4	1440	9.5(2.6)	0.79(0.2)	12.1	150.6	2.2	120	4	28.8	0.08	0.19	.001	.000	199	.015	6.1	1.33	0.0	0.0	78	1.20
e	20.0	1.2	1440	20.5(806)	0.45(18)	45.2	70.4	3.9	120	4	28.7	0.17	0.11	.039	.062		.000	0.4	0.21	5.3	10.0		