Future Accelerator Machines and R&D

D. Schulte, CERN
Overview

Following the charge, I will cover the main future projects with a collaboration pushing forward

Circular colliders:
• FCC (Future Circular Collider)
• CEPC / SppC (Circular Electron-positron Collider/Super Proton-proton Collider)

Linear colliders
• ILC (International Linear Collider)
• CLIC (Compact Linear Collider)

Others will not be covered
• Detectors, physics, ...
• Muon collider, effort strongly reduced but some recent progress with the source (MICE and novel idea)
• Photon-photon collider
• Gamma factory based on ions
• ...
ILC

Parameters | Value
---|---
C.M. Energy | 500 GeV
Peak luminosity | $1.8 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$
Beam Rep. rate | 5 Hz
Pulse duration | 0.73 ms
Average current | 5.8 mA (in pulse)
E gradient in SCRF acc. cavity | 31.5 MV/m +/-20% $Q_0 = 1E10$

TDR exists
Aim for cost reduction
Political process in Japan ongoing
ILC Cavities

800 cavities produced for European XFEL

Goal 24 MV/m

In vertical test stand (one Vendor):
Average gradient for $Q_0 > 10^{10}$
$G = 29.4$ MV/m

ILC goal 31.5 MV/m installed

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Future Accelerator Machines, EPS 2017
Cost saving studies, e.g.
• Coupler design 1-2%
• Cavity material 2-3%
• No more hydrofluoric acid for chemical treatment 1-2%
• Higher gradient and more efficient cavities 4-5%
• ...

Nitrogen infusion appears very promising
• Increase in gradient
• Increase in $Q_0$

Modified exposure to nitrogen (from FNAL)
Before: doping with few minutes at 800 °C
Now: a day or so at 120 °C
Technical improvements can decrease cost by 10-20%
More seems to be required, so staging is being considered

Baseline 500 GeV running example

Example: 250 GeV (F) and upgrade

Goal:
4 ab\(^{-1}\) @ 500 GeV
100 fb\(^{-1}\) @ 350 GeV
2 ab\(^{-1}\) @ 250 GeV

Luminosity increase
- 2 x by increasing RF
- 2 x by increasing cryogenics and repetition rate
CLIC (3 TeV)

1.5 TeV / beam

Drive Beam

540 klystrons
20 MW, 148 μs

drive beam accelerator
2.4 GeV, 1.0 GHz

delay loop

2.5 km

CR1

CR2

circumferences
delay loop 73 m
CR1 293 m
CR2 439 m

BC2

BDS
2.75 km

e⁻ main linac, 12 GHz, 72/100 MV/m, 21 km

50 km

Main Beam

540 klystrons
20 MW, 148 μs

drive beam accelerator
2.4 GeV, 1.0 GHz

delay loop

2.5 km

decelerator, 25 sectors of 878 m

TA

CR combiner ring
TA turnaround
DR damping ring
PDR predamping ring
BC bunch compressor
BDS beam delivery system
IP interaction point

dump

50 km

e⁻ injector
2.86 GeV

e⁺ injector
2.86 GeV

e⁻ DR
427 m

e⁺ DR
427 m

e⁻ PDR
389 m

e⁺ PDR
389 m

booster linac
2.86 to 9 GeV

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**CLIC (3 TeV)**

**Drive beam time structure - initial**
- 240 ns
- 140 μs train length - 24 × 24 sub-pulses
- 4.2 A - 2.4 GeV - 60 cm between bunches

**Drive beam time structure - final**
- 240 ns
- 5.8 μs
- 24 pulses - 101 A - 2.5 cm between bunches

1.5 TeV / beam
1.5 TeV / beam

CLIC (3 TeV)

Drive beam time structure - initial

- 140 µs train length - 24 × 24 sub-pulses
- 4.2 A - 2.4 GeV - 60 cm between bunches

