THE FEASIBILITY STUDY OF MEASURING THE POLARIZATION OF A RELATIVISTIC ELECTRON BEAM USING A COMPTON SCATTERING GAMMA-RAY SOURCE*

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Abstract

The Compton scattering of a circularly polarized photon beam and a polarized electron beam leads to an asymmetric spatial distribution of the gamma rays. This asymmetry has been calculated for the High Intensity Gamma-ray Source (HIGS) beam at Duke University. Owing to the high intensity of the HIGS beam, this asymmetry is determined to be measurable with a small statistical error using a simple optical imaging system for gamma-ray beams. We propose to set up this system to measure the polarization of the electron beam in the Duke storage ring.

INTRODUCTION

For a polarized electron beam head-on collision with a polarized photon beam (see Fig. 1) without regard to their polarizations after the scattering, the cross section in the lab frame is given by [1, 2]

$$\frac{d\sigma}{d\Omega} = \Sigma_0 + P_t\Sigma_1 + P_c[S_z\Sigma_{2z} + S_x\Sigma_{2x} + S_y\Sigma_{2y}], \quad (1)$$

where, P_t and P_c are the degrees of linear and circular polarization of the initial photon beam in the lab frame; S_x, S_y and S_z are the degrees of polarization of the initial electron beam with respect to xyz axes. The terms Σ's are given by

$$\begin{aligned}
\Sigma_0 &= C[(\frac{1}{x}-\frac{1}{y})^2 + \frac{1}{x} - \frac{1}{y} + \frac{1}{4}(\frac{x}{y}+\frac{y}{x})],\\
\Sigma_1 &= C[(\frac{1}{x}-\frac{1}{y})^2 + \frac{1}{x} - \frac{1}{y}]\cos(2\tau-2\phi),\\
\Sigma_{2z} &= \frac{1}{2}C(\frac{1}{x}-\frac{1}{y}+\frac{1}{2})(\frac{x}{y}-\frac{y}{x}),\\
\Sigma_{2x} &= \frac{1}{2}Cy(\frac{1}{x}-\frac{1}{y})\sqrt{-(\frac{1}{x}-\frac{1}{y})(\frac{1}{x}-\frac{1}{y}+1)}\cos\phi,\\
\Sigma_{2y} &= \frac{1}{2}Cy(\frac{1}{x}-\frac{1}{y})\sqrt{-(\frac{1}{x}-\frac{1}{y})(\frac{1}{x}-\frac{1}{y}+1)}\sin\phi,\\
C &= \frac{2r_e^2}{[\gamma(1+\beta)]^2}(\frac{\omega'}{\omega})^2. \quad (2)
\end{aligned}$$

The quantities x, y here are the invariant quantities defined by

$$x = \frac{s-m^2}{m^2}, \qquad y = \frac{m^2-u}{m^2},$$

$$s = (p+k)^2, \qquad u = (p-k')^2, \quad (3)$$

where, the nature units $\hbar = c = 1$ are used; r_e is the classical electron radius; $\hbar\omega$ and $\hbar\omega'$ are the initial and final photon energies in the lab frame; $\gamma = (1-\beta^2)^{-\frac{1}{2}}$ and $\beta = \frac{v}{c}$ is the relativistic velocity of the initial electron; m is the rest mass energy of an electron; p, k are the 4-momenta of the initial electron and photon; p', k' are the 4-momenta of the final electron and photon; ϕ is the azimuthal angle of the scattering plane formed by the initial and final photon momentum $\vec{k}$ and $\vec{k}'$; τ is the azimuthal angle of the linear polarization of the initial photon beam with respect to x-axis.

From the Eq. 1, it can be seen that the term Σ_0 is not related to the polarizations of the initial electron and photon beams. However, the terms Σ_1 and $\Sigma_{2x,2y,2z}$ are polarization dependent: Σ_1 term comes from the scattering involving the linearly polarized initial photon beam ($P_t \neq 0$); Σ_{2z} term comes from the scattering between longitudinally polarized electron beam and circularly polarized photon beam ($P_cS_z \neq 0$); $\Sigma_{2x,2y}$ terms come from the scattering between transversely polarized electron beam and circularly polarized photon beam ($P_cS_{x,y} \neq 0$). Therefore, the polarizations of the initial electron and photon beams can be obtained by measuring the cross section asymmetry. In the following section, we will discuss how the transverse polarization of the initial electron beam is obtained.

