Linear Colliders

A. De Roeck
CERN
Aspen Winter Conference 2005

Contents
- Recent LC history
- The ILC: a TeV collider
- CLIC: a multi-TeV collider
Linear e+e- Colliders

Since end of 2001 there seems to be a worldwide consensus (ECFA/HEPAP/Snowmass 2001...)

The machine which will complement and extend the LHC best, and is closest to be realized is a Linear e+e- Collider with a collision energy of at least 500 GeV

PROJECTS:

⇒ TeV Colliders (cms energy up to 1 TeV) → Technology ~ready
  August’04 ITRP: NLC/GLC/TESLA → ILC superconducting cavities

⇒ Multi-TeV Collider (cms energies in multi-TeV range) → R&D
  CLIC (CERN + collaborators) → Two Beam Acceleration
A LC is a Precision Instrument

- Clean e+e- (polarized initial state, controllable $\sqrt{s}$ for hard scattering)
- Detailed study of the properties of Higgs particles
  - Mass to 0.03%, couplings to 1-3%, spin & CP structure, total width (6%) factor 2-5 better than LHC/measure couplings in model indep. way
- Precision measurements of SUSY particles properties, i.e. slepton masses to better than 1%, if within reach
- Precision measurements a la LEP (TGC’s, Top and W mass)
- Large indirect sensitivity to new phenomena (eg $W_L W_L$ scattering)

LC will very likely play important role to disentangle the underlying new theory

$$e_L e_R^\pm \rightarrow \tilde{\mu}_L \tilde{\mu}_R \rightarrow \mu \tilde{\chi}_2^0$$
**Understanding SUSY**
High accuracy of sparticle mass measurements relevant for reconstruction of SUSY breaking mechanism

**Dark Matter**
LC will accurately measure $m_\chi$ and couplings, i.e. Higgsino/Wino/Bino content

→ Essential input to cosmology & searches

→ LC will make a prediction of $\Omega_{DM}h^2 \sim 3\%$ (SPS1a)

→ A mismatch with WMAP/Planck would reveal extra sources of DM (Axions, heavy objects)

**Quantum level consistency:** $M_H$(direct) = $M_H$(indirect)?

$\Delta \sin^2 \theta_W \sim 10^{-5}$ (GigaZ), $\Delta M_W \sim 6$ MeV

(+theory progress)

→ $\Delta M_H$ (indirect) $\sim 5\%$

---

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The next e+e-collider must be linear

C. Pagani  LCWS04 Paris

- Synchrotron Radiation (SR) becomes prohibitive for electrons in a circular machine above LEP energies:
  \[ U_{SR} [\text{GeV}] = 6 \cdot 10^{-21} \cdot \gamma^4 \cdot \frac{1}{r [\text{km}]} \]
  \( U_{SR} \) = energy loss per turn
  \( \gamma \) = relativistic factor
  \( r \) = machine radius

- RF system must replace this loss, and \( r \) scale as \( E^2 \)
- LEP @ 100 GeV/beam: 27 km around, 2 GeV/turn lost
- Possible scale to 250 GeV/beam i.e. \( E_{cm} = 500 \text{ GeV} \):
  - 170 km around
  - 13 GeV/turn lost

- Consider also the luminosity
  - For a luminosity of \(~ 10^{34}/\text{cm}^2/\text{second}\), scaling from b-factories gives
    \(~ 1 \text{ Ampere of beam current}\)
  - 13 GeV/turn \times 2 \text{ amperes} = 26 \text{ GW RF power}
  - Because of conversion efficiency, this collider would consume more power than the state of California in summer: \(~ 45 \text{ GW}\)

- Both size and power seem excessive
Generic Linear Collider

30-40 km

All collider elements are challenging
Superconducting cavities

Two beam acceleration

Warm cavities
Meanwhile: LC getting on the Roadmap

Study groups of ACFA, ECFA, HEPAP       The next large accelerator-based project of particle physics should be a linear collider

US DOE Office of Science Future Facilities Plan: LC is first priority mid-term new facility for all US Office of Science

