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DESIGN OF AN INTERACTION REGION FOR THE ELECTRON-ION COLLIDER ERHIC *

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Abstract

The electron-ion collider eRHIC currently under study at BNL consists of an electron storage ring added to the existing RHIC complex to facilitate the study of collisions between $10\,\mathrm{GeV}$ electrons and $250\,\mathrm{GeV}$ protons or $100\,\mathrm{GeV/u}$ ions, with luminosities in the range of several $10^{32}\,\mathrm{cm}^{-2}\mathrm{sec}^{-1}$ (e-p case). The interaction region of this facility is particularly challenging, since it has to provide the required low-β focusing, while simultaneously accomodating the synchrotron radiation generated by beam separation close to the interaction point. We present the latest design status of the eRHIC IR.

INTRODUCTION

The interaction region of an electron-ion collider has to serve several purposes. First of all, the two beams, travelling in separate storage rings, have to be brought into collision at the interaction point (IP). Since this merge and subsequent separation is accomplished by bending the lower-energy electron beam away from the ion beam in common magnetic dipole fields, this results in a fair amount of synchrotron radiation that has to be taken into account when designing the interaction region. Most importantly, the detector must be shielded appropriately by a special masking scheme. Finally, both beams have to be focused to small, equal spot sizes at the IP to maximize luminosity.

BEAM SEPARATION

To avoid the generation of synchrotron radiation in the interaction region altogether, one might consider introducing a crossing angle, which would naturally provide the required beam separation without the need of magnetic dipole fields. Assuming a minimum required beam separation of $25\,\mathrm{mm}$ at the entrance of the first ion quadrupole, $5\,\mathrm{m}$ from the IP, this translates into a crossing angle of $\Theta = 5\,\mathrm{mrad}$. With an ion bunch length of $\sigma_z \approx 20\,\mathrm{cm}$, this reduces the resulting luminosity by a factor of 5. This can in principle be cured by introducing a crab-crossing scheme [1], which rotates the long ion bunches into the direction of the oncoming electron bunches, thus resulting in head-on collisions in a co-moving frame.

The required transverse deflecting voltage of the RF crab cavities is calculated as

$$V_\perp = \frac{cE\tan\Theta}{e\omega_{\mathrm{RF}}\sqrt{\beta^*\beta_{\mathrm{crab}}}} \qquad (1)$$

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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
particles/bunch	$1.0\cdot10^{11}$
beam-beam tune shift hor./vert.	0.027/0.08
damping times hor./vert./long. [turns]	1740/1740/870
ions:	
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	$1.0\cdot10^{11}$ (p), $1.0\cdot10^{9}$ (Au)
beam-beam tune shift hor./vert.	0.007/0.0035
luminosity $[\mathrm{cm}^{-2}\mathrm{sec}^{-1}]$	$4.4\cdot10^{32}$

Table 1: Parameter table.

where c is the velocity of light, E the beam energy, e the beam particle charge, and ω_{RF} the RF voltage. β^* and β_{crab} denote the β-functions at the IP and the location of the crab cavity, respectively.

For a $250\,\mathrm{GeV}$ proton beam, an RF frequency of $\omega_{\mathrm{RF}} = 2\pi\cdot200\,\mathrm{MHz}$, and β-functions of $\beta^* = 1.08\,\mathrm{m}$ and $\beta_{\mathrm{crab}} = 400\,\mathrm{m}$, the required RF voltage is calculated as

$$V_\perp = 14.4\,\mathrm{MV}. \qquad (2)$$

This value is about ten times higher than that for the KEKB crab cavities, a system which has been developed but has not yet been installed and tested with beam. Therefore, it was decided to design the eRHIC interaction region with zero crossing angle.

In the case of zero crossing angle, the two beams have to be separated by magnetic dipole fields. At the entrance of the first ion septum quadrupole, $5\,\mathrm{m}$ from the IP, this separation has to be sufficiently large to provide and $20\sigma_{x,e}$ for the electron beam, $12\sigma_{x,p}$ for the ion beam, plus the thickness of the septum between the two beams itself, including vacuum chambers. To limit the required separation to reasonably small values, horizontal rms beams sizes $\sigma_{x,e}$ and $\sigma_{x,p}$ of electron and ion beam at this location have to be kept small. Since the ion beam emittance is given by the current RHIC beam, and

$$\sigma_{x,p}(5\,\mathrm{m}) \propto \sqrt{\beta^*_{x,p} + \frac{(5\,\mathrm{m})^2}{\beta^*_{x,p}}} \approx \frac{5\,\mathrm{m}}{\sqrt{\beta^*_{x,p}}}, \qquad (3)$$

this poses a lower limit on the horizontal β-function for the ions at the IP, and therefore limits the achievable luminosity.
The electron beam size $\sigma_{x,e}$ at the septum can in principle be minimized by reducing the emittance accordingly. However, since beam sizes at the IP have to be matched, this requires larger electron β functions at the IP. Increased β-functions at the IP result in a larger beam-beam tuneshift and therefore limit luminosity. Table 1 lists the main interaction region parameters chosen in this design.

