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

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Overview of my presentation:

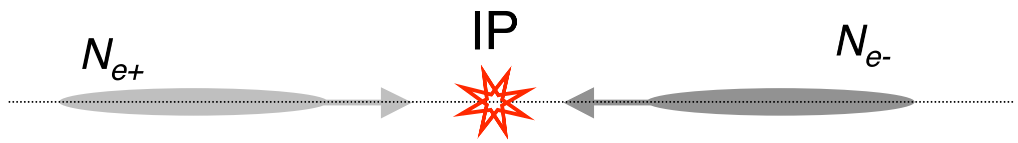
1. **Introduction**
   - Challenges for future LC's
   - The Compact LInear Collider (CLIC)
2. **Alignment and stabilization in a LC**
   - Linac and final focus systems
   - How we will operate CLIC
   - CLIC tolerance table
3. **Counteracting errors of magnet positions**
   - Sources of motion
   - 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: $N_{\text{event}} = \sigma_{\text{interest}} \times \mathcal{L}$



Linear colliders:

$$\mathcal{L} \propto \frac{f_{\text{rep}} N_{\text{e}}^2}{\sigma_x \sigma_y}$$

Repetition rate (f_{rep}), *Beam charge* (N_e), *Transverse beam sizes* ($\sigma_x \sigma_y$)

$$P \propto [N_{\text{e}} f_{\text{rep}}] E_{\text{b}}$$

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

Promise of future linear colliders:

Collide beam of nanometre spot size (*nanobeams*)!

The Compact LInear Collider (CLIC) study at CERN

Achieved:
1.7x0.9μm *(SLC)*
Advance in accelerator technology required!

Energy (c.m.)	3-5 TeV
Luminosity	0.8 x 10^{35} $cm^{-2}s^{-1}$
Repetition rate	100 Hz
Colliding beam size	**60 nm** (H) **x 0.7 nm** (V)
Beam area	4.2 10^{-13} cm^2
Total machine length	~ 2 x 17.5 km

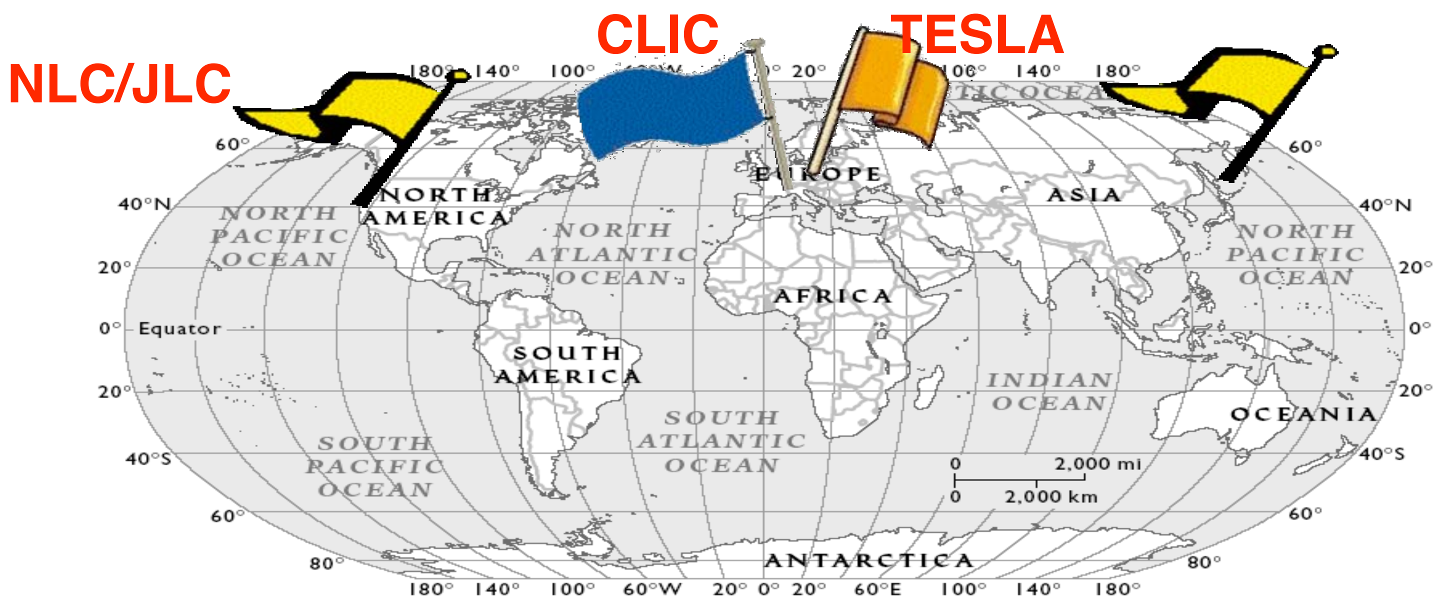
… a water molecule!

Main challenges:

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

- *Production of small emittance beams*
- *Emittance preservation along ~ 35 km*
- *Stable collision of nanobeams*

A lot of interest on linear colliders around the world!



ILC

"Nanobeams"

	Where?	Energy [TeV]	Luminosity [cm^{-2} s^{-1}]	Length [km]	Technology	Beam size [nm]
CLIC	CERN	3-5	8.0×10^{34}	33.2	Two-beam acceleration	0.7
TESLA	DESY	0.8	5.8×10^{34}	32.0	Superconducting RFs	5
NLC/JLC	SLAC/KEK	1	2.5×10^{34}	33.0	Normal conducting RFs	2.1

Stabilization of nanobeams: hot topic since several years!

- G.E. Fisher, *Ground motion and its effects on accelerator design* (1985)
- ICFA ground motion workshop (SLAC, Stanford, 2000)
- ICFA nanobeam workshop (*Nanobeam2002*, Lausanne, 2002)
- Nanobeam 2005, in Japan (Kyoto)?

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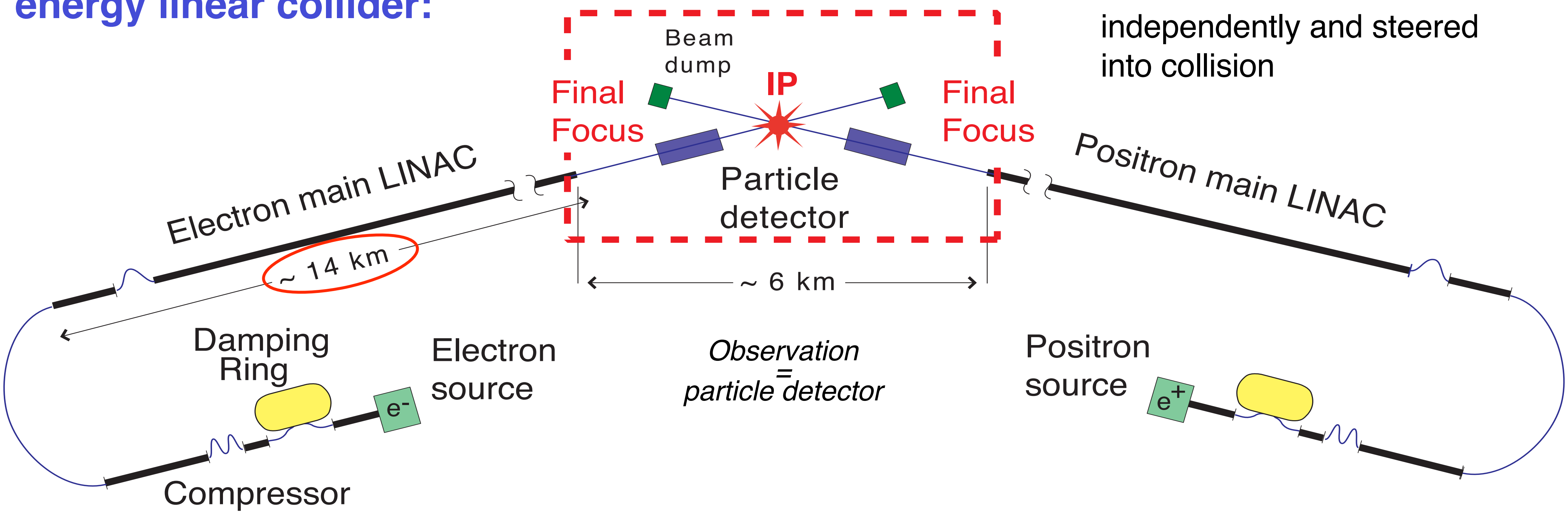
Scheme of a high energy linear collider:



Main sub-systems:

1. Injectors	Provide e^+/e^- beams
2. Damping rings	Provide small emittance
3. Bunch compressors	Provide short bunches
4. Linear accelerator	Provide acceleration
5. Collimation system	Provide small background
6. Final focus system	Provide small beams

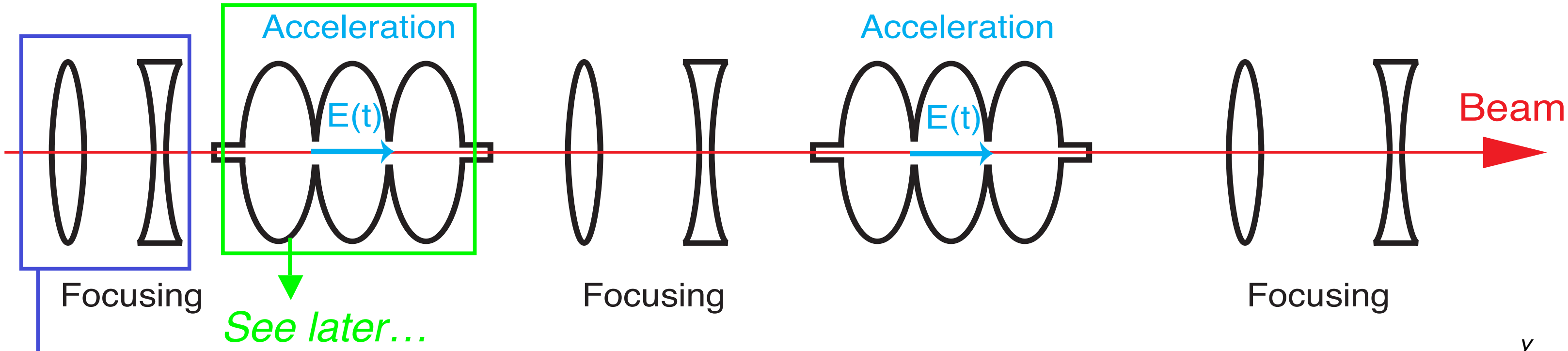
Circular! See previous talk → 2. Damping rings

