Accelerator Technologies II

D. Schulte, CERN
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**
## Proposed Colliders with at least a CDR

<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>ILC</td>
<td>ee</td>
<td>0.25</td>
<td>2</td>
<td>11</td>
<td>129 (upgr. 150-200)</td>
<td>4.8-5.3 GILCU + upgrade</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.5</td>
<td>4</td>
<td>10</td>
<td>163 (204)</td>
<td>7.8 GILCU</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.0</td>
<td></td>
<td></td>
<td>300</td>
<td>?</td>
</tr>
<tr>
<td>CLIC</td>
<td>ee</td>
<td>0.38</td>
<td>1</td>
<td>8</td>
<td>168</td>
<td>5.9 GCHF</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.5</td>
<td>2.5</td>
<td>7</td>
<td>(370)</td>
<td>+5.1 GCHF</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>5</td>
<td>8</td>
<td>(590)</td>
<td>+7.3 GCHF</td>
</tr>
<tr>
<td>CEPC</td>
<td>ee</td>
<td>0.091+0.16</td>
<td>16+2.6</td>
<td></td>
<td>149</td>
<td>5 G$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.24</td>
<td>5.6</td>
<td>7</td>
<td>266</td>
<td></td>
</tr>
<tr>
<td>FCC-ee</td>
<td>ee</td>
<td>0.091+0.16</td>
<td>150+10</td>
<td>4+1</td>
<td>259</td>
<td>10.5 GCHF</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.24</td>
<td>5</td>
<td>3</td>
<td>282</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.365 (+0.35)</td>
<td>1.5 (+0.2)</td>
<td>4 (+1)</td>
<td>340</td>
<td>+1.1 GCHF</td>
</tr>
<tr>
<td>LHeC</td>
<td>ep</td>
<td>60 / 7000</td>
<td>1</td>
<td>12</td>
<td>(+100)</td>
<td>1.75 GCHF</td>
</tr>
<tr>
<td>FCC-hh</td>
<td>pp</td>
<td>100</td>
<td>30</td>
<td>25</td>
<td>580 (550)</td>
<td>17 GCHF (+7 GCHF)</td>
</tr>
<tr>
<td>HE-LHC</td>
<td>pp</td>
<td>27</td>
<td>20</td>
<td>20</td>
<td></td>
<td>7.2 GCHF</td>
</tr>
</tbody>
</table>
European Strategy in a Nutshell

Highest priority is HL-LHC

Highest priority for next collider is a higgs factory
• currently four candidates FCC-ee, CEPC, ILC or CLIC

Japan community is considering to host ILC, but process is very slow
China community is considering to host CEPC, but progress very slow
CERN aims to have FCC-ee as next project and later FCC-hh, decision only at next European strategy

But
• No consensus which is the best higgs factory
• No consensus that FCC-ee and ILC/CEPC would be complementary enough to justify both
• Prudently, prepare alternatives
  • e.g. muon collider

US unfortunately not pushing for the high-energy frontier, might hopefully change
• Muon collider has been mainly a US development

Beate will give much more detail in the next talk
Future Lepton Colliders
High Energy Leptons: Overview

Past circular and linear electron positron colliders
- **LEP** (circular) centre-of-mass energy of 205 GeV
- **SLC** (linear) reached 92 GeV

Studies of future electron-positron colliders
- **ILC**, superconducting linear collider
- **CLIC**, normal conducting linear collider
- **FCC-ee** and **CEPC**, circular collider
- A (circular) **muon collider** is being studied

LHeC and FCC-eh quickly covered
Plasma technology is being considered for linear collider, but long way to go
Gamma-gamma collisions are also being considered
Note: The typical higgs factory energies are close to the cross over in luminosity
Linear collider have polarised beams (80% e\(^-\), ILC also 30% e\(^+\)) and beamstrahlung
• All included in the physics studies
The picture is much clearer at lower or higher energies

Energy dependence:
At low energies circular colliders look good
• Reduction at high energy due to synchrotron radiation

At high energies linear colliders excel
• Luminosity per beam power roughly constant

