Future Circular Collider Feasibility Study

FCCee Centre-of-mass calibration and Polarization, Monochromatization (EPOL)

A beamstrahlung monitor?

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A. Blondel FCC-EPOL Welcome Introduction
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, and simulating the resonant depolarization itself. 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.

- The mitigation of collision effects such as opposite sign dispersion should be developed. Should verify that Polarization at IP is 0 for colliding bunches within precision required for cross-section and $A_{FB}^{\mu\mu}$.

- 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 or low angle radiative Bhabha 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.
Beam Polarization can provide two main ingredients to Physics Measurements

1. beam energy calibration by resonant depolarization
   measure the fractional part of
   \[ \nu_s = \frac{g - 2}{2} \frac{E_b}{m_e} = \frac{E_b}{0.4406486(1)} \]
   → low (transverse) polarization required (~10% is sufficient)
   → at Z & W pair threshold comes naturally \( \sigma_E \propto E^2/\sqrt{\rho} \)
   → at Z use of asymmetric wigglers at beginning of fills
     since polarization time is otherwise very long (250h→ ~1h)
   → should be used also at ee → H(126)
   → use ~200 ‘pilot’ bunches and calibrate continuously
     during physics fills to avoid issues encountered at LEP
   → Compton polarimeter for both e+ and e-
   → should calibrate at energies close to half-integer spin tune
   → must be complemented by analysis of «average EBeam-to-E_Cm» relationship

For beam energies higher than ~90 GeV can use ee → Z\( \gamma \) or ee → WW events
   to calibrate \( E_{CM} \) at ±1-5 MeV level: \( m_H \) (5 MeV) and \( m_{top} \) (20 MeV) measts
RESONANT DEPOLARIZATION

Once the beams are polarized, an RF kicker at the spin precession frequency will provoke a spin flip and complete depolarization.

Simulation of FCC-ee by I. Kopp:

\[ \delta \theta_{\text{spin}} = \left( \frac{g-2}{2} \right) \frac{E}{m} \delta \theta_{\text{trajectory}} \]
\[ = \nu \cdot \delta \theta_{\text{trajectory}} \]
\[ \nu = \frac{E_{\text{beam}}}{0.4406486} \]
\[ = 103.5 \text{ at the Z peak} \]

RD precision expected to be \( \sim 5 \times 10^{-7} \). \( E_b \sim 25 \text{ keV} \)

Figure 39. Simulation of a frequency sweep with the depolarizer on the Z pole showing a very sharp depolarization at the exact spin tune value.
From beam energy to $E_{\text{CM}}$

$$\sqrt{s} = 2\sqrt{E_{b}^+ E_{b}^- \cos \alpha/2}, \quad \approx E_{b}^+ + E_{b}^-$$

Energy gain (RF) = losses in the storage ring
Synchrotron radiation (SR)
beamstrahlung (BS)

$$\Delta_{\text{RF}} = 2\Delta_{\text{SRi}} + 2\Delta_{\text{SRe}} + 2\Delta_{\text{BS}}$$

at the Z (O of mag.):

$$\Delta_{\text{SR}} = 2\Delta_{\text{SRi}} + 2\Delta_{\text{SRe}} = 39 \text{ MeV}$$

$$\Delta_{\text{SRe}} - \Delta_{\text{SRi}} \approx \alpha/2\pi \Delta_{\text{SR}} = 0.20 \text{ MeV}$$

$$\Delta_{\text{BS}} = 0 \text{ up to 0.62 MeV}$$

the average energies $E_0$ around the ring are determined by the magnetic fields

$\Rightarrow$ same for colliding or non-colliding beams
-- measured by resonant depolarization
-- can be different for $e^+$ and $e^-$

$$E^+ = E_{0}^+ + 0.5\Delta_{\text{RF}} - 2\Delta_{\text{SRi}} - \Delta_{\text{SRe}} - 1.5\Delta_{\text{BS}}$$

$$E^- = E_{0}^- - 0.5\Delta_{\text{RF}} - \Delta_{\text{SRi}} - 0.5\Delta_{\text{BS}}$$

$$\Rightarrow E^+ + E^- = E_{0}^+ + E_{0}^- (+ \Delta_{\text{SRe}} + \Delta_{\text{SRi}})$$

$\leftarrow E_0$ at half RF

**single RF system** $\Rightarrow E^+ + E^-$ constant
if $e^+$, $e^-$ energy losses are the same
(mod higher order corrections)

**cross-checks:** $E^+ - E^-$ (boost of CM),
+ measured Z masses!

$\Rightarrow E^+ + E^- = E_{0}^+ + E_{0}^- (+ \Delta_{\text{SRe}} - \Delta_{\text{SRi}})$
--- Study has converged on **1 baseline layout** (and 2 fallback solutions)
--- 8 pits (was 12) total circumference of 91.173km (was 97km in CDR) → cost savings. Luminosity smaller by ~10%
--- Consistent with ee (2 or 4IP), hh; flexibility. Optimization of 4IP parameters under study for realistic machines.

