INVESTIGATION OF TECHNIQUES FOR PRECISE COMPTON POLARIMETRY AT ELSA*

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Abstract

A Compton polarimeter is currently being installed at the Electron Stretcher Facility ELSA to monitor the degree of polarization of the stored electron beam. For this purpose, circularly polarized light that is emitted by a laser and backscattered off the beam has to be detected. When the polarization of the laser light is switched from left-hand to right-hand circular polarization, the spatial distribution of the backscattered photons is shifted. The extent of this modification is a measure of the beam's polarization degree. Two different experimental techniques that are suitable for a measurement of the effect were compared and evaluated closer through numerical simulations that will be presented in this contribution.

MOTIVATION

The fast ramping electron stretcher ring at ELSA is able to supply a spin polarized electron beam of up to 3.5 GeV to hadron physics experiments. The degree of polarization can be measured directly after the 50 keV electron source via a Mott polarimeter as well as at the external beamline by a Møller polarimeter. During the acceleration process, depolarizing resonances in the circular accelerators lead to a polarization loss. In order to minimize this loss, correction measures which require information on the polarization of the stored electron beam have to be undertaken. Since both monitoring methods currently in use require scattering targets, neither of them is appropriate for a parasitic measurement of the polarization degree in the stretcher ring during operation. Compton polarimetry, by contrast, offers a fast and accurate possibility to determine polarization with negligible electron loss and without other significant negative impact on the beam. Figure 1 shows the position of all polarimeters in the stretcher ring.

MEASUREMENT TECHNIQUES

The head on collision of circularly polarized laser light of polarization degree P_γ with an unpolarized electron beam leads to an intensity profile of the backscattered photons that can be detected. Figure 2 shows the scattering process for an electron beam in the stretcher ring: Photons with an initial energy of $E_{\gamma,\mathrm{i}} = 2.4$ eV (corresponding to the photon energy of the acquired laser) colliding with an electron beam of $E_{\mathrm{e,i}} = (1 - 3.5)$ GeV will lead to backscattered photons in the energy range of $E_{\gamma,\mathrm{f}} =$

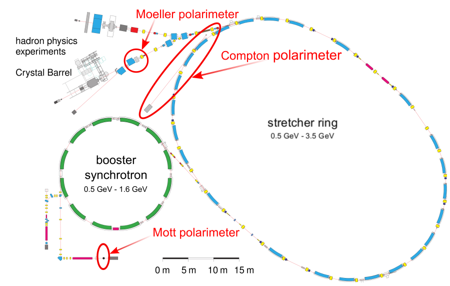

Figure 1: Electron stretcher facility ELSA with the positions of the Mott and Møller polarimeter as well as the proposed Compton polarimeter.

$(5-300)$ MeV, leaving back electrons with a final energy of $E_{\mathrm{e,f}} = E_{\mathrm{e,i}}$. The resulting photon distribution is symmetric around the beam axis. For an electron beam with—as is the case in the ELSA stretcher ring—transversely polarized electrons of polarization degree P_e, however, an asymmetric intensity profile of the backscattered photons is obtained due to polarization dependent Compton scattering. When the light polarization is reversed from left-handed to right-handed, the distribution of the photons is shifted as indicated by the red and blue curve. The extend of the effect depends on P_e and P_γ and can be described by different parameters. In the following, two of these, corresponding to different polarization measurement techniques, are investigated further.

One way to experimentally determine the polarization of the electron beam is to install two detectors in the plane perpendicular to the electron beam, each one measuring either the counting rate in the upper (N_u) or lower (N_d) half space sucessively for left-handed (^{l}) and right-handed (^{r}) laser polarization. These counting rates can also be calculated by

$$N_{u(d)} \propto \int_{0(\pi)}^{\pi(2\pi)} d\phi \int_0^\pi d\theta [\sin\theta \frac{d\sigma}{d\Omega}(P_\mathrm{e}, P_\gamma)], \quad (1)$$

where $\frac{d\sigma}{d\Omega}$ is the differential cross section of the Compton process. The resulting so called *integral up-down counting asymmetry*

$$A := \frac{\sqrt{N_u^r N_d^l} - \sqrt{N_u^l N_d^r}}{\sqrt{N_u^r N_d^l} + \sqrt{N_u^l N_d^r}} \quad (2)$$

is proportional to the product of the electron's and laser's beam polarization $P_\mathrm{e} P_\gamma$:

$$A = A_{100\%} \cdot P_\mathrm{e} P_\gamma, \quad (3)$$

* Work supported by the DFG SFB/TR16

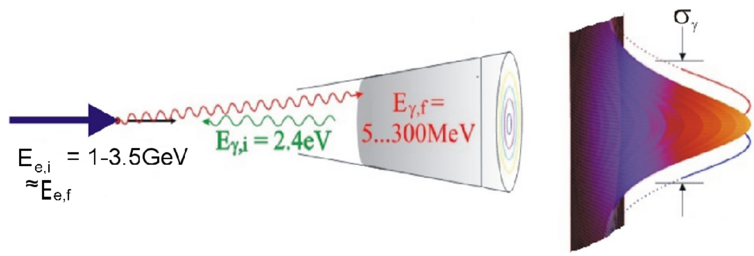

Figure 2: Compton scattering process. On the right, the distribution of backscattered photons for unpolarized light as well as circularly left-handed (blue curve) and right-handed (red curve) is shown.

