EPOL:
The roadmap to the final report

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On behalf of the
FCC-ee EPOL working group

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FCC-ee Overview

- **Particle Physics:**
  - Higgs and electro-weak factory
  - 4 baseline beam energies and diverse particle physics program
    - 45.6 GeV: Z-pole
    - 80 GeV: W-pair-threshold
    - 120 GeV: ZH-production
    - 182.5 GeV: top-pair-threshold
  - High number of statistics

- **Accelerator Physics:**
  - 4-fold super-symmetric layout
    - Up to 4 Interaction Points (IPs)
    - 1 RF-section per beam
    - 1 collimation section
    - 1 section for injection and dump
  - Nanometer beam size at IPs
  - Strong synchrotron radiation

Precision particle physics experiments  Center-of-mass energy determination
Center-of-mass Energy Uncertainty

**Absolut scale error (abs)**
- Error between measured and true $E_{cm}$
- Large effect on mass measurement
- Stems from systematic errors

**Point-to-point errors (ptp)**
- Fluctuation between measurements
- Large effect on resonance width measurements
- Stems from variability of measurement conditions

Courtesy: A. Blondel
Expected Precision

<table>
<thead>
<tr>
<th>Quantity</th>
<th>statistics</th>
<th>$\Delta E_{CM_{abs}}$</th>
<th>$\Delta E_{CMSyst-\gamma}$</th>
<th>calib. stats.</th>
<th>$\sigma E_{CM}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_Z$ (keV)</td>
<td>4</td>
<td>100</td>
<td>28</td>
<td>1</td>
<td>(84) ± 0.05 MeV</td>
</tr>
<tr>
<td>$\Gamma_Z$ (keV)</td>
<td>4</td>
<td>2.5</td>
<td>22</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>$sin^2 \theta_W^{\text{eff}} \times 10^6$ from $A_{FB}^{\mu\mu}$</td>
<td>2</td>
<td>-</td>
<td>2.4</td>
<td>0.1</td>
<td>-</td>
</tr>
<tr>
<td>$\frac{\Delta \alpha_{QED}(M_Z)}{\alpha_{QED}(M_Z)} \times 10^5$</td>
<td>3</td>
<td>0.1</td>
<td>0.9</td>
<td>-</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Further clarification ongoing

- $m_W$ (MeV) 0.200 (?) 300 keV 75 keV?
- $\Gamma_W$ (MeV) (75?) small OK

- Large expected luminosity $\rightarrow$ huge statistics $\rightarrow$ small statistical error: $4 / 100$ keV per $Z / W$ - boson
- Aim to achieve same order of magnitude for systematic errors $\rightarrow$ Scope of the EPOL working group
- EPOL: Energy calibration, polarization and monochromatization

arXiv:1909.12245
How to?

Special mode: monochromatization

Detector input

Polarization build-up -> Depolarization -> Polarimetry -> ECM

- Resonances
- Wiggles
- Beam tests
- Resonant depolarization
- Free spin precession
- Polarimeter incl.
- Laser, Si-detectors
- E.g. EIC experience
- Systematic errors
- Statistical errors
- Accurate models
Polarization Build-Up

- Statistically every $10^{10}$ emitted synchrotron photon flips the spin
- Probability depends on the initial spin orientation

- Leads to a natural polarization build-up over time
- Orientation is anti-parallel to the guiding magnetic field

- Maximum theoretical polarization of 92.4 %
- Spin precesses through the lattice → Spin tune

\[ \nu = a \times \gamma_{\text{Rel}} \]

\( a \) ... gyro-magnetic anomaly
\( \gamma_{\text{Rel}} \) ... Lorentz-factor
Resonances and Orbit Bumps

- Polarization decreases with resonances, orbits, machine errors etc.
- Improved with special closed-orbit bumps

- Example: at 45.394 GeV → ν = 103.016
- Maximum polarization improved from 60 to 87 %
- Requires orbit and angle measurement between dipoles

- What is the max. allowed closed orbit for polarization?
- How many BPMs are needed where, with which precision?
- Can this scheme be tested somewhere?

Courtesy: Y. Wu
Beam Test Polarization and Bumps

- KARA at KIT, polarization time ~ 10 min
- Polarization measurements via Touschek lifetime change

Possible beam test:
- Generate strong depolarizing source
- Find orbit bumps to increase max. polarization

Can FCC-ee orbit bumps be tested at KARA?

