Alignment and Stabilization Issues in the Compact Linear Collider (CLIC)

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Overview of my presentation:

1. Introduction
   - Challenges for future LC’s
   - The Compact Linear Collider (CLIC)

2. Alignment and stabilization in a LC
   - Linac and final focus systems
   - How we will operate CLIC
   - CLIC tolerance table

3. Counteracting errors of magnet positions
   - Sources of motion
   - Achieving the required pre-alignment in CLIC
   - Stabilize CLIC quadrupoles to the sub-nm level

4. Conclusions
Introduction

**Goal of accelerator physicists:** design/build machines that produce high energy beams and deliver high luminosities!

1) Centre-of-mass **ENERGY** \( (E_b) \)

Discovery reach of new particles’ production \( (E=mc^2) \)

2) **LUMINOSITY** \( (L) \)

Event rate:

\[
N_{\text{event}} = \sigma_{\text{interest}} \times L
\]

**Linear colliders:**

\[
L \propto \frac{f_{\text{rep}} N_e^2}{\sigma_x \sigma_y}
\]

Beam charge

Repetition rate

Transverse beam sizes

**Beam power** (~30 MW) limits the repetition rate in linear colliders high energy \( \Rightarrow \) small \( f_{\text{rep}} \)

Promise of future linear colliders:

Collide beam of nanometre spot size \( (\text{nanobeams})! \)
The Compact Linear Collider (CLIC) study at CERN

<table>
<thead>
<tr>
<th>Energy (c.m.)</th>
<th>3-5 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity</td>
<td>$0.8 \times 10^{35}$ cm$^{-2}$s$^{-1}$</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>100 Hz</td>
</tr>
<tr>
<td>Colliding beam size</td>
<td>60 nm (H) x 0.7 nm (V)</td>
</tr>
<tr>
<td>Beam area</td>
<td>$4.2 \times 10^{-13}$ cm$^2$</td>
</tr>
<tr>
<td>Total machine length</td>
<td>$\sim 2 \times 17.5$ km</td>
</tr>
</tbody>
</table>

Main challenges:

1. Small beam sizes
2. Large accelerating fields (150 MV/m)
3. Efficient particle sources
4. Operation with pulsed beams (low $f_{\text{rep}}$)

- Production of small emittance beams
- Emittance preservation along $\sim 35$ km
- Stable collision of nanobeams

Achieved: $1.7 \times 0.9 \mu m$ (SLC)
Advance in accelerator technology required!

… a water molecule!
A lot of interest on linear colliders around the world!

### Beam size [nm]

<table>
<thead>
<tr>
<th>Where?</th>
<th>Energy [TeV]</th>
<th>Luminosity [cm(^{-2}) s(^{-1})]</th>
<th>Length [km]</th>
<th>Technology</th>
<th>Beam size [nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLIC</td>
<td>3-5</td>
<td>(8.0 \times 10^{34})</td>
<td>33.2</td>
<td>Two-beam acceleration</td>
<td>0.7</td>
</tr>
<tr>
<td>TESLA</td>
<td>0.8</td>
<td>(5.8 \times 10^{34})</td>
<td>32.0</td>
<td>Superconducting RFs</td>
<td>5</td>
</tr>
<tr>
<td>NLC/JLC</td>
<td>1</td>
<td>(2.5 \times 10^{34})</td>
<td>33.0</td>
<td>Normal conducting RFs</td>
<td>2.1</td>
</tr>
</tbody>
</table>

Stabilization of nanobeams: hot topic since several years!

- ICFA ground motion workshop (SLAC, Stanford, 2000)
- ICFA nanobeam workshop (*Nanobeam2002*, Lausanne, 2002)
- Nanobeam 2005, in Japan (Kyoto)?
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**Scheme of a high energy linear collider:**

- **Electron main LINAC**
  - Compressor
  - Electron source
  - Damping Ring
  - Final Focus
  - Particle detector
  - Beam dump
  - Final Focus
  - IP
  - Electron source
  - ~ 14 km

- **Positron main LINAC**
  - Positron source
  - Final Focus

Two beams accelerated independently and steered into collision.

**Main sub-systems:**

<table>
<thead>
<tr>
<th>Sub-system</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Injectors</td>
<td>Provide e+/e- beams</td>
</tr>
<tr>
<td>2. Damping rings</td>
<td>Provide small emittance</td>
</tr>
<tr>
<td>3. Bunch compressors</td>
<td>Provide short bunches</td>
</tr>
<tr>
<td>4. Linear accelerator</td>
<td>Provide acceleration</td>
</tr>
<tr>
<td>5. Collimation system</td>
<td>Provide small background</td>
</tr>
<tr>
<td>6. Final focus system</td>
<td>Provide small beams</td>
</tr>
</tbody>
</table>

Circular! See previous talk

Addressed here!