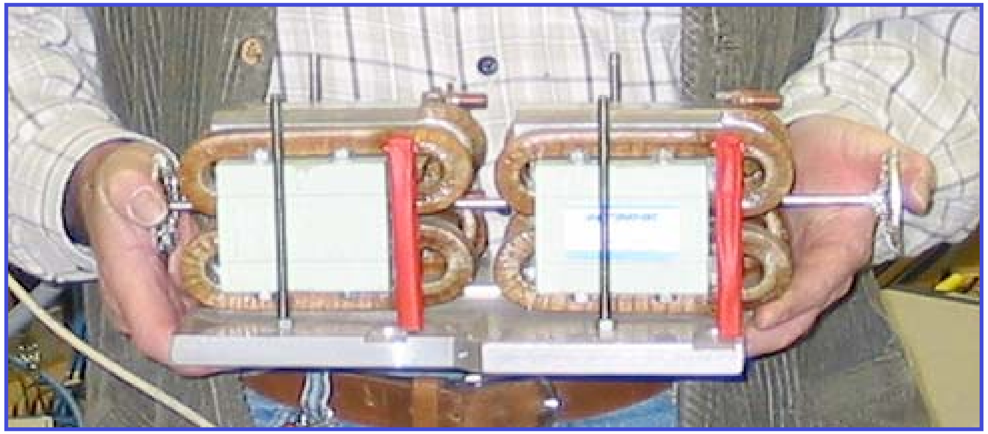
Addressed here ! → 4. Linear accelerator, 6. Final focus system

Concerned by alignment / stability ← 2, 4, 6

The linear accelerator:

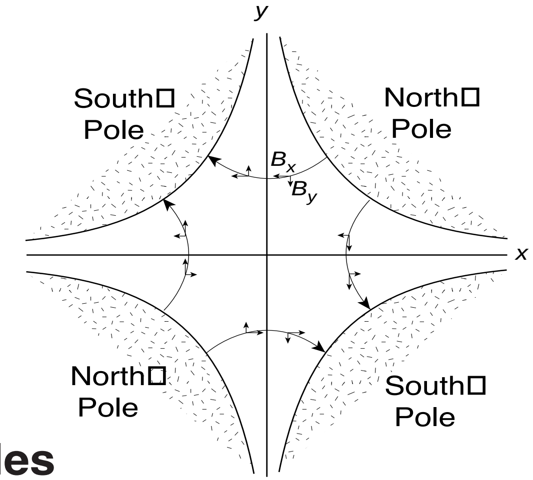
1. *Accelerate the beam* — *RF cavities*
2. *Keep beams focused* — *Quadrupole magnets*
3. *Correct orbit* — *Diagnostics / Correctors*



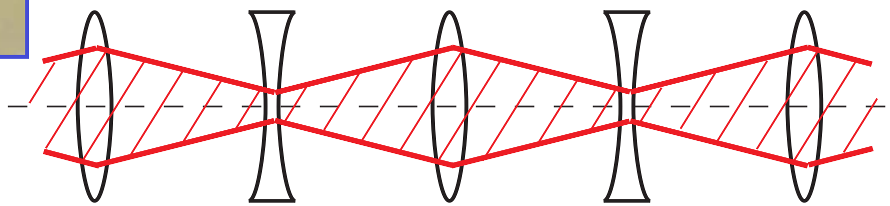


2 x 1300 quadrupoles required
for the two linacs!!

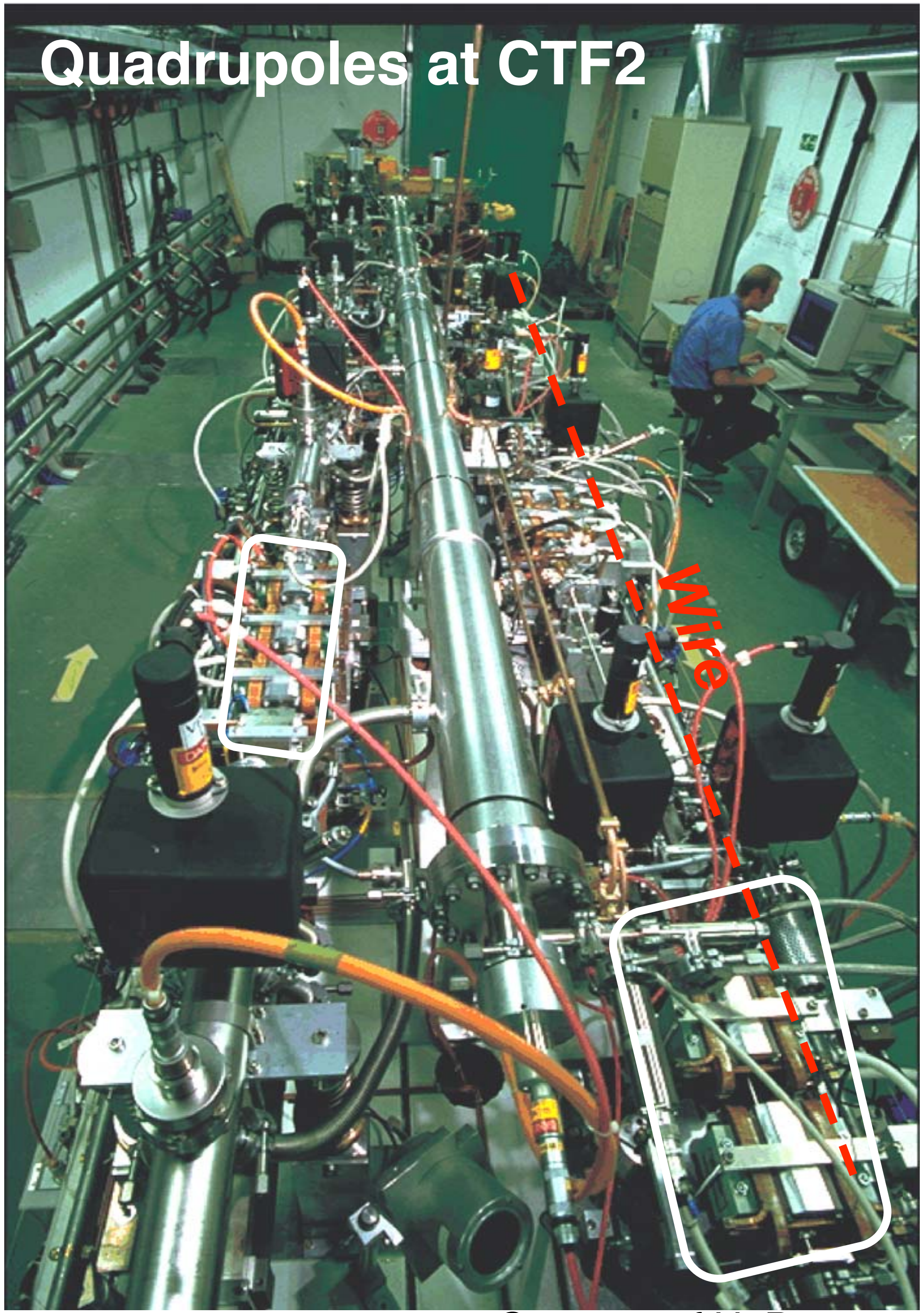
Cross section:



