Future High-Energy Collider Projects I

D. Schulte
Introduction

• What will be the next high energy frontier project for particle physics?
• What will be the next high energy frontier project for Europe (and CERN)?

• Actually, we do not know

• There is a process ongoing “European Strategy for Particle Physics” to figure out what to do
  – Proposals have been sent in by end of last year
  – Selected presentations were given in Granada this year
  – A summary document is being prepared by September
  – Recommendation report writing will start next January
  – Results will be known and approved by council May 2020

• I will present candidates for future colliders
Previous European Strategy

Conclusion in 2012

• Highest priority is exploitation of the LHC including luminosity upgrades

• Europe should be able to propose an ambitious project after the LHC
  – Either a high energy proton collider (FCC-hh) with lepton collider (FCC-ee) as potential (now likely) intermediate step
  – Or a high energy linear lepton collider (CLIC)

• Europe welcomes Japan to make a proposal to host ILC

• Long baseline neutrino facility (not covered here)

New process ongoing 2018-2020
Decision expected in May 2020
Collaborations

Work is done in collaborations

Global collaborations for FCC and CLIC

Also for ILC

Some collaboration for CEPC / SppC

FCC Collaboration

- 74 institutes
- 26 countries + EC

Collaborations are still dynamic

A way to contribute to a project while not at CERN
Considered High Energy Frontier Collider

Circular colliders:
- **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
  - HE-LHC: Stronger magnets in LHC tunnel
  - Lower field version of FCC-hh
- **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

Mentioned
- Muon collider, past effort in US, maybe new interest in Europe
- Plasma acceleration in linear collider
- Photon-photon collider
- LHeC
## Key Collider Considerations

<table>
<thead>
<tr>
<th>Physics potential</th>
<th>Particle type</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>The collider energy</td>
</tr>
<tr>
<td></td>
<td>The collider luminosity</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Feasibility</th>
<th>The technical maturity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>The risk</td>
</tr>
<tr>
<td></td>
<td>The schedule</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Affordability</th>
<th>The collider cost</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>The collider power consumption</td>
</tr>
<tr>
<td></td>
<td>Availability of site</td>
</tr>
</tbody>
</table>
## Comparisons

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<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>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>

D. Schulte

Future High-energy Colliders, CERN 2019
Collider 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
  - Electrons, positrons and probably muons
  - Collision process known
  - Well defined energy
  - Less background
  - Lepton collisions $\Rightarrow$ precision measurements

- Photons also possible
Energy Limit

Hadron collider is typically circular
Maximum energy defined by ability to keep particle on circular orbit

Required radius $R$ of the ring is given by

$$R \mu \frac{E}{B}$$

⇒ Make magnetic field $B$ of bending dipoles as big as possible

Very convenient
• Accelerate beam in many turns
• Let beam collide many times

Electron-positron colliders have been mostly circular so far (one exception)

Energy (and luminosity) are limited by synchrotron radiation

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

Electrons are 2000 time lighter than protons
At LEP2 lost 2.75GeV/turn for $E=105$GeV
Solutions for Leptons

Use a linear collider
- Essentially no synchrotron radiation
- But
  - Have to accelerate beams rapidly
  - Only collide once

Hence challenges
- High accelerating gradient
- Small beams at collision

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

Or use heavier particles
Muons are 200 times heavier than electrons
But they have a short lifetime
Electron-positron Luminosity

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.
Linear Colliders
Damping Rings
Polarised electron source

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

e- Main Linac
e+ Main Linac

E+ source

31km

Parameters | Value
---|---
C.M. Energy | 250 GeV
Peak luminosity | $1.35 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
Beam power | 5 MW
Beam Rep. rate | 5 Hz
E gradient | $31.5 \text{ MV/m} \pm 20\%$
Accelerating cavities O(65%) of linac length
Beam guiding quadrupole
Beam position monitor
Corrector kicker

Total length for 500 GeV cms 31 km, some length for beam cleaning and focusing
Superconducting cavity (Ni at 2 K)

RF frequency is 1.3 GHz, 23 cm wavelength

Length is 9 cells = 4.5 wavelengths = 1 m

Standing wave structure

Gradient is 31.5 MV/m

Need about 8000 cavities
Theoretical gradient limit is 50-60 MV/m
• But can quench at lower gradient

Cavity quality $Q_0$ degrades for high gradients
Each one is different
ILC Cavity Treatment

Control of material
Avoid defects
Ensure high quality

Electropolishing
-> fill with $\text{H}_2\text{SO}_4$, apply current to remove thin surface layer

