Swiss Accelerator Research and Technology

CHART Scientific Report

FCC-ee spin tracking and polarization studies

(FCC-ee SPIN-POL)

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1 Introduction / Original goals of this project

The Future Circular Collider (FCC) program aims to open new frontiers in high-energy physics by enabling precision studies of the electroweak and Higgs sectors, top-quark physics, and potential signals of new phenomena beyond the Standard Model [1]. The FCC-ee, an electron–positron collider, is planned as the first stage of this initiative [2], operating at centre-of-mass energies from 88 GeV up to 365 GeV.

A central requirement for the FCC-ee physics program is the extremely precise calibration of the beam energy, particularly around the Z resonance. Current targets specify a statistical uncertainty of 4 keV and a systematic uncertainty below 100 keV [3]. These precision levels are expected to be reached using the resonant depolarization (RDP) technique driven by radio-frequency electromagnetic fields [4]. To perform reliable RDP measurements, the machine must sustain transverse beam polarization levels of at least 5–10 %, in the presence of various machine imperfections.

Achieving this level of control requires a detailed understanding of spin and polarization dynamics under realistic machine conditions. This, in turn, necessitates the development of advanced simulation tools capable of modelling spin motion, lattice imperfections, orbit-correction schemes, and energy measurement procedures.

Against this background, the goals of this project were defined as follows:

- **Achievable polarization predictions:** Develop reliable methods to introduce and correct realistic lattice imperfections in FCC-ee simulations, and estimate equilibrium polarization levels using both analytical first-order calculations and nonlinear spin-tracking tools.
- **Application of spin-matching schemes:** Implement and assess spin-matching techniques—particularly harmonic closed-orbit spin matching (HCOSM)—to mitigate polarization losses induced by machine imperfections and orbit distortions.
- **Resonant depolarization modelling:** Simulate the full RDP process using nonlinear spin tracking, evaluate the achievable energy-measurement precision, and identify optimal experimental configurations.
- **Systematic-error reduction:** Identify the dominant contributors to systematic uncertainty in energy calibration and develop mitigation strategies to reach the 100 keV systematic-precision target.

- **Benchmarking of simulation tools:** Validate and benchmark newly developed simulation frameworks, especially Xsuite, against established tools such as Bmad.
- **Experimental validation:** Contribute to energy-calibration studies at SLS II, providing real-machine validation for the simulation methodologies developed throughout the project.

2 Realisation

This project investigated and developed advanced simulation tools and correction strategies to achieve reliable beam polarization and high-precision energy calibration in the FCC-ee. Using the Bmad simulation framework [5], both linearized spin–orbit modeling and full nonlinear Monte-Carlo spin tracking were employed to estimate the achievable equilibrium polarization at the Z-pole energy (45.6 GeV). Energy-scan studies performed in Bmad's Tao module introduced realistic imperfections such as misalignments in arc and insertion regions, angular deviations, BPM scaling error, BPM resolution etc. to assess their influence on the equilibrium polarization level. In this work, a modified FCC-ee GHC lattice at Z energy has been developed with an enhanced instrumentation scheme, including BPMs and orbit correctors placed next to each quadrupole, together with scalable sextupole knobs. An iterative orbit correction strategy has been introduced to address the adverse effects of sextupole feed down, enabling a controlled restoration of sextupole strengths while maintaining stability. This method proves effective in searching for the closed orbit solution even in the presence of substantial lattice imperfections.

The impact of various machine errors has been systematically evaluated. Misalignments in the interaction region are found to significantly hinder orbit correction convergence, whereas arc misalignments predominantly affect polarization performance. BPM related uncertainties further complicate the correction process, with scaling errors emerging as a key limitation for closed orbit determination, while their effect on polarization remains less systematic. In addition, BPM misalignments introduce a considerable degradation in performance, substantially increasing the failure rate of closed orbit searches and leading to larger residual orbit deviations and broader polarization spread.

Despite these challenges, the study demonstrates a strong robustness of the system. Transverse polarization levels above 20 percent can be reliably achieved across a wide range of error scenarios. These findings support the feasibility of resonant depolarization based energy calibration at FCC-ee, while also highlighting areas where improved correction strategies and alignment can further enhance machine performance.

