Future Circular Collider Study

Status and Progress

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gratefully acknowledging input from FCC coordination group
global design study team and all other contributors

Work supported by the European Commission under the HORIZON 2020 project EuroCirCol, grant agreement 654305
• FCC Study Scope & Time Line
• Machine Design
• Technologies
• FCC Organisation & Collaboration
International FCC collaboration (CERN as host lab) to study:

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

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

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

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

- **HE-LHC** with **FCC-hh** technology
Must advance fast now to be ready for the period 2035 – 2040

Goal of phase 1: CDR by end 2018 for next update of European Strategy
Review panel – Decision to focus on 100 km tunnel

FCC week 2016 in Rome:
- Single and double tunnel
- Inclined access tunnels
- hh and ee requirements

- Revised layout for realisation studies
- Naming convention

Cost and schedule study ongoing with 2 consultants

- Cost & schedule estimates
- Inclined access shafts assessment
- Tunnel and shaft cross-section designs

Nov. 2015

Apr. 2016

Aug. 2016

Sept. 2016


- Quaternary
- Lake
- Wildflysch
- Molasse subepilithic
- Molasse
- Limestone
- Shaft
- Alignment
• 90 – 100 km fits geological situation well
• LHC suitable as potential injector
• The 97.75 km version, tangent to LHC, is now being studied in more detail
FCC-hh injector studies

Injector options:
- SPS \rightarrow LHC \rightarrow FCC
- SPS/SPS_{\text{upgrade}} \rightarrow FCC

Current baseline:
- Injection energy 3.3 TeV LHC

Alternative option:
- Injection around 1.5 TeV
- SPS_{\text{upgrade}} could be based on fast-cycling SC magnets, 6-7T, \sim 1T/s ramp
Common layouts for hh & ee

FCC-ee 1, FCC-ee 2,
FCC-ee booster (FCC-hh footprint)

• 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.
### Hadron collider parameters

<table>
<thead>
<tr>
<th>parameter</th>
<th>FCC-hh</th>
<th>HE-LHC* tentative</th>
<th>(HL) LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>collision energy cms [TeV]</td>
<td>100</td>
<td>&gt;25</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># IP</td>
<td>2 main &amp; 2</td>
<td>2 &amp; 2</td>
<td>2 &amp; 2</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</td>
<td>1 (0.2)</td>
<td>(2.2) 1.15</td>
</tr>
<tr>
<td>bunch spacing [ns]</td>
<td>25</td>
<td>25 (5)</td>
<td>25</td>
</tr>
<tr>
<td>beta* [m]</td>
<td>1.1</td>
<td>0.3</td>
<td>(0.15) 0.55</td>
</tr>
<tr>
<td>luminosity/IP $[10^{34} \text{ cm}^{-2}\text{s}^{-1}]$</td>
<td>5</td>
<td>20 - 30</td>
<td>(5) 1</td>
</tr>
<tr>
<td>events/bunch crossing</td>
<td>170</td>
<td>&lt;1020 (204)</td>
<td>850</td>
</tr>
<tr>
<td>stored energy/beam [GJ]</td>
<td>8.4</td>
<td>1.2</td>
<td>(0.7) 0.36</td>
</tr>
<tr>
<td>synchrotr. rad. [W/m/beam]</td>
<td>30</td>
<td>3.6</td>
<td>(0.35) 0.18</td>
</tr>
</tbody>
</table>
Contributions from teams at CERN and other institutes:
• Complete optics, collective effects, collimation studies

NEW LAYOUT NOV. 2016

Basis for design evaluation:
• Beam dynamics, losses
Feedback to element designs, e.g. magnet quality specifications
High synchrotron radiation load of proton beams @ 50 TeV:

- \(~30\ \text{W/m/beam (}@16\ \text{T})\) (LHC <0.2W/m)
- 5 MW total in arcs (@1.9 K!!!)

New Beam screen with ante-chamber

- absorption of synchrotron radiation at 50 K to reduce cryogenic power by a factor 50 to 100 MW total
Progress on
- Geometry design and beam screen support
- Prototype construction
- Thermal load to cold bore reduction
- Synchrotron Radiation absorber
- Pumping speed optimisation
- Pumping holes optimisation
- Misalignment effects

Simulated quench behaviour
Max displacement 0.47 mm
Cryo power for cooling of SR heat

Overall optimisation of cryo-power, vacuum and impedance

Temperature ranges: <20, 40K-60K, 100K-120K

Multi-bunch instability growth time: 25 turns 9 turns (ΔQ=0.5)
Nb$_3$Sn is one of the major cost & performance factors for FCC-hh and requires highest attention

Main development goals until 2020:
- $J_c$ 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
Collaborations FCC Nb$_3$Sn program

Procurement of state-of-the-art conductor for protoyping:
- Bruker – European,
- OST – US

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

Characterisation 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
CERN-EU program ‘EuroCirCol’ on 16 T dipole design

European Union Horizon 2020 program
- Support for FCC study
- Grant agreement 654305
- 3 MEURO co-funding

Scope:
- FCC hadron collider
  - Optics Design
  - Cryo vacuum design
  - 16 T dipole design, construction folder for demonstrator magnets
16 T dipole options and plans

- Down-selection of options mid 2017 for detailed design work
- Model production 2018 - 2022
- Prototype production 2023 - 2025

Swiss contribution via PSI

Canted Cos-theta
Program (MDP) Goals:

GOAL 1:
Explore the performance limits of Nb$_3$Sn accelerator magnets with a focus on minimizing the required operating margin and significantly reducing or eliminating training.

