

CHART Scientific Report (Final Report for Phase 2)

FCC-ee Spin Tracking and Polarization Studies (FCC-ee SPIN-POL)

Y. Wu, L. van Riesen-Haupt, T. Pieloni, M. Seidel, J. Wenninger and the EPOL working group.

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1. Introduction

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]. This precision goal is expected to be met by employing resonant depolarization techniques utilizing radio-frequency external electromagnetic fields [4]. To ensure the efficacy of this method, it is imperative to maintain a minimum beam polarization of 5% to 10% in the presence of diverse machine imperfections [4].

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.

3. Results

To evaluate tolerances on machine errors, ensure adequate polarization, and propose correction schemes, this study examines the effects of various machine errors with realistic

magnitudes using a refined lattice correction procedure. Orbit correction and optics tuning are performed using the MAD-X code [5], while equilibrium polarization levels at the Z energy (45.6 GeV) are estimated with the BMAD software package [6].

Adaptations were made to the FCC-ee V22 baseline lattice at the Z pole, including adding a Beam Position Monitor (BPM) and an Orbit Corrector (OC) next to each quadrupole and configuring sextupole knobs to control all sextupole strengths proportionally.

The designed orbit correction procedure aims to mitigate significant sextupole feed-down effects, which could distort optics and alter the tune, potentially leading to resonance conditions. By alternating orbit correction with gradual recovery of sextupole strength and tune matching, a stable closed orbit can be achieved despite substantial machine errors.

Critical machine errors investigated include misalignments, dipole rotation around the s-axis, and BPM errors, incorporated into the lattice individually or in combination. These errors are randomly generated from truncated Gaussian distributions, with standard deviations σ and truncation at 2.5σ .

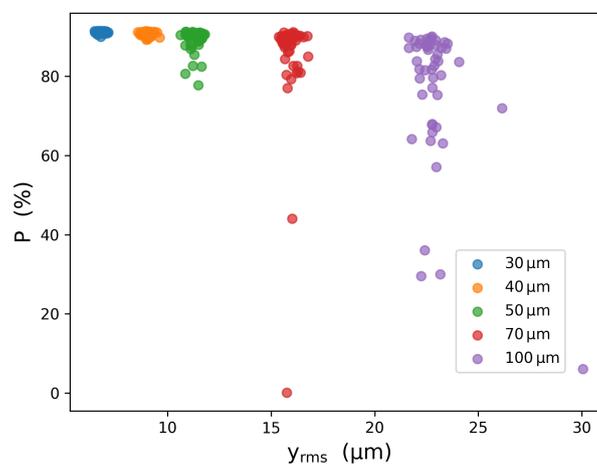


Figure 1 RMS vertical orbits after correction and the computed equilibrium polarizations of 50 seeds in the presence of arc misalignments ($\sigma_{dx,dy,ds} = 30,40,50,70,100\mu\text{m}$)

Realistic random misalignments ($\sigma_{(dx,dy,ds)} = 30\text{-}100\mu\text{m}$) are initially applied to all non-IR elements, including dipoles, quadrupoles, and sextupoles. Figure 1 shows the RMS vertical orbits and equilibrium polarizations of 50 random seeds after correction, with increasing arc misalignment magnitudes. As misalignment increases, the variation in orbits and polarizations becomes broader. Although not strictly linear, polarization shows a subtle correlation with vertical orbit distortion. Cases with significantly lower polarization reveal that large dispersion and chromaticity are key factors in this reduction. A first “realistic” machine configuration has been analyzed to establish tolerances and develop a robust correction scheme.

