FCC-ee Accelerator Performance

Mogens Dam, Niels Bohr Institute, Copenhagen
for the FCC-ee study teams
Lepton-Photon 2019, Toronto, 8 August 2019
International FCC collaboration to study (since 2014)

- ~100 km tunnel infrastructure in Geneva area, linked to CERN
- Ultimate goal: ≥ 100 TeV pp-collider (FCC-hh)
  → defining infrastructure requirements

Two possible first steps:

- $e^+e^-$ collider (FCC-ee)
  High Lumi, $E_{\text{CM}} = 90$-400 GeV

- HE-LHC: 16 T ⇒ 27 TeV in LEP/LHC tunnel

Possible addition

- p-e (FCC-he)

≥16 T magnets

FCC CDR available at
http://fcc-cdr.web.cern.ch/
The FCC integral program

Comprehensive cost-effective program maximizing physics opportunities

- Stage 1: FCC-ee (Z, W, H, tt) as Higgs factory, EW and top factory at highest luminosities
- Stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, with ion and eh options
  - Complementary physics
  - Common civil engineering and technical infrastructures
  - Building on and reusing CERN’s existing infrastructure
  - Fully integrated with HL-LHC exploitation and provides for seamless continuation of HEP in Europe
double ring $e^+e^-$ collider ~100 km
follows footprint of FCC-hh, except around IPs
asymmetric IR layout & optics to limit synchrotron radiation towards the detector
presently 2 IPs (alternative layout with 4 IPs under study)
large horizontal crossing angle 30 mrad, crab-waist optics
synchrotron radiation power 50 MW/beam at all beam energies
top-up injection scheme; requires booster synchrotron in collider tunnel
Exploiting lessons from past & present colliders

Combining successful ingredients of several recent colliders

$\Rightarrow$ extremely high luminosity at high energies

$\frac{L}{IP}$

- **LEP:** high energy, SR effects
- **$B$-factories:** KEKB & PEP-II: double-ring colliders, high beam currents, top-up injection
- **DAFNE:** crab waist, double ring
- **Super $B$-factories, S-KEKB:** low $\beta_y$*
- **KEKB, SuperKEKB:** $e^+$ source
- **HERA, LEP, RHIC:** spin gymnastics
- **VEPP-4M, LEP:** precision energy calibration

Combining successful ingredients of several recent colliders

$\Rightarrow$ extremely high luminosity at high energies
FCC-ee luminosity versus energy

FCC-ee: Ultimate luminosity for Z, W, Higgs, and top factory in 88-365 GeV range
crab-waist crossing for flat beams

regular crossing

crab waist crossing

vertical waist position in $s$ varies with horizontal position $x$

- allows for small $\beta_y$ and for small $\varepsilon_{x,y}$
- avoids betatron resonances

$\rightarrow$ higher beam-beam tune shift

arXiv:physics/0702033
### FCC-ee collider parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Z</th>
<th>WW</th>
<th>H (ZH)</th>
<th>ttbar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy [GeV]</td>
<td>45</td>
<td>80</td>
<td>120</td>
<td>182.5</td>
</tr>
<tr>
<td>Beam current [mA]</td>
<td>1390</td>
<td>147</td>
<td>29</td>
<td>5.4</td>
</tr>
<tr>
<td>No. bunches/beam</td>
<td>16640</td>
<td>2000</td>
<td>393</td>
<td>48</td>
</tr>
<tr>
<td>Bunch intensity [$10^{11}$]</td>
<td>1.7</td>
<td>1.5</td>
<td>1.5</td>
<td>2.3</td>
</tr>
<tr>
<td>SR energy loss / turn [GeV]</td>
<td>0.036</td>
<td>0.34</td>
<td>1.72</td>
<td>9.21</td>
</tr>
<tr>
<td>Total RF voltage [GV]</td>
<td>0.1</td>
<td>0.44</td>
<td>2.0</td>
<td>10.9</td>
</tr>
<tr>
<td>Long. damping time [turns]</td>
<td>1281</td>
<td>235</td>
<td>70</td>
<td>20</td>
</tr>
<tr>
<td>Horizontal beta* [m]</td>
<td>0.15</td>
<td>0.2</td>
<td>0.3</td>
<td>1</td>
</tr>
<tr>
<td>Vertical beta* [mm]</td>
<td>0.8</td>
<td>1</td>
<td>1</td>
<td>1.6</td>
</tr>
<tr>
<td>Horiz. geometric emittance [nm]</td>
<td>0.27</td>
<td>0.28</td>
<td>0.63</td>
<td>1.46</td>
</tr>
<tr>
<td>Vert. geom. emittance [pm]</td>
<td>1.0</td>
<td>1.7</td>
<td>1.3</td>
<td>2.9</td>
</tr>
<tr>
<td>Bunch length with SR / BS [mm]</td>
<td>3.5</td>
<td>3.0</td>
<td>3.3</td>
<td>2.0</td>
</tr>
<tr>
<td>Luminosity per IP [$10^{34}$ cm$^{-2}$s$^{-1}$]</td>
<td>230</td>
<td>28</td>
<td>8.5</td>
<td>1.55</td>
</tr>
<tr>
<td>Beam lifetime rad Bhabha / BS [min]</td>
<td>68</td>
<td>49</td>
<td>38</td>
<td>40</td>
</tr>
</tbody>
</table>

