Future Circular Collider (FCC) Study

Michael Benedikt, Frank Zimmermann
Outline

- Motivation & scope
- Parameters & design challenges
- Preparing global FCC collaboration
- Study organization – WBS
- Study Time Line, next steps
- EU FCC design study proposal
- Summary
...“to propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy update”: d) CERN should undertake design studies for accelerator projects in a global context,

- with emphasis on proton-proton and electron-positron high-energy frontier machines.
- These design studies should be coupled to a vigorous accelerator R&D programme, including high-field magnets and high-gradient accelerating structures,
- in collaboration with national institutes, laboratories and universities worldwide.

CLIC CDR and cost study (2012)

- 3 volumes CDR: physics & detectors, accelerator complex, strategy, cost & schedule
- Collaborative effort: 40+ institutes worldwide
Future Circular Collider Study - SCOPE CDR and cost review for the next ESU (2018)

Forming an international collaboration to study:

- **pp-collider (FCC-hh)** → defining infrastructure requirements
  - \( \sim 16 \text{ T} \implies 100 \text{ TeV } pp \text{ in 100 km} \)
  - \( \sim 20 \text{ T} \implies 100 \text{ TeV } pp \text{ in 80 km} \)

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

- **p-e (FCC-he)** option

- 80-100 km infrastructure in Geneva area
FCC motivation: pushing energy frontier

High-energy hadron collider *FCC-hh* as long-term goal
- Seems only approach to get to 100 TeV range in the coming decades
- High energy and luminosity at affordable power consumption
- Lead time design & construction > 20 years (LHC study started 1983!)
  → Must start studying now to be ready for 2035/2040

Lepton collider *FCC-ee* as potential intermediate step
- Would provide/share *part of infrastructure*
- Important *precision measurements* indicating the energy scale at which new physics is expected
- Search for *new physics in rare decays of* \( Z, W, H, t \) and rare processes

Lepton-hadron collider *FCC-he* as option
- High precision *deep inelastic scattering and Higgs physics*

Most aspects of collider designs and R&D non-site specific. Tunnel and site study in Geneva area as ESU requests.
Main areas of FCC design study

Accelerators and infrastructure conceptual designs

- Hadron collider conceptual design
- Lepton collider conceptual design
- Hadron and lepton injectors
- Safety, operation, energy management environmental aspects
- Infrastructure

Technologies R&D activities planning

- High-field magnets
- Superconducting RF systems
- Cryogenics
- Specific technologies
- Planning

Physics experiments detectors

- Hadron coll. physics experiments interface, integration
- $e^+ e^-$ coll. physics experiments interface, integration
- $e^-$ - p physics, experiments, Interface, integration
### FCC-\textit{hh} parameters – starting point

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Energy</td>
<td>100 TeV c.m.</td>
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<tr>
<td>Dipole field</td>
<td>(\sim 16 \text{ T (Nb}_3\text{Sn)}), [20 T option HTS]</td>
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<tr>
<td>Circumference</td>
<td>(\sim 100 \text{ km})</td>
</tr>
<tr>
<td>#IPs</td>
<td>2 main (tune shift) + 2</td>
</tr>
<tr>
<td>Luminosity/IP_{\text{main}}</td>
<td>(5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1})</td>
</tr>
<tr>
<td>Stored beam energy</td>
<td>8.2 GJ/beam</td>
</tr>
<tr>
<td>Synchrotron radiation</td>
<td>26 W/m/aperture (filling fact. (\sim 78%) in arc)</td>
</tr>
<tr>
<td>Long. emit damping time</td>
<td>0.5 h</td>
</tr>
<tr>
<td>Bunch spacing</td>
<td>25 ns [5 ns option]</td>
</tr>
<tr>
<td>Bunch population (25 ns)</td>
<td>(1 \times 10^{11} \text{ p})</td>
</tr>
<tr>
<td>Transverse emittance</td>
<td>2.2 micron normalized</td>
</tr>
<tr>
<td>#bunches</td>
<td>10500</td>
</tr>
<tr>
<td>Beam-beam tune shift</td>
<td>0.01 (total)</td>
</tr>
<tr>
<td>(\beta^*)</td>
<td>1.1 m (HL-LHC: 0.15 m)</td>
</tr>
</tbody>
</table>

