EVALUATION AND MITIGATION OF SYNCHROTRON RADIATION BACKGROUND IN THE eRHIC RING-RING INTERACTION REGION*

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Abstract

Synchrotron radiation is a potential source of background in the detector of any future electron-ion collider. In the case of the eRHIC ring-ring design, a 22mrad crossing angle eliminates the need for a separator dipole, which would otherwise be a major source of synchrotron radiation. However, electrons in the transverse tails experience strong magnetic fields in the low-beta quadrupoles near the interaction point. Despite the low electron density in the tails the resulting hard radiation generated in these strong fields is a major concern, and a set of masks needs to be in place to shield the detector from these photons. We present simulation studies and a first design of a synchrotron radiation masking scheme.

INTRODUCTION

The electron-ion collider eRHIC [1] aims at providing electron-nucleon luminosities in the 10^{33} to 10^{34} cm^{-2}sec^{-1} range, by colliding 5 - 18 GeV electrons with the appropriate ion species stored in one of the existing RHIC rings. To minimize the photon background in the detector the interaction region is based on a total crossing angle of 22 mrad. This scheme avoids the necessity of separator dipoles in or near the detector which would generate a wide fan of hard synchrotron radiation photons. However, the nearby low-β quadrupoles generate a synchrotron radiation cone that can be equally harmful for the detector if not handled appropriately.

In contrast to the homogeneous fan produced by dipole magnets, the photon cone generated by quadrupoles consists of a huge number of weak photons in its center, and a comparatively small number of very high energy photons at increasing distances from the center that stem from electrons in the transverse tails of the beam deistribution that have experienced strong magnetic fields at large amplitudes in these low-β quadrupoles. Additionally, since the beam-beam interaction tends to result in an over-population of the transverse electron beam tails, especially in the vertical plane, the number of hard photons produced in the quadrupoles by large-amplitude electrons can be significantly higher than for a pure Gaussian distribution. All these factors therefore have to be taken into account when evaluating the synchrotron radiation background in the detector, and designing a masking scheme.

GEOMETRIC CONSIDERATIONS

To maximize luminosity, eRHIC needs to operate at the beam-beam limit, with electron beam-beam parameters reaching $\xi_0 = 0.1$. Beam-beam parameters of this magnitude have been successfully demonstrated in routine operations at the B-factories PEP-II and KEKB. However, they require operating at betatron tunes near the integer of half-integer, where nonlinear resonances are comparatively sparse and dynamic focusing effects can be taken advantage of. In the case of eRHIC, which requires spin-polarized electron beams, operating near the half-integer resonance is not viable because of the depolarizing nature of such a working point. Therefore, only near-integer working points are viable for the eRHIC electron ring.

Table 1: Effect of Dynamic Focusing on IR β-functions in the eRHIC Electron Storage Ring

	Hor.	Vert.
fractional tune μ_0	.08	.06
beam-beam parameter ξ_0	.092	.083
nominal β_0^* [m]	0.62	0.073
dynamic β^* [m]	0.37	0.040

Due to the focusing effect of the beam-beam interaction, tunes slightly above the integer resonance lead to additional focusing due to the β-beat introduced by the beam-beam force itself,

$$\beta^* = \frac{\beta_0^*}{\sqrt{1 + 4\pi\xi_0 \cot\mu_0 - 4\pi^2\xi_0^2}}. \quad (1)$$

Here, β_0^* denotes the nominal β-function at the interaction point (IP), while μ_0 is the machine tune in absence of the beam-beam force. β^* is the resulting β-function at the IP as modified by the beam-beam kick.

Weak-strong beam-beam simulations indicate that a working point around $(Q_x, Q_y) = (.08/.06)$ results in electron beam sizes well matched to the hadron beam cross section at the IP as a net result of both beam-beam induced emittance blow-up and dynamic focusing [2, 3]. At this working point, significant dynamic focusing occurs, as shown in Table 1.

As a consequence, the β-functions throughout the IR are modified. In particular, they grow more rapidly between the IP and the first focusing quadrupole. However, due to the nonlinear nature of the beam-beam interaction, this dynamic focusing only affects the core of the beam where the kick is largely linear, while the focusing of the tails is unaffected. Dynamic focusing can therefore be ignored when determining the required apertures of magnets and masks in the interaction region design [4].

