

FCC-ee ENERGY CALIBRATION AND POLARIZATION – TOWARDS THE REFERENCE DESIGN

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Abstract

The FCC-ee aims at delivering high-precision particle-physics measurements over a wide beam-energy range, from the Z pole at 45.6 GeV up to 182.5 GeV, above the top-pair production threshold. Achieving the target physics precision requires an exceptionally accurate determination of the centre-of-mass energy and, consequently, of the beam energies. The baseline approach relies on resonant depolarization scan of dedicated, transversely polarized pilot bunches up to 80 GeV. By analysing the depolarization signatures with a 3D polarimeter, the spin tune can be extracted with a goal of reaching systematic uncertainties on the beam energy at the level of up to a few 10 keV. This contribution presents the latest progress of the FCC-ee Energy Calibration and Polarization Working Group, covering recent developments in polarization build-up studies, resonant-depolarization techniques, machine-optics optimization, and polarimetry concepts. The current status is summarized, and the roadmap of technical and conceptual milestones required for the reference design is outlined.

INTRODUCTION

The Future Circular electron-positron Collider (FCC-ee) is designed as an Higgs- and electroweak factory, with a centre-of-mass energy range, from the Z-pole at 45.6 GeV up to above the top-pair production threshold at 365 GeV. Achieving the target physics precision requires an exceptionally accurate determination of the centre-of-mass energy, \sqrt{s} , and, hence also of the beam energies, which is in the scope of the energy calibration, polarization and monochromatization working group (EPOL) [1, 2].

In the Feasibility Study Report [3–5], the baseline scenario to achieve polarized pilot bunches in the FCC-ee collider rings, relied on the build-up of transverse polarization via the Sokolov–Ternov effect [6]. However, the long natural polarization times ($\tau \approx 200$ h), even when reduced by the use of polarization wigglers, could significantly reduce achievable integrated luminosity [7]. This motivated to investigate the feasibility of injecting already transversely

polarized pilot bunches. While this technique could improve availability, polarization transport and preservation must be ensured.

While the baseline method to determine the change of polarization when pilot bunches are depolarized with dedicated RF kickers is Resonant Depolarization (RDP), aimed to be applicable until 80 GeV [8], a novel technique, called Near Resonance Polarization Modulation (NRPM) [9], has recently been presented which could reduce the time required for one measurement.

Recently, studies have been performed for two FCC-ee optics designs, namely the Global Hybrid Correction (GHC) [10] and the Local Chromaticity Correction (LCC) [11]. After an extensive review, the LCC is recommended as the baseline lattice. Important findings which are associated with energy calibration and polarization are recalled here, while more information can be found in [12–14].

The FCC-ee is currently in the reference design phase, with the central objective to establish a coherent and robust machine design, including the energy calibration and polarization strategies under realistic conditions through detailed simulations. This paper summarises the current status of the FCC-ee EPOL team and outlines the key open challenges for the reference design phase.

PRECISION PHYSICS

Precision targets for physics observables are the most demanding at the lower energies for the Z and W-mass measurement, as also given in Table 1 [4, 8]. At higher energies, first estimates based on physics requirements indicate that a few MeV prevision at ZH and $t\bar{t}$ -energy are required [15].

The Sokolov–Ternov effect also leads to a polarization build-up of colliding bunches. Assuming a $\tau \approx 200$ h and a top-up of 10% of the nominal bunch every 70 s, a vertical asymptotic polarization of close to 1×10^{-3} could be present. At the IP the longitudinal polarization must be controlled below 1×10^{-5} , and hence demanding a control of the axis of the invariant spin field, n_0 , below 10 mrad.

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Table 1: \sqrt{s} -related Uncertainties from [4, 8]

Uncertainty	m_z (keV)	Γ_z (keV)	m_w (keV)
Absolute	100	2.5	150
Point-to-point	14	11	50
Sample size	1	1	3
Energy spread	–	5	–
Total \sqrt{s} -related	101	12	158
FCC-ee statistical	4	4	180

CODE DEVELOPMENT

Significant effort has been devoted into implementing spin tracking in Xsuite [16, 17], which has also been extensively benchmarked against the Large Electron Positron ring (LEP) [18]. Furthermore, it has also been applied to first studies to Karlsruhe Research Accelerator (KARA), and a wide range of FCC-ee studies including achievable polarization in the presence of machine errors and depolarization [19]. In future studies it is aimed to further benchmark it against other established frameworks such as BMAD.