Electron-positron Luminosity

Luminosity per facility

\[ L \mu P_{\text{synrad}} E_{cm}^{3.5} \]

\[ L \mu P_{RF} \]

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Energy Limit

Circular collider
• Accelerate beam in many turns
• Let beam collide many times
• But synchrotron radiation

At LEP2 lost 2.75 GeV/turn for $E = 105$ GeV

Linear electron-positron collider
• Essentially no synchrotron radiation
• But have to accelerate beams in one pass
• and only collide once, so small beams

Or use heavier particles in circular collider
Muons are 200 times heavier than electrons
But they have a short lifetime (2.2 μs)
Linear Collider Principle

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

- damping ring
- main linac
- detector
- main linac
- damping ring
- e-source
- RTML
- BDS
- BDS
- RTML
- e+ source

\[ \sigma_{x,y} = \frac{\beta_{x,y} \epsilon_{x,y}}{\gamma} \]
SLC: The only Linear Collider that existed

Built to study the $Z^0$ and demonstrate linear collider feasibility

Energy = 92 GeV
Luminosity = 2e30

Has all the features of a 2nd gen. LC except both e+ and e- used the same linac

A 10% prototype!
ILC Scenarios

Waiting for Japan to make a commitment
- Site identified and being investigated
- But executive not yet endorsed project
- Process is going on for many years

Baseline running example
Note: contains up to 500 GeV, which is not part of current baseline proposal
Damping Rings

Polarised electron source

Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>C.M. Energy</td>
<td>250 GeV</td>
</tr>
<tr>
<td>Peak luminosity</td>
<td>$1.35 \times 10^{34}$ cm$^{-2}$s$^{-1}$</td>
</tr>
<tr>
<td>Beam power</td>
<td>5 MW</td>
</tr>
<tr>
<td>Beam Rep. rate</td>
<td>5 Hz</td>
</tr>
<tr>
<td>E gradient</td>
<td>31.5 MV/m +/-20%</td>
</tr>
</tbody>
</table>

Ring to Main Linac (RTML) (including bunch compressors)

31km

e- Main Linac

e+ Main Linac

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# Examples of ILC and CLIC Main Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol [unit]</th>
<th>SLC</th>
<th>ILC</th>
<th>CLIC</th>
<th>CLIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centre of mass energy</td>
<td>$E_{cm}$ [GeV]</td>
<td>92</td>
<td>250</td>
<td>380</td>
<td>3000</td>
</tr>
<tr>
<td>Luminosity</td>
<td>$L$ [$10^{34}$cm$^{-2}$s$^{-1}$]</td>
<td>0.0003</td>
<td>1.35</td>
<td>1.5</td>
<td>6</td>
</tr>
<tr>
<td>Luminosity in peak</td>
<td>$L_{0.01}$ [$10^{34}$cm$^{-2}$s$^{-1}$]</td>
<td>0.0003</td>
<td>1</td>
<td>0.9</td>
<td>2</td>
</tr>
<tr>
<td>Gradient</td>
<td>$G$ [MV/m]</td>
<td>20</td>
<td>31.5</td>
<td>72</td>
<td>100</td>
</tr>
<tr>
<td>Particles per bunch</td>
<td>$N$ [$10^{9}$]</td>
<td>37</td>
<td>20</td>
<td>5.2</td>
<td>3.72</td>
</tr>
<tr>
<td>Bunch length</td>
<td>$\sigma_z$ [$\mu$m]</td>
<td>1000</td>
<td>300</td>
<td>70</td>
<td>44</td>
</tr>
<tr>
<td>Collision beam size</td>
<td>$\sigma_{x,y}$ [nm/nm]</td>
<td>1700/600</td>
<td>516/7.7</td>
<td>149/2.9</td>
<td>40/1</td>
</tr>
<tr>
<td>Vertical emittance</td>
<td>$\varepsilon_{x,y}$ [nm]</td>
<td>3000</td>
<td>35</td>
<td>30</td>
<td>$20^*$</td>
</tr>
<tr>
<td>Bunches per pulse</td>
<td>$n_b$</td>
<td>1</td>
<td>1312</td>
<td>352</td>
<td>312</td>
</tr>
<tr>
<td>Bunch distance</td>
<td>$\Delta z$ [mm]</td>
<td>-</td>
<td>554</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>$f_r$ [Hz]</td>
<td>120</td>
<td>5</td>
<td>50</td>
<td>50</td>
</tr>
</tbody>
</table>

