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THE STATUS OF THE ENERGY CALIBRATION, POLARIZATION AND MONOCHROMATIZATION OF THE FCC-ee

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Abstract

The Future Circular electron-positron Collider, FCC-ee, is designed for unprecedented precision for particle physics experiments from the Z-pole up to above the top-pair-threshold, corresponding to a beam energy range from 45.6 to 182.5 GeV. Performing collisions at various particle-physics resonances requires precise knowledge of the centre-of-mass energy (ECM) and collision boosts at all four interaction points. Measurement of the ECM by resonant depolarization of transversely polarized pilot bunches in combination with a 3D polarimeter, aims to achieve a systematic uncertainty of 4 and 100 keV for the Z-pole and W-pair-threshold energies respectively. The ECM itself depends on the RF-cavity locations, beamstrahlung, longitudinal impedance, the Earth's tides, opposite sign dispersion and possible collision offsets. Application of monochromatization schemes are envisaged at certain beam energies to reduce the energy spread. The latest results of studies of the energy calibration, polarization and monochromatization are reported here.

INTRODUCTION AND MOTIVATION

With a circumference of 90.6574 km and at least four different operation modes, namely at the Z-pole, W-pair-production, ZH-peak and top-pair-threshold, corresponding to 45.6, 80, 120 and 182.5 GeV beam energy, the Future Circular electron-positron Collider, FCC-ee, has the potential for being the leading Higgs- and Electroweak physics factory of the 21st century [1, 2]. This goal demands precise determination of the centre-of-mass energy (ECM) and collision boosts at up to four interaction points (IPs). Due to the high number of expected di-fermion events, it has been demonstrated in [3] that a statistical precision of 4 and 100 keV is achievable for studying the Z- and W-boson masses respectively. Hence, the aim is to lower current systematic uncertainties for energy calibration to the same order of magnitude using transversely spin-polarized pilot bunches and resonant depolarization (RDP) [4]. At higher energy stages, RDP can no longer be applied due to stronger radiative depolarization. For ZH- and top-pair-production the ECM calibration relies on measurements of di-fermion events, e.g. $e^+e^- \rightarrow Z(\gamma)$ and $e^+e^- \rightarrow W^+W^-$. Thanks to the huge number of such tracked events, a statistical error of approximately 3 and 17 MeV on the ECM is expected, respectively [3,5]. Ways to determine the ECM at all energy stages as precisely as possible are being investigated in the FCC-ee Energy Calibration, Polarization and Monochromatization (EPOL) working group [6], and were first published in [7,8], with the current status being reported here. We note that monochromatization is required at a special operation mode with a beam energy of 62.5 GeV for Higgs-production, which is currently not part of the FCC-ee baseline design, with more information given in [9].

BEAM POLARIZATION

Spin polarization of electron and positron beams in storage rings builds up naturally over time, with a maximum theoretical polarization of 92.4% anti-parallel and parallel to the magnetic guide field [10]. In a perfectly flat machine without solenoids, this means that the polarization is fully vertical. The spin precession through electromagnetic fields is described via the T-BMT equation [11]. The design-orbit spin tune is then equal to $\nu_0 = a\gamma_{\rm rel}$, with the gyro-magnetic anomaly a and the relativistic Lorentz-factor $\gamma_{\rm rel}$. It is demonstrated in [12] for the FCC-ee at 45.6 GeV that the achievable polarization level decreases drastically with increasing vertical closed-orbit distortion, demanding excellent optics tuning, measurement and correction techniques. Recent progress is reported in [13, 14]. In particular, special closed-orbit bumps could be envisaged for improving the polarization in the presence of depolarizing sources such as magnetic or misalignment errors as seen in Fig. 1 [15–17].

Although stored electron and positron beams become spin-polarized naturally over time, in the case of the FCC-ee the natural polarization time is about 250 h at 45.6 GeV. To reduce the polarization time, the current design includes wiggler magnets, following the three-block design of the Large Electron Positron collider (LEP) [3, 18]. The polarization

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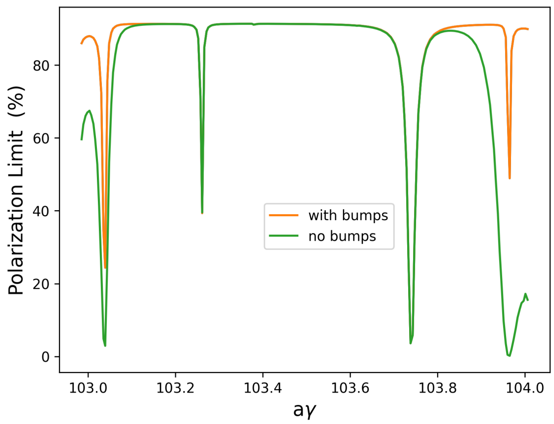

