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BEAM POLARIZATION MEASUREMENTS WITH THE REVISED COMPTON POLARIMETER AT ELSA

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Abstract

The Compton Polarimeter at the ELSA 3.2 GeV storage ring has been designed to measure the polarization degree of the stored electron beam by analyzing the profile of the backscattered gamma-beam with a silicon microstrip detector. Utilizing a scattering asymmetry from interaction with circularly polarized laser light, the electron beam polarization is determined from the vertical shift of the gamma-beam's center of gravity in respect to the handedness of the laser light. The installation of a new laser source and silicon strip detector has improved the polarimeter's performance significantly. Additionally, the profile analysis could be enhanced by using a Pearson type peak function fit. The analyzing power was determined through the observation of the Sokolov-Ternov effect and a statistical measurement accuracy of 2% could be obtained within 5 minutes of measurement time. The polarimeter resolves the expected spin dynamical effects occurring in the storage ring and has shown to be a robust and reliable measurement system for operation with the GaAs source for polarized electrons.

INTRODUCTION

Electron beam polarimetry based on the Compton effect has been successfully performed at multiple laboratories operating with spin-polarized beams. However, the approach to determine the beam polarization from a profile analysis of the backscattered photons is to our knowledge unique at ELSA [1]. The backscattered beam profile has a polarization-dependent vertical asymmetry which results in a shift of the profile's center of gravity $\bar{z}$ under photon beam helicity change (left to right-handed or vice-versa):

$$\Delta z = \bar{z}_L - \bar{z}_R = \mathscr{D} \cdot \mathscr{P}_e \cdot S_3 \,, \tag{1}$$

where $\mathscr{D}$ is the analyzing power of the polarimeter, S_3 the degree of circular photon polarization and $\mathscr{P}_e$ the electron polarization degree parallel or anti-parallel to the magnetic bending field. Simulations for ELSA [2] show that $\mathscr{D} \gtrsim 70\,\mu\text{m}$ for a detector 15 m away from the photon-electron interaction point. Hence, we use a silicon microstrip detector with sufficient vertical resolution to measure the backscattered beam profile to obtain the polarization degree of the electron beam.

THE COMPTON POLARIMETER

Optical System and γ-Beam Detector

Circularly polarized laser photons of 532 nm wavelength are focused onto the center of a defocusing quadrupole magnet (compare with Fig. 1), where the transverse electron beam profile has minimum ellipticity $\sigma_z/\sigma_x = 0.69$ to 0.44 between 1.2 GeV to 3.2 GeV.

With an **optical system** [3] the beam waist can be varied from $\omega_0 = 0.66$ mm to 1.6 mm to match the transverse size of the electron beam. As photon source a cw laser with 18 W beam power is used, of which approx. 14 W were measured to be available at the interaction point. The helicity of the photon polarization can be changed through pneumatically driven rotatable $\lambda/4$ waveplates. The degree of circular polarization is measured before the beam dump.

The **detector** [4] for the backscattered photons with up to 328 MeV energy consists of a lead converter target in front of an in-house developed silicon microtrip detector. With 768 vertically distributed 13-bit channels at 50 µm pitch it yields a resolution of $\Delta z_b = 14\,\mu\text{m}$.

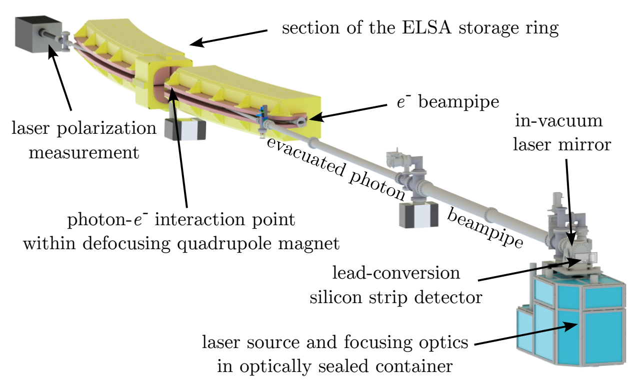

Figure 1: Compton polarimeter at ELSA: A cw laser beam of circularly polarized photons is focused onto the center of a quadrupole magnet. The backscattered γ-photons from head-on collisions with stored electrons are detected by a microstrip detector with vertical resolution.

