The linear road to a Higgs Factory and beyond

Eckhard Elsen
LC projects - strategies

- European Strategy priorities related to the Energy Frontier:
  - LHC and LHC luminosity upgrades (until ~2030)
  - Higgs and BSM physics in long term programme

- What are the best machines to access such physics directly post-LHC…we don’t know but we can prepare main options the next years towards next strategy update (~2018)
  - Two alternatives considered; higher energy hadrons (HE-LHC or VHE-LHC), or highest possible energy $e^+e^-$ with CLIC

- ILC in Japan will explore the Higgs in detail, starting at 250 GeV
  - maps out the Higgs sector in particular

- In accordance with this, pursue three connected activities:
  - ILC project development – towards a construction project and dependent on developments in Japan
  - CLIC as option for the energy frontier
  - Common activities wherever possible
Organization of LCC

Program Advisory Committee

Linear Collider Board

Regional Directors
- Brian Foster
- Harry Weerts

Directorate
- Lyn Evans

Deputy (Physics)
- Hitoshi Murayama

ILC
- Mike Harrison

CLIC
- Steinar Stapnes

Physics & Detectors
- Hitoshi Yamamoto

FALC
LCC Objectives

• Support the construction of a staged linear collider in Japan.

• Support long-term R&D on CLIC, the only credible way we have today to access multi-TeV leptons, as a possible future option after LHC.

• Exploit the synergy between ILC and CLIC. Prepare a plan for the sharing of the work.
Physics case for the Linear Collider

- Higgs physics (SM and non-SM)
  - various couplings and thresholds
- Top
- SUSY
- Higgs strong interactions
- New Z’ sector
- Contact interactions
- Extra dimensions
- ....

Higgs boson Production Cross-Sections

Several thresholds:
- 126 GeV Hvν, He⁺e⁻
- 217 GeV HZ
- 252 GeV HHvv
- 343 GeV HHZ
- 472 GeV Htt

Optimization determines optimal signal to bkgd

Lebrun et al., arXiv:1209.2543
## Model-independent Global Fit for Couplings

### Canonical ILC program

(M_H = 125 GeV)

<table>
<thead>
<tr>
<th>coupling</th>
<th>250 GeV</th>
<th>250 GeV + 500 GeV</th>
<th>250 GeV + 500 GeV + 1 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>HZZ</td>
<td>1.3%</td>
<td>1.3%</td>
<td></td>
</tr>
<tr>
<td>HWW</td>
<td>4.8%</td>
<td>1.4%</td>
<td></td>
</tr>
<tr>
<td>Hbb</td>
<td>5.3%</td>
<td>1.8%</td>
<td></td>
</tr>
<tr>
<td>Hcc</td>
<td>6.5%</td>
<td>2.9%</td>
<td></td>
</tr>
<tr>
<td>Hgg</td>
<td>7.0%</td>
<td>2.5%</td>
<td></td>
</tr>
<tr>
<td>Hττ</td>
<td>5.7%</td>
<td>2.5%</td>
<td></td>
</tr>
<tr>
<td>Hγγ</td>
<td>25%</td>
<td>12%</td>
<td></td>
</tr>
<tr>
<td>Hμμ</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Γ_0</td>
<td>11%</td>
<td>5.9%</td>
<td></td>
</tr>
<tr>
<td>Htt</td>
<td>-</td>
<td>16%</td>
<td></td>
</tr>
<tr>
<td>HHH</td>
<td>-</td>
<td>104%</td>
<td></td>
</tr>
</tbody>
</table>

P(e-,e+)=(-0.8,+0.3) @ 250, 500 GeV  
P(e-,e+)=(-0.8,+0.2) @ 1 TeV

<table>
<thead>
<tr>
<th>Energy</th>
<th>Luminosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>250 GeV</td>
<td>250 fb⁻¹</td>
</tr>
<tr>
<td>500 GeV</td>
<td>500 fb⁻¹</td>
</tr>
<tr>
<td>1 TeV</td>
<td>1000 fb⁻¹</td>
</tr>
</tbody>
</table>

K.Fujii @ ECFA LCWS 2013
Mass Coupling Relation
After Canonical ILC Program

Full ILC Program
- 250 fb⁻¹ @ 250 GeV
- 500 fb⁻¹ @ 500 GeV
- 1000 fb⁻¹ @ 1000 GeV

Notice the rare mode like $H \rightarrow \mu^+ \mu^-$ and significant improvement in top Yukawa and self-coupling measurements.
**Higgs studies at higher energies**

**ILD: HH → bbbb**

- Junping Tian

**prospects**

<table>
<thead>
<tr>
<th></th>
<th>0</th>
<th>+0.3 (+0.2)</th>
<th>+0.6 (+0.4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZHH @ 500 GeV</td>
<td>50%</td>
<td>44%</td>
<td>40%</td>
</tr>
<tr>
<td>ψψHH @ 1 TeV</td>
<td>20%</td>
<td>18%</td>
<td>16%</td>
</tr>
</tbody>
</table>

**ILD: HH → bbWW**

- Masakazu Kurata

- Higgs self-coupling analysis using the events with H → WW is ongoing.
- Multivariate analysis to reject the backgrounds
- Unfortunately, c jet analysis doesn't give significant contribution
- Total sensitivity is $\sim 1.4\sigma$

**CLIC: HH → bbbb**

**Ways to increase the number of signal events**

- Polarization significantly increases the signal cross section e.g. from 0.63 fb (unpolarized) to 1.37 fb (-80%, +30%)

