Future strategies and technologies

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

http://cern.ch/fcc

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High energy accelerators & colliders

- Using **electrical fields (RF cavities)** to accelerate and **magnetic fields (accelerator magnets)** to guide and collide **charged particle beams** (electrons, protons & anti-particles)

- **Aim at higher energy accelerators for 2 reasons:**
  - **Production of new heavier particles (according to Einstein):** \( E = mc^2 \leq 2E \text{ beam (collider)} \)
  - **Resolving smaller distances (according to de Broglie):**
    
    Wavelength \( \lambda = \frac{hc}{E} \) for LHC \( \sim 2 \cdot 10^{-18} \text{ cm} \)

Higher energy → **Increased potential for discoveries**
Discoveries by colliders

Colliders are powerful instruments in High Energy physics for particle discoveries and precision measurements.
LHC: present collider flagship

2012: Higgs boson discovery

- Completes standard model describing known matter, **BUT this is only 5% of the universe!**
- what is dark matter?
- what is dark energy?
- why is there more matter than antimatter?
- what about gravity?
- etc...

=> Upgrade and full exploitation of LHC as first step
More than 100 new SC magnets
36 large magnets in Nb₃Sn
Powering via SC Links and HTS Current Leads

20 new RF cavities
New tunnel and surface infrastructures
New and upgraded cryo plants
HL-LHC significantly increases data rate to improve statistics, measurement precision, and energy reach in search of new physics. Gain of a factor 5 in rate, factor 10 in integral data wrt initial design.
For physics beyond the LHC and beyond the Standard Model, under study (synergy of):

- **Linear e^+e^- colliders** (CLIC, ILC)
  \[ E_{\text{CM}} \text{ up to } \sim 3 \text{ TeV} \]

- **Circular e^+e^- colliders** (CepC, FCC-ee)
  \[ E_{\text{CM}} \text{ up to } \sim 400 \text{ GeV} - \text{limited by } e^\pm \text{ synchrotron radiation. Ideal for precision measurements} \]

- **Circular p-p colliders** (SppC, FCC)
  \[ E_{\text{CM}} \text{ up to } \sim 100 \text{ TeV} \]
  Ideal for **discoveries at higher energy frontiers**
High Energy Colliders under study

100 TeV

100 TeV pp → 10^{-19} m

discovery of new particles at 10 TeV mass scale
“CERN should undertake design studies for accelerator projects in a global context, with emphasis on proton-proton and electron-positron high-energy frontier machines.”
Future Circular Collider Study
GOAL: CDR and cost review for the next ESU (2019)

International FCC collaboration (CERN as host lab) to study:

- **pp-collider (FCC-hh)**
  - main emphasis, defining infrastructure requirements
  - $\sim 16 \text{ T} \Rightarrow 100 \text{ TeV } pp$ 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

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Tevatron (closed)
Circumference: 6.2 km

Energy: 2 TeV
Large Hadron Collider

Circumference: 27 km

Energy:
- 14 TeV (pp)
- 209 GeV (e^+e^-)
Future Circular Collider

Circumference: 80-100 km

Energy:
- 100 TeV (pp)
- >350 GeV (e^+e^-)
FCC-hh: 100 TeV pp collider as long-term goal → defines infrastructure needs
FCC-ee: $e^+e^-$ collider, potential intermediate step
HE-LHC: based on FCC-hh technology

Launch R&D on key enabling technologies in dedicated R&D programmes, e.g.
16 Tesla magnet program, cryogenics, SRF technologies and RF power sources

Tunnel infrastructure in Geneva area, linked to CERN accelerator complex; site-specific, as requested by European strategy
Elaborate and document
- Physics opportunities
- Discovery potentials

Experiment concepts for $hh$, $ee$ and $he$
Machine Detector Interface studies
R&D needs for detector technologies

Overall cost model for collider scenarios
including infrastructure and injectors
Develop realization concepts
Forge partnerships with industry
Role of CERN

- **Host** the study
- **Prepare** organisation frame
- **Setup** collaboration
- **Identify** R&D needs
- **Estimate** costs
Strategic Goals

• Make funding bodies aware of strategic needs for research community

• Provide sound basis to policy bodies to establish long-range plans in European interest

• Strengthen capacity and effectiveness in high-tech domains

• Provide a basis for long-term attractiveness of Europe as research area
A sustained decrease in specific cost

**Specific cost vs center-of-mass energy of CERN accelerators**

Will FCC pass below the specific cost of 100 kCHF/GeV c.m.?
CERN Circular Colliders & FCC


 Constr.  Physics  LEP

 Design  Proto  Construction  Physics  LHC – operation run 2

 HL-LHC - ongoing project

 Design  Construction  Physics

 ~20 years

 FCC – design study

 Design  Proto  Construction  Physics

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
**Case:** LHC superconducting dipole magnets

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<td>Conceptual studies</td>
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- Conceptual studies: ~ 15 years
- Industry participation: ~ 15 years
- Total: ~ 25 years
Geological background

