Future Circular Colliders

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CERN
7 September 2017
Future HEP: The Three Frontiers

Evaluation in all regions: Europe, Asia, the Americas

- European strategy group
- Snowmass study and IP5
- Japan strategy group

Will concentrate here on the Energy Frontier

2012-2014

After the Higgs discovery
Europe Strategy Group

European Strategy for Particle Physics

- Update formally adopted by CERN council at the European Commission in Brussels on 30 May 2013
- The discovery of the Higgs boson is the start of a major programme of work to measure this particle’s properties with the highest possible precision for testing the validity of the Standard Model and to search for further new physics at the energy frontier. The LHC is in a unique position to pursue this programme.
- Europe’s top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030. This upgrade programme will also provide further exciting opportunities for the study of flavour physics and the quark-gluon plasma.
....“to propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy update”:

d) CERN should undertake design studies for accelerator projects in a global context,

- with emphasis on proton-proton and electron-positron high-energy frontier machines.
- These design studies should be coupled to a vigorous accelerator R&D programme, including high-field magnets and high-gradient accelerating structures,
- in collaboration with national institutes, laboratories and universities worldwide.

The CERN Medium Term Plan approved by June’14 Council, implements the **European Strategy** including a long-term outlook.

The scientific programme is concentrated around four priorities:

1. **Full LHC exploitation** – the highest priority - including the construction of the High Luminosity Upgrade until 2025

2. **High Energy Frontier** – CERN’s role and preparation for the next large scale facility

3. **Neutrino Platform** – allow for to contribute to a future long baseline facility in the US and for detector R&D for neutrino experiments

4. **Fixed-target programme** – maintain the diversity of the field and honour ongoing obligations by exploiting the unique facilities at CERN
FCC General Yearly Meeting May 2017

> 500 participants
147 institutes
a lot of young people
(>35% younger than 35)

FCC Week 2017
Future Circular Collider Conference
BERLIN, GERMANY
29 MAY - 02 JUNE
fccw2017.web.cern.ch

Slides from M. Benedikt, M. Mangano, W. Riegler, Y. Wang, F. Zimmerman, A Blondel
The LHC Upgrade
Approved program at CERN to collect 3000 fb⁻¹ with the LHC (HL-LHC)
Maximize the reach for searches and for precision measurements (e.g., Higgs)
FCC study continues effort on high-field collider in LHC tunnel

2010 EuCARD Workshop Malta; Yellow Report CERN-2011-1

- based on 16-T dipoles developed for FCC-hh
- extrapolation of other parts from the present (HL-)LHC and from FCC developments


CM Energy 25-28 TeV
Various options, with increasing amount of HW changes, technical challenges, cost, and physics reach.

**WG set up to explore technical feasibility of pushing LHC energy to:**
1) **design value:** 14 TeV
2) **ultimate value:** 15 TeV (corresponding to max dipole field of 9 T)
3) **beyond** (e.g. by replacing 1/3 of dipoles with 11 T Nb$_3$Sn magnets)
   - Identify open risks, needed tests and technical developments, trade-off between energy and machine efficiency/availability
   - Report on 1) end 2016, 2) end 2017, 3) end 2018 (in time for ES)

**HE-LHC** (part of FCC study): ~16 T magnets in LHC tunnel (→ $\sqrt{s}$~ 30 TeV)
- uses existing tunnel and infrastructure; can be built at fixed budget
- strong physics case if new physics from LHC/HL-LHC
- powerful demonstration of the FCC-hh magnet technology
Beyond the LHC

• Proton-proton machines at higher energy…
• Electron-positron machines for high precision…
• Both? And allowing for electron-proton collisions..?

New projects will take 10-20 years before they turn into operation, hence need a vision & studies now!
International FCC collaboration (CERN as host lab) to design:

- **$pp$-collider ($FCC-hh$)**
  - main emphasis, defining infrastructure requirements

  $\sim 16 \text{ T} \Rightarrow 100 \text{ TeV} \, pp \text{ in } 100 \text{ km}$

- **80-100 km tunnel infrastructure** in Geneva area, site specific

- **$e^+e^-$ collider ($FCC-ee$), as a possible first step**

- **$p$-$e$ ($FCC-he$) option**, one IP, FCC-hh & ERL

- **HE-LHC w $FCC-hh$ technology**
CDR plans

1 - PHYSICS

2 Hadron Collider Summary

3 - Hadron Collider Comprehensive
   - Accelerator
   - Injectors
   - Technologies
   - Infrastructure
   - Operation
   - Experiment
   - eh

4 Lepton Collider Summary

5 - Lepton Collider Comprehensive
   - Accelerator
   - Injectors
   - Technologies
   - Infrastructure
   - Operation
   - Experiment

6 High Energy LHC Summary

7 - High Energy LHC Comprehensive
   - Accelerator
   - Injectors
   - Infrastructure
   - Refs to FCC-hh, HL-LHC, LHeC

- Required for end 2018, as input for European Strategy Update
- Common physics summary volume
- Three detailed volumes FCCChh, FCCee, HE-LHC
- Three summary volumes FCCChh, FCCee, HE-LHC
Optimisation in view of accessibility surface points, tunneling rock type, shaft depth, etc. optimum: **97.5 km**

**Tunneling**
- Molasse 90% (good rock),
- Limestone 5%, Moraines 5% (tough)

**Shallow implementation**
- ~ 30 m below Léman lakebed
- Reduction of shaft lengths etc...
- One very deep shaft **F** (476m) (RF or collimation), alternatives being studied, e.g. inclined access
common layouts for hh & ee

Lepton beams must cross over through the common RF to enter the IP from inside. Only a half of each ring is filled with bunches.