<table>
<thead>
<tr>
<th>collision energy</th>
<th>Polarization e/e^+</th>
<th>$\sqrt{s} = 1.4$ TeV</th>
<th>$\sqrt{s} = 1.4$ TeV</th>
<th>$\sqrt{s} = 3.0$ TeV</th>
<th>$\sqrt{s} = 3.0$ TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>unpolarized</td>
<td>$-30%$ / $+30%$</td>
<td>$-30%$ / $+30%$</td>
<td>$-80%$ / $+30%$</td>
<td>$-80%$ / $+30%$</td>
</tr>
<tr>
<td>$\Delta \sigma$(HHv)</td>
<td>$22%$</td>
<td>$18%$</td>
<td>$10%$</td>
<td>$7%$</td>
<td></td>
</tr>
<tr>
<td>$\Delta \lambda_{HH}$</td>
<td>$26%$</td>
<td>$22%$</td>
<td>$16%$</td>
<td>$11%$</td>
<td></td>
</tr>
</tbody>
</table>

Numbers with polarized beams obtained by scaling signal and background cross sections, ignoring polarization-dependent changes to kinematic properties.

**Note:**
- $\sigma = 128$ GeV results in slightly smaller signal cross sections
- c(HHv) = 0.15 fb at 1.4 TeV
- c(HHv) = 0.59 fb at 3.0 TeV

Other Channels contributing at 1.4 TeV: ZHH cross section ≤ 50% of HHv

< 15% of W boson fusion cross section

Jan Strube
Detectors

**ILD: International Large Detector**
- Large: tracker radius 1.8m
- B-field: 3.5 T
- Tracker: TPC + Silicon
- Calorimetry: high granularity particle flow
- ECAL + HCAL inside large solenoid

**SiD: Silicon Detector**
- Small: tracker radius 1.2m
- B-field: 5 T
- Tracker: Silicon
- Calorimetry: high granularity particle flow
- ECAL + HCAL inside large solenoid

### CLIC detectors based on ILC concepts:
- Instrumented return yoke for muon ID
- Complex forward region with final beam focusing
- Strong SC solenoid 4 T or 5 T
- Fine grained calorimeters for PFA: 1 + 7.5 \( \lambda_{\text{jet}} \)
- Tracking: TPC+silicon (CLIC_ILD) all-silicon (CLIC_SiD)
- Ultra low-mass vertex detector with 20 \( \mu \text{m} \) pixels

- CLIC timing structure demanding:
- Detailed GEANT 4 simulation
  - Consider in particular pair background and \( \gamma \gamma \)-processes
- Studied using full reconstruction with background
  - Make full use of timing and fine granularity to reconstruct the physics objects with very high precision
- Shown to be fully compatible with high precision e+e- physics
ILC Layout

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

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>500 GeV</td>
</tr>
<tr>
<td>Peak luminosity</td>
<td>$1.8 \times 10^{34}$ cm$^{-2}$s$^{-1}$</td>
</tr>
<tr>
<td>Beam Rep. rate</td>
<td>5 Hz</td>
</tr>
<tr>
<td>Pulse duration</td>
<td>0.73 ms</td>
</tr>
<tr>
<td>Average current</td>
<td>5.8 mA (in pulse)</td>
</tr>
<tr>
<td>Field in SCRF acc. cavity</td>
<td>$31.5$ MV/m ± 20% $Q_0 = 10^{10}$</td>
</tr>
</tbody>
</table>
## ILC nominal parameters

