Swiss Accelerator
Research and
Technology

Project: FCC-ee SPIN-POL

FCC-ee spin tracking and polarization studies

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1. Polarization studies and Spin-tune to beam energy relationship

1.1 Motivation

The Future Circular Collider (FCC) project aims to provide unprecedented opportunities for high-energy physics research by exploring the electroweak and Higgs sectors, top quark physics, and by searching for new physics beyond the Standard Model [1]. The FCC-ee is the electron-positron collider envisaged for the first phase of the FCC project [2]. The planned centre-of-mass energy of the FCC-ee ranges from 88 GeV to 365 GeV [1].

The current targets for the precision of energy calibration at the Z and W energies are 4 keV and 100 keV respectively [3], and it is expected that they can be realized using resonant depolarization with radio-frequency external electromagnetic fields [4]. For this, at least 5-10% beam polarization should be maintained in the presence of various misalignments [4].

1.2 Research Goal

The main technical goals of the study is to gain knowledge about polarization dynamics for the FCC-ee accelerator. Review existing tools for modelling and simulate the spin-tune to beam energy relationship for the FCC-ee.

- Confirm the technical feasibility and the performance of the scheme proposed in the FCC-ee CDR, by sufficiently detailed simulations; in particular by completing the study of the depolarization method.
- The existing simulation codes for luminosity and polarization must be unified, while calculating both the spin tune and the IR centre-of-mass energy. The relationship between these two quantities and its sensitivity to tuning knobs, centre-of-mass energy and various imperfections should be investigated and if possible mitigated.

1.3 Research Activity

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Thus calculations of spin polarization have been undertaken to investigate the influence of lattice imperfections on polarization. In this project, the equilibrium polarization levels near the Z energy (45.6 GeV) are estimated using the software package Bmad [5] with its facilities for analytical linearized spin-orbit motion and for 3-D Monte-Carlo spin-orbit tracking simulations. In addition, we focus on the use of special closed-orbit bumps to alleviate the effects of misalignments and further improve the polarization.

1. The influences of orbit distortions on equilibrium polarization in linear regime have been investigated via energy scans using the Tao module in Bmad [5], which reveals the sensitivity of polarization curves to the orbits. The equilibrium polarization near Z energy decreases with increasing rms vertical orbit distortion as shown in Figure 1. The orbits are simulated by generating small random misalignments (σ = 200 nm) and angular deviations (σ = 2 µrad) for quadrupoles, sextupoles and dipole magnets in the FCC lattice, without orbit or optics corrections applied. Figure 2 and 3 shows the distributions of the rms vertical orbits and the equilibrium polarization at Z energy using 100 hypothetical error seeds with 1 µm rms misalignments and 1 µrad rms angular deviations of quadrupoles and dipoles, without orbit or optics correction.