Max. separation of 3(4) rings is about 12 m: wider tunnel or two tunnels are necessary around the IPs, for ±1.2 km.

FCC-ee 1, FCC-ee 2,
FCC-ee booster (FCC.hh footprint)
Asymmetric IR for ee, limits SR to expt
Sharing the FCC experimental caverns
(Prelim. layout as of FCC-Rome meeting)
HE-LHC:
constraints:
No civil engineering, same beam height as LHC
→ Magnets OD ca. 1200 m max
QRL (shorter than FCC) OD ca. 850 mm (all included)

Magnet suspended during „handover“ from transport vehicle to installation transfer table

Compliant 16T magnet design ongoing + still many items to study!

If HE-LHC can work in 3.8m ⌀ ... it will feed-back to FCC tunnel design!
LHeC or FCC-eh function as an add-on to LHC or FCC-hh respectively: additional 10km circumference Electron Recirculating Linac ERL.

The possibility to collide FCC-ee with FCC-hh is not considered in the framework of the study.

In the case of FCC-eh it could profit from the -- then existing -- FCC-hh, and, perhaps, from considerable RF of the -- then dismantled -- FCC-ee.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Z</th>
<th>W</th>
<th>H</th>
<th>tt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference [km]</td>
<td>97.750</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bending radius [km]</td>
<td>10.747</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beam energy [GeV]</td>
<td>45.6</td>
<td>80</td>
<td>120</td>
<td>175</td>
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<tr>
<td>Beam current [mA]</td>
<td>1390</td>
<td>147</td>
<td>29</td>
<td>6.4</td>
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<tr>
<td>Bunches / beam</td>
<td>18800</td>
<td>2000</td>
<td>375</td>
<td>45</td>
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<tr>
<td>Bunch spacing [ns]</td>
<td>15</td>
<td>150</td>
<td>455</td>
<td>6000</td>
</tr>
<tr>
<td>Bunch population [10^{11}]</td>
<td>1.5</td>
<td>1.5</td>
<td>1.6</td>
<td>2.9</td>
</tr>
<tr>
<td>Horizontal emittance $\epsilon$ [nm]</td>
<td>0.267</td>
<td>0.25</td>
<td>0.61</td>
<td>1.33, 2.03</td>
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<tr>
<td>Vertical emittance $\epsilon$ [pm]</td>
<td>1.0</td>
<td>1.0</td>
<td>1.2</td>
<td>2.66, 3.1</td>
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<tr>
<td>Momentum comp. [$10^{-6}$]</td>
<td>14.79</td>
<td>7.31</td>
<td>7.31</td>
<td>7.31</td>
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<tr>
<td>Arc sextupole families</td>
<td>208</td>
<td>292</td>
<td>292</td>
<td>292</td>
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<tr>
<td>Betatron function at IP</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>- Horizontal $\beta^*$ [m]</td>
<td>0.15</td>
<td>0.20</td>
<td>0.5</td>
<td>1</td>
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<tr>
<td>- Vertical $\beta^*$ [mm]</td>
<td>0.8</td>
<td>1</td>
<td>1.2</td>
<td>2</td>
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<tr>
<td>Horizontal beam size at IP $\sigma^*$ [\mu m]</td>
<td>6.3</td>
<td>7.2</td>
<td>17</td>
<td>45</td>
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<tr>
<td>Vertical beam size at IP $\sigma^*$ [nm]</td>
<td>28</td>
<td>32</td>
<td>38</td>
<td>79</td>
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<tr>
<td>Free length to IP $l$ [m]</td>
<td>2.2</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Solenoid field at IP [T]</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Full crossing angle at IP [mrad]</td>
<td>30</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy spread [%]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Synchrotron radiation</td>
<td>0.038</td>
<td>0.066</td>
<td>0.10</td>
<td>0.145</td>
</tr>
<tr>
<td>- Total (including BS)</td>
<td>0.130</td>
<td>0.153</td>
<td>0.14</td>
<td>0.194</td>
</tr>
<tr>
<td>Bunch length [mm]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Synchrotron radiation</td>
<td>3.5</td>
<td>3.27</td>
<td>3.1</td>
<td>2.4</td>
</tr>
<tr>
<td>- Total</td>
<td>11.2</td>
<td>7.65</td>
<td>4.4</td>
<td>3.3</td>
</tr>
<tr>
<td>Energy loss / turn [GeV]</td>
<td>0.356</td>
<td>0.34</td>
<td>1.71</td>
<td>7.7</td>
</tr>
<tr>
<td>SR power / beam [MW]</td>
<td>50</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total RF voltage [GV]</td>
<td>0.10</td>
<td>0.44</td>
<td>2.0</td>
<td>9.5</td>
</tr>
<tr>
<td>RF frequency [MHz]</td>
<td>400</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Longitudinal damping time [turns]</td>
<td>1281</td>
<td>235</td>
<td>70</td>
<td>23</td>
</tr>
<tr>
<td>Energy acceptance RF / DA [%]</td>
<td>1.9, 1.9</td>
<td>2.4</td>
<td>5.3, 2.5 (2.0)</td>
<td></td>
</tr>
<tr>
<td>Synchrotron tune $Q_0$</td>
<td>-0.025</td>
<td>-0.023</td>
<td>-0.036</td>
<td>-0.069</td>
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<tr>
<td>Polarization time $\tau_p$ [min]</td>
<td>15040</td>
<td>905</td>
<td>119</td>
<td>18</td>
</tr>
<tr>
<td>Interaction region length $L_s$ [mm]</td>
<td>0.42</td>
<td>1.00</td>
<td>1.45</td>
<td>1.85</td>
</tr>
<tr>
<td>Hourglass factor $H (L_s)$</td>
<td>0.95</td>
<td>0.95</td>
<td>0.87</td>
<td>0.85</td>
</tr>
<tr>
<td>Luminosity/IP for 2IPs [$10^{34} \text{cm}^{-2}\text{s}^{-1}$]</td>
<td>215</td>
<td>310</td>
<td>7.9</td>
<td>1.5</td>
</tr>
<tr>
<td>Beam-beam parameter</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Horizontal</td>
<td>0.004</td>
<td>0.007</td>
<td>0.033</td>
<td>0.092</td>
</tr>
<tr>
<td>- Vertical</td>
<td>0.134</td>
<td>0.126</td>
<td>0.141</td>
<td>0.150</td>
</tr>
<tr>
<td>Beam lifetime rad Bhabha, BS [min]</td>
<td>72</td>
<td>54</td>
<td>42</td>
<td>47, 70 (12)</td>
</tr>
</tbody>
</table>
Luminosities for Future ee colliders