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Main Linac Unit

Accelerating cavities
O(65%) of linac length

Beam guiding quadrupole
Beam position monitor
Corrector kicker

Accelerating cavities
ILC Cavities

Superconducting cavity (Ni at 2 K)
Standing wave structure
RF frequency is 1.3 GHz, 23 cm wavelength
Length is 9 cells = 4.5 wavelengths = 1 m

Pulsed operation:
5 x 1.6 ms pulses per second
Gradient is 31.5 MV/m

In rings typically
• no pulsing
• lower frequencies (400 MHZ in LHC)
• lower gradient (O(<20 MV/m))
Theoretical gradient limit is 50-60 MV/m
- But can quench at lower gradient
- or Q value decreases

Cavities have different performancies
ILC Cavity Treatment

Control of material
- Avoid defects
- Ensure high quality

Electropolishing
- Fill with H₂SO₄, apply current to remove thin surface layer

Bakeout

High pressure rinsing

Novel process found (FNAL): Nitrogen infusion
- Fill cavity at 120°C for a day with low pressure of N₂

Increase in gradient
- Increase in Q₀
- Under test in many labs
5 RF pulses of 1.6 ms per second (1312 bunches in 0.73 ms):

Because field leads to losses in the wall
• About 1 W/m
• With no pulsing losses would be O(100 W/m)

RF power in pulse: \( \frac{5 \text{ MW}}{5 \times 0.73 \text{ ms}} = O(1500 \text{ MW}) = O(150 \text{ klystrons}) \)
Cavities have small losses

\[ P_{\text{loss}} = \text{const} \frac{1}{Q_0} G^2 \]

About 1W/m

But cooling costly at low temperatures

Remember Carnot:

\[ P_{\text{cryo}} = \frac{1}{T_{\text{room}}} \frac{T_{\text{source}}}{T_{\text{source}}} \cdot P_{\text{loss}} \]

\[ P_{\text{cryo}} \quad 700 \quad P_{\text{loss}} \]

The typical heat load of 1 W/m ⇒ about 1 kW/m for cryogenics

Average RF power: 1.6kW/m (3kW/m)
Power into beam about 0.7kW/m
### CLIC Staged Scenario

<table>
<thead>
<tr>
<th>Stage</th>
<th>$\sqrt{s}$ [TeV]</th>
<th>$\mathcal{L}_{\text{int}}$ [ab$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.38 (and 0.35)</td>
<td>1.0</td>
</tr>
<tr>
<td>2</td>
<td>1.5</td>
<td>2.5</td>
</tr>
<tr>
<td>3</td>
<td>3.0</td>
<td>5.0</td>
</tr>
</tbody>
</table>

Luminosity targets from Physics Study group
Hopefully input from LHC

#### Luminosity evolution

Lower gradient optimum for lower energy
CLIC: The Basis

Stages at $E_{\text{cms}}=0.38$, 1.5 and 3TeV $L=6 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$ at 3TeV

Beam power 30MW at 3TeV
CLIC Accelerating Structure

12 GHz, 23 cm long, normal conducting
Loaded gradient 100 MV/m
⇒ Allows to reach higher energies
⇒ 140,000 structures at 3 TeV

But strong losses in the walls
⇒ 50 RF bursts per second
⇒ 240 ns, 60 MW, 312 bunches
⇒ Power during pulse $8.5 \times 10^6$ MW (3000 x ILC)

Power flow
- 1/3 lost in cavity walls
- 1/3 in filling the structure and into load
- 1/3 into the beam

Average RF power about 3 kW/m
About 1 kW/m into beam
CLIC Gradient Limitations

Breakdowns (discharges during the RF pulse)
• Require \( p \leq 3 \times 10^{-7} \text{ m}^{-1} \text{pulse}^{-1} \)