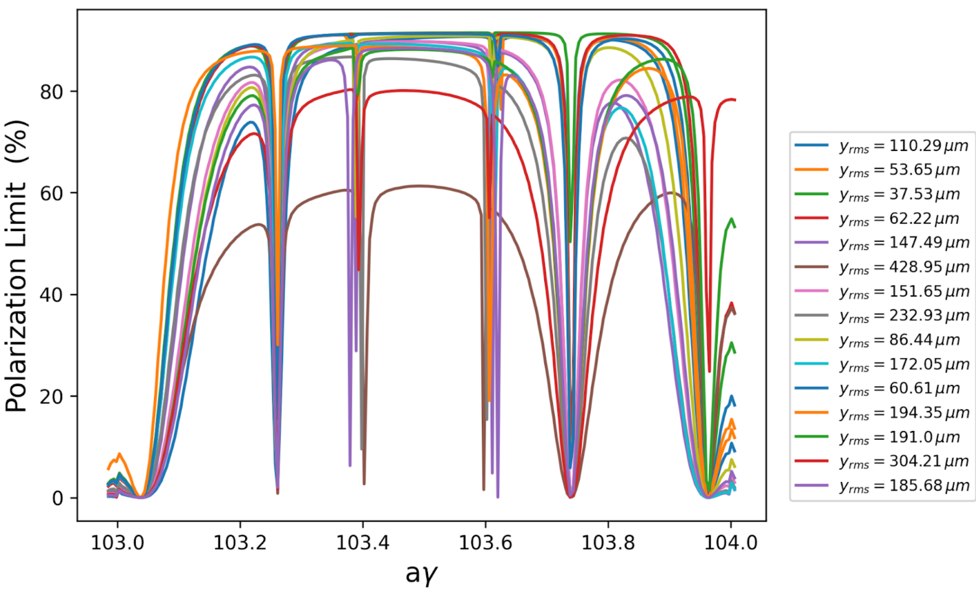

Figure 1 First order energy scan near Z energy using Bmad

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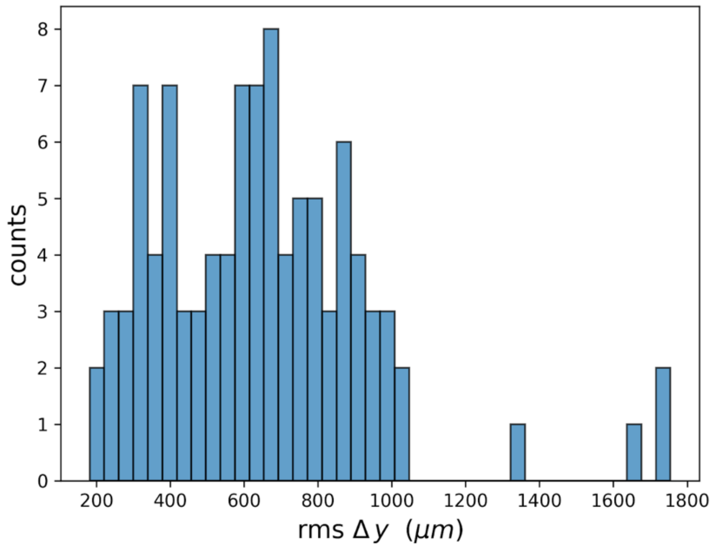

Figure 2 Distributions of the rms vertical orbits at Z energy using 100 hypothetical error seeds

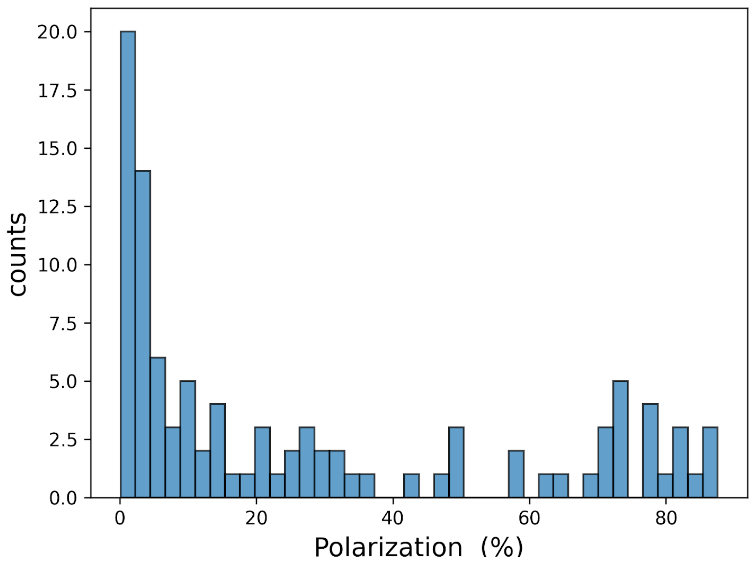

Figure 3 Distributions of the equilibrium polarization at Z energy using 100 hypothetical error seeds

The latest studies have explored the orbit correction and optics tuning techniques for polarization estimation, for which the FCC-ee V22 Z lattice has been modified by adding 1 beam position monitor (BPM) and one orbit corrector next to each quadrupole in the ring, and by setting sextupole knobs to proportionally control all sextupole strengths. Realistic large random misalignments (σ = 30 μm - 100 μm) have been added

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to all arc lattice elements, along with the 10 μm random misalignments introduced to IR elements. The orbit correction follows a carefully refined procedure, designed to mitigate the impact of strong sextupole feedown. This approach interleaves orbit correction using singular value decomposition (SVD) algorithm, with gradual sextupole strength recovery and tune matching. Figure 4 shows the distribution of obtained polarization after applying different levels of random misalignments to arc elements, along with proper orbit correction. Each group has 50 random error seeds. This suggests that as misalignment magnitude increases, both the obtained polarization and the rms orbit after correction exhibit larger variations, which makes them less predictable from the current error settings. Besides, the impact of BPM performance, including BPM scaling error, BPM resolution, BPM misalignment and random BPM missing, on orbit correction and polarization has been investigated thoroughly. Figure 5 depicts the polarization distribution of all survived seeds in the presence of misalignments and BPM errors (4 groups have BPM scaling error, resolution and missing considered, while 2 groups have also BPM misalignments considered). Errors in IR elements tend to have a more significant impact compared with that in arc. There are a certain percentage of error seeds, in which a stable closed orbit has not yet been found. This issue could potentially be resolved through further refinement of the correction process. In general, polarization remains high when a proper orbit correction procedure is applied. Additional dispersion correction and chromaticity correction could further improve the polarization levels, particularly in a very few cases where they are relatively lower. Future studies aim to determine the maximum acceptable orbits for achieving a sufficient level of polarization.