Major Funding Agencies       Regular meetings concerning LC

ICFA (February 2004)       reaffirms its conviction that the highest priority for a new machine for particle physics is a linear electron-positron collider with an initial energy of 500 GeV, extendible up to about 1 TeV, with a significant period of concurrent running with the LHC

LCWS04 Paris (April 2004)       publication of the document “understanding matter, space and time” by 2600 physicists, in support of a linear collider

EUROTEV selected by EC       9 MEuro for R&D for a LC

Very sizable community wants a e+e- Linear Collider
ILC Parameters & options

Several years of intense physics studies have led to:

• Baseline Linear Collider
  - Minimum energy of 500 GeV, with int. luminosity of 500 fb\(^{-1}\) in the first 4 years
  - Scan energies between from LEP2 till new energy range: 200-500 GeV with a luminosity \(\sim \sqrt{s}\). Switch over should be quick (max 10% of data taking time)
  - Beam energy stability and precision should 0.1% or better.
  - Electron beam polarization with at least 80%
  - Two interaction regions should be planned for
  - Should allow for calibration running at the Z (\(\sqrt{s} = 90\) GeV)
  - Upgrade: Energy upgrade up to \(\sim 1\) TeV with high luminosity should be planned

• Options beyond the baseline: enhance the physics reach
  - Running as an e-e- collider
  - Running as a e\(\gamma\) or \(\gamma\gamma\) collider
  - Polarization of the positron beam
  - Running at Z\(^0\) with a luminosity of several \(10^{33}\) cm\(^{-2}\)s\(^{-1}\) (GigaZ)
  - Running at WW mass threshold with a luminosity of a few times \(10^{33}\) cm\(^{-2}\)s\(^{-1}\)
Machine Parameters

Table from ILC-Technical Review Comittee (2003)

```
<table>
<thead>
<tr>
<th>TABLE 2.1: Overall parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>TESLA</td>
</tr>
<tr>
<td>-------</td>
</tr>
<tr>
<td>Center of mass energy [GeV]</td>
</tr>
<tr>
<td>RF frequency of main linac [GHz]</td>
</tr>
<tr>
<td>Design luminosity [10^{33} cm^{-2} s^{-1}]</td>
</tr>
<tr>
<td>Linac repetition rate [Hz]</td>
</tr>
<tr>
<td>Number of particles/bunch at IP [10^{10}]</td>
</tr>
<tr>
<td>Number of bunches/pulse</td>
</tr>
<tr>
<td>Bunch separation [nsec]</td>
</tr>
<tr>
<td>Bunch train length [usec]</td>
</tr>
<tr>
<td>Beam power/beam [MW]</td>
</tr>
<tr>
<td>Unloaded/loaded gradient c [MV/m]</td>
</tr>
<tr>
<td>Total two-linac length [km]</td>
</tr>
<tr>
<td>Total beam delivery length [km]</td>
</tr>
<tr>
<td>Proposed site length [km]</td>
</tr>
<tr>
<td>Total site AC power e [MW]</td>
</tr>
<tr>
<td>Tunnel configuration f</td>
</tr>
</tbody>
</table>
```


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ITRP Recommendation to ICFA/ILCSC

ITRP Mission: select a technology R&D to support both technologies becomes too demanding on resources

Conclusion at ICHEP Beijing August '04
⇒ Both technologies mature
⇒ Select the cold technology to continue

Some arguments in favor of cold

• The large cavity aperture and long bunch interval simplify operations, reduce the sensitivity to ground motion, permit inter-bunch feedback, and may enable increased beam current.
• The main linac and rf systems, the single largest technical cost elements, are of comparatively lower risk.
• The construction of the superconducting XFEL free electron laser will provide prototypes and test many aspects of the linac.
• The industrialization of most major components of the linac is underway.
• The use of superconducting cavities significantly reduces power consumption.