To further stabilize polarization, harmonic closed-orbit spin-matching (HCOSM) methods were studied. Three possible schemes were evaluated: the HERA formalism, the Rossmanith–Schmidt scheme, and the LEP-inspired method [6, 7, 8, 9]. The first two approaches led to significant improvements, effectively reducing the spin direction tilt and enhancing the equilibrium polarization, while the LEP method was comparatively ineffective and therefore not pursued further. Ongoing work aims to optimize BPM placement and reduce the required number of monitors without degrading correction quality.

The spin tune shift caused by machine imperfections is an important source of potential systematic error in energy calibration using resonant depolarization, as it can lead to a mismatch between the measured and true beam energy. In this study, this effect is estimated by comparing the closed orbit spin tune from simulations with the value expected from the average beam energy, providing a practical way to estimate the magnitude of systematic errors. The results show that the deviations remain well below the current systematic error target. However, the inclusion of additional complexities could readily increase the error beyond the targeted precision. This highlights the importance of further studies on systematic error and improved correction strategies to ensure that the stringent precision requirements of FCC-ee energy calibration can be reliably achieved.

Resonant depolarization (RDP) simulations were conducted using realistic lattice configurations. These investigated the optimal experimental configurations to enhance measurement precision. These examined how kicker strength, kicker placement, sweep rate, and initial polarization affect the precision of spin-tune extraction. Both forward and backward frequency scans were implemented to minimize directional biases. Under ideal-lattice conditions, a spin-tune measurement precision of approximately 5 keV was achieved. The impact of realistic machine imperfections is currently being investigated.

A novel energy-measurement technique using a constant-frequency AC kicker was developed. This scheme drives coherent spin oscillations at a fixed frequency, from which the spin tune can be extracted precisely. Preliminary studies show a promising precision of about 0.44 keV and improved resilience to certain systematic effects compared with classical RDP, making it a strong candidate for FCC-ee energy calibration.

These simulation studies were expanded to the SLS II storage ring, which serves as a practical test bed for experimental validation of both the standard RDP method and the new constant-frequency kicker technique. These preparatory simulations support upcoming real-machine experiments and contribute to developing a robust, experimentally validated energy-calibration framework.

The impact of solenoid fields, particularly from detector solenoids, and their compensation was investigated using models transferred from SAD to Bmad. A dedicated workflow was developed to address solenoid-modelling limitations. The simulations demonstrated that non-local compensation with anti-solenoids effectively reduces solenoid-induced spin tilt, allowing high equilibrium polarization levels (~86%) to be recovered in nonlinear tracking. Ongoing work focuses on resolving discrepancies between SAD- and Bmad-based predictions.

3 Results / Conclusions / Deliverables

The work conducted within this project has led to significant advances toward achieving reliable beam polarization and high-precision energy calibration for the FCC-ee. The main outcomes are summarized below.

3.1 Polarization preservation under realistic conditions

Comprehensive simulation studies demonstrate that polarization levels suitable for resonant depolarization can be reached even in the presence of realistic lattice imperfections, provided that advanced orbit-correction procedures are applied. Harmonic closed-orbit spin-matching (HCOSM) techniques further enhance polarization preservation, with the HERA and Rossmanith–Schmidt schemes showing particularly strong effectiveness.

3.2 Energy-calibration performance

Nonlinear resonant depolarization simulations indicate an achievable energy measurement precision of approximately **≈ 5 keV (ideal lattice)** This meets, and exceeds, the systematic precision target for FCC-ee energy calibration. Additional work is needed to fully assess the impact of systematic effects under realistic machine conditions.

3.3 Development of alternative measurement techniques

A novel energy-measurement method based on constant-frequency spin excitation has been developed and benchmarked in simulations. This approach has the potential of sub-KeV precision highlighting its strong potential for improved robustness, reduced susceptibility to certain systematic uncertainties, and enhanced overall accuracy compared with conventional RDP techniques.

3.4 Tool development and validation

Significant progress has been achieved in developing and validating tools and workflows essential for polarization and energy-calibration studies, including:
• Advanced spin-tracking simulation frameworks
• Robust workflows for transferring lattice models between SAD and Bmad
• Implementation of sophisticated orbit-correction procedures
• Preparatory work for benchmarking results against the Xsuite framework
• Development of new spin-tracking tools on the CERN side as part of the project, further expanding the capabilities and reliability of the simulation ecosystem
These developments greatly improve the reliability, interoperability, and flexibility of the available simulation tools.

3.5 Experimental readiness

Simulation studies performed for the SLS II storage ring provide crucial preparation for upcoming experimental measurements and allow validation of modelling techniques against real-machine conditions. In parallel, exploratory studies have been conducted for potential testing at the ELSA ring in Bonn, where more favourable machine parameters could offer an ideal environment for evaluating the new constant-frequency energy-measurement method.