SYNCHROTRON RADIATION ACCOMODATION

Since it is desirable to bring the ion low-β quadrupoles as close as possible to the IP, beams also have to be separated near the interaction point. This results in several kilowatts of synchrotron radiation being generated close to the IP and the detector. Therefore, this radiation cannot be collimated upstream of the detector, but has to be passed safely through the interaction region with its detector and electron low-β quadrupoles. The width of the radiation fan resulting from the separation must be kept small enough to fit through the aperture of these magnets. This is accomplished by separating the beams very close to the IP.
Since a certain fraction of the synchrotron radiation fan unavoidably hits the septum of the first ion quadrupole, this septum is equipped with an absorber to minimize the amount of back-scattered synchrotron radiation photons that may potentially hit detector components. Additional masks ensure that back-scattered photons from the absorber cannot hit the detector directly. To prevent direct synchrotron radiation from hitting the "back" side of these masks, from where photons could also be back-scattered into the detector, the incoming synchrotron radiation fan is collimated such that the fraction originating from electrons at amplitudes larger than 5σ is scraped away without reducing the aperture for the electrons themselves below 20σ. GEANT-3 simulations of synchrotron radiation background in the eRHIC detector region are reported in [2]. A top view of the central part of the interaction region is shown in Figure 1.

LOW-β FOCUSING

Starting at a distance of $5\,\mathrm{m}$ from the IP, low-β focusing of the ions is provided by a normal-conducting quadrupole doublet. Both lenses of these doublets consist of several individual magnets with aperture radii tailored to the actual beam cross section to ensure a minimum aperture of 12σ at a maximum pole tip field of $1.0\,\mathrm{Tesla}$. These magnets are actually realized as magnetic septum quadrupoles to provide sufficient field-free space for the nearby electron beam. Figure 2 depicts the optics of the hadron low-β insertion.

Low-β focusing of the electron beam is provided by a superconducting quadrupole triplet, starting at a distance of $1.0\,\mathrm{m}$ from the IP. These magnets are shared by both the electron and the ion beam, but due to its much larger energy the ion beam is practically unaffected. Additional dipole windings on these magnets provide the required separation of the two beams by deflecting the electron beam by a much larger angle than the ion beam. Since the required aperture of these magnets on the electron-downstream side of the IP is much larger due to the large width of the synchrotron radiation fan, a slightly asymmetric lattice has been designed that keeps magnet apertures at their minimum to provide as much space as possible for detector components. The pole tip fields of these superconducting magnets are below some $2.1\,\mathrm{Tesla}$. Figure 3 shows the electron low-β optics.

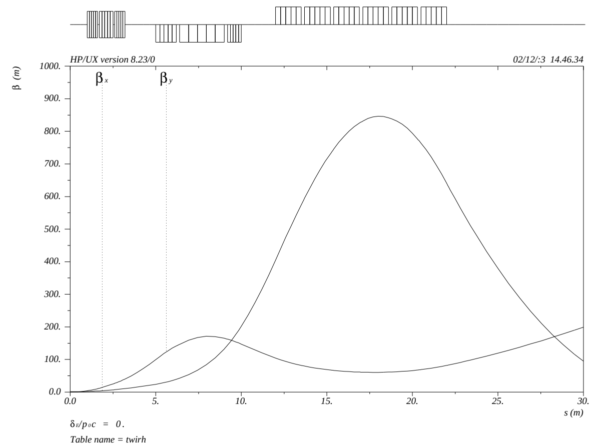

Figure 2: Optics of the ion low-β focusing section.

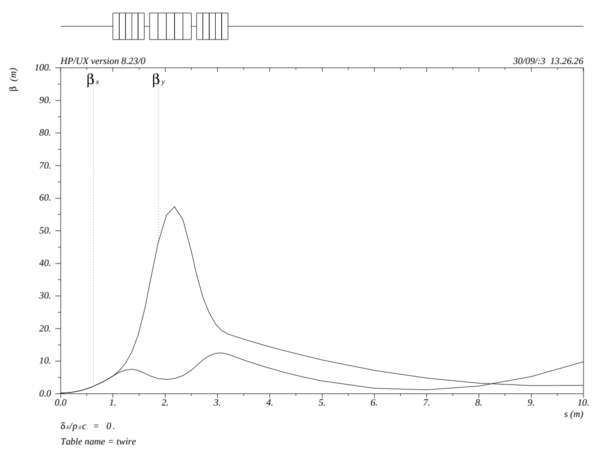

Figure 3: Electron low-β optics.

