CERN roadmap and FCC

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CERN
CERN’s Future Circular Colliders (FCC) study

International FCC collaboration (CERN as host lab) to study:

- **pp-collider (FCC-hh)**
  - main emphasis, defining infrastructure requirements
  - ~16 T ⇒ 100 TeV pp in 100 km

- ~100 km tunnel infrastructure in Geneva area, site specific

- **e^+e^- collider (FCC-ee)**, as potential first step

- **HE-LHC** with FCC-hh technology

- **p-e (FCC-he)** option, integration of one IP, e from ERL

- **CDR for end 2018**
Overall layout optimization

- Optimized length: 97.5 km
  - Accessibility, rock type, shaft depth, etc.
  - Tried different options from 80 to 100 km

- Tunneling
  - Molasse 90% (easy to dig)
  - Limestone 5%, Moraines 5% (tougher)

- Shallow implementation
  - 30m below Leman lakebed
  - Only one very deep shaft (F, 476m)
    - Alternatives studied (e.g. inclined access)
• 2 main IPs in A, G for both machines
• asymmetric IR optic/geometry for ee to limit synchrotron radiation to detector

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-hh injector studies

Injector options:
- SPS \( \rightarrow \) LHC \( \rightarrow \) FCC
- SPS/SPS\textsubscript{upgrade} \( \rightarrow \) FCC

Current baseline:
- Injection energy 3.3 TeV LHC

Alternative option:
- Injection around 1.5 TeV
- SPS\textsubscript{upgrade} could be based on fast-cycling SC magnets, 6-7T, \( \sim \) 1T/s ramp
Baseline is comprised of:

- An $e^-$ and $e^+$ LINAC (length 250 m @ 25 MV/m) from ~0 to 6 GeV
- An $e^+$ production target and an $e^\pm$ damping ring (circumference 250 m)
- A pre-booster ring (from 6 to 20 GeV) – probably in the SPS tunnel
- A booster ring (from 20 GeV to the full FCC-ee energy), for continuous top-up injection
## FCC-ee collider parameters

<table>
<thead>
<tr>
<th></th>
<th>Z</th>
<th>W</th>
<th>H (ZH)</th>
<th>ttbar</th>
</tr>
</thead>
<tbody>
<tr>
<td>beam energy [GeV]</td>
<td>45.6</td>
<td>80</td>
<td>120</td>
<td>182.5</td>
</tr>
<tr>
<td>arc cell optics</td>
<td>60/60</td>
<td>90/90</td>
<td>90/90</td>
<td>90/90</td>
</tr>
<tr>
<td>emittance hor/vert [nm]/[pm]</td>
<td>0.27/1.0</td>
<td>0.28/1.0</td>
<td>0.63/1.3</td>
<td>1.45/2.7</td>
</tr>
<tr>
<td>$\beta^*$ horiz/vertical [m]/[mm]</td>
<td>0.15/.8</td>
<td>0.2/1</td>
<td>0.3/1</td>
<td>1/2</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>0.10</td>
<td>0.44</td>
<td>2.0</td>
<td>10.9</td>
</tr>
<tr>
<td>energy acceptance [%]</td>
<td>1.3</td>
<td>1.3</td>
<td>1.5</td>
<td>2.5</td>
</tr>
<tr>
<td>energy spread (SR / BS) [%]</td>
<td>0.038 / 0.132</td>
<td>0.066 / 0.153</td>
<td>0.099 / 0.151</td>
<td>0.15 / 0.20</td>
</tr>
<tr>
<td>bunch length (SR / BS) [mm]</td>
<td>3.5 / 12.1</td>
<td>3.3 / 7.65</td>
<td>3.15 / 4.9</td>
<td>2.5 / 3.3</td>
</tr>
<tr>
<td>bunch intensity [$10^{11}$]</td>
<td>1.7</td>
<td>1.5</td>
<td>1.5</td>
<td>2.8</td>
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<tr>
<td>no. of bunches / beam</td>
<td>16640</td>
<td>2000</td>
<td>393</td>
<td>39</td>
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<tr>
<td>beam current [mA]</td>
<td>1390</td>
<td>147</td>
<td>29</td>
<td>5.4</td>
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<tr>
<td>SR total power [MW]</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>luminosity [$10^{34}$ cm$^{-2}$s$^{-1}$]</td>
<td>230</td>
<td>32</td>
<td>7.8</td>
<td>1.5</td>
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<td>luminosity lifetime [min]</td>
<td>70</td>
<td>50</td>
<td>42</td>
<td>44</td>
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<tr>
<td>allowable asymmetry [%]</td>
<td>±5</td>
<td>±3</td>
<td>±3</td>
<td>±3</td>
</tr>
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</table>
Luminosity goals and operation model

