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Investigation of the radiation background in the interaction region of the medium-energy electron relativistic heavy ion collider (MeRHIC)

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DISCLAIMER

INVESTIGATION OF THE RADIATION BACKGROUND IN THE INTERACTION REGION OF THE MEDIUM-ENERGY ELECTRON RELATIVISTIC HEAVY ION COLLIDER (MeRHIC)*

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Abstract

There are three main sources of the radiation background in MeRHIC: forward synchrotron radiation generated upstream of the detector, the direct backward radiation caused by the photons hitting beampipe downstream of the detector, and the indirect secondary radiation caused by hard photons hitting vacuum systems, masks, collimators, absorbers or any other elements in the interaction region. In this paper, we first calculate the primary radiation distribution by employing electromagnetic theory. Then we obtain the direct backward scattering rate by applying the kinematic Born approximation deduced from scattering dynamics. The diffuse scattering cross section is calculated as a function of the surface properties of the MeRHIC vacuum system. Finally, the dominating physical processes and minimization of indirect secondary radiation is presented and discussed.

INTRODUCTION

A staged approach towards the development of a high energy RHIC-based electron-ion collider has been proposed at BNL [1]. In the first stage, a medium-energy electron Relativistic Heavy Ion Collider (MeRHIC) would be constructed. It would utilize a high energy ion beam, accelerated in one of the two existing rings of the RHIC facility, colliding with a medium energy (4 GeV) electron beam, generated by a proposed energy-recovery linac (ERL). The central detector is equipped with a solenoid of up to 5 T to facilitate particle identication. A pair of strong dipoles with a magnetic field of 3 T are added at both end of the solenoid, forming forward spectrometers. These dipole magnets also provide the necessary separation of the two beams [2]. Synchrotron radiation is generated close to the interaction point and requires attention as part of the interaction region design. The detector needs to be shielded from synchrotron radiation photons with an appropriate masking scheme. It is also necessary to investigate the background radiation in the physics experiment detector.

FORWARD SYNCHROTRON RADIATION IN THE INTERACTION REGION

The hard photons generated by the electron beam bent by the strong horizontal dipole field upstream of the detector would produce unacceptable background conditions in the detector if they were allowed to hit any surfaces within. The width of this hard synchrotron radiation fan is reduced as much as possible by a primary synchrotron radiation collimator. In order to facilitate complete removal of the remaining hard synchrotron radiation fan, a weak vertical dipole magnet is added between the central solenoid and the strong dipole magnet. The bending angle of this dipole is chosen such that at the location of the secondary collimator, the hard synchrotron radiation fan is completely separated from the electron and ion beams, and can therefore be removed completely by the collimator [2]. The physical parameters and synchrotron radiation properties of both hard and soft bending magnets are listed in Table 1.

Table 1: Physical parameters and synchrotron radiation properties of bending magnets located upstream and downstream of the MeRHIC detector.

Magnet (up/down streams)	Magnet Length [m]	Bending Angle [mrad]	Critical Energy [keV]	Radiation Power [W]
up hard	3.0	200	9.5	2403
up soft	1.0	5	0.7	4.5
down hard	3.0	250	11.8	3755
down hard	1.0	4	0.6	2.9

The photon spectrum of forward synchrotron radiation can be calculated with [3]:

$$\frac{d^2n}{dtdE} = \frac{P_0\gamma}{E_C^2}\frac{S(\omega/\omega_C)}{(\omega/\omega_C)}$$

where P_0 is the synchrotron radiation power, γ is the electron relativistic factor E^e_{total}/E^e_{rest}, E_C is the critical photon energy, and the S-function is defined as:

$$S\left(\frac{\omega}{\omega_C}\right) = \frac{9\sqrt{3}\omega}{8\pi\omega_C}\int_{\omega/\omega_C}^{\infty} K_{5/3}(z)\,dz\,.$$

Here, $K_{5/3}(z)$ is the modified Bessel function of the second kind. Based on the physical parameters and the radiation properties listed in Table 1 the calculated photon spectrum of forward synchrotron radiation in the interaction region (without masks) is shown in Figure 1.