- $Z (91.2 \text{ GeV}) : 4.3 \times 10^{36} \text{ cm}^{-2}\text{s}^{-1}$
- $W^+W^- (161 \text{ GeV}) : 6.4 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$
- $t\bar{t} (340-370 \text{ GeV}) : 3.8 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
- $HZ (240 \text{ GeV}) : 1.7 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$
- $HZ : 1.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$

LEP$x10^5$!
FCC-ee Physics Runs

• FCC-ee physics goals (sum of two IPs):
  • 150 ab\(^{-1}\) at and around the Z pole (88, 91, 94 GeV)
  • 10 ab\(^{-1}\) at the WW threshold (~161 GeV with a +/- few GeV scan)
  • 5 ab\(^{-1}\) at the HZ maximum (~240 GeV)
  • 1.5 ab\(^{-1}\) at and above the ttbar threshold (a few 100 fb\(^{-1}\) with a scan from 340 to 350 GeV, and the rest at 365-370 GeV)

• Assumptions:
  • 200 scheduled physics days per year, i.e. 7 months – 13 days of MD/stops.
  • “Hübner factor” H=0.75 (lower than value achieved with top-up injection at KEKB, ~0.8).
  • Half the design luminosity in the first two years of Z operation, assuming machine starts with Z (similar to LEP-1; LEP-2 start up was much faster)
  • Machine configuration between WPs is changed during winter shutdowns (effective time of about 3 months/year)
IMPLEMENTATION AND RUN PLAN

Three sets of RF cavities for FCCee & Booster:

- Installation as LEP (≈30 CM/winter)
- High intensity (Z, FCC-hh): 400 MHz mono-cell cavities, ≈ 1MW source
- High energy (W, H, t): 400 MHz four-cell cavities, also for W machine
- Booster and t machine complement: 800 MHz four-cell cavities
- Adaptable 100MW, 400MHz RF power distribution system

→ Spreads the funding profile

<table>
<thead>
<tr>
<th>Z 150 ab⁻¹</th>
<th>W 10 ab⁻¹</th>
<th>ZH thresh 5ab⁻¹</th>
<th>tt thresh + tt 365 1.5ab⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 years</td>
<td>2 yrs</td>
<td>3 years</td>
<td>5 years</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>V_tot (GV)</th>
<th>n_bunch</th>
<th>I_beam (mA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z</td>
<td>0.2</td>
<td>91500</td>
</tr>
<tr>
<td>W</td>
<td>0.8</td>
<td>5260</td>
</tr>
<tr>
<td>H</td>
<td>3</td>
<td>780</td>
</tr>
<tr>
<td>t</td>
<td>10</td>
<td>81</td>
</tr>
</tbody>
</table>

“Ampere-class” machine

“High gradient” machine

indicative: 2(comm) + 2 2 3 5 total ~14 years
FCC-ee Detectors

Two integration, performance and cost estimates ongoing:
-- Linear Collider Detector group at CERN has undertaken the adaption of CLIC-SID detector for FCC-ee
-- new IDEA, detector specifically designed for FCC-ee (and CEPC)