*FCC-ee* refers to the Future Circular Collider Electron-Electron.
off-energy dynamic aperture

Dynamic apertures in $z$-$x$ plane after sextupole optimisation with particle tracking for each energy.

important for top-up injection and for beam lifetime with beamstrahlung
FCC-ee interaction region

3D sketch of IR magnet system in the first 3 m from the IP

Unique and flexible design at all energies
- $L^* = 2.2$ m
- Acceptance: 100 mrad

Solenoid compensation scheme
- Reduce $\varepsilon_y$ blow-up $\Rightarrow B_{\text{Detector}} \leq 2T$

Beam pipe
- Warm, liquid cooled (~SuperKEKB)
- Be in central region, then Cu
- $R = 15$ mm in central region
  - 1st vertex detector layer 17 mm from IP
- SR masks, W shielding

Mechanical design and assembly concept under engineering study
Asymmetric IR optics to suppress synchrotron radiation towards IP, $E_{critical} < 100$ keV, from 450 m from IP

Masking and shielding of beam pipe:
- No SR from dipoles or from quads hits directly the central beam pipe
- Small SR impact on detectors
  - Vertex Detector, Tracking Detector, Luminometer
Energy calibration

**Via resonant depolarization at Z and WW**

Simulation shows transverse polarization at the Z (w wigglers) and WW energies

- Energy calibration by resonant depolarization every 10 mins on pilot bunches

**Via Compton polarimeter**

end point of recoil $e^-$: independent continuous beam energy monitoring at $\sim 10^{-5}$ level

**UNIQUE TO CIRCULAR COLLIDERS**

centre-of-mass energy uncertainty at $10^{-6}$ level

- $\sim 100$ keV at Z pole
- $\sim 300$ keV at W-pair threshold

Centre-of-mass energy uncertainty at $10^{-5}$ level

- For H and tt running: a few MeV

At Z pole, beam energy spread determined with relative precision of $<0.2\%$, every 5 minutes by from acollinearity of $10^6$ muon pairs recorded; also measures average energy difference between the two beams
FCC-ee physics operation model and statistics

<table>
<thead>
<tr>
<th>Working point</th>
<th>Z, years 1-2</th>
<th>Z, later</th>
<th>WW</th>
<th>HZ</th>
<th>tt threshold...</th>
<th>... and above</th>
</tr>
</thead>
<tbody>
<tr>
<td>√s (GeV)</td>
<td>88, 91, 94</td>
<td>157, 163</td>
<td>240</td>
<td>340 – 350</td>
<td>365</td>
<td></td>
</tr>
<tr>
<td>Lumi/IP (10^{34} cm^{-2}s^{-1})</td>
<td>100</td>
<td>200</td>
<td>25</td>
<td>7</td>
<td>0.8</td>
<td>1.4</td>
</tr>
<tr>
<td>Lumi/year (2 IP)</td>
<td>24 ab^{-1}</td>
<td>48 ab^{-1}</td>
<td>6 ab^{-1}</td>
<td>1.7 ab^{-1}</td>
<td>0.2 ab^{-1}</td>
<td>0.34 ab^{-1}</td>
</tr>
<tr>
<td>Physics goal</td>
<td>150 ab^{-1}</td>
<td>10 ab^{-1}</td>
<td>5 ab^{-1}</td>
<td>0.2 ab^{-1}</td>
<td>1.5 ab^{-1}</td>
<td></td>
</tr>
<tr>
<td>Run time (year)</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>4</td>
</tr>
</tbody>
</table>