Novel process found (FNAL): **Nitrogen infusion**
Fill cavity at 120°C for a day with low pressure of $\text{N}_2$

Increase in gradient
Increase in $Q_0$
Under test in many labs

D. Schulte

Future High-energy Colliders, CERN 2019
ILC Achieved Gradient

From N. Walker
Note: Pulsed Operation

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) times worse

RF power in pulse: $5 \text{ MW} / (5 \times 0.73 \text{ ms}) = O(1500 \text{ MW}) = O(150 \text{ klystrons})$
Note: Cryogenics

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:

\[ P_{\text{cryo}} = \frac{1}{T_{\text{room}}} \frac{T_{\text{source}}}{T_{\text{source}}} P_{\text{loss}} \]
\[ P_{\text{cryo}} = 700 \quad P_{\text{loss}} \]

The typical heat load of 1 W/m \( \Rightarrow \) about 1 kW/m for cryogenics

Average RF power: 1.6kW/m (3kW/m)
Power into beam about 0.7kW/m
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: The Basis

Goal: Lepton energy frontier

Drive Beam Generation Complex

Stages at $E_{\text{cms}}=0.38$, 1.5 and 3TeV
$L=6\times10^{34}\text{cm}^{-2}\text{s}^{-1}$ at 3TeV
Beam power 30MW at 3TeV
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 MV/m)

Shorter pulses have less breakdowns
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
CLIC: The Basis

Drive Beam Generation Complex

540 klystrons 20 MW, 148 μs

Drive Beam Accelerator
acceleration in fully loaded linac

2.4 GeV, 1.0 GHz

2.5 km

DRF Transverse Deflectors

Combiner Ring × 4

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

Combiner Ring × 3

Drive Beam Decelerator Section (2 × 24 total)

Power Extraction

Drive Beam Generation Complex

circumferences delay loop 73 m
CR1 293 m
CR2 439 m

Drive Beam Accelerator
2.4 GeV, 1.0 GHz

drive beam accelerator 540 klystrons 20 MW, 148 μs

540 klystrons 20 MW, 148 μs

drive beam accelerator 2.4 GeV, 1.0 GHz

2.5 km
CLIC Test Facility (CTF3)

D. Schulte

Future High-energy Colliders, CERN 2019
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%

Maximum gradient 145 MV/m
# 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>

D. Schulte  
Future High-energy Colliders, CERN 2019
Luminosity and Parameter Drivers

Can re-write normal luminosity formula

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

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

Need to ensure that we can achieve each parameter

Luminosity spectrum

Beam power

Beam Quality (+bunch length)
Beam-beam Effect

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

Dense beams to reach high luminosity
Beam focus each other

\[ \mathcal{L} \propto \frac{N}{\sigma_x \sigma_y} \]

\[ \sigma_x \gg \sigma_y \quad \sigma_x + \sigma_y \approx \sigma_x \]

Beam-beam force off

Beam-beam force on
Beam-beam Effect

\[ \mathcal{L} \propto N_n f_r \left( \frac{N}{\sigma_x} \right) \frac{1}{\sigma_y} \]

Emitt beamstrahlung
Develop luminosity spectrum

\[ \mathcal{L} \propto \frac{N}{\sigma_x \sigma_y} \]

Typically aim for O(1)

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

\[ \sigma_x \gg \sigma_y \quad \sigma_x + \sigma_y \approx \sigma_x \]

Beam-beam force on

D. Schulte
Future High-energy Colliders, CERN 2019
Beam Quality

- Cannot cover the very rich field of studies

- Address the issue by
  - Clever system design
  - Clever tuning algorithms
  - Technical development of components
  - Experiments
**Example: Wakefields**

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

Wakefields can lead to instability/emittance growth

This effect is larger in higher frequency structures, hence \( N=2\times10^{10} \) vs. \( N=4\times10^9 \)

D. Schulte

Future High-energy Colliders, CERN 2019
Example Issue: Ground Motion at CLIC

\[ \mathcal{L} \propto H_D \frac{N}{\sigma_x} \frac{N n_b f_T}{\sigma_y} \]

Time: 0.02 s

- B10

\( \text{ground motion [}\mu\text{m]} \)
\( \text{position [km]} \)

ML. \( e^- \)  IP  ML. \( e^+ \)