Note: technology selected, not a design

Endorsed by ICFA/ILCSC ⇒ call project the International Linear Collider ILC

ILCSC = International Linear Collider Steering Committee

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World wide effort on designing the ILC machine has started

First meeting at KEK November
Discussion/study of the machine parameters, injector chain, beam delivery, interaction region etc., based on the NLC/JLC/TESLA experience
Next full meeting: Snowmass 14-27/8/05

E.g. discussions related to the machine-detector interface:
crossing angles, polarization measurements, luminosity measurements, backgrounds, constraints from special options, low angle tagging

Recommendations from the WG4 (KEK)
Tentative, not frozen configuration, working hypotheses, “strawman”
November 04

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LC Time Scales

ILCSC Road Map

R. Heuer LCWS04

2004 Technology recommendation (done)
Start Global Design Initiative/Effort (GDI/GDE): central team director job as been offered a few days ago

2005 Conceptual Design Report for Linear Collider
Start Global Design Organization (GDI/GDO)

2007 Technical Design Report for a Linear Collider

2008 Site selection

2009/2010 Construction could start (if budget approved)

First collisions in 2014/2015?

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CLIC Compact Linear Collider

- BERLIN Technical University (Germany) : Structure simulations GdfidL
- Finnish Industry (Finland) : Sponsorship of a mechanical engineer
- INFN / LNF (Italy): CTF3 delay loop, transfer lines & RF deflectors
- JINR & IAP (Russia): Surface heating tests of 30 GHz structures
- KEK (Japan): Low emittance beams in ATF
- LAL (France): Electron guns and pre-buncher cavities for CTF3
- LAPP/ESIA (France) : Stabilization studies
- LLBL/LBL (USA) : Laser-wire studies
- North Western University (Illinois) : Beam loss studies & CTF3 equipment
- RAL (England) : Lasers for CTF3 and CLIC photo-injectors
- SLAC (USA) : High Gradient Structure testing, structure design, CTF3 drive beam injector design
- UPPSALA University (Sweden) : Beam monitoring systems for CTF3
CLIC

• An e+e- linear collider optimized for a cms energy of 3 TeV with a luminosity of \( \approx 10^{35} \text{ cm}^{-2}\text{s}^{-1} \)

• Aim: 3 TeV complementing LHC/TeV class LC and breaking new ground, with a final stage up to 5 TeV

• To achieve this with reasonable cost (less than \( \sim 35 \text{ km} \)) and not too many active elements
  → High accelerating gradient: \( \sim 150 \text{ MV/m} \)
    two beam acceleration (TBA)
  → High beamstrahlungs regime to reach high luminosity
  → Challenging beam parameters and machine requirements (nm stability, strong final focus, 30GHz accelerating structures)

⇒ CLIC TBA to date the only known way to reach multi-TeV

• Test facilities
  CTF2 (‘96-’02): 150-193 MV/m in TBA (16 ns pulses)
  CTF3 (‘02-’09): Test of drive beam, R1’s/ R2’s of TRC (2003)

Comparison with ILC
• TESLA 500 GeV 25 MV/m
  800 GeV 35 MV/m
• Future ILC study?: 44 MV/m

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CLIC: a Multi-TeV Linear Collider

⇒ CERN: accelerate CLIC R&D support to evaluate the technology by 2009 with extra external contributions ⇒ CLIC collaboration.

FAQs:
• CLIC technology O(5) years behind ILC
• CLIC can operate from 90 GeV → 3 (5) TeV.
Demonstrated that 2 beam acceleration works
Reached up to 190 MV/m for short pulses (16ns)

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### CLIC Parameters & Backgrounds