*already available from SPS for 25 ns*
**FCC-hh design challenges**

**Optics and beam dynamics**
- IR design, dynamic aperture studies, SC magnet field quality

**Impedances, instabilities, feedbacks**
- Beam-beam, e-cloud, resistive wall, feedback systems design

**Synchrotron radiation damping**
- controlled blow up, luminosity levelling, etc…

**Energy in beam & magnets → dump, collimation, quench protection**
- **Stored beam energy critical**: 8 GJ/beam (0.4 GJ LHC)
- Beam losses, radiation effects → collimation, shielding
- Synergies intensity frontier (SNS, J-PARC, PSI, PIP, FRIB, ESS, FAIR)

**High synchrotron radiation load on beam pipe**
- **Up to 26 W/m/aperture in arcs, total of ~5 MW for FCC-hh**
- (LHC has a total of 1W/m/aperture from different sources)
- Heat extraction: photon stop, beam screen temperature, cryo load,
- Synergies with SSC, VLHC, LHC, light sources, SppC, …
High-field magnet R&D targets

**FCC-hh** baseline 16T Nb$_3$Sn technology for ~100 TeV c.m. in ~100 km

Develop Nb$_3$Sn-based 16 T dipole technology,

- with sufficient aperture (~40 mm) and
- accelerator features (field quality, protectability, cycled operation).
- In parallel conductor developments

Possible goal:

- 16T short dipole models by 2018 (America, Asia, Europe)

In parallel HTS development targeting 20 T:

- HTS insert, generating $O(5 \text{ T})$ additional field
- in large aperture $O(100 \text{ mm, } 15 \text{ T})$

Possible goal:

demonstrate HTS/LTS 20 T technology in two steps

- a field record attempt to break the 20 T barrier (no aperture), and
- a 5 T insert, with sufficient aperture (40 mm) and accel. features
FCC-ee parameters – starting point

Design choice: max. synchrotron radiation power set to 50 MW/beam

- Defines the maximum beam current at each energy
- 4 physics operation points (energies) foreseen $Z$, $WW$, $H$, $ttbar$
- Optimization at each operation point, mainly via bunch number and arc cell length

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$Z$</th>
<th>$WW$</th>
<th>$H$</th>
<th>$ttbar$</th>
<th>$LEP2$</th>
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</thead>
<tbody>
<tr>
<td>$E/beam$ (GeV)</td>
<td>45</td>
<td>80</td>
<td>120</td>
<td>175</td>
<td>105</td>
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<tr>
<td>$L ,(10^{34} ,cm^{-2}s^{-1})/IP$</td>
<td>28.0</td>
<td>12.0</td>
<td>5.9</td>
<td>1.8</td>
<td>0.012</td>
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<tr>
<td>Bunches/beam</td>
<td>16700</td>
<td>4490</td>
<td>1330</td>
<td>98</td>
<td>4</td>
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<tr>
<td>$I$ (mA)</td>
<td>1450</td>
<td>152</td>
<td>30</td>
<td>6.6</td>
<td>3</td>
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<tr>
<td>Bunch popul. $[10^{11}]$</td>
<td>1.8</td>
<td>0.7</td>
<td>0.47</td>
<td>1.40</td>
<td>4.2</td>
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<td>Cell length $[m]$</td>
<td>300</td>
<td>100</td>
<td>50</td>
<td>50</td>
<td>79</td>
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<tr>
<td>Tune shift / IP</td>
<td>0.03</td>
<td>0.06</td>
<td>0.09</td>
<td>0.09</td>
<td>0.07</td>
</tr>
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</table>
**FCC-ee design challenges**

Short beam lifetime from high luminosity (radiative Bhabha scattering)
- **Top-up injection** (single injector booster in collider tunnel)

Additional lifetime limit from beamstrahlung at top operation energy
- Flat beams (small vertical emittance, small vertical $\beta^* \sim 1$ mm)
- Final focus with large ($\sim 2\%$) energy acceptance to reduce losses

Machine layout for high currents, large #bunches at Z pole, WW, H
- Two ring layout and configuration of the RF system.