Quadrupoles

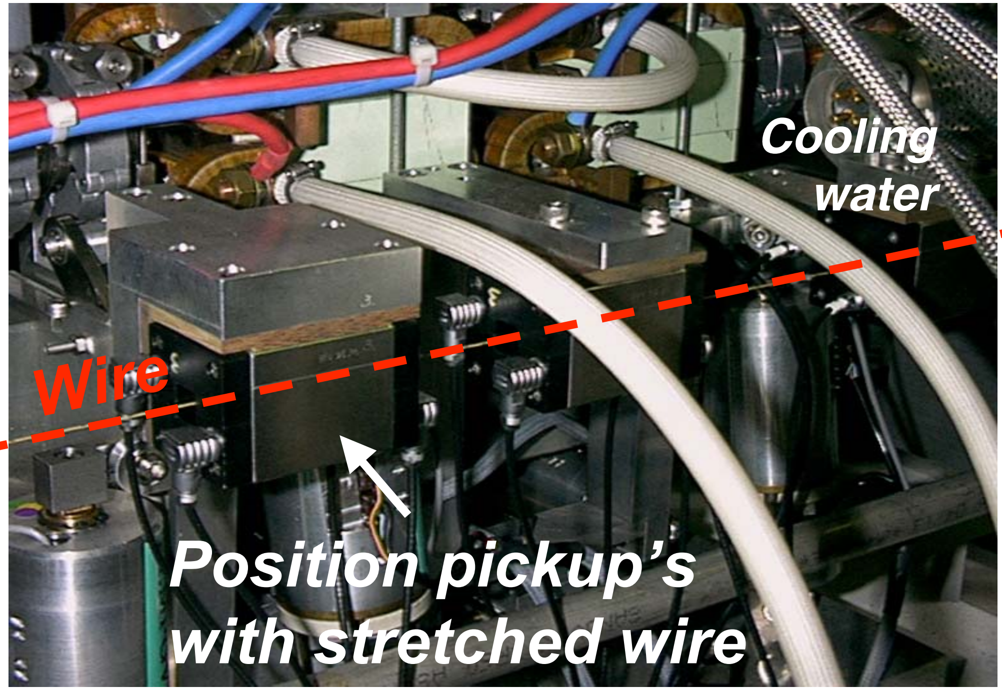


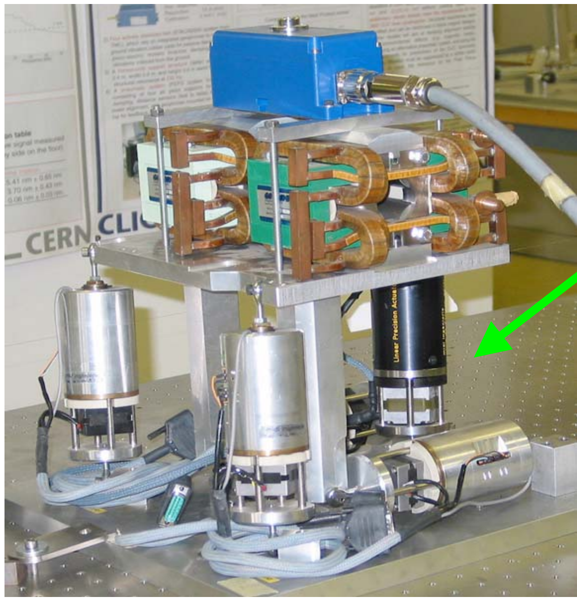
Beam envelope



Courtesy of H. Braun

Active Alignment System



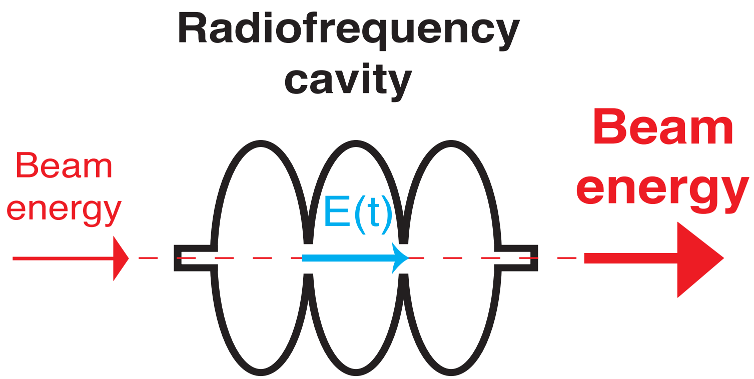


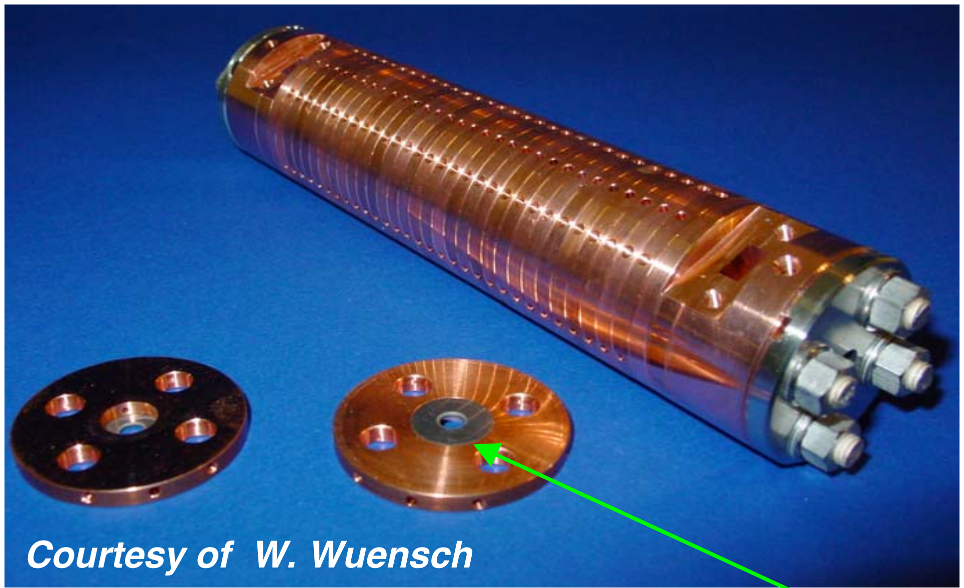
Support for active alignment

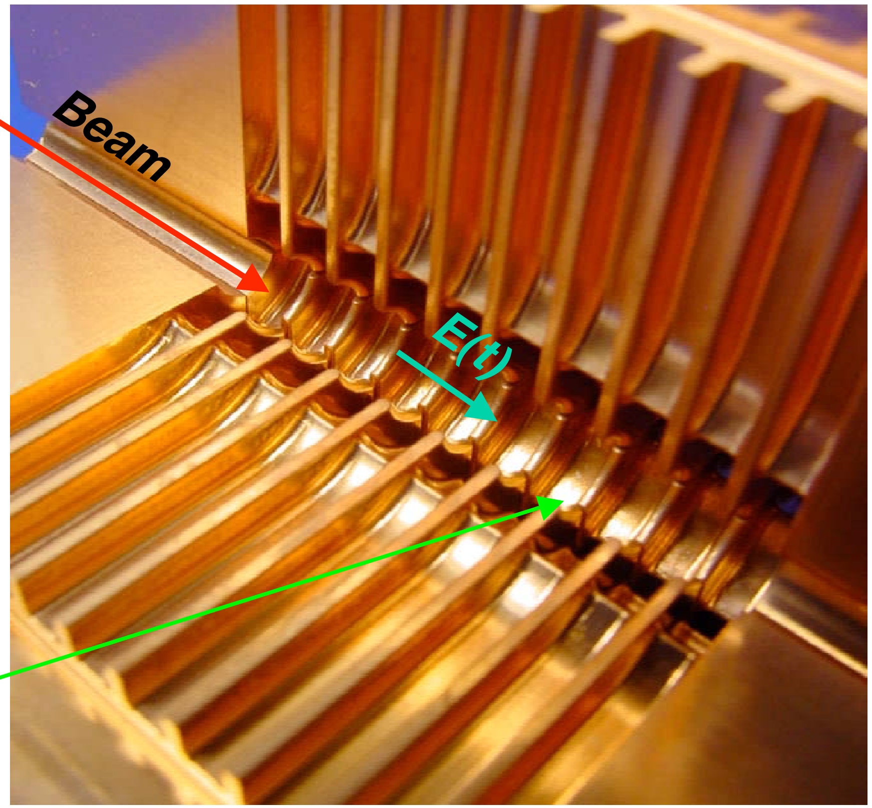
Possible to visit a mock-up of CTF2 accelerator!

RF cavities

- *E(t)* field that accelerates the bunches
- E ≥ 150 MV/m; f = 30 GHz
- We need **MANY** cavities to maximize beam energy ⇒ 90% of total length ≥ **13 km filled with cavities!**





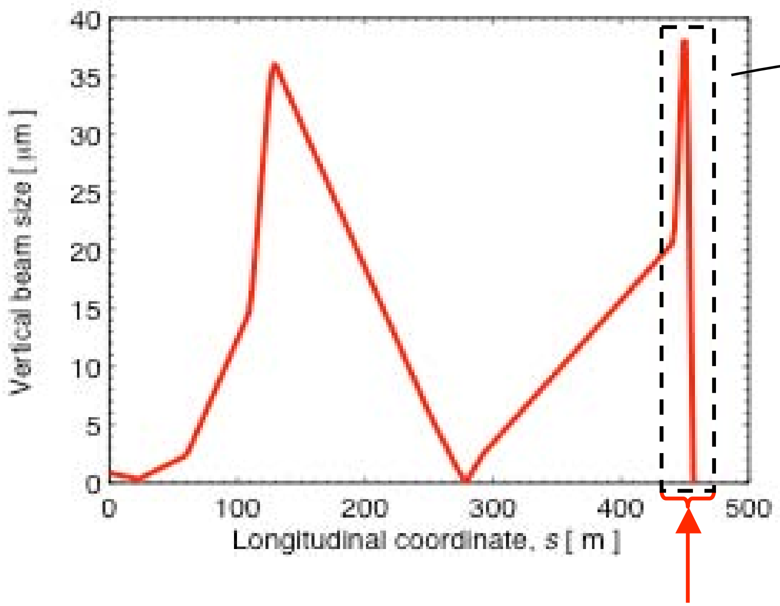


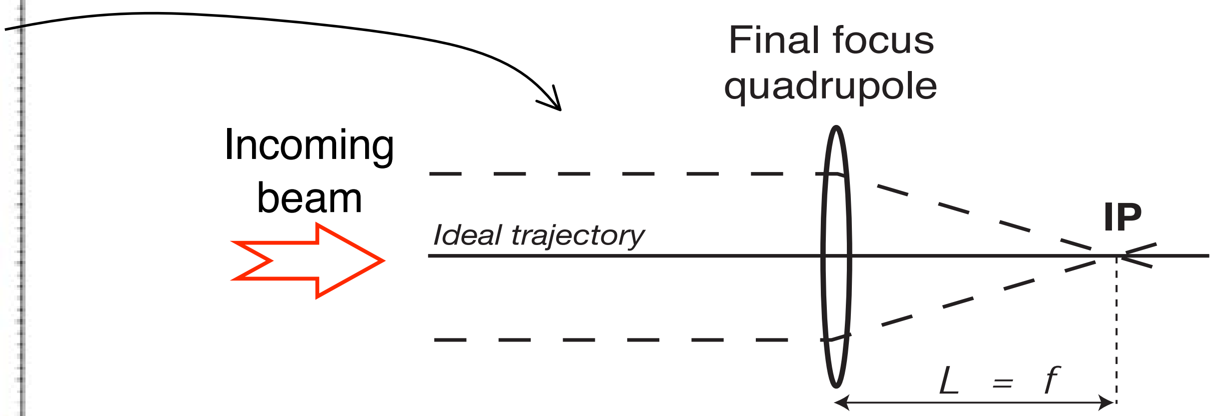
Iris diameter = 4 mm

The final focus system:

1. Strong final focus quadrupoles to squeeze beams

2. Diagnostics / beam steering (feedback)

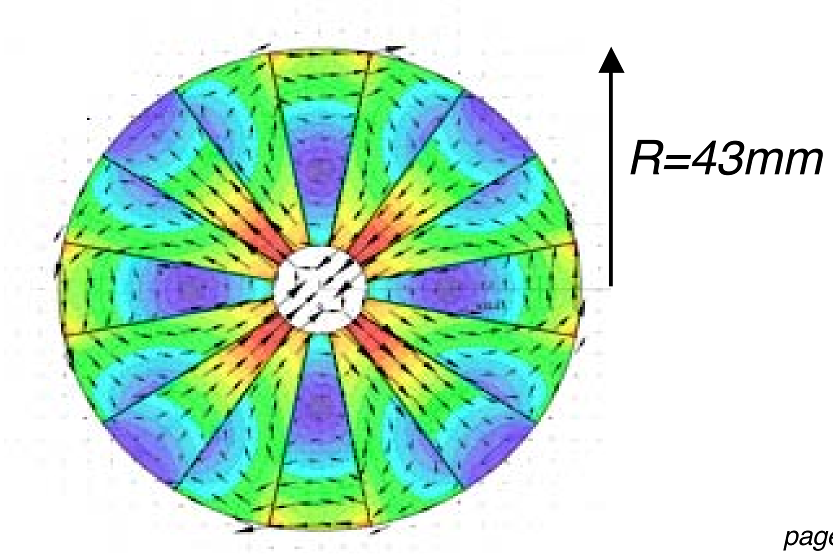




Actually, two quadrupoles used to squeeze both horizontal and vertical size!