“CLIC-detector revisited”

“IDEA”

- Vertex detector: ALICE
- Tracking: MEG2
- Si Preshower
- Ultra-thin solenoid (2T)
- Calorimeter: DREAM
- Equipped return yoke
Today we do not know how nature will surprise us. A few things that FCC-ee could discover:

EXPLORE 10-100 TeV energy scale (and beyond) with Precision Measurements

\[ m_Z, m_W, m_{\text{top}}, \sin^2 \theta_{W}^{\text{eff}}, R_b, \alpha_{\text{QED}}(m_z), \alpha_s(m_z, m_W, m_{\tau}), \text{Higgs and top quark couplings} \]

DISCOVER a violation of flavour conservation or universality

\[ \text{-- e.g. FCNC (Z \to \mu\tau, e\tau) in } 5 \times 10^{12} \text{ Z decays.} \]
\[ \text{+ flavour physics (} 10^{12} \text{ bb events)} \]

DISCOVER dark matter as «invisible decay» of H or Z or in LHC loopholes.

DISCOVER very weakly coupled particle in 5-100 GeV energy scale

\[ \text{such as: Right-Handed neutrinos, Dark Photons etc...} \]

+ an enormous amount of clean, unambiguous work on QCD etc.

NB the «Z factory» plays an important role in the ‘discovery potential’

“First Look at the Physics Case of TLEP”, JHEP 1401 (2014) 164,
FCC-ee: Need for Precise Theory

Theoretical limitations

SM predictions (using other input)

\[ M_W = 80.3593 \pm 0.0005 \]

\[ \sin^2 \theta^\ell_{\text{eff}} = 0.231496 \pm 0.000006 \]

Experimental errors at FCC-ee will be 20-100 times smaller than the present errors. BUT can be typically 10-30 times smaller than present level of theory errors. Will require significant theoretical effort and additional measurements!

The above explains why we want the top running – and high Z statistics.

Freitas, Heinemeyer, Jadach, Gluza ... need for 3 loop calculations for the future! Suggest including manpower for theoretical calculations in the project cost.
## Hadron Collider Parameters ($pp$)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>FCC-hh</th>
<th>HE-LHC</th>
<th>(HL) LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collision Energy CMS [TeV]</td>
<td>100</td>
<td>27</td>
<td>14</td>
</tr>
<tr>
<td>Dipole Field [T]</td>
<td>16</td>
<td>16</td>
<td>8.3</td>
</tr>
<tr>
<td>Circumference [km]</td>
<td>100</td>
<td>27</td>
<td>27</td>
</tr>
<tr>
<td>Beam Current [A]</td>
<td>0.5</td>
<td>1.12</td>
<td>(1.12) 0.58</td>
</tr>
<tr>
<td>Bunch Intensity [$10^{11}$]</td>
<td>1 (0.2)</td>
<td>2.2</td>
<td>(2.2) 1.15</td>
</tr>
<tr>
<td>Bunch Spacing [ns]</td>
<td>25 (5)</td>
<td>25 (5)</td>
<td>25</td>
</tr>
<tr>
<td>Norm. Emittance $\gamma \varepsilon_{x,y}$ [\mu m]</td>
<td>2.2 (0.44)</td>
<td>2.5 (0.5)</td>
<td>(2.5) 3.75</td>
</tr>
<tr>
<td>IP $\beta^{*}_{x,y}$ [m]</td>
<td>1.1</td>
<td>0.3</td>
<td>0.25</td>
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<tr>
<td>Luminosity/IP [$10^{34}$ cm$^{-2}$s$^{-1}$]</td>
<td>5</td>
<td>30</td>
<td>25</td>
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<tr>
<td>Peak #Events/Bunch Crossing</td>
<td>170</td>
<td>1000 (200)</td>
<td>800 (160)</td>
</tr>
<tr>
<td>Stored Energy/Beam [GJ]</td>
<td>8.4</td>
<td>1.4</td>
<td>(0.7) 0.36</td>
</tr>
<tr>
<td>SR Power / Beam [kW]</td>
<td>2400</td>
<td>100</td>
<td>(7.3) 3.6</td>
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<tr>
<td>Transv. Emit. Damping Time [h]</td>
<td>1.1</td>
<td>3.6</td>
<td>25.8</td>
</tr>
<tr>
<td>Initial Proton Burn Off Time [h]</td>
<td>17.0</td>
<td>3.4</td>
<td>3.6</td>
</tr>
</tbody>
</table>
16 Tesla Magnets

FCC goal is 16 T operating field
- Requires to use Nb$_3$Sn technology
- At 11 T used for HL-LHC
  ⇒ Strong synergy with HL-LHC

Key cost driver
16 T demonstrated in coil
Hope for US model test early 2018: 14-15 T
Short magnet models in 2018 – 2023
12 T for HL-LHC

R&D on cables in test stand at CERN

Target: $J_c > 2300$ A/mm$^2$ at 1.9 K and
16 T (50% above HL-LHC)