Structure design based on empirical constraints, not first principle
• Maximum surface field
• Maximum temperature rise
• Maximum power flow

R&D programme established gradient \( O(100 \text{ MV/m}) \)

Shorter pulses have fewer breakdowns
CLIC Two-beam Concept

100 A drive beam

1.2 A main beam

Total instantaneous power of $O(10\text{TW})$
CLIC Two-beam Module

80 % filling with accelerating structures
11 km for 380 GeV cms
50 km for 3 TeV

1st module
CLIC: The Basis

Drive Beam Accelerator
- acceleration in fully loaded linac

Delay Loop × 2
- gap creation, pulse compression & frequency multiplication

RF Transverse Deflectors

Combiner Ring × 4

Drive Beam Decelerator Section (2 × 24 total)

Power Extraction

Drive Beam

circuit lengths
- CR1 293 m
- CR2 439 m

540 klystrons
- 20 MW, 148 μs

Drive Beam Decelerator

2.5 km

Drive Beam Accelerator
- 2.4 GeV, 1.0 GHz
Luminosity and Parameter Drivers

Can re-write normal luminosity formula

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

\[ \mathcal{L} \propto H_D \] \[
\frac{N}{\sigma_x} \quad \frac{N n_b f_r}{\sigma_y} \quad \frac{1}{\sigma_y} \]

Luminosity spectrum
Beam power
Beam Quality (+bunch length)

Need to ensure that one can achieve each parameter

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Beam-beam Effect

Dense beams focus each other
⇒ emitt beamstrahlung

\[ L \propto H_D \left( \frac{N}{\sigma_y} \right) N n_b f_r \frac{1}{\sigma_y} \]

Typically aim for O(1)

\[ n_\gamma \propto E_\gamma \propto \frac{N}{\sigma_x + \sigma_y} \]

\[ \sigma_x \gg \sigma_y \quad \sigma_x + \sigma_y \approx \sigma_x \]
Note: Technology Transfer

The technology developed for linear colliders is useful for other fields, e.g.

- FELs (Examples: European X-FEL in Hamburg, LCLS at SLAC, SACLA in Japan, Swiss FEL, ...)
- Medical facilities
- Safety
- Industrial applications
Note: Gamma-gamma Collider Concept

Based on $e^+e^-$ collider

Collide electron beam with laser beam before the IP

Backscattered photons form a spectrum

Practical maximum energy is 83% of electron energy

Luminosity
Plasma can be generated by electron beam, proton beam or laser beam

50 GV/m demonstrated with 42 GeV energy gain


- Practical solution for efficient acceleration of positrons has to be developed
- Efficiency and beam quality have severe challenges
- Strong plasma focusing is good for beam stability but generates synchrotron radiation
- Application in other fields seem promising, e.g. free electron laser
FCC-ee
Electron-positron collider in the FCC-hh tunnel

Operation at different energies

Synchrotron radiation leads to strong dependence of beam current and luminosity on energy (100 MW limit)

\[ \Delta E \propto \left( \frac{E}{m} \right)^4 \frac{1}{R} \]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Z</th>
<th>WW</th>
<th>ZH</th>
<th>tt</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E_{\text{cm}} ) [GeV]</td>
<td>91.2</td>
<td>160</td>
<td>240</td>
<td>365</td>
</tr>
<tr>
<td>I [mA]</td>
<td>1390</td>
<td>147</td>
<td>29</td>
<td>5.4</td>
</tr>
<tr>
<td>( L ) ([10^{34} \text{ cm}^{-2}\text{s}^{-1}])</td>
<td>200</td>
<td>25</td>
<td>7</td>
<td>1.4</td>
</tr>
<tr>
<td>Years</td>
<td>4</td>
<td>1</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Int. L. ([\text{ab}^{-1}])</td>
<td>2 x 78</td>
<td>2 x 3.5</td>
<td>2 x 2.7</td>
<td>2 x 0.18</td>
</tr>
</tbody>
</table>