**CLIC 3 TeV e+e- collider with a luminosity ~ 10^{35} cm^{-2}s^{-1} (1 ab^{-1}/year)**

**CLIC operates in a regime of high beamstrahlung**

### CLIC Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Old</th>
<th>New</th>
</tr>
</thead>
<tbody>
<tr>
<td>(E_{cm})</td>
<td>TeV</td>
<td>0.5</td>
<td>3</td>
</tr>
<tr>
<td>(\mathcal{L})</td>
<td>([10^{34} \text{cm}^{-2}\text{s}^{-1}])</td>
<td>2.1</td>
<td>10.0</td>
</tr>
<tr>
<td>(\mathcal{L}_{0.99})</td>
<td>([10^{34} \text{cm}^{-2}\text{s}^{-1}])</td>
<td>1.5</td>
<td>3.0</td>
</tr>
<tr>
<td>(f_r)</td>
<td>Hz</td>
<td>200</td>
<td>100</td>
</tr>
<tr>
<td>(N_b)</td>
<td></td>
<td>154</td>
<td>154</td>
</tr>
<tr>
<td>(\Delta_b)</td>
<td>ns</td>
<td>0.67</td>
<td>0.67</td>
</tr>
<tr>
<td>(N)</td>
<td>([10^{10}])</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>(\sigma_z)</td>
<td>(\mu \text{m})</td>
<td>35</td>
<td>30</td>
</tr>
<tr>
<td>(\varepsilon_x)</td>
<td>(\mu \text{m})</td>
<td>2</td>
<td>0.68</td>
</tr>
<tr>
<td>(\varepsilon_y)</td>
<td>(\mu \text{m})</td>
<td>0.01</td>
<td>0.02</td>
</tr>
<tr>
<td>(\sigma_{z^*})</td>
<td>nm</td>
<td>202</td>
<td>43</td>
</tr>
<tr>
<td>(\sigma_{x^*})</td>
<td>nm</td>
<td>(\approx 1.2)</td>
<td>1</td>
</tr>
<tr>
<td>(\delta)</td>
<td>%</td>
<td>4.4</td>
<td>31</td>
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<tr>
<td>(n_\gamma)</td>
<td></td>
<td>0.7</td>
<td>2.3</td>
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<tr>
<td>(N_\perp)</td>
<td></td>
<td>7.2</td>
<td>60</td>
</tr>
<tr>
<td>(N_{Hadr})</td>
<td></td>
<td>0.07</td>
<td>4.05</td>
</tr>
<tr>
<td>(N_{MJ})</td>
<td></td>
<td>0.003</td>
<td>3.40</td>
</tr>
</tbody>
</table>

**Time between 2 bunches = 0.67\,\text{ns}**

**Expect large backgrounds**

- e+e- pair production
- \(\gamma\gamma\) events
- Muon backgrounds
- Neutrons
- Synchrotron radiation

*Expect distorted lumi spectrum*

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Taking into account backgrounds, lumi spectrum, detector...

Measure $\sigma_{b\bar{b}}$, $A_{FB}^{\mu^+\mu^-}$ and $A_{FB}^{b\bar{b}}$

Examples:
$$\frac{\delta\sigma_{b\bar{b}}}{\sigma_{b\bar{b}}} = 0.012 / \text{1 ab}^{-1}$$
$$\frac{\delta A_{FB}^{\mu^+\mu^-}}{A_{FB}^{\mu^+\mu^-}} = 0.018 / \text{1 ab}^{-1}$$

- $1 \text{ ab}^{-1}$, $P_r=0.8$, $\Delta P/P=0\%$
- $e^+e^- \rightarrow b\bar{b}$, $P_r=0.0$, $\Delta y=0$
- $\Delta y=0.5\%$, $\Delta P/P=0.5\%$, $P_r=0.4$
- LC, 1 TeV

<table>
<thead>
<tr>
<th>Observable</th>
<th>Relative Stat. Accuracy $\delta O/O$ for 1 ab$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{\mu^+\mu^-}$</td>
<td>±0.010</td>
</tr>
<tr>
<td>$\sigma_{b\bar{b}}$</td>
<td>±0.012</td>
</tr>
<tr>
<td>$\sigma_{t\bar{t}}$</td>
<td>±0.014</td>
</tr>
<tr>
<td>$A_{FB}^{\mu\mu}$</td>
<td>±0.018</td>
</tr>
<tr>
<td>$A_{FB}^{b\bar{b}}$</td>
<td>±0.055</td>
</tr>
<tr>
<td>$A_{FB}^{t\bar{t}}$</td>
<td>±0.040</td>
</tr>
</tbody>
</table>

E.g.: Contact interactions: Sensitivity to scales up to 100-800 TeV

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Resonance Production

Resonance scans, e.g. a $Z'$

**FIT ACCURACY**

<table>
<thead>
<tr>
<th>Observable</th>
<th>Breit Wigner</th>
<th>CLIC.01</th>
<th>CLIC.02</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{Z'}$ (GeV)</td>
<td>3000 ± .12</td>
<td>± .15</td>
<td>± .21</td>
</tr>
<tr>
<td>$\Gamma(Z')/\Gamma_{SM}$</td>
<td>1. ± .001</td>
<td>± .003</td>
<td>± .004</td>
</tr>
<tr>
<td>$\sigma_{\text{eff}}$ (fb)</td>
<td>1493 ± 2.0</td>
<td>564 ± 1.7</td>
<td>669 ± 2.9</td>
</tr>
</tbody>
</table>