Possible long term idea: Is it possible to install and test an FCC-like polarimeter?

Courtesy: B. Härer, E. Blomley
Wigglers

- At 45.6 GeV energy: Polarization time of 248 h
- Solution: wiggler magnets
  - Reduce polarization time to 12 h
  - Increase energy spread by factor ~ 3.5
- **Aim to have a realistic design of wiggler magnet.**

![Graph of wigglers showing beam parameters and magnetic field configurations.](image)
Operational Scenario

- Inject a few (100-200) non-colliding pilot bunches (~$10^{10}$ ppb)
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- Switch on wigglers until ~5-10% **vertical polarization** reached
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• Switch wigglers off
Operational Scenario

- Inject a few (100-200) non-colliding pilot bunches (~$10^{10}$ ppb)

- Switch on wigglers until ~5-10 % **vertical polarization** reached

- Switch wigglers off and inject ~$10^5$ colliding bunches (~$10^{11}$ ppb)
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• Switch wigglers off and inject ~$10^5$ colliding bunches (~$10^{11}$ ppb)

• Measure beam energy with pilots while collisions take place

• **What is the minimum required polarization level?**

• **Which pilot bunch intensities are required?**

• **What is their lifetime and do they need to be topped-up?**
Resonant Depolarization

- Independent depolarizers per beam
- Easily accessible for maintenance
- TEM wave propagating towards a pilot bunch
- Varying exciting frequency

- Exciting frequency = spin tune = depolarization

Natural width ~ 200 keV at Z
And 1.4 MeV at W

Where is the best location for depolarizers?
Do we need to scan in opposite directions simultaneously? (2 depolarizers per beam?)

Courtesy: I. Koop
Free Spin Precession

- Stronger depolarizer kicks the vertical spin into other plane
- Observation of oscillation between these planes
- Spin tune obtained via Fourier Transform
- Yields the full spin spectrum

- Is this technique feasible in a realistic machine?
- How often should this be performed?
- Can we flip the spin and re-use the same bunches?

Courtesy: I. Koop
Polarimeter

- In present experimental interaction region design space foreseen, but possibly more space in RF-section

- *Where is the best integration point for the polarimeters?*
Polarimeter

- ~520 nm circular polarized laser interacts with beam
- Back-scattered photons sufficient for resonance measurement
- Additional measurement of scattered electrons for 3D spin vector
- At least 1 polarimeter per beam

- What can be gained more polarimeters?
- Can we learn from other projects, such as from EIC-experts?
Colliding Bunches Polarization

• Take away message:
  - **Longitudinal** polarization could spoil measurements and must be < 10^{-5}
  - Depolarizers must also act on colliding bunches → Consider closed-orbit bumps to avoid impact at IP
  - To be measured also with polarimeters

  - What could be the impact of RF-kickers acting on colliding bunches?
  - Which RF-kicker and polarimeter design is the most suitable for pilot and colliding bunches?

[Graphs showing longitudinal polarization effects] Courtesy: I. Koop
From Beam Energy to $E_{CM}$

- 40 MeV synchrotron radiation losses per turn
- Additional beamstrahlung (BS) (synchrotron radiation due to field of colliding bunch) $\lesssim 0.62$ MeV/beam/IP

- **Same RF-section for both beams** to compensate losses
  - $\Delta E_{cm} \sim -8$ keV (PA, PD) and $\sim 0.7$ keV (PG, PJ)
  - Boosts $\sim +/- 10$ MeV (PA, PD) and $\sim +/- 30$ MeV (PG, PJ)

- Pilot and colliding bunches have different local energy
- Accurate models essential
- *What are the systematics between pilot bunches and colliding ones?*
Dispersion and Collision Offset

\[ \Delta \sqrt{s} = -u_0 \frac{\sigma_E^2 \Delta D^*}{E_0 \sigma_u^2} \]

\[ |\Delta \sqrt{s}| = 96 |u_0| \text{ [keV/nm]} \]

for \( \Delta D^* = 1 \, \mu\text{m} \), \( \sigma_E/E = 0.13\% \)

For \( \Delta D^* = 10 \, \mu\text{m} \), the CM error is \( \sim 1 \, \text{MeV/nm} \), i.e., the uncertainty on / average separation must be below \( u_0 < 0.1 \, \text{nm} \) to limit the systematic errors < 100 keV.