Short beam lifetime requires top-up injection

vertical beam size \(O(30-70 \text{ nm})\)
Top-up Injection

Beam lifetime is short (18-200 minutes)

- Bremsstrahlung
- Beamstrahlung
- ...

\[ \tau_{ee} \propto \frac{I}{L\sigma_{ee}n_{ip}} \]

Have to refill beam permanently

\( \Rightarrow \) top-up injection with booster ring
5 energy stages
Each year 8 months of operation / 4 months winter shutdown
• hardware upgrades during shutdown
Only 1 year-long shutdown to got for top
Need a crossing angle at IP
Cannot bend beams close to IP
Requires additional tunnel

Very short beam lifetime
requires top-up injection, i.e. booster ring
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

Four-cell cavities at high energy:
• Low current but high voltage

High frequency at highest energies

Efficient klystrons, based on design ideas for CLIC

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Muon Collider
CLIC is at the limit of what one can do (decades of R&D)
- No obvious way to improve

Muon collider
- Power efficient
  - Luminosity per beam power increases with energy
- Site is compact
  - 10 TeV comparable to 3 TeV CLIC
- Staging is natural
  - acceleration by a factor of a few is done in rings
- Appears to promise cost effectiveness
  - but need detailed study
- Other synergies exist (neutrino/higgs

Muon collider promises unique opportunity for a high-energy, high-luminosity lepton collider

Main challenge muons are not stable (2.2 μs at rest)
Proton-driven Muon Collider Concept

The muon collider has been developed by the MAP collaboration mainly in the US. Muon cooling demonstration by MICE in the UK, some effort on alternative mainly at INFN.

Protons produce pions. Pions decay to muons.

Short, intense proton bunches to produce hadronic showers.

Muon are captured, bunched and then cooled by ionisation cooling in matter.

Acceleration to collision energy.

Collision

Not as mature as linear collider, but performing study to make informed decision by 2025.
**Luminosity Goals**

<table>
<thead>
<tr>
<th>$\sqrt{s}$ (TeV)</th>
<th>$\int L dt$ (ab$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>14</td>
<td>20</td>
</tr>
</tbody>
</table>

**Target integrated luminosities**

**Tentative target parameters Scaled from MAP parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>3 TeV</th>
<th>10 TeV</th>
<th>14 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L$</td>
<td>$10^{34}$ cm$^{-2}$s$^{-1}$</td>
<td>1.8</td>
<td>20</td>
<td>40</td>
</tr>
<tr>
<td>$N$</td>
<td>$10^{12}$</td>
<td>2.2</td>
<td>1.8</td>
<td>1.8</td>
</tr>
<tr>
<td>$f_r$</td>
<td>Hz</td>
<td>5.3</td>
<td>5.3</td>
<td>5.3</td>
</tr>
<tr>
<td>$P_{beam}$</td>
<td>MW</td>
<td>5.3</td>
<td>14.4</td>
<td>20</td>
</tr>
<tr>
<td>$C$</td>
<td>km</td>
<td>4.5</td>
<td>10</td>
<td>14</td>
</tr>
<tr>
<td>$&lt;B&gt;$</td>
<td>T</td>
<td>7</td>
<td>10.5</td>
<td>10.5</td>
</tr>
<tr>
<td>$\varepsilon_L$</td>
<td>MeV m</td>
<td>7.5</td>
<td>7.5</td>
<td>7.5</td>
</tr>
<tr>
<td>$\sigma_E/E$</td>
<td>%</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>$\sigma_z$</td>
<td>mm</td>
<td>5</td>
<td>1.5</td>
<td>1.07</td>
</tr>
<tr>
<td>$\beta$</td>
<td>mm</td>
<td>5</td>
<td>1.5</td>
<td>1.07</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>μm</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>$\sigma_{x,y}$</td>
<td>μm</td>
<td>3.0</td>
<td>0.9</td>
<td>0.63</td>
</tr>
</tbody>
</table>