- **The FCC-ee physics goals require at least**
  - $150 \text{ ab}^{-1}$ at and around the Z pole ($\sqrt{s} \sim 91.2 \text{ GeV}$)
  - $10 \text{ ab}^{-1}$ at the WW threshold ($\sqrt{s} \sim 161 \text{ GeV}$)
  - $5 \text{ ab}^{-1}$ at the HZ cross section maximum ($\sqrt{s} \sim 240 \text{ GeV}$)
  - $0.2 \text{ ab}^{-1}$ at the top threshold ($\sqrt{s} \sim 350 \text{ GeV}$) and $1.5 \text{ ab}^{-1}$ above ($\sqrt{s} \sim 365 \text{ GeV}$)

- **Operation model (with 10% safety margin) with two IPs**
  - 200 scheduled physics days per year (7 months – 13 days of MD / stops)
  - Hübner factor ~ 0.75 (lower than achieved with KEKB top-up injection, ~0.8)
  - Half the design luminosity in the first two years of Z operation (~LEP1)
  - Machine configuration between WPs changed during Winter shutdowns (3 months/year)

<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>365 GeV</th>
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</thead>
<tbody>
<tr>
<td>Lumi/IP (10$^{34}$ cm$^{-2}$s$^{-1}$)</td>
<td>100</td>
<td>200</td>
<td>13</td>
<td>7</td>
<td>1.6</td>
<td>1.3</td>
</tr>
<tr>
<td>Lumi/year (2 IP)</td>
<td>26 ab$^{-1}$</td>
<td>52 ab$^{-1}$</td>
<td>7.8 ab$^{-1}$</td>
<td>1.8 ab$^{-1}$</td>
<td>0.4 ab$^{-1}$</td>
<td>0.35 ab$^{-1}$</td>
</tr>
<tr>
<td>Physics goal</td>
<td>150</td>
<td>10</td>
<td>5</td>
<td>0.2</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>Run time (year)</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>0.5</td>
<td>4</td>
</tr>
</tbody>
</table>

- **Total running time: 12-13 years (~ LEP)**

Patrick Janot  
Academic Training  
11 Oct 2017
The SCRF system: optimization and staging

- Very broad range of operation parameters
  - SR energy loss from 36 MeV to 9.21 GeV
  - Total voltage from 0.1 (Z) to 11 GV (tt)
  - Total current from 5.4 mA (tt) to 3.9 A (Z)
    - Aim at acceleration efficiency and cost reduction at high energy
    - Aim at cell shape and impedance optimization against HOMs at high current
  - Fast acceleration from 20 to 45 – 182.5 GeV in the booster

- Solution: Operation staging
  - Start with 400 MHz Nb/Cu cavities @ 4.5K for the Z, WW, and Higgs operation modes
  - Realign all cavities to make RF common to both beams
  - Add 800 MHz bulk Nb cavities @ 2K for the ttbar operation mode

- Total length ~1.8km

Patrick Janot

11 Oct 2017
Power consumption

- The RF system needs to compensate for 100 MW SR losses
  - Corresponds to 200 MW electric power with 50% RF power sources (klystrons)
    - Klystron efficiency was ~55% at LEP2
  - Recent (2015) breakthroughs in klystron design promise 90% efficiency
    - Assume 85% will be achieved and take 10 – 20% margins