GHC VS LCC

As part of the FCC-ee optics comparison, EPOL aspects for GHC and LCC have been compared [12]. The synchrotron radiation energy loss per turn is about 9% smaller for the LCC optics compared to the GHC optics, resulting in a slightly less prominent energy sawtooth. Consequently, the boosts at the IPs are smaller for the LCC. As it has already been shown in [20], if all the RF is located in one long straight section, the centre-of-mass energies at all IPs agree within a few keV. Since the energy loss is smaller for LCC, the polarization time is longer, given in Table 2.

Table 2: High Level Polarization Parameters

Parameter	GHC	LCC
Energy loss per turn at Z [MeV]	39.2	35.1
Polarization time at Z [h]	190	237

The equilibrium level of polarization, obtained by linear approximation in Xsuite is evaluated in the presence of very optimistic misalignment errors, only present in the arcs and after orbit correction to rms $150\ \mu\text{m}$ for both optics. In these studies a similar level of maximum polarization above 83% for all seeds is found if the orbit is well corrected.

For efficient depolarization while simultaneously avoiding a propagating orbit wave, closed-orbit bumps are foreseen, which are implemented in the return arc, downstream of the IP, for the GHC and the dispersion suppressor for the LCC. The latter is more flexible, than the proposal for the GHC. It must be noted that a change of the phase advance between Z and WW operation in the region of the RDP bumps may require a re-location of the kickers or a significant modifications of their strength, relevant for both optics.

The performance of the polarimeter is evaluated by comparing the lepton beam interaction rates at the laser IPs, where parameters are compared in Table 3. Backgrounds at

Table 3: Parameters at the Laser IP

Parameter	GHC	LCC
Bending angle of dipole [mrad]	2.2	2.3
Dipole length [m]	19.43	17.35
Distance Compton IP to Bend [m]	1.25	1.25
Drift space Bend to Detectors [m]	75.0	96.6
Scatters per bunch crossing	875	937
Scatters per second	2.5×10^6	2.8×10^6

the polarimeter detectors are neglected. For GHC and LCC the number of scatters per bunch crossing is similar.

From an EPOL perspective, no clear differences between the GHC and the LCC are found.

POLARIZATION STRATEGY

Injecting polarized pilots could improve availability, hence, its feasibility and implications are currently being investigated. This requires the development of a complete polarization chain through the injectors, including a polarized electron source, a positron polarization ring, and the preservation of polarization during transport and acceleration up to the collider rings.

First lattice and optics designs for a polarization ring are available. Assuming the same circumference as for the damping rings of 345.3 m, a polarization time of roughly 1 h is achievable [21]. Reducing the circumference, or the addition of more wiggler magnets which is currently being studied, could improve the required time along with improving dynamic aperture.

Currently no complete optics design of the transfer lines is available. However, preliminary studies show that by adjusting slightly the energy at the end of the linac to 19.873 GeV, compared to 20 GeV, the total spin phase advance of transfer line segments is brought to an integer, which maximizes the polarization transport [8]. Furthermore, interleaving horizontal and vertical bending fields must be avoided.

In the booster, the beam is ramped up to the nominal energy, and numerous resonances are being crossed, which could lead to polarization loss. First studies assuming only girder misalignments of $100\ \mu\text{m}$, polarization is largely preserved, even up to the W-energy, as shown in Fig. 1. Recent studies suggest a strong interplay between polarization preservation and the orbit correction strategy [22]. Com-

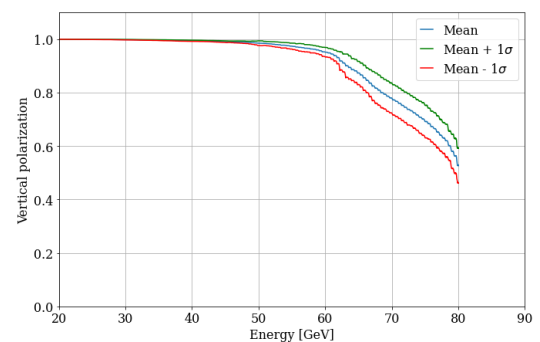


Figure 1: Polarization loss through the booster ramp.

plementary, injecting with 1% momentum offset, leads to about 60 integer spin tune crossings, which could reduce the polarization by 20% [23].

