FDS Working group on Center-of-mass Energy, Polarization and Monochromatization

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Context

Upon recommendation by the European Strategy Group in 2020, CERN undertakes, in collaboration with its international partners, a technical and financial Feasibility Design Study (FDS) of the Future Circular Colliders, with the FCC-ee, described in the CDR[1], as a first step. It has been shown that the availability of centre-of-mass energy calibration using resonant depolarization of the stored beams would provide the basis for unique precision measurements of the Z and W boson mass and width and other fundamental properties. Furthermore, the feasibility of monochromatization would offer the unique possibility of measuring the Higgs Yukawa coupling to the electron. The FCC-ee Energy Calibration and Polarization working group demonstrated[2], at the outset of the Conceptual Design Study, that the precise energy calibration program was feasible, conditional to a number of further developments; the group established a first list of R&D to be pursued.

Monochromatization schemes have been proposed, but a satisfactory performance still needs to be established.

These studies have to be deepened in the framework of the FDS, with the aim of reaching feasibility conclusions and costed design included in the FDS report (FDR) in 2025. This will require joint efforts from the world-wide accelerator and experimentalist communities.

Goals

The goals of the working group on Center-of-mass Energy, Polarization and Monochromatization (EPOL), in the context of the FDS, are as follows (they are developed further in [3] and [4]). The following list is for discussion and correction.

1. For centre-of-mass energy calibration:
    - confirm the technical feasibility and the performance of the scheme proposed in [2], by sufficient level of simulations; in particular complete the study of the depolarization method and its precision at the W energy.
    - 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.
    - In particular, the mitigation of collision effects such as opposite sign dispersion should be developed.

- The design and implementation of the instrumentation must be completed and costed; this includes e^+ and e^- polarimeter/spectrometer, wigglers, depolarization kicker and possibly additional IR instrumentation such as beamstrahlung monitors.
- The simultaneous and coordinated operation of the accelerator, of the continuous polarization and depolarization measurements, and of the beam monitoring devices, should be analysed in order to ensure a precise extrapolation from beam energies to the knowledge of centre-of-mass energy and energy spread.
- The contributions of the particle physics experiments to the determination of the centre-of-mass energy and its spread should be quantified and integrated in analysis and operation.

2. For monochromatization:
   - The schemes of combination of schemes able to provide monochromatization should be investigated quantitatively to establish the feasibility of useful monochromatization.
   - At the same time the experimental working group should explore further the optimization of purity and efficiency for the selection of Higgs s-channel production, possibly taking into account the specific beam set-ups.
   - Realistic implementation scenarios should be proposed and analyzed with the tools developed above.
   - The monitoring developed at the Z and W energies for ECM determination should be adapted for the Higgs s-channel production and possible additional actions to be foreseen should be identified and studied.

Organization

To be discussed with senior members of the group: Angeles Faus-Golfe, Eliana Gianfelice, Ivan Koop, Katsunobu Oide, Tatiana Pieloni, Frank Zimmermann.

References (here are some latest references)

[1] FCC Collaboration, A. Abada et al., FCC-ee: The Lepton Collider, The European Physical Journal Special Topics 228 (Jun, 2019) 261-623.

[2] A. Blondel, P. Janot, J. Wenninger (ed.) et al., Polarization and Centre-of-mass Energy Calibration at FCC-ee, arXiv:1909.12245

[3] A. Blondel and E. Gianfelice, “The challenges of beam polarization and keV scale centre-of-mass energy calibration at the FCC-ee”, in A future Higgs and Electroweak factory (FCC): Challenges towards discovery, EPJ+ special issue, Focus on FCC-ee.

[4] A. Faus-Golfe, M. A. Valdivia Garcia and F. Zimmermann, “Challenges of monochromatization”, in A future Higgs and Electroweak factory (FCC): Challenges towards discovery, EPJ+ special issue, Focus on FCC-ee.