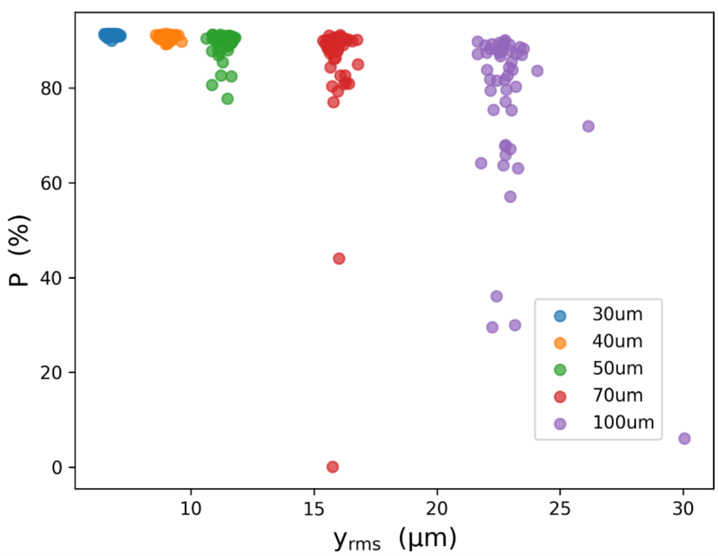

Figure 4 Distribution of equilibrium polarization at Z energy when applying different levels (30, 40, 50, 70 and 100 μm) of misalignments to all arc elements and with orbit corrected

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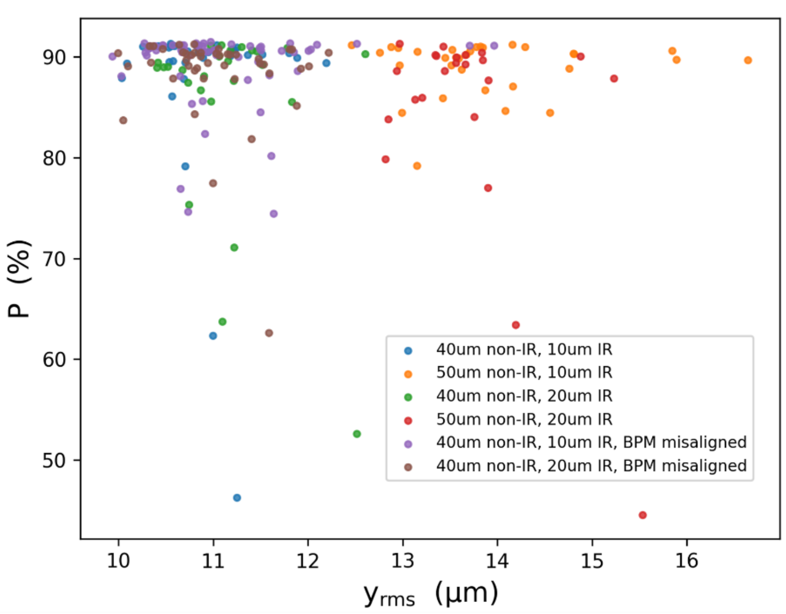

Figure 5 Distribution of equilibrium polarization of survived seeds at Z energy when applying different levels of misalignments to both arc and IR elements, with BPM errors and orbit correction applied

2. After conventional lattice correction, one method to improve polarization level and alleviate the effects of misalignments is Harmonic Closed Orbit Spin Matching (HCOSM) by using closed vertical orbit bumps to manipulate the stable spin direction on the closed orbit (n_0) and minimise the polarization loss due to the spin diffusion [6][7]. Each bump will contain three individually powered vertical orbit correctors, which can be installed in front of three consecutive vertically focusing arc quadrupoles. Response matrix can be used to represent the linear contribution of each bump to the target harmonics, thus the required bump amplitudes for the harmonics correction of a misaligned lattice can be predicted.