In the collider rings, a minimum level of roughly 20% polarization is required in presence of realistic machine imperfections. Depolarization effects are shown to be mitigated using dedicated spin-orbit bumps to enhance the achievable polarization [24]. However, it is found that in presence of machine errors, after applying a linear optics tuning procedure and achieving low orbit and optics errors, significant spin tune shifts could arise [22]. Similar to before, recent investigations suggest that the spin tune shift could also depend on the orbit correction strategy, which should be investigated in detail in parallel with optics tuning [13].

ENERGY MEASUREMENT STRATEGY

The implementation of RDP in FCC-ee relies on the generation of vertical closed orbit bumps, which are, however, not transparent to the spin motion because of dipoles in-between. The current LCC configuration consists of two pairs of bumps, located around IP4 and IP8, as illustrated in Fig. 2. Each bump consists of 3 kickers.

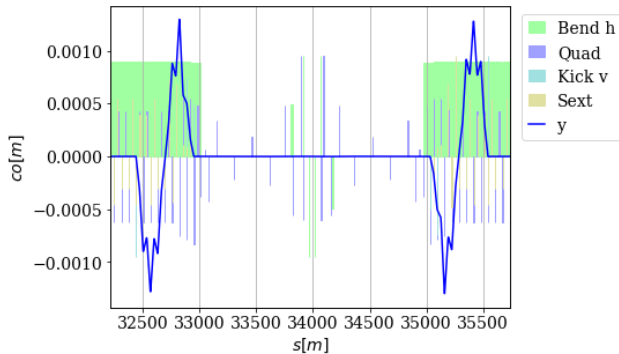


Figure 2: Vertical closed orbit with depolarizer bumps.

Developments on the RF-kicker design foresees study in addition to a broadband stripline [25], a $\lambda/4$ cavity concept [26]. The latter offers a higher transverse shunt impedance, up to a factor 2, while maintaining the required bandwidth, and thereby reducing power requirements and improving efficiency for RDP.

RDP scans using Xsuite are performed for the GHC and LCC lattice. The main principle is that by applying a frequency sweep of the RF-kickers while simultaneously monitoring the polarization, the spin resonance is found. An example for the LCC over 300 000 turn, corresponding to 15 min is shown in Fig. 3.

Recently, a novel, complementary technique, NRPM [9], is being investigated. In this method, a constant frequency, close to the spin resonance, is applied to coherently force spin oscillation. The spin tune is then extracted by analysing the time-dependent polarization signal. On the one hand, compared to RDP, NRPM could have a higher precision, while, on the other hand, tracking polarisation variations happening over a few turns time scale could become a real challenge for the polarimeter instrument design.

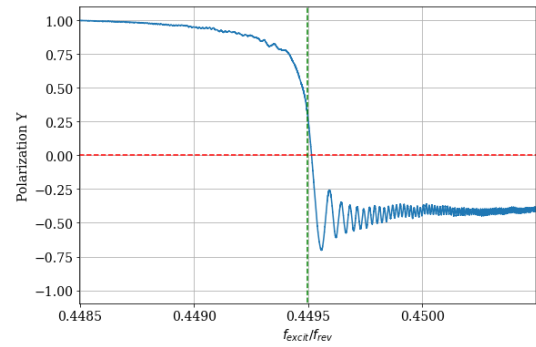


Figure 3: Evolution of the vertical polarization during RDP scans for the LCC over 300 000 turns.

The measurement of the beam polarization is based on an inverse Compton polarimeter; its concept is already described, for example, in [2, 8]. Currently two polarimeters per beam are foreseen for redundancy, given that the laser cannot be accessed during operation. First studies indicate that a relative precision on the vertical polarisation level of about 1% can be achieved by integrating the polarimeter sensor signals over 1 s with a 100% polarised beam. We note that precision would decrease with a lower polarization level [27].

