Status of the FCC-hh Design Study

D. Schulte, CERN

For the FCC-hh collaboration
FCC Goal

FCC study develops a conceptual design of a new facility

**FCC-hh** defines infrastructure
- 100 TeV proton-proton collisions, 20 ab\(^{-1}\)
- 7x LHC energy and 7x HL-LHC integrated luminosity
- Use existing infrastructure to generate beam
- New ~100km-long collider ring

Potential first stage **FCC-ee** offers electron-positron collisions from 90 GeV to 365 GeV
- Unprecedented electron-positron collision energies >208 GeV
- Much higher event rates at previously reached energies (O(10\(^5\)) times as many Z as at LEP/LEP2)

**FCC-eh** Proton-electron option is also possible

**HE-LHC** Proton-proton option in LHC tunnel with FCC-hh technology

Consistent with implementation at CERN
FCC Collaboration

124 Institutes
30 Companies
32 Countries

EC H2020

D. Schulte
FCC-hh, ICHEP, Seoul, July 2018
FCC-hh Layout

Layout for CERN site

- Two high-luminosity experiments (A and G)
- Two other experiments combined with injection at 3.3 TeV (L and B)
- Two collimation insertions
  - Betatron cleaning (J)
  - Momentum cleaning (E)
- Extraction insertion (D)
- Clean insertion with RF (H)
- Circumference 97.75km
- Can be integrated into the area
- Can use LHC or SPS as injector
# Hadron Collider Parameters

<table>
<thead>
<tr>
<th></th>
<th>LHC / HL-LHC</th>
<th>HE-LHC (tentative)</th>
<th>FCC-hh</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Initial</td>
<td>Ultimate</td>
<td></td>
</tr>
<tr>
<td>Cms energy [TeV]</td>
<td>14</td>
<td>27</td>
<td>100</td>
</tr>
<tr>
<td>Luminosity ([10^{34}\text{cm}^{-2}\text{s}^{-1}])</td>
<td>1 / 5</td>
<td>16</td>
<td>5</td>
</tr>
<tr>
<td>Machine circumference</td>
<td>26.7</td>
<td>26.7</td>
<td>97.75</td>
</tr>
<tr>
<td>Arc dipole field [T]</td>
<td>8</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Bunch charge</td>
<td>1.15 / 2.2</td>
<td>2.2</td>
<td>1</td>
</tr>
<tr>
<td>Bunch distance [ns]</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Background events/bx</td>
<td>27 / 135</td>
<td>440</td>
<td>170</td>
</tr>
<tr>
<td>Bunch length [cm]</td>
<td>7.5</td>
<td>7.5</td>
<td>8</td>
</tr>
</tbody>
</table>
Magnet Development

Magnet is key cost driver
• Improve cable performance
• Reduce cable cost
• Improve fabrication of magnet
• Minimise amount of cables
• Push lattice filling factor

Cost

Need 16 T to reach 50 TeV /beam
⇒ Move from NbTi (LHC technology) to Nb₃Sn
14.3 m long dipoles

Safety margin from 18% to 14%
Reduced inter-beam distance from 250 to 204 mm
Stray field up to 0.1 T
⇒ Total conductor (incl. copper) from O(10 kt) to 7.6 kt

Iterations with lattice designers for field quality

Short models in 2018 – 2023
Prototypes 2026 -- 2032
Magnet Models

With today’s state of the art conductors:

- 15 T achievable at 14 % margin
- 17 T at short sample
- Cos-theta and common-coil model magnet programs are under preparation

15 T dipole demonstrator
60-mm aperture
4-layer graded coil
New activity with many collaborators started in 2017 with ambitious targets

FCC Conductor Development Workshop at CERN, 5-6 March 2018

Participants

Switzerland

Japan

Russia

Korea

Germany

Italy

Finland/USA

China

TVEL

Austria

Western Superconducting Technologies Co., Ltd.

TU Wien

7 companies, two universities and two national research institutes

First wires almost reached HL-LHC requirements

<table>
<thead>
<tr>
<th>Wire diameter</th>
<th>mm</th>
<th>~ 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-Cu Jc (16 T, 4.2 K)*</td>
<td>A/mm²</td>
<td>( \geq 1500 )</td>
</tr>
<tr>
<td>Unit length</td>
<td>km</td>
<td>( \geq 5 )</td>
</tr>
<tr>
<td>Cost</td>
<td>( \text{€}/\text{kA m}^{**} )</td>
<td>( \leq 5 )</td>
</tr>
</tbody>
</table>

Yellow: FCC_1
Green: FCC_2
Blue: FCC_3
Dashed red: FCC_4
Dashed blue: HL-LHC

Measurements @ CERN (4.2 K)

Mixing of superconductors (Non-Cu with Cu)

