Accelerator Technologies I

D. Schulte, CERN
Collider Particle Choices

• Hadron collisions: compound particles
  – Protons or ions
  – Mix of quarks, anti-quarks and gluons: variety of processes
  – Parton energy spread
  – QCD processes large background sources
    – Hadron collisions $\Rightarrow$ can typically achieve higher collision energies

• Lepton collisions: elementary particles
  – Sofar always electrons and positrons
  – Muons are an option but have limited lifetime
  – Collision process known
  – Well defined energy
    – Lepton collisions $\Rightarrow$ precision measurements

• Photons also possible
Considered High Energy Frontier Collider

Circular colliders:

- **HL-LHC**
- **FCC** (Future Circular Collider)
  - FCC-hh: 100 TeV proton-proton cms energy, ion operation possible
  - FCC-ee: First step 90-350 GeV lepton collider
  - FCC-he: Lepton-hadron option
- **CEPC / SppC** (Circular Electron-positron Collider/Super Proton-proton Collider)
  - CepC : $e^+e^- 90 - 240$ GeV cms
  - SppC : pp 70 TeV cms

Linear colliders

- **ILC** (International Linear Collider): $e^+e^- 250$ GeV cms energy, Japan considers hosting project
- **CLIC** (Compact Linear Collider): $e^+e^- 380$ GeV - 3 TeV cms energy (also lower possible), CERN hosts collaboration

Other options

- **Muon collider**, past effort in US, new interest also in Europe and Asia
- Plasma acceleration in linear collider
- Photon-photon collider
- **LHeC**
Typically the key cost and power drivers and hence the defining technologies:

- **Magnet technology**
  - superconducting dipoles are the key for hadron colliders and very important for muon collider
  - beam-guiding quadrupoles are important for all

- **RF technology**
  - critical for linear colliders, superconducting ILC or normal-conducting CLIC, and for circular high-energy lepton colliders
  - important for circular hadron colliders

Many other technologies are also important and can drive the design

- Cryogenics
- Machine protection
- Collimation
- Vacuum
- Beam instrumentation
- CLIC stabilisation and alignment system
- ...

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Council charged the lab directors group (LDG) to deliver a European Accelerator R&D Roadmap

The extended LDG will deliver to council a report with a prioritised workplan

Five panels:
High-field magnets: P. Vedrine
Plasma accelerators: R. Assmann
RF: S. Bousson
Muons: D. Schulte
Energy recovery linacs: M. Klein
Hadron Colliders
High Energy Protons: Overview

The LHC is the current high energy frontier collider
• Target centre-of-mass energy 14 TeV
• Currently reached 13 TeV
• 27 km circumference collider at CERN
• Discovery of the Higgs boson in 2012
• Upgrade to higher luminosity ongoing: HL-LHC

Studies of future proton colliders that use a larger tunnel are FCC-hh and SppC
An option to use FCC-hh magnets in the LHC tunnel has been studied (HE-LHC) but is not maintained

Also the option to collide the LHC or FCC-hh beam with electrons is considered
• Named LHeC and FCC-eh
Upgrade of existing LHC

- A peak luminosity of $L_{\text{peak}} = 5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ with levelling, allowing:
- An integrated luminosity of 250 fb$^{-1}$ per year, enabling the goal of
- $L_{\text{int}} = 3000 \text{ fb}^{-1}$ twelve years after the upgrade.
I guess, everybody is familiar

Two multi-purpose experiments
- ATLAS and CMS

Two specialised experiments
- ALICE and LHCb
- Combined with injection

Other insertions
- Betatron cleaning
- Momentum cleaning
- RF insertion
- Dump insertion

Machine is producing physics since 2010
FCC Goal

FCC study develops a conceptual design of a new facility

**FCC-hh** defines infrastructure
- 100 TeV proton-proton collisions, 20 ab^{-1}
- 7x LHC energy and 7x HL-LHC integrated luminosity
- Use existing infrastructure to generate beam
- New ~100km-long collider ring

(Potential) first stage **FCC-ee** offers electron-positron collisions from 90 GeV to 365 GeV
- Unprecedented electron-positron collision energies >208 GeV
- Much higher event rates at previously reached energies (O(10^5) times as many Z as at LEP/LEP2)

**FCC-eh** Proton-electron option is also possible

**HE-LHC** Proton-proton option in LHC tunnel with FCC-hh technology

Consistent with implementation at CERN
FCC-hh Layout

Layout for CERN site

- Two high-luminosity experiments (A and G)
- Two other experiments combined with injection at 3.3 TeV (L and B)
- Two collimation insertions
  - Betatron cleaning (J)
  - Momentum cleaning (E)
- Extraction insertion (D)
- Clean insertion with RF (H)
- Circumference 97.75km
- Can be integrated into the area
- Can use LHC or SPS as injector
## Hadron Collider Parameters

