FCC Feasibility Study & FCCIS Project

Michael Benedikt, CERN

on behalf of the FCC collaboration and FCCIS DS team

Work supported by the European Commission under the HORIZON 2020 projects EuroCirCol, grant agreement 654305; EASITrain, grant agreement no. 764879; ARIES, grant agreement 730871, FCCIS, grant agreement 951754, and E-JADE, contract no. 645479

http://cern.ch/fcc

photo: J. Wenninger
The FCC integrated program inspired by successful LEP – LHC programs at CERN

Comprehensive cost-effective program maximizing physics opportunities

- **Stage 1:** FCC-ee (Z, W, H, \( t \bar{t} \)) as Higgs factory, electroweak & 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
- FCC integrated project allows seamless continuation of HEP after HL-LHC
## FCC-ee collider parameters (stage 1)

<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 / 12.1</td>
<td>3.0 / 6.0</td>
<td>3.3 / 5.3</td>
<td>2.0 / 2.5</td>
</tr>
<tr>
<td>luminosity per IP [10^{34} cm^{-2}s^{-1}]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></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 / &gt;200</td>
<td>49 / &gt;1000</td>
<td>38 / 18</td>
<td>40 / 18</td>
</tr>
</tbody>
</table>
Luminosity $L$ per supplied electrical wall-plug power $P_{WP}$ is shown as a function of centre-of-mass energy for several proposed future lepton colliders.

Operation plan and integrated luminosity compliant with physics requirements at the four working points Z, WW, ZH, tt.
<table>
<thead>
<tr>
<th>parameter</th>
<th>FCC-hh (pp) collider parameters (stage 2)</th>
<th>HL-LHC</th>
<th>LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>collision energy cms [TeV]</td>
<td>100</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>dipole field [T]</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>
</tr>
<tr>
<td>beam current [A]</td>
<td>0.5</td>
<td>1.1</td>
<td>0.58</td>
</tr>
<tr>
<td>bunch intensity [10^{11}]</td>
<td>1</td>
<td>1</td>
<td>2.2</td>
</tr>
<tr>
<td>bunch spacing [ns]</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>synchr. rad. power / ring [kW]</td>
<td>2400</td>
<td>7.3</td>
<td>3.6</td>
</tr>
<tr>
<td>SR power / length [W/m/ap.]</td>
<td>28.4</td>
<td>0.33</td>
<td>0.17</td>
</tr>
<tr>
<td>long. emit. damping time [h]</td>
<td>0.54</td>
<td>12.9</td>
<td>12.9</td>
</tr>
<tr>
<td>beta* [m]</td>
<td>1.1</td>
<td>0.3</td>
<td>0.15 (min.)</td>
</tr>
<tr>
<td>normalized emittance [µm]</td>
<td>2.2</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>5 (lev.)</td>
</tr>
<tr>
<td>events/bunch crossing</td>
<td>170</td>
<td>1000</td>
<td>132</td>
</tr>
<tr>
<td>stored energy/beam [GJ]</td>
<td>8.4</td>
<td>0.7</td>
<td>0.36</td>
</tr>
</tbody>
</table>
FCC-hh: highest collision energies

- order of magnitude performance increase in both energy & luminosity
- 100 TeV cm collision energy (vs 14 TeV for LHC)
- 20 ab\(^{-1}\) per experiment collected over 25 years of operation (vs 3 ab\(^{-1}\) for LHC)
- similar performance increase as from Tevatron to LHC

**key technology: high-field magnets**

- from LHC technology: 8.3 T NbTi dipole
- via HL-LHC technology: 12 T Nb\(_3\)Sn quadrupole
- FNAL dipole demonstrator: 14.5 T Nb\(_3\)Sn
Present baseline position was established considering:
- lowest risk for construction, fastest and cheapest construction
- Molasse rock preferred for tunnelling, avoid limestone with karstic structures
- 90 – 100 km circumference
- 12 surface sites with few ha area each
Civil Engineering construction schedule