Figure 1: The equilibrium polarization calculated at first order (SLIM level) with and without special closed-orbit bumps, showing the positions of some first-order depolarizing resonances [16, 17].

time is then reduced to 12 h at the Z-pole, while increasing the energy spread to 64 MeV. In the currently-foreseen operational scenario, low-intensity ($\approx 10^{10}$ particles) pilot bunches are injected, and polarized using wigglers. Once roughly 5-10% polarization is achieved after 45 to 90 min, the wigglers are switched off, and subsequently all nominal-intensity colliding bunches are injected and brought to collision. Measuring the beam energy about 5 times per hour by depolarizing 2 pilot bunches, requires approximately 200 pilot bunches per day. Their estimated lifetime is of the order of 10 h for approximately 10^{10} leptons per bunch.

RESONANT DEPOLARIZATION

A transverse-field kicker (RF-kicker) excites one pilot bunch via a TEM-wave travelling towards the beam with a varying tune ω. The proposed tune-changing rate is equivalent to about 1 keV/s of beam energy change and the kick is approximately 1 µrad per turn. Assuming a stripline design located close to the IP with 1 m longitudinal length, magnetic and electric fields of 75 µT and 225 V/m respectively are required at the Z-pole [19]. Once $\omega \pm \nu_0 = n$, with $n \in \mathbb{N}$, the polarization is lost. However, due to the energy spread within the bunch, a slow decrease in the polarization level is observed instead of a sudden fall. The natural width of a spin-resonance line in FCC-ee, due to energy spread and radiative diffusion of the spin-precession phase, is about 200 keV [20] at 45.6 GeV and thus drastically larger than the desired precision. However, it is shown in [21] that using 2 selective RF kickers on 2 pilot bunches and scanning their frequencies in opposite directions allows the resonant frequency, and thus the spin tune, to be determined with a precision better than 10 keV. Recently, RDP has also been simulated successfully for the first time at the W-pair energy [4]. RDP only yields a sufficiently large change in polarization if the spin-modulation index $B = \nu_0\sigma_E/Q_s < 1.5$, with the energy spread σ_E and the synchrotron tune Q_s [22, 23]. This constraint limits the number of synchrotron-tune sidebands inside the distribution of the spin-precession tune.

Residual longitudinal polarization in colliding bunches could modify the cross-section for collisions and thus spoil high-energy physics measurements. It must therefore be controlled to below 10^{-5} [24]. It is thus currently envisaged to achieve this by use of a selective RF kicker acting on those bunches.

A complementary method to RDP, and under current investigation, is to flip the vertical polarization into the horizontal plane and to observe the coherent precession in that plane, known as Free Spin Precession (FSP). The closed-orbit spin tune is then obtained by a Fourier transform of the horizontal polarization over many turns, to yield a full spectrum of the spin motion. Compared to RDP, FSP requires about a 10 times stronger depolarization pulse to perform the spin flip [25].

POLARIMETER

The change of polarization in pilot bunches is measured with a polarimeter in combination with a spectrometer [3]. Thus, before the beam is bent with a 2 mrad horizontally-bending dipole, a pulsed and circularly polarized laser beam shines against the particle beam, crossing its path with an angle of a few mrad in the so-called laser-interaction region (LIR). It is planned to use either a Q-switched Nd:YAG 532 nm, few-nsec pulse-duration laser [3] or a mode-locked Ytterbium 515 nm laser, allowing operation from 10 psec to a few nsec pulse duration [26]. The photons interact with the particle bunch via inverse Compton scattering. Silicon pixel detectors record the back-scattered photons and the scattered leptons [27] about 100 m downstream of the LIR. The optimum design and placement of these detectors is currently being investigated. The current baseline foresees one polarimeter per beam. Nevertheless, one polarimeter per beam per IP could help to measure the FSP between each IP and therefore facilitate the reconstruction of the ECM. The technical and financial feasibility of this is currently being studied.

BEAM ENERGY AND ECM

With one polarimeter per beam the average one-revolution beam energy averaged over the measured bunch to be measured can be obtained using RDP. Precise models for relating these measured beam energies to those at the IP are needed. The ECM ($\sqrt{s}$) for colliding electron and positron beams with beam energies E_- and E_+, respectively, with a crossing angle α is in an ideal scenario $\sqrt{s} = 2\sqrt{E_+E_-}\cos\alpha/2$. Due to strong synchrotron radiation (SR), the beam energy is not constant over one revolution. SR losses are about 39 MeV at the Z-pole, while up to 9 GeV at the top-pair-threshold. However, by integrating RF cavities in the same straight section for both beams an almost-constant ECM is achieved [28]. Colliding bunches experience the electromagnetic field generated by the opposing bunch. This leads to photon emission, known as beamstrahlung, which reduces the beam energy. For example, at the Z-pole this results in roughly 0.31 MeV of energy loss per IP. While