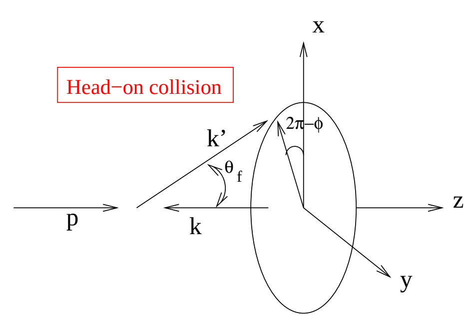

Figure 1: Compton scattering in a lab frame. The finial electron is not shown in this figure.

CROSS SECTION ASYMMETRY

The measurement of the $\cos\phi$ or $\sin\phi$ dependence of the scattered gamma-ray photon distribution can give us the transverse polarization S_x and S_y of the electron beam before the collision. The vertical polarization S_y is obtained by measuring the asymmetry in the vertical distribu-

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tion ($\phi = \frac{\pi}{2}, \frac{3\pi}{2}$) of the gamma-ray photons produced by the Compton scattering between vertically polarized electron beam and circularly polarized photon beam. For this scattering, the contribution from Σ_{2x} term to vertical distribution is zero because of the $\cos\phi$-dependence, the contributions from Σ_1 and Σ_{2z} terms can be neglected because the linear polarization of the photon beam P_t and the longitudinal polarization of the electron beam S_z are expected to be small. Now, there are only two terms contributing to the vertical distribution of scattered gamma-ray photons

$$\Delta N(y_c) \propto d\sigma = (\Sigma_0 + P_c S_y \Sigma_{2y})\frac{dx_c dy_c}{L^2}. \quad (4)$$

The solid angle $d\Omega$ has been written as $\frac{dx_c dy_c}{L^2}$, where x_c and y_c are the coordinates in the measurement plane, L is the distance from the collision point to this plane and $L \gg x_c, y_c$. Since we are only considering the vertical distribution ($\phi = \frac{\pi}{2}, \frac{3\pi}{2}$), x_c is fixed to zero. Therefore, $\Delta N(y_c)$ is the number of photons measured in the region $[y_c, y_c + dy_c]$ and $[-\frac{dx_c}{2}, \frac{dx_c}{2}]$. The asymmetry of the vertical gamma-ray photon distribution, for example, with left circularly polarized photons ($P_c = 1$) is defined by

$$\begin{aligned} A(y_c) &= \frac{\Delta N_L(y_c) - \Delta N_L(-y_c)}{\Delta N_L(y_c) + \Delta N_L(-y_c)} \\ &= S_y \frac{\Sigma_{2y}}{\Sigma_0} = S_y Q_{2y}, \end{aligned} \quad (5)$$

Q_{2y} is called analyzing power which is equal to the asymmetry $A(y_c)$ when $S_y = 1$. This asymmetry is shown in Fig. 2, and is also compared to the simulation result by a Monte-Carlo simulation code CAIN2.35 [3].

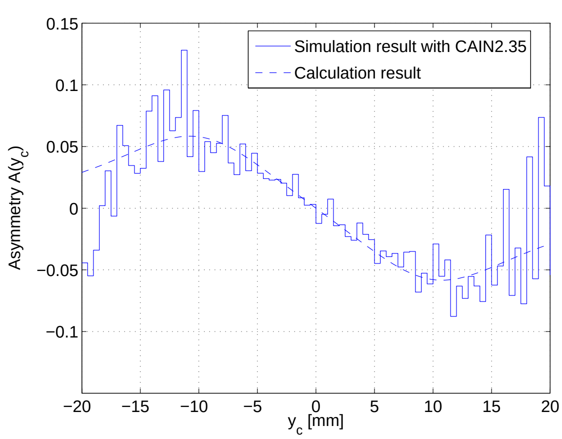

Figure 2: Vertical asymmetry at 30 m from the collision point for 190 nm laser photons scattering with 1.1 GeV electrons. The stairs plot corresponds to the simulation result with CAIN2.35, and the dash curve corresponds to the theoretical calculation.