<table>
<thead>
<tr>
<th>lepton collider</th>
<th>Z</th>
<th>W</th>
<th>ZH</th>
<th>tt</th>
<th>LEP2</th>
</tr>
</thead>
<tbody>
<tr>
<td>luminosity / interaction point [10^{34} cm^{-2}s^{-1}]</td>
<td>207</td>
<td>90</td>
<td>19</td>
<td>5</td>
<td>1.3</td>
</tr>
<tr>
<td>total RF power [MW]</td>
<td>163</td>
<td>163</td>
<td>145</td>
<td>145</td>
<td>42</td>
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<tr>
<td>collider cryogenics [MW]</td>
<td>3</td>
<td>2</td>
<td>5</td>
<td>23</td>
<td>18</td>
</tr>
<tr>
<td>collider magnets [MW]</td>
<td>3</td>
<td>10</td>
<td>24</td>
<td>50</td>
<td>16</td>
</tr>
<tr>
<td>booster RF &amp; cryogenics [MW]</td>
<td>4</td>
<td>4</td>
<td>6</td>
<td>7</td>
<td>N/A</td>
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<tr>
<td>booster magnets [MW]</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>5</td>
<td>N/A</td>
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<tr>
<td>pre-injector complex [MW]</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>physics detectors (2) [MW]</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>9</td>
</tr>
<tr>
<td>cooling &amp; ventilation [MW]</td>
<td>47</td>
<td>49</td>
<td>52</td>
<td>62</td>
<td>16</td>
</tr>
<tr>
<td>general services [MW]</td>
<td>36</td>
<td>36</td>
<td>36</td>
<td>36</td>
<td>9</td>
</tr>
<tr>
<td>total electrical power [MW]</td>
<td>276</td>
<td>~275</td>
<td>~288</td>
<td>~308</td>
<td>~364</td>
</tr>
</tbody>
</table>

- For comparison
  - CLIC: 250 MW (at 380 GeV) to 580 MW (at 3 TeV)
<table>
<thead>
<tr>
<th>parameter</th>
<th>FCC-hh</th>
<th>HE-LHC</th>
<th>HL-LHC</th>
<th>LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>collision energy cms [TeV]</td>
<td>100</td>
<td>27</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>dipole field [T]</td>
<td>16</td>
<td>16</td>
<td>8.33</td>
<td>8.33</td>
</tr>
<tr>
<td>circumference [km]</td>
<td>97.75</td>
<td>26.7</td>
<td>26.7</td>
<td>26.7</td>
</tr>
<tr>
<td>beam current [A]</td>
<td>0.5</td>
<td>1.12</td>
<td>1.12</td>
<td>0.58</td>
</tr>
<tr>
<td>bunch intensity [10^{11}]</td>
<td>1</td>
<td>1 (0.2)</td>
<td>2.2 (0.44)</td>
<td>2.2</td>
</tr>
<tr>
<td>bunch spacing [ns]</td>
<td>25</td>
<td>25 (5)</td>
<td>25 (5)</td>
<td>25</td>
</tr>
<tr>
<td>synchr. rad. power / ring [kW]</td>
<td>2400</td>
<td>101</td>
<td>7.3</td>
<td>3.6</td>
</tr>
<tr>
<td>SR power / length [W/m/ap.]</td>
<td>28.4</td>
<td>4.6</td>
<td>0.33</td>
<td>0.17</td>
</tr>
<tr>
<td>long. emit. damping time [h]</td>
<td>0.54</td>
<td>1.8</td>
<td>12.9</td>
<td>12.9</td>
</tr>
<tr>
<td>beta* [m]</td>
<td>1.1</td>
<td>0.3</td>
<td>0.25</td>
<td>0.20</td>
</tr>
<tr>
<td>normalized emittance [μm]</td>
<td>2.2 (0.4)</td>
<td>2.5 (0.5)</td>
<td>2.5</td>
<td>3.75</td>
</tr>
<tr>
<td>peak luminosity [10^{34} cm^{-2}s^{-1}]</td>
<td>5</td>
<td>30</td>
<td>25</td>
<td>5</td>
</tr>
<tr>
<td>events/bunch crossing</td>
<td>170</td>
<td>1k (200)</td>
<td>~800 (160)</td>
<td>135</td>
</tr>
<tr>
<td>stored energy/beam [GJ]</td>
<td>8.4</td>
<td>1.3</td>
<td>0.7</td>
<td>0.36</td>
</tr>
</tbody>
</table>
Developed model including most relevant effects

- Improvement with more detail planned

⇒ Reach 8fb⁻¹/day with ultimate for 25ns spacing
⇒ 5ab⁻¹ per 5 year run

⇒ Beam is burned quickly
  ⇒ A reason to have enough charge stored
look @ Zimmermann’s slides for many more details, 25ns vs 5ns, etc

=> total of O(20) ab-1 over 25 years of operation.
FCC-hh cryogenic beam vacuum system

- Synchrotron radiation (~ 30 W/m/beam (@16 T field)) (LHC <0.2W/m) ~ 5 MW total load in arcs
- Absorption of synchrotron radiation at ~50 K for cryogenic efficiency (5 MW → 100 MW cryoplant)
- Provision of beam vacuum, suppression of photo-electrons, electron cloud effect, impedance, etc.