$1 \text{ ab}^{-1} \Rightarrow \delta M/M \sim 10^{-4}$ & $\delta \Gamma/\Gamma = 3.10^{-3}$

Degenerate resonances e.g. D-BESS model

Can measure $\Delta M$ down to 13 GeV

Smeared lumi spectrum allows still for precision measurements

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Supersymmetry

Post-WMAP Benchmarks

E.G. $m_{1/2} = 1500$ GeV, $m_0 = 420$ GeV, $\tan \beta = 20$, $A = 0$ GeV, $\text{sign}(\mu) > 0$ (mSUGRA) (point H)

$\Rightarrow M_{\tilde{\mu}} = 1150$ GeV

Measure inclusive muon spectrum in $\tilde{\mu} \rightarrow \mu \chi^0$

$\Rightarrow E_{\text{max/min}} = \frac{E_{\text{beam}}}{2} (1 - \frac{M_{\tilde{\mu}}^2}{M_{\text{tilde}\mu}}) \times (1 \pm \sqrt{1 - \frac{M_{\tilde{\mu}}^2}{E_{\text{beam}}^2}})$

(Battaglia at al hep-ph/0306219)

# sparticles that can be detected
Higher mass precision at LC vs LHC

Mass measurements to $O(1\%)$ for smuons

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Summary: Physics at CLIC

Experimental conditions at CLIC are more challenging than at LEP, or ILC.

Physics studies for CLIC have included the effects of the detector, and backgrounds e.g. e+e- pairs and γγ events.

Benchmark studies show that CLIC will allow for precision measurements in the TeV range.

CLIC has a very large physics potential, reach beyond that of the LHC.

Urgent: Detector R&D will be needed: Tracking with good time stamping, improved calorimetry, mask area,…
Technological issues (R1/R2) for CLIC are being addressed with the CLIC Test Facility CTF3 @ CERN

- Aim to get all necessary results by 2009 and produce a CDR
- By 2009 first results of the LHC should start shaping the physics landscape

J.P. Delahaye
GIF 2004

Assumes extra resources via CLIC collaboration

CLIC is working together with ILC on common issues
CARE, EuroTeV

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Machine Detector Interface related issues to keep in mind if one plans for a facility that can be upgraded to a multi-TeV collider in future:

- Crossing angle needed of ~20 mrad (multi-bunch kink stability)
- Present design: Long collimator syst. and final focus (2.5 km each side)
- Energy collimators most important.
  Fast kicker solution not applicable. Maybe rotating collimators ...
- Gentle bending to reduce SR & beam spot growth → construct the linacs already under an angle of ~ 20 mrad
- Internal geometry differences of the collimation system and final focus, allow for enough space in the tunnels (O(m))
Summary

- LC physics and accelerator community has a lot of momentum
- ILC design starting to take shape
  - Machine to produce a CDR soon
  - All regions actively involved in its preparation
- Roadmap aims for a decision/start construction around 2009
  - First LHC data should be available by then
- CLIC multi-TeV study aims at proof of feasibility/CDR by 2009

Interesting times ahead!!

Important meeting grounds in 2005

**Snowmass**
ALCPG/ILC  
14-27/8

**Aspen**
Collider Physics from the Tevatron to the LHC to the nLinear Collider  
15/8-11/9
Albert De Roeck (CERN)
Developing Organization

International Technical Review Panel

IUPAP
ICFA
(J. Dorfan)
ILCSC
(M. Tigner)

1922
46 member countries -
Argentina ...... USA

1976
countries active
in HEP

2002
-outreach, define LC,
coordinate R/D,
facilitate tech choice,
identify ILC org. models

Phys & Det Sub-com
(D. Miller
H. Yamamoto
J. Brau)

Accel Sub-com
(G. Loew)

ITRP
(2004)
(B. Barish)