- Total construction duration 7 years
- First sectors ready after 4.5 years
FCC integrated project technical schedule

1. Project preparation & administrative processes
2. Permis- 
sions
3. Funding strategy
4. Funding and in-kind contribution agreements
5. Geological investigations, infrastructure detailed design and tendering preparation
6. Tunnel, site and technical infrastructure construction
7. FCC-ee accelerator R&D and technical design
8. FCC-ee detector construction, installation, commissioning
9. Set up of international experiment collaborations, detector R&D and concept development
10. FCC-ee detector technical design
11. Superconducting wire and magnet R&D, short models
12. FCC-ee detector technical design
13. FCC-ee detector construction, installation, commissioning
14. Long model magnets, prototypes, preseries
15. 16 T magnet industrialization and series production
16. Long model magnets, prototypes, preseries
17. Update Permissions
18. Funding and in-kind contribution agreements
19. FCC-ee dismantling, CE & infrastructure adaptations FCC-hh
20. FCC-hh accelerator, R&D and technical design
21. FCC-hh detector R&D, technical design
22. FCC-hh detector construction, installation, commissioning
23. FCC-hh accelerator construction, installation, commissioning
24. FCC-hh detector construction, installation, commissioning
25. Long model magnets, prototypes, preseries
26. 16 T magnet industrialization and series production
27. Long model magnets, prototypes, preseries
28. Update Permissions
29. Funding and in-kind contribution agreements
30. FCC-ee dismantling, CE & infrastructure adaptations FCC-hh
31. FCC-hh accelerator, R&D and technical design
32. FCC-hh detector R&D, technical design
33. FCC-hh detector construction, installation, commissioning
34. Future Circular Collider Study
35. Michael Benedikt
36. FCCIS kick-off meeting, 9 November 2020
37. ~ 25 years operation
38. 15 years operation
39. Future Circular Collider Study
40. Michael Benedikt
41. FCCIS kick-off meeting, 9 November 2020
42. ~ 25 years operation
43. 15 years operation
44. Future Circular Collider Study
45. Michael Benedikt
46. FCCIS kick-off meeting, 9 November 2020
47. ~ 25 years operation
48. 15 years operation
49. Future Circular Collider Study
50. Michael Benedikt
51. FCCIS kick-off meeting, 9 November 2020
52. ~ 25 years operation
53. 15 years operation
54. Future Circular Collider Study
55. Michael Benedikt
56. FCCIS kick-off meeting, 9 November 2020
57. ~ 25 years operation
58. 15 years operation
59. Future Circular Collider Study
60. Michael Benedikt
61. FCCIS kick-off meeting, 9 November 2020
62. ~ 25 years operation
63. 15 years operation
64. Future Circular Collider Study
65. Michael Benedikt
66. FCCIS kick-off meeting, 9 November 2020
67. ~ 25 years operation
68. 15 years operation
69. Future Circular Collider Study
70. Michael Benedikt
71. FCCIS kick-off meeting, 9 November 2020
FCC CDR and Study Documentation

- **FCC-Conceptual Design Reports:**
  - CDRs published in *European Physical Journal C* (Vol 1) and ST (Vol 2 – 4)
    - EPJ C 79, 6 (2019) 474, EPJ ST 228, 2 (2019) 261-623,

- **Summary documents provided to EPPSU SG**
  - FCC-integral, FCC-ee, FCC-hh, HE-LHC
Core sentence and main request “order of the further FCC study”:

“Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update.”
Feasibility study to be delivered end 2025 as input for ESPP Update expected for 2026/2027, to enable a project decision:

- **Feasibility study of the 100 km tunnel** (infrastructure aspects, administrative aspects, local authorities, environment, energy, etc.)
- **High-risk areas site investigations included**, to confirm principle feasibility
- **Host-state related processes**, to allow start of construction early 2030ies.
- **CDR+ for colliders and injectors**, including key technology proofs.
- **HFM program intermediate milestones**, in line with long-term R&D plan.
- **Physics and experiments CDR+ for FCC integrated project.**
- **Financing concept & organization model for project and operation phases.**
- For all these activities the sequential nature of implementation of the colliders and the overall timeline needs to be taken into account!
• Technical schedule of main processes leading to start of construction begin 2030ies
• For proof of principle feasibility: High risk area site investigations, 2022 – 2024
• Followed by update of civil engineering conceptual design and CE cost estimate 2025
**FCC key deliverables: prototypes by 2025**

**FCC-ee complete arc half-cell mock up**
including girder, vacuum system with antechamber + pumps, dipole, quadrupole + sext. magnets, BPMs, cooling + alignment systems, technical infrastructure interfaces.

**key beam diagnostics elements**
bunch-by-bunch turn-by-turn *longitudinal charge density profiles* based on electro-optical spectral decoding (beam tests at KIT/KARA);

ultra-low emittance measurement (X-ray interferometer tests at SuperKEKB, ALBA);
beam-loss monitors (IJCLab/KEK?);
beamstrahlung monitor (KEK);
polarimeter; luminometer.
FCC key deliverables: prototypes by 2025

400 MHz SRF cryomodule, + prototype multi-cell cavities for FCC ZH operation
High-efficiency RF power sources

high-yield positron source
target with DC SC solenoid or flux concentrator

beam test of $e^+$ source & capture linac
at SwissFEL – yield measurement

Strong support from Switzerland via CHART II program 2019 – 2024 for
FCC-ee injector, HFM, beam optics developments, geology and geodesy activities.
SuperKEKB – pushing luminosity and $\beta^*$

Design: double ring $e^+e^-$ collider as *B*-factory at $7(e^-) \& 4(e^+)$ GeV; design luminosity $\sim 8 \times 10^{35}$ cm$^{-2}$s$^{-1}$; $\beta_y^* \sim 0.3$ mm; nano-beam – large crossing angle collision scheme (crab waist w/o sextupoles); beam lifetime $\sim 5$ minutes; top-up injection; $e^+$ rate up to $\sim 2.5 \times 10^{12}$/s; under commissioning

SuperKEKB is demonstrating FCC-ee key concepts

$\beta_y^* = 0.8$ mm achieved in both rings – using the FCC-ee-style “virtual” crab-waist collision scheme

Y. Funakoshi, Y. Ohnishi, K. Oide

M. Tobiyama, K. Oide
<table>
<thead>
<tr>
<th>Parameter</th>
<th>NSLS-II</th>
<th>EIC</th>
<th>FCC-ee-Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy [GeV]</td>
<td>3</td>
<td>10 (20)</td>
<td>45.6</td>
</tr>
<tr>
<td>Bunch population [$10^{11}$]</td>
<td>0.08</td>
<td>1.7</td>
<td>1.7</td>
</tr>
<tr>
<td>Bunch spacing [ns]</td>
<td>2</td>
<td>10</td>
<td>15, 17.5 or 20</td>
</tr>
<tr>
<td>Rms bunch length [mm]</td>
<td>4.5 - 9</td>
<td>2</td>
<td>3.5 (SR)</td>
</tr>
<tr>
<td>Beam current [A]</td>
<td>0.5</td>
<td>2.5 (0.27)</td>
<td>1.39</td>
</tr>
<tr>
<td>RF frequency [MHz]</td>
<td>500</td>
<td>591</td>
<td>400</td>
</tr>
</tbody>
</table>

Similarity of several parameters strongly suggests collaboration to exploit synergies in areas such as beam instrumentation, SRF, vacuum system with SR handling, etc.

