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FCC-ee Energy Calibration and Polarization

J. Keintzel,* M. Benedikt, A. Blondel, I. Koop, R. Tomás, J. Wenninger, G. Wilkinson and F. Zimmermann

On behalf of the FCC-ee collaboration
and the FCC-ee Energy Calibration, Polarization and Monochromatization Working Group
CERN, 1211 Geneva 23, Switzerland
E-mail: jacqueline.keintzel@cern.ch, michael.benedikt@cern.ch, alain.blondel@cern.ch, iakoop@mail.ru, rogelio.tomas@cern.ch, jorg.wenninger@cern.ch, guy.wilkinson@cern.ch, frank.zimmermann@cern.ch

The Future Circular electron-positron Collider, FCC-ee, is designed for unprecedented precision for particle physics experiments from the Z-pole to above the top-pair-threshold. This demands a precise knowledge of the centre-of-mass energy (ECM) and collision boosts at all four interaction points and all operation energies. From the Z-pole to the W-pair-region, determining the average beam energies is foreseen using resonant depolarization, with a precision of a few keV, using transversely polarized non-colliding pilot bunches. While wigglers are foreseen to improve the polarization time, misalignment and field errors can limit the achievable polarization level, and might alter the relationship between the resonant depolarization frequency and the beam energies. Strong synchrotron radiation losses range from 40 MeV per turn at the Z-pole, to 10 GeV per turn at the highest beam energy of 182.5 GeV can lead to different ECM and boosts for each interaction point. Beamstrahlung generates further energy losses. Other sources of ECM bias stem from collision offsets and must be controlled. A first evaluation has been published in 2019 with promising results. Further studies are ongoing in the framework of the Feasibility Study to be delivered in 2025 and a first set of further improvements on energy calibration, polarization and monochromatization are presented here.

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*Speaker

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1. Introduction and Motivation

The electron-positron Future Circular Collider (FCC-ee) [1] with a circumference of about 90 km is designed to be embedded into the Franco-Swiss-basin and the existing CERN infrastructure with a possible start of collisions in the 2040s and is the first step of the FCC integrated project [2]. The FCC-ee is planned to operate at four different beam energies, namely 45.6 GeV, 80 GeV, 120 GeV and 182.5 GeV. Corresponding to the Z-pole, the W-pair-threshold, HZ-maximum, at and above the top-pair-threshold. Design luminosity at each Interaction Point (IP), as well as relevant FCC-ee parameters for the newest layout are given in Table 1 [3]. Further details on the present status of the lattice and optics can be found in [4].

Table 1: Selected FCC-ee parameters for the newest four IP layout, taken from [3].

	Z	WW	ZH	ttbar
Beam energy [GeV]	45.6	80	120	182.5
Beam current [mA]	1280	135	26.7	5.0
Luminosity/IP [10^{34} cm^{-2}s^{-1}]	182	19.4	7.26	1.25
Polarization time [s]	15000	900	120	4.6
Natural energy spread [MeV]	17	55	124	287
Radiation losses/turn [GeV]	0.039	0.370	1.869	10.0

Knowing the ECM and the Lorentz boosts (difference between the electron and the positron beam energy at the IPs) as precisely as possible is one of the major challenges for the FCC-ee, since the achievable precision on the energy reconstruction will determine the possible discovery potential. Since in an electron (positron) storage ring the beam energy is directly related to the spin tune it is planned to measure the latter using resonant depolarization (RDP) of transversely polarized beams in combination with a polarimeter. Based on experience at the Large Electron Positron Collider (LEP), this technique is expected to be applicable at the Z-pole and the WW-mode, once a polarization level of 5 to 10 % is achieved. At higher beam energies, harder SR leads to an enhanced energy spread and spin decoherence, so that sufficient polarization can no longer be guaranteed. In certain modes of operation, the energy spread at the IP could be controlled using dedicated monochromatization techniques. In addition to the two average beam energies, the boosts will be reconstructed from dimuon events, i.e. $e^+e^- \rightarrow \mu^+\mu^-(\gamma)$ [5].

Thanks to the unprecedented luminosity a statistical precision of 4 keV and 250 keV on the Z- and the W-mass is predicted [5]. Efforts are underway to reduce the systematic error due to the ECM calibration to a similar order of magnitude. These challenges have first been addressed in [5], and they are continually followed up in the FCC-ee energy calibration, polarization and monochromatization (EPOL) working group [6]. The latest results have been reported at a recent workshop [7] and a few important findings are reported here.

2. Polarization, Spin Tune and Wigglers

In electron or positron storage rings SR photons are emitted by a stochastic process. On average, the emission of 10^{10} photons leads to a spin flip of the electron or positron, G.H. Hoffstaetter in [7].