J. Pfingstner

D. Schulte  Future High-energy Colliders, CERN 2019 36
Resulting Beam Jitter

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

- Time: 0.02 s
- GM B10
- Beam motion

D. Schulte

Future High-energy Colliders, CERN 2019
Beams at Collision

\[ \mathcal{L} \propto H_D \frac{N}{\sigma_x} N_{nbf_T} \left( \frac{1}{\sigma_y} \right) \]

Time: 0.00s

- B10, no PRE
- IPFB, OFB
- no STAB

x offset

y offset

J. Pfingstner
Stabilisation System

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

K. Artoos et al.

J. Snuverink, et al.

D. Schulte
Future High-energy Colliders, CERN 2019
Impact of Stabilisation on Beam

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

Time: 0.02 s

- GM B10
- Beam motion
- Beam motion, STAB, OFB

J. Pfingstner
Beam at Collision

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

Time: 0.00s

- B10, no PRE
- IPFB, OFB
- no STAB

- B10, PRE
- IPFB, OFB
- curr. STAB

\[ x \text{ offset} \]

\[ y \text{ offset} \]
Beam at Collision

\[ \mathcal{L} \propto H_D \left( N \frac{1}{\sigma_x} \frac{N n_b f_{\pi}}{\sigma_y} \right) \]

- B10, no PRE, IPFB, OFB, no STAB
- B10, PRE, IPFB, OFB, curr. STAB
- B10, PRE, IPFB, OFB, future STAB

Time: 0.00s

x offset

y offset
Active Stabilisation Results

Luminosity achieved/lost [%]

<table>
<thead>
<tr>
<th></th>
<th>B10</th>
</tr>
</thead>
<tbody>
<tr>
<td>No stab.</td>
<td>53%/68%</td>
</tr>
<tr>
<td>Current stab.</td>
<td>108%/13%</td>
</tr>
<tr>
<td>Future stab.</td>
<td>118%/3%</td>
</tr>
</tbody>
</table>

Close to/better than target

Machine model
Beam-based feedback

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

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

Instrumentation
Further improvements

Active alignment
Further improvements

New module design
Reduce cost of mechanical system and control

Klystron-based first energy stage
As alternative

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

And many more ...
Luminosity targets from Physics Study group
Hopefully input from LHC

<table>
<thead>
<tr>
<th>Stage</th>
<th>$\sqrt{s}$ [TeV]</th>
<th>$L_{\text{int}}$ [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>

Lower gradient optimum for lower energy
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
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

\[
x = \frac{4E_0\hbar\omega_0}{m^2c^4}
\]

\[
\hbar\omega_m = \frac{x}{x + 1} E_0
\]
Plasma can be generated by electron beam, proton beam or laser beam

See also additional slides
Examples of Achieved Accelerations

Using SLC beam $L=0.85\text{m}$, $G=\mathcal{O}(50 \text{ GV/m})$  
$\Rightarrow 42 \text{ GeV}$

E167 collaboration SLAC, UCLA, USC  

Using laser beam to generate the plasma at Berkeley  
$\Rightarrow 1\text{GeV}$

Driving plasma with protons is planned in AWAKE  
Using a proton bunch to create many minibunches

Example: Beam-driven Plasma Collider (PWFA)

Main e-beam (CW):
- \( Q = 1.0 \times 10^{10} e^- @ 15 \text{ kHz} \)
- \( P_{\text{beam}} = 12 \text{ MW} \)

20 plasma stages, \( \Delta E = 25 \text{ GeV} \) each stage

Magnetic chicanes: 4 ns delay

Main e-plasma acceleration (0.5 km)

Injection every half turn, \( C = 1000 \text{ m}, P_{\text{loss}}/P_{\text{beam}} = 8\% \)

Main e+ plasma acceleration (0.5 km)

Magnetic chicanes: 4 ns delay

Accumulator ring

4 passes Recirculating SRF CW linacs
- Each linac: 3.16 GeV, 19 MV/m, 250 m
- Each arc: 437.5 m

Drive beam after accumulation:
- Trains of 20 bunches, 4 ns apart @ 15 kHz

DB dump

\( \Delta z_{\text{DB,WS}} \approx 187 \text{ um} \) @ injection

Drive beam (CW):
- \( E = 25 \text{ GeV}, Q = 2.0 \times 10^{10} e^- @ 15 \times 40 \text{ kHz} \)
- \( P_{\text{beam,initial}} = 2 \times 24 \text{ MW} \)

A Beam Driven Plasma-Wakefield Linear Collider:
From Higgs Factory to Multi-TeV
Summarized for CSS2013