Appendix: a first list of possible work packages for the Energy calibration (monochromatization not included)

A- Simulations of spin-tune to beam energy relationship
-A1a- Benchmarking of BMAD with SITROS

-A1b- Implementation of FCC-ee optics in existing code (BMAD) to evaluate, both at first order ("SLIM" or improved version with thick lenses) and with multi-turn spin tracking, the relationship between nominal energy, ECM, the polarization level, and of the (calculated) spin tune of the two beams (also the beam energies at the position of the LBIP of the respective polarimeters, see below).

-A2- implementation of polarization calculations and procedures in the MADx simulation code for FCC-ee. Benchmark against the BMAD implementation.

-A3- Simulation of the resonant depolarization process in view of establishing the depolarizer parameters, the depolarization procedures. Study the possible deviations from the relationship between the calculated spin tune and measured resonant depolarization frequency. This relationship might be affected by interference with various single particle and collective oscillations. Establish the accuracy reachable for the resonant depolarization at the Z pole (ECM=88-95 GeV), WW threshold (ECM=158-164 GeV) and single-Higgs energies (ECM= m_{Higgs}).

-A4- Effect of imperfections: simulate, one at the time, the various imperfections affecting the accelerator -- polarization is particularly sensitive to effects generating vertical dispersion, x-y betatron coupling and any spurious spin rotation -- and any residual effect on the above relationships; beam energy itself is particularly sensitive to the main magnetic field and ground motion. Systematic study of absolute and point-to-point ECM errors.

-A5- Spin and energy correction knobs and procedures establish the list and suggest an ordering of required correction procedures, acting on each beam individually (individual energy tuning, spin matching, vertical dispersion) or for both beams (main dipole, RF shift).

B. Simulation of the relationship between beam energies and centre-of-mass energy.

-B1- Collision effects on centre-of-mass energy: opposite sign horizontal and vertical dispersion combined with collision offsets, leads to a shift in centre- of-mass energy. Possible remedies are as follows
-- detection of the offset by detection of induced vertical or horizontal excitation
-- detection and measurement of the offset and its sign by use of low angle radiative Bhabha scattering or beamstrahlung
-- measurement of the horizontal or vertical dispersion
-- detection and measurement by experiment of position dependence of average ECM or CM boost upon one of the axes at the interaction point.
NB contrary to the deviations in the spin-tune to energy relation, the relation between collision offsets

and dispersion and the resulting energy shifts does not have a hidden ECM dependence other than the randomness of imperfections.

-B2- Design and performance of the low angle/beamstrahlung monitors

These are low angle calorimeters in a region where a considerable amount of soft radiation will be present from the collision point. This is also related to the MDI work.

-B3- Monitoring of opposite sign dispersion and possible offsets in the PP detectors

This was done using large angle muons in the EPOL paper [2], for the primary sake of measuring the ECM spread. Work should be extended to the detection of the effects listed in B1 above, and of the monochromatization (see point D below)

-B4- Beam energy losses around the ring

One of the sources of uncertainties on ECM is the proper calculation of the energy loss of the beams around the ring (saw-tooth). This can be calculated from the orbit but can also be monitored from

-- the energy difference between e+ and e- particles resulting in a well-measured CM boost in the experiments.

-- the measurement of the beam energy in the polarimeter/spectrometers

-- and other means of control such as beam positions in dispersion regions etc.

C. Polarimeter design and performance

The two compton backscattering polarimeter/spectrometer devices are little experiments of their own. They study the recoil photon e+(or e-) as well as the backscattered photon. In principle this device can be used to extract all three components of the polarization vector at the location of the interaction point of the laser with the beam (LBIP). The polarization transverse to the accelerator plane can be obtained both from the photons and the charge lepton. The end-point of the recoil lepton provides a measurement of the beam momentum at the LBIP, which can be used as a precious relative monitor of the beam energy with potentially different point-to-point systematics than the RDP measurement.