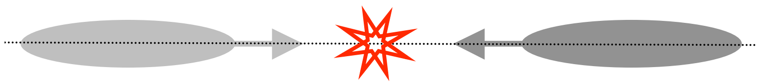
Final focus quadrupoles:

- 2 x 2 = 4 magnet in total, at 3.5 m from IP
- Gradient = ~ 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!



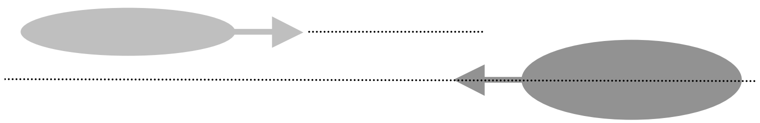
$$\mathcal{L} \propto \frac{f_{\text{rep}} N_{\text{e}}^2}{\sigma_x \sigma_y}$$

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 μm 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!* ⇒ ***Beam-based alignment***

2. We use a beam-based alignment procedure to align the various components to the optimum beam trajectory

Active positioning to the μm level

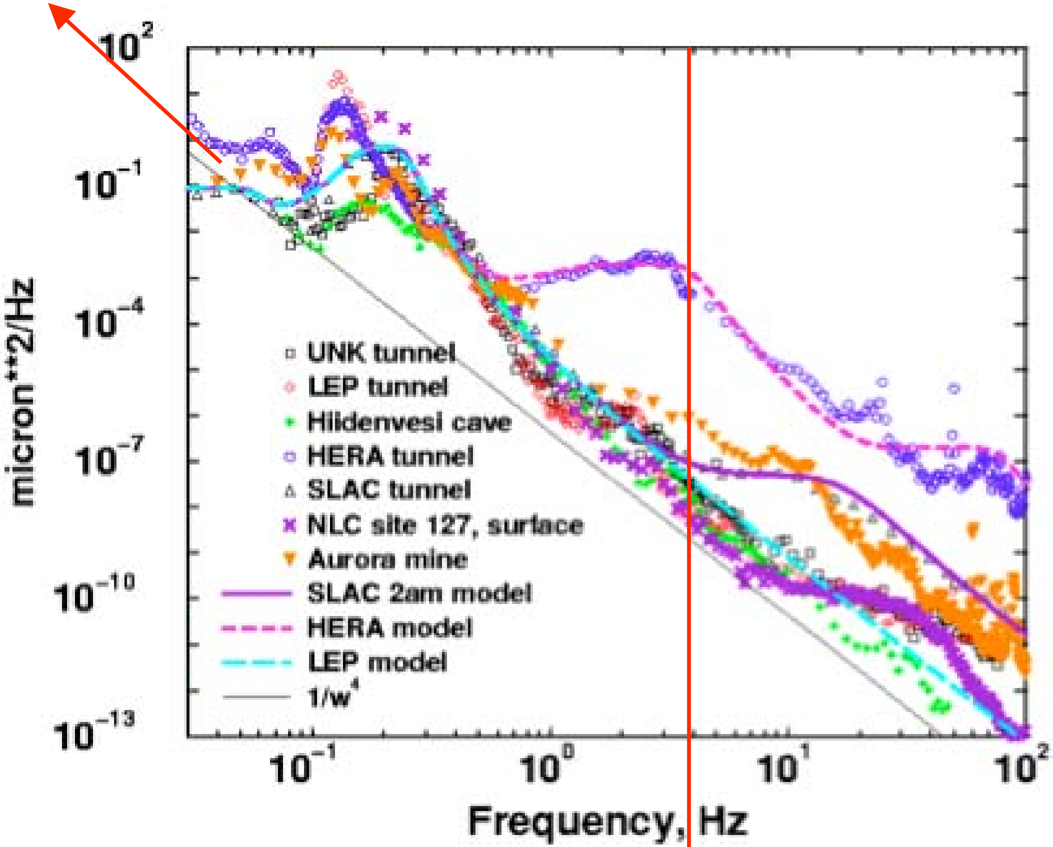
Then: *Optimization of the luminosity performance!* ⇒ ***Beam-based feedbacks / mechanical stabilization***

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.

Correction with beam based feedbacks

Limited by f_{rep}

Slow motion

Fast motion

Mechanical stability of magnets

$f_{cut} \approx f_{rep}$ /25 = 4 Hz (CLIC)

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)

		Number of elements	Horizontal tolerance	Vertical tolerance
Beam offsets →	Final focus	2 x 2	0.0078 μm	**0.0002 μm**
	LINAC	1300 x 2	0.014 μm	0.0013 μm
Beam sizes →	RF's	> 13 km	> 100 μm	≈ 1 μm

Horiz. tolerances looser : $\sigma_x = 100 x \sigma_y$

MECHANICAL STABILITY required for fast motion **above 4 Hz**!!

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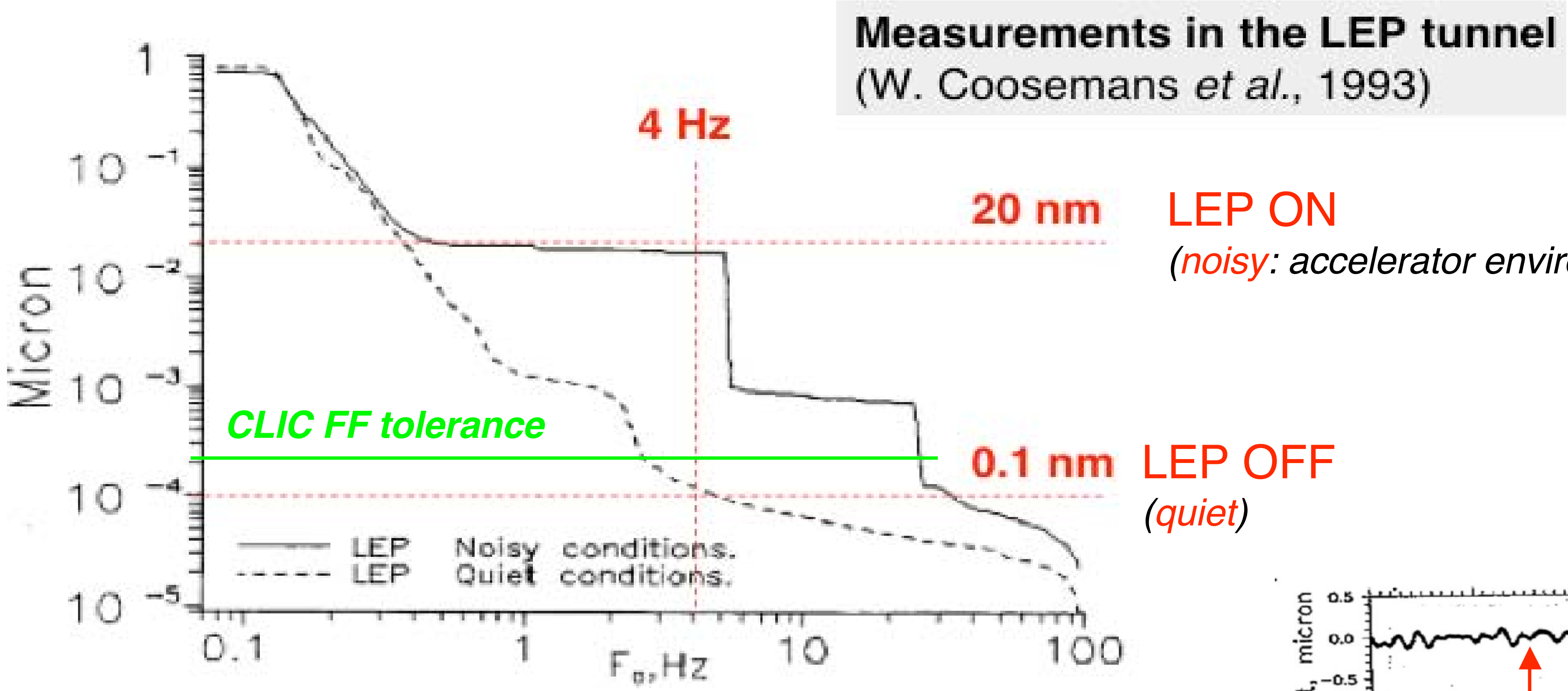
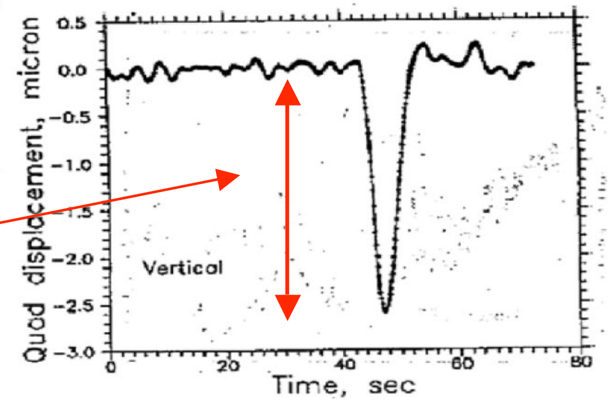
Sources of motion:

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



LEP ON
(*noisy*: accelerator environment)

LEP OFF
(*quiet*)

