

SIMULATION STUDIES FOR FCC-EE COMPTON POLARIMETERS

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Abstract

This work focuses on the energy calibration of the FCC-ee and aims to develop precise techniques for ensuring accurate beam energy measurements, essential for improving the precision of electroweak parameter determinations. To do so, resonant depolarisation technique will be employed, requiring the continuous operation of a depolariser and Compton polarimeters for both electrons and positrons beam. Extraction of pilot bunches polarization is realized from the spatial distribution of scattered electrons and photons. The work explores the determination of Compton-scattering parameters. Preliminary conceptual studies of the fitting procedure required for this extraction are presented here. In addition, studies on the fast extraction of bunch polarisation parameters for each turn in the ring are included, aiming to enable faster, turn-by-turn monitoring of the beam polarisation.

INTRODUCTION

The Future Circular Collider (FCC-ee) is a high-luminosity e^+e^- collider designed for precision electroweak measurements. To achieve its physics goals, it utilizes the Resonant Depolarization (RDP) technique, which has been established as the gold standard for energy calibration at circular machines such as LEP, VEPP-4M, and KEDR [1].

The RDP technique exploits the linear relationship between the spin precession frequency and the beam energy. The spin tune ν_s , representing the number of spin precessions per revolution, is defined by:

$$\nu_s = a\gamma = a \frac{E}{m_e c^2}, \quad (1)$$

where a is the anomalous magnetic moment of the electron. By exciting the beam using a kicker, a resonance is induced when the frequency of the orbital motion matches ν_s . This leads to a coherent accumulation of spin tilts and a measurable destruction of the beam polarization. Identifying the exact frequency of this depolarization provides a high-precision measurement of the average beam energy.

Inverse Compton scattering is the primary method for measuring beam polarization in lepton machines, as demonstrated at LEP [2] and HERA [3]. Building upon the analytical work by Muchnoi [4], this study introduces advancements in the modeling of Compton polarimetry for FCC-ee. We incorporate a comprehensive description of the interaction region, including the beam crossing angle and the physical integration of the electron detector. Three methods for polarization extraction are evaluated: a multi-parameter fit of 2D distributions, spatial asymmetries, and a fast tracking algorithm.

METHODS

Figure 1 illustrates the Compton polarimeter layout. In the interaction region, the laser beam collides with the electron beam at a crossing angle $\theta_{in} = 13.9626$ mrad. Following the interaction, scattered photons propagate forward along the incoming electron beam axis over a distance $L_1 = 117.12$ m to the detection plane. Similarly, electrons are deflected by a dipole magnet with a bending angle $\theta_0 = 2.1$ mrad and travel a distance $L_2 = 100.6$ m toward the electron detector. The coordinate system aligns the z -axis with the electron beam, while the y -axis is perpendicular to the machine plane.

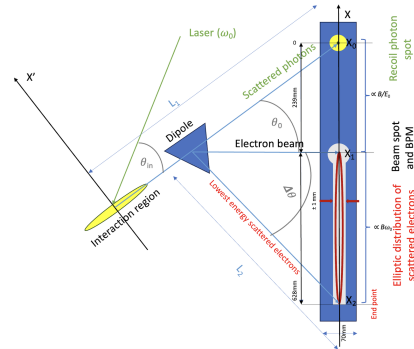


Figure 1: Compton polarimeter initial layout.