Industrial fabrication:
Target cost: 3.4Euro/kAm

Magnet design to *minimise material* use
and limit margins to essential level

Common coils
Cos-theta
Blocks
Canted Coil

EuroCirCol
A key to New Physics

CIEMAT, CEA, INFN

Swiss contribution via PSI

--- possible shorter term application SCSPS or HE-LHC
--- For longer timescale HTS is also studied \( \Rightarrow 20T \)

D. Schulte, EPS’17
16 Tesla Magnets

Total duration of magnet program:
~20 years
Baseline FCC-hh Detector 2016

King Size Detector!
Diameter 27m
Length 60m

<table>
<thead>
<tr>
<th>Twin Solenoid</th>
<th>Dipole</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stored energy</td>
<td>53 GJ</td>
</tr>
<tr>
<td>Total mass</td>
<td>6 kt</td>
</tr>
<tr>
<td>Peak field</td>
<td>6.5 T</td>
</tr>
<tr>
<td>Current</td>
<td>80 kA</td>
</tr>
<tr>
<td>Conductor</td>
<td>102 km</td>
</tr>
<tr>
<td>Bore x Length</td>
<td>12 m x 20 m</td>
</tr>
</tbody>
</table>

But the detector would be a multi-Billion project. Reasonable?

Twin solenoid
6 Tesla
12m bore
10 Tm dipole
FCC-hh Reference Detector 2017

New Design 2017

Solenoids in Central *and* forward areas no flux return.
FCC-hh Discovery Highlights

**FCC-hh is a HUGE discovery machine (if nature ...), but not only.**

FCC-hh physics is dominated by three features:

-- **Highest center of mass energy** $\rightarrow$ a big step in high mass reach!

  ex: strongly coupled new particle up to 50 TeV
  Excited quarks, Z', W', up to $\sim$ tens of TeV
  Give the final word on natural Supersymmetry, extra Higgs etc.. reach up to 5-20 TeV
  Sensitivity to high energy phenomena in e.g. WW scattering

-- **HUGE production rates** for single and multiple production of SM bosons (H,W,Z) and quarks

-- **Higgs precision tests** using ratios to e.g. $\gamma\gamma/\mu\mu/\tau\tau/ZZ$, $t\bar{t}H/t\bar{t}Z$ @% level

-- **Precise determination of triple Higgs coupling** ($\sim$3% level) and quartic Higgs coupling

-- **detection of rare decays** $H \rightarrow V\gamma$ ($V=\rho,\varphi,J/\psi,\Upsilon,Z$...)

-- **search for invisibles** (DM searches, RH neutrinos in W decays)

-- renewed interest for long lived (very weakly coupled) particles.

-- rich top and HF physics program

-- **Cleaner signals for high Pt physics**

  $\Rightarrow$ allows clean signals for channels presently difficult at LHC (e.g. $H \rightarrow bb$)
Hadron colliders: direct exploration of the “energy frontier”

$\sigma$ [nb] vs $\sqrt{s}$ [TeV]

<table>
<thead>
<tr>
<th>Process</th>
<th>$\sigma$ (100 TeV)/$\sigma$ (14 TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total pp</td>
<td>1.25</td>
</tr>
<tr>
<td>W</td>
<td>$\sim$7</td>
</tr>
<tr>
<td>Z</td>
<td>$\sim$7</td>
</tr>
<tr>
<td>WW</td>
<td>$\sim$10</td>
</tr>
<tr>
<td>ZZ</td>
<td>$\sim$10</td>
</tr>
<tr>
<td>tt</td>
<td>$\sim$30</td>
</tr>
<tr>
<td>H</td>
<td>$\sim$15 (ttH $\sim$60)</td>
</tr>
<tr>
<td>HH</td>
<td>$\sim$40</td>
</tr>
<tr>
<td>stop</td>
<td>$\sim10^3$</td>
</tr>
</tbody>
</table>

With 40/ab at $\sqrt{s}=100$ TeV expect: $\sim10^{12}$ top, $10^{10}$ H bosons, $10^5$ m=8 TeV gluino pairs, ...

If new (heavy) physics discovered at the LHC $\rightarrow$ completion of spectrum is a “no-lose” argument for future $\sim100$ TeV pp collider: extend discovery potential up to $m\sim50$ TeV
Supersymmetry

Summary from FCC Report:

The paradigm of low energy supersymmetry has dominated ideas in physics beyond the Standard Model for decades. FCC-hh would provide the final word, by pushing far beyond the naturalness paradigm.
Physics Complementarity

Some examples

Higgs Physics  -- ee → ZH fixes Higgs width and HZZ coupling, (and many others)
                -- FCC-hh gives huge statistics of HH events for Higgs self-coupling

Search for Heavy Physics
                -- ee gives precision measurements (m_Z m_W to < 0.5 MeV, m_top 10 MeV, etc...) sensitive to heavy physics up to ... 100 TeV
                -- FCC-hh gives access to direct observation at unprecedented energies
                   Also huge statistics of Z,W and top → rare decays

QCD
                -- ee gives \( \alpha_s \pm 0.0002 \) (R_{had})
                   also H→gg events (gluon fragmentation!)
                -- ep provides structure functions and \( \alpha_s \pm 0.0002 \)
                -- all this improves the signal and background predictions
                   for new physics signals at FCC-hh