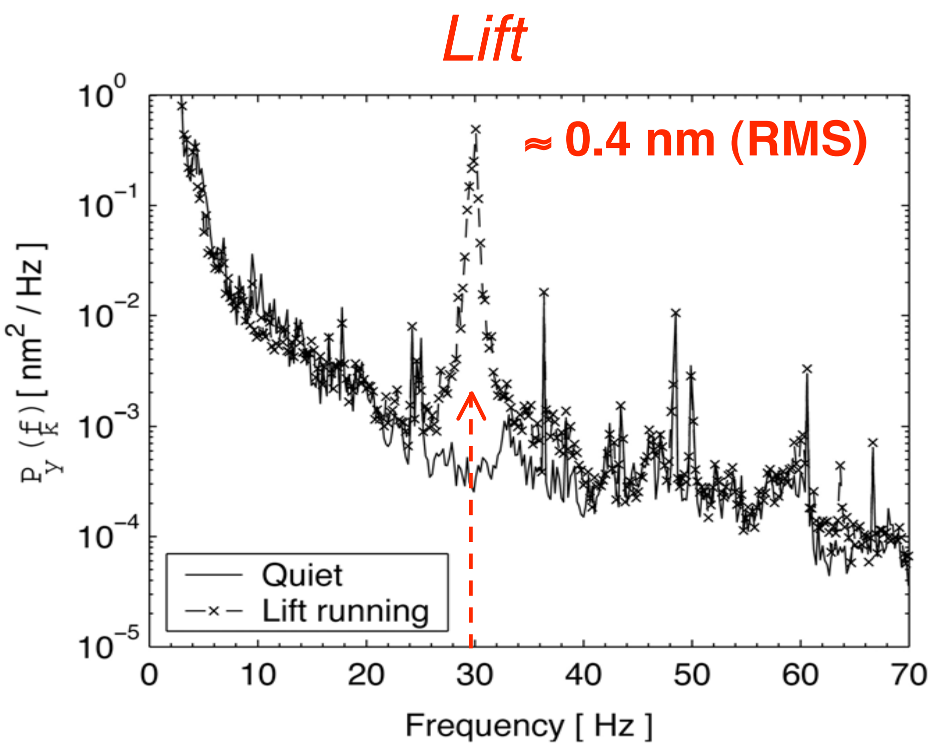


2.5 μm
3600 x σ_y!

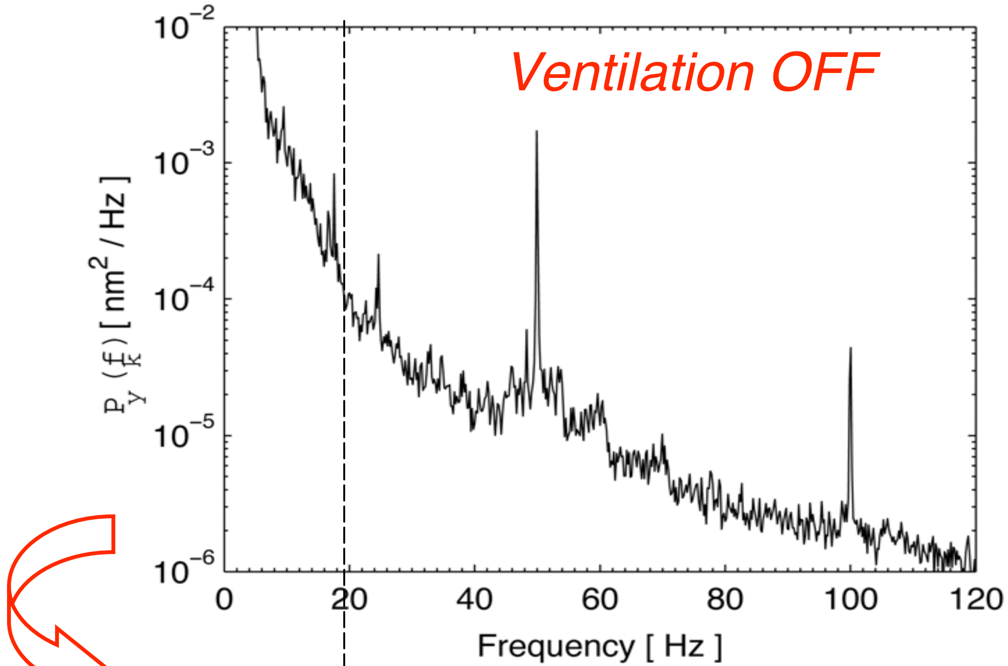
(Shiltsev et al., 1994)

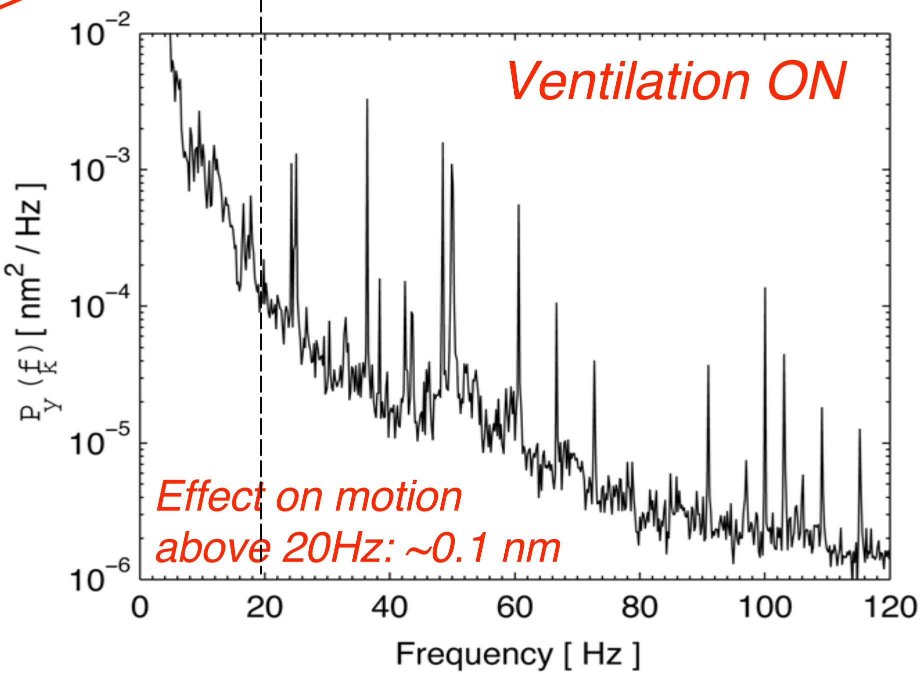
Noise in the quiet LHC tunnel:

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



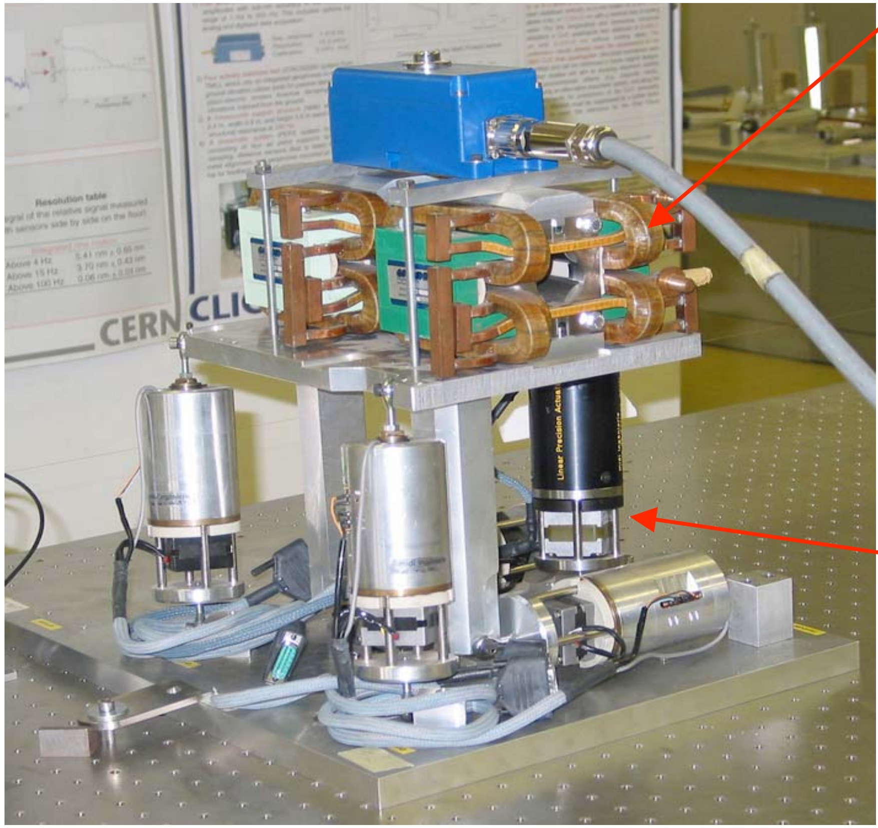
Vibration measured in the detector cave, tens of metres away from the lift.