--- **Placement of RF stations has made considerable progress** (point B unpractical, L,H preferred, F possible)
  --- 1 RF point for Z, WW, HZ, (eeH) acceleration of e+ and e- in separate RF cavities (low gradient, high current)
    eliminate uncertainties on $E_{cm}$ due to beam energy losses (synchrotron radiation, beamstrahlung)
  --- 2 RF points (HZ), tt ($E_{cm} = 340-365$) e+ and e- acceleration in the same RF cavities (low current, high gradient)
    → centre of mass boosts!

08.03.2022  Alain Blondel  FCC PE&D; NEWS  7
Approximate energy loss per turn (91.3km machine)

<table>
<thead>
<tr>
<th>E_{cm} (GeV)</th>
<th>E_{beam}</th>
<th>\Delta E_{beam} (GeV)</th>
<th>\Delta E_{cm} (GeV)</th>
<th>\Delta E_{turn} (GeV)</th>
<th>\text{maximal boost } P_{cm}</th>
</tr>
</thead>
<tbody>
<tr>
<td>91</td>
<td>45</td>
<td>0.039</td>
<td>0.030</td>
<td></td>
<td></td>
</tr>
<tr>
<td>125</td>
<td>62.5</td>
<td>0.140</td>
<td>0.105</td>
<td></td>
<td></td>
</tr>
<tr>
<td>160</td>
<td>80</td>
<td>0.374</td>
<td>0.280</td>
<td></td>
<td></td>
</tr>
<tr>
<td>240</td>
<td>120</td>
<td>1.89</td>
<td>1.420</td>
<td></td>
<td></td>
</tr>
<tr>
<td>350</td>
<td>175</td>
<td>7.98</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>365</td>
<td>182.5</td>
<td>10.0</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

scaling law: \( E^4 / \rho \): increase of 6% with new 91.3km layout

\[
\Delta E_{cm} = \Delta E_{e^+} + \Delta E_{e^-} = (0, 0, 0, 0)
\]

\[
P_{cm} = \Delta E_{e^+} - \Delta E_{e^-} = \{ \frac{3}{4} \Delta E_{\text{turn}}, \frac{1}{4} \Delta E_{\text{turn}}, -\frac{1}{4} \Delta E_{\text{turn}}, \frac{3}{4} \Delta E_{\text{turn}} \}
\]

with a single RF location and two or four experiments all IP have the same energy (within small corrections)

different c.m. boost OK

Boosts will be very well measured at all energies with \( \mu^+\mu^- \) events and serve as a measure of the beam energy loss!
ECM and Boosts for Z-Mode

- PH: 0.1 GV 400 MHz cavity
- 0.62 MeV beamstrahlung losses per beam and IP (simulations)
- 40 MeV radiation losses per revolution

Simulations performed in MAD-X
Benchmarking with analytical equations ongoing
→ Exact numbers not final

\[ \Delta E \propto \gamma_{\text{rel}}^4 \]

One 8 h shift will give 5 keV precision
Sum of losses close to sum of absolute boosts

<table>
<thead>
<tr>
<th>IP</th>
<th>ΔECM [keV]</th>
<th>Boost [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PA</td>
<td>-7.851</td>
<td>10.665</td>
</tr>
<tr>
<td>PD</td>
<td>-7.931</td>
<td>-10.108</td>
</tr>
<tr>
<td>PG</td>
<td>0.570</td>
<td>-30.883</td>
</tr>
<tr>
<td>PJ</td>
<td>0.844</td>
<td>31.439</td>
</tr>
</tbody>
</table>

1 RF → almost constant ECM

Boost: + for e+; - for e−
FCC-ee Beam Polarization and Energy Calibration

3. From spin tune measurement to center-of-mass determination

\[ \nu_s = \frac{g-2}{2} \frac{E_b}{m_e} = \frac{E_b}{0.4406486(1)} \]

3.1 Synchrotron Radiation energy loss (10 MeV @Z in 4 ‘arcs’) calculable to < permil accuracy

3.3 Beamstrahlung energy loss (<0.62 MeV per beam at Z pole), compensated by RF (Shatilov)

3.4 layout of accelerator with single RF section

3.5 \( E_b^+ \) vs \( E_b^- \) asymmetries and energy spread can be measured/monitored in expt:

\[ e^+e^- \rightarrow \mu^+ \mu^- \] longitudinal momentum shift and spread (Janot)

D. Shatilov: beam energy spectrum without/with beamstrahlung

\[ 5 \text{ min/exp @Z } \rightarrow 10^6 \mu^+ \mu^- /\text{expt} \rightarrow \]

\rightarrow 50 \text{ keV meas both on } \sigma_{ECM} \text{ and } E^+ - E^- \rightarrow \text{ and beam crossing angle } \alpha \text{ (error negl.)} \rightarrow \text{ also } 300\text{keV (stat) on relative ECM (p-t-p!)}
Experience from LEP – Vernier scans

No effect. \[ ECM = (E_e^+ + E_e^-) \]

NB energy spread is reduced.

