Future Circular Collider Study – Status and Plans

Michael Benedikt, CERN
on behalf of FCC collaboration & FCCIS design study

http://cern.ch/fcc

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
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, tt) 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
Future Circular Collider Study
Michael Benedikt
IAS Program on HEP, HKUST IAS, Hong Kong, 18 January 2021

**FCC-ee basic design choices**

double ring $e^+e^-$ collider ~100 km
follows footprint of FCC-hh, except around IPs
asymmetric IR layout & optics to limit synchrotron radiation towards the detector
presently 2 IPs (alternative layouts with 3 or 4 IPs under study), large horizontal crossing angle $30 \text{ mrad}$, crab-waist optics
synchrotron radiation power 50 MW/beam at all beam energies; tapering of arc magnet strengths to match local energy
common RF for $t\bar{t}$ running

top-up injection requires booster synchrotron in collider tunnel

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<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>
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<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>
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<tr>
<td>vertical beta* [mm]</td>
<td>0.8</td>
<td>1</td>
<td>1</td>
<td>1.6</td>
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<tr>
<td>horiz. geometric emittance [nm]</td>
<td>0.27</td>
<td>0.28</td>
<td>0.63</td>
<td>1.46</td>
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<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 $[10^{34} \text{ cm}^{-2} \text{s}^{-1}]$</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>
FCC-ee: high-luminosity Higgs/electroweak factory
R&D aimed at improving performance & efficiency and reducing cost:

- improved Nb/Cu coating/sputtering, partner STFC (e.g. ECR fibre growth, HiPIMS)
- new cavity fabrication techniques, partner STFC (e.g. EHF, improved polishing, seamless)
- coating of A15 superconductors (e.g. Nb$_3$Sn), cryo-module design optimisation
- bulk Nb cavity R&D at FNAL, JLAB, Cornell, also KEK and CEPC/IHEP
- MW-class fundamental power couplers for 400 MHz; novel high-efficiency klystrons

Prototype FCC SRF cavities at JLAB

High-efficiency klystron at CERN

Novel klystron bunching methods: LHC klystron retrofit as proof of principle for FCC
## FCC-hh (pp) collider parameters (stage 2)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>FCC-hh</th>
<th>HL-LHC</th>
<th>LHC</th>
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<tbody>
<tr>
<td>Collision energy [TeV]</td>
<td>100</td>
<td>14</td>
<td>14</td>
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<tr>
<td>Dipole field [T]</td>
<td>16</td>
<td>8.33</td>
<td>8.33</td>
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<tr>
<td>Circumference [km]</td>
<td>97.75</td>
<td>26.7</td>
<td>26.7</td>
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<td>Beam current [A]</td>
<td>0.5</td>
<td>1.1</td>
<td>0.58</td>
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<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>
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<tr>
<td>Synchr. rad. power / ring [kW]</td>
<td>2400</td>
<td>7.3</td>
<td>3.6</td>
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<tr>
<td>SR power / length [W/m/ap.]</td>
<td>28.4</td>
<td>0.33</td>
<td>0.17</td>
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<tr>
<td>Long. emit. damping time [h]</td>
<td>0.54</td>
<td>12.9</td>
<td>12.9</td>
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<tr>
<td>Beta* [m]</td>
<td>1.1</td>
<td>0.3</td>
<td>0.15 (min.)</td>
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<tr>
<td>Normalized emittance [(\mu m)]</td>
<td>2.2</td>
<td>2.5</td>
<td>3.75</td>
</tr>
<tr>
<td>Peak luminosity ([10^{34} \text{ cm}^{-2}\text{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>
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</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
• feasible positions for large span caverns (most challenging structures)
• 90 – 100 km circumference
• 12 surface sites with few ha area each
civil engineering studies

- Total construction duration 7 years
- First sectors ready after 4.5 years
FCC-tunnel integration in the arcs