BACKWARD SYNCHROTRON RADIATION IN INTERACTION REGION

On the downstream side, the strong spectrometer dipole produces a very wide, hard synchrotron radiation fan that

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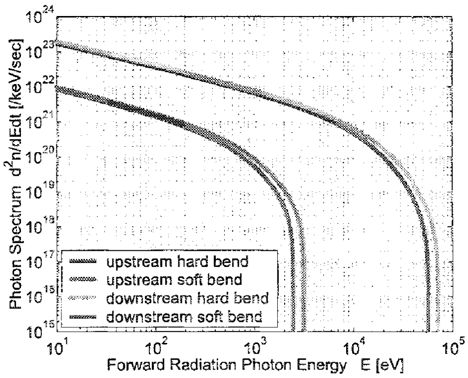

Figure 1: Photon spectrum of forward synchrotron radiation in the interaction region without masks.

needs to be absorbed properly. To prevent back-scattered photons from entering the central detector, any direct line-of-sight into the detector has to be avoided. This is again accomplished by adding a weak, vertically bending dipole between the solenoid and the strong spectrometer dipole (see Table 1). Two synchrotron radiation masks on the downstream side of the detector minimize the opening angle of the back-scattered photon distribution entering the central detector beampipe [2]. However, the soft synchrotron radiation fan generated in the upstream vertical bending dipole magnet would still pass through the opening of the detector and the first downstream mask, then hit the second downstream mask or beam pipe, and cause backward scattering of soft X-rays.

In order to estimate the backward scattering rate, we apply the kinematic Born approximation deduced from scattering dynamics. The diffuse scattering cross-section of soft X-rays off rough surfaces can be expressed in polar coordinates as [4]:

$$S(\vec{q}) = \frac{\rho_{el}^2 r_{el}^2 L_x L_y}{q_z^2} \int e^{-\frac{1}{2}q_z^2 A R^{2h}} J_0(q_r R) R\, dR$$

where ρ_{el} is the electron density of the surface material, r_{el} is the classical electron radius, and q_z and $q_r = \sqrt{q_x^2 + q_y^2}$ are the off-plane and in-plane scattering wave-vectors, respectively. J_0 is the zero order Bessel function. h is a surface property parameter describing the roughness of the surface, ranging from 0 for extremely rough surfaces to 1 for surfaces that are extremely smooth. A is a surface parameter describing the correlation of the surface structure. In general, the above integral can be calculated numerically. However, there are analytical solutions for $h = 0.5$ and $h = 1$ given by

$$S(\vec{q}) = \begin{cases} A\pi\rho_{el}^2 r_{el}^2 L_x L_y \Big/ \left[q_r^2 + \left(\frac{A}{2}\right)^2 q_z^4\right]^{\frac{3}{2}} & h = 0.5 \\ \dfrac{2\pi\rho_{el}^2 r_{el}^2 L_x L_y}{A q_z^4} e^{-\frac{q_r^2}{2Aq_z^2}} & h = 1.0 \end{cases}$$

In this investigation the surface material is stainless steel and the properties of iron are used. Figure 2 shows the calculated cross-section of diffuse scattering over the range of MeRHIC radiation energy and surface parameters A, with h=0.5 which represents a somewhat 'jagged' surface structure. The unit of the cross-sections are normalized to $L_x L_y$. It can be observed from these results that on typically rough surfaces, with $h \leqslant 0.5$, the diffuse scattering cross-section is very small ($\leqslant 10^{-12}$). The worst case scenario corresponds to the extremely smooth surface, h=1. In this case, as shown in Figure 3, the diffuse scattering cross-section could be as high as 10^{-2} in the normalized unit.

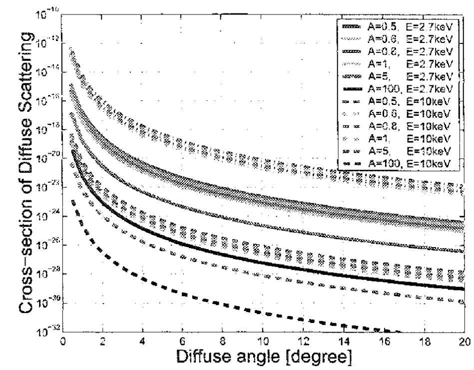

Figure 2: Cross-section of diffuse scattering for h =0.5.

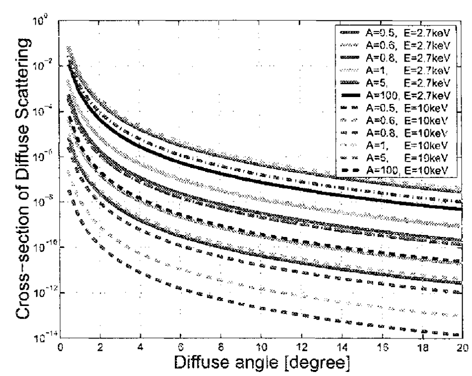

Figure 3: Cross-section of diffuse scattering for h =1.