Backscattered Beam Profile and Function Fit

An exemplary measured vertical photon profile which backscattered off a 1.3 GeV electron beam is shown in Fig. 2. While the measurands $\bar{z}_L$ and $\bar{z}_R$ can be obtained by determining the distribution's mean ("center of gravity"), this approach was found to be prone to the influence of stray radiation and statistical count fluctuation [3]. A more robust method includes a data fit to a conformable function, such as the Pearson type IV distribution:

$$P_{IV}(x) = h \cdot \left[1 + \left(\frac{x - x_0}{s}\right)^2\right]^{-l} \cdot \exp\left[-\nu \cdot \arctan\left(\frac{x - x_0}{s}\right)\right] . \tag{2}$$

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For $\nu = 0$ the distribution holds no skewness and it is called Pearson type VII. As indicated by the residuals

$$e(x) = y(x) - f(x)$$

between model $y(x)$ and fit to model data $f(x)$ in Fig. 2 (bottom), the skewness is non-zero and should be accounted for in the model. However, in practice the number of free parameters in Eq. (2) or in a spline fit reduces the robustness of the method and it has shown that a fit to the Pearson type VII distribution determines the measurand most reliably [3].

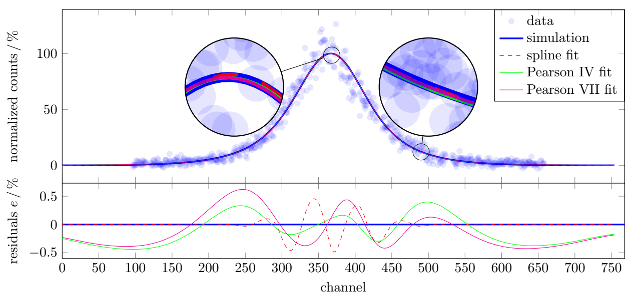

Figure 2: Measurement data compared to simulation data, on which different fit algorithms are applied. Their goodness is here indicated by the magnitude of the residuals.

A measurement with source-polarized 1.32 GeV electrons is shown in Fig. 3. Therein, electrons with alternating helicity are injected into the storage ring for a typical spill cycle interval of approx. 6 s. The photon distribution is analyzed accumulatively and the measurand visualized for the different electron spin helicities ($\Delta z_{e\uparrow}$ and $\Delta z_{e\downarrow}$) as well as the mean of their absolute values

$$\Delta z_{e\downarrow\uparrow} = \left(|\Delta z_{e\uparrow}| + |\Delta z_{e\downarrow}|\right)/2 \,.$$

While $\Delta z_{e\downarrow\uparrow}$ engages the vicinity of its final value within a minute of measuring time, it remains within the decreasing statistical error boundaries, especially when the Pearson VII fit function is chosen. This behavior was observed for the majority of measurements perforemed in the scope of [3], allowing the Compton polarimeter to be used for "quick measurements", when spin-related machine parameters are to be optimized or *scanned*.

Polarimeter Calibration

The analyzing power of Eq. (1) is measurable via the Sokolov-Ternov effect [5] (self-polarization) occurring for stored electron beams:

$$\mathcal{P}_e(t) = \mathcal{P}_\infty\left(1 - e^{-t/\tau}\right) \quad \equiv \quad \Delta z(t) = \Delta z_\infty\left(1 - e^{-t/\tau}\right) \,.$$

A data fit to the exponential increase of beam polarization $\mathcal{P}_e(t)$ determines the time constant τ and equilibrium polarization $\mathcal{P}_\infty$. It is noteworthy that $\mathcal{P}_\infty$ is beam-energy dependent, as depolarizing mechanisms occur at different magnitudes for different spin-tunes (compare e.g. with [3,6]). Calibration measurements are to be carried out where $\mathcal{P}_\infty$ is