FCC-ee
5.5 m inner diameter

FCC-hh
## FCC integrated project technical schedule

### 15 years operation

<table>
<thead>
<tr>
<th>Project</th>
<th>Start</th>
<th>End</th>
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<tbody>
<tr>
<td>Project preparation &amp; administrative processes</td>
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<td>Permis-</td>
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<tr>
<td>Funding strategy</td>
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<tr>
<td>Funding and in-kind contribution agreements</td>
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<td></td>
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<tr>
<td>Geological investigations, infrastructure detailed design and tendering preparation</td>
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<td></td>
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<tr>
<td>Tunnel, site and technical infrastructure construction</td>
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<tr>
<td>FCC-ee accelerator R&amp;D and technical design</td>
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<tr>
<td>FCC-ee detector construction, installation, commissioning</td>
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<tr>
<td>Set up of international experiment collaborations, detector R&amp;D and concept development</td>
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<tr>
<td>FCC-ee detector technical design</td>
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<tr>
<td>Superconducting wire and magnet R&amp;D, short models</td>
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<tr>
<td>Long model magnets, prototypes, preseries</td>
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### ~ 25 years operation

<table>
<thead>
<tr>
<th>Project</th>
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<td>Update Permis-</td>
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</tr>
<tr>
<td>Funding and in-kind contribution agreements</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FCC-ee dismantling, CE &amp; infrastructure adaptations FCC-hh</td>
<td></td>
<td></td>
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<tr>
<td>FCC-hh accelerator R&amp;D and technical design</td>
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<tr>
<td>FCC-hh detector construction, installation, commissioning</td>
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<tr>
<td>FCC-hh detector R&amp;D, technical design</td>
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<tr>
<td>FCC-hh detector construction, installation, commissioning</td>
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<tr>
<td>16 T magnet industrialization and series production</td>
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</table>

### Key Activities

- **Engineering design, energy efficiency, maintainability**
- **Conductors & high-field magnet technology**
### FCC-integrated project cost estimate

<table>
<thead>
<tr>
<th>Domain</th>
<th>Cost in MCHF</th>
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</thead>
<tbody>
<tr>
<td>Stage 1 - Civil Engineering</td>
<td>5,400</td>
</tr>
<tr>
<td>Stage 1 - Technical Infrastructure</td>
<td>2,200</td>
</tr>
<tr>
<td>Stage 1 - FCC-ee Machine and Injector Complex</td>
<td>4,000</td>
</tr>
<tr>
<td>Stage 2 - Civil Engineering complement</td>
<td>600</td>
</tr>
<tr>
<td>Stage 2 - Technical Infrastructure adaptation</td>
<td>2,800</td>
</tr>
<tr>
<td>Stage 2 - FCC-hh Machine and Injector complex</td>
<td>13,600</td>
</tr>
<tr>
<td>TOTAL construction cost for integral FCC project</td>
<td>28,600</td>
</tr>
</tbody>
</table>

**Total construction cost**

- **FCC-ee (Z, W, H)**: \(\sim 10,500 \text{ MCHF} \& 1,100 \text{ MCHF (tt)}\)
- **Total construction cost for subsequent FCC-hh**: 17,000 MCHF.
- (FCC-hh stand alone cost \(\sim 25 \text{ BCHF}\))
FCC CDR and Study Documentation

- FCC-Conceptual Design Reports:
  - CDRs published in European Physical Journal C (Vol 1) and ST (Vol 2 – 4)
- Summary documents provided to EPPSU SG
  - FCC-integral, FCC-ee, FCC-hh, HE-LHC
  - Accessible on http://fcc-cdr.web.cern.ch/

>1350 contributors from >350 institutes, a truly global effort as suggested by EPPSU 2013
“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.”
Financial feasibility

- cost of tunnel: ~5.5 BCHF; FCC-ee: ~5-6 BCHF; FCC-hh: ~17 BCHF (if after FCC-ee)
  - cannot be funded only from CERN’s (constant) budget + “one-off” contributions from non-Member States → need new mechanisms (global project funding model; EC? private?)

1st priority of feasibility study: find ~ 5 BCHF for the tunnel from outside CERN’s budget

Technical and administrative feasibility of tunnel

- highly-populated area; two countries with different legislative frameworks
- land expropriation and reclassification
- high-risk zones
- environmental aspects

1st priority of feasibility study: no show-stopper for ~100 km tunnel in Geneva region

Technologies of machine and experiments

- huge challenges, but under control of our scientific community
- pressing environmental aspects: energy, cooling, gases, etc.