where the constant of proprotionality $A_{100\%}$ is called *analyzing power* and corresponds to the maximum A that is achieved for $P_\mathrm{e}P_\gamma = 1$. Under the premise that P_γ is monitored, the measurement of A would therefore offer an experimentally easy to implement technique for the determination of P_e. A value for $A_{100\%}$ can be obtained through a calibration utilizing the *SokolovTernov effect*.

The measurement of the vertical shift of the center of the photon's spatial distribution

$$\Delta\bar{z} = \bar{z}^r - \bar{z}^l = \frac{\int dx \int dz\{z[N^r(x,z) - N^l(x,z)]\}}{\int dx \int dz[N^r(x,z) - N^l(x,z)]} \quad (4)$$

provides another tool to determine the beam's polarization. Here, $N(x, z)$ signifies the number of incident photons at the coordinates (x, z) of the detector, and the integration covers the whole sensor area. As was the case for A, also $\Delta\bar{z}$ is proprotional to the product $P_\mathrm{e}P_\gamma$:

$$\Delta\bar{z} = D_{100\%} \cdot P_\mathrm{e}P_\gamma, \quad (5)$$

in analogy to Eq 3. The analyzing power $D_{100\%}$ that follows from Eq 5—as opposed to $A_{100\%}$ arising out of Eq 3—can be improved by increasing the distance of the detector from the beams' interaction zone.

When both measurement techniques are compared regarding their ease of experimental implementation, the first method offers clear advantages since only two simple crystal detectors would be needed. In contrast, for the measurement of the center shift, a detector with an especially high vertical resolution is necessary. Since numerical calculations yield to small values of $D_{100\%} \approx 70$ μm, more elaborate detection techniques have to be employed. For ELSA, Si-strip detectors were escecially considered, making a conversion target necessary to enable the detection of photons in the expected energy range. This contribution will discuss the reasons why, despite the obvious advantages, the polarization measurement through the integral counting asymmetry was discarded.

COMPTON POLARIMETRY AT ELSA

For a reasonable polarization measurement error, maximizing $D_{100\%}$ or $A_{100\%}$ is a main concern. Also, since either method will need calibration, an analyzing power that is mostly independent of the properties of the electron beam would be preferable. The shift of the intensity profile of the backscattered photons increases with the distance of the detector from the interaction zone. Furthermore, for the detection of Compton backscattering in ELSA's stretcher ring, background radiation originating from collisions of electrons on residual gas atoms has to be taken into account. This radiation exhibits energy levels comparable to the energy of the photons to be detected. Therefore, for a high signal to noise ratio, a high laser power is of critical importance. Also, large photon energies lead to larger analyzing powers and a small beam interaction area is favorable.

Hence, for Compton polarimetry at ELSA, the TEM_{00} mode (corresponding to a low beam divergence) of a high power 40 W disc laser, emitting light at a wavelength of 515 nm ($E_\gamma = 2.4$ eV) is used. Circular polarization is obtained by means of a quarter-wave plate. The laser beam will collide almost frontally with the electron beam, forming only a small vertical angle of $\alpha = 3$ mrad in order to protect the optics from synchrotron radiation. The intensity profile of the backscattered photons is measured at the maximum realizable distance of 15 m from the interaction zone, which is set up at a position with a low vertical electron beam width of $\sigma_z \approx 1$ mm. The interaction region has a length of $l \approx 0.7$ m and is positioned in a quadrupole. According to Eq. 3 and Eq. 5, it is also necessary to measure P_γ, which will be done during the whole measurement process.

Numerical Simulation of the Compton Process

Extensive numerical simulations have been carried out with the ELSA parameters described above to study the Compton process in more detail. These simulations provide quantitative results for the distribution of the backscattered photons and the analyzing powers $A_{100\%}$ and $D_{100\%}$ in dependence of the parameters selected. In a first step, only ideal laser and electron beams with $\sigma_x = \sigma_z = 0$ were considered.