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beamstrahlung leads to bunch lengthening, together with an increased energy spread and energy loss, its impact on the ECM is small [28]. On the other hand, this beam-beam interaction accelerates the particles before collision, while it decelerates them afterwards. This effect modifies the crossing angle, designed to be 30 mrad, by up to 0.6% [29]. Again, however, the ECM is not affected over the luminous region. Wakefields, generated by beams passing through the beam pipe with possible discontinuities such as collimators, RF cavities or BPMs, lead to energy losses characterised by impedances. The resistive-wall effect provides the largest source of impedance in the FCC-ee, leading to an almost uniformly distributed energy loss around the circumference. Such energy losses are estimated to be 0.8 MeV and 1.6 MeV for low-intensity pilot bunches (3×10^{10}) and nominal bunches (2.6×10^{11}) respectively [30].

The ECM shift increases with opposite-sign vertical dispersion (OSVD) in combination with a transverse collision offset at the IP. Recent tuning studies predict an OSVD of 1 µm [31], which leads to an ECM shift of 100 keV per nm of offset [32]. It is presumed that the latter can be reduced by performing beam-beam and luminosity scans, similar to those at LEP or SuperKEKB. Assuming that colliding and pilot bunches display the same OSVD at the IP, it is proposed to determine their dispersion at the IP with a transverse kicker to change the path length of the pilot bunches and measure the resulting orbit change. Since this method does not rely on changing the RF frequency, a possible generation of the flip-flop effect on colliding bunches is avoided.

MONOCHROMATIZATION

In addition to four baseline beam energies, operation with beams of 62.5 GeV is currently being studied, corresponding to the peak of Higgs production. Due to the narrow resonance width of 4.2 MeV monochromatization, allowing reduction of the spread of the ECM, is required. The most direct way to implement this seems to be by introducing opposite-sign horizontal dispersion (see Ref. [33, 34] where a possible solution was presented). Other schemes with vertical dispersion or local non-zero chromaticity are also being investigated.

DETECTOR INPUT

Input from the detectors themselves is vital for the exact calibration of the ECM and collision boosts. At the FCC-Z mode with an instantaneous luminosity ($\mathcal{L}$) of 10^{36} cm^{-2}s^{-1}, about one million di-muon events are expected every 5 min, allowing the determination of numerous quantities. For example, the crossing angle (α) can be reconstructed with a precision of 0.0003 mrad using 10^6 events. Furthermore, the di-muon topology allows the energy boost to be measured on an event-by-event basis and the width of this distribution allows the energy spread ($\sigma_{E_{\mathrm{CM}}}$) to be obtained. It is found that α is linear, proportional to $\mathcal{L}^{1/2}\sigma_{E_{\mathrm{CM}}}^{1/6}$ [29]. Measuring α for various bunch intensities therefore allows extrapolation to zero luminosity and, thus, yields the crossing angle without beam-beam effects, as illustrated in Fig. 2.

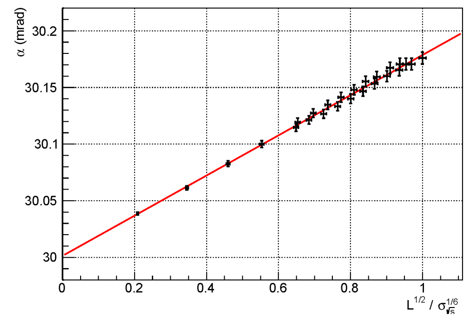

Figure 2: Crossing angle over $\mathcal{L}^{1/2}\sigma_{E_{\mathrm{CM}}}^{1/6}$ [29].

SUMMARY AND OUTLOOK

Performing high-energy particle physics experiments requires a precise knowledge of the ECM and collision boosts at all IPs at the FCC-ee. Reduction of the systematic uncertainties on these measurements is one of the key challenges, and this is being addressed in the EPOL working group. For the Z- and W-pair modes, due to the high number of collision events, a statistical precision 4 and 100 keV is expected, respectively. The aim is therefore to achieve the same order of magnitude for systematic uncertainties. The beam energy is measured by depolarizing low-intensity, previously polarized pilot bunches with an RDP, and measuring the change in the polarization with a laser-based polarimeter. While one polarimeter per beam is the baseline, the merits of one device per beam and IP are currently being explored. The main contributions to the ECM are the beam energies, the crossing angle, the bunch population, impedance energy losses, beamstrahlung energy losses, opposite sign vertical dispersion and collision offsets. Studies of methods to measure and mitigate the numerous effects and allow the ambitious precision-goals to be achieved are currently ongoing. No show-stopper has been found so far.

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