Concerned by alignment / stability
The linear accelerator:

1. Accelerate the beam  
   RF cavities
2. Keep beams focused  
   Quadrupole magnets
3. Correct orbit  
   Diagnostics / Correctors

Acceleration

Focusing

See later…

Cross section:

Quadrupoles

Beam envelope

2 x 1300 quadrupoles required for the two linacs!!
Support for active alignment

Position pickup’s with stretched wire

Cooling water

Possible to visit a mock-up of CTF2 accelerator!

Courtesy of H. Braun
RF cavities

• $E(t)$ field that accelerates the bunches
• $E \geq 150$ MV/m; $f = 30$ GHz

• We need MANY cavities to maximize beam energy $\Rightarrow$ 90% of total length $\geq 13$ km filled with cavities!

Courtesy of W. Wuensch

Iris diameter = 4 mm
The final focus system:

1. Strong final focus quadrupoles to squeeze beams
2. Diagnostics / beam steering (feedback)

Final focus quadrupoles:
- 2 x 2 = 4 magnet in total, at 3.5 m from IP
- Gradient $\approx 400$ T/m
- Small aperture: 3.8 mm inner radius
- Permanent magnet design (cake pieces)
What would we like to have to obtain the desired luminosity performance?

ALL lattice components along the ~ 35 km of CLIC perfectly aligned to the nominal beam trajectory!

\[ \mathcal{L} \propto \frac{f_{\text{rep}} N_e^2}{\sigma_x \sigma_y} \]

The two opposing beams have the desired spot sizes at the interaction point and always collide

⇒ We get the optimum luminosity!

What would will we actually get?

Magnet aligned within some tolerances ⇒ Beams do not follow the ideal trajectory!

Larger beam sizes
Relative BB offsets
Pulse-to-pulse jitters (position/size)
Asymmetric collisions

⇒ Degradation of the luminosity performance (design value)!

How do we get some luminosity?
What luminosity reduction can we tolerate?
How do we make the accelerator work?

1. We pre-align the machine sufficiently well to send a pilot beam
   Static error of $10-50 \, \mu\text{m}$ relative RMS over distances of 100-200 m
   (< a few betatron oscillations)

   Then: Information from beam measurements can be used
   to optimize the position of quadrupoles and RF’s!

2. We use a beam-based alignment procedure to align the various
   components to the optimum beam trajectory
   Active positioning to the $\mu\text{m}$ level

   Then: Optimization of the luminosity performance!

3. We stabilize the pulse-to-pulse jitter to reliably produce
   luminosity: keep beams in collision, keep small emittances
   Absolute stability to the nanometre level!!
Different frequency regimes of motion have different impacts on the beam dynamics…

Alignment…

Graph from Andrei Seryi, SLAC.

\[ f_{\text{cut}} \approx \frac{f_{\text{rep}}}{25} = 4 \text{ Hz (CLIC)} \]

Correction with beam based feedbacks

Limited by \( f_{\text{rep}} \)

Mechanical stability of magnets

Based on experience on previous machines!
Summary of CLIC tolerances

Static pre-alignment requirements for the LINAC
(alignment of the BPM’s required to know beam orbit)

RF’s: 10 µm
Quadrupoles: 50 µm

RMS alignment error over distances of 100-200 m

// Beam-based active alignment (~ µm level) //

Tolerances of pulse-to-pulse jitter stability of quadrupoles (2% ΔL/L)
(after beam-based alignment)

<table>
<thead>
<tr>
<th>Number of elements</th>
<th>Horizontal tolerance</th>
<th>Vertical tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final focus</td>
<td>2 x 2</td>
<td>0.0078 µm</td>
</tr>
<tr>
<td>LINAC</td>
<td>1300 x 2</td>
<td>0.014 µm</td>
</tr>
<tr>
<td>RF’s</td>
<td>&gt; 13 km</td>
<td>&gt; 100 µm</td>
</tr>
</tbody>
</table>

Horiz. tolerances looser: \( \sigma_x = 100 \times \sigma_y \)

MECHANICAL STABILITY required for fast motion above 4 Hz!!
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4. **Conclusions**
Sources of motion:  

Natural ground motion + cultural noise  
Accelerator environment (pumps, ventilation, water…)  
Resonances of magnet supports

Measurements in the LEP tunnel  
(W. Coosemans et al., 1993)

- **CLIC FF tolerance**
- **LEP ON**  
  (noisy: accelerator environment)
- **LEP OFF**  
  (quiet)

- 2.5 μm
- 3600 x σ_y

(Shiltsev et al., 1994)
Noise in the quiet LHC tunnel:

- **Lift** induces a vibration of the detector cave at ~ 30 Hz
- **Ventilation** increases the noise with many contributions at various frequencies

Lift

\[ \text{\textasciitilde 0.4 nm (RMS)} \]

Vibration measured in the detector cave, tens of metres away from the lift.