**Comparison: CLIC at 3 TeV: 28 MW**

**Long-term development**

Aim to have muon collider as option for the next European project (or in some other region), if required (e.g. higgs factory somewhere else)
MAP collaboration

Limit muon decay, cavities with **high gradient in a magnetic field**

tests much better than design

**Compact integration** to minimise muon loss

Minimise betafunction with **strongest solenoids (40+ T)**

32 T achieved, 40+ T planned

\[
\frac{d\epsilon_\perp}{ds} = -\frac{1}{(v/c)^2} \frac{dE}{ds} \frac{\epsilon_\perp}{E} + \frac{1}{2} \frac{1}{(v/c)^3} \left( \frac{14 \text{ MeV}}{E} \right)^2 \frac{\beta \gamma}{L_R}
\]
Cooling: The Emittance Path

- **Specification**
  - For acceleration to multi-TeV collider

- **Final Cooling**
  - For acceleration to Higgs Factory

- **Bunch Merge**

- **pre-merge 6D Cooling**

- **post-merge 6D Cooling**

- **Exit Front End (15mm, 45mm)**

- **Target Phase Rotator**

- **MAP collaboration**

D. Schulte, Accelerator Technologies

CERN-Fermilab HCP Summer School 2021
Cavities with very high accelerating gradient in strong magnetic field

Very strong solenoids (> 30 T) for the final cooling

- simplified: Luminosity is proportional to the field

Integrated system test

MuCool: >50 MV/m in 5 T field

Two solutions

- Copper cavities filled with hydrogen
- Be end caps

NHFML
32 T solenoid with low-temperature HTS

We would like to push even further

Plans for 40+ T exist

MICE (UK)

D. Schulte, Accelerator Technologies
MICE (in the UK)

Principle of ionisation cooling has been demonstrated

More particles at smaller amplitude after absorber is put in place

More complete experiment with higher statistics, more than one stage required

Integration of magnets, RF, absorbers, vacuum is engineering challenge

Nature volume 578, pages 53-59 (2020)
LHeC/FCC-eh
LHeC / FCC-eh

Development of accelerator technology
E.g. RF power required to control cavities

Test facility (PERLE) planned in Orsay

<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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</thead>
<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>$L \cdot 10^{33} \text{cm}^{-2} \text{s}^{-1}$</td>
<td>1</td>
<td>8</td>
<td>12</td>
<td>15</td>
</tr>
</tbody>
</table>

Interaction region
design ongoing

M. Klein et al
Conclusion and Thanks

• Touched only a small part of the exciting accelerator technologies
• Quite some work ahead to develop and the future colliders
• ILC and CLIC are mature
• FCC-ee and CEPC are being developed
  – FCC-ee for next European Strategy
  – In the long run FCC-hh can follow
• Muon collider is less mature but would offers a long-term lepton path
• Plasma-based colliders are more speculative at this moment
• LHeC would offer electron proton collisions

Many thanks to Reende Steerenberg, Steinar Stapnes, Lucio Rossi, Mark Palmer, Ralph Assmann, Jean-Pierre Delahaye, Lucie Linssen, Steffen Doebert, Alexej Grudiev, Frank Tecker, Walter Wuensch, Stephane Poss, Jan Strube, Joerg Wenninger, M. Benedikt, Frank Zimmermann, Bernhard Holzer, Roberto Kersevan, Ph. Lebrun, ...

If you can look into the seeds of time, And say which grain will grow and which will (Shakespeare)
CLIC Test Facility (CTF3)
Drive Beam Combination in CTF3

Note: Efficiencies
RF to drive beam >95%
Drive beam to RF >95%

Total efficiency wall plug to main beam is about 10%

Measured accelerating gradient

Maximum gradient 145 MV/m

Accelerating gradient (MV/m)