Drive beam time structure - final

- 240 ns
- 5.8 ns

1.5 Te

100A drive beam

1.2A main beam

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Plenty of good physics at lower energies

⇒ First stage at 380 GeV
⇒ HZ, WW fusion, top asymmetry

Further stages re-use infrastructure and equipment

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<table>
<thead>
<tr>
<th>Parameter</th>
<th>unit</th>
<th>380 GeV</th>
<th>3 TeV</th>
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<tbody>
<tr>
<td>L</td>
<td>$10^{34}$ cm$^{-2}s^{-1}$</td>
<td>1.5</td>
<td>5.9</td>
</tr>
<tr>
<td>G</td>
<td>MV/m</td>
<td>72</td>
<td>72/100</td>
</tr>
<tr>
<td>Length</td>
<td>km</td>
<td>11</td>
<td>50</td>
</tr>
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</table>
**CLIC Staged Scenario**

### Luminosity targets from Physics Study group

<table>
<thead>
<tr>
<th>Stage</th>
<th>$\sqrt{s}$ (GeV)</th>
<th>$\mathcal{L}_{int}$ (fb$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>380</td>
<td>500</td>
</tr>
<tr>
<td>2</td>
<td>350</td>
<td>100</td>
</tr>
<tr>
<td>3</td>
<td>1500</td>
<td>1500</td>
</tr>
<tr>
<td>3</td>
<td>3000</td>
<td>3000</td>
</tr>
</tbody>
</table>

Hopefully input from LHC

### Central complex on Preveissin site

### Luminosity evolution

- 0.38 TeV
- 1.5 TeV
- 3 TeV

Legend:
- CERN existing LHC
- CLIC 880 GeV
- CLIC 1.5 TeV
- CLIC 3 TeV

Unsused arcs

Drive beam

Main beam

L=1.87 km

L=2.75 km
CLIC Roadmap

2013 - 2019 Development Phase
Development of a Project Plan for a staged CLIC implementation in line with LHC results; technical developments with industry, performance studies for accelerator parts and systems, detector technology demonstrators

2020 - 2025 Preparation Phase
Finalisation of implementation parameters, preparation for industrial procurement, Drive Beam Facility and other system verifications, Technical Proposal of the experiment, site authorisation

2026 - 2034 Construction Phase
Construction of the first CLIC accelerator stage compatible with implementation of further stages; construction of the experiment; hardware commissioning

2019 - 2020 Decisions
Update of the European Strategy for Particle Physics; decision towards a next CERN project at the energy frontier (e.g. CLIC, FCC)

2025 Construction Start
Ready for construction; start of excavations

2035 First Beams
Getting ready for data taking by the time the LHC programme reaches completion

CERN Future Accelerator Machines, EPS 2017
From CTF3 to CLEAR

CTF3 has demonstrated drive beam production and main beam acceleration
- Technology
- Beam quality
- Operation

Closed end 2016

New facility is coming online: CLEAR
CERN Linear Electron Accelerator for Research

Figure 1: The current CALIFES beam line. The length of the facility (as shown) is ~20m.
Further development and industrialisation of accelerating structures is ongoing.

Several klystron-based test stands exist that test structures (X-boxes)

Conditioning procedure is being optimised.

Growing interest in X-band (FELs, novel technologies, …)
- DESY, PSI, INFN, Cockcroft, …
- CompactLight proposal to EU, 24 partners
Other CLIC Technology Development

Redesign CLIC modulators and klystrons
Increase efficiency from 62% to 90%
Reduce cost (low voltage, no oil)

\[ \eta_{\text{Total}} = 0.9 \]

Permanent magnets
Use tunable permanent magnets where possible
- Quadruoles in drive beam
- Strongest permanent magnet developed in UK