Heavy Neutrinos  -- ee: very powerful and clean, but flavour-blind
                    -- hh and eh more difficult, but potentially flavour sensitive
                   NB this is very much work in progress!!
### HIGGS PHYSICS

#### Higgs couplings \( g_{Hxx} \) precisions

*hh, eh precisions assume SM or ee measurements*  

<table>
<thead>
<tr>
<th>( g_{Hxx} )</th>
<th>FCC-ee</th>
<th>FCC-hh</th>
<th>FCC-eh</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZZ</td>
<td>0.15%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WW</td>
<td>0.20%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \Gamma_H )</td>
<td>1%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \gamma\gamma )</td>
<td>1.5%</td>
<td>&lt;1%</td>
<td></td>
</tr>
<tr>
<td>( Z\gamma )</td>
<td>--</td>
<td>1%</td>
<td></td>
</tr>
<tr>
<td>( tt )</td>
<td>13%</td>
<td>1%</td>
<td></td>
</tr>
<tr>
<td>( bb )</td>
<td>0.4%</td>
<td></td>
<td>0.5%</td>
</tr>
<tr>
<td>( \tau\tau )</td>
<td>0.5%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( cc )</td>
<td>0.7%</td>
<td></td>
<td>1.8%</td>
</tr>
<tr>
<td>( \mu\mu )</td>
<td>6.2%</td>
<td>2%</td>
<td></td>
</tr>
<tr>
<td>( uu,dd )</td>
<td>H ( \rightarrow \rho\gamma )</td>
<td>H ( \rightarrow \rho\gamma )</td>
<td></td>
</tr>
<tr>
<td>( ss )</td>
<td>H ( \rightarrow \phi\gamma ) ?</td>
<td>H ( \rightarrow \phi\gamma ) ?</td>
<td></td>
</tr>
<tr>
<td>ee</td>
<td>ee ( \rightarrow H )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HH</td>
<td>30%</td>
<td>~3%</td>
<td>20%</td>
</tr>
<tr>
<td>inv, exo</td>
<td>&lt;0.45%</td>
<td>10(^{-3})</td>
<td>5%</td>
</tr>
</tbody>
</table>
NB this is an ‘impression plot’ not the consistent result of a Higgs coupling fit!

hh, eh precisions assume SM or ee measurements!
The CEPC/SppC Design (China)

CEPC+SppC:

2012-2014: idea

SppC: 50 – 100 TeV
CEPC: 240 – 250 GeV

e⁺e⁻ Higgs Factory

2015 pre-CDR

• Proton-proton collider (~100 TeV)
  – Directly search for new physics beyond SM
  – Precision test of SM
    • e.g., h³ & h⁴ couplings
Site selection ongoing
Possibilities among others..
• Qinhuangdao (1 hr by train from Beijing)
• Close to Hong-Kong?...
Alternative CEPC Sites

1) Qinhuangdao
   (site technical exploring done)
2) Shanxi Province
   (under site technical exploring, started from Jan. 2017)
3) Near Shenzhen and Hong Kong
   (site technical exploring done)
Designs for future circular $e^+e^-$ colliders are converging.

**FCC-ee Design**
- IP: 11.9 m, 30 mrad
- FCC-hh/ee Booster: 9.4 m
- Lepton beams must cross over through the common RF to enter the IP from inside. Only a half of each ring is filled with bunches.
- Max. separation of 3(4) rings is about 12 m: wider tunnel or two tunnels are necessary around the IPs, for ±1.2 km.

- $C=97.75$ km

**CEPC Design**
- IP: 20 mrad
- Booster
- Linac
- RF Station (Higgs, Z, Z-HL)
- Extremity (LSS6)
- LSS3
- LSS4
- Inj (LSS8)
- C=100 km

**“Bowtie” Final Focus**
(M. Koratzinos, A. Blondel, K. Oide)
CEPC data-taking starts before the LHC program ends

- Possibly con-current with the ILC program
FCC WEEK 2018

AMSTERDAM, 9-13 April 2018

also: 2018 FCC Physics Workshop, 15-19 January 2018, CERN
Future Circular Colliders: Summary

• FCC collider design is being developed as option for future flagship project at CERN for the world-wide high energy physics community. It includes hh-ee-eh options
  – Goal is to have CDR ready by end 2018 for European strategy update. No show stoppers so far
  – https://indico.cern.ch/category/5153/
• A High Energy LHC scenario is also being studied (again)
• SppC//CEPC in China is moving to a CDR phase
  – Detailed magnet R&D program ramping up for hh-mode
• Detailed physics studies for pp at 100 TeV, e+e- and ep at FCC in progress. Interested people are very welcome to join!
Using an Energy Recovery Linac

Super Conducting Recirculating Linac with Energy Recovery

Choose $\frac{1}{3}$ of LHC circumference

Two 1 km long, 10 GeV SC LINACs with 3 accelerating and 3 decelerating passes in CW operation

$\Rightarrow$ SRF sees 6*current at the IP ($\approx$ 4ns spacing)