Power in accelerating structure (MW)
# LHeC / FCC-eh Parameters

<table>
<thead>
<tr>
<th>parameter [unit]</th>
<th>LHeC CDR</th>
<th>ep at HL-LHC</th>
<th>ep at HE-LHC</th>
<th>FCC-he</th>
</tr>
</thead>
<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>$\sqrt{s}$ [TeV]</td>
<td>1.3</td>
<td>1.3</td>
<td>1.7</td>
<td>3.5</td>
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<tr>
<td>bunch spacing [ns]</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td>25</td>
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<tr>
<td>protons per bunch [$10^{11}$]</td>
<td>1.7</td>
<td>2.2</td>
<td>2.5</td>
<td>1</td>
</tr>
<tr>
<td>$\gamma \epsilon_p$ [$\mu$m]</td>
<td>3.7</td>
<td>2</td>
<td>2.5</td>
<td>2.2</td>
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<td>electrons per bunch [$10^9$]</td>
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<td>2.3</td>
<td>3.0</td>
<td>3.0</td>
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<tr>
<td>electron current [mA]</td>
<td>6.4</td>
<td>15</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>IP beta function $\beta_p^*$ [cm]</td>
<td>10</td>
<td>7</td>
<td>10</td>
<td>15</td>
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<tr>
<td>hourglass factor $H_{geom}$</td>
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<td>0.9</td>
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<td>pinch factor $H_{b-b}$</td>
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<td>1.3</td>
<td>1.3</td>
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<td>proton filling $H_{coll}$</td>
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<td>luminosity [$10^{33}$cm$^{-2}$s$^{-1}$]</td>
<td>1</td>
<td>8</td>
<td>12</td>
<td>15</td>
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</tbody>
</table>
LHeC and FCC-eh Reports

Design of LHeC documented in report 2012, updated planned next year
Design for FCC-eh is similar, except of interaction region
# Key FCC-ee Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Z</th>
<th>WW</th>
<th>H (ZH)</th>
<th>ttbar</th>
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<tbody>
<tr>
<td>beam energy [GeV]</td>
<td>45</td>
<td>80</td>
<td>120</td>
<td>182.5</td>
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<td>beam current [mA]</td>
<td>1390</td>
<td>147</td>
<td>29</td>
<td>5.4</td>
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<tr>
<td>no. bunches/beam</td>
<td>16640</td>
<td>2000</td>
<td>393</td>
<td>48</td>
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<tr>
<td>bunch intensity $[10^{11}]$</td>
<td>1.7</td>
<td>1.5</td>
<td>1.5</td>
<td>2.3</td>
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<tr>
<td>SR energy loss / turn [GeV]</td>
<td>0.036</td>
<td>0.34</td>
<td>1.72</td>
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<tr>
<td>total RF voltage [GV]</td>
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<td>0.44</td>
<td>2.0</td>
<td>10.9</td>
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<tr>
<td>long. damping time [turns]</td>
<td>1281</td>
<td>235</td>
<td>70</td>
<td>20</td>
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<tr>
<td>horizontal beta* [m]</td>
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<td>0.2</td>
<td>0.3</td>
<td>1.0</td>
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<tr>
<td>vertical beta* [mm]</td>
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<td>1.0</td>
<td>1.6</td>
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<td>horiz. geom. emit. [nm]</td>
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<td>0.28</td>
<td>0.63</td>
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<td>vert. geom. emit. [pm]</td>
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<td>1.7</td>
<td>1.3</td>
<td>2.9</td>
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<tr>
<td>bunch length w. SR / BS [mm]</td>
<td>3.5 / 12.1</td>
<td>3.0 / 6.0</td>
<td>3.3 / 5.3</td>
<td>2.0 / 2.5</td>
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<tr>
<td>L per IP $[10^{34} \text{ cm}^{-2} \text{s}^{-1}]$</td>
<td>$&gt;200$</td>
<td>$&gt;25$</td>
<td>$&gt;7$</td>
<td>$&gt;1.4$</td>
</tr>
<tr>
<td>lifetime Bhabha / BS [min]</td>
<td>68 / $&gt;200$</td>
<td>49 / $&gt;1000$</td>
<td>38 / 18</td>
<td>40 / 18</td>
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</table>
Different layout options are being studied
Different optimisation to FCC-hh
but maintaining FCC-hh

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<td>13058</td>
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<td>10256</td>
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<td>2.0</td>
<td>1.45 (km)</td>
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