3 Regional Steering Committees
(W. Namkung - Asia)
(B. Foster - Europe)
(J. Dorfan - US)

Params Sub-com
(2003)
(R. Heuer)

GDI Task Force
(S. Ozaki)

Albert De Roeck (CERN)
### Summary: CLIC vs Hadron Colliders

ADR, F. Gianotti, J. Ellis hep-ph/0112004
U. Bauer et al. hep-ph/0201227

<table>
<thead>
<tr>
<th>Process</th>
<th>LHC 14 TeV 100 fb⁻¹</th>
<th>SLHC 14 TeV 1000 fb⁻¹</th>
<th>VLHC* 200 TeV 100 fb⁻¹</th>
<th>CLIC 3-5 TeV 1000 fb⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>squarks (TeV)</td>
<td>2.5</td>
<td>3</td>
<td>20.</td>
<td>1.5-2.5</td>
</tr>
<tr>
<td>sleptons (TeV)</td>
<td>0.34</td>
<td></td>
<td></td>
<td>1.5-2.5</td>
</tr>
<tr>
<td>Z' (TeV)</td>
<td>5.4</td>
<td>6.5</td>
<td>30-40</td>
<td>20-30</td>
</tr>
<tr>
<td>q* (TeV)</td>
<td>6.5</td>
<td>7.5</td>
<td>70-75</td>
<td>3-5</td>
</tr>
<tr>
<td>l* (TeV)</td>
<td>3.4</td>
<td></td>
<td></td>
<td>3-5</td>
</tr>
<tr>
<td>ED (ADD/2D/TeV)</td>
<td>9</td>
<td>12</td>
<td>65</td>
<td>30-55</td>
</tr>
<tr>
<td>WₖWₖ</td>
<td>3.4 σ</td>
<td>&gt; 4.0 σ</td>
<td>30 σ</td>
<td>70-90 σ</td>
</tr>
<tr>
<td>TGC (95%)</td>
<td>0.0014</td>
<td>0.0006</td>
<td>0.0003</td>
<td>0.00013- 0.00008</td>
</tr>
<tr>
<td>Λ Compos (TeV)</td>
<td>30</td>
<td>40</td>
<td>100</td>
<td>300-400</td>
</tr>
</tbody>
</table>

CLIC Comparable to VLHC

* Very Large Hadron Collider: 233 km Circumference

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Linear Colliders

Europe

TESLA
Superconducting Cavity

USA
NLC
High Power Klystron

Japan

GLC
Accelerator Test Facility

International collaborations

TESLA/NLC/GLC: 90 GeV → 1 TeV with 35-70 MV/m

CERN: CLIC Two-Beam acceleration scheme to reach >3 TeV with 150 MV/m

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Official Time Schedule

2005.2  Decide the director and location of Central GDI
2005.8  Establish Regional GDIs
2005.8  Decide the **design outline in Snowmass Workshop**
         (acc.gradient, 1 or 2 tunnel, dogbone/small DR, 
e+ generation etc)
2005 end Complete CDR with rough cost/schedule
2007 end Complete TDR, role of regions, start site selection
2008   Decide the site, budget approval
2009   Ground breaking
2014   Commissioning starts
Development of 45MV/m

- Single-cell test in Dec 2004
- Individual vertical test of four 9-cell cavities by Sep. 2005
  - Just in time for CDR completion
  - In existing facilities (AR east)
  - If expected performance not obtained,
    ⇒ change to slower plan for ILC 2nd stage
- Cryomodule test by end of 2006 ⇒ STF Phase 1
- Industrial design by TDR
The complementarity of the LHC and LC results has been studied by a working group and has produced a huge document (>450 pages, G. Weiglein principal editor, finishing stage...)

- Working group contains members from LHC and LC community + theorists
- Most meetings at CERN (one in the US)

Conclusion: lot to gain for analysis of BOTH machines if there is a substantial overlap in running time.