Method	$(\delta n_0)_{rms}$ mrad	Polarization %
no correction	2.28	10.68
HERA formalism	0.90	90.96
Rossmanith-Schmidt scheme	0.90	89.65
LEP method	2.03	13.72

Table 1 Comparison of the effectiveness of different HCOSM methods

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There are three possible optimisation schemes developed in the past and that are currently being tested, the HERA formalism [7], the Rossmanith-Schmidt scheme [8], and the LEP method [9]. Their efficacies are compared. The FCC-ee V22 lattice together with an effective lattice with 72 μm rms vertical orbit distortion is used for the tests. As shown in Table 1, the polarsation loss near the integer resonances next to Z energy (dashed line in Fig.4) so far can be largely improved by using HCOSM (orange line). The current effectiveness of applying HCOSM relies on the vertical orbit information obtained from the BPM system, which are assumed to be installed at both ends of each dipole or quadrupole. No misalignments or calibration errors are considered in this first study. The large number of monitors, and consequent high cost, required to make this method effective represents the main obstacle to applying HCOSM. Future investigations aim to explore possible HCOSM scheme that utilises fewer BPMs, and test the efficacy of this scheme in the presence of various lattice conditions, BPM misalignments and calibration errors. For the future the two most promising methods will be explored while the LEP method will be abandoned.

The balance between costs and benefits shall be the next goal of this study. In addition, applying HCOSM at Higgs and top quark energies will be explored with the expectation that a polarization level can be achieved at higher energies.

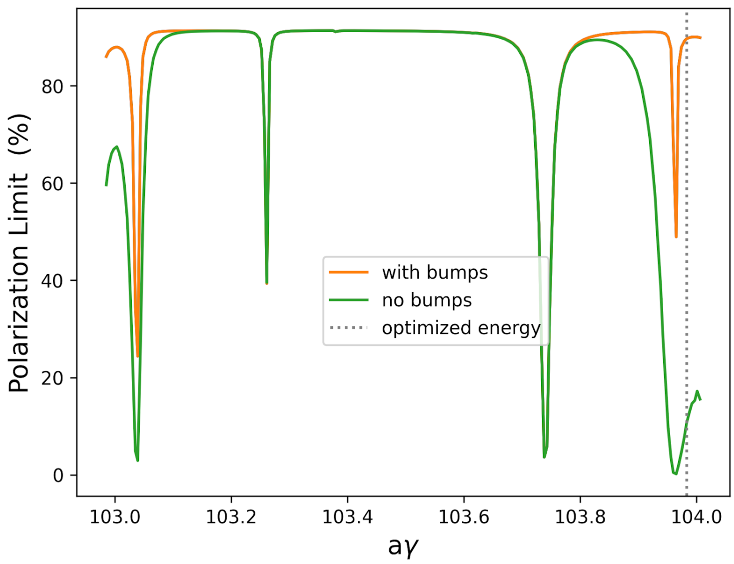

Figure 6 First order energy scan with and without harmonic bumps optimised at 45.82 GeV (aγ = 103.983) using the Rossmanith-Schmidt scheme in V22 lattice

1.4 Outlook and Future Development

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This project will delve into several key problems. Firstly, more realistic machine error models, such as long-range alignment error model, will be constructed and simulated. Secondly, innovative lattice correction strategies will be explored to improve the machine performance. Thirdly, quantification of the influence of machine errors to polarization remains to be investigated. Simulations of resonant spin depolarization will soon be conducted by using spin tracking, to serve the purpose of exploring the feasibility of employing resonant depolarization for energy calibration in the FCC-ee.

1.5 List of 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
- Poster at 14th International Particle Accelerator Conference, Venice, 7-12 May 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

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1.6 List of publications:

- 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.
- 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.
- 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

1.7 List of references:

1) FCC collaboration, "FCC Physics Opportunities: Future Circular Collider Conceptual Design Report Volume 1", in European Physical Journal, 79(6), pp. 474, 2019.
2) FCC collaboration, "FCC-ee: The Lepton Collider: Future Circular Collider Conceptual Design Report Volume 2", in European Physical Journal: Special Topics, 228, pp. 261-623, 2019.
3) A. Blondel, "PED Overview: Centre-of-mass energy calibration".
4) A. Blondel et al., "Polarization and centre-of-mass energy calibration at FCC-ee", arXiv:1909.12245v1, 2019.
5) D. Sagan, "Bmad, a subroutine library for relativistic charged particle dynamics".
6) D. P. Barber et al., "High spin polarization at the HERA electron storage ring", in Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 338(2-3), pp. 166-184, 1994.
7) D. P. Barber et al., "A general harmonic spin matching formalism for the suppression of depolarisation caused by closed orbit distortion in electron storage rings", No. DESY-85-044, DESY, 1985.
8) R. Rossmanith and R. Schmidt, "Compensation of depolarizing effects in electron-positron storage rings", in Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 236(2), pp. 231-248, 1985.
9) R. W. Assmann, Optimierung der transversalen Spin-Polarisation im LEP-Speicherring und Anwendung fur Prazisionsmessungen am Z-Boson. Diss. Munich U., 1994.