Klystron-based first energy stage
As alternative

Main beam injector
e.g. halved power for positron production

New module design
Reduce cost of mechanical system and control

I. Syratchev et al.
C. Rossi et al.
J. Clarke et al.
Plasma Acceleration as Upgrade Option?

Very high gradients of 50 GV/m demonstrated

Can use laser or particle beam to generate field

R&D programmes are ongoing

Require excellent beam quality and high efficiency
- Preservation of beam quality during acceleration has to be studied in theory and experimentally
- This is particularly tough for high efficiency

Application of novel technologies to colliders
- Started a working group for CLIC to understand potential
- Plasma community started a working group on colliders
Proposal for project at CERN
• CDR for EU strategy end 2018

FCC-hh
• pp collider with 100 TeV cms
• Ion option
• Defines infrastructure

FCC-ee
• Potential $e^+e^-$ first stage

FCC-eh
• additional option

HE-LHC
• LHC with high field magnets

Proposal for project in China
• CDRs exist but changes since

CEPC
• $e^+e^-$ collider 90-240 GeV
• focus on higgs

SppC
• Hadron collider to later be installed in the same tunnel
  75 to $O(150)$ TeV
**FCC-hh / SppC Layouts**

**FCC-hh layout**
Optimised for Geneva site
Circumference 97.75 km
Can use LHC or SPS as injector

**SppC layout**
Recently adopted 100 km circumference
New injectors are required
# Hadron Collider Parameters

<table>
<thead>
<tr>
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<th></th>
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<th></th>
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</thead>
<tbody>
<tr>
<td>Cms energy [TeV]</td>
<td>14</td>
<td>27</td>
<td>100</td>
<td>100</td>
<td>75</td>
<td>150</td>
</tr>
<tr>
<td>Luminosity [$10^{34}$cm$^{-2}$s$^{-1}$]</td>
<td>1 (5)</td>
<td>25</td>
<td>5</td>
<td>&lt; 30</td>
<td>10</td>
<td>?</td>
</tr>
<tr>
<td>Machine circumference</td>
<td>27</td>
<td>27</td>
<td>97.75</td>
<td>97.75</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Arc dipole field [T]</td>
<td>8</td>
<td>16</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 (5)</td>
<td>25</td>
<td>25 (5)</td>
<td>25 (10/5)</td>
<td>?</td>
</tr>
<tr>
<td>Background events/bx</td>
<td>27 (135)</td>
<td>800 (160)</td>
<td>170</td>
<td>&lt; 1020</td>
<td>490</td>
<td>?</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(&lt; 202)</td>
<td>(196/98)</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>

FCC integrated luminosity goal is 17.5 ab$^{-1}$

$L^* = 40$ m

5 ns to limit background, but more challenging and will lose some luminosity
Luminosity Evolution (FCC-hh)

Significant damping of the proton beam

Burn beam rapidly

Have to inject enough beam

Can consider luminosity levelling

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Future Accelerator Machines, EPS 2017
FCC-hh Magnet Development

FCC goal is 16 T operating field
- Requires to use Nb$_3$Sn technology
- At 11 T used for HL-LHC
⇒ Strong synergy with HL-LHC

R&D on cables in test stand at CERN

Target: $J_C > 2300 \text{ A/mm}^2$ at 1.9 K and 16 T (50% above HL-LHC)

Industrial fabrication:
Target cost: 3.4 Euro/kAm

Key cost driver
16 T demonstrated in coil
Hope for US model test early 2018: 14-15 T
Short magnet models in 2018 – 2023
12 T for HL-LHC

Magnet design to **minimise material** use and limit margins to essential level

Common coils
Cos-theta
Blocks
Canted Coil

Swiss contribution via PSI

D. Schulte
D. Tommasini at al.

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FCC goal is 16 T operating field

High-temperature superconductors (HTS) are also explored
• Fields of 20+ T
SppC considers to use fe-HTS

Material use level

CIEMAT, CEA, INFN

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D. Tommasini at al.