However, the nonlinear nature of the beam-beam interaction leads to the formation of non-Gaussian tails with an enhanced electron density. As Figure 1 shows, the colliding electron beam requires about 50 percent larger apertures

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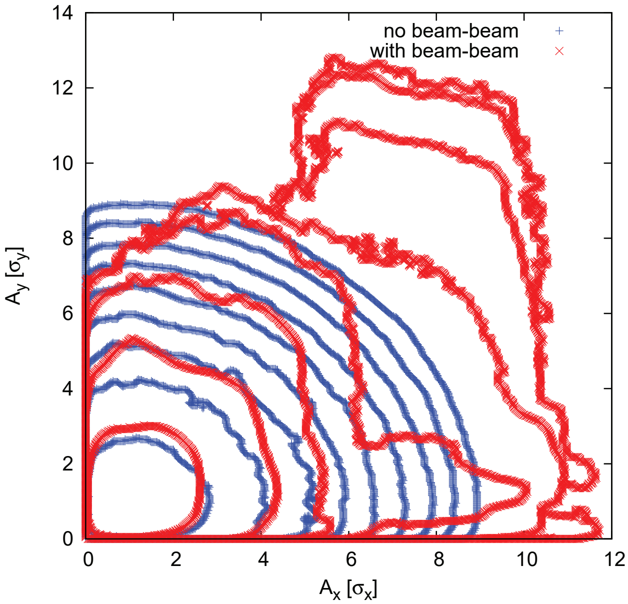

Figure 1: Transverse electron density distribution with (red) and without (blue) beam-beam interaction. The contour lines are spaced by a factor 10.

than without beam-beam interactions. Magnet apertures have to be large enough for these tails to pass through in order to provide beam lifetimes on the order of at least several hours. Since the synchrotron radiation masks have to provide sufficient aperture for the circulating electron beam as well these effects have to be taken into account in their layout.

The eRHIC Physics program requires a machine element free region of ±4.5 m around the IP for the installation of the central detector [5]. As a consequence, any synchrotron radiation mask that gets hit by direct radiation can only be installed at least 4.5 m from the IP. The aperture of those masks has to be sufficiently large to ensure beam lifetimes on the order of several hours. With aperture radii corresponding to 10 transverse RMS beam sizes of the Gaussian, non-colliding beam, we can accommodate non-Gaussian tails that correspond to a 6σ aperture restriction. Based on this we expect beam lifetimes of the order of 25 hours [6].

The first focusing element (quadrupole Q1) starts at a distance of 8.79 m from the IP. In order to reduce the peak magnetic fields encountered by electrons in the transverse tails, this magnet as well as the following quadrupole Q2 are comparatively long; the length is limited by the requirement to fit in-between focusing elements in the hadron beam line in an interleaved fashion. Table 2 lists the design parameters of the last four quadrupoles upstream of the IP.

To shield the detector from direct hits by synchrotron radiation photons we assume a mask at $s = 4.5$ m upstream of the IP, just outside the central detector. This mask minimizes the width and height of the fan generated by upstream quadrupoles through the detector. A second mask is located further upstream; the purpose of this mask is to reduce the heat load on the 4.5 m mask by capturing photons that originate further upstream.

Table 2: Electron IR Magnet Parameters on the upstream side of the detector, for the highest design energy of 18 GeV

Name	s_i [m]	l [m]	IR [cm]	B [T]	g [T/m]
Q1	8.79	1.72	3.0	0.20	-6.66
Q2	13.93	2.00	4.9	0.18	3.66
Q3	49.93	0.60	4.9	0.19	3.85
Q4	54.53	0.60	4.9	0.16	-3.27

This masking scheme results in an elliptical cone of the synchrotron radiation fan through the central detector. On the incoming side, its cross section is identical to that of the mask at $s = 4.5$ m, which is determined by the 10σ beam size at that location. The radii of that upstream ellipse are 11 mm in the horizontal plane, and 10 mm vertically. At the downstream end of the central detector, the cone radii have substantially increased, to 71 mm horizontally, and 19 mm vertically. This cone determines the minimum dimensions of the detector beam pipe that ensure no background from primary photons generated by the electron beam.