Furthermore, it was shown in [8] that the probability of photon emission marginally depends on the electron (positron) initial spin state, which leads to the natural maximum polarization of the beam of 92.4 %, anti-parallel (parallel) to the magnetic field. In absence of solenoids or horizontal bending magnets, this means that the beam polarization is fully vertical in a flat machine. Similar to betatron and synchrotron oscillations, also the particle's spin precesses through the lattice. In an ideal electron or positron storage ring, the spin tune (number of precessions per turn) is equal to $a\gamma_{\rm rel}$, with the gyro-magnetic moment, a and the Lorentz-factor, $\gamma_{\rm rel}$. In a realistic storage ring, various processes can lead to depolarization, such as overlap of the beam energy (and spin tune) spread with the spin resonances, spin diffusion by SR, spin resonances with the particle motion in the transverse and longitudinal planes, or vertical closed orbit distortions.

For the FCC-ee at the Z-pole the natural polarization time is 250 h, while at the WW-threshold it is reduced to 15 h. To shorten the polarization time at the Z-pole, the integration of wiggler magnets is foreseen, following the three-block design of LEP [9]. At the Z-pole the planned wigglers reduce the polarization time to 12 h, while the energy spread is increased to 64 MeV, M. Hofer in [7]. The presently foreseen operational scenario is to inject about 200 low intensity (10^{10}) pilot bunches and using the wigglers to achieve about 5-10 % polarization. Once this goal is attained the wigglers are switched off, and subsequently all high-intensity nominal bunches are injected and brought to collision. In the wigglers, photons with a critical energy in the order of a few MeV will be emitted, which could generate neutrons and, thus, impose radiation protection constraints and preclude their use with full intensity.

3. Resonant Depolarization and Polarimeter

As a first step to obtaining the beam energy, the level of polarization of the polarized pilot bunches is decreased by a transverse kicker (RF-kicker). While performing a depolarising frequency sweep, polarization is lost exactly at the spin tune, if the energy spread is sufficiently small, as it is the case at the Z-pole. At the W-pair-threshold, the same method has recently been used successfully in simulations as shown in Fig. 1.

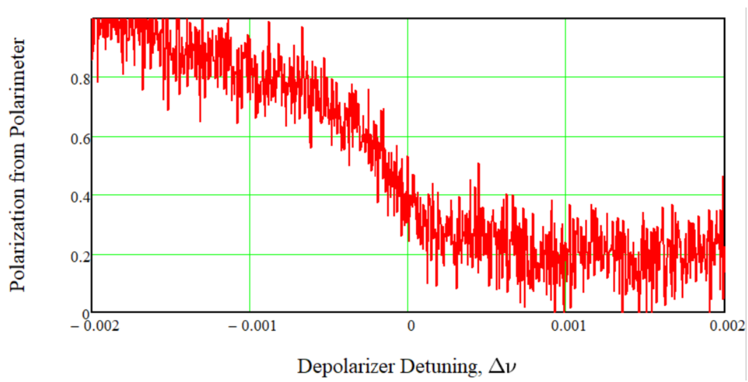

Figure 1: Resonant depolarization at the WW-mode with a depolarization parameter of 2×10^{-4}.

The level of polarization and the change due to RDP is measured with a polarimeter, based on inverse Compton scattering. Laser photons travelling in the opposite direction as the beam interact with the leptons in the so-called Laser Interaction Region (LIR). About 2 m downstream the beam is bent by a dipole with a bending angle of approximately 2 mrad, which separates the leptons which have not interacted with the laser photons from the scattered ones. Detecting the scattered leptons with the minimum energy together with the back-scattered laser photons is assumed to be performed with silicon-pixel detectors, placed approximately 100 m further downstream of the LIR. This structure allows measuring the transverse and the longitudinal direction of the spin-vector and, thus, this technique is known as 3D-polarimetry.

While previously RDP in combination with a polarimeter at LEP has allowed retrieving the beam energy with a accuracy of 1 MeV, the physics requirements for the FCC-ee demand an accuracy in the order of 10 keV, which will be pursued in future R&D studies. As a complementary measurement of the spin tune, it also is proposed to directly observe the spin precession of the scattered electrons or positrons on each turn, in combination with a Fourier analysis to retrieve the spin spectrum. Promising first studies [10], performed for an ideal and simplified electron storage ring with 100 m circumference, suggest that by using the projection of the spin tune on the horizontal and the longitudinal axis, an accuracy of 10^{-5} on the spin tune measurement could be achieved. It has to be noted that polarimeters allow only retrieving the local beam energy at the LIR and, thus, recent studies suggest the integration of one polarimeter per beam upstream of each IP, so that one can reconstruct the local beam energies as close as possible to the IP, aiming to reconstruct the ECM more precisely.