$Q_0 = 10^{10}$ requires cryogenic system comparable to LHC system! $Q_0 > 10^{10}$

<table>
<thead>
<tr>
<th></th>
<th>PROTONS</th>
<th>ELECTRONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Energy [GeV]</td>
<td>7000</td>
<td>60</td>
</tr>
<tr>
<td>Luminosity [$10^{33}$ cm$^{-2}$s$^{-1}$]</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Normalized emittance $\gamma \epsilon_{x,y}$ [µm]</td>
<td>2.5</td>
<td>20</td>
</tr>
<tr>
<td>Beta Function $\beta^*_x,\gamma$ [m]</td>
<td>0.05</td>
<td>0.10</td>
</tr>
<tr>
<td>rms Beam size $\sigma^*_x,\gamma$ [µm]</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>rms Beam divergence $\sigma_{x,y}^*$ [µrad]</td>
<td>80</td>
<td>40</td>
</tr>
<tr>
<td>Beam Current @ IP [mA]</td>
<td>1112</td>
<td>25</td>
</tr>
<tr>
<td>Bunch Spacing [ns]</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Bunch Population</td>
<td>$2.2 \times 10^{11}$</td>
<td>$4 \times 10^9$</td>
</tr>
<tr>
<td>Bunch charge [nC]</td>
<td>35</td>
<td>0.64</td>
</tr>
</tbody>
</table>
A successful model!

PHYSICS WITH VERY HIGH ENERGY
\( e^+ e^- \) COLLIDING BEAMS

L. Camilleri, D. Cundy, P. Darriulat, J. Ellis, J. Field,
H. Fischer, E. Gabathuler, M.K. Gaillard, H. Hoffmann,
K. Johnsen, E. Keil, F. Palmonari, G. Preparata, B. Richter,
C. Rubbia, J. Steinberger, B. Wiik, W. Willis and K. Winter

ABSTRACT

This report consists of a collection of documents produced by a Study
Group on Large Electron-Positron Storage Rings (LEP). The reactions of

Did these people know that we would be running HL-LHC in that tunnel >60 years later?

\( e^+ e^- \) 1989-2000

p p 2009-2039

LARGE HADRON COLLIDER IN THE LEP TUNNEL

Let's not be SHY!
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>PreCDR</th>
<th>“CDR”</th>
<th>“Ultimate”</th>
<th>FCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference</td>
<td>km</td>
<td>54.4</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>c.m. energy</td>
<td>TeV</td>
<td>70.6</td>
<td>75</td>
<td>125-150</td>
<td>100</td>
</tr>
<tr>
<td>dipole field</td>
<td>T</td>
<td>20</td>
<td>12</td>
<td>20-24</td>
<td>16</td>
</tr>
<tr>
<td>injection energy</td>
<td>TeV</td>
<td>2.1</td>
<td>2.1</td>
<td>4.2</td>
<td>3.3</td>
</tr>
<tr>
<td>#IPs</td>
<td></td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>luminosity per IP</td>
<td>$10^{35}$ cm$^{-2}$s$^{-1}$</td>
<td>1.2</td>
<td>1.0</td>
<td>-</td>
<td>0.5</td>
</tr>
<tr>
<td>norm. emittance</td>
<td>μm</td>
<td>4.1</td>
<td>2.4</td>
<td>?</td>
<td>2.2</td>
</tr>
<tr>
<td>IP beta function</td>
<td>m</td>
<td>0.75</td>
<td>0.75</td>
<td>-</td>
<td>1.1</td>
</tr>
<tr>
<td>beam current</td>
<td>A</td>
<td>1.0</td>
<td>0.7</td>
<td>-</td>
<td>0.5</td>
</tr>
<tr>
<td>bunch separation</td>
<td>ns</td>
<td>25</td>
<td>25</td>
<td>-</td>
<td>25</td>
</tr>
<tr>
<td>bunch population</td>
<td>$10^{11}$</td>
<td>2.0</td>
<td>1.5</td>
<td>-</td>
<td>1.0</td>
</tr>
<tr>
<td>SR power /beam</td>
<td>MW</td>
<td>2.1</td>
<td>1.1</td>
<td>-</td>
<td>2.5</td>
</tr>
<tr>
<td>SR heat load/ap</td>
<td>W/m</td>
<td>45</td>
<td>13</td>
<td>-</td>
<td>30</td>
</tr>
</tbody>
</table>
Preliminary results show co-existence of Z/H programs are possible. Reconfiguration of CEPC can lead to much better luminosity at the Z pole → Z factor
### Feasibility & Optimized Parameters