FCC-hh beam-screen test set-up at ANKA:
Beam tests since June 2017, confirming vacuum design simulations

2.5 GeV ANKA storage ring
**Nb$_3$Sn conductor development program**

Nb$_3$Sn is one of the key cost & performance factors for FCC-hh / HE-LHC

Main development goals:
- $J_c$ increase (16T, 4.2K) > 1500 A/mm$^2$ i.e. 50% increase wrt HL-LHC wire
- Reference wire diameter 1 mm
- Potentials for large-scale production and cost reduction

Impact on coil section and conductor mass
- $5400 \text{ mm}^2$ to $3150 \text{ mm}^2$ ~1.7 times less SC
- ~10% margin HL-LHC
- ~10% margin FCC ultimate
collaborations FCC Nb$_3$Sn program

procurement of state-of-the-art conductor for prototyping:
➢ Bruker/OST – European/US

stimulation of conductor development with regional industry:
➢ CERN/KEK – Japanese industry (JASTEC, Furukawa, SH Copper) and laboratories (Tohoku Univ. and NIMS).
➢ CERN/Bochvar High-technology Research Inst. – Russian industry (TVEL) and laboratories
➢ CERN/KAT – Korean industrial contribution
➢ CERN/Bruker – European industrial contribution

characterization of conductor & research with universities:
➢ Europe: Technical Univ. Vienna, Geneva University, University of Twente
➢ Applied Superconductivity Centre at Florida State University

new US DOE MDP effort – US activity with industry (OST) and labs

see S.Prestemon talk
16 T dipole design activities and options

Short model magnets (1.5 m lengths) will be built from 2017 - 2021

see D. Tommasini talk
15T dipole prototyping at FNAL (60mm aperture, L=1m)

ready for testing by mid-2018
total duration of magnet program: ~20 years
would follow HL-LHC $Nb_3Sn$ program with long models w industry from 2023/24
technical schedule defined by magnets program and by CE
→ earliest possible physics starting dates:
- FCC-hh: 2043
- FCC-ee: 2039
- HE-LHC: 2040 (with HL-LHC stop at LS5 / 2034)
Detector studies

• **Detector design** group leader: Werner Riegler
  • Indico site of mtgs: [http://indico.cern.ch/category/8920/](http://indico.cern.ch/category/8920/)
  • join the mailing list

• **Physics Simulation** subgroup leaders: Heather Gray & Filip Moortgat
  • Indico site of mtgs: [http://indico.cern.ch/category/6067/](http://indico.cern.ch/category/6067/)
  • join the mailing list

• Monthly mtgs of each group, if interested register to the mailing lists
Reference detector

earlier design

6 T, 12 m bore solenoid, 10 Tm dipoles, shielding coil

- 65 GJ stored energy
- 28 m diameter
- >30 m shaft
- multi billion project

current design

4 T, 10 m bore solenoid, 4 T forward solenoids, no shielding coil

- 14 GJ stored energy
- rotational symmetry for tracking!
- 20 m diameter (~ ATLAS)
- 15 m shaft
- ~1 billion project

latest ℓ* = 40 m

W. Riegler et al.
Comparison to ATLAS & CMS
HE-LHC:

27 TeV pp in the LHC tunnel
Evolution, with beam energy, of scenarios with the discovery of a new particle at the LHC
Possible questions/options

• If $m_X \sim 6$ TeV in the gg channel, rate grows $\times 200$ @27 TeV:
  • Do we wait 40 yrs to go to pp@100 TeV, or fast-track 27 TeV in the LHC tunnel?
  • Do we need 100 TeV, or 50 is enough ($\sigma_{100}/\sigma_{14} \sim 4 \cdot 10^4$, $\sigma_{50}/\sigma_{14} \sim 4 \cdot 10^3$)?
  • .... and the answers may depend on whether we expect partners of $X$ at masses $\gtrsim 2m_X$ ($\Rightarrow 27$ TeV would be insufficient ....)

• If $m_X \sim 0.5$ TeV in the qqbar channel, rate grows $\times 10$ @100 TeV:
  • Do we go to 100 TeV, or push by $\times 10 \int L$ at LHC?
  • Do we build CLIC?