The differential cross section for electron distribution depends on all the terms of the polarization parameters and is given in terms of unit circle coordinates x and y [4]:

$$\frac{1}{r_e^2} \frac{d\sigma_0}{dx dy} = \frac{1 + (1+u)^2 - (1+u)(1-\Delta^2)}{(1+u)^3 \sqrt{1-x^2-y^2}}, \quad (2a)$$

$$\frac{1}{r_e^2} \frac{d\sigma_{\xi_1}}{dx dy} = \frac{-y^2 + A^2 x^2}{(1+u)^2 \sqrt{1-x^2-y^2}}, \quad (2b)$$

$$\frac{1}{r_e^2} \frac{d\sigma_{\xi_2}}{dx dy} = \frac{2Ayx}{(1+u)^2 \sqrt{1-x^2-y^2}}, \quad (2c)$$

$$\frac{1}{r_e^2} \frac{d\sigma_{\xi_3 \xi_x}}{dx dy} = \frac{Axu}{(1+u)^3 \sqrt{1-x^2-y^2}}, \quad (2d)$$

$$\frac{1}{r_e^2} \frac{d\sigma_{\xi_3 \xi_y}}{dx dy} = \frac{yu}{(1+u)^3 \sqrt{1-x^2-y^2}}, \quad (2e)$$

$$\frac{1}{r_e^2} \frac{d\sigma_{\xi_3 \xi_z}}{dx dy} = -\frac{u(2+u)\Delta}{(1+u)^3 \sqrt{1-x^2-y^2}}. \quad (2f)$$

The parameters A and B originate from the transformation of the coordinates to the unit circle. They are defined by the following expressions:

$$A = \frac{1}{\sqrt{1+\gamma^2\theta_0^2}} \quad \text{and} \quad B = \frac{\gamma\theta_0}{\sqrt{1+\gamma^2\theta_0^2}}, \quad (3)$$

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where γ is the electron Lorentz factor. The parameter $\theta_0 = \frac{\int B_{\perp} dl}{m_e c / e}$ represents the characteristic bending angle, corresponding to the maximum deflection of the electron trajectory induced by the dipole magnetic field $B_{\perp}$, m_e is the electron mass, and e is the elementary charge. The parameter u is defined as the ratio between the scattered photon energy $\hbar\omega$ and the scattered electron energy ϵ .

Under the high-energy approximation, second-order terms are neglected and omitted from the mathematical model and Monte-Carlo simulations. The suppression of terms (2c) and (2e) renders ξ_2 and ξ_x unmeasurable. Physically, the horizontal electron distribution in the recoil detector is dominated by energy rather than polarization. Consequently, these parameters remain fixed during the fitting procedure.

Fit of Particle Distribution

The fitted parameters for the electron distribution and the corresponding residuals are displayed in Fig. 2. Seven parameters for the electron are fitted, namely the ellipse edges in the horizontal and vertical directions X_1 , X_2 , Y_1 , Y_2 , and the polarization components: the linear terms ξ_1 and the coupled terms $\xi_3\xi_y$, $\xi_3\xi_z$.

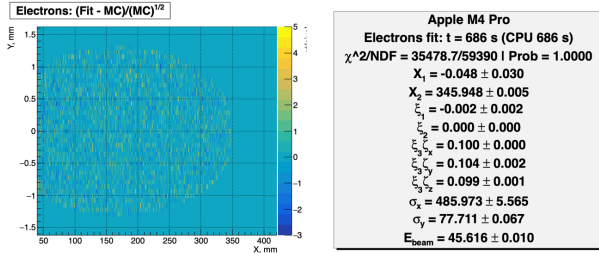


Figure 2: Electron distribution fitted parameters for Monte-Carlo simulation and fitted residuals.

We perform a dedicated analysis involving a large number of Toy Monte Carlo experiments, and the result for the extracted electron polarization is shown in Fig. 3.

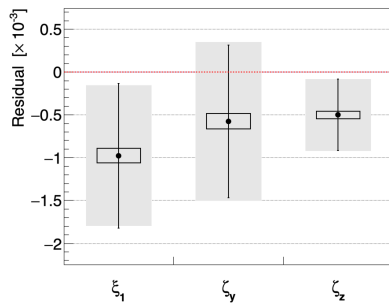


Figure 3: Residuals of the fit for the electron distribution. The data points indicate the mean residual, accompanied by vertical error bars representing the dispersion (standard deviation, σ) across the pseudo-experiments. The solid gray boxes define the mean uncertainty evaluated by the fit procedure. The transparent boxes with black outlines delineate the statistical error on the mean ($\sigma/\sqrt{N_{\text{runs}}}$). The figure shows residuals for polarization.