- **MOLASSE** (Grès, Marnes)
- **TERRAINS MEUBLES** (Moraine, Alluvions)
- **Karsts**
- **CALCAIRE**
Progress on site investigations
• 90 – 100 km fits geological situation well
• LHC suitable as potential injector
• The 100 km version, intersecting LHC, is now being studied in more detail
Tunnelling options for crossing the lake

- Open Shield TBM
- Slurry TBM
- Immersed Tube Tunnel
- Superficial sediments
- Moraine
- Molasse
• Total construction duration 7 years
• First sectors ready after 4.5 years
FCC – tunnel integration in arcs

FCC-ee
5.5 m inner diameter

FCC-hh
## Hadron collider parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>FCC-hh</th>
<th>HE-LHC*</th>
<th>(HL) LHC</th>
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<tbody>
<tr>
<td>collision energy cms [TeV]</td>
<td>100</td>
<td>27</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>
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<tr>
<td>beam current [A]</td>
<td>0.5</td>
<td>1.12</td>
<td>(1.12) 0.58</td>
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<tr>
<td>bunch intensity $[10^{11}]$</td>
<td>1</td>
<td>1 (0.2)</td>
<td>(2.2) 1.15</td>
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<tr>
<td>bunch spacing [ns]</td>
<td>25</td>
<td>25 (5)</td>
<td>25</td>
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<tr>
<td>beta* [m]</td>
<td>1.1</td>
<td>0.3</td>
<td>(0.15) 0.55</td>
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<td>luminosity/IP $[10^{34} \text{ cm}^{-2} \text{ s}^{-1}]$</td>
<td>5</td>
<td>20 - 30</td>
<td>&gt;25</td>
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<tr>
<td>events/bunch crossing</td>
<td>170</td>
<td>&lt;1020 (204)</td>
<td>850</td>
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<tr>
<td>stored energy/beam [GJ]</td>
<td>8.4</td>
<td>1.2</td>
<td>(0.7) 0.36</td>
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<tr>
<td>synchrotron rad. [W/m/beam]</td>
<td>30</td>
<td>3.6</td>
<td>(0.35) 0.18</td>
</tr>
</tbody>
</table>
High energy and large size of the ring requires a pre-injector chain:

“gear-box” principle

Baseline:
• 3 TeV, directly from LHC, reusing the whole CERN complex

Alternative:
• 1.5 TeV with new SPS (7 km machine circumference) based on fast-cycling SC magnets, 6-7T, ~ 1T/s ramp
Physics prospects

Physics at the FCC-hh

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/FutureHadroncollider

- Volume 1: SM processes (238 pages)
- Volume 2: Higgs and EW symmetry breaking studies (175 pages)
- Volume 3: beyond the Standard Model phenomena (189 pages)
- Volume 4: physics with heavy ions (56 pages)
- Volume 5: physics opportunities with the FCC-hh injectors (14 pages)

- Being published as CERN yellow report

Future Strategies and Technologies
Michael Benedikt
International Teacher Weeks 2017, CERN
Key Technologies

- 16 T superconducting magnets
- Synchrotron radiation
- Affordable & reliable cryogenics
- Superconducting RF cavities
- RF power sources
- Reliability & availability concepts
High –field SC dipoles

- **SC dipole**: field defined via current distribution
  - High current densities close to the beam for high fields
  - Only possible with super conductors $I > 1 \text{ kA/mm}^2$

- **Ideal coil geometry for dipolar fields**:
  - Azimuthal current distribution $I(\phi) = I_0 \cos(\phi)$ Dipol, $(I_0 \cos(2\phi)$ Quadrupol)
  - 2 horizontally displaced circles
Cryo-magnet cross sections

LHC

FCC-hh

$\cos \theta$

block coil

Nb$_3$Sn as SC material

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$0.57 \text{ m}$

$0.78 \text{ m}$

$\sim 0.8 \text{ m}$

$\sim 1.1 \text{ m}$

$\sim 1.2 \text{ m}$
Main SC Magnet system
FCC (16 T) vs LHC (8.3 T)

FCC

Bore diameter: 50 mm
Dipoles: 4578 units, 14.3 m long, 16 T ⇔ ∫ Bdl~1 MTm
 Stored energy ~ 200 GJ (GigaJoule) ~44 MJ/unit
Quads: 762 magnets, 6.6 m long, 375 T/m

LHC

Bore diameter: 56 mm
Dipoles: 1232 units, 14.3 m long, 8.3 T ⇔ ∫ Bdl~0.15 MTm
 Stored energy ~ 9 GJ (GigaJoule) ~7 MJ/unit
Quads: 392 units, 3.15 m long, 233 T/m
**Nb$_3$Sn conductor program**

**Nb$_3$Sn is one of the major cost & performance factors**

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**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

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![Graph showing $J_c$ vs. Field (T) with Nb$_3$Sn, LHC, and FCC data points.](image)

- **LHC**: 1000 A/mm$^2$  
  - High Luminosity
- **FCC**: 1500 A/mm$^2$

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**Impact on coil section and conductor mass**