While depolarization of pilot bunches is performed only if the beam energy is being measured, all colliding bunches need to be depolarized regularly, since colliding transversely polarized beams can reduce, or affect, the cross-section of numerous physics events [11]. Investigations for such an RF-kicker design are presently ongoing.

4. From Beam Energy to Centre-of-Mass Energy

For beams colliding head-on with a crossing angle α the ECM reads $\mathrm{E_{cm}} = 2\sqrt{E_{e^-}E_{e^+}}\cos\alpha/2$, where a beam divergence on the order of 10^{-5} is neglected for both beams. The electron and the positron beam energies, E_{e^-} and E_{e^+}, respectively, are not constant over each revolution due to energy losses from SR, beamstrahlung losses, energy shifts due to crossing angles for colliding bunches, or longitudinal impedance. The latter stemming mainly from the resistive wall impedance, are estimated to cause 0.4 MeV loss per revolution at the Z-pole, E. Carideo in [7]. All systematic energy losses need to be compensated by the RF-cavities, including additional systematic biases e.g. from Earth tides as in LEP [12]. Beam energy losses from SR increase with γ_{rel}^4 and reach almost 10 GeV (5.5 %) per turn for the highest beam energy of 182.5 GeV. Beamstrahlung losses experienced by colliding bunches increase with beam energy and bunch population. Ref. [13] shows for the Z-mode, that if all RF-cavities are installed in one straight section for both beams, the ECM is equal to twice the design energy within a few keV. With more than one RF-sections for the main rings, the ECM depends on their location.

Beams colliding with a transverse offset $u = x, y$ and a small nonzero dispersion at the IP experience a shift of the ECM by [5] $\Delta\mathrm{E_{cm}} = -2 * u_0 * \sigma_E (D_{u,1} - D_{u,2})/(E_0(\sigma_{u,1}^2 + \sigma_{u,2}^2))$, with the IP dispersion $D_{u,1}, D_{u,2}$, the transverse beam size $\sigma_{u,1}, \sigma_{u,2}$ and the energy spread of both beams σ_E at the IP. Collision offsets are presumed to be controlled by beam-beam deflection scans. To clearly distinguish the beam-beam effect from the vertical offset at the IP, it is suggested to also store a few non-colliding bunches at the nominal intensity. For example, with a 1 µm residual vertical dispersion at the IP, suggested by T. Charles in [7], performed within the FCC-ee optics tuning working group, e.g. [14, 15], the ECM shift is approximately 100 keV per nm vertical offset at the Z-pole [5].

5. Monochromatization

High precision experiments require reducing the ECM energy spread of colliding beams, especially for observing narrow resonances such as $e^+e^- \to H$ with a width of $\Gamma_H \approx 4.2\,\mathrm{MeV}$ [16], by e.g. introducing opposite sign dispersion at the IP, $D^*_{x/y,1} = -D^*_{x/y,2}$. Contrarily to previous lepton colliders, the FCC experiences strong beamstrahlung and, thus, it is favourable introducing opposite sign horizontal (rather than vertical) dispersion, by additional dipole magnets in the final focus region. They reduce the energy spread from beamstrahlung while limiting luminosity loss since the vertical beam size remains unchanged. Another novel monochromatization technique uses the local chromaticity correction sextupoles for introducing a residual non-zero local vertical chromaticity at the IP. This results in a dependence of the vertical beam size waist on the momentum offset. The merits of both monochromatization methods are presently being explored.

6. Summary and Outlook

The FCC-ee requires an accurate knowledge of the ECM and boosts at the four IPs. The most ambitious design goals are those for the Z-pole and W-pair-threshold, where we aim to reach a systematic uncertainty on the ECM measurement of, respectively, 4 keV and 100 keV. The beam energy will be measured by depolarizing transversely polarized beams and measuring the impact on the 3D polarization vector by polarimeters. At least one polarimeter per beam is required, although the technical and financial feasibility of one polarimeter per IP per beam is presently under investigation, which would allow retrieving the beam energy close to the IPs and, thus, simplify reconstructing the ECM. The ECM itself depends on the RF-location, beamstrahlung, longitudinal impedance, the Earth tides, opposite sign dispersion and collision offsets. Complementary to reconstructing the ECM, in special operation modes, we plan to reduce the collision energy spread by monochromatization, through introducing either dispersion or chromaticity at the IP. To summarize, reducing the systematic uncertainties of the energy measurement to a few keV is one of the key challenges for the FCC-ee, which is being addressed within the framework of EPOL working group. Numerous studies are presently ongoing, and no show-stopper has yet been found.

Acknowledgements

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