E. Adli, J.P. Delahaye, S.J. Gessner, M.J. Hogan, T. Raubenheimer (SLAC)
W. An, C. Joshi, W. Mori (UCLA)
Plasma Collider Issues

- Practical solution for acceleration of positrons is missing
- Efficiency and beam quality has to be addressed
- Significant effort needed to arrive at a paper design
- Need very important technology development to make it real
- A long-term effort
References

ILC

These papers and supporting documents in:
https://ilchome.web.cern.ch/content/ilc-european-strategy-document

More about ILC: https://ilchome.web.cern.ch

CLIC

These paper and supporting documents in:
https://clic.cern/european-strategy

More about CLIC: https://clic.cern
CLIC detector concepts are based on SiD and ILD. Modified to meet CLIC requirements.
Linear Collider Experiment

10⁹ readout cells

Field return and muon particle identification

Final steering of nm-size beams

B-field for momentum and charge measurement

Energy measurement of (charged and) neutral particles

Measure momentum and charge of charged particles

Measure vertex and Short-lived particles

B-field for momentum and charge measurement

Energy measurement of (charged and) neutral particles

Measure momentum and charge of charged particles

Field return and muon particle identification

Final steering of nm-size beams

Measure vertex and Short-lived particles
Lepton Pair Production

Colliding Photons can produce electron-positron pairs (incoherent pair production) $O(10^5)$ per bunch crossing

Beamstrahlung photons can turn into pair in strong field (coherent pair production) $O(1-10^8)$ per bunch crossing

Breit–Wheeler process

Bethe–Heitler process

Landau–Lifshitz process

Trident cascade

Macroscopic field

D. Schulte
Future High-energy Colliders, CERN 2019
Spent beam particles

Beamstrahlung

Coherent pairs

Trident cascade pairs

Incoherent pairs

Hadrons

...
Spent Beam Divergence

Beam particles are focused by oncoming beam

Photons are radiated into direction of beam particles

Coherent pair particles can be focused or defocused by the beams but deflection limited due to their high energy

-> Extraction hole angle should be significantly larger than 6 mrad

We chose 10 mrad for CLIC

-> 20 mrad crossing angle

ILC requires 14 mrad crossing angle

D. Schulte

Future High-energy Colliders, CERN 2019
The last focusing magnet of the machine is inside of the detector.
Inner Detector Layout

For the beam

To fit the quadrupole

10mradian

A. Seiler
Incoherent Pairs

Breit–Wheeler process

Bethe–Heitler process

Landau–Lifshitz process

\[ r B_z \]

\[ \vartheta_0 \]

\[ \rho_t \text{ [MeV/c]} \]

\[ \theta \text{ [radian]} \]

\[ x \text{ [m]} \]

\[ s \text{ [m]} \]

Not to scale
Vertex Detector Design

FTDs

ECal  LumiCal BeamCal

SITs  TPC Endplate

Have to avoid backscattering

Full simulation shows 1.5 hits/mm²

A. Seiler, D. Dannheim
Hadronic Background

Only events used with

\[ W_{\gamma\gamma} \geq 5 \text{ GeV} \]

Most energy is in forward/backward direction

- \( E_{\text{vis}} \approx 450\text{ GeV} \) per hadronic event
- \( E_{\text{vis}} \approx 23\text{ GeV} \) for \( \theta > 0.1 \)
- \( E_{\text{vis}} \approx 12\text{ GeV} \) for \( \theta > 0.2 \)
- 20% from \( e^+e^- \) (cannot be reduced)

Adds about 20% charged hits in the inner layer of the vertex detector

Can be used to monitor luminosity

![Diagram](image.png)