In addition, this method allows extracting the beam energy from the electron distribution geometry:

$$E_0 = \frac{mc^2}{2\hbar \cos \theta_{\text{in}}} \frac{X_2 - X_1}{X_1 - X_0} \left(1 - \frac{2 + \frac{X_2 - X_1}{X_1 - X_0}}{(2\gamma\theta_0)^2} \right). \quad (4)$$

The average beam energy extracted from 100 pseudo-experiments is shown in Fig. 4.

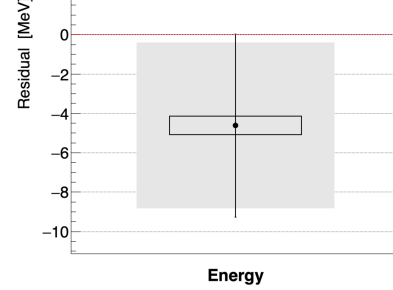


Figure 4: Energy extraction.

An identical analysis is applied to the scattered photons. Unlike for electrons, the photon differential cross-section depends on all polarization terms [4], allowing the extraction of the complete set of polarization parameters. The results and corresponding residuals are presented in Fig. 5.

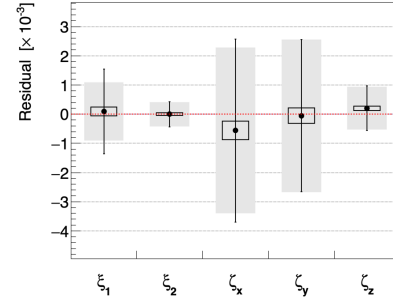


Figure 5: Polarization extraction for scattered photons.

Fit of Particle Asymmetry

The aim of the first toy Monte-Carlo experiment is the extraction of systematic uncertainties in the measurement of the beam energy while performing the simulation with a realistic pixel detector and a crossing angle between the laser and the electron beam.

In fact, the precise measurement of the beam energy relies on exploiting the resonant depolarization effect. These strategies require robustness against systematic uncertainties in transverse polarization extraction, and the asymmetry induced by the laser helicity flip $\xi_3 = \pm$ fulfills this condition. Indeed, by forming the ratio of the difference over the sum of cross-sections for opposite laser helicities, common multiplicative factors such as luminosity fluctuations and detector efficiencies cancel out. The average of the extracted polarization over 100 pseudo-experiments is displayed in Fig. 6.

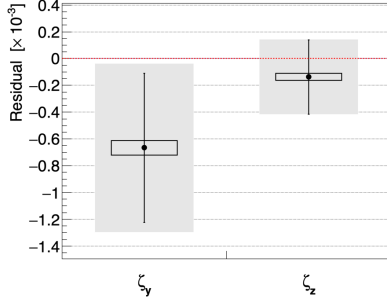


Figure 6: Residuals of the fit for the electron beam polarization.

Fast Tracking

The measurement of turn-by-turn vertical polarization in the accelerator relies on identifying an observable with a linear response to the polarization parameters. The extraction of vertical polarization is performed using the vertical asymmetry of the electron counts in the detector plane as a first-order estimator. This approach utilizes the differential Compton scattering cross-section integrated over the azimuthal angle ϕ in the observation frame, effectively mapping the polarization state to the observed spatial distribution.