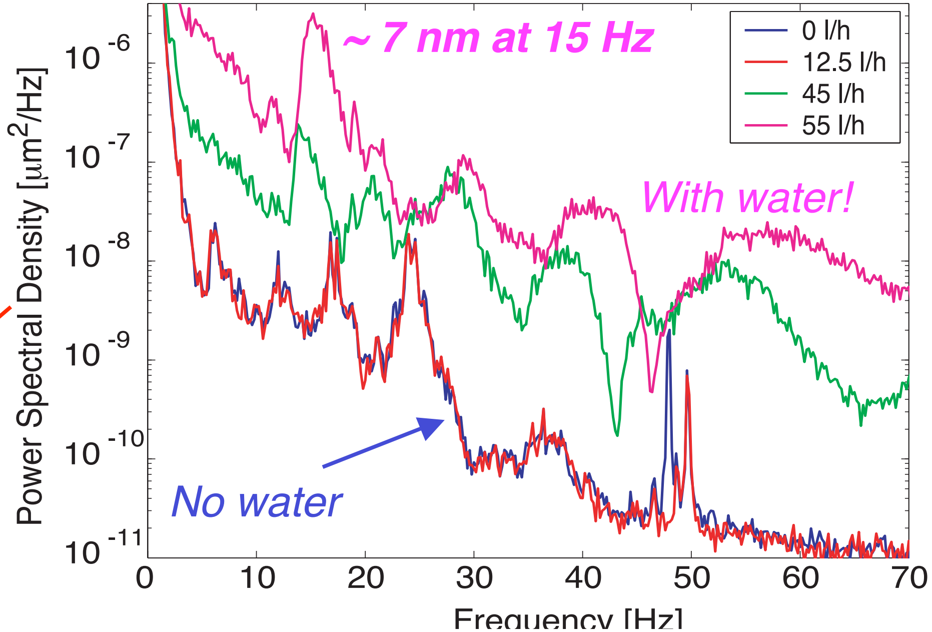


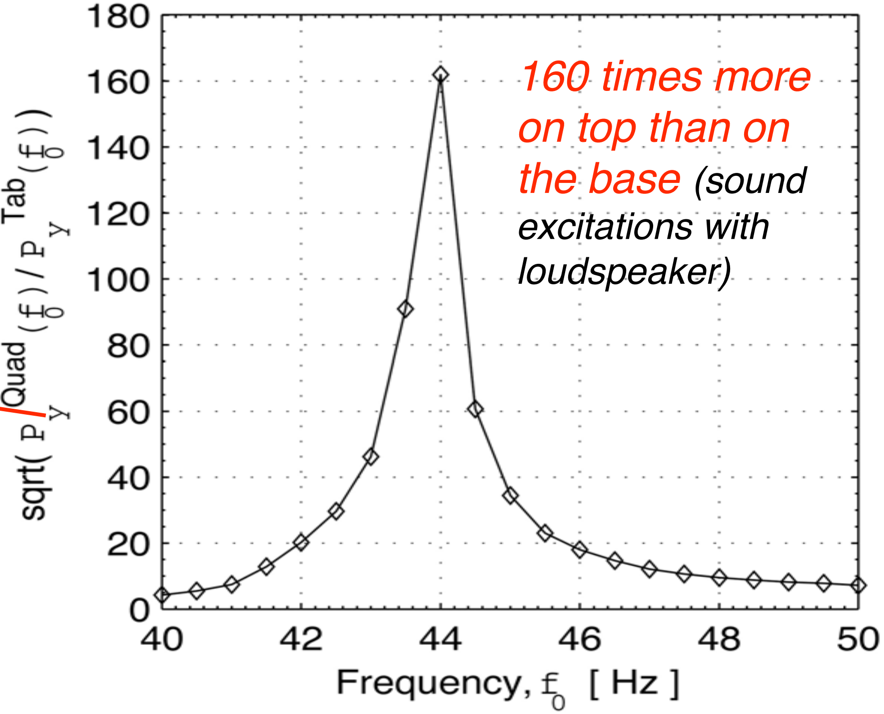


Effects of vibration measured in the laboratory (CERN, surface)

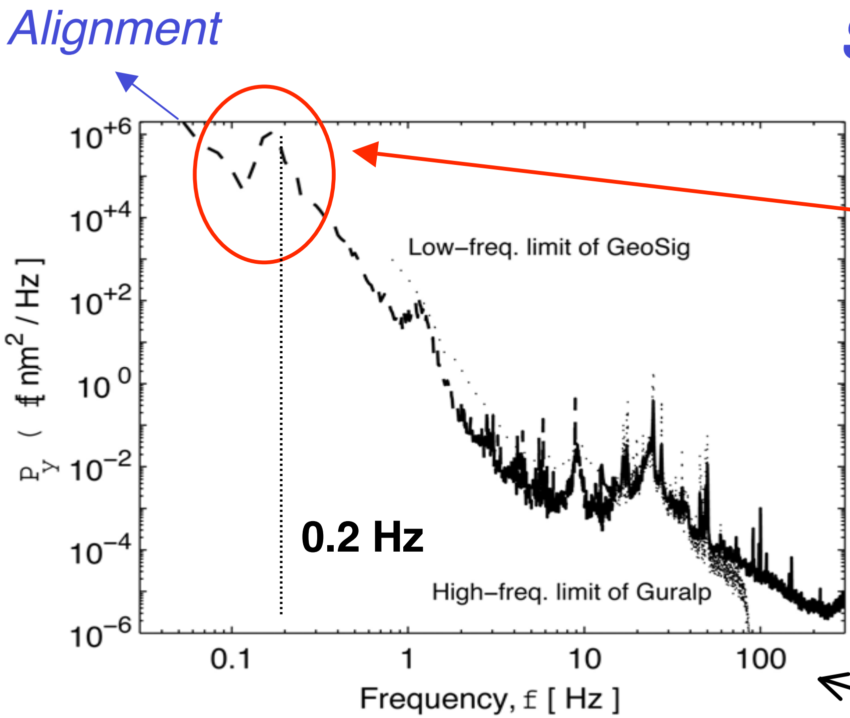
- *Effect of cooling water* (different flows)
  ⇒ increase the motion by several nm, but can be kept under control!
- *Resonances of the alignment support* (not optimized!) ⇒ dangerous vibrations, well beyond the limit of beam-based feedbacks







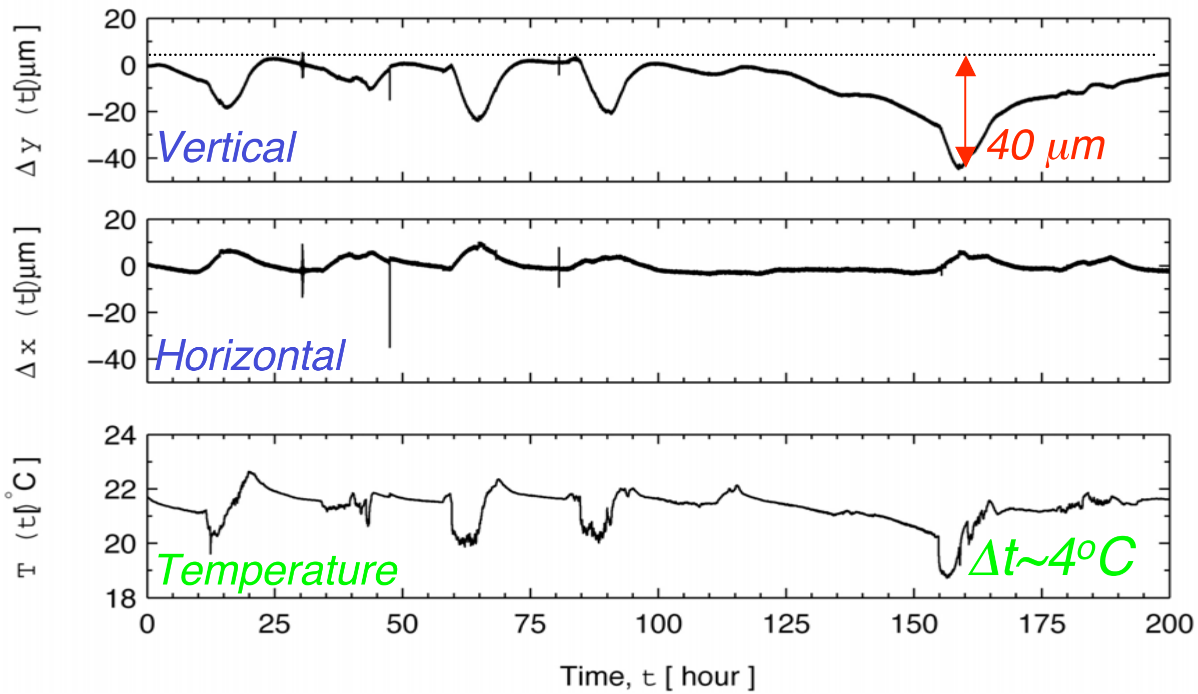
Slow motion…



Ocean wave motion (up to a few μm)

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 ~40μm due to shrinkage of rubber in the feet.

Should be easily compensated with beam-based feedbacks!

Measurement done at CERN with the stretche-wire system.

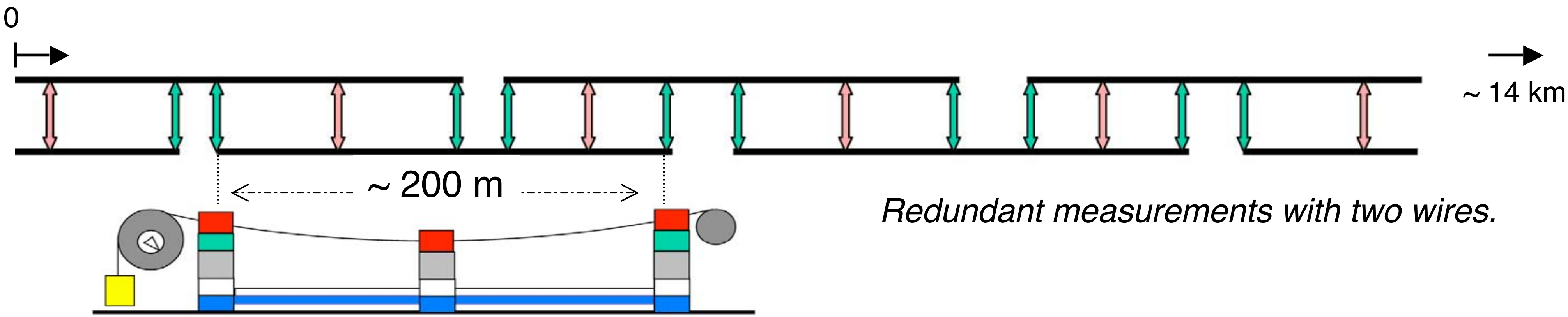
Achieving the required pre-alignment in CLIC

Work of F. Becker, W. Coosemans, R. Pittin, I. Wilson, H. Mainaud-Durand, *et al*

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

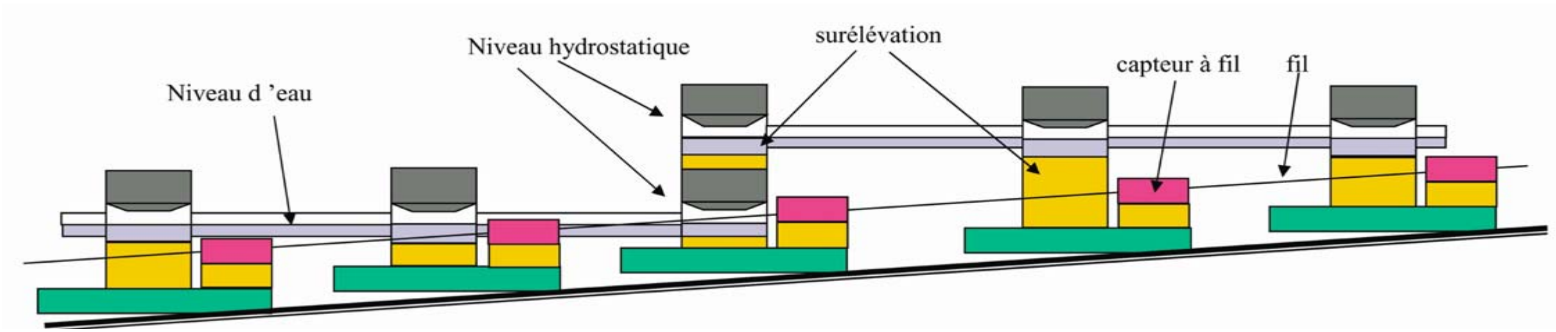
Pre-alignment achieved with a system that includes:

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:



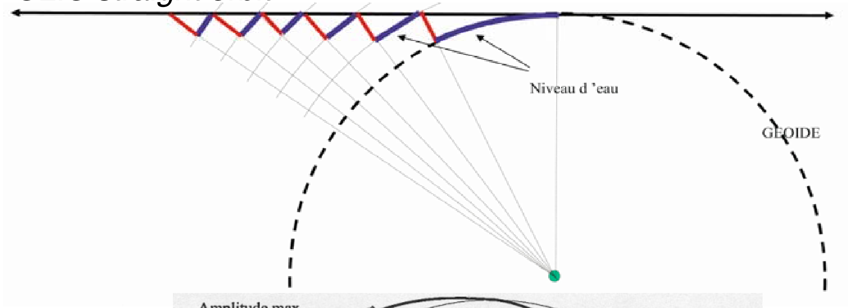
Pictures by W. Coosemans F.Becker

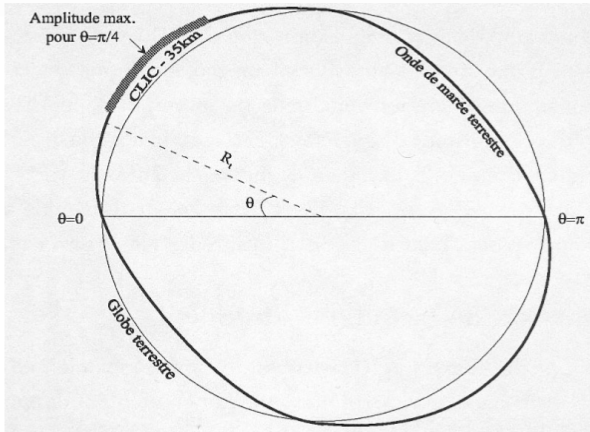
Issues:

- effect of slope of surface
- local distortions of gravity (rocks, holes)
- tidal motion (earth, water)

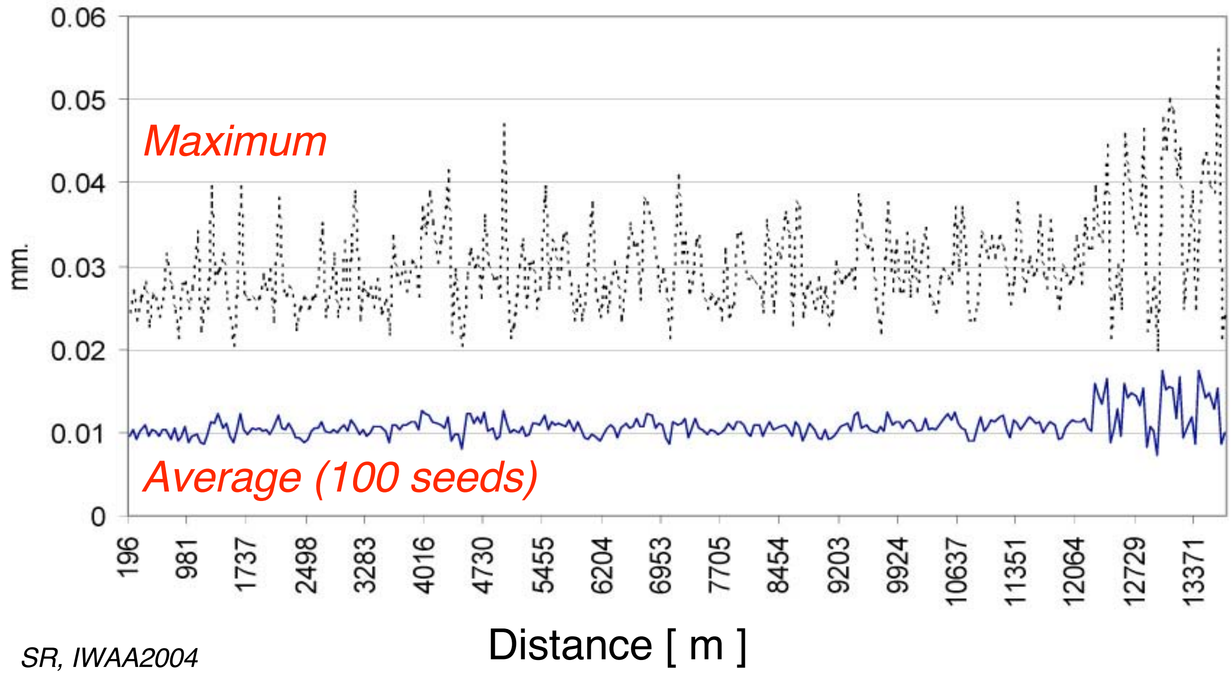
Most of these effects seem under control!

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**

R. Assmann, W. Coosemans, G. Guignard,
S. Redaelli, D. Schulte, F. Zimmermann, I. Wilson

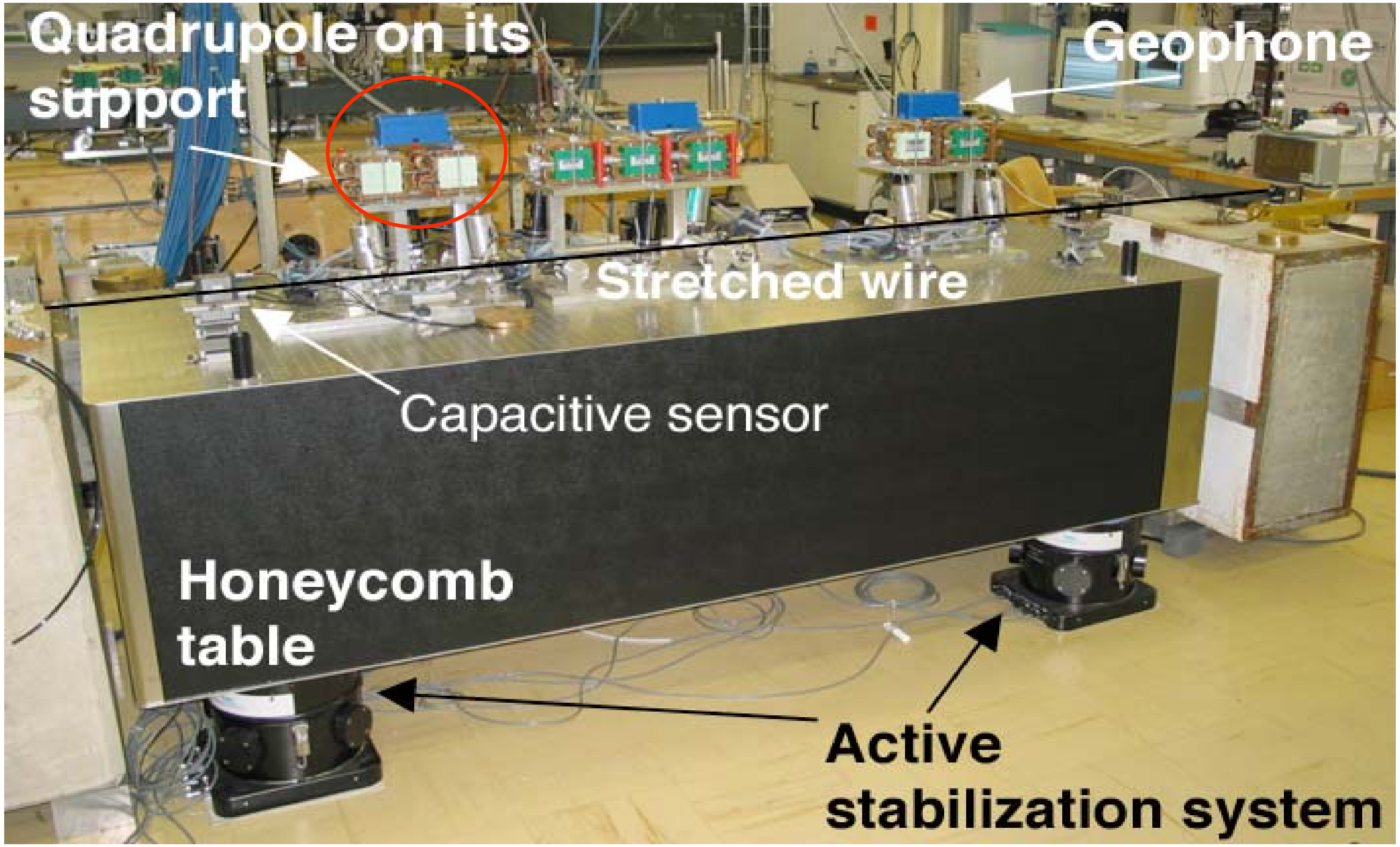
Goal of our study:

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:

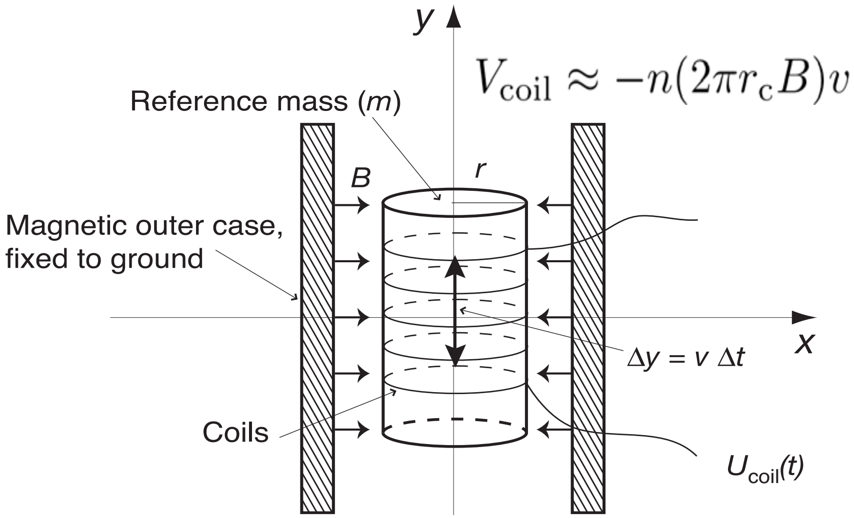


The experimental setup includes:

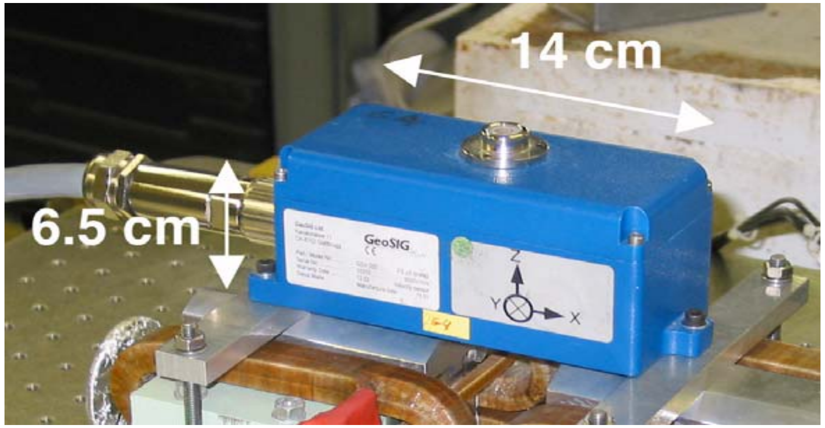
- **Sensors for vibration measurements** (geophones)
- Honeycomb table (virtually) with no internal resonances
- Prototypes accelerator magnets
- **State-of-the-art stabilization equipment**
- Stretched-wire system for alignment measurements

How do we measure nanometre vibrations?

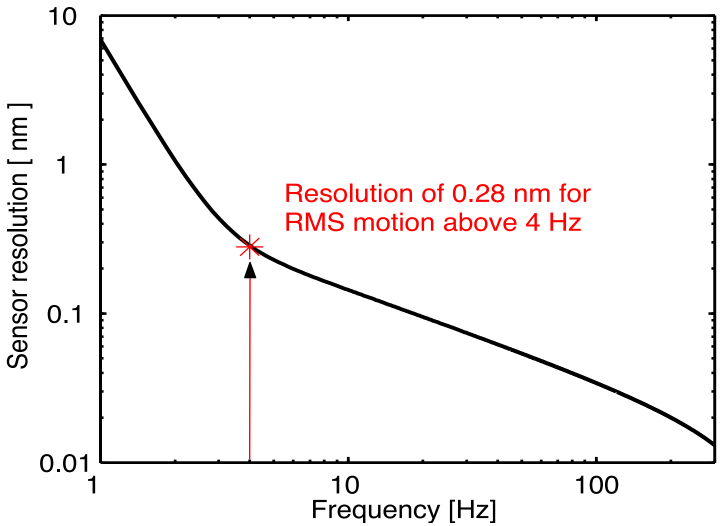
Triaxial **geophones** are used to measure vibrations (~ 4Hz-315 Hz frequency range).



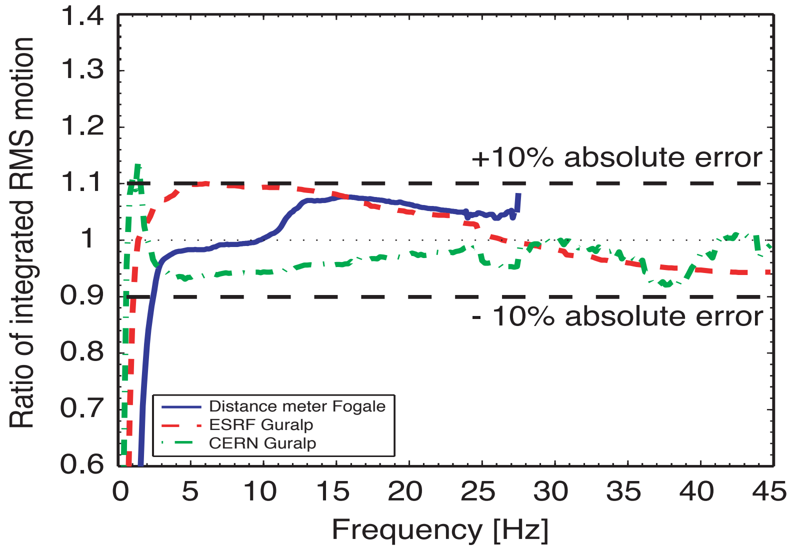
The geophones are seismometers that measures velocities versus time with respect to a reference mass at rest.



Sub-nanometre resolution!

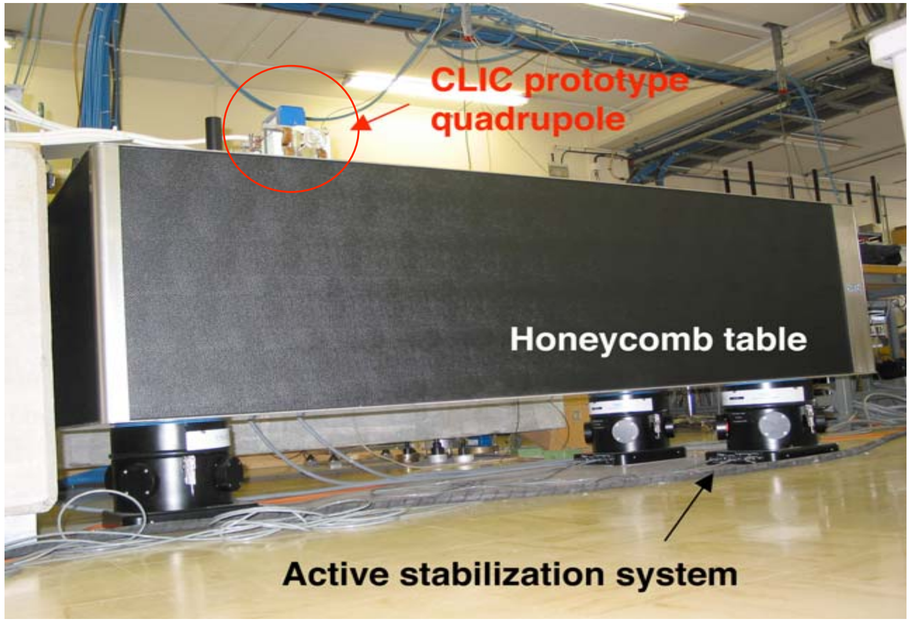


Absolute error < 10 % !

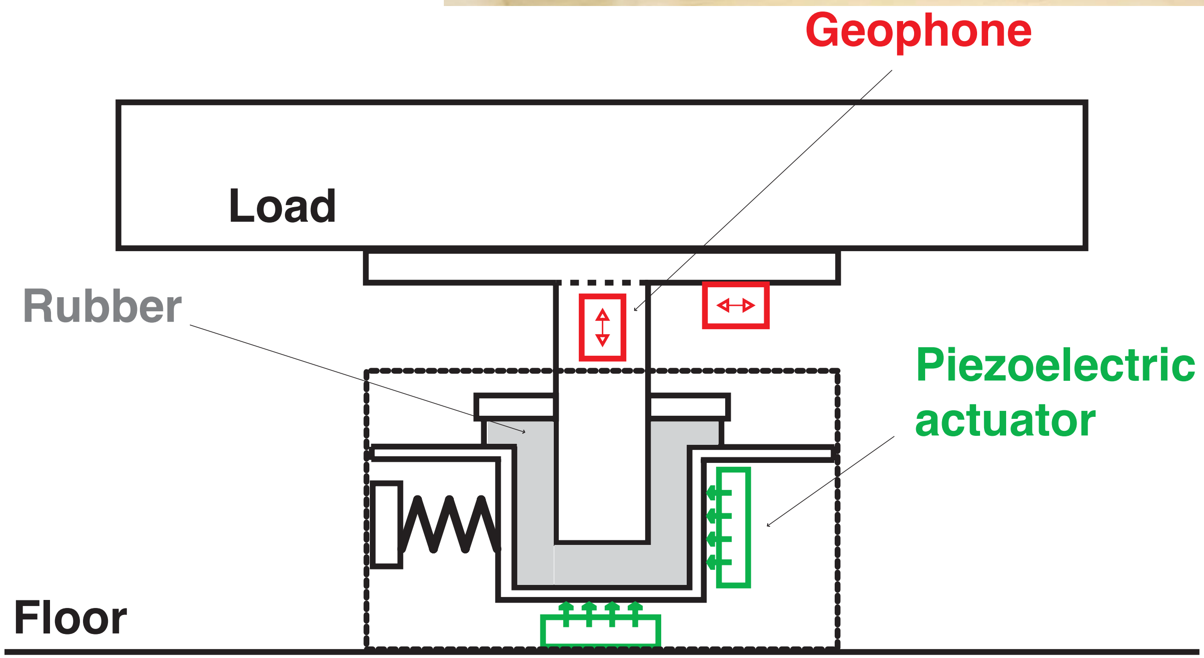


How do we stabilize accelerator magnets?

4 feet stabilize a honeycomb table.

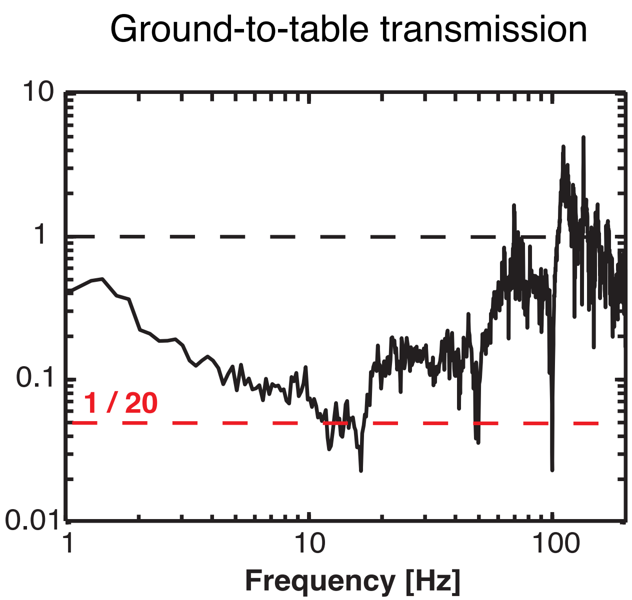


