Precision Energy Calibration for a Future Circular Electron-Positron Collider

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Abstract

The Future Circular Collider integrated project foresees as a first stage a high-luminosity electron-positron collider (FCC-ee). A key component of the FCC-ee physics program is the accurate determination of the collision energy. On the Z pole and around the W pair threshold, the average beam energy needs to be measured with extremely high precision (ppm level) using the technique of resonant depolarization. At higher energies the polarimeter infrastructure could be used to extract the local beam energy using Compton back scattering. In either case, the centre-of-mass energy of the collisions must be derived by applying further corrections. Dimuon events $e^+e^-\rightarrow\mu^+\mu^-$ recorded by the detectors provide a complementary measure of the centre-of-mass energy spread, of the beam crossing angle (required for determining the centre-of-mass energy from the beam energies), and of the e^+ vs. e^- energy difference.

A key component of the FCC-ee physics program is the extremely precise (ppm) measurements of the W and Z masses and widths [1,2,3]. To this end, the centre-of-mass collision energy should be determined at similarly high precision [4], benefitting in turn many other EWPO measurements.
On the Z pole and around the W pair threshold, transverse self-polarisation (Sokolov-Ternov effect), possibly achieved with the help of harmonic closed-orbit spin matching [5], should enable an extremely precise measurement of the average beam energy, using the technique of resonant depolarization. This approach is extrapolated from the successful energy calibration at LEP 1 [6]. An operation scheme based on regular measurements of the beam energy by resonant depolarization of pilot bunches, during physics data taking, is proposed, which includes the use of polarization wigglers [4]. This scheme needs to be further elaborated.
At higher energies, other approaches need to be employed, e.g. techniques from LEP 2, such as combinations of spectrometer dipole magnets with calibrations at lower energy, synchrotron tune dependence on RF voltage, or recorded $e^+e^- \rightarrow Z\gamma$, ZZ and WW events [7,8,9,10]. The polarimeter infrastructure could also be used to extract the local beam energy using Compton back scattering [11,12], albeit with lesser precision than attainable by resonant depolarisation.
In either case, the centre-of-mass energy of the collisions must still be derived from the average or local beam energy by applying further corrections, related to the beam acceleration, synchrotron radiation, wake fields, beamstrahlung or even subtler effects at the collision point. All these effects, and additional new ones perhaps, need to be tracked, monitored and corrected for.
The high rate of dimuon events $e^+e^- \rightarrow \mu^+\mu^-$ (10^6 new events at the Z pole every 5 minutes in each experiment), allows the determination of the beam crossing angle, the centre-of-mass energy spread, and the e^+ and e^- energy difference, through the non-collinearity of the two muons.
Outstanding issues and questions for FCC-ee energy calibration include [4]:

1. The tools used for simulations of the orbit and optics correction processes, and of the simultaneous optimization of luminosity and polarization (e.g., SAD, MAD, Lifetrack, BBWS, Bmad, SITROS, SLICKTRACK) in realistic machines, including spin matching [13], should be further developed, modernized and integrated. This is essential to confirm the feasibility and operability of the proposed data taking scheme. The underlying knowledge, especially for modelling the self-polarization and maximising polarization in practice via subtle machine tuning, has to be transferred to the young generation.
2. The design of the diagnostics allowing control of the beam-beam offsets and the measurement of residual dispersion at the interaction point. These diagnostics will allow the centre-of-mass energy shifts to be reduced and monitored, but it should also benefit the optimization of luminosity.
3. The resonant depolarization process and its sensitivity to the energy spread and synchrotron tune should be explored to optimize the procedures and the machine settings.
4. A detailed design of wigglers including proper management of the radiation is required.
5. The polarimeter design should be scrutinized and integrated in the collider layout. Its use for Compton-backscattering based measurements [12] and the precision and stability of the available beam momentum measurement should be explored.
6. A thorough assessment and possible further reduction of the energy-point-to-energy-point systematic uncertainties. This exercise involves, amongst others, the development of an energy model and a thorough design of the monitoring devices.

In a configuration where the Z run is scheduled at the beginning of the life of FCC-ee, all procedures, instrumentation, data processing and analyses should be ready well before the commissioning of the machine.

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