<table>
<thead>
<tr>
<th></th>
<th>LHC</th>
<th>HL-LHC</th>
<th>FCC-hh Initial</th>
<th>FCC-hh Final</th>
<th>SppC</th>
<th>SppC ultimate</th>
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<tbody>
<tr>
<td>Cms energy [TeV]</td>
<td>14</td>
<td>14</td>
<td>100</td>
<td>100</td>
<td>75</td>
<td>150</td>
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<tr>
<td>Luminosity ([10^{34}\text{cm}^{-2}\text{s}^{-1}])</td>
<td>1</td>
<td>5</td>
<td>5</td>
<td>&lt; 30</td>
<td>10</td>
<td>?</td>
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<tr>
<td>Machine circumference</td>
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<td>27</td>
<td>97.75</td>
<td>97.75</td>
<td>100</td>
<td>100</td>
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<tr>
<td>Arc dipole field [T]</td>
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<td>8</td>
<td>16</td>
<td>16</td>
<td>12</td>
<td>24</td>
</tr>
<tr>
<td>Bunch distance [ns]</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td>?</td>
</tr>
<tr>
<td>Background events/bx</td>
<td>27</td>
<td>135</td>
<td>170</td>
<td>&lt; 1020</td>
<td>490</td>
<td>?</td>
</tr>
<tr>
<td>Bunch length [cm]</td>
<td>7.5</td>
<td>7.5</td>
<td>8</td>
<td>8</td>
<td>7.55</td>
<td>?</td>
</tr>
</tbody>
</table>

HL-LHC promises more luminosity

FCC-hh promises more energy and luminosity, requires larger ring
LHC Injection Complex

The LHC obtains its beam from a chain of injectors

Typically few hours to fill and several hours of luminosity
Hadron Collider Energy
Magnets and Energy

Arrows consist mainly of dipoles to bend the beam (80% dipoles in LHC or shown FCC-hh arcs) Maximum field and size of ring then define maximum collision energy

\[ r = \frac{T}{0.3 \text{GeV}} \frac{E}{B} \]

LHC: \( E=7 \) TeV, \( \rho=2.8 \) km, \( B = 8.3 \) T

FCC-hh: \( E=50 \) TeV, \( \rho=10.6 \) km, \( B = 15.6 \) T
Dipole Basic Concept (“Cosine Theta”)

Need two apertures with opposite field to bend both proton beams
If the beams had different signs of charge one aperture could be sufficient
High-field Magnet Technologies

Superconducting magnets reach highest fields, three main technologies for the cables

**NbTi** (niob-titanium)
- is standard, **used in LHC** limited to $O(8\ T)$

**Nb$_3$Sn** (niobium-tin)
- can reach $O(16\ T)$
- but difficult technology and needs to mature further
- expensive
- Used in some points for HL-LHC
- Foreseen for FCC-hh also in arcs

**HTS** (high-temperature superconductor)
- can reach $O(20\ T)$ or more
- in solenoids $> 30\ T$
- very expensive

Cut through a cable with superconductor embedded in copper, so some remains conductivity in case of a quench
The cables are only superconducting below a certain field and current. It depends also in the temperature. Above the magnet "quenches", this can cause machine protection issues.

**Conductors**

- **Nb**
- **Ti**
- **Nb₃Sn**

**HTS (REBCO)**

- Nb-Ti
- Nb₃Sn

**IBS- Iron Based Superconductor**

- Much lower cost and better mechanical properties expected.

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Q. Xu, CERN EPF Edition, April 2019, Oxford

Modified version by Q. Xu in Oct. 2017
Magnet Designs (FCC-hh)

This is similar to LHC

Criteria: Amount of conductor, stress in magnets, ...
The conductor is a major cost item of the magnet
⇒ try to minimise the amount

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Cost Effective Magnet Design

Field builds up to toward the centre

Could use cheaper conductor for the outer coils, but generates design challenges
With today’s state of the art conductors:

- 15 T achievable at 14 % margin
- 17 T at short sample
- Cos-theta and common-coil model magnet programs are under preparation

15 T dipole demonstrator
60-mm aperture
4-layer graded coil
New activity with many collaborators started in 2017 with ambitious targets