D. Schulte

FCC-hh, ICHEP, Seoul, July 2018
## Beam Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Initial</th>
<th>Ultimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity $L$ [$10^{34}\text{cm}^{-2}\text{s}^{-1}$]</td>
<td>5</td>
<td>20-30</td>
</tr>
<tr>
<td>Background events/bx</td>
<td>170</td>
<td>&lt;1020</td>
</tr>
<tr>
<td>Bunch distance $\Delta t$ [ns]</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>Bunch charge $N$ [$10^{11}$]</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Fract. of ring filled $\eta_{\text{fill}}$ [%]</td>
<td>80</td>
<td></td>
</tr>
<tr>
<td>Norm. emitt. [\mu m]</td>
<td>2.2</td>
<td></td>
</tr>
<tr>
<td>Max $\xi$ for 2 IPs</td>
<td>0.01</td>
<td>0.03</td>
</tr>
<tr>
<td>IP beta-function $\beta$ [m]</td>
<td>1.1</td>
<td>0.3</td>
</tr>
<tr>
<td>IP beam size $\sigma$ [$\mu$m]</td>
<td>6.8</td>
<td>3.5</td>
</tr>
<tr>
<td>RMS bunch length $\sigma_z$ [cm]</td>
<td>8</td>
<td></td>
</tr>
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<td>Crossing angle [$\sigma_{\square}$]</td>
<td>12</td>
<td>Crab. Cav.</td>
</tr>
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<td>Turn-around time [h]</td>
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<td>4</td>
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</table>
Full integrated lattice exists
• large amount of work (code, matching, tuning, …)
• some small issues remain to be solved
• some proposals for improved designs to be integrated
Beam Dynamics

Beam-beam studies

Beam dynamics studies validate the design

Instabilities:
Impedances, octupoles, electron lens, feedback, ...
Electron cloud, coatings, ...

Beam handling:
Collimation, injection, extraction, ...

Lattice design, integration of octupoles for stability etc. corrector design, dynamic aperture studies, ...

\[ \mathcal{L} = \frac{1}{\beta} \frac{N}{\Delta t} \eta_{\text{fill}} \]
FCC-hh Technology Example

30 W/m synchrotron radiation (LHC: 1 W/m)
Make it small to make magnet cheap

Magnet aperture 50 mm (LHC 56 mm)

Prototype

Laser treatment / carbon coating against ecloud

Test station in ANKA

Extract photons for great vacuum

Strong to withstand quench

50 K for efficiency

Hide pumping holes from beam for low impedance
FCC-hh MDI

Tracking
Ecal
HCAL
Magnets and cryostat
Muons

- Uses forward solenoid
- Alternative option with forward dipole considered

Hall half length: 33m
Detector half length: 23.5m

L*=40 m
Space to open: 9.5m

Tunnel before triplet: 7m
Add. protection
TAS
Triplet

D. Schulte
FCC-hh, ICHEP, Seoul, July 2018
8 GJ kinetic energy per beam
- Boing 747 at cruising speed
- 2000 kg TNT
- 400 kg of chocolate
  - Run 25,000 km to spent calories
- O(20) times LHC

Collimation system design
- Designed system that can cope with the losses
- Detailed studies and optimisation of performance
- Also reduction of impedance
Detailed studies of site, civil engineering, power availability
Planning of project implementation

Use of LHC or SPS as injector is possible
Physics goals:
• 2 x LHC collision energy in LHC tunnel using FCC-hh magnets
  • I. e. cms energy > 27 TeV
  • Required some iterations of the design
• Target integrated luminosity ≥ 10 ab⁻¹ over 20 years

Strategy:
• Use FCC-hh magnets & FCC-hh vacuum system
• Use HL-LHC crab cavities & long-range wire compensation
• Use HL-LHC/LIU parameters (25 ns baseline)
• No major modifications of LHC tunnel
HE-LHC Challenges and Optics

Challenges:
- LHC tunnel is small
- Insertions are short
- But seem able to cope with this

Two arc lattice options considered
- First has higher energy (27.3 TeV)
- Second has better dynamic aperture

Injector (SPS) likely needs upgrade with superconducting magnets (from 0.45 to 1.3 TeV)

Insertions design requires new approaches (e.g. superconducting magnets in collimation section?)
FCC Schedules

CDR concise summary volumes (FCC-hh, FCC-ee, HE-LHC)
- Print-ready by November 2018

CDR technical volumes
- Proof reading and approval February to March 2019
Conclusion

• FCC studies advances quickly in all areas
  • Collider concept designs ready, CDR is being edited
    • Including HE-LHC

• Good progress on all key technologies
  • In particular worldwide R&D programme in place, on Nb$_3$Sn superconductor, high-field magnets, and on highly-efficient SC RF

• International FCC collaboration growing steadily, focusing now on completing the CDRs as input for European Strategy Update

• R&D programme towards a technical design
Beam Parameters and Luminosity

\[ \mathcal{L} = \xi \frac{1}{\beta} \frac{N}{\Delta t} \eta_{\text{fill}} \]

Beam physics

- Interaction region design
- Power consumption
- Beam stability
- Damage potential

Beam dynamics studies show this will work

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Synchrotron radiation is important at 50 TeV
• 5 MW for both beams
• 30 W/m per beam in the arc
⇒ Need to protect magnets from heat
⇒ Significant damping (1 h transverse damping time)

Beam burns off rapidly
Fast turn-around is key
LHC with modified magnet powering