In order to measure this vertical asymmetry correctly, the center of the distribution must be located precisely, which will be difficult. To improve the accuracy, we can measure the asymmetry at the same vertical position of the distribution with opposite laser light helicities ($P_c = \pm 1$). Now the asymmetry is defined by

$$\begin{aligned} A(y_c) &= \frac{\Delta N_L(y_c) - \Delta N_R(y_c)}{\Delta N_L(y_c) + \Delta N_R(y_c)} \\ &= S_y \frac{\Sigma_{2y}}{\Sigma_0} = S_y Q_{2y}. \end{aligned} \quad (6)$$

The vertical polarization S_y is obtained by fitting the measured vertical asymmetry to Eq. 6 with S_y as a free parameter.

The vertical distribution of the gamma-ray photons produced by Compton scattering for the left and right circularly polarized photon beams are shown in Fig. 3. It is clearly seen that the centroids of the two vertical profiles are shifted. This shift can also be used to obtain the vertical polarization of the electron beam in following way,

$$\begin{aligned} \Delta < y_c > &= \frac{< y_c >_L - < y_c >_R}{2} = S_y \Pi, \\ S_y &= \frac{\Delta < y_c >}{\Pi}, \end{aligned} \quad (7)$$

where Π is equal to the centroid shift when $S_y = 1$.

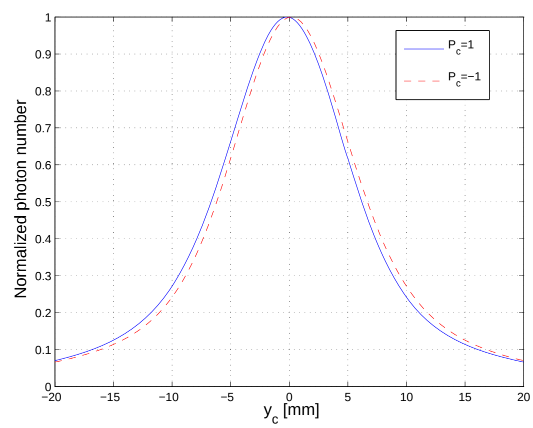

Figure 3: Vertical profiles of scattered gamma-ray photons for 190 nm circularly polarized FEL photons scattering with 1.1 GeV vertically polarized electrons. The solid curve corresponds to the $P_c = 1$ polarized laser, and the dash curve corresponds to the $P_c = -1$ polarized laser.

STATISTICAL ERROR

The polarization of the electron beam is obtained by measuring the cross section asymmetry which is determined by the analyzing power Q_{2y}. The dependence of maximum analyzing power Q_{2ymax} on the electron beam energy and laser wavelength is shown Fig. 4. It can be seen that the higher the electron beam energy, the bigger the analyzing power. At the Hadron Electron Ring Accelerator (HERA) of DESY (513 nm laser photon scattering with

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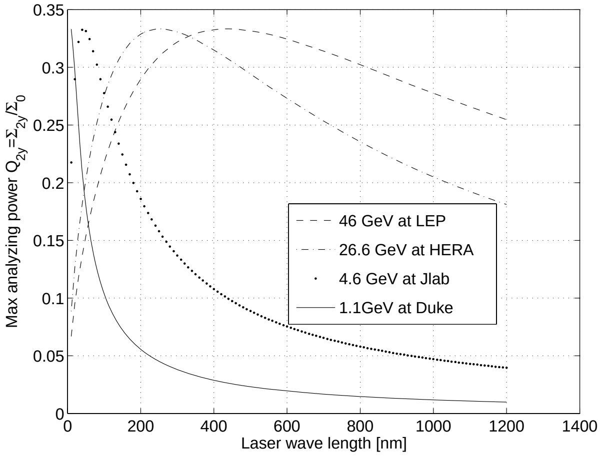

Figure 4: The maximum analyzing power for different electron beam energy and laser wavelength. At the Large Electron-Positron storage ring (LEP) of CERN [5], HERA [4], the Hall A Compton Polarimeter of JLAB [6], and the Duke storage ring, the electron beam energy is 46, 26.6, 4.6 and 1.1 GeV respectively.