Polarization for high precision energy calibration at Z pole and WW with long natural polarization times ($WW: \sim 10$ hours, $Z: \sim 200$ hours)

Important expertise available worldwide and potential synergies:
- IR design, experimental insertions, machine detector interface, (transverse) polarization
  - RHIC, VEPP-2000, BEPC-II, SLC, LEP, B- and Super-B factories, CEPC, ILC, CLIC
SC-RF main R&D areas

SC cavity R&D
- Large $Q_0$ at high gradient and acceptable cryogenic power
  - Recent results at 4 K with Nb$_3$Sn coating on Nb at Cornell
  - 800 °C ÷ 1400 °C heat treatment at JLAB
  - Beneficial effect of impurities observed at FNAL
- Relevant for many other accelerator applications

High efficiency RF power generation from grid to beam
- Power converter technology
- Klystron efficiencies beyond 65%, alternative RF sources as Solid State Power Amplifier or multi-beam IOT (inductive output tube), etc.
- Relevant for all high power accelerators, intensity frontier (drivers): J-PARC, SNS, νstorm, LBNE, XFEL, μcoll, ESS, MYRRHA, …

Overall RF system reliability → relevant for FCC-hh and FCC-ee

R&D Goal is optimization of overall efficiency, reliability and cost!
- Power source efficiency, low-loss high-gradient SC cavities, operation temperature vs. cryogenic load, total system cost and dimension.
**FCC-he parameters – starting point**

- **Design choice:** beam parameters as available from $hh$ and $ee$
  - Max. $e^\pm$ beam current at each energy determined by 50 MW SR limit.
  - 1 physics interaction point, optimization at each energy

<table>
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<tr>
<th>collider parameters</th>
<th>$e^\pm$ scenarios</th>
<th>protons</th>
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<tbody>
<tr>
<td>species</td>
<td>$e^\pm$ (polarized)</td>
<td>$e^\pm$</td>
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<tr>
<td>beam energy [GeV]</td>
<td>80</td>
<td>120</td>
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<tr>
<td>luminosity [$10^{34}$cm$^{-2}$s$^{-1}$]</td>
<td>2.3</td>
<td>1.2</td>
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<tr>
<td>bunch intensity [$10^{11}$]</td>
<td>0.7</td>
<td>0.46</td>
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<tr>
<td># bunches per beam</td>
<td>4490</td>
<td>1360</td>
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<tr>
<td>beam current [mA]</td>
<td>152</td>
<td>30</td>
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<tr>
<td>$\sigma_{x,y}$ [micron]</td>
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</table>
**FCC-he design challenges**

Integration aspects, machine detector interface
- Synchrotron radiation
- Large polar angle acceptance

IR optics & magnets with 3 beams
- Crossing scheme
- Detector integrated dipole, final SC quadrupoles, crab cavities,

Concurrent operation of $e^\pm h$ with $hh$ or/and $e^+ e^-$ operation?

Relevant expertise available worldwide and potential synergies:
\( \leftrightarrow \) HERA, eRHIC, MEIC, HIAF-EIC, ...

Alternative option for $eh$ collisions in connection with **FCC-hh**:
- Potential reuse of an energy recovery linac (ERL) that is being studied in the frame of the LHeC study.
Following ESU in May 2013, creation of a small preparation group in autumn 2013 to prepare on a short time scale:

- preliminary **draft baseline parameter sets** for all options
- a possible work breakdown structure and study organisation
- an international kick-off meeting (*now!*)

**Kick-off event should start process of internat. collaboration**

- presenting **preparatory work** as basis for discussion
  - *draft parameter sets & WBS documents available*
- inviting feedback and suggestions
- working towards **formation of a**
  - global design study collaboration integrating all aspects of machines, physics and detectors