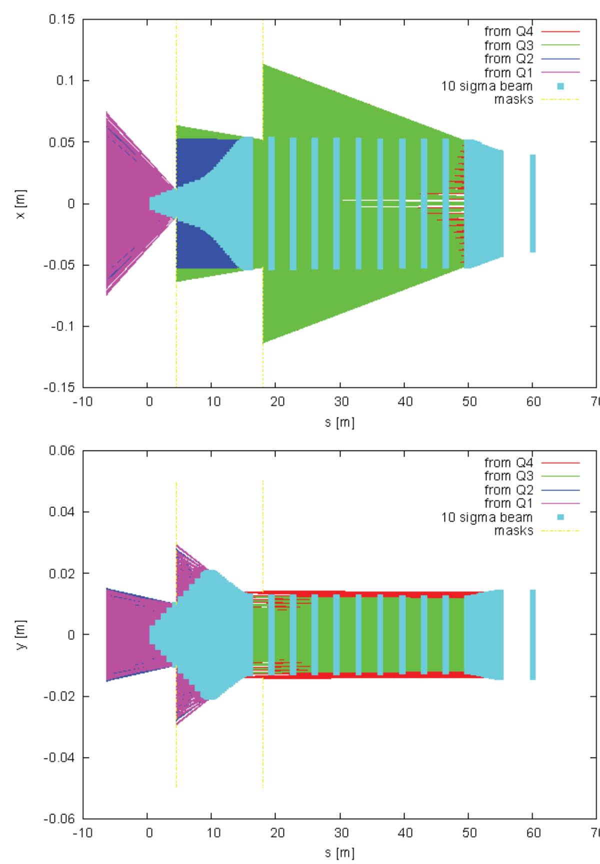

Figure 2: Synchrotron radiation fans from the last four quadrupoles through the IR, top view (top) and side view (bottom).

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DETECTOR BACKGROUND SIMULATIONS

In the next step, the impact of potentially backscattered photons on the detector is simulated using the code DESYNC [7]. In addition to the two masks that protect the detector beam pipe from primary photons, a third mask is added upstream of the first magnet on the downstream side of the detector at $s = -8.0$ m to shield that superconducting low-β quadrupole from synchrotron radiation and the associated heat load. The aperture radius of this mask is set to 34 mm, which is one millimeter smaller than the adjacent magnet. This mask gets hit by a large number of primary photons, and backscattered photons may end up in the central detector and result in unacceptable background conditions or radiation damage to the detector.

The focusing upstream of the detector is designed such as to minimize the magnetic fields of the last two quadrupoles encountered by electrons in the transverse tails of the beam. This is accomplished by long quadrupoles Q1 and Q2 with a low gradient. Even at the highest beam energy of 18 GeV this results in peak fields of only 0.2 T at the 15σ design aperture of these magnets. However, since the moveable upstream mask at $s = 4.5$ m has an aperture radius of only 10σ, no electrons are present in the beam beyond this limit. Therefore, the maximum magnetic field sampled is only 2/3 of the peak field of those quadrupoles, namely $B_{\text{max}} = 0.133$ T. The corresponding critical energy of the synchrotron radiation generated by the small number of electrons at the outer edges of the beam is therefore reduced to

$$\begin{aligned} E_c &= \frac{3}{2}\frac{\hbar c^2 e E^2 B}{E_0^3} \\ &= 28.7\,\text{keV}, \end{aligned} \tag{2}$$

at 18 GeV, or $E_c = 4.9$ keV at $E = 10$ GeV. Here $E_0 = m_e c^2$ is the electron rest energy.

Photon scattering in the IR geometry described above has been simulated with the code DESYNC [7]. Assuming a detector beam pipe that is tailored to accommodate the primary synchrotron radiation fan according to Figure 2 the radiation load outside the 1 mm thick beryllium detector pipe reaches a maximum of 2.2 rad/hour in the two 1 m-long segments at the two ends of the detector at 18 GeV, and less than a μrad/hour everywhere else throughout the central detector. These two maxima are caused by scattering off the masks at $s = 4.5$ m and $s = -8$ m. At a beam energy of 10 GeV these maxima reduce by 2-3 orders of magnitude.

While these radiation levels are likely acceptable more detailed simulations including the actual eRHIC detector are required. These simulations are beyond the capabilities of DESYNC and will therefore be carried out using a simulation code such as GEANT4 [8].

CONCLUSIONS

With the eRHIC interaction region being based on a 22 mrad total crossing angle, the only source of synchrotron radiation near the interaction point is from quadrupoles. A single mask at the entrance of the detector is capable of collimating the photon fan to an acceptable size, such that detector elements can be placed close to the beam. Downstream of the detector the remaining radiation fan is restricted by the first quadrupole at $s = -8$ m from the IP. Backscattering of photons from this aperture restriction, as well as tip scattering from the mask at the detector entrance, is therefore a potential source of background in the detector. Simulations with the Monte-Carlo code DESYNC [7] indicate that radiation levels in the detector are likely acceptable at 18 GeV electron beam energy, and negligible at 10 GeV. More detailed studies that include the actual detector in the simulation will be performed using GEANT4 [8].

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