DESIGN OF THE 2015 eRHIC RING-RING INTERACTION REGION *

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Abstract

The 2015 ring-ring design study of the electron-ion collider eRHIC aims at an e-p luminosity around 10^{33} cm^{-2}sec^{-1} over a center-of-mass energy range from 32 to 141 GeV, while at the same time providing the required detector geometry and acceptance for the proposed physics program. The latest interaction region design will be presented.

INTRODUCTION

The eRHIC ring-ring design aims at a low-risk approach to an electron-ion collider based on the existing RHIC hadron ring and a new electron storage ring, colliding electrons at 5-20 GeV with protons of 50-250 GeV, or Au ions up to 100 GeV/n [1]. The required luminosity for a meaningful physics program is about 10^{33} cm^{-2}sec^{-1} over the center-of-mass energy range from 32 to 141 GeV, and future upgradeability to 10^{34} cm^{-2}sec^{-1} is desirable. In the interest of risk minimization the interaction region of this machine is based on rather conventional, albeit superconducting, magnets. Due to the requirements of the physics program separating the electron and hadron beams by means of dipoles is not feasible, thus requiring a crossing angle [2].

The eRHIC interaction region provides ±4.5 m of element-free space around the interaction point for the central detector, and a dedicated location in the outgoing hadron beamline for the installation of Roman Pots between the dipoles of the horizontal dogleg, see Figure 1. Five angles are vital in this design:

- The electron and hadron beams are separated by a total horizontal crossing angle of 15 mrad, thus suppressing long-range beam-beam interactions. The associated luminosity loss is compensated by crab cavities in the hadron beamline.

- The RMS divergence angles of both the hadron and electron beam determine the required apertures in the low-β quadrupoles, with the minimum apertures being $10\,\sigma$ for the hadron beam and $15\,\sigma$ for the electron beam.The divergence angles may be different in the two planes, depending on the beam emittances and Twiss parameters.

- An element free conical space with an opening angle of ±4 mrad in the forward hadron direction to allow unobstructed detection of neutrons. To separate these neutrons from the hadron beam or charged background particles, a magnetic dipole field of 2.6 T over a total length of 6 m is applied.

- The proton transverse momentum acceptance angle corresponds to the minimum deflection angle that should be detectable by the Roman Pots in-between the dogleg dipoles. To be detectable, a deflected proton needs to be well outside the the circulating hadron beam. This condition is satisfied if the deflection angle is about 10 times larger than the RMS proton beam divergence angle at the IP. For the detection of 250 GeV protons with a transverse momentum as low as 200 MeV/c, which corresponds to a deflection angle of 0.8 mrad, the RMS beam divergence at the IP should therefore not exceed about 80 μrad.

MAGNET LAYOUT

Focusing of both electron and hadron beams is provided by superconducting quadrupole magnets. While the transverse beam emittances of hadron beams are typically equal in the two planes, electron beams have unequal emittances in the horizontal and vertical planes due to the effects of synchrotron radiation damping and quantum excitation. At the interaction point the transverse RMS dimensions of the two colliding beams have to be equal to avoid transverse emittance blow-up of the larger beam. This is achieved by a large horizontal β-function for the hadron beam while minimizing the vertical hadron β-function, and nearly equal β-functions in the two planes for the electron beam. S low-β quadrupole triplet for the electron beam and a low-β doublet for the hadrons provide the necessary focusing.

The electron low-β quadrupole triplet is located 10.2 m from the IP, resulting in a 5.7 m long drift space between the central detector and the triplet. This allows for efficient collimation of the synchrotron radiation generated in the triplet quadrupoles to a convergent fan that passes safely through the central detector into the downstream electron beamline where it eventually grazes the inner wall of the vacuum chamber. Synchrotron radiation masks in this downstream electron beamline then minimize the amount of photons backscattered towards the central detector.

At the location of the triplet quadrupoles there is sufficient separation between the 15σ electron beam and the ±4 mrad neutron cone, so the magnet coils can be placed in-between, thus avoiding the necessity of large magnet apertures to pass the neutron cone as well. Table 1 lists the design parameters of the individual electron triplet quadrupoles.