Example: at LHC masses of the measured particles are strongly correlated with the mass of the lightest neutralino

- sleptons
- squarks
- sbottom

Largely improve LHC mass measurements when LC $\chi_1^0$ value is used

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# Summary: Indicative Physics Reach

Units are TeV (except $W_L W_L$ reach)

$L_{\text{det}}$ correspond to 1 year of running at nominal luminosity for 1 experiment

<table>
<thead>
<tr>
<th>PROCESS</th>
<th>LHC 14 TeV 100 fb$^{-1}$</th>
<th>SLHC 14 TeV 1000 fb$^{-1}$</th>
<th>28 TeV 100 fb$^{-1}$</th>
<th>VLHC 40 TeV 100 fb$^{-1}$</th>
<th>VLHC 200 TeV 100 fb$^{-1}$</th>
<th>LC 0.8 TeV 500 fb$^{-1}$</th>
<th>LC 5 TeV 1000 fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Squarks</td>
<td>2.5</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>20</td>
<td>0.4</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td>$2\sigma$</td>
<td>$4\sigma$</td>
<td>$4.5\sigma$</td>
<td>$7\sigma$</td>
<td>$18\sigma$</td>
<td>$6\sigma$</td>
<td>$30\sigma$</td>
</tr>
<tr>
<td>$W_L W_L$</td>
<td>5</td>
<td>6</td>
<td>8</td>
<td>11</td>
<td>35</td>
<td>8†</td>
<td>30†</td>
</tr>
<tr>
<td>$Z'$</td>
<td>9</td>
<td>12</td>
<td>15</td>
<td>25</td>
<td>65</td>
<td>5-8.5†</td>
<td>30-55†</td>
</tr>
<tr>
<td>Extra-dim ($\delta=2$)</td>
<td>6.5</td>
<td>7.5</td>
<td>9.5</td>
<td>13</td>
<td>75</td>
<td>0.8</td>
<td>5</td>
</tr>
<tr>
<td>$q^*$</td>
<td>30</td>
<td>40</td>
<td>40</td>
<td>50</td>
<td>100</td>
<td>100</td>
<td>400</td>
</tr>
<tr>
<td>$\Lambda$ compositeness</td>
<td>0.0014</td>
<td>0.0006</td>
<td>0.0008</td>
<td>0.0003</td>
<td>0.0003</td>
<td>0.0004</td>
<td>0.00008</td>
</tr>
<tr>
<td>TGC ($\lambda_\gamma$)</td>
<td>0.0014</td>
<td>0.0006</td>
<td>0.0008</td>
<td>0.0003</td>
<td>0.0003</td>
<td>0.0004</td>
<td>0.00008</td>
</tr>
</tbody>
</table>

† indirect reach
(from precision measurements)

Don't forget: (much) better precision at an $e^+e^-$ machine

Ellis, Gianotti, ADR
[hep-ex/0112004](https://arxiv.org/abs/hep-ex/0112004)+ few updates

Albert De Roeck (CERN)
FROM MAIN BEAM GENERATION COMPLEX

Main Beams - 9 GeV/c
154 bunches of $4 \times 10^9$ e$^+$e$^-$
20 cm between bunches

e$^-$ MAIN LINAC (30 GHz - 150 MV/m)

DRIVE BEAM DECELERATOR 624 m
- $\approx 460$ MW/m
- RF power at 30 GHz

DRIVE BEAM ACCELERATOR
937 MHz - 1.18 GeV - 3.9 MV/m
- 182 modulators / klystrons
- 50 MW - 100 $\mu$s

INJECTOR

FINAL FOCUS

~ 39 m

FINAL FOCUS

Detectors

E-$e^+$

1248 m 39 m 2 cm between bunches

22 drive beams of 1952 bunches at 1.18 GeV
Charge 31 $\mu$C/beam - Energy 37 kJ/beam

312 m

COMBINER RINGS

78 m

BUNCH COMPRESSION

32 cm between bunches

Mean current 7.5 A
64 cm between bunches

42,944 bunches up to 16 nC/bunch at 50 MeV

78 m 39 m 32 cm between bunches

92 $\mu$s

352 trains of 122 bunches at 1.18 GeV
Total energy 812 kJ

Seminar on CLIC technology: 12/4
It is possible!

Geological analyses show that there is a continuous stretch of 40 km parallel to the Jura and the lake, with good geological conditions.