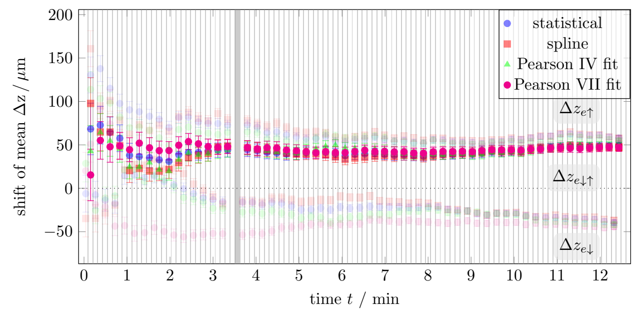

Figure 3: Measurement of the shift in the means Δz of alternatingly polarized 1.32 GeV electrons with different profile analysis methods. The gray background indicates inhibited time intervals which occur during storage ring injection or due to erroneous machine spills.

expected to be ≈ 92.38% and where τ is in the order of minutes (e.g. > 2.2 GeV). The polarimeter's effective analyzing power

$$\mathcal{D} = \frac{\Delta z_\infty}{\mathcal{P}_\infty \cdot \mathcal{P}_\gamma}$$

also includes the finite degree of circular photon polarization $S_3 = \mathcal{P}_\gamma = (98.03 \pm 0.02)\,\%$ and was determined to amount

$$\mathcal{D}_{\text{eff}} = \mathcal{D} \cdot \mathcal{P}_\gamma = (60.0 \pm 8.8)\ \mu\text{m}/100\% \qquad (3)$$

for a calibration measurement at 2.73 GeV, as shown in Fig. 4. The rather large measurement error is to be reduced in the future by further measurements and therewith systematic studies of the energy-dependency of depolarizing effects.

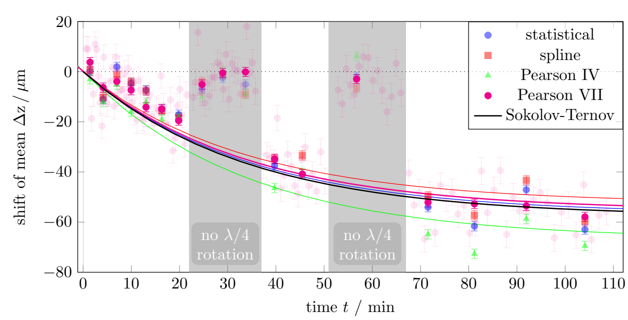

Figure 4: Self-polarization of a stored electron beam (Sokolov-Ternov effect), where the backscattering profile is analyzed through different methods. The solid dots represent time-averaged data of the individual opaque measurement nodes. The polarimeter functionality was verified with halted $\lambda/4$ waveplate rotation (gray background) which resulted in a sufficiently precise null-measurement.

Measurement Error

The polarimeter measurement error is given by

$$\Delta\mathcal{P}_e = \sqrt{\underbrace{\left(\frac{1}{\mathcal{D}_{\text{eff}}}\Delta(\Delta z)\right)^2}_{\text{statistical}} + \underbrace{\left(\frac{\Delta z}{\mathcal{D}_{\text{eff}}^2}\Delta\mathcal{D}_{\text{eff}}\right)^2}_{\text{systematic}} + \ldots} \,, \qquad (4)$$

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where the systematic error is assumed to be dominated from the calibration procedure (compare with Eq. (3)). The statistical error is depending on the total signal count N, the distribution's standard deviation σ, the strip resolution Δz_b and the distribution's shape, given by the individual detector counts n_i:

$$\Delta\bar{z} = \sqrt{\frac{\sigma^2}{N} + \Delta z_b^2 \cdot \frac{\sum_i n_i^2}{N^2}} \,.$$

The obtainable detector count rate depends on the stored beam current, the available laser power, and on how well the laser beamline is adjusted. Typically it amounts approx. 250 Hz/(W · mA). Therewith, a statistical accuracy of 2% could be achieved within 5 minutes and 1.4% within 15 minutes of measuring time. The scattering rate scales somewhat with beam energy, as shown in Fig. 5.