The hadron low-β quadrupole doublet is located 32 m from the IP. To reduce the required voltage of the crab cavities, the horizontal β-function a the second quadrupole, where the crab cavities are located, is intentionally kept large. The magnet apertures are large enough to accomodate a 10σ proton beam at 50 GeV without having to increase the β-functions at the IP. The design parameters of the proton quadrupole doublet magnets are listed in Table 2.

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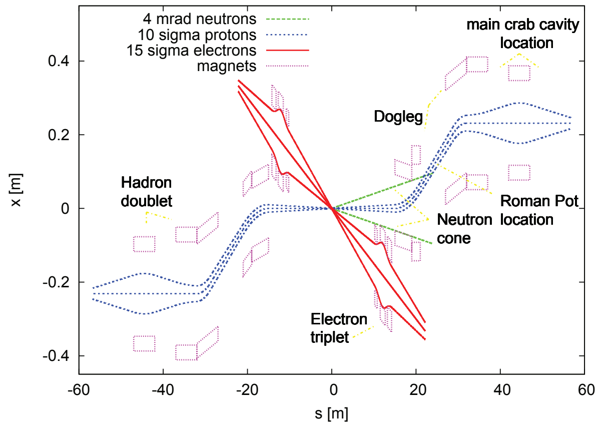

Figure 1: Layout of the eRHIC ring-ring interaction region, with proton beam enevelopes shown for 250 GeV.

Table 1: Design Parameters of the Low-β Electron Triplet Quadrupoles

	length [m]	strength [m^{-2}]	aperture radius [mm]	peak field [T]
QE1	0.6	-0.43	70	2.1
QE2	1.2	0.43	87.5	2.5
QE3	1.0	-0.30	68	1.4

Separation of the hadron beam from the forward neutron cone is provided by a set of dipole magnets forming a dogleg upstream of the hadron low-β doublet. The first dipole of the dogleg consists of two individual magnets that are 4 m and 2 m long, respectively. The first, longer of these two magnets is tilted by -4 mrad in the horizontal plane to maximize the distance between its coils and the electron beam. The electron beam passes just outside the cold mass of these dipoles. Additional coils are foreseen to reduce the magnetic field at the electron beam to a few Gauss. The long drift space between the two bends of the dogleg allows for the installation of Roman Pots for the detection of protons with a transverse momentum as low as 200 MeV/c.

CRAB CROSSING

The 15 mrad total crossing angle between the two beams necessitates crab crossing to restore the luminosity. The crab

Table 2: Design Parameters of the Low-β Hadron Doublet Quadrupoles at 250 GeV Proton Energy

	length [m]	strength [m^{-2}]	aperture radius [mm]	peak field [T]
QP1	5.0	-0.022	140	2.6
QP2	5.0	0.026	115	2.6

cavities are ideally placed at a location with large horizontal β-function, at a betatron phase advance of $\delta\phi_{\rm crab} = \frac{\pi}{2} + k\cdot\pi$, where k is an integer.

In the eRHIC interaction region the crab cavities are located up- and/or downstream of the horizontally focusing low-β quadrupole, where the horizontal β-function is about $\beta_{\rm crab} = 2400$ m. However, the phase advance is less than ideal, at $\phi_{\rm crab} = 86$ degrees. This introduces an additional closed-orbit angle for the head and the tail of the bunch at the interaction point that needs to be corrected.

The orbit angle introduced by the imperfect phase advance is governed by the M_{22} element of the transfer matrix from the crab cavity to the IP,

$$M_{22} = \sqrt{\frac{\beta_{\rm crab}}{\beta^*}}\cos\phi_{\rm crab}, \tag{1}$$

where β^* denotes the horizontal β-function at the IP.

