Future (circular) colliders

M. Benedikt

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
Step 1: HL-LHC upgrade – ongoing

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.
Step 2: Future high energy colliders

For physics beyond the LHC and beyond the Standard Model, under study (synergy of):

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

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

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

Future Circular Colliders
Michael Benedikt
International Teacher Program 2019, CERN

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

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

- **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**
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 Scope: Accelerator and Infrastructure

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.? → ~170 kCHF/GeV
CERN Circular Colliders & FCC


Constr. Physics

Design Proto Construction Physics

LEP

LHC – operation run 2

Design Construction Physics

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
Phase 1 completed: CDR for update of European Strategy by end 2018
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<td>Industry participation</td>
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<td>~ 15 years</td>
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<td>Total</td>
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<td>~ 25 years</td>
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**Case:** LHC superconducting dipole magnets
Geological background

- MOLASSE (Grès, Marnes)
- TERRAINS MEUBLES (Moraine, Alluvions)
- Karsts
- CALCAIRE
Future Circular Colliders
Michael Benedikt
International Teacher Program 2019, CERN

Progress on site investigations
• 90 – 100 km fits geological situation well
• LHC suitable as potential injector
• The 100 km version, intersecting LHC, is the baseline and studied in more detail
Tunnelling options for crossing the lake

- Slurry TBM
- Immersed Tube Tunnel
- Open Shield TBM
- 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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<tr>
<td>collision energy cms [TeV]</td>
<td>100</td>
<td>27</td>
<td>14</td>
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<tr>
<td>dipole field [T]</td>
<td>16</td>
<td>16</td>
<td>8.3</td>
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<tr>
<td>circumference [km]</td>
<td>100</td>
<td>27</td>
<td>27</td>
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<tr>
<td># IP</td>
<td>2 main &amp; 2</td>
<td>2 &amp; 2</td>
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<td>beam current [A]</td>
<td>0.5</td>
<td>1.12</td>
<td>(1.12) 0.58</td>
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<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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<td>events/bunch crossing</td>
<td>170</td>
<td>&lt;1020 (204)</td>
<td>850</td>
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<td>stored energy/beam [GJ]</td>
<td>8.4</td>
<td>1.2</td>
<td>(0.7) 0.36</td>
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<td>synchrotron rad. [W/m/beam]</td>
<td>30</td>
<td>3.6</td>
<td>(0.35) 0.18</td>
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</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
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

Nb3Sn as SC material

0.57 m

0.78 m

~0.8 m

~1.1 m

~1.2 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 $\Leftrightarrow \int Bdl \sim 1 \text{ MTm}$
Stored energy $\sim 200 \text{ GJ (GigaJoule)} \sim 44 \text{ MJ/unit}$
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 $\Leftrightarrow \int Bdl \sim 0.15 \text{ MTm}$
Stored energy $\sim 9 \text{ GJ (GigaJoule)} \sim 7 \text{ MJ/unit}$
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**

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

Impact on coil section and conductor mass

- ~10% margin HL-LHC
- ~1.7 times less SC
- ~10% margin FCC ultimate
**16 T dipole options under consideration**

- **Cos-theta**: INFN, CEA, CIEMAT
- **Common coils**: INFN, CEA, CIEMAT, PSI
- **Swiss contribution**: PSI
- **Canted Cos-theta**: INFN, CEA, CIEMAT

**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
All coil parts, structural components and tooling are available at FNAL.
Coil fabrication and the work with mechanical structure are in progress.
Magnet reached 14 T in May 2019.
Synchrotron radiation

- 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.
Synchrotron radiation beam screen prototype

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

Beam screen, 40-60 K (50 bar)
Magnet thermal shield 60 K (44 bar)
Support post

Vacuum vessel
Bayonet heat exchanger, 1.85 K saturated
Cold mass, 1.9 K (1.3 bar)

Temperature level | [W/m] |
---|---|
1.9 K, cold mass of magnets | 1.4 |
• Beam losses
• Resistive heating of splices

40-60 K, beam screen, thermal shield | 71 |
• Synchrotron radiation
• Beam Image current

Total load
1 MW equivalent @4.5 K

Cryoplants overall layout

Baseline
10 cryoplants
20 MW electrical/plant
6 technical sites

<table>
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<tr>
<th>Cryoplant</th>
<th>40-60 K [kW]</th>
<th>1.9 K [kW]</th>
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<tr>
<td></td>
<td>592</td>
<td>11</td>
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<td>618</td>
<td>12</td>
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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

MgB$_2$ industrial conductor, He gas cooled
Example HL-LHC ($I_{\text{tot}}$ up to $\sim|150\ \text{kA}| @ 25\ \text{K}$)
All circuits in single cryostat – compact & efficient

$14 \times 2\ \text{kA}$
$6 \times 18\ \text{kA}$
$\Phi \sim 20\ \text{mm}$
$0.2\ \text{kA}$

$\Phi_{\text{ext}} \sim 65\ \text{mm}$
$|I_{\text{tot}}| \sim 150\ \text{kA}$

Mass $\sim 11\ \text{kg/m}$

$\Phi_{\text{ext}} \sim 220\ \text{mm}$

2x20 kA @ 24 K
2x20 m long CERN cable
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!
FCC-hh beam dilution system

Huge energy to be extracted and dumped => need large dump section
Beam rigidity: 167 T.km => need long way to dilute beam ~2.5km!

2.5 km dump line
1.4 km dump insertion
2.8 km collimation insertion

Kicker Septum 10 mrad bend Dilution Absorber

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)

SC septum
Status of global FCC Collaboration

- Institutes: 136
- Companies: 32
- Countries: 34
- EC H2020
Results of FCC Conceptual Design Study

Study Documentation:
4 CDR volumes submitted to EPJ in December 2018.
- FCC Physics Opportunities
- FCC-ee
- FCC-hh
- HE-LHC
- Preprints available since 15 January 2019
  http://fcc-cdr.web.cern.ch/

CDR presentation during welcome event this evening.
Paper copies can be requested at
  http://get-fcc-cdr.web.cern.ch

more than 1350 contributors from 350 institutes, a truly global collaboration and effort as suggested by the EPPSU 2013
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)