Reflected in kick-off meeting programme.
International collaboration process in 2014

Proposal for next steps:

• Suggestions and comments from international community and discussion on study contents, organisation and resources
• Invitation of non-committing expressions of interest for contributions from worldwide institutes by end May 2014
• Prepare for formation of International Collaboration Board (ICB); proposed date first meeting 9-11 September 2014, to start FCC study

Process can be moderated by preparation group (possibly extended – following EOI) until global collaboration is formed and an international team is put in place to conduct the further study

Process remains open, further joining possible …
# FCC Kick-Off & Study Preparation Team

**Future Circular Colliders - Conceptual Design Study**  
Study coordination, M. Benedikt, F. Zimmermann

<table>
<thead>
<tr>
<th>Hadron collider</th>
<th>Hadron injectors</th>
<th>e+ e- collider and injectors</th>
<th>Infrastructure, cost estimates</th>
<th>Technology</th>
<th>Physics and experiments</th>
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<td>D. Schulte</td>
<td>B. Goddard</td>
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<td>Hadrons</td>
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<td>L. Bottura</td>
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<td>Specific Technologies</td>
<td>M. Klein</td>
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<td>Operation aspects, energy efficiency, safety, environment</td>
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<td>JM. Jimenez</td>
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<td>F. Sonnemann, J. Gutleber</td>
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**Future Circular Collider Study**  
Michael Benedikt  
FCC Kick-Off 2014
Proposal for FCC WBS top level

preliminary

Future Circular Collider

- Physics and Experiments
  - Hadron Collider Physics
  - Hadron Collider Experiments
  - Lepton Collider Physics
  - Lepton Collider Experiments
  - Lepton-Hadron Collider Physics
  - Lepton-Hadron Collider Experiment
- Accelerators
  - Hadron Injectors
  - Hadron Collider
  - Lepton Injectors
  - Lepton Collider
  - Lepton-Hadron Collider
- Infrastructures and Operation
  - Civil Engineering
  - Technical Infrastructures
  - Operation and Energy Efficiency
  - Integration
  - Computing and Data Services
  - Safety, RP and Environment
- Implementation and Planning
  - Project Risk Assessment
  - Implementation
  - Cost Estimates
- Study and Quality Management
  - Study Administration
  - Communications
  - Conceptual Design Report
### Draft work packages and units

#### Lepton injectors

**Functional machine design**
- LEP chain performance and gaps
- LEP chain compatibility with hadron injectors
- New injector chain baseline

**Technical systems**
- Low energy beam transfer lines
- LIL/EPA re-installation feasibility
- Existing injectors to be decommissioned for lepton operation
- Technologies that require R&D
- SuperKEKB-type injector option
- CTF3 option usability
- Planned LHeC test facility usability
- Electron and positron sources

#### Lepton collider

**Functional machine design**
- Beam dynamics and collective effects
- Collimation concepts
- Injection and extraction concepts and designs
- Interaction region and final focus design
- Booster ring conceptual design and integration
- Lattice design and single particle dynamics
- Polarization and energy calibration
- Machine detector interface
- Machine protection concepts
- Radiation effects

**Technical systems**
- Beam diagnostics requirements and conceptual design
- Beam transfer elements requirements and conceptual design
- Collimation systems and absorber requirements and conceptual design
- Dump and stopper requirements and conceptual design
- Element support and alignment requirements and conceptual design
- Machine detector integration
- Machine protection system requirements and conceptual design
- Normal magnet requirements and element conceptual design
- Power converter requirements and conceptual design
- Quench protection and stored energy management requirements and concepts
- RF system requirements and conceptual design
- Superconducting magnet and cryostat requirements and conceptual design
- Proximity cryogenics for RF and magnets
- Vacuum system requirements and conceptual design
- Shielding

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International contributors and convenors needed for technical areas and study organisation
Proposed international organization structure