Polarized pilot bunch injection would require polarization measurements along the injector chain. First ideas for such a measurement system are being considered [28]. While these polarisation level measurements will require less precision than the collider ones, they nevertheless need to be adapted to the energy scale. Mott and Møller destructive polarimeter types could cover the injectors and booster needs. This remains to be further investigated within the reference design phase.

MONOCHROMATIZATION

Measuring the Yukawa couplings would require a dedicated run at a beam energy of 62.5 GeV. To reduce the \sqrt{s} spread from about 50 MeV, monochromatization is also implemented for the LCC. With an opposite vertical dispersion of 1.6 mm a \sqrt{s} of 9 MeV is achieved [29].

SUMMARY AND OUTLOOK

Significant progress has been made under the framework of the FCC-ee EPOL team, including comparing GHC and LCC lattice, first considerations on injection of polarized pilot bunches, RF-kicker and RDP studies for the LCC in Xsuite, and most notably, a novel technique called NRPM.

Several open questions remain to be addressed in the Reference Design Phase. This includes preservation of polarization during booster ramps until at least the W energy, and spin tune shift control in the presence of realistic imperfections and tuning. Further work is also required regarding RF-kicker and polarimeters. Finally, a consistent model linking beam energy measurements to the centre-of-mass energy at the IPs remains a key objective.