- 5400 mm$^2$  
  - ~10% margin  
  - HL-LHC

- 3150 mm$^2$  
  - ~10% margin  
  - FCC ultimate

- ~1.7 times less SC

Short model magnets (1.5 m lengths) from 2018 – 2022
Russian 16 T magnet program launched by BINP recently.
Towards 16T magnets

Record fields for SC magnets in “dipole” configuration

16 T “dipole” levels reached with small racetrack coils Berkeley 2004, CERN 2015

Field records

Magnets with bore (need of margin)

LBNL HD1

CERN RMC
15 T dipole demonstrator (US-MDP)

- All coil parts, structural components and tooling are available at FNAL
- Coil fabrication and the work with mechanical structure are in progress
- First magnet test in September 2018
• Charged particles on a curved trajectory irradiate energy:

\[ \Delta E \sim \text{const} \cdot \gamma^4/r = \text{const} \cdot (E/E_0)^4/r = \text{konst} \cdot (E/m_0)^4/r \]

– Energy loss \( \Delta E \) must be compensated and corresponding heat has to be removed from cold mass of SC magnets (for hadron collider)

\[ \Delta W = \Delta Q \cdot (T - T_{\text{tief}}) / T_{\text{tief}} = \Delta Q \cdot (300 - 1.9) / 1.9 \sim 155 \cdot \Delta Q \]

For realistic process efficiency is \(~1000: 1\) W@1.9 K == 1 kW@ room temp.
High synchrotron radiation load of proton beams @ 50 TeV:

- ~30 W/m/beam (@16 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
- factor 50! reduction of power for cryo system
FCC-hh beam-screen test set-up at ANKA/Germany: beam tests since June 2017, for prototypes, confirming vacuum design simulations

ANKA $e^-$ photon spectrum = FCC –hh spectrum

2.5 GeV ANKA/KIT storage ring
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)
Main cryogenics parameters and layout

<table>
<thead>
<tr>
<th>Temperature level</th>
<th>[W/m]</th>
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</thead>
<tbody>
<tr>
<td>1.9 K, cold mass of magnets</td>
<td>1.4</td>
</tr>
<tr>
<td>• Beam losses</td>
<td></td>
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<tr>
<td>• Resistive heating of splices</td>
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<tr>
<td>40-60 K, beam screen, thermal shield</td>
<td>71</td>
</tr>
<tr>
<td>• Synchrotron radiation</td>
<td></td>
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<tr>
<td>• Beam Image current</td>
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</tbody>
</table>

Total load
1 MW equivalent @4.5 K

Cryoplants overall layout

Baseline
10 cryoplants
20 MW electrical/plant
6 technical sites

Future Strategies and Technologies
Michael Benedikt
International Teacher Weeks 2017, CERN
Detector Concepts for 100 TeV pp

Very large volume of high magnetic field needed to measure momentum of charged particles.

Expanding from LHC detector concepts:

B=6 T, 12 m bore, solenoid with shielding coil and 2 dipoles 10 Tm. Length 64 m, diam. 30 m, magnet 7000 tons, stored energy 50 GJ
Detector Magnet Studies

Today’s baseline:

4T/10m bore 20m long Main Solenoid
4T Side Solenoids – all unshielded
14 GJ stored energy, 30 kA and
2200 tons system weight

Alternative challenging design:

4T/4m Ultra-thin, high-strength Main Solenoid
allowing positioning inside the e-calorimeter,
280 MPa conductor (side solenoids not shown)
0.9 GJ stored energy, elegant, 25 t only,
but needs R&D!
SC links for circuit powering

\[ \text{MgB}_2 \text{ industrial conductor, He gas cooled} \]

Example HL-LHC (\( l_{\text{tot}} \) up to \(|150 \text{ kA}| \) @ 25 K)

All circuits in single cryostat – compact & efficient

\[ \Phi_{\text{ext}} \sim 65 \text{ mm} \]
\[ |l_{\text{tot}}| \sim 150 \text{ kA} \]

\[ \text{Mass} \sim 11 \text{ kg/m} \]

\[ \Phi_{\text{ext}} \sim 220 \text{ mm} \]
Stored energy 8.4 GJ per beam

- Factor 25 higher than for LHC, equivalent to A380 (560 t) at nominal speed (850 km/h). Can melt 12t of copper.

- Collimation, control of beam losses and radiation effects (shielding) are of prime importance.
- Injection, beam transfer and beam dump all critical.

Machine protection issues to be addressed early on!

Hydrodynamic tunneling: beam penetrates ~300 m in Cu
Huge energy to be extracted and dumped => need large dump section
Beam rigidity: 167 T.km => need long way to dilute beam ~2.5km!

Fluka studies:
- Bunch separation >1.8 mm
- Branch separation: 4 cm
- Keeps T<1500°C

Very reliable kickers, high segmentation, new methods for triggering (laser)
FCC Collaboration & Industry Relations

124 Institutes
30 Companies
32 Countries
EC H2020
Future Circular Collider Study

Large scale technical infrastructures
Conceptual design study 2014 – 2018
Driven by international contributions
Establish long-term liaisons with industry
Collaborate on technology evolution (> 2025)