![Graph](graph.png)
PandoraNewPFAs

1 TeV Z=\rightarrow qqbar

1.4 TeV of background!

M. Thomson. J. Marshall

with 60 BX background
LooseSelectedPandoraNewPFAs

0.3 TeV of background
SelectedPandoraNewPFAs

0.2 TeV of background
TightSelectedPandoraNewPFAs

0.1 TeV of background
Impact of timing cuts on jets

Impact of the PFOSelector timing cuts on the jet energy resolution

<table>
<thead>
<tr>
<th>$E_{\text{jet}}$ [GeV]</th>
<th>45</th>
<th>100</th>
<th>250</th>
<th>500</th>
</tr>
</thead>
<tbody>
<tr>
<td>no cut</td>
<td>3.98 ± 0.05</td>
<td>3.15 ± 0.04</td>
<td>3.00 ± 0.04</td>
<td>3.26 ± 0.06</td>
</tr>
<tr>
<td>loose cut</td>
<td>4.40 ± 0.06</td>
<td>3.34 ± 0.04</td>
<td>3.08 ± 0.04</td>
<td>3.29 ± 0.06</td>
</tr>
<tr>
<td>default cut</td>
<td>5.15 ± 0.07</td>
<td>3.64 ± 0.05</td>
<td>3.17 ± 0.04</td>
<td>3.33 ± 0.06</td>
</tr>
<tr>
<td>tight cut</td>
<td>5.95 ± 0.08</td>
<td>3.99 ± 0.05</td>
<td>3.30 ± 0.04</td>
<td>3.37 ± 0.06</td>
</tr>
</tbody>
</table>
Beam-Induced Background Summary

- **Beamstrahlung**
  - Disappear in the beam pipe

- **Coherent pairs**
  - Largely disappear in beam pipe

- **Incoherent pairs**
  - Suppressed by strong solenoid-field

- **Hadronic events**
  - Impact reduced by time stamping

- **Muon background from upstream linac**
  - Not discussed here

---

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>CLIC</th>
<th>CLIC</th>
<th>ILC (RDR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{\text{cm}}$</td>
<td>[TeV]</td>
<td>0.5</td>
<td>3.0</td>
<td>0.5</td>
</tr>
<tr>
<td>$f_{\text{rep}}$</td>
<td>[Hz]</td>
<td>50</td>
<td>50</td>
<td>5</td>
</tr>
<tr>
<td>$n_b$</td>
<td>[ns]</td>
<td>354</td>
<td>312</td>
<td>2625</td>
</tr>
<tr>
<td>$\Delta t$</td>
<td></td>
<td>0.5</td>
<td>0.5</td>
<td>369</td>
</tr>
<tr>
<td>$L_{\text{total}}$</td>
<td>$[10^{34}\text{cm}^{-2}\text{s}^{-1}]$</td>
<td>2.3</td>
<td>5.9</td>
<td>2.0</td>
</tr>
<tr>
<td>$L_{0.01}$</td>
<td>$[10^{34}\text{cm}^{-2}\text{s}^{-1}]$</td>
<td>1.4</td>
<td>2.0</td>
<td>1.45</td>
</tr>
<tr>
<td>$n_\gamma$</td>
<td></td>
<td>1.3</td>
<td>2.2</td>
<td>1.3</td>
</tr>
<tr>
<td>$\Delta E/E$</td>
<td></td>
<td>0.07</td>
<td>0.29</td>
<td>0.024</td>
</tr>
<tr>
<td>$N_{\text{coh}}$</td>
<td>$[10^5]$</td>
<td>$10^{-3}$</td>
<td>$3.8 \times 10^3$</td>
<td>—</td>
</tr>
<tr>
<td>$E_{\text{coh}}$</td>
<td>$[10^3\text{TeV}]$</td>
<td>0.015</td>
<td>$2.6 \times 10^5$</td>
<td>—</td>
</tr>
<tr>
<td>$n_{\text{incoh}}$</td>
<td>$[10^6]$</td>
<td>0.08</td>
<td>0.3</td>
<td>0.1</td>
</tr>
<tr>
<td>$E_{\text{incoh}}$</td>
<td>$[10^6\text{GeV}]$</td>
<td>0.36</td>
<td>22.4</td>
<td>0.2</td>
</tr>
<tr>
<td>$n_\perp$</td>
<td></td>
<td>20.5</td>
<td>45</td>
<td>28</td>
</tr>
<tr>
<td>$n_{\text{had}}$</td>
<td></td>
<td>0.19</td>
<td>2.7</td>
<td>0.12</td>
</tr>
</tbody>
</table>
These images are derived from the simulation models for the CDR
Linear Collider
Some Detailed Issues
Ground Motion and Its Mitigation

Natural ground motion can impact the luminosity
• typical quadrupole jitter tolerance $O(1 \text{nm})$ in main linac and $O(0.1 \text{nm})$ in final doublet

$\rightarrow$ develop stabilisation for beam guiding magnets
CLIC: Why 100 MV/m and 12 GHz?