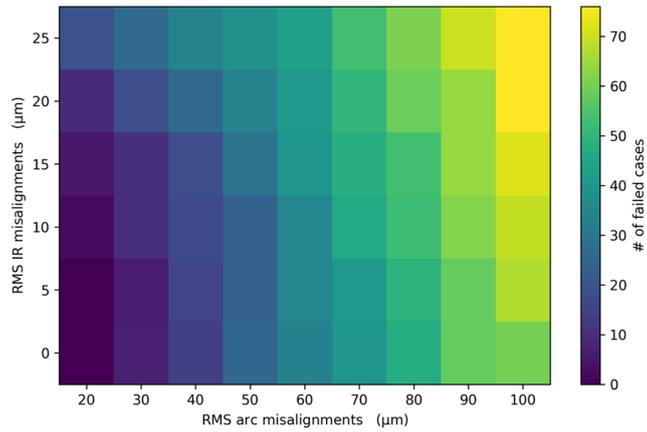


Figure 2 Colormap of the variation of the number of failed seeds with RMS arc and IR misalignments

To investigate the impact of misalignments in both the arc and IR, a colormap format was used for illustrations. Each square on the colormap represents a specific misalignment magnitude, including the same 100 initial error seeds. As shown in Fig. 2, varying the magnitudes of arc and IR misalignments affects the number of failed seeds, with IR misalignments having a greater impact on closed-orbit searching. Figure 3 shows that average RMS vertical orbit (y_{rms}) and equilibrium polarization vary with RMS arc and IR misalignments, confirming that arc misalignment primarily influences the final orbits and polarization.

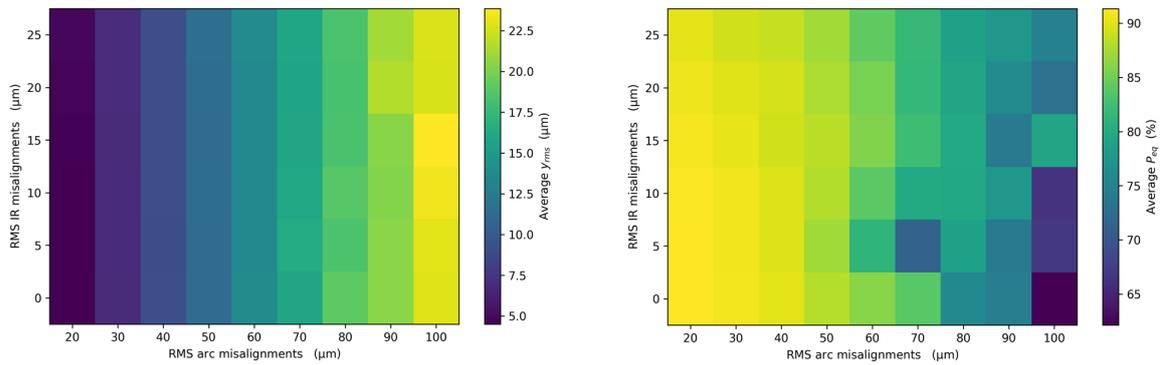


Figure 3 Colormap of the variations of average y_{rms} (left) and average equilibrium polarization (right) with RMS arc and IR misalignments

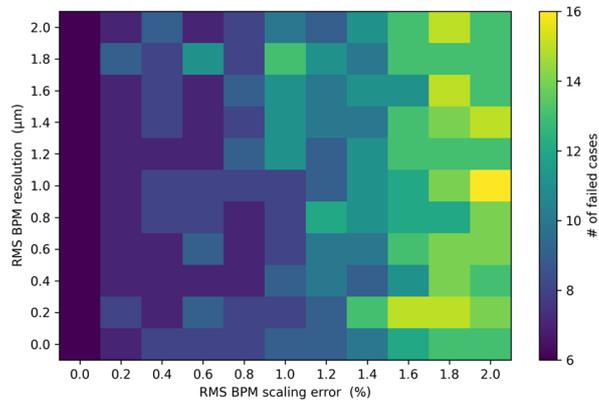


Figure 4 Colormap of the variation of the number of failed seeds with RMS BPM scaling error and resolution

To assess the impact of BPM scaling error and resolution, Fig. 4 shows the number of failed seeds under various scaling errors (0% to 2%) and resolution settings (0 μm to 2 μm) with RMS misalignments of 30 μm in the arc and 10 μm in the IR. Each square represents the same 50 initial seeds. Scaling error clearly has the most significant effect on closed-orbit searching. In contrast, Fig. 5 indicates that BPM resolution primarily affects vertical orbits. The effect on polarization appears more random, reflecting the complexity of machine imperfections and their interaction with multiple lattice parameters.