With an ideal alignment of the detector, the position where the depolarization occurs is equal to $Y = 0$ and thus we can construct the asymmetry in terms of P_y from the data. The theoretical vertical asymmetry A_{th} at a given vertical position y_a is defined by the ratio of the integrated differential cross-sections:

$$A_{th}(y_a) = \frac{\int_{y_a}^{y_1} \int_{-\sqrt{1-y^2}}^{\sqrt{1-y^2}} \frac{d\sigma_{tot}}{dx dy} dx dy - \int_{y_2}^{y_a} \int_{-\sqrt{1-y^2}}^{\sqrt{1-y^2}} \frac{d\sigma_{tot}}{dx dy} dx dy}{\int_{y_2}^{y_1} \int_{-\sqrt{1-y^2}}^{\sqrt{1-y^2}} \frac{d\sigma_{tot}}{dx dy} dx dy}. \quad (5)$$

Numerically the asymmetry is constructed by counting the scattered flux on either side of the axis $Y = 0$:

$$A(P_y) = \frac{N_B - N_T}{N_B + N_T}, \quad (6)$$

where N_T and N_B represent the number of particles in respectively the top and bottom of the axis $Y = 0$ in the recoil detector.

The extraction of the beam polarization P_y is performed using a first-order polynomial fit:

$$F(P_y) = c_0 + c_1 P_y. \quad (7)$$

Numerical simulations yield an expected statistical uncertainty of 0.52 per turn and a precision of $9.4 \times 10^{-3} \text{ s}^{-1}$. The

systematic bias induced by a single-pixel spatial shift of $18 \mu\text{m}$ is estimated to be $1.1 \times 10^{-2} \mu\text{m}$. Figure 7 shows the variation of the asymmetry obtained from a Monte Carlo simulation with 100 million events, corresponding to 60 seconds of data taking.

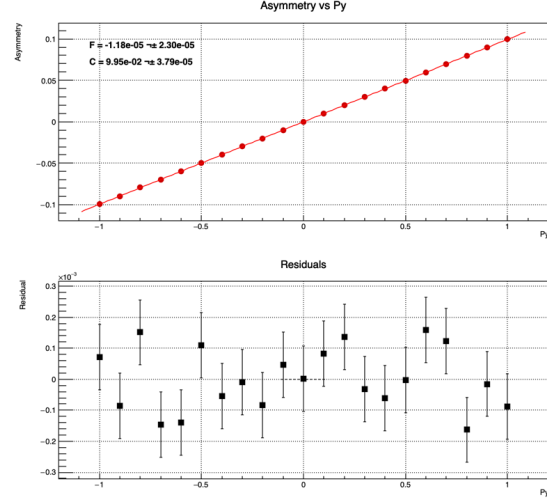


Figure 7: Asymmetry P_y fit with residuals.

CONCLUSION

This study evaluated several vertical electron polarization extraction methods for the FCC-ee. A comparison between real-time, turn-by-turn fast extraction and the more comprehensive distribution and asymmetry fitting was performed. While the fast extraction enables immediate monitoring, the fitting methods — despite requiring multi-minute data accumulation — demonstrate significantly lower statistical and systematic uncertainties.

Future developments will focus on the integration of robust background models and the implementation of high-fidelity realistic detector simulations to further refine the accuracy of these precision measurements.

REFERENCES

- [1] V. V. Anashin *et al.*, “Final analysis of kedr data on j/psi and psi(2s) masses”, *Phys. Lett. B*, vol. 749, pp. 50–56, 2015. [doi:10.1016/j.physletb.2015.07.057](https://doi.org/10.1016/j.physletb.2015.07.057)
- [2] L. Knudsen *et al.*, “First observation of transverse beam polarization in lep”, *Phys. Lett. B*, vol. 270, pp. 97–104, 1991. [doi:10.1016/0370-2693\(91\)91545-7](https://doi.org/10.1016/0370-2693(91)91545-7)
- [3] D. P. Barber *et al.*, “The hera polarimeter”, *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 321, pp. 426–444, 1992. [doi:10.1016/0168-9002\(93\)90924-7](https://doi.org/10.1016/0168-9002(93)90924-7)
- [4] N. Y. Muchnoi, “Compton polarimeter for FCC-ee”, *JINST*, vol. 17, P10014, 2022. [doi:10.48550/arXiv.1803.09595](https://doi.org/10.48550/arXiv.1803.09595)