Reminder

The CLIC study is a site independent feasibility study aiming at the development of a realistic technology at an affordable cost for an $e^+e^-$ Linear Collider in the post-LHC era for Physics in the multi-TeV center of mass colliding beam energy range.
Luminosity Spectrum

Spectra for CLIC studies (sharper ↔ high lumi)

CLIC.01: \( \mathcal{L} = 1.05 \times 10^{35} \)  
CLIC.02: \( \mathcal{L} = 0.40 \times 10^{35} \)

Energy loss due to beam-beam interactions

Luminosity within 1% & 5% of c.m. energy

<table>
<thead>
<tr>
<th>Energy (TeV)</th>
<th>0.5</th>
<th>1</th>
<th>3</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mathcal{L} ) in 1% ( \sqrt{s} )</td>
<td>71%</td>
<td>56%</td>
<td>30%</td>
<td>25%</td>
</tr>
<tr>
<td>( \mathcal{L} ) in 5% ( \sqrt{s} )</td>
<td>87%</td>
<td>71%</td>
<td>42%</td>
<td>34%</td>
</tr>
</tbody>
</table>

Preliminary Results: expect accuracy \( \frac{\Delta \sqrt{s}}{\sqrt{s}} \approx 10^{-4} \) for 100 fb\(^{-1}\)

Luminosity spectrum not as sharply peaked as e.g. at LEP

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**γγ Background**

\[ \gamma\gamma \rightarrow \text{hadrons: 4 interactions/bx with } W_{\text{HAD}} > 5 \text{ GeV} \]

Neutral and charged energy as function of \( \cos\theta \) per bx

Particles accepted within \( \theta > 120\text{mrad} \)

For studies: take 20 bx and overlay events

Most activity at small angles
CLIC Tools for Background/Detector

Physics generators (COMPHEP PYTHIA6,...) 
+ CLIC lumi spectrum (CALYPSO)

+ \gamma \gamma \rightarrow \text{hadrons background}
  e.g. overlay 20 bunch crossings
  (+ e+e- pair background files...)

Detector simulation
• SIMDET (fast simulation)
• GEANT3 based program

⇒ Study benchmark processes
A Detector for a LC

TESLA TDR Detector

Background at the IP enforces use of a mask

CLIC: Mask covers region up to 120 mrad
Energy flow measurement possible down to 40 mrad

~TESLA/NLC detector qualities: good tracking resolution, jet flavour tagging, energy flow, hermeticity,...
Higgs Production

Cross section at 3 TeV:
- Large cross section at low masses
- Large CLIC luminosity → Large events statistics
- Keep large statistics also for highest Higgs masses

Low mass Higgs: 400 000 Higgses/year
45K/100K for 0.5/1 TeV LC

\[ \sigma_{ZH+H\gamma} \text{ (fb)} \]

\[ \sqrt{s} = 3000 \text{ GeV} \]
\[ \sqrt{s} = 500 \text{ GeV} \]
\[ \sqrt{s} = 350 \text{ GeV} \]

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Higgs: Strength of a multi-TeV collider

- Precision measurements of the quantum numbers and properties of Higgs particles, for large Higgs mass range
- Study of Heavy Higgses (e.g. MSSM H, A, H$^\pm$)
- Rare Higgs decays, even for light Higgs
- Higgs self coupling over a wide range of Higgs masses
- Study of the CP properties of the Higgs...

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$M_H$ (GeV)</th>
<th>$\delta X/X$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta g_{Htt}/g_{Htt}$</td>
<td>120–180</td>
<td>0.05–0.10</td>
</tr>
<tr>
<td>$\delta g_{Hbb}/g_{Hbb}$</td>
<td>180–220</td>
<td>0.01–0.03</td>
</tr>
<tr>
<td>$\delta g_{H\mu\mu}/g_{H\mu\mu}$</td>
<td>120–150</td>
<td>0.03–0.10</td>
</tr>
<tr>
<td>$\delta g_{HHH}/g_{HHH}$</td>
<td>120–180</td>
<td>0.07–0.09</td>
</tr>
<tr>
<td>$g_{HHHH}$</td>
<td>120</td>
<td>$\neq 0$ (?)</td>
</tr>
</tbody>
</table>