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Swiss contribution via PSI

Canted Coil

EuroCirCol
A key to New Physics
FCC-hh Technology Example

30 W/m synchrotron radiation (LHC: 1 W/m)
Make it small to make magnet cheap

Magnet aperture 50 mm (LHC 56 mm)

Laser treatment / carbon coating against ecloud

Extract photons for great vacuum

Strong to withstand quench

Hide pumping holes from beam for low impedance

P. Chiggio at al.

Test station in ANKA

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FCC-hh Beam Losses

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

Up to 500 kW collision debris per experiment
Mainly lost in triplets, challenge for lifetime and quench

FCC-hh beam dilution pattern at dump

LHC beam dilution pattern at dump

F. Cerutti et al.

Triplet design allows for thick shielding
- Up to 1 of 300 atoms displaced in conductor
- Can survive project lifetime

Collimation system design ongoing
- Identified hot spots
- Will implement ideas to get rid of them

R. Bruce et al.

B. Goddard al.
Goal is 4 x HL-LHC luminosity
HL-LHC injectors
FCC-hh magnets and vacuum system

Make FCC-hh magnets more compact to fit in LHC tunnel
- Challenge is field leakage into tunnel
- Use kryostat as partial return yoke
- Active compensation

Cannot increase lengths of insertions
- Currently beta-function around 0.4 m
  - 0.7ab⁻¹ per year
  - Hope to improve
- Beam extraction is a challenge
- Collimation to be looked at

F. Zimmermann et al.
### FCC-ee / CEPC Parameters

#### Energies [GeV]

<table>
<thead>
<tr>
<th>Energy</th>
<th>Years</th>
<th>Int. Luminosity [ab⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>91.2</td>
<td>4 / 2</td>
<td>2 x 75 / 2 x 1.25</td>
</tr>
<tr>
<td>160</td>
<td>2 / not spec.</td>
<td>2 x 5 / not specified</td>
</tr>
<tr>
<td>240</td>
<td>3 / 10</td>
<td>2 x 2.5 / 2 x 2.5</td>
</tr>
<tr>
<td>350</td>
<td>5 / ---</td>
<td>2 x 1.5 / ---</td>
</tr>
</tbody>
</table>

#### Still moving targets

L. Wang et al. IHEP-AC-2017-01
F. Zimmermann et al. priv. comm.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Z</th>
<th>W</th>
<th>H</th>
<th>t</th>
<th>LEP2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cms E [GeV]</td>
<td>91.2</td>
<td>160</td>
<td>240</td>
<td>350</td>
<td>208</td>
</tr>
<tr>
<td>I [mA]</td>
<td>1390 / 370-1450</td>
<td>147 / 51</td>
<td>29 / 11-30</td>
<td>6.4 / --</td>
<td>4</td>
</tr>
<tr>
<td>L [10³⁴ cm⁻²s⁻¹]</td>
<td>200 / 18-71</td>
<td>25 / 4.1</td>
<td>7 / 2.1-5.4</td>
<td>1.3 / --</td>
<td>0.012</td>
</tr>
</tbody>
</table>
Detailed MDI design ongoing

Large crossing angle requires additional tunnel

Short beam lifetime at high energy requires top-up scheme
FCC-ee Technologies

Cost effective magnets

Two-in-one design of dipoles and quadrupoles

Optimised windings to reduce cost and power consumption

Optimised RF cavities

Single cells at low energy:
Low voltage but high current

Double cells at high energy:
Low current but high voltage

Efficient klystrons, based on design ideas for CLIC
LHeC / FCC-he

<table>
<thead>
<tr>
<th></th>
<th>LHeC CDR</th>
<th>HL-LHeC</th>
<th>HE-LHeC</th>
<th>FCC-he</th>
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<tbody>
<tr>
<td>$E_p$ [TeV]</td>
<td>7</td>
<td>7</td>
<td>12.5</td>
<td>50</td>
</tr>
<tr>
<td>$E_e$ [GeV]</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>$L$ [$10^{33}$ cm$^{-2}$s$^{-1}$]</td>
<td>1</td>
<td>8</td>
<td>12</td>
<td>15</td>
</tr>
</tbody>
</table>