Event statistics

- $5 \times 10^{12} e^+e^- \to Z$
- $10^8 e^+e^- \to W^+W^-$
- $10^6 e^+e^- \to HZ$
- $10^6 e^+e^- \to tt$

Vs precision

- 100 keV
- 300 keV
- 1 MeV
- 2 MeV

Total: 15 years

Luminosity [ab^{-1}]

- Z pole
- WW $\times 10$
- HZ $\times 10$
- Top $\times 10$
FCC-ee RF staging scenario

Three sets of RF cavities:

- **High intensity (Z):** 400 MHz mono-cell cavities (4/cryomodule), Nb/Cu, 4.5 K
- **Higher energy (W, H, t):** 400 MHz four-cell cavities (4/cryomodule), Nb/Cu, 4.5 K
- **tt̅ machine complement:** 800 MHz five-cell cavities (4/cryomodule), bulk Nb, 2 K

### Table: RF Staging Scenario

<table>
<thead>
<tr>
<th>WP</th>
<th>V_{rf} [GV]</th>
<th>#bunches</th>
<th>I_{beam} [mA]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z</td>
<td>0.1</td>
<td>16640</td>
<td>1390</td>
</tr>
<tr>
<td>W</td>
<td>0.44</td>
<td>2000</td>
<td>147</td>
</tr>
<tr>
<td>H</td>
<td>2.0</td>
<td>393</td>
<td>29</td>
</tr>
<tr>
<td>tt̅</td>
<td>10.9</td>
<td>48</td>
<td>5.4</td>
</tr>
</tbody>
</table>

**“Ampere-class” machine**

**“High-gradient” machine**

Installation sequence comparable to LEP (≈ 30 CM/shutdown)
Post-CDR study of 4 IPs; tentative conclusions

- 4 IP scheme looks acceptable
- huge impact on layout; FCC-hh design
- Increased beamstrahlung (bunch length)
- luminosity per IP decreases by $10\div20\%$

$\Rightarrow$ factor $1.6\div1.8$ increase of total integrated luminosity
EXPLORE the 10-100 TeV energy scale
- Precision measurements of the properties of the Z, W, Higgs, and top particles
  - Up to 20-50-fold improved precision on ALL electroweak observables (EWPO)
    - \( m_Z, m_W, m_{\text{top}}, \Gamma_Z, \sin^2 \theta_w, R_b, \alpha_{\text{QED}}(m_Z), \alpha_s(m_Z, m_W, m_t), \) top EW couplings ...
  - Up to 10-fold more precise and model-independent Higgs couplings measurements

DISCOVER that the Standard Model does not fit
- NEW PHYSICS ! Pattern of deviations may point to the source.

DISCOVER a violation of flavour conservation / universality
- Examples: \( Z \rightarrow \tau\mu \) in \( 5 \times 10^{12} \) Z decays; \( q\tau \rightarrow \mu\gamma / \tau \rightarrow e\gamma \) in \( 2 \times 10^{11} \) \( \tau \) decays; ...
- Examples: \( B^0 \rightarrow K^{*0}\tau^+\tau^- \) or \( B_S \rightarrow \tau^+\tau^- \) in \( 10^{12} \) \( \text{bb} \) events

DISCOVER dark matter as invisible decays of Higgs or Z
- Precise invisible width measurements

DIRECT DISCOVERY of very-weakly-coupled particles
- in the 5-100 GeV mass range, such as right-handed neutrinos, dark photons, ALPs, ...
  - Motivated by all measurements / searches at colliders (SM and “nothing else”)

All 4 phases of the FCC-ee programme, \( Z, WW, H, \) and \( t\bar{t} \), are important for the physics potential
Conclusions

FCC-ee design incorporates many lessons from recent & present e⁺e⁻ colliders
- double ring, top-up injection, high current
- crab waist, low βy
- handling of spin, beam energy calibration

The design provides ultimate luminosities for the precise exploration of the four heaviest particles of the Standard Model: Z, W, and Higgs bosons, and the top quark
- also ultimate heavy flavor factory: b quark, τ lepton, ...