- Optimisation 1
  - Luminosity per linac input power

- Optimisation 2
  - Total project cost
Parameter and Structure Choice

- Potential structures designs
- Beam physics constraints
- RF limitations
- Parameter set
- Cost model
- Design choice

Physics requirements

Structure chosen to work for beam physics
Will tell the story as if we had a structure given

D. Schulte
Future High-energy Colliders, CERN 2019
Pushing the Bunch Charge

Single bunch wakefields kick the tail of a bunch

Guiding quadrupoles act like a spring

Comparable to driven oscillator

\[ x'' + \frac{1}{\beta^2} x = \frac{F(s)}{E(s)} \]

Increasing spring strength reduces oscillation

Put in as many strong quadrupoles as reasonable (O(10%) of CLIC main linac)

Become sensitive to quadrupole position errors
CLIC Beam-Based Alignment Tests at FACET

Dispersion-free Steering (DFS) proof of principle – March 2013

DFS correction applied to 500 meters of the SLC linac
- SysID algorithms for model reconstruction
- DFS correction with GUI
- Emittance growth is measured

Graphic User Interface:

Incoming oscillation/dispersion is taken out and flattened; emittance in LI11 and emittance growth significantly reduced.

Before correction

After 1 iteration

After 3 iterations
CLIC Pre-alignment System

• Test of prototype shows
  • vertical RMS error of 11μm
  • i.e. accuracy is approx. 13.5μm
• Improvement path identified

• Required accuracy of reference points is 10μm
Beam Delivery System Test

Goal: 37nm

Simulation with 100 models
Beam size region < 1 σ

December 2010 Data
Feb.-June 2012 Data
Dec. 2012 Data

Vertical Beam Size in nanometre

Tuning Knob Iteration Step

2 to 8 deg  30 deg  174 deg
Lepton Collider Physics Case

Know physics for Higgs and top
• low energies for many branching rations
• high energies for others, e.g. $H\nu\nu$
• 350GeV for top threshold scan
• maybe precision measurements at Z and W

Currently not known physics
• hope to get hints from LHC
• e.g. SUSY

Have to wait for LHC input
But need to prepare scenarios

Consistent with current LHC results

D. Schulte
Beamstrahlung Optimisation

For low energies (classical regime) number of emitted photons

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

\[ \mathcal{L} \propto \frac{N}{\sigma_x \sigma_y} \]

Hence use \( \sigma_x \gg \sigma_y \)

\[ \sigma_x + \sigma_y \approx \sigma_x \]

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

For CLIC at 3 TeV (quantum regime)

- \( \sigma_z = 25 \mu m \)
- \( \sigma_z = 50 \mu m \)
- \( \sigma_z = 75 \mu m \)
- \( \sigma_z = 100 \mu m \)

Total luminosity grows for smaller beams, luminosity in peak starts to decrease again

D. Schulte

Future High-energy Colliders, CERN 2019
SLC: The only Linear Collider that existed

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

Energy = 92 GeV
Luminosity = $2 \times 10^{30}$

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

A 10% prototype!
ILC Main Linac Layout
• Test of prototype shows
  • vertical RMS error of 11μm
  • i.e. accuracy is approx. 13.5μm

• Improvement path identified

• Required accuracy of reference points is 10μm
The photon beam from the helical undulators presents challenges for the target and capture magnet.

**Helical undulator to generate a circularly polarized photon beam**

**Optical Matching Device to get high capture efficiency**

Rotating target to smear out the long 1ms pulse
Example Transverse Tolerance

First order estimate for middle part of cell

Laser or drive beam centre defines centre of the focusing

\[ \sigma_y \approx 42 \text{ nm} \left( \frac{\text{GeV} \times 10^{16} \text{ cm}^{-3}}{E} \right)^{\frac{1}{4}} \left( \frac{\epsilon_y}{\text{nm}} \right) \]

PWFA beam at 1.5TeV has \( \sigma_y = O(30 \text{ nm}) \) for \( n_0 = 2 \times 10^{16} \text{ cm}^{-3} \)

⇒ Beam jitter stability \( O(1 \text{ nm}) \)?
⇒ Tough for laser/drive beam
⇒ Static misalignment is also critical
⇒ but depends on beam energy spread and tuning methods

Important to understand tolerances correctly
R&D programme essential on transverse alignment and stabilisation
Note: Linear Collider Staging

- Design has been done for 500 GeV (ILC) and 3 TeV (CLIC)
  - Staging is a good option

- CLIC is planned to be constructed in stages
  - 0.38, 1.5 and 3 TeV
  - Just add more length as needed/money becomes available

- ILC could also be done in stages (250 GeV)
Tunnel implementations (laser straight)

Geneva

Central MDI & Interaction Region