1st priority of feasibility study: magnets; minimise environmental impact; energy efficiency & recovery

Gathering scientific, political, societal and other support

- requires “political work” and communication campaign for “consensus building” with governments and other authorities, scientists from other fields, industry, general public, etc.
  - can FCC be a facility also for other disciplines (nuclear science, photon science, etc.)?
- creative and proactive ideas for technology transfer from FCC to society
Feasibility Study of FCC integrated project

Feasibility study to be delivered end 2025 as input for next ESPP Update expected by 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 sequential nature of implementation and overall timeline need to be taken into account!
FCC roadmap towards stage 1

- 2011 circular Higgs factory proposal
- 2013 ESPPU
- 2014 FCC study kickoff
- 2018 FCC CDR
- 2020 FCCIS kickoff
- 2020 FCCIS H2020 DS
- 2020 2025 FCC Feasibility Study
- 2025/26 Financing model Operation concept
- 2026/7 ESPPU
- 2028 approval
- 2025/26 Feasibility proof
- 2026 - 30 full technical design
- >2026 - 30 element production
- >2030 - 37 element production
- >2030 start tunnel construction
- >2036 machine installation
- >2040 first ee collisions

today

2012 Higgs discovery announced
2011 circular Higgs factory proposal

Future Circular Collider Study
Michael Benedikt
IAS Program on HEP, HKUST IAS, Hong Kong, 18 January 2021
CE preparatory activities 2020 - 2030

- 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
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FCC key deliverables: prototypes by 2025

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

• Freq : 2.856 GHz
• 96 cells per structure
• Length: 3.254 m
• Distance between two TWs: 45 cm
• Gradient: 30 MV/m
• Aperture: 30 mm

strong support from Switzerland via CHART II program 2019 – 2024 for FCC-ee injector, HFM, beam optics developments, geology and geodesy activities.

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

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

postitron capture linac
large aperture S-band linac

SwissFEL
0.4-6 GeV Linac
ARAMIS Undulator Line

Diagnostics:
Screen for spectrum
Charge monitor
Beam stop
smaller IR chamber, no longer trapped HOM

start of 3D mechanical design & integration

Q1 prototype, measured multipoles very small, confirming design approach

M. Boscolo

M. Lückhof

L. Pellegrino

preliminary
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
Potential US/EIC – FCC collaboration

NSLS-II, EIC & FCC-ee beam parameters

<table>
<thead>
<tr>
<th></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>
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<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>
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<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 at FCC-IS kick-off meeting towards EIC-FCC collaboration
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

Beneficiaries
- ULIV, United Kingdom
- DESY, Germany
- IFJPAN, Poland
- KIT, Germany
- TMFS, Austria
- MUL, Austria
- CERN
- Cerema, CETU, France
- LD, Switzerland
- CSIL, Italy
- INFN, Italy
- CEA, 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
**FCCIS Objectives (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

### Luminosity-frontier Collider Design

<table>
<thead>
<tr>
<th>High Technology Readiness</th>
<th>Low Technology Readiness</th>
<th>Beam optics validated at BINP, DESY, INFN, KIT. Components specified. Performance calculated &amp; simulated.</th>
<th>FCCIS Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>9</td>
<td></td>
<td>4</td>
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</table>

### Research Infrastructure Placement

<table>
<thead>
<tr>
<th>High Technology Readiness</th>
<th>Low Technology Readiness</th>
<th>Ecodesigned layout and responsible resource use validated for the relevant environment.</th>
<th>FCCIS Result</th>
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<tbody>
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FCC November Week 2020

• Kick-Off FCC Innovation Study
  (organisers M. Benedikt, J. Gutleber, F. Zimmermann)
  FCC-ee Collider Design (WP2)
  Integrate Europe (WP3)
  Impact & Sustainability (WP4)
  Leverage & Engage (WP5)

• 4th FCC Physics & Experiments Workshop
  (organisers A. Blondel, M. Mangano, M. Dam, P. Janot)
  Physics Prospects, Detector development, Collaboration Forming,
  Physics Benchmark Measurements, New Ideas and Challenges,
  Detector Technologies, Experimental Environment, and Machine-Detector Interface.

http://cern.ch/FCCNoW2020
layout & placement optimisation across both host states (Switzerland and France) ; following "avoid-reduce-compensate" directive of European & French regulatory frameworks ; diverse requirements and constraints:

- permitting world-leading scientific research
- technical feasibility of civil engineering and subsurface constraints
- territorial constraints on surface and subsurface
- nature, accessibility, technical infrastructure, resource needs & constraints
- economic factors including benefits for, and synergies, with the regional developments

collaborative effort: CERN technical experts, consulting companies, 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 submitted to 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: world-leading HEP infrastructure for 21st century to push the particle-physics precision and energy frontiers far beyond present limits.

• Success of FCC relies on strong global participation !