Carefully designed optics and efficient masking and shielding reduces synchrotron radiation into detector region to a low level; negligible everywhere except top energy

Transverse beam polarization provides beam energy calibration at \(O(10^{-6})\) level at Z and WW energy points; at higher energies \(O(10^{-5})\) level via Compton polarimeter
Extras
Z running:
single-cell cavities,
400 MHz, Nb/Cu at 4.5 K,
like LHC cavities

$t\bar{t}$ running:
five-cell cavities,
800 MHz bulk Nb at 2 K,
prototyped at JLAB,
added to 400 MHz Nb/Cu
four-cell cavities at 4.5 K,
similar to LEP-2 cavities

Z-pole FCC-ee:
116 single-cell cavities (collider + booster)

$t\bar{t}$ FCC-ee:
396 four-cell 400 MHz + 852 five-cell 800 MHz cavities
(collider + booster)
FCC-ee cost-effective, energy-efficient arc magnets

twin-dipole magnet design with $2 \times$ power saving 16 MW (at 175 GeV), with Al busbars

twin F/D arx quadrupole design with $2 \times$ power saving; 25 MW (at 175 GeV), with Cu conductor

**FCC-ee arc vacuum chambers and integration**

- Chambers feature **lumped SR absorbers with NEG-pumps** placed next to them.
- **Construction of chamber prototypes and integration with twin magnets.**

**Vacuum chamber cross section:** 70 mm ID with "winglets" in the plane of the orbit (SuperKEKB-like).
### FCC-ee power consumption [MW]

<table>
<thead>
<tr>
<th>Beam energy (GeV)</th>
<th>45.6 Z</th>
<th>80 W</th>
<th>120 ZH</th>
<th>182.5 ttbar</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF (SR = 100)</td>
<td>163</td>
<td>163</td>
<td>145</td>
<td>145</td>
</tr>
<tr>
<td>Collider cryo</td>
<td>1</td>
<td>9</td>
<td>14</td>
<td>46</td>
</tr>
<tr>
<td>Collider magnets</td>
<td>4</td>
<td>12</td>
<td>26</td>
<td>60</td>
</tr>
<tr>
<td>Booster RF &amp; cryo</td>
<td>3</td>
<td>4</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>Booster magnets</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Pre injector</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Physics detector</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Data center</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Cooling &amp; ventilation</td>
<td>30</td>
<td>31</td>
<td>31</td>
<td>37</td>
</tr>
<tr>
<td>General services</td>
<td>36</td>
<td>36</td>
<td>36</td>
<td>36</td>
</tr>
<tr>
<td>Total</td>
<td>259</td>
<td>278</td>
<td>282</td>
<td>359</td>
</tr>
<tr>
<td>HL-LHC</td>
<td></td>
<td></td>
<td></td>
<td>260</td>
</tr>
</tbody>
</table>
figure of merit for lepton colliders

FCC-ee: most efficient from $Z$ to $t\bar{t}$
energy calibration at Z & W via resonant depolarisation

Z pole with polarisation wigglers

orbit correction + harmonic bumps

WW threshold

orbit correction + harmonic bumps

simulated frequency sweep with depolariser

Z pole: 8 asymmetric wigglers per beam lower the polarisation rise time to 12 hours allowing a level of 10% (5%) beam polarisation, sufficient for the energy calibration by RDP, to be obtained in 90 (45) minutes.

W pair threshold: spontaneous polarisation with a rise-time of around 10 hours without wigglers.

RF located in one point!

Largest remaining systematic error: vertical closed-orbit distortions - at the Z, 300 μm error will induce a possible systematic shift of around 45 keV.

~200 non-colliding ‘pilot’ bunches injected at start of fill and polarised using wigglers depolarisation technique used at LEP

~100 keV at Z pole

~300 keV at W pair threshold

energy calibration using Compton polarimeter

end point of recoil e⁻: independent continuous beam energy monitoring at $\sim 10^{-5}$ level

luminosity-averaged centre-of-mass energy uncertainty for H and $t\bar{t}$ running: a few MeV

at Z pole beam energy spread determined with a relative precision of <0.2%, every 5 minutes by the experiments from acollinearity of the $10^6$ muon pairs recorded; this acollinearity also measures the average energy difference between the two beams
Future Circular Collider

Base the next generation of colliders on a proven model

- 27 km tunnel

- The next step: 100 km tunnel