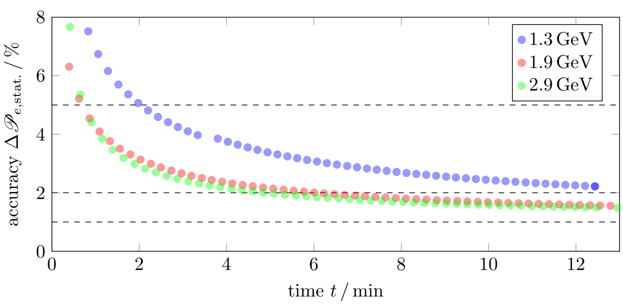

Figure 5: Statistical error in dependence of measuring time for different electron beam energies.

POLARIZATION MEASUREMENTS

The polarimeter performance is well demonstrated by observing the beam polarization degree in dependence of spin-rotating effects. For example, a solenoid field was applied in the transfer beamline between 50 kV polarizing GaAs source [1] and linear accelerator, acting as spin rotator, where complete loss of beam polarization is expected at ±90° (spin precession axis perpendicular to bending field). As shown in Fig. 6, the measureand Δz and its statistical error agrees well with the expected dependancy on the spin rotation angle.

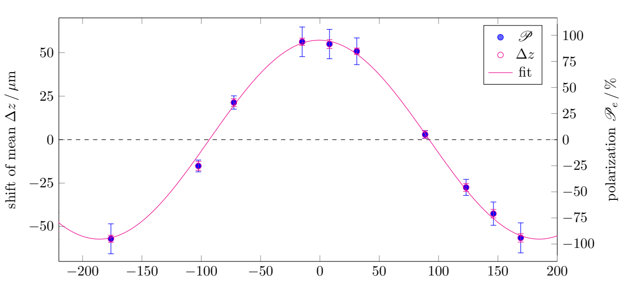

Figure 6: Measured beam polarization in the storage ring (uncalibrated and calibrated) as function of spin rotation angle by application of an additional solenoid field in the transfer beamline behind the polarizing source.

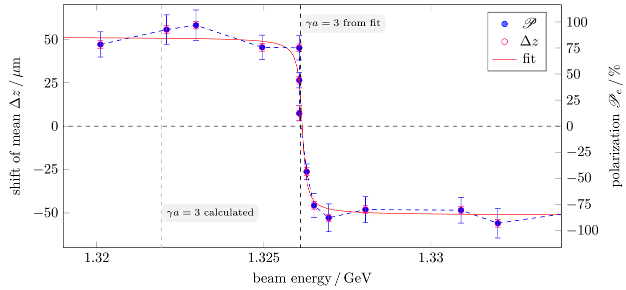

Figure 7: Measured spin-flip around a depolarizing imperfection resonance $\gamma a = 3$. The difference between measured and calculated resonance energy indicates a slight deviance of set and actual electron beam energy.

Polarization measurements were performed in the vicinity of the $\gamma a = 3$ imperfection resonance (a being the anomalous magnetic dipole moment), as shown in Fig. 7. Therein, a spin flip is observable after crossing the resonance, whose impact was artificially increased by applying slight orbit misalignments. The difference between calculated and observed resonance energy suggests a minor deviance of the storage ring's beam energy calibration.

CONCLUSION

We successfully demonstrated the operation of the Compton polarimeter at ELSA. The achievable statistical precision shows that reliable polarization measurements of stored electrons can be performed and spin-dynamical effects are well observable within minutes. The systematic error due to calibration of the analyzing power is expected to be improved with further self-polarization measurements.

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