- Measurement and control of dispersion and collision offsets at IP essential
  - \( \Delta D < 1 \, \mu\text{m} \) relaxes requirements on collision offsets

- Can it be demonstrated that collision offsets can be controlled to \( \sim 0.1 \sigma_y \)?

- How can we best measure dispersion at the IP? (RF-shift, orbit bump)

J. Wenninger: Beam-beam and OSVD
Experiments

- G. Wilkinson: *Di-muon events* - “The gift that keeps on giving”
- Reliable and frequent logging of parameters essential
- Possibility to measure Z-bosons from higher $E_{cm}$ events

Important message

All these results come from ‘proof-of-principle’ studies. They need to be repeated and consolidated with state-of-the-art ISR generators, proper simulation, realistic treatment of detector resolutions etc., and extended to other fermion types and (in top regime) WW events. Many important & interesting studies to be performed!

One million di-muon events per 8h shift
~ 5 keV statistical precession achievable

$10^6$ dimuon events at Z-pole: $e^+e^- \rightarrow \mu^+\mu^- (\gamma)$
($\gamma$)… Initial-State-Photon (ISR)

Boost reconstruction from di-muon events
Monochromatization

- 62.5 GeV beam energy corresponds to the peak of Higgs-production with narrow width of 4.2 MeV
- For minimization of collision energy spread → monochromatization techniques required
- What is the most suitable monochromatization technique and how can it be implemented?

Introducing dispersion

\[ e^- \quad e^+ \]

Same sign dispersion at the interaction point leads to change of \( E_{CM} \)

\[ e^- \quad e^+ \]

Opposite sign dispersion helps reducing \( E_{CM} \) spread

Introducing chromaticity

Non-zero local vertical chromaticity to reduce collision energy spread presently explored

Courtesy: A. Faus-Golfe, H. Jiang and P. Raimondi
Summary

• High precision particle physics experiments require excellent determination of $E_{cm}$ and collision boosts

• Presently aimed to achieve $4 / 100$ keV systematic uncertainty for the $Z$- / $W$- mass $\rightarrow$ EPOL

• A lot of great results produced so far and summarized in the mid-term report and FCC-note

• Many questions aimed to be answered until the end of the feasibility study, including beam tests

Regular EPOL meetings:
indico.cern.ch/category/8678/
Typically every second Thursday 16:30-18:30

Mailing list:
fcc-ee-PolarizationAndEnergyCalibration@cern.ch

Self-subscription from:
https://e-groups.cern.ch/e-groups/EgroupsSearch.do

Any help is welcome!
Thank you!

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FCC Week 2023
London, United Kingdom
June 08, 2023
Algorithm for disentangling of SR and coherent losses

Two beam Energies in a detector $E_e, E_p$ depend on beam currents $I_1, I_2$ (coherent losses) and on SR losses. These dependences can be parametrized via simple power law:

$$E_e = E_1 + a_1 \cdot (I_1)^\alpha + b_1 \cdot (E_1)^\beta$$
$$E_p = E_2 + a_2 \cdot (I_2)^\alpha + b_2 \cdot (E_2)^\beta$$

- where $E_1, E_2$ - RD-energies; $I_1, I_2$ – beam currents; $\alpha, \beta$ – the coherent and the SR power law degrees $a_1, a_2, b_1, b_2$ – unknown fit coefficients.

In our MC simulation we chose $\alpha=1$, $\beta=4$. Power law index $\alpha$ can be measured/fitted by interpolation of the closed orbit shift dependence on the current in high dispersion places near RF straight section (Jorg’s remark at august 2022 EPOL meeting).

Energy boost: $E_e - E_p = E_1 - E_2 + a_1(I_1)^\alpha - a_2(I_2)^\alpha + b_1(E_1)^\beta - b_2(E_2)^\beta$

N equations: $n=1, 2, ..., N$ with known $E_1, E_2; I_1, I_2; \alpha, \beta$; and with unknown linear fit coefficients $a_1, a_2, b_1, b_2$. The reconstructed c.m. energy is a sum of beams energy:

$$E_{cm} = E_e + E_p = E_1 + E_2 + a_1(I_1)^\alpha + a_2(I_2)^\alpha + b_1(E_1)^\beta + b_2(E_2)^\beta$$