Ventilation OFF

Ventilation ON

Effect on motion above 20Hz: \( \text{\textasciitilde 0.1 nm} \)
**Effects of vibration measured in the laboratory (CERN, surface)**

- **Effect of cooling water** (different flows) ⇒ increase the motion by several nm, but can be kept under control!

- **Resonances of the alignment support** (not optimized!) ⇒ dangerous vibrations, well beyond the limit of beam-based feedbacks.
Slow motion…

Ocean wave motion (up to a few $\mu$m)

Measurements carried out with low- and high-frequency geophones, in our laboratory on surface (CERN-Meyrin).

Measurements over four orders of magnitude in frequency!

Effect of temperature on alignment

Slow (~hours) displacement up to $\sim 40 \mu$m due to shrinkage of rubber in the feet.

Should be easily compensated with beam-based feedbacks!

Measurement done at CERN with the stretchewire system.
Achieving the required pre-alignment in CLIC


See talk at this workshop by H. Mainaud-Durand (07/10)

Pre-alignment achieved with a system that includes:

- Optical offset measurements (RASNIK/Nikhef)  
  Resolution = 1 μm, over a few m
- Stretched wire system (WPS)  
  Resolution = 10 μm over ~200 m
- Hydrostatic levelling system (HLS)  
  Height reference for wire every ~50 m

Redundant measurements with two wires.

Wire sagitta monitored with HLS system:

*Pictures by W. Coosemans F. Becker*
**Issues:**
- effect of slope of surface
- local distortions of gravity (rocks, holes)
- tidal motion (earth, water)

**Most of these effects seem under control!**

*Detailed studies of these effects in the CERN area carried out by W. Coosemans et al and implemented in simulations…*

**Expected alignment error along the CLIC linac (~14 km)**

Alignment error along ~14 km with stretched wires of 200 metres stay around the **10 µm level!**

*(Simulations with 100 seeds)*

*Courtesy of W. Coosemans, I. Wilson et al.*
Stabilize CLIC quadrupoles to the sub-nanometre level

Results achieved in the framework of the CLIC Stability Study


Goal of our study:

Demonstrated the feasibility of stabilizing accelerator magnets to the sub-nanometre level required by future linear colliders like CLIC (0.2 nm RMS above 4 Hz)

Our approach:

Use state-of-the-art stabilization equipment to stabilize CLIC quadrupoles in a normal working environment
The CLIC test stand for vibration measurements and magnet stabilization:

The experimental setup includes:

- Sensors for vibration measurements (geophones)
- Honeycomb table (virtually) with no internal resonances
- Prototypes accelerator magnets
- State-of-the-art stabilization equipment
- Stretched-wire system for alignment measurements
How do we measure nanometre vibrations?

Triaxial geophones are used to measure vibrations (~ 4Hz-315 Hz frequency range).

\[ V_{\text{coil}} \approx -n(2\pi r_c B)v \]

The geophones are seismometers that measure velocities versus time with respect to a reference mass at rest.

Sub-nanometre resolution!

Resolution of 0.28 nm for RMS motion above 4 Hz

Absolute error < 10 %!
How do we stabilize accelerator magnets?

- **Passive damping** → stiff rubber
- **Active damping** → geophones / piezo crystals

This system provides a damping of 3D table vibrations!

4 feet stabilize a honeycomb table.

---

**Stacis2000 by TMC**

**Active stabilization system**

**Load**

**Rubber**

**Piezoelectric actuator**

**Geophone**

**Floor**

CLIC prototype quadrupole

Honeycomb table
Vertical stabilization of a CLIC prototype quadrupole

CLIC prototype magnets stabilized to the sub-nanometre level !!

Above 4Hz: 0.43 nm on the quadrupole instead of 6.20 nm on the ground.
Stability of stabilization performance

Quadrupole vibrations kept below the 1 nm level over a period of several days, in a normal working area!
Conclusions

1. Linear colliders are the most promising option for near-future high-energy particle physics of light leptons ($e^+e^-$)

2. **Promise:** reliably produce and collide **nanobeams**!

3. The imposed **tolerances** are three orders of magnitudes tighter than what has been needed so far in particle accelerators
   - Pre-alignment of the linac ($\sim$15km x 2) 10 $\mu$m (RMS over 200m)
   - LINAC quadrupoles (2 x 1300) 1.3 nm
   - FF quadrupoles (2 x 2) 0.2 nm

4. **Encouraging results** have been achieved so far:
   - Pre-alignment 10 $\mu$m tolerance is within reach!
   - Stabilization ($f > 4$Hz) CLIC quadrupoles stabilized to 0.5 nm!

5. Even though a final demonstration in a **real environment** (tunnel, noise from accelerator, detector cave, …) remains to be fully demonstrated, the required technology will be in hand when needed!
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