### 2.2. Top-Level Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>( E_{CM} )</th>
<th>200</th>
<th>230</th>
<th>250</th>
<th>350</th>
<th>500</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centre-of-mass energy</td>
<td>( E_{CM} )</td>
<td>GeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Luminosity pulse repetition rate</td>
<td>Hz</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Positron production mode</td>
<td>( P_{AC} )</td>
<td>MW</td>
<td>10 Hz</td>
<td>10 Hz</td>
<td>nom.</td>
<td>nom.</td>
</tr>
<tr>
<td>Estimated AC power</td>
<td>( N )</td>
<td>( \times 10^{10} )</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Bunch population</td>
<td>( n_{b} )</td>
<td>1312</td>
<td>1312</td>
<td>1312</td>
<td>1312</td>
<td>1312</td>
</tr>
<tr>
<td>Linac bunch interval</td>
<td>( \Delta t_{b} )</td>
<td>ns</td>
<td>554</td>
<td>554</td>
<td>554</td>
<td>554</td>
</tr>
<tr>
<td>RMS bunch length</td>
<td>( \sigma_{z} )</td>
<td>( \mu m )</td>
<td>300</td>
<td>300</td>
<td>300</td>
<td>300</td>
</tr>
<tr>
<td>Normalized horizontal emittance at IP</td>
<td>( \gamma_{e_{x}} )</td>
<td>( \mu m )</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Normalized vertical emittance at IP</td>
<td>( \gamma_{e_{y}} )</td>
<td>nm</td>
<td>35</td>
<td>35</td>
<td>35</td>
<td>35</td>
</tr>
<tr>
<td>Horizontal beta function at IP</td>
<td>( \beta_{x}^{*} )</td>
<td>mm</td>
<td>16</td>
<td>14</td>
<td>13</td>
<td>16</td>
</tr>
<tr>
<td>Vertical beta function at IP</td>
<td>( \beta_{y}^{*} )</td>
<td>mm</td>
<td>0.34</td>
<td>0.38</td>
<td>0.41</td>
<td>0.34</td>
</tr>
<tr>
<td>RMS horizontal beam size at IP</td>
<td>( \sigma_{x}^{*} )</td>
<td>nm</td>
<td>904</td>
<td>789</td>
<td>729</td>
<td>684</td>
</tr>
<tr>
<td>RMS vertical beam size at IP</td>
<td>( \sigma_{y}^{*} )</td>
<td>nm</td>
<td>7.8</td>
<td>7.7</td>
<td>7.7</td>
<td>5.9</td>
</tr>
<tr>
<td>Vertical disruption parameter</td>
<td>( D_{y} )</td>
<td></td>
<td>24.3</td>
<td>24.5</td>
<td>24.5</td>
<td>24.3</td>
</tr>
<tr>
<td>Fractional RMS energy loss to beamstrahlung</td>
<td>( \delta_{BS} )</td>
<td>%</td>
<td>0.65</td>
<td>0.83</td>
<td>0.97</td>
<td>1.9</td>
</tr>
<tr>
<td>Luminosity</td>
<td>( L )</td>
<td>( \times 10^{34} ) ( \text{cm}^{-2} \text{s}^{-1} )</td>
<td>0.56</td>
<td>0.67</td>
<td>0.75</td>
<td>1.0</td>
</tr>
<tr>
<td>Fraction of ( L ) in top 1% ( E_{CM} )</td>
<td>( L_{0.01} )</td>
<td>%</td>
<td>91</td>
<td>89</td>
<td>87</td>
<td>77</td>
</tr>
<tr>
<td>Electron polarisation</td>
<td>( P_{-} )</td>
<td>%</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>Positron polarisation</td>
<td>( P_{+} )</td>
<td>%</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Electron relative energy spread at IP</td>
<td>( \Delta p/p )</td>
<td>%</td>
<td>0.20</td>
<td>0.19</td>
<td>0.19</td>
<td>0.16</td>
</tr>
<tr>
<td>Positron relative energy spread at IP</td>
<td>( \Delta p/p )</td>
<td>%</td>
<td>0.19</td>
<td>0.17</td>
<td>0.15</td>
<td>0.10</td>
</tr>
</tbody>
</table>
ILC with planned luminosity upgrade

Double number of klystrons

<table>
<thead>
<tr>
<th></th>
<th>Baseline</th>
<th>L upgrade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gradient (MV/m)</td>
<td>31.5</td>
<td>31.5</td>
</tr>
<tr>
<td>Bunch spacing (ns)</td>
<td>554</td>
<td>366</td>
</tr>
<tr>
<td>Bunch charge (nC)</td>
<td>3.2</td>
<td>3.2</td>
</tr>
<tr>
<td>Bunches per pulse</td>
<td>1312</td>
<td>2625</td>
</tr>
<tr>
<td>Beam current (mA)</td>
<td>5.8</td>
<td>8.8</td>
</tr>
<tr>
<td>Beam pulse length (μs)</td>
<td>727</td>
<td>961</td>
</tr>
<tr>
<td>$Q_{ext}$ (matched) ($\times 10^6$)</td>
<td>5.5</td>
<td>3.6</td>
</tr>
<tr>
<td>Fill time (μs)</td>
<td>927</td>
<td>613</td>
</tr>
<tr>
<td>RF pulse length (ms)</td>
<td>1.65</td>
<td>1.57</td>
</tr>
<tr>
<td>RF to beam power eff.</td>
<td>44 %</td>
<td>61 %</td>
</tr>
</tbody>
</table>

$\varepsilon_{RF\rightarrow beam}$ increases; cold machines more efficient with long pulses
ILC 250 GeV staging options

- Option 1
  - 1/2 RTML long transfer line

- Common
  - Full length tunnel
  - BDS
    - for 1 TeV
    - 1/2 magnets
  - 10 Hz mode e⁻ linac

- Option 2
  - 5 km transport @ 125 GeV
  - full RTML long transfer line

quasi-adiabatic energy upgrade
ILC TeV upgrade

- construction during operation
- shutdown for "connection" and installation of additional magnets in focussing section
- 3 variants depending on expectations for increase of gradient (31.5 MV/m or 45 MV/m). Linac length varies from 17.5 km to 25 km.

### Table 12.3: Comparison of main linac energy upgrade

<table>
<thead>
<tr>
<th>Energy range (GeV)</th>
<th>Baseline</th>
<th>Scenario A</th>
<th>Scenario B</th>
<th>Scenario C</th>
</tr>
</thead>
<tbody>
<tr>
<td>15–250</td>
<td>7400</td>
<td>21.0</td>
<td>8190</td>
<td>10 700</td>
</tr>
<tr>
<td>15–500</td>
<td>15 280</td>
<td>17.5</td>
<td>7090</td>
<td>17.5</td>
</tr>
<tr>
<td>15–750</td>
<td>10 700</td>
<td>17.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15–500</td>
<td>10 700</td>
<td>17.5</td>
<td>7090</td>
<td>17.5</td>
</tr>
<tr>
<td>250 GeV</td>
<td>10 700</td>
<td>17.5</td>
<td>7090</td>
<td>17.5</td>
</tr>
<tr>
<td>500 GeV</td>
<td>10 700</td>
<td>17.5</td>
<td>7090</td>
<td>17.5</td>
</tr>
</tbody>
</table>

- Making use of the existing baseline linac in this way has three key implications for the upgrade:
  - The existing linac lattice — which is initially designed to transport a beam energy from 15 GeV to 250 GeV — must now transport a beam energy of 15–500 GeV.
  - This will require the removal/relocation of BC magnets and BDS magnets, and additional tunnel (two to three vertical shafts/horizontal access ways) per linac.
  - The installation of additional tunnel can take place during the commissioning and operation at 1 TeV.