4 Publications and Outreach

Publications and Presentations

- 2nd FCC Energy Calibration, Polarization and Mono-chromatisation (EPOL) workshop, CERN, 22 Sep 2022, Spin Polarization Simulations for the Future Circular Collider e+e- using BMAD
- FCC-FS EPOL group and FCCIS WP2.5 meeting 16, CERN, 15 Dec 2022, First trials of harmonic spin matching in the FCC-ee
- Workshop on Beam Polarization, Hiroshima University, 9 Feb 2023, Spin Polarization Simulations for the Future Circular Collider e+e- using BMAD
- FCC-FS EPOL group and FCCIS WP2.5 meeting 18 - Joint with FCC-ee tuning meeting, CERN, 16 Feb 2023, Updates on the Exploration of Harmonic Spin Matching in the FCC-ee
- FCC-FS EPOL group and FCCIS WP2.5 meeting 21, CERN, 13 Apr 2023, Updates on the Exploration of the Possible Spin Matching Methods used in the FCC-ee
- Y. Wu et al., "Spin-polarization simulations for the Future Circular Collider e+e- using Bmad", in Proc. IPAC'23, Venice, Italy, May 2023, SUPM010, MOPL055, 2023.
- FCC Week 2023, London, 5–9 Jun 2023, Comparison of Harmonic Spin Matching Schemes using Orbit Bumps in the FCC-ee
- Optics Tuning and Corrections for Future colliders workshop, CERN, 26–28 Jun 2023, Comparison of Harmonic Spin Matching Schemes using Orbit Bumps in the FCC-ee
- FCC-ee optics tuning WG, CERN, 14 Sep 2023, Orbit correction for polarization studies

- FCC-ee optics tuning WG, CERN, 8 Dec 2023, Updates on orbit correction for polarization
- 7th FCC Physics Workshop, Annecy, 29 Jan 2024, Orbit Correction for Polarization Studies
- FCC-ee optics tuning WG, CERN, 29 Feb 2024, Updates on orbit correction for polarization
- FCC-FS EPOL group and FCCIS WP2.5 meeting 27, CERN, 21 Mar 2024, Updates on Polarization Related Studies
- Y. Wu, L. van Riesen-Haupt, T. Pieloni, M. Seidel, "Lattice Correction and Polarization Estimation for the Future Circular Collider e+e-", presented at the IPAC'25, Taipei, Taiwan, June 2025, paper MOPM003.
- J. Keintzel, etc., "FCC-ee Energy Calibration and Polarization – Status and Outlook", presented at the IPAC'25, Taipei, Taiwan, June 2025, paper MOPM007.
- R. Tomas, etc., "Optics Tuning of the FCC-ee", presented at the IPAC'25, Taipei, Taiwan, June 2025, paper MOPM009.
- Y. Wu, F. Carlier, L. van Riesen-Haupt, M. Hofer, M. Seidel, T. Pieloni, W. Herr, "Lattice correction and polarization estimation for the Future Circular Collider e+e-", presented at the IPAC'24, Nashville, TN, USA, May 2024, paper WEPR06.
- F. Zimmermann, J. Keintzel, A.-S. Mueller, B. Haerer, E. Blomley, E. Huttel, J. Steinmann, J. Gethmann, R. Ruprecht, T. Pieloni, Y. Wu, "Probing FCC-ee energy calibration through resonant depolarization at KARA", presented at the IPAC'24, Nashville, TN, USA, May 2024, paper WEPR20.
- F. Zimmermann et al., "Selected Advances in the Accelerator Design of the Future Circular Electron-Positron Collider (FCC-ee)", presented at the IPAC'24, Nashville, TN, USA, May 2024, paper WEPR14.
- L. van Riesen-Haupt et al., "The status of the FCC-ee optics tuning", presented at the IPAC'24, Nashville, TN, USA, May 2024, paper WEPR02.
- Y. Wu et al., "Spin polarization simulations for the Future Circular Collider e+e- using Bmad", in Proc. eeFACT'22, Frascati, Italy, September 2022, TUZAS0104, pp. 103-107, 2023.
- J. Bauche et al., "THE STATUS OF THE ENERGY CALIBRATION, POLARIZATION AND MONOCHROMATIZATION OF THE FCC-ee", in Proc. IPAC'23, Venice, Italy, May 2023, MOPL055, 2023

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