Feasibility analysis: TPC and Passive Cooling Calorimeter is valid for CEPC

<table>
<thead>
<tr>
<th></th>
<th>CEPC v1 (≈ ILD)</th>
<th>Optimized (Preliminary)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Track Radius</td>
<td>1.8 m</td>
<td>&gt;= 1.8 m</td>
<td>Requested by Br(H→di muon) measurement</td>
</tr>
<tr>
<td><strong>B Field</strong></td>
<td>3.5 T</td>
<td>3 T</td>
<td>Requested by MDI</td>
</tr>
<tr>
<td>ToF</td>
<td>-</td>
<td>50 ps</td>
<td>Requested by pi-Kaon separation at Z pole</td>
</tr>
<tr>
<td>ECAL Thickness</td>
<td>84 mm</td>
<td>84(90) mm</td>
<td>84 mm is optimized on Br(H→di photon) at 250 GeV;</td>
</tr>
<tr>
<td>ECAL Cell Size</td>
<td>5 mm</td>
<td>10 – 20 mm</td>
<td>Passive cooling request ~ 20 mm. 10 mm should be highly appreciated for EW measurements – need further evaluation</td>
</tr>
<tr>
<td>ECAL NLayer</td>
<td>30</td>
<td>20 – 30</td>
<td>Depends on the Silicon Sensor thickness</td>
</tr>
<tr>
<td>HCAL Thickness</td>
<td>1.3 m</td>
<td>1 m</td>
<td></td>
</tr>
<tr>
<td>HCAL NLayer</td>
<td>48</td>
<td>40</td>
<td>Optimized on Higgs event at 250 GeV;</td>
</tr>
</tbody>
</table>
CEPC Funding

HEP seed money

11 M RMB/3 years (2015-2017)

R&D Funding - NSFC

Increasing support for CEPC D+R&D by NSFC

<table>
<thead>
<tr>
<th>CEPC相关基金名称（2015-2016）</th>
<th>基金类型</th>
<th>负责人</th>
<th>承担单位</th>
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</thead>
<tbody>
<tr>
<td>高精度气体径迹探测器及激光校正的研究 (2015)</td>
<td>重点基金</td>
<td>李玉兰/陈元柏</td>
<td>清华大学/高能物理研究所</td>
</tr>
<tr>
<td>成像型电磁量能器关键技术研究(2016)</td>
<td>重点基金</td>
<td>刘志刚</td>
<td>中国科学院</td>
</tr>
<tr>
<td>CEPC局部双环对撞区挡板系统设计及螺线管场补偿(2016)</td>
<td>面上基金</td>
<td>白莎</td>
<td>高能物理研究所</td>
</tr>
<tr>
<td>用于顶点探测器的高分辨、低功耗SOI像素芯片的若干关键问题的研究(2015)</td>
<td>面上基金</td>
<td>卢云鹏</td>
<td>高能物理研究所</td>
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<tr>
<td>基于粒子流算法的电磁量能器性能研究 (2016)</td>
<td>面上基金</td>
<td>王志刚</td>
<td>高能物理研究所</td>
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<tr>
<td>基于THGEM探测器的数字量能器的研究 (2015)</td>
<td>面上基金</td>
<td>王恒</td>
<td>高能物理研究所</td>
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<tr>
<td>高精度量能器上的通用粒子流算法开发(2016)</td>
<td>面上基金</td>
<td>陈志宏</td>
<td>高能物理研究所</td>
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<tr>
<td>正离子反馈连续抑制型气体探测器的实验研究(2016)</td>
<td>面上基金</td>
<td>祁辉</td>
<td>高能物理研究所</td>
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<tr>
<td>CEPC对撞区最终聚焦系统的设计研究(2015)</td>
<td>青年基金</td>
<td>王诺</td>
<td>高能物理研究所</td>
</tr>
<tr>
<td>利用无尘型CPS提高顶点探测器空间分辨精度的研究 (2016)</td>
<td>青年基金</td>
<td>周扬</td>
<td>高能物理研究所</td>
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<tr>
<td>关于CEPC中子束物理研究(2016)</td>
<td>青年基金</td>
<td>王毅</td>
<td>高能物理研究所</td>
</tr>
</tbody>
</table>

~60M RMB CAS-Beijing fund, talent program

~500M RMB Beijing fund (light source)

2017 year funding request (45M) to MOST and other agencies under preparation

funding needs for carrying out CEPC design and R&D should be fully met by end of 2018

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Physics Requirements (FCC-hh)

Higgs boson physics: 125 GeV object at 100 TeV can be highly boosted + need for optimal sensitivity to multi-Higgs and VBF processes.

- Precision tracking (momentum spectroscopy) and ECAL up to $\eta=4$
- Tracking and highly granular calorimetry for jets up to $\eta=6$.
- Sensitivity to low $pT$ tracks vital for broad physics acceptance.

Searches require excellent performance at the highest energies.

- Calorimetry: hermetic and 1-2% constant term (shower containment needs $12\,\lambda$).
- Tracking: high momentum resolution $\sim 10\%$ at $pT=10$ TeV.

Pile-up for $30\times10^{34}$ and 25ns would reach $\sim 1000$ events/bunch crossing.

- Calorimeter granularity of $\Delta R \leq 0.05\times0.05$ or $0.025\times0.025$ to mitigate pile-up and measure jet substructure and boosted objects.
- Precision track association with primary vertex, timing for pileup rejection etc. …

Efficient b, c, $\tau$ -tagging despite intense radiation levels at low radii.

Contact: Werner.Riegler@cern.ch

E-mail-list: fcc-experiments-hadron@cern.ch