REFERENCES

- [1] J. Keintzel *et al.*, “Probing FCC-ee energy calibration through resonant depolarization at KARA”, in *Proc. IPAC'24*, Nashville, TN, USA, May 2024, pp. 2516–2519. doi:10.18429/JACoW-IPAC2024-WEPR20
- [2] “FCC-ee energy calibration and polarization - Status and outlook”, in *Proc. IPAC'25*, Taipei, Taiwan, Jun. 2025, pp. 274–277. doi:10.18429/JACoW-IPAC2025-MOPM007
- [3] M. Benedikt *et al.*, “Future Circular Collider feasibility study report volume 1: physics and experiments”, Tech. Rep. CERN-FCC-PHYS-2025-0002, CERN, Geneva, Switzerland, 2025. doi:10.17181/CERN.9DKX.TDH9
- [4] M. Benedikt *et al.*, “Future Circular Collider feasibility study report volume 2: accelerators, technical infrastructure and safety”, Tech. Rep. CERN-FCC-ACC-2025-0004, CERN, Geneva, Switzerland, 2025. doi:10.17181/CERN.EBAY.7W4X
- [5] M. Benedikt *et al.*, “Future Circular Collider feasibility study report volume 3: civil engineering, implementation and sustainability”, Tech. Rep. CERN-FCC-ACC-2025-0003, CERN, Geneva, Switzerland, 2025. doi:10.17181/CERN.I26X.V4VF
- [6] A. Sokolov and I. Ternov, “Polarization and spin effects in the synchrotron radiation theory”, *Doklady Akad. Nauk SSSR*, vol. 153, p. 1052, 1963.
- [7] J. W. Heron *et al.*, “Availability assurance in the future circular electron-positron collider (FCC-ee)”, in *Proc. IPAC'25*, Taipei, Taiwan, Jun. 2025, pp. 3018–3021. doi:10.18429/JACoW-IPAC2025-THPS027
- [8] A. Blondel, J. Keintzel, J. Wenninger and G. Wilkinson, “Collision-energy calibration and monochromatisation studies at FCC-ee”, CERN Tech. Rep., 2025. doi:10.17181/y6s2j-dhh22
- [9] Y. Wu *et al.*, “Near resonance polarization modulation (NRPM), a novel method for high precision beam energy measurement in storage rings”, presented at IPAC'26, Deauville, France, May 2026, paper SUP1013, this conference.
- [10] K. Oide *et al.*, “Design of beam optics for the future circular collider e^+e^- collider”, *Phys. Rev. Accel. Beams*, vol. 19, p. 111005, 2016. doi:10.1103/PhysRevAccelBeams.19.111005
- [11] P. Raimondi, M. Hofer, S. Liuzzo, L. Farvacque and S. White, “Local chromatic correction optics for Future Circular Collider e^+e^- ”, *Phys. Rev. Accel. Beams*, vol. 28, p. 021002, 2025. doi:10.1103/PhysRevAccelBeams.28.021002
- [12] S. Kostoglou and G. Roy, Eds., “FCC-ee optics comparison report”, CERN, Geneva, Switzerland, 2026, unpublished.
- [13] J. Keintzel *et al.*, “FCC-ee optics tuning – towards the reference design”, presented at IPAC'26, Deauville, France, May 2026, paper MOP1039, this conference.
- [14] J. Keintzel *et al.*, “Defining the new FCC-ee baseline optics”, presented at IPAC'26, Deauville, France, May 2026, paper MOV1002, this conference.
- [15] J. Eysermans, “Physics measurements relevant for ECM and related quantities”, presented at the FCC-ee EPOL group meeting 48, 27 Feb. 2026. <https://indico.cern.ch/event/1654645/>
- [16] G. Iadarola *et al.*, “Xsuite: an integrated beam physics simulation framework”, in *Proc. HB'23*, Geneva, Switzerland, Oct. 2023, paper TUA211. doi:10.18429/JACoW-HB2023-TUA211
- [17] G. Iadarola *et al.*, “Spin tracking and equilibrium polarization computation in Xsuite: implementation and benchmarks”, presented at IPAC'26, Deauville, France, May 2026, paper MOP1028, this conference.
- [18] G. Iadarola *et al.*, “Benchmarking the Xsuite code with beam polarization data of the Large Electron Positron Collider”, presented at IPAC'26, Deauville, France, May 2026, paper WEP5003, this conference.
- [19] J. Keintzel, “RDP simulations in KARA”, presented at the FCC-ee EPOL group meeting 46, 12 Dec. 2025. <https://indico.cern.ch/event/1614718/>
- [20] J. Keintzel *et al.*, “Centre-of-mass energy in FCC-ee”, in *Proc. IPAC'22*, Bangkok, Thailand, Jun. 2022, pp. 1683–1686. doi:10.18429/JACoW-IPAC2022-WEPOST007
- [21] C. Carli, H. Bartosik and S. Keskar, “A low energy polarizer ring for FCC-ee”, presented at IPAC'26, Deauville, France, May 2026, paper WEP5048, this conference.
- [22] J. Wenninger, “Updates on the polarization studies in the booster”, presented at the FCC-ee booster meeting, 21 Apr. 2026. <https://indico.cern.ch/event/1670694/>
- [23] J. Wenninger, “Polarisation studies on injection of polarized beams and booster ramp”, presented at the FCC-ee EPOL group meeting 49, 2 Apr. 2026. <https://indico.cern.ch/event/1667089/>
- [24] Y. Wu *et al.*, “Spin-polarization simulations for the Future Circular Collider e^+e^- using Bmad”, in *Proc. IPAC'23*, Venice, Italy, May 2023, pp. 670–673. doi:10.18429/JACoW-IPAC2023-MOPL055
- [25] W. Höfle, I. Karpov, D. Sittard, L. Thiele and H. Timko, “Considerations for the transverse feedback system for the CERN FCC-ee collider ring”, in *Proc. IPAC'25*, Taipei, Taiwan, Jun. 2025, pp. 3206–3209. doi:10.18429/JACoW-IPAC2025-THPS120
- [26] D. Sittard, “Progress on depolariser”, presented at the FCC Physics Workshop 2026. <https://indico.cern.ch/event/1588696/>
- [27] J. Burvill, “First steps on the photon sensor for the polarimeter”, presented at the FCC-ee EPOL group meeting 46, 12 Dec. 2025. <https://indico.cern.ch/event/1614718/>
- [28] J. Keintzel, “Summary of discussion of polarimeters in the booster”, presented at the FCC-ee EPOL group meeting 50, 17 Apr. 2026. <https://indico.cern.ch/event/1675118/>
- [29] A. Korsun *et al.*, “Monochromatization optics update and beam-beam performance studies for the FCC-ee GHC v23 lattice and first attempt at implementation in FCC-ee LCC v105 lattice”, presented at IPAC'26, Deauville, France, May 2026, paper SUP1004, this conference.