-C1- Bibliography

retrieve documentation on historical examples of backscattered laser compton polarimeters:
LEP, Hera, SLC, ILC etc. Review existing work ongoing on EIC and FCC-ee.

-C2-Possible collaboration

review possible groups involved in polarimeter activities globally, establish contact and organize possibly kick-off meeting.

-C3- Overall specifications

We assume that the design will be based on N. Muchnoi design as in arXiv:1803.09595v1 arXiv:1909.12245v1

-- define possible beam-laser interaction points specifying requirement on available space for laser injection, laser collision point, detection of scattered photon and electron.

-- given the foreseen use, define electron bunch populations, beam sizes, specify desirable photon spot size and intensity. (uses are: depolarization of pilot bunches, measurement of polarization of colliding bunches, beam energy measurement)

-- Compare to past and existing designs

-- Specify parameters of the laser (wavelength, repetition rate, intensity, instantaneous and average

power, precision of laser polarization)
-- specify size and rates, resolution and accuracy for the detectors of scattered photons and electrons

-C4- Insertion in the storage ring
define location and study synchrotron radiation exposure; design laser ports and mirrors, beam exit ports; consider transverse mode coupling to circulating beams and sources of heating; propose detailed design.

-C5- Laser light box: compile desired polarization states for the laser, design laser light box accordingly, controls and monitoring in synchronization with accelerator bunches

-C6- Detector
1. Photon counter design photon counter for detection of transverse movement of backscattered photon beam, foresee electronics able to deal with pilot bunches and colliding bunches. Arrange movable SR shielding and data acquisition
2. Spectrometer and electron counter

- Specify the spectrometer magnet, measurement and control of relevant magnetic field
- Design electron detector – preferably as one single mechanical unit with photon detector. Specify precision or measurement of construction accuracy and stability.
- Design electronics as above, data acquisition and the possible need for online processing

-C7- Overall data acquisition and operator interface
describe possible operation mode, operator interface for input and output of results. Possibly connect with other polarization-related operation systems (spin correctors, injection etc.)

D. Measurements in Particle Physics Experiments

-D1- muon pairs will provide measurements of the distribution of i) ECM boost, ii) ECM value; possibly as a function of the coordinates (x, z, t – it is assumed that vertical coordinate cannot be distinguished) of interactions. It was already shown in [2] that one can extract the ECM energy spread, the average $<E_{e+} - E_{e-}>$, the collision angle and possibly monitor the relative ECM between the scan points of the Z resonance or WW threshold, or[3] on the Higgs resonance. The following remains to be determined
-- possibility to evaluated the opposite sign dispersion and ECM spread in the horizontal plane (x-dependence of longitudinal boost distribution)
-- possibility to evaluate opposite sign dispersion in the longitudinal plane (z and t dependence of longitudinal boost distribution)

-D2- Independent ECM determination and point-to-point uncertainty
The muon pairs and possibly the Bhabha scattering events might be able to provide a measurement of ECM. Evaluate the precision that can be achieved for the ECM relative and absolute measurements. This point requires
-- understanding of the QED corrections to ECM and their ECM dependence.
-- understanding of the stability of the momentum and energy determinations.
-- detector magnetic field stability and small corrections related to the change in magnetic fields of the accelerator components when changing the ECM setting.
-- possible calibration of detector magnetic system using fixed candles such as J/ψ, K_s decays etc.

-D3- Application to the monochromatization scheme

Investigate the possibility to use the above studies for

-- a demonstration of the monochromatization scheme at the Z pole energy taking advantage of the high statistics of dimuons, and evaluation of the performance and monitoring precision.

-- monitoring of the monochromatization if running at the H(125) energy.

-D4- Tracking of the overall ECM calibration results

The participation of experimenters in the EPOL group is essential to understand the nature of the sources of ECM uncertainty and variability, and monitor progress by evaluating their impact on the uncertainties on the precision measurement.