### Figure 12.3: Scope of energy upgrade to 1 TeV centre-of-mass energy

- 500 GeV operations
- TeV Upgrade
- Installation/upgrade shutdown
- Commissioning / operation at 1TeV

- Linac length km: 12 (base) to 25 (upgrade)
- Num. of cavities: 7400 (base) to 8190 (upgrade)
- Energy range: 15–250 GeV (base) to 15–500 GeV (upgrade)
- Total cavities: 15 280
- Total length: 21.0 km
Milestones passed towards TDR

- SCRF technology and beam acceleration:
  - Cavity gradient specified: 31.5 MV/m
  - ILC SCRF cavity R&D
    - gradient progress: $E_{\text{acc}} = <37 \text{ MV/m}>$, record: 46 MV/m at DESY in 9-cell TESLA style cavity
    - system engineering: S1-Global program with global participation
- electron cloud mitigation
  - Cesr-TA
- nano-beam handling
  - ILC requires a beam size $\sim 6$ nm (vertical):
    - Progress in KEK-ATF:
      - achieved $\sim 70$ nm (at 1.3 GeV), goal is 37 nm corresponding to 10 nm (at 250 GeV, ILC)
Progress in ILC SCRF Cavity Gradient

![Graph showing progress in ILC SCRF cavity gradient](Image)

Yield: 94% @ 28 MV/m

\(<E_{\text{acc}}> = 37.1 \text{ MV/m}\)
Progress in 1.3 GHz ILC cavity production

- Industrialisation of cavity has been successful globally
- Number of qualified vendors has tripled
- Key to global approach of construction

<table>
<thead>
<tr>
<th>year</th>
<th># 9-cell cavities qualified</th>
<th>Labs achieving 35 MV/m processing</th>
<th>Companies achieving 35 MV/m fabrication</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>10</td>
<td>DESY</td>
<td>ACCEL, ZANON</td>
</tr>
<tr>
<td>2011</td>
<td>41</td>
<td>DESY, JLAB, FNAL, KEK</td>
<td>RI, ZANON, AES, MHI</td>
</tr>
<tr>
<td>2012</td>
<td>(45)</td>
<td>DESY, JLAB, FNAL, KEK, Cornell</td>
<td>RI, ZANON, AES, MHI, Hitachi</td>
</tr>
</tbody>
</table>
Status of European XFEL accelerator construction project

Successful start of cavity production

- Cavity production (DESY–INFN/Milano) and test stand operation (DESY–Wroclaw Univ.–IFJ-Kracow) started few months late, but remarkably smooth
- By now >30 cavities (Zanon is ahead of RI…), increasing every week
  - Average gradient 27.9 MV/m well above XFEL spec 24 MV/m
  - 3 cavities with field emission rinsed at DESY with ultrapure water → good performance afterwards

1st batch of 8 cavities was delayed 2 months (for 1st pre-series module assembly), but by now have comforting buffer of cavities

SCRF cavity production for European XFEL

- Start-up of mass production looks promising
- 800 cavities in ~2 years
- now receiving nominal rate for 1 cryomodule/week; from both vendors

Industrial cavity production

- Start-up of mass production looks promising
- 800 cavities in ~2 years
- now receiving nominal rate for 1 cryomodule/week; from both vendors

Additional HPR 4/2013
SCRF beam acceleration tests

- DESY: FLASH
  - SCRF-CM string + Beam,
    - ACC7/PXFEL1 $<E_{\text{acc}}> = 32$ MV/m
  - 9 mA beam, 2009
  - 800μs, 4.5mA beam, 2012
- KEK: STF
  - S1-Global: complete, 2010
  - Cavity string: $< 26$ MV/m
  - Quantum Beam: 6.7 mA, 1 ms,
  - CM1 & beam, 2014 ~2015
- FNAL: NML/ASTA
  - CM1 test complete
  - CM2 operation, in 2013
  - CM2 + Beam, 2013 ~ 2014
Technical Design Report completed

ILC Technical Progress Report ("interim report")

Reference Design Report

2007

2011

AD&I

2013

~250 pages Deliverable 2

~300 pages Deliverables 1, 3 and 4

Technical Design Report

ILC ready to go

TDR handover to ICFA
…and 2400 signatories agreed
ILC TDR cost estimate

- TDR contains a detailed cost estimate
- includes comparison to RDR
- 7.78 bn ILCU
  1 ILCU = $1 US as of 1.1.2012
- 22.6 M person hours in addition (lab staff or hired)

Largest cost in main linac components – attractive for a global project
ILC construction and commissioning

Chapter 14. Construction schedule

Figure 14.2. The construction and commissioning schedule for the flat topography design variant. Years after construction start are represented vertically, while construction progress along the machine footprint is indicated horizontally (not to scale). The vertical lines represent the locations of shafts.

Figure 14.3. The construction and commissioning schedule for the mountain topography design variant. See Fig. 14.2 caption for details.

14.3.1 Civil engineering
14.3.1.1 Flat-Topography Sites

The ILC layouts that are being considered in this study are significantly different from the one presented in the RDR. The Main Linac and BDS consist of a single tunnel of varying diameter. For the FT sites, it was decided that using two types of TBMs with respective diameters of 8m and 5.2m would facilitate the construction. Figure 14.4 shows where each type of TBM is to be used.