ECM lower than \((E_e^+ + E_e^-)\)

\[ \Delta E_{CM} = -\frac{1}{2} \cdot \frac{\delta y \cdot \sigma E_b^2}{E_b} \cdot \Delta D^* \]

Relative position of beams measured to 80 nanometers from one scan.

From resonant depolarization to Center-of-mass energy

2. from beam energy to \(E_{CM}\)

Van Der Meer today

Opposite sign dispersion

M. Koratzinos, FCC week 2019 Brussels
For FCC-ee at the Z we have in vertical direction:

- Parasitic dispersion of e+ and e- beams at IP $10\mu m$ the difference is $\Delta D_y = 14\mu m$.
- Sigma_y is 28nm
- Sigma_E is $0.132\% \times 45000\text{MeV} = 60\text{MeV}$
- Delta_ECM is therefore $1.4\text{MeV}$ for a 1nm offset
- Note that we cannot perform Vernier scans like at LEP, we can only displace the two beams by $\sim 10\% \text{sigma}_y$
- Assume each Vernier scan is accurate to $1\% \text{sigma}_y$, we get a precision of 400 keV.

The process should be simulated

- we need 100 beams scans to get an $E_{\text{CM}}$ accuracy of 40keV – suggestion: vernier scan every hour or more.
- It is likely that Vernier scans will be performed regularly at least once per hour or more. $(\to 100 \text{ per week})$ we end up with an uncertainty of $\sim 10\text{keV}$ over the whole running period.
- The dispersion must be measured as well; this can be done by using the vernier scans with offset RF frequency.

Critical effect is in the vertical plane, but horizontal plane should be investigated as well.
At full luminosity, a vernier scan is a tricky operation and beam beam blow up effects might affect the result.

Therefore a beamstrahlung or radiative bhabha monitor seems highly worthwhile as it gives information on the direction of the interacting particles. It detects the hard photons emitted in either \( e^+e^- \rightarrow e^+e^- \gamma \)
or the hard beamstrahlung photons.

Photons are not affected by the IR magnetic fields. The beam-beam offset leads to a shift in the beamstrahlung photon beam which is proportional to the offset (and to the charge of the opposite beam) for small offsets. The measurement is passive; the zero position can be operationally established by colliding beams at lower intensity where large vernier scan amplitude is possible.

An angular kick of up to 0.18 mrad is expected in the horizontal plane due to EM attraction.
Beamstrahlung Radiation generated at the IP

[GuineaPig++]

- A significant flux of photons is generated at the IP in the very forward direction by Beamstrahlung, radiative Bhabha, and solenoidal and quadrupolar magnetic fields.
- **Beamstrahlung** interactions produce an intense source of locally lost beam power.
- The impinging angle of the **Beamstrahlung** photons with the pipe is about 1 mrad for both beam energies.

Handling of incident beamstrahlung

<table>
<thead>
<tr>
<th>Beam energy</th>
<th>Beamstrahlung Radiation power</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;E_\gamma&gt; = 2 MeV</td>
<td>45.6 GeV</td>
</tr>
<tr>
<td>&lt;E_\gamma&gt;=67 MeV</td>
<td>182.5 GeV</td>
</tr>
</tbody>
</table>

Beamstrahlung photons tracked up to their loss points, at about 50-60 m after the IP.
Beamstrahlung/radiative Bhabha monitor: ongoing work by Andrea Ciarma

± 1 cm spot of beamstrahlung photons

detect photons at exit from bending magnet in a detector system that is all to be designed!
This offers a continuous monitoring of the beam-beam offset with a linear measurement.

Large amplification!

effect should be well measurable IFF we can build a device that
1. can take the radiation
2. take 1 bunch at a time
3. has appropriate resolution (100micron pads should be enough)

A nice study on-going!
next time : where are the radiative Bhabhas?

1σ = 28nm
Conclusion and challenges

1. The beam energy calibration and polarization group is investigating center-of-mass energy control with a precision of a few tens of keV ➔ precision measurement programme with precisions reduced by two orders of magnitude

2. A potentially significant systematic error due to the combination of beam collision offset with spurious opposite sign dispersion. Opposite sign dispersion can be measured by modulating the RF frequency but the beam offsets are more difficult.

4. The radiation emitted by the beams offers a sensitive way to monitor and measure the effect directly, and passively. It would also provide a very fast monitor for beam tuning.

5. Unfortunately the beam power is 380kW which is ~40 times more radiation density in the arcs of the machine --