→ Two dedicated sessions Thursday afternoon, towards EIC-FCC collaboration.
**Future Circular Collider Study**

Michael Benedikt

**FCCIS kick-off meeting, 9 November 2020**

---

**Beneficiaries**

- CERN, Switzerland
- ULIV, United Kingdom
- Springer, The Netherlands
- DESY, Germany
- IFJPAN, Poland
- KIT, Germany
- TMFS, Austria
- MUL, Austria
- CEA, France
- Cerema, France
- CETU, France
- LD, Switzerland
- CSIL, Italy
- INFN, Italy
- CNRS, France
- USC, Spain

**Partners**

- DOE
  - United States of America
- UOXF
  - United Kingdom
- Writelatex DBA Overleaf
  - United Kingdom
- D.R.R.T
  - France
- Etat de Genève
  - Switzerland
- BINP
  - Russian Federation

---

**H2020 DS FCC Innovation Study 2020-24**

**Topic** | **INFRADEV-01-2019-2020**
--- | ---
Grant Agreement | FCCIS 951754
Duration | 48 months
From-to | 2 Nov 2020 – 1 Nov 2024
Project cost | 7 435 865 €
EU contribution | 2 999 850 €
Beneficiaries | 16
Partners | 6
Objectives of FCCIS (Description of Action)

- **O1**: Design a circular luminosity frontier particle collider with a research programme to remain at the forefront of research.
- **O2**: Demonstrate the technical and organizational feasibility of a 100 km long, circular particle collider.
- **O3**: Develop an innovation plan for a long-term sustainable research infrastructure that is seamlessly integrated in the European research landscape.
- **O4**: Engage stakeholders from different sectors of the society.
- **O5**: Demonstrate the role and impact of the research infrastructure in the innovation chain, focusing on responsible resource use and managing environmental impacts.

[Diagram showing luminosity-frontier collider design and research infrastructure placement with technology readiness levels and results.]
FCCIS Work Packages

**WP1: study management**

**WP2: collider design**
Deliver a performance optimised machine design, integrated with the territorial requirements and constraints, considering cost, long-term sustainability, operational efficiency and design-for- socio-economic impact generation.

**WP3: integrate Europe**
Develop a feasible project scenario compatible with local – territorial constraints while guaranteeing the required physic performance.

**WP4: impact & sustainability**
Develop the financial roadmap of the infrastructure project, including the analysis of socio-economic impacts.

**WP5: leverage & engage**
Engage stakeholders in the preparation of a new research infrastructure. Communicate the project rationale, objectives and progress. Create lasting impact by building theoretical and experimental physics communities, creating awareness of the technical feasibility and financial sustainability, forging a project preparation plan with the host states (France, Switzerland).
An overall layout and placement optimisation process across both host states that follows the "avoid-reduce-compensate" directive according to European and French regulatory frameworks.

Process integrates a diverse set of requirements and constraints, such as:

- Performance for the scientific research to be competitive at international scale
- Civil engineering technical feasibility and subsurface constraints
- Territorial constraints at surface and subsurface
- Nature, accessibility, technical infrastructure and resource needs and constraints
- Economic factors including the development of benefits for and synergies with the regional developments

Work takes place as a collaborative effort by technical experts at CERN, consultancy companies and government notified bodies.
Increasing international collaboration as a prerequisite for success: links with science, research & development and **high-tech industry** will be essential to further advance and prepare the implementation of FCC.
Status and Outlook

• **1st phase** of FCC design study completed → baseline machine designs, performance matching physics requirements, in 4 CDRs

• **Integrated FCC programme** was submitted to the European Strategy Update 2019/20 → Request for feasibility study as basis for project decision by 2026/27.

• **Next steps:** concrete local/regional implementation scenario in collaboration with host state authorities, accompanied by machine optimization, physics studies and technology R&D, performed via global collaboration and supported by EC H2020 Design Study FCCIS, to prove feasibility by 2025/26.

• Long term goal: a *world-leading HEP infrastructure for the 21st century* to push the particle-physics *precision and energy frontiers* far beyond present limits.

• Welcome all new participants to the FCC feasibility study phase and FCCIS project.