The civil construction phase is expected to be complete in the first four years of the construction schedule (Fig. 14.2 years 1–4). The first step in the civil engineering (CE) phase is to excavate the access shafts that will be used to launch the TBMs and start excavating the caverns in the interaction region. Experience from LHC implies one year is necessary to deliver a fully equipped shaft.
ILC Technical Board – in LCC phase

KEK LC Project Office
Organization at KEK
Head: Akira Yamamoto
Deputy: H. Hayano (Acc.)
K. Fujii (Phys/Det)
T. Shidara (General)

LCC Directorate

ILC Collaboration
“Technical Organization”
Director – Mike Harrison (BNL)
Deputy Director – Hitoshi Hayano (KEK)

Technical Board
Nobuhiro Terunuma (KEK)
Yasuchika Yamamoto (KEK)
Nick Walker (DESY)
Olivier Napoly (CEA)
Marc Ross (SLAC)
Nikolay Solyak (Fermilab)

Working Groups
CLIC Layout at 3 TeV

- Drive Beam accelerator: 2.4 GeV, 1.0 GHz
- 819 klystrons, 15 MW, 142 μs
- 2.5 km delay loop
- CR1: 293 m, CR2: 439 m
- Circumferences: delay loop 73 m
- 2.5 km delay loop
- Decelerator: 24 sectors of 878 m
- e- main linac: 12 GHz, 100 MV/m, 21 km
- e+ main linac
- 48.3 km overall length
- Booster linac: 2.86 to 9 GeV
- e- injector, 2.86 GeV
- e- PDR: 389 m, e- DR: 427 m
- e+ PDR: 389 m, e+ DR: 427 m
- TA turnaround
- CR combiner ring
- DR damping ring
- PDR predamping ring
- BC bunch compressor
- BDS beam delivery system
- IP interaction point
- Dump
## CLIC key elements

### Compression of drive beam

- **4.2 A**
- **to 101 A**
- **140 μs** train length
- **24 × 24 sub-pulses**
- **4.2 A** - **2.4 GeV** - **60 cm** between bunches

### Drive beam time structure - initial

- **240 ns**

### Drive beam time structure - final

- **5.8 μs**
- **24 pulses - 101 A - 2.5 cm** between bunches

### Power extraction from drive beam and transfer to main beam

### Accelerating structure

- **12 GHz, 68 MW**
- **RF**
- **BPM**
- **101 A**
- **2.5 cm** between bunches

---

**Figure:**

- Drive beam time structure
- Accelerating structure components
- Power extraction and transfer structure (PETS)
Conclusion of CLIC CDR studies

<table>
<thead>
<tr>
<th>Component</th>
<th>Status and Findings</th>
</tr>
</thead>
</table>
| Main linac gradient           | - Ongoing test close to or on target  
- Uncertainty from beam loading being tested          |
| Drive beam scheme             | - Generation tested, used to accelerate test beam above specifications, deceleration as expected  
- Improvements on operation, reliability, losses, more deceleration studies underway |
| Luminosity                    | - Damping ring like an ambitious light source, no show stopper  
- Alignment system principle demonstrated  
- Stabilisation system developed, benchmarked, better system in pipeline  
- Simulations on or close to the target    |
| Operation & Machine Protection| - Start-up sequence and low energy operation defined  
- Most critical failure studied and first reliability studies |
| Implementation                | - Consistent three stage implementation scenario defined  
- Schedules, cost and power developed and presented  
- Site and CE studies documented |

TD24 baseline: Unloaded 106 MV/m Expected with beam loading 0-16% less

Fig. 3.6: Simplified upgrade scheme for CLIC staging scenario B.
The CLIC CDR documents

Vol 1: The CLIC accelerator and site facilities
- CLIC concept with exploration over multi-TeV energy range up to 3 TeV
- Feasibility study of CLIC parameters optimized at 3 TeV (most demanding)
- Consider also 500 GeV, and intermediate energy range
- [https://edms.cern.ch/document/1234244/](https://edms.cern.ch/document/1234244/)

Vol 2: Physics and detectors at CLIC
- Physics at a multi-TeV CLIC machine can be measured with high precision, despite challenging background conditions
- External review procedure in October 2011

Vol 3: “CLIC study summary”
- Summary and available for the European Strategy process, including possible implementation stages for a CLIC machine as well as costing and cost-drives
- Proposing objectives and work plan of post CDR phase (2012-16)

In addition a shorter overview document was submitted as input to the European Strategy update, available at: [http://arxiv.org/pdf/1208.1402v1](http://arxiv.org/pdf/1208.1402v1)

An input document to Snowmass 2013 has also been submitted: [http://arxiv.org/abs/1305.5766](http://arxiv.org/abs/1305.5766)
Possible CLIC stages studied

Key features:
• High gradient (energy/length)
• Small beams (luminosity)
• Repetition rates and bunch spacing (experimental conditions)


CLIC physics potential

LHC complementarity at the energy frontier:
- How do we build the optimal machine given a physics scenario (partly seen at LHC?)