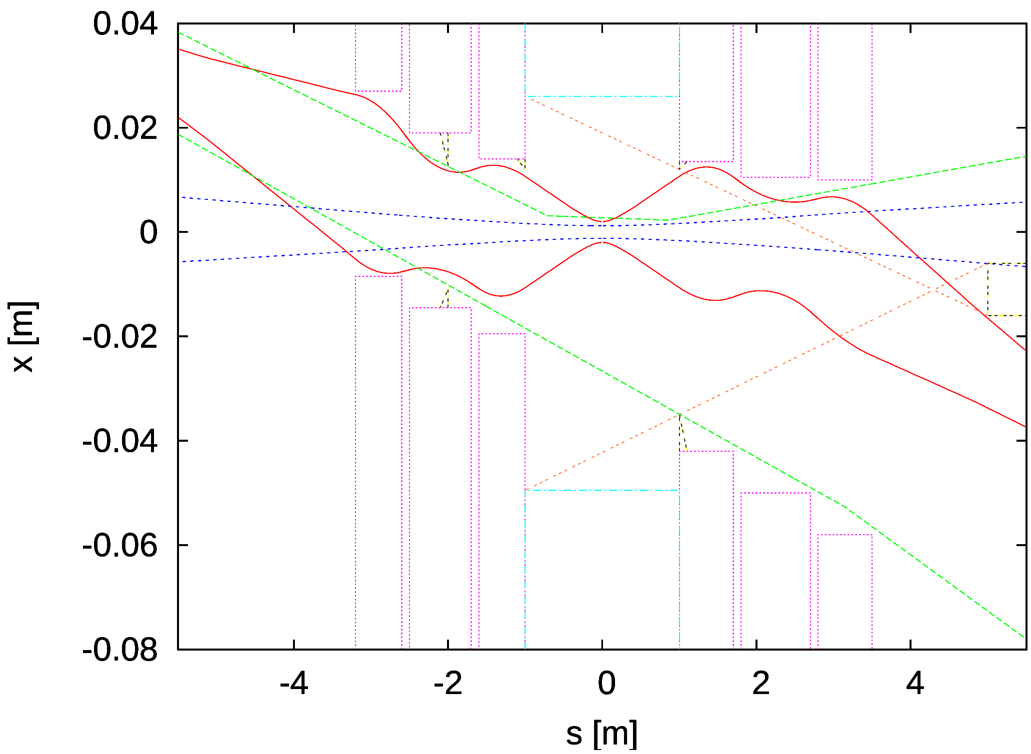

Figure 1: Top view of the eRHIC interaction region with the 20σ electron beam (red), the 12σ ion beam (blue), and the synchrotron radiation fan generated by the 5σ electron beam (green). The apertures of the superconducting electron low-β quadrupoles (magenta) are tailored according to the sizes of the beams and the fan. The central detector (light blue) is protected from backscattered synchrotron radiation photons by a set of masks (black) on the electron-downstream side of the IP. To illustrate this, the trajectories of two photons (orange) backscattered from the septum absorber on the right are shown. These two extreme trajectories define the geometrical requirements for the masking scheme. Another set of masks upstream of the IP limits the width of the incoming synchrotron radiation fan to photons generated by the 5σ beam without reducing the aperture for the electron or the ion beam.

CONCLUSION

We presented an interaction region design for the electron-ion collider eRHIC that is capable of providing an electron-proton luminosity of $4.4 \cdot 10^{32}\,\mathrm{cm}^{-2}\mathrm{sec}^{-1}$ with the given eRHIC parameters. Apertures are 20σ for the electron beam and 12σ for the ion beam at magnetic pole tip fields of $1.0\,\mathrm{T}$ for normalconducting magnets and less than $2.1\,\mathrm{T}$ for superconducting magnets. Figure 4 shows a 3-D view of the eRHIC interaction region with the electron ring and the BLUE RHIC ring interacting inside the detector. The YELLOW RHIC ring is bend down by three meters to provide sufficient spaced for the eRHIC detector.

REFERENCES

[1] KEKB B-Factory Design Report, KEK Report 95-7

[2] J. Beebe-Wang, C. Montag, to be published

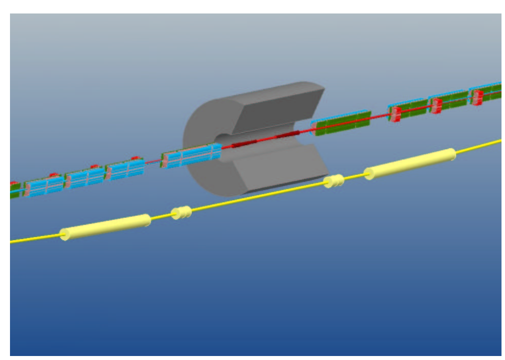

Figure 4: 3-D view of the eRHIC interaction region.