Development of accelerator technology
E.g. RF power required to control cavities
**Test facility (PERLE)** planned in Orsay

Interaction region
design ongoing

M. Klein et al
Preliminary FCC Draft Schedules

Technically limited schedule

Strategy Update 2026 – assumed project decision

Dipole short models
Dipole long models
16 T dipole indust. prototypes
16 T dipoles preseries
16 T series production

Civil Engineering FCC-hh ring
CE TL to LHC
LHC Modification
Installation + test FCC-hh

CE FCC-ee ring + injector
Injector
Installation + test FCC-ee

LHC Removal
Installation HE-LHC

M. Benedikt
Conclusion

Important progress toward the EU strategy

- **ILC**
  - Focus on cost reduction
  - Political process

- **CLIC**
  - Further optimising 380 GeV first energy stage
  - Work on further stages, including novel technologies
  - Project Implementation Plan for 2018

- **SppC and CEPC**
  - CDRs available

- **FCC**
  - CDR end of 2018 for hh (with he), ee and HE-LHC options
  - Including R&D plan

Many thanks to L. Evans, S. Stapnes, W. Wuensch, Ph. Burrows, I. Syratchev, M. Benedikt, K. Oide, F. Zimmermann, M. Klein, ... the ILC, CLIC, FCC and SppC/CEPC teams
FCC-hh MDI

Tracking
Ecal
HCAL
Magnets and cryostat
Muons

Uses forward solenoid
Alternative option with forward dipole considered

Tunnel before triplet: 7m
L* = 40 m
Hall half length: 33m
Detector half length 23.5m
Space to open 9.5m

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CLIC RF Technology Development

- Common modulator 366 kV, 265 A
- 2x 68 MW, 1.625 µsec
- 2x 213 MW, 325 ns
- 10 x 42.5 MW x 325 ns
- 10 x CLIC AS x 0.25 m x 75 MV/m
- 10 x BOC
- 2 x Klystron
- Load#1
- Load#2
- Also study alternative 380 GeV stage with klystrons
- Develop novel high efficiency klystrons
- Novel pulse compressors
- Optimised structure

Also study alternative 380 GeV stage with klystrons

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Muon collider effort has been reduced dramatically

Effort on source still ongoing (MICE)

New idea to generate muon beam
• But need to evaluate efficiency
Proposal of a Low emittance muon beam production from positrons on target

direct μ pair production: e⁺e⁻ → μ⁺μ⁻ just above the μ⁺μ⁻ production threshold with minimal muon energy spread, with direct annihilation of ≈ 45GeV e⁺ with atomic e⁻ in a thin target O(0.01 radiation length)

very small emittance at μ production point → no cooling needed!

Goal
very low emittance, sufficient rate
normalized muon emittance εₙ = 40 nm
muon production rate at target ≈ 10¹¹ μ/s allows competitive luminosity at low fluxes

Advantages:
1. Low emittance possible: can be very small close to the μ⁺μ⁻ threshold
2. Low background: Luminosity at low emittance will allow low background and low ν radiation (easier experimental conditions, can go up in energy)
3. Reduced losses from decay: muons can be produced with a relatively high boost in asymmetric collisions
4. Energy spread: muon energy spread also small at threshold

Disadvantage: rate: much smaller cross section wrt protons (≈ mb)

Key topics for feasibility
• Low emittance and high momentum acceptance 45 GeV e⁺ ring
• O(100 kW) class target in the e⁺ ring for μ⁺ μ⁻ production
• High rate positron source
• High momentum acceptance muon accumulator rings

Ref. NIM A 807 101-107 (2016), WEOBA3 in Proc. of IPAC17