Examples highlighted in the CDR:
- Higgs physics (SM and non-SM)
- Top
- SUSY
- Higgs strong interactions
- New $Z'$ sector
- Contact interactions
- Extra dimensions

Detailed studies at 350 (500), 1400 and 3000 GeV for these processes

Operation at lower than nominal energy

Stage 1: ~350-375 GeV => Higgs and top physics
Stage 2: ~1.5 TeV => $t\bar{t}H$, $\nu\nuHH$ + New Physics (lower mass scale)
Stage 3: ~3 TeV => New Physics (higher mass scale)
## SUSY Benchmark Results (1.4 TeV)

<table>
<thead>
<tr>
<th>$\sqrt{s}$ (TeV)</th>
<th>Process</th>
<th>Decay mode</th>
<th>SUSY model</th>
<th>Measured quantity</th>
<th>Unit</th>
<th>Generator value</th>
<th>Stat. error</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.4</td>
<td>Sleptons production</td>
<td>$\tilde{\tau}_R \tilde{\tau}_R \rightarrow \ell^+ \ell^- \chi_1 \chi_1$</td>
<td>III</td>
<td>$\sigma$</td>
<td>fb</td>
<td>1.11</td>
<td>2.7%</td>
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<tr>
<td></td>
<td></td>
<td>$\ell$ mass</td>
<td>GeV</td>
<td>560.8</td>
<td>0.1%</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\chi_1^0$ mass</td>
<td>GeV</td>
<td>357.8</td>
<td>0.1%</td>
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<tr>
<td>1.4</td>
<td>Stau production</td>
<td>$\tilde{\tau}_R \tilde{\tau}_R \rightarrow e^+ e^- \chi_1 \chi_1$</td>
<td>III</td>
<td>$\sigma$</td>
<td>fb</td>
<td>5.7</td>
<td>1.1%</td>
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<tr>
<td></td>
<td></td>
<td>$\ell$ mass</td>
<td>GeV</td>
<td>558.1</td>
<td>0.1%</td>
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<tr>
<td></td>
<td></td>
<td>$\chi_1^0$ mass</td>
<td>GeV</td>
<td>357.1</td>
<td>0.1%</td>
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<tr>
<td>1.4</td>
<td>Chargino production</td>
<td>$\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow \chi_1 \chi_1 h/Z^0 h/Z^0 \chi_1 \chi_1$</td>
<td>III</td>
<td>$\sigma$</td>
<td>fb</td>
<td>5.6</td>
<td>3.6%</td>
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<tr>
<td></td>
<td></td>
<td>$\ell$ mass</td>
<td>GeV</td>
<td>644.3</td>
<td>2.5%</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>$\chi_1^0$ mass</td>
<td>GeV</td>
<td>487.6</td>
<td>2.7%</td>
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<td></td>
<td>Neutralino production</td>
<td>$\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow h/Z^0 h/Z^0 \chi_1 \chi_1$</td>
<td>III</td>
<td>$\sigma$</td>
<td>fb</td>
<td>5.4</td>
<td>1.2%</td>
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</table>

## SUSY Benchmark Results (3 TeV)

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<thead>
<tr>
<th>$\sqrt{s}$ (TeV)</th>
<th>Process</th>
<th>Decay mode</th>
<th>SUSY model</th>
<th>Measured quantity</th>
<th>Unit</th>
<th>Generator value</th>
<th>Stat. error</th>
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<tbody>
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<td>3.0</td>
<td>Sleptons production</td>
<td>$\tilde{\tau}_R \tilde{\tau}_R \rightarrow \ell^+ \ell^- \chi_1 \chi_1$</td>
<td>II</td>
<td>$\sigma$</td>
<td>fb</td>
<td>0.72</td>
<td>2.8%</td>
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<td></td>
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<td>$\ell$ mass</td>
<td>GeV</td>
<td>1010.8</td>
<td>0.6%</td>
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<tr>
<td></td>
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<td>$\chi_1^0$ mass</td>
<td>GeV</td>
<td>340.3</td>
<td>1.9%</td>
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<td>3.0</td>
<td>Chargino production</td>
<td>$\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow \chi_1 \chi_1 W^+ W^-$</td>
<td>II</td>
<td>$\sigma$</td>
<td>fb</td>
<td>6.05</td>
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<tr>
<td></td>
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<td>$\ell$ mass</td>
<td>GeV</td>
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<td>0.3%</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>$\chi_1^0$ mass</td>
<td>GeV</td>
<td>340.3</td>
<td>1.0%</td>
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<td></td>
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<tr>
<td></td>
<td>Neutrino production</td>
<td>$\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow h/Z^0 h/Z^0 \chi_1 \chi_1$</td>
<td>III</td>
<td>$\sigma$</td>
<td>fb</td>
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<td>$\ell$ mass</td>
<td>GeV</td>
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<td>0.4%</td>
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<tr>
<td></td>
<td></td>
<td>$\chi_1^0$ mass</td>
<td>GeV</td>
<td>643.2</td>
<td>0.6%</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Production of right-handed squarks</td>
<td>$\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow h/Z^0 h/Z^0 \chi_1 \chi_1$</td>
<td>II</td>
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<td>0.4%</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\chi_1^0$ mass</td>
<td>GeV</td>
<td>643.2</td>
<td>0.6%</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Heavy Higgs production</td>
<td>$H^0 A^0 \rightarrow b\bar{b} b\bar{b}$</td>
<td>I</td>
<td>Mass Width</td>
<td>GeV</td>
<td>902.4</td>
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<tr>
<td></td>
<td></td>
<td>$\alpha$</td>
<td>fb</td>
<td>10.6</td>
<td>2.4%</td>
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<td></td>
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<td>Heavy Higgs production</td>
<td>$H^+ H^- \rightarrow t\bar{b} \bar{b}$</td>
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<td>Mass Width</td>
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<td>fb</td>
<td>1123.7</td>
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</table>
CLIC near CERN