- **CERN DG**
  - **Collaboration Board**
    - 1 person/inst.
  - **Steering Committee**
    - 2-3 persons/region
  - **Advisory Committee**
    - 1-2 experts/field
  - **FCC Study Coordination**

- **Hadron Collider Physics Experiments**
- **Lepton Collider Physics Experiments**
- **e-p Physics Experiments Accelerators**
- **Hadron Injectors**
- **Hadron Collider**
- **Lepton Injectors**
- **Lepton Collider**
- **Accelerator R&D Technologies**
- **Infrastructure Operation**
- **Costing Planning**
# Proposal for FCC Study Time Line

<table>
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<tr>
<th></th>
<th>2014</th>
<th>2015</th>
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<th>2017</th>
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<tr>
<td>Prepare</td>
<td>Kick-off, collaboration forming, study plan and organisation</td>
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<td>Ph 1: Explore options “weak interaction”</td>
<td>Workshop &amp; Review → identification of baseline</td>
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<td>Workshop &amp; Review, cost model, LHC results → study re-scoping?</td>
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<td>Ph 2: Conceptual study of baseline “strong interact.”</td>
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<td>Ph 3: Study consolidation</td>
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<td>Workshop &amp; Review on next steps</td>
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<tr>
<td>Report</td>
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4 large FCC Workshops distributed over participating regions
Possible FCC Study Phases

Phase 1: Explore options, now – spring 2015:
- Investigate different options in all technical areas, taking a broad view
- Deliverables: description and comparison of options with relative merits/cost
- FCC workshop to converge to common baseline with small number of options
- Proposed WS date 23 – 27 March 2015 (presently no known collisions…)
- Followed by review ~2 months later, begin June 2015

Phase 2: Conceptual design: spring 2015 – autumn 2016
- Conceptual study of baseline and remaining options with iterations between all areas
- Deliverable: description of baseline with first cost model, identification of critical areas, cost drivers, performance limitations
- FCC workshop to discuss conceptual design, performance and cost figures
- Proposed date autumn 2016.
- Followed by review 2 months later to take into account LHC results and do re-scoping of study for phase 3

Phase 3: Study consolidation: winter 2016 – winter 2017
- Detailed conceptual design of re-scoped baseline
- Deliverables: description of re-scoped baseline with cost model, identification of critical areas, cost drivers, performance limitations, planning for further R&D activities
- FCC workshop to discuss conceptual design, performance and cost figures and contents for CDR editing.
- Proposed date autumn 2017.
- Followed by review 2 months later to confirm CDR contents

Phase 4: Editing conceptual design report: winter 2017 – summer 2018
FCC EU Design Study (DS) Proposal

Horizon2020 call – design study, deadline 02.09.2014
Prepare proposal parallel to FCC collaboration setup

**Goals fo EU DS:** conceptual design, prototypes, cost estimates, …
From FP7 HiLumi LHC DS → positive experience:
- 5-6 work packages as sub-set of FCC study
- ~10-15 beneficiaries (signatories of the contract with EC)

**Time line**

- **Kick-off event**
- **discussions**
- **input from interested partners, end of May**
- **complete draft proposal, end of June**
- **iteration, agreements, signatures**
- **submission of EU FCC DS proposal, 2 Sept.**

March April May June July August September 2014

**Non-EU partners can join as beneficiary – signatory** with or w/o EC contribution (**contractual commitment**) or as associated partner – non-signatory (in-kind contribution with own funding, no contractual commitment)
FCC Study - Summary

- In line with the European Strategy, CERN is launching a 5-year international design study for Future Circular Colliders;

- Worldwide collaboration in all areas - physics, experiments and accelerators – is essential to reach CDR level by 2018.

- FCC R&D areas e.g. SC high-field magnets and SC RF are of general interest & relevant for many other applications.

- Significant R&D investments have been made over last decade(s), e.g. in the framework of LHC and HL-LHC; further continuation will ensure efficient use of past investments.

- Goals of kick-off meeting: Introducing FCC study, discussing study scope and organization, preparing and establishing collaboration!  
  
  Invitation to join!