Correcting this angle error requires a second set of crab cavities at or near a betatron phase advance of $k\cdot\pi$ from the IP. The corrective effect of this cavity is described by its matrix element

$$\begin{aligned} m_{22} &= \sqrt{\frac{\beta_{\rm corr}}{\beta^*}}\cos\phi_{\rm corr} \\ &= \sqrt{\frac{\beta_{\rm corr}}{\beta^*}}. \end{aligned} \tag{2}$$

from this second crab cavity to the IP. Here, $\beta_{\rm corr}$ denotes the horizontal β-function at this correction crab cavity.

It is desirable that the required voltage $V_{\rm corr}$ of the correction cavity does not exceed that of the main crab cavity $V_{\rm crab}$. This condition is fulfilled if

$$m_{22} > M_{22}. \tag{3}$$

Inserting the corresponding numbers for eRHIC into Equations 1 and 2 yields that this is the case at any location with the appropriate phase advance where $\beta_{\rm corr} > 10$ m. With few exceptions, this condition is met almost everywhere in the ring.

OPERATIONAL CONSIDERATIONS

Due to the absence of transverse cooling in the eRHIC ring-ring design RMS proton beam sizes at the IP vary with the proton beam energy. The apertures of the focusing elements in the hadron ring are chosen such that they can accommodate proton beams over the entire energy range from 50 to 250 GeV at the same IP β-functions.

The apertures of the focusing elements in the electron beamline are designed such that they can accomodate the electron beam when it collides with 250 GeV protons. This situation presents the smallest occuring beam sizes at the IP, with the electron RMS beam emittances ϵ_e being 53 nm horizontally and 9.5 nm vertically.

Table 3: Beam Parameters for Three Different Proton Beam Energies

E_p [GeV]	50	100	250
ϵ_p [nm]	47.5	23.75	9.5
β_p^* h/v [m]	2.16/0.27	2.16/0.27	2.16/0.27
ϵ_e h/v [nm]	118/21	84/15	53/9.5
β_e^* h/v [m]	0.85/0.60	0.60/0.43	0.38/0.27

At proton energies E_p lower than 250 GeV the RMS proton beam sizes at the IP increase due to the increasing proton beam emittance at constant β-functions,

$$\sigma_p^2(E_p) = \sigma_p^2(250\,\text{GeV})\frac{250}{E_p[GeV]}. \tag{4}$$

Since beam sizes of the two beams must be matched at the IP,

$$\sigma_e^2(E_p) = \epsilon_e(E_p)\beta_e^*(E_p) = \sigma_p^2(E_p). \tag{5}$$

To accommodate the electron beam in its low-β quadrupoles, its angular divergence at the IP must be kept constant at all proton energies E_p,

$$\begin{aligned} \sigma'^2(E_p) &= \frac{\epsilon_e(250\,\text{GeV})}{\beta_e^*(250\,\text{GeV})} \\ &= \frac{\epsilon_e(E_p)}{\beta_e^*(E_p)} \\ &= \kappa = \text{const.} \end{aligned} \tag{6}$$

Combining Equations 5 and 6 yields

$$\beta_e^{*2}(E_p) = \frac{250}{\kappa E(\text{GeV})}\sigma^2(250\,\text{GeV}), \tag{7}$$

and from this we can derive the electron emittance requirement as

$$\begin{aligned} \epsilon_e(E_p) &= \frac{\sigma^2(250\,\text{GeV})}{\beta_e^*(E_p)} \\ &= \sigma(250\,\text{GeV})\sqrt{\frac{\kappa E(\text{GeV})}{250}}. \end{aligned} \tag{8}$$

Table 3 lists beam parameters for three different proton beam energies.

CONCLUSION

We have designed an interaction region for the eRHIC ring-ring electron-ion collider, based on rather conventional superconducting magnets, a crossing angle, and crab cavities in the hadron beam line to restore the luminosity. Detailed detector simulations are currently being carried out to ensure that this design meets the requirements of the physics program. The interaction region design intentionally has some parameters that can easily be adjusted to either improve the detector acceptance or to reduce machine parameters such as the chromaticity of the IR, for instance the bending angle or the long drift space in-between the two bends of the dogleg that separates the hadron beam from the forward neutron cone. These design parameters will be optimized in an iterative process.

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