Legend
- CERN existing LHC
- Potential underground siting:
  - CLIC 500 Gev
  - CLIC 1.5 TeV
  - CLIC 3 TeV

Tunnel implementations (laser straight)

Central MDI & Interaction Region

Legend:
- CERN existing LHC
- Potential underground siting:
  - CLIC 500 Gev
  - CLIC 1.5 TeV
  - CLIC 3 TeV

Jura Mountains

Lake Geneva

Geneva
Possible luminosity examples

Based on 200 days/year at 50% efficiency (accelerator + data taking combined)

Target figures: >600 fb⁻¹ at first stage, 1.5 ab⁻¹ at second stage, 2 ab⁻¹ at third stage

Fig. 5.2: Integrated luminosity in the scenarios optimised for luminosity in the first energy stage (left) and optimised for entry costs (right). Years are counted from the start of beam commissioning. These figures include luminosity ramp-up of four years (5%, 25%, 50%, 75%) in the first stage and two years (25%, 50%) in subsequent stages.
Power/energy consumption

Considering 150 days per year of normal operation at nominal power and a luminosity ramp-up in the early years at each stage of collision energy, the development of yearly energy consumption can be sketched.

Re-optimize parts
- Reduced current density in normal-conducting magnets
- Reduction of heat loads to HVAC
- Re-optimization of accelerating gradient with different objective function

Efficiency
- Grid-to-RF power conversion
- Permanent or super-ferric superconducting magnets

Energy management
- Low-power configurations in case of beam interruption
- Modulation of scheduled operation to match electricity demand: Seasonal and Daily
- Power quality specifications

Waste heat recovery
- Possibilities of heat rejection at higher temperature
- Waste heat valorization by concomitant needs, e.g. residential heating, absorption cooling

Beyond:
Scale with inst. luminosity – i.e. running at the very end of the project lifetime might be power limited and require more time.
CLIC Costs

**Fig. 6:** Cost structure of the CLIC accelerator complex at 500 GeV for scenarios A and B.

**Caveats:**
- Uncertainties 20-25%
- Possible savings around 10%
- However – first stage not optimised (work for next phase), parameters largely defined for 3 TeV final stage
An optimised machine:
- Higgs mass scale known and much improved cost and power models allow significant optimization
- Re-baselining studies ongoing (~375 GeV, ~1.5 TeV, 3 TeV) – including more work on a klystron based initial phase
- Overall design and system optimisation, technical parameters for all systems
- Cost, power/energy optimisation, scheduling, site including specific developments/studies

Energy reach:
- Linked to X-band technology development and industrialisation
- Increase test-capacity (several sites)
- Detailed studies and optimisation of all the critical RF elements (main structures the most central) as well as further industrialisation

Luminosity performance:
- Overall performance simulation and optimisation of each system – in some case linked to experimental benchmarking and/or tests (some examples below)
- Damping ring designs including experimental development and studies
- Main linac alignment and stability, wakefield studies, BBA alignment
- Final focus optimisation and studies
- Overall performance, reliability, robustness and risk studies

System tests:
- Studies of drive-beam stability and RF units, beam-loading experiments, deceleration, RF power generation and two beam acceleration with complete modules, as well as beam based alignment/beam delivery system/final focus studies
- CTF3+ programme
- ATF, FACET for luminosity performance and various other smaller programmes for specific technology developments
- Continuing/increasing links to light source community related to low emittance rings and X-band based FELs design studies

Technical developments:
- Critical elements, for performance, costs or power consumption, industrial developments or as needed for systemtest (some examples below)
- Module development including complete modules (RF, alignment/stability, magnets, instrumentation, vacuum, cooling, controls) for lab and CTF3
- RF power systems development (1 GHz)
- Alignment and stability methods and hardware
Current CLIC Collaboration

CLIC multi-lateral collaboration - 48 Institutes from 25 countries

ACAS (Australia)
Aarhus University (Denmark)
Ankara University (Turkey)
Argonne National Laboratory (USA)
Athens University (Greece)
BINP (Russia)
CERN
CIEMAT (Spain)
Cockcroft Institute (UK)
ETH Zurich (Switzerland)
FNAL (USA)
Gazi Universities (Turkey)
Helsinki Institute of Physics (Finland)
IAP (Russia)
IAP NASU (Ukraine)
IHEP (China)
INFN / LNF (Italy)
Instituto de Fisica Corpuscular (Spain)
IRFU / Saclay (France)
Jefferson Lab (USA)
John Adams Institute/Oxford (UK)
Joint Institute for Power and Nuclear Research SOSNY / Minsk (Belarus)
John Adams Institute/RHUL (UK)
JINR
Karlsruhe University (Germany)
KEK (Japan)
LAL / Orsay (France)
LAPP / ESIA (France)
NIKHEF/Amsterdam (Netherland)
NCP (Pakistan)
North-West. Univ. Illinois (USA)
Patras University (Greece)
Polytech. Univ. of Catalonia (Spain)
Psi (Switzerland)
RAL (UK)
RRCAT / Indore (India)
SLAC (USA)
Sincrotrone Trieste/ELETTRA (Italy)
Thrace University (Greece)
Tsinghua University (China)
University of Oslo (Norway)
University of Vigo (Spain)
Uppsala University (Sweden)
UCSC SCIPP (USA)
What are the next steps?
Geological survey of the 2 Japanese ILC sites