The differential Compton cross section described in [2] for $P_\mathrm{e} = 1$ and $P_\gamma = \pm 1$ is given by

$$\frac{d\sigma}{d\Omega}(1, \pm 1) = \Sigma_0 \pm \Sigma_{2Z} \cdot \sin\phi^*, \quad (6)$$

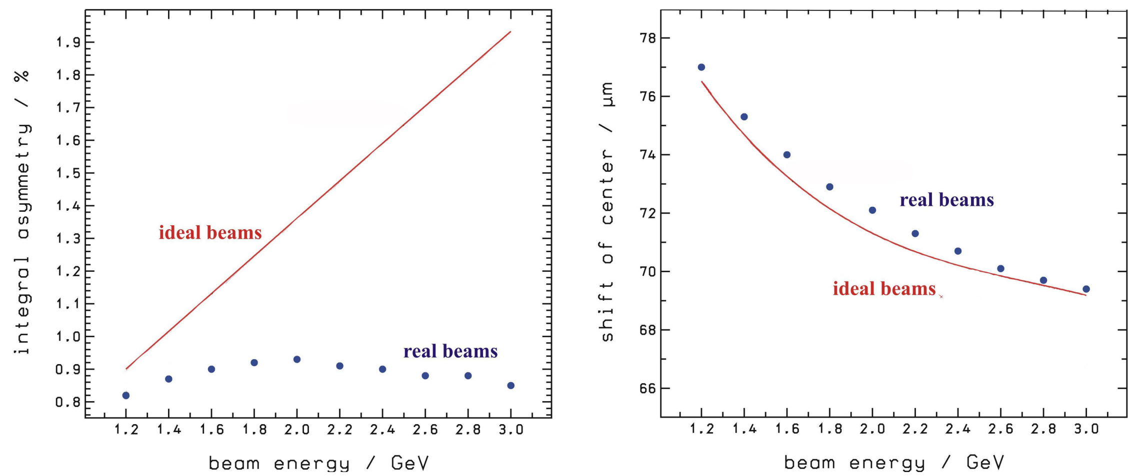

Figure 3: Simulation results for the integral asymmetry and the shift of the center of the photon's spatial distribution in dependence of ELSA's beam energy.

with Σ_0 and Σ_{2Z} being functions of the polar angle θ^* as well as the initial and final wave numbers K_i^* and K_f^* of the photons. $\sin\phi^*$ represents the azimuthal modulation of the photon's scattering angle that is the cause for the asymmetry in the intensity profile. All parameters indicated with * have to be considered in the rest frame of the electrons. The mathematical expressions for the differential cross section yield to analyzing powers of

$$A_{100\%} = \frac{\int_0^{2\pi} d\phi^* \int_0^{\pi} \sin\theta^* d\theta^* \Sigma_{2Z}}{\int_0^{2\pi} d\phi^* \int_0^{\pi} \sin\theta^* d\theta^* \Sigma_0} \tag{7}$$

and

$$D_{100\%} = \frac{\int_0^{2\pi} d\phi^* \int_0^{\pi} \sin\theta^* d\theta^* \frac{\partial(x,z)}{\partial(\theta^*,\phi^*)} z(\theta^*,\phi^*)\Sigma_{2Z}}{\int_0^{2\pi} d\phi^* \int_0^{\pi} \sin\theta^* d\theta^* \{\frac{\partial(x,z)}{\partial(\theta^*,\phi^*)}\Sigma_0\}} \tag{8}$$

respectively. When proceeding to the more complex case of finite detector areas as well as beams with realistic, nonzero widths and dispersions, the simulation software divides the detector area into small area sections. The rate of detected photons for each detector point is then extracted from a fivefold integration of the Compton scattering probability over the whole phase space of the electron beam and the length of the interaction zone [1].

The calculation for both detection techniques was carried out for a detector size of $4.0 \times 3.84\ cm^2$. The simulation of $\Delta\bar{z}$ was based on a strip detector with a pitch of $100\ \mu m$. Also a Pb-conversion target for e^+/e^- pair conversion of 1.7 decay lengths was assumed. The asymmetry and the shift of the center of the photon's spatial distribution resulting from the simulation are shown in Fig 3. In the case of the integral asymmetry, the mismatch between the idealized and the more realistic simulation increases with higher energies. This increase can be attributed to the energy dependence of the electron beam's divergence and emittance.

In contrast, the analyzing powers $D_{100\%}$ for idealized and more realistic beams nearly show the same response to an energy increase. Therefore, the electron polarization that is proportional to $\Delta\bar{z}$ is almost independent of the emittance and divergence of the electron beam in the interaction zone. Neither the emittance nor the divergence of the beam are parameters that are known with high accuracy. Therefore, when aiming at a precise determination of the electron beam's transversal polarization degree, $\Delta\bar{z}$ is a more appropriate experimental parameter than the integral counting asymmetry.

SUMMARY AND OUTLOOK

Two techniques for a precise determination of the electron beam's polarization degree through Compton polarimetry were investigated in this contribution. Since the measurement of the vertical shift of the center of the photon's spatial distribution proved to be a superior technique compared to the measurement of A, the focus at ELSA was the in-house development and acquisition of suitable polarimeter components featuring a reliable measurement technique for $\Delta\bar{z}$. By now, most of the optics has been set up at the intended position. A counting silicone microstrip detector has been developed in cooperation with the SiLab/ATLAS group of the Physics Institute of the University of Bonn. With the hardware installed, we are confident to be able to determine electron polarization with a reasonably high accuracy and short measurement times.

REFERENCES

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ISBN 978-3-95450-115-1