26.6 GeV electron) [4], the maximum analyzing power is about 0.33, however at Duke (190 nm laser photon scattering with 1.1 GeV electron), the analyzing power is only about 0.08, making it difficult to measure the electron transverse polarization with a good accuracy. For the centroid shift measurement, the statistical error is given by

$$\frac{\delta S_y}{S_y} = \frac{\sigma_y}{S_y \Pi \sqrt{N}}, \tag{8}$$

where σ_y is the RMS width of the vertical profile and N is the total photon number to define this profile. For 190 nm FEL photons scattering with 1.1 GeV electrons, it can be calculated that $\Pi = 239\ \mu m$ and the RMS width $\sigma_y = 7.29$ mm at the measurement plane 30 m away from the collision point. In order to measure the vertical polarization of electron beam as small as $S_y = 0.1$, with a statistical error of $\frac{\delta S_y}{S_y} = 1\%$, it requires $N = 9.5 \times 10^8$ photons. However, we know that only the gamma-ray photons in the region $[-\frac{dx_c}{2}, \frac{dx_c}{2}]$ are used to define the vertical profile. For $dx_c = 2$ mm, the gamma-ray photons in this region are about 10% of total gamma-ray photon flux. Therefore, a total of 9.5×10^9 gamma-ray photons are needed. Assuming a HIGS beam flux of 2×10^8 γ/s, the measuring time will be about 47 seconds if the detector efficiency is 100%.

GAMMA-RAY IMAGING SYSTEM

The spatial distribution of the scattered gamma-ray photons can be measured by a gamma-ray imaging system. The prototype of this imaging system at the HIGS was first designed by Thomas Z. Regier [8]. Fig. 5 is the conceptual design of this system, which consists of an aluminum shutter that is used to block the laser, a layer of BGO crystal to convert the gamma rays into visible photons, an optics system, and a CCD camera. In order to obtain a high sensitivity and good spatial resolution, it is essential to optimize the thickness of the aluminum shutter and the BGO converter as a part of the system design. The Geant4 [7], a Monte Carlo simulation code, has been used to optimize the selection of the aluminum shutter and BGO converter.

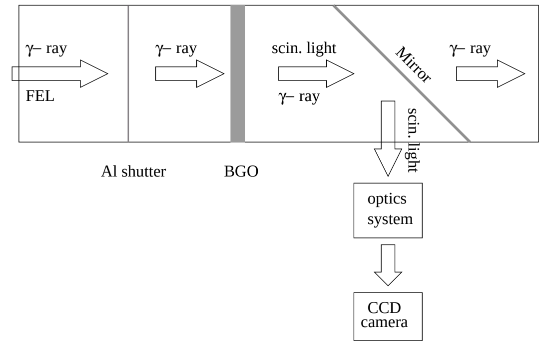

Figure 5: Conceptual design of the gamma-ray imaging system.

CONCLUSION

Using Compton scattering to measure electron beam polarization has been studied at HIGS. Owing to the high intensity of this beam, the study shows that the transverse polarization of the electron beam is measurable at HIGS.

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REFERENCES

[1] A.G. Grozin, "Complete analysis of polarization effects in $e\gamma \to e\gamma$ with REDUCE," Proc. VIII Int. Workshop on HEP and QFT, 1994, p.60.

[2] C.Sun, "Characterization of Compton gamma-ray beam for electron beam polarization research," Preliminary report of physics department, Duke University, Feb. 2007.

[3] K.Yokoya, "User's Manual of CAIN, Version 2.35," Apr.30, 2003, http://lcdev.kek.jp/ yokoya/CAIN/cain235/.

[4] D. P. Barber *et al.*,"The HERA polarimeter and the first observation of electron spin polarization at HERA," Nucl. Instrum. Meth. A **329** (1993) 79.

[5] G. Alexander *et al*, "Measurements of Polarization in LEP". In "Polarization at LEP", G. Alexander et al, eds., CERN Yellow report **88-06** (1988) Vol.II,3.

[6] N. Falletto *et al.* [HAPPEX Collaboration], "Compton scattering off polarized electrons with a high finesse Fabry-Perot cavity at JLab," Nucl. Instrum. Meth. A **459**, 412 (2001).

[7] "Geant4: A toolkit for the simulation of the passage of particles through matter," http://geant4.web.cern.ch/geant4/.

[8] T.Z. Regier, "Development of a gamma-ray beam profile monitor for the high-intensity gamma-ray source", Master's thesis, University of Saskatchewan, Canada, 2003.