Common Subject: Central Campus

Reports to be completed summer 2013
Considerations for ILC location

A concept: Relative distance from main campus such that in reach within \( \leq 30 \) min.
### Estimate of persons at ILC laboratory

<table>
<thead>
<tr>
<th></th>
<th>Under construction Peak (year 8)</th>
<th>Operation start (year 11)</th>
<th>In operation (year 15)</th>
<th>In operation (year 20)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Laboratory Staffs #1</strong></td>
<td>1,600</td>
<td>1,200</td>
<td>1,200</td>
<td>1,200</td>
</tr>
<tr>
<td><strong>Experiment participants #2</strong></td>
<td>500</td>
<td>700</td>
<td>800</td>
<td>1,000</td>
</tr>
<tr>
<td><strong>Laboratory Support #3</strong></td>
<td>300</td>
<td>300</td>
<td>400</td>
<td>500</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>2,400</td>
<td>2,200</td>
<td>2,400</td>
<td>2,700</td>
</tr>
</tbody>
</table>

**#1:** including the regular/permanent staff and temporary staff (Post-Doc),
**#2:** including researchers, engineers and students for two experiments,
**#3:** including subcontracted specialist to support acc. & exp. activities
General Plan for ILC Central Campus

- Major facilities:
  - Offices
  - Laboratory
  - Meeting rooms
  - Visitor’s accommodation
- General services
- Parking
- Utility plant, etc.

- Assuming:
  - ~ 100,000 m²
  - in total floor area

<table>
<thead>
<tr>
<th>Classification</th>
<th>Assuming facilities</th>
<th>Area (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Offices</td>
<td>Research office University &amp; Institute</td>
<td>35,000</td>
</tr>
<tr>
<td>laboratory facilities</td>
<td>Control center Assembly hall Technology development hall</td>
<td>33,000</td>
</tr>
<tr>
<td>meeting and exchange</td>
<td>Lecture hall Meeting room</td>
<td>3,500</td>
</tr>
<tr>
<td>Accommodation</td>
<td>Dormitory Visitor accommodation</td>
<td>23,000</td>
</tr>
<tr>
<td>Service facilities</td>
<td>Reception, Users office Library, exhibition hall Cafeteria, Convenient store Health care &amp; Training center</td>
<td>3,200</td>
</tr>
<tr>
<td>Transportation</td>
<td>Parking, Bus Terminal</td>
<td>-</td>
</tr>
<tr>
<td>Energy plant, etc.</td>
<td></td>
<td>1,100</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>99,800</td>
</tr>
</tbody>
</table>
Case studies: Zoning and Facility Layout

- **High-Rise**
  - Area: 30000 m²

- **Flat**
  - Area: 40000 m²

- **Spacious**
  - Area: 80000 m²
European Assets
XFEL test facility AMTF at DESY

• Cold RF test of all XFEL superconducting cavities before cryomodule module assembly, 800 cavities, rate 6/week, 2 of 2 vert. test stands in operation
• Complete cold performance test of all XFEL cryomodules before tunnel installation: RF, vacuum, cryo-losses, tuner, quad, 100 cryomodules, rate: 1/week, 1 of 3 test stands in cryomodule commissioning
• Cold test of all superconducting magnet packages before cryomodule assembly, 100 magnets, 1/week, 1 of 1 stand in operation
• Assembly and tests of RF Waveguides at Waveguide Assembly and Test Facility, in operation
European assets
XFEL module assembly

- New and complex infrastructure build at CEA, Saclay
- Clean Room Cold Coupler Area (ISO4-CC-WS1)
  - Cold coupler assembly
- Clean Room String Assembly Area (ISO4-SA-WS1, ISO4-SA-WS2)
  - String connections (1 gate valve + 8 cavities + 1 Qpole unit)
- Roll-out Area (RO-WS1, RO-WS2)
  - HOM tuning, magnetic shielding, tuners,…
  - 2Ph-tube welding, cold-mass connection
- Alignment Area (AL-WS1, AL-WS2)
  - Cavity and quadrupole fine alignment
  - Coupler shields and braids, tuner electric tests
- Cantilever Area (CA-WS1)
  - Welding of 4K and 70 K shields, super insulation
  - Quad current lead
  - Insertion into vacuum vessel and string alignment
- Coupler Area (CO-WS1, CO-WS2)
  - Warm couplers + coupler pumping line
  - Control operations (electrical, RF)
- Shipment Area (SH-WS1, SH-WS2)
  - CEA-Alsyom “acceptance test”
  - End-caps closing, N2-insulation, loading.

In full production, this chain of workstations will be fully occupied with 7 cryomodules (XMn-6 @ WS1,…, XMn @ WS7) stationed for one week.
Joint European effort to ILC

- European contributions to ILC construction obviously possible – based on XFEL construction and reaching considerably further

- Significant work and expertise – and huge common potential with CLIC related to “luminosity performance/critical systems and associated system tests”:

  - CERN, Spain, UK, Italy, France … : Sources, damping rings, beam-delivery systems, instrumentation, stability/alignment
Summary

• Major milestones achieved for CLIC (CDR 2012) and ILC (TDR 2013)

• The Higgs discovery – and future measurements – set up a clear scenario for linear colliders (to complement the results from LHC)

• CLIC programme for 2018 defined (being revised now after the Strategy document), collaboration based developments of key aspects of the technology

• ILC may enter construction in Japan
  • Site choice next, followed by statements by government? Involvement by other regions, Europe and US, is key
  • Europe well prepared to contribute technically

• European Strategy welcomes the Japanese initiative and supports R&D for CLIC