MULTIPLE SCATTERING ISSUES

Some hard photons produced in the strong dipole magnets could have energies up to 70 keV, as can be observed from Figure 1. Even though these photons are masked from the detector opening, they could undergo multiple scattering through photon-matter interactions and cause increased background in the detector. It is therefore necessary to minimize the secondary scattering by careful design and choice of material for vacuum systems, masks, collimators, absorbers and any other elements in the interaction region. There are many physical processes involving photon-matter interactions. These include the photoelectric effect, Rayleigh (coherent) scattering, Compton (incoherent) scattering, continuous energy loss, (e+, e-) pair production, positron annihilation, hadronic interaction, Bremsstrahlung, ionization and δ-ray production.

A simulation study of secondary radiation with photon energies up to 70 keV in the eRHIC interaction region was carried out in BNL previously [5] using GEANT [6]. The simulation included all the physics processes listed above and implemented stainless steel vacuum chambers and copper radiation absorbers as in the current eRHIC design. It was noticed that the spectrum of backward radiation peaked around 8 keV [5], which is close to the K-shell energies of iron (7.11 keV) and copper (8.98 keV). A careful investigation indicates that in the photon energy range of MeRHIC only the first three physical processes are important. Figures 4, 5 and 6 show the reaction coefficients of photons in the energy range of MeRHIC with 12 different materials, for the photoelectric effect, Rayleigh (coherent) scattering and Compton (incoherent) scattering, respectively [7]. Comparing the coefficients of the three main reactions, it can be seen that the secondary radiation is dominated by the values of the shell energies in the photoelectric coefficients (Fig. 4). The radiation background in the MeRHIC interaction region can be minimized with proper knowledge of the photon energy distribution and selection of suitable materials. In this regard, material properties with respect to the photoelectric effect are paramount.

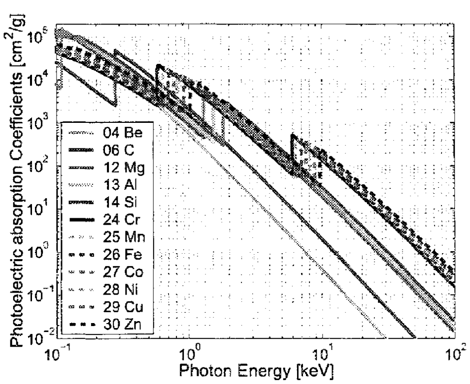

Figure 4: Photoelectric absorption coefficients

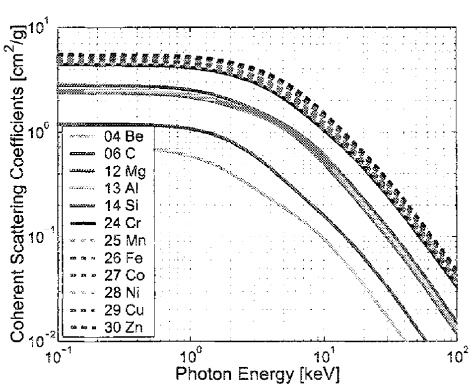

Figure 5: Rayleigh scattering coefficients

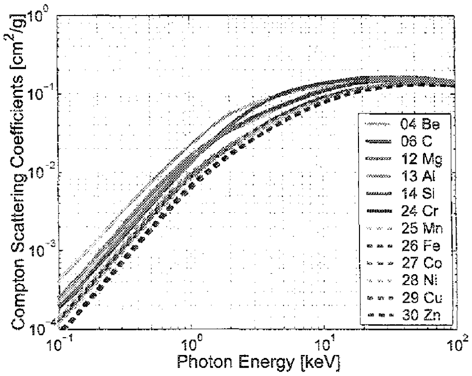

Figure 6: Compton scattering coefficients

CONCLUSION AND DISCUSSION

In the current MeRHIC interaction design a collimation and mask system will be implemented to prevent synchrotron radiation from entering the central detector. A pair of weak vertically bending dipoles will be added between the detector solenoid and the strong dipoles to provide the complete removal of "direct line-of-sight" into the detector. The investigation of the radiation background in the detector consists of evaluation of forward radiation, direct backward radiation, and the indirect secondary radiation.

The photon spectrum of forward synchrotron radiation in the interaction region (without masks) provide good understanding of the energy range and distribution of both hard and soft X-rays in MeRHIC. The rate of direct backward scattering due to the soft X-rays is dominated by the surface property. The rate of multiple scattering of hard X-rays is dominated by the photoelectric property of the material. These results offer a guideline for the choice of the material and surface in the design of vacuum system, masks, collimators and absorbers. Computer simulations will be needed to obtain the final estimate of background level in MeRHIC detector due to multiple scattering.

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