• etc. etc.
HE-LHC pile up & performance

with 160 days of physics, 70% availability, 3 h turnaround time

$\beta^* = 25\text{ cm}: 820\text{ fb}^{-1}/\text{year}$

$\beta^* = 40\text{ cm}: 700\text{ fb}^{-1}/\text{year}$

not quite 4x HL-LHC, but close

$\sim 15\%$ reduction with 2x lower peak pile up

$\Rightarrow O(15\text{ ab}^{-1})\text{ over }20-25\text{ years}$
What does the HE-LHC entail?

• **Necessary:**
  • empty the tunnel (more time & $s$ than removing LEP)
  • full replacement of the magnets (today’s cost $\sim 4\times$LHC. First prototypes in $\sim 2026$)
  • upgrade of RF, cryogenics, collimation, beam dumps, …

• **Very likely:**
  • major upgrade of SPS, to inject at $O(1\ \text{TeV})$ (magnets, RF, transfer lines, cryo if SC, …)
  • major overhaul of detectors (radiation damage after HL-LHC, use of new technologies)

=> it’s like building the LHC ex-novo
  • very unlikely to be cheaper …
  • … but not incompatible with a $\sim$constant CERN budget
  • nevertheless feasibility to be proven (eg magnets bigger than LHC’s: will they fit in the tunnel ??)
requirement: no major CE tunnel modifications
• challenges for tunnel integration
• maximum magnet cryostat external diameter compatible with LHC tunnel ~1200 mm
• classical 16 T cryostat design based on LHC approach gives ~1500 mm diameter!

strategy: develop a single 16 T magnet, compatible with both HE LHC and FCC-hh requirements:
• options und consideration:
  • allow stray-field and/or cryostat as return-yoke
  • active compensation with (simple) shielding coils
  • optimization of inter-beam distance (compactness)
  • (QRL integrated in magnets, \(\rightarrow\) reduced integral field because of longitudinal space required for service module (5%))

\(\rightarrow\) smaller diameter, also relevant for FCC-hh cost optimization
Challenges of compact (1.2mØ) 16T dipoles

- Dipole bend for HE-LHC (5mm over 14m)
- Field errors $\Rightarrow$ reduced dynamic aperture at 100 TeV
- Physical aperture loss due to beam screen
- Impact of stray fields on tunnel electronics, esp. during quench

For more details on the challenges of HE-LHC (optics, injection, collimation/extraction, IR and triplet protection, …) see Zimmermann at [https://indico.cern.ch/event/647676](https://indico.cern.ch/event/647676)
# Conceptual Design Report

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<td>Infrastructure</td>
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<tr>
<th>4 Lepton Collider Summary</th>
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<th>6 High Energy LHC Summary</th>
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</table>

Refs to FCC-hh, HL-LHC, LHeC

Detailed volumes

⇒ to be completed by end 2018
European Strategy for Particle Physics

- Sept 2017: Council establishes the Strategy Secretariat:
  - Halina Abramovicz Scientific Secretary, with Chairs of SPC (R.K.Ellis), ECFA (tba, November), european laboratory directors group (L.Rivkin)
- Sept 2018: Council nominates Preparatory Group and Strategy Group
- Dec 2018: deadline for submission of input from the community
- 2019: Community discussions
  - Open Symposium (~Sept ‘19, and possibly one in early ‘19)
  - Preparatory group summarizes community feedback in Briefing Books
- Early 2020: Strategy Group discussion and preparation of the draft Strategy (1-week mtg, inspired by briefing books)
- May 2020: adoption of the Strategy by Council
remarks

- Input welcome from the full international community, addressing also other global, regional or national plans

- Strategy group includes 1 voting rep / member state, as well as observers from associate/observer states, other regions, astro and nuclear communities, EU, …

- Final Strategy statements endorsed and signed by Council.

- However, the Strategy is a collection of resolutions and statements, not an implementation plan. Implementation of the Strategy, and consideration/approval of specific initiatives/facilities emerging from it, is a subsequent process, in the hands of Council and CERN’s management.

- Timeline of Strategy releases so far:

  - 2006, 2013, 2020 ⇒ ~7 year timeframe
FCC Collaboration & Industry Relations

113 Institutes
25 Companies
32 Countries
EC H2020
also 2018 FCC Physics Workshop, 15-19 January 2018, CERN
https://indico.cern.ch/event/618254/
Resources

Talks at HL/HE-LHC workshop:


FCC academic training lectures:


thanks to all of them and M.Benedikt for sharing slides