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wire diameter</td>
<td>mm</td>
</tr>
<tr>
<td>Non-Cu Jc (16 T, 4.2 K)*</td>
<td>A/mm²</td>
</tr>
<tr>
<td>Unit length</td>
<td>km</td>
</tr>
<tr>
<td>Cost</td>
<td>€/kA m**</td>
</tr>
</tbody>
</table>

First wires almost reached HL-LHC requirements

[Measurements @ CERN (4.2 K)]

Green: FCC_2
Blue: FCC_3
Dashed red: FCC_4
Dashed blue: HL-LHC

7 companies, two universities and two national research institutes

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HL-HLC and Hadron Collider Luminosity
Upgrades to higher current
Injectors
Collimation
Detectors (phase 1)

... Small luminosity increase

Upgrade to full luminosity
Detectors (phase 2)
Triplets

...
Some Key HL-LHC Ingredients

**Higher field focusing magnets** at experiments
Models tested

**Crab cavities** to reduce luminosity reduction by crossing angle (recent first tests in SPS)

**Injector upgrade**

**Additional collimators** to protect arcs
**Stronger dipoles** to make space for additional collimators (recent first prototype)

**Civil engineering** and more kryogenics

**Improved collimators** design and material

And many more
Instrumentation, vacuum, availability, ...
Optics design, electron cloud, impedances, ...

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Luminosity $\mathcal{L}$ determines the event rate

It depends on the geometrical overlap of the colliding beams

\[
\mathcal{L} = \frac{N^2}{4\pi \sigma_x \sigma_y} \cdot f_r
\]

- Bunch charge ($N^2 = N_1 N_2$)
- Number of bunch collisions per second
- Horizontal rms beam size (Gaussian beam)
- Vertical rms beam size (Gaussian beam)
Beam Size

Lattice property

$$\sigma_{x,y} = \sqrt{\frac{\beta_{x,y}\varepsilon_{x,y}}{\gamma}}$$

Particle coordinates at one location

Area $\varepsilon$ does not change

Particle coordinates at other location

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Hadron Collider Luminosity Drivers

\[ \mathcal{L} \propto \frac{N}{\varepsilon} \frac{1}{\beta_c} N n_b f_r \]

Use high beam current

Risks:
- High stored energy and losses
- Impedance and electron cloud
- Aperture should be minimised for dipole cost
- High synchrotron radiation load due to high beam energy

Squeeze the beam as much as possible
Mitigate more collision debris due to higher luminosity and energy

Make small emittance and large charge
Limited by emittance growth, imperfections and particle losses

For integrated luminosity:
- Fast turn-around critical for luminosity
- Minimise time for stops etc.
- High availability with more components than LHC
- Maximising current also maximises time between new fills
Peak luminosity is leveled to limit background.

Luminosity decays because beam particles are lost in the collisions.

Time between fills is a few hours:
- ramp magnets down
- inject beam in small batches
- Ramp beam energy and magnets up
Detector and Machine

Hall half length: 33m
Detector half length: 23.5m
L* = 40 m
Space to open: 9.5m

Uses forward solenoid
Alternative option with forward dipole considered

Tracking
Ecal
HCAL
Magnets and cryostat
Muons

Tunnel before triplet: 7m
FCC-hh example

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Interaction Region and Final Focus Design

\[ \mathcal{L} = \frac{1}{\beta} \frac{N}{t} n_{\text{fill}} \]

Beam size is limited by aperture in the magnets

- Beamsize at IP: 3.5 microns
- Beamsize at IP: 7 microns

Smaller beta-function requires larger aperture

FCC-hh example

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Quadrupole Design

Quadrupoles can focus the beam
The vertical field is proportional to $x$
$\Rightarrow$ horizontal force is proportional to $x$

$$B_y = \frac{B_y}{x}x$$

Maximum field in quadrupole depends on product of focal strength and aperture
$\Rightarrow$ LHC can use NbTi
$\Rightarrow$ HL-LHC needs Nb$_3$Sn (and FCC-hh) need 11 T
Total collision debris per experiment

- $O(10 \text{ kW})$ for HL-LHC
- LHC magnets have to be replaced due to the accumulated radiation
- Shielding is required and further increases magnet aperture
- note: up to $O(500 \text{ kW})$ in FCC-hh

FCC-hh example shown
Beam Physics Limitations

\[ \mathcal{L} = \xi \frac{1}{\beta} \frac{N}{\Delta t} \eta_{\text{fill}} \]

Beam-beam studies ongoing, promising results

Many limitation for the beam current exist:

- Impedances
  - parasitic electromagnetic fields induced by the beam
- Electron cloud
  - electrons hitting the beam screen can produce avalanche of more electrons
- Losses in
  - Collimation
  - Injection
  - Extraction
  - ...
Beam-beam Effects

\[ L = \frac{1}{\beta} \frac{N}{\Delta t} \eta_{\text{fill}} \]

Turn : 004

Momentum \([\sigma_x]\) vs. Position \([\sigma_x]\)
Beam-beam Effects

\[ \mathcal{L} = \left( \frac{1}{\beta} \frac{N}{\Delta t} \eta_{\text{fill}} \right) \]

X. Buffat
\[ \mathcal{L} = \xi \frac{N}{\beta \Delta t} \eta_{\text{fill}} \]

**Beam-beam Effects**

Turn: 003

- **Position** $[\sigma_x]$
- **Momentum** $[\sigma_x]$
Beam-beam Effects

\[ \mathcal{L} = \left( \frac{1}{\beta} \right) \frac{N}{\Delta t} \eta_{\text{fill}} \]
Crossing angle and Crab Cavities

Larger crossing angle reduces impact of parasitic crossings

But reduces luminosity

Crab cavities give a kick to beam head and tail to rotate it the beam to avoid this

\[ \mathcal{L} = H_D \frac{N^2 f_r n_b}{4\pi \sigma_x \sigma_y} \frac{1}{\sqrt{1 + \left( \frac{\sigma_z}{\sigma_x} \tan \frac{\theta_c}{2} \right)^2}} \]
At collision, the final triplets at experiments are the bottleneck

⇒ particles that drift into the tails get lost here
⇒ Need to introduce a new, smaller bottleneck to have losses in less sensitive region, the collimation system

Collimation also protects from injection failure, asynchronous beam dump, ...
Collimation System

Transverse collimation ("betatron") system is most challenging FCC-hh design is shown, but a copy of LHC system

Primary collimators intercept protons

Secondary collimators and absorbers intercept showers

Some protons only lose energy and make it to next arc, where they are lost

Protect arcs with additional collimators

- No space in LHC
  ⇒ replace some 8 T dipoles with shorter 11 T ones
- Foreseen in FCC-hh

\[ \mathcal{L} = \xi \frac{N}{\Delta t} \eta_{\text{fill}} \]

Betatron Collimation Insertion (2.8km)

Dispersion suppressor region

<table>
<thead>
<tr>
<th>Dipoles</th>
<th>Primary collimators</th>
<th>Secondary collimators</th>
<th>Shower absorbers</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.5cm</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1MW

200kW

230kW

5kW Dispersion suppressor collimators

Some protons only lose energy and make it to next arc, where they are lost
Intensity Limitation: Beam Energy and Dump

\[ \mathcal{L} = \xi \frac{N}{\Delta t} \eta_{fill} \]

- 2.5 km dump line
- 1.4 km dump insertion
- 2.8 km collimation insertion
- Kicker
- Septum
- 10 mrad bend
- Dilution
- Absorber

LHC pattern (same scale)

In LHC / HL-LHC 400 to 800 MJ per beam

In FCC-hh 8 GJ kinetic energy per beam
- Airbus A380 at 720 km/h
- 2000 kg TNT
- 400 kg of chocolate
  - Run 25,000 km to spent calories
- O(20) times LHC
- Can drill 300 m long hole in copper
**Impedance**

Beam produces parasitic electromagnetic fields in collimators, beam screen etc that can kick beam and induce instability.

**Electron cloud**

Free electrons are kicked into wall by proton beam and can produce secondary electrons which can build-up to cloud of electrons and render beam unstable.
Beamscreen Design

LHC beamscreen

FCC-hh beamscreen

\[ L = \frac{N}{\Delta t} \eta_{\text{fill}} \]
30 W/m synchrotron radiation (LHC: 1 W/m)
Make it small to make magnet cheap

Magnet aperture 50 mm (LHC 56 mm)

- Extract photons for great vacuum
- Strong to withstand quench
- Hide pumping holes from beam for low impedance
- Laser treatment / carbon coating against ecloud
- 50 K for efficiency
- Prototype
- Test station in ANKA
- 30 W/m synchrotron radiation (LHC: 1 W/m)
Some Key HL-LHC Ingredients

**Higher field focusing magnets** at experiments
Models tested

**Crab cavities** to reduce luminosity reduction by crossing angle (recent first tests in SPS)

**Additional collimators** to protect arcs
**Stronger dipoles** to make space for additional collimators (recent first prototype)

**Civil engineering and more kryogenics**

**And many more**
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Optics design, electron cloud, impedances, ...

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