GOAL 2:
Develop and demonstrate an HTS accelerator magnet with a self-field of 5 T or greater compatible with operation in a hybrid LTS/HTS magnet for fields beyond 16 T.

GOAL 3:
Investigate fundamental aspects of magnet design and technology that can lead to substantial performance improvements and magnet cost reduction.

GOAL 4:
Pursue Nb$_3$Sn and HTS conductor R&D with clear targets to increase performance and reduce the cost of accelerator magnets.
### lepton collider parameters

<table>
<thead>
<tr>
<th>parameter</th>
<th>FCC-ee (400 MHz)</th>
<th>LEP2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physics working point</td>
<td>Z</td>
<td>WW</td>
</tr>
<tr>
<td>energy/beam [GeV]</td>
<td>45.6</td>
<td>80</td>
</tr>
<tr>
<td>bunches/beam</td>
<td>30180</td>
<td>91500</td>
</tr>
<tr>
<td>bunch spacing [ns]</td>
<td>7.5</td>
<td>2.5</td>
</tr>
<tr>
<td>bunch population [$10^{11}$]</td>
<td>1.0</td>
<td>0.33</td>
</tr>
<tr>
<td>beam current [mA]</td>
<td>1450</td>
<td>1450</td>
</tr>
<tr>
<td>luminosity/IP x $10^{34}$cm$^{-2}$s$^{-1}$</td>
<td>210</td>
<td>90</td>
</tr>
<tr>
<td>energy loss/turn [GeV]</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>synchrotron power [MW]</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>RF voltage [GV]</td>
<td>0.4</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Identical FCC-ee baseline optics for all energies

FCC-ee: 2 separate rings, LEP: single beam pipe
FCC-ee exploits lessons & recipes from past $e^+e^-$ and $pp$ colliders

combining successful ingredients of recent colliders $\rightarrow$ extremely high luminosity at high energies

- LEP: high energy SR effects
- B-factories: KEKB & PEP-II: high beam currents, top-up injection
- DAFNE: crab waist
- Super B-factories
  - S-KEKB: low $\beta_y^*$
- KEKB: $e^+$ source
- HERA, LEP, RHIC: spin gymnastics
FCC-ee optics design

Optics design for all working points achieving baseline performance
Interaction region: asymmetric optics design

- Synchrotron radiation from upstream dipoles <100 keV up to 450 m from IP
- Dynamic aperture & momentum acceptance requirements fulfilled at all WPs
RF system requirements

Very large range of operation parameters

“Ampere-class” machines

<table>
<thead>
<tr>
<th></th>
<th>$V_{\text{total}}$ GV</th>
<th>$n_{\text{bunches}}$</th>
<th>$I_{\text{beam}}$ mA</th>
<th>$\Delta E$/turn GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>hh</td>
<td>0.032</td>
<td></td>
<td>500</td>
<td></td>
</tr>
<tr>
<td>Z</td>
<td>0.4/0.2 30000/90000</td>
<td></td>
<td>1450</td>
<td>0.034</td>
</tr>
<tr>
<td>W</td>
<td>0.8</td>
<td>5162</td>
<td>152</td>
<td>0.33</td>
</tr>
<tr>
<td>H</td>
<td>5.5</td>
<td>770</td>
<td>30</td>
<td>1.67</td>
</tr>
<tr>
<td>t</td>
<td>10</td>
<td>78</td>
<td>6.6</td>
<td>7.55</td>
</tr>
</tbody>
</table>

“high gradient” machines

Naive scale up from an hh system

- Voltage and beam current ranges span more than factor $> 10^2$
- No well-adapted single RF system solution satisfying requirements
400 MHz single-cell cavities preferred for hh and ee-Z (few MeV/m)
- Baseline Nb/Cu @4.5 K, development with synergies to HL-LHC, HE-LHC
- R&D: power coupling 1 MW/cell, HOM power handling (damper, cryomodule)

400 or 800 MHz multi-cell cavities preferred for ee-ZH, ee-tt and ee-WW
- Baseline options 400 MHz Nb/Cu @4.5 K, 800 MHz bulk Nb system @2K
- R&D: High $Q_0$ cavities, coating, long-term: Nb$_3$Sn like components
collaboration & industry relations

96 Institutes

19 Companies

30 Countries
Summary

• FCC study is advancing well towards the CDR for end 2018
• Consolidated parameter sets exists for FCC-hh and FCC-ee machines with complete baseline optics design and beam dynamics compatible with parameter requirements
• First round of geology, civil engineering & infrastructure studies completed
• Superconductivity is the key enabling technology for FCC. The Nb3Sn program towards 16 T model magnets is of prime importance for FCC-hh and so is the development of high-efficiency SRF systems for FCC-ee.
• International collaboration is essential to advance on all challenging subjects to prepare a solid and convincing case for the next European Strategy update.