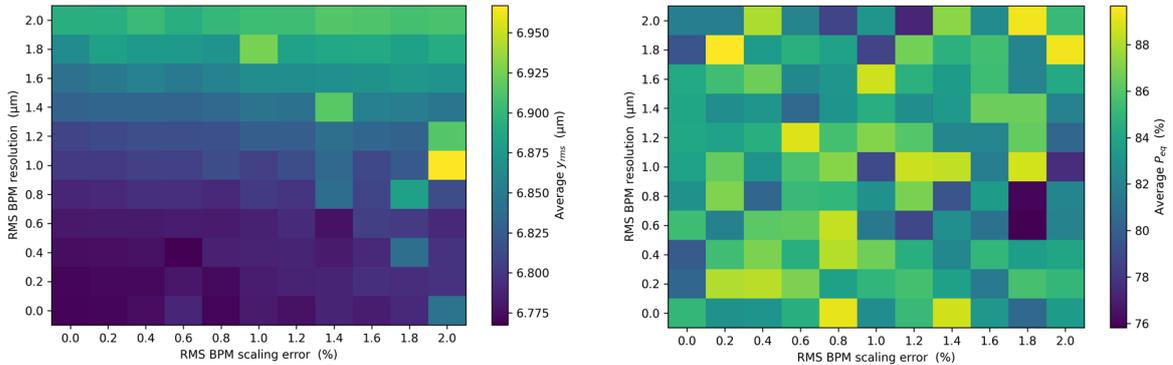


Figure 5 Colormap of the variations of average y_{rms} (left) and average equilibrium polarization (right) with RMS BPM scaling error and resolution

Table 1 provides examples of the outcomes of the closed orbit search under various misalignment settings, including a 100 μrad arc dipole roll, 1% random BPM scaling error, 1 μm random BPM resolution, and 5% random BPM missing. For each configuration, 200 initial seeds were tested, and the table indicates the percentage of cases where a closed orbit could not be found. The proportion of failed seeds noticeably increases with larger errors in the IR, suggesting the need for a more stringent alignment procedure for the IR in the real machine. While unsuccessful seeds may not necessarily pose a challenge in the actual machine, this ratio provides an approximate prediction for the tolerable error limit.

Case	Misalignments (μm)		Failed percentage (%)
	arc	IR	
1	40	10	13.5
2	40	20	36
3	50	10	19
4	50	20	40

Table 1 Closed orbit searching results under different misalignment settings

Fig. 6 shows the polarization and orbits of all surviving seeds from the previous table. Despite survivorship bias, it is clear that arc misalignments predominantly impact the orbit, while IR misalignments further compound the challenge of finding a closed orbit.

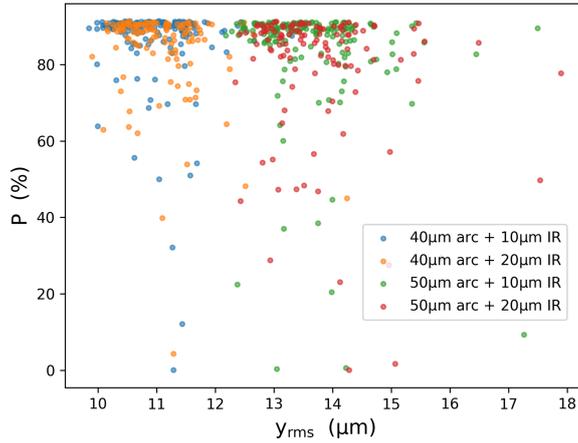


Figure 6 RMS vertical orbits after correction and equilibrium polarizations of 200 seeds under various error settings as in Table 1

In an ideally aligned flat machine, the beam energy correlates with the spin precession frequency as $\nu_0 = a\gamma$. However, this relationship is disrupted by factors like energy-dependent momentum compaction and vertical orbit distortions, resulting in systematic errors in energy calibration through resonant depolarization [4]. Using the closed orbit spin tune ν_0 from simulations with linearized spin-orbit motion, Fig. 7 shows how arc and IR misalignments contribute to the spin tune shift from ν_0 . As error magnitudes increase, the RMS spin tune shift also grows, significantly reducing energy calibration precision. To meet the current precision target, the spin tune shift $|\nu_0 - a\gamma|$ must be reduced to 10^{-4} , a goal still far from reach. Continued efforts will focus on identifying and mitigating sources of these systematic errors.

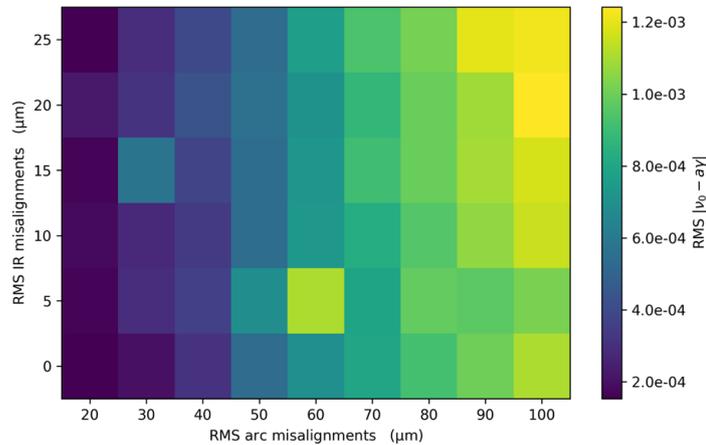


Figure 7 Colormap of the variation of RMS spin tune shift with arc and IR misalignments

This study models various machine errors to assess their effects on orbit distortion and polarization, leveraging a refined correction and tuning procedure. The findings show that achieving high polarization is closely linked to maintaining a stable closed orbit. Misalignments in IR elements notably disrupt this stability, underscoring their critical impact. Enhancing polarization further may be possible through additional dispersion and chromaticity corrections. Future research will focus on defining the thresholds for tolerable machine errors to ensure adequate polarization levels. This will include simulating more realistic errors, such

as long-range alignment deviations, and exploring innovative lattice correction techniques to optimize performance. Additionally, significant efforts will be directed toward identifying and mitigating the sources of systematic errors to meet stringent energy calibration precision targets.

4. 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](#)
- 65th ICFA Advanced Beam Dynamics Workshop on High Luminosity Circular e+e- Colliders (eeFACT2022), Frascati, 12 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, Anecy, 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](#)
- Poster at 15th International Particle Accelerator Conference, Nashville, May 2023
- FCC Week 2024, San Francisco, 10-16 Jun 2024, [FCC-ee Orbit Correction and Polarization](#)
- FCC-ee optics tuning WG meeting, 28 Jun 2024, [Updates on Orbit Correction for Polarization Studies](#)

5. Publications

- 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.
- Y. Wu, D. Barber, F. Carlier, E. Gianfelice-Wendt, T. Pieloni, and L. van Riesen-Haupt, “*Spin-polarization simulations for the Future Circular Collider e+e- using Bmad*”, in Proc. IPAC'23, Venice, Italy, May 2023, pp. 670-673.
- Y. Wu, F. Carlier, T. Pieloni, L. van Riesen-Haupt, “*Spin Polarization Simulations for the Future Circular Collider e+e- using BMAD*”, JACoW eeFACT 2022 (2023), INFN, Frascati, Italy, 12 - 16 Sep 2022, pp.103-107.
- 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.
- 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, pp. 674-677.
- J. Bauche et al., “Progress of the FCC-ee optics tuning working group”, JACoW IPAC 2023 (2023), Venice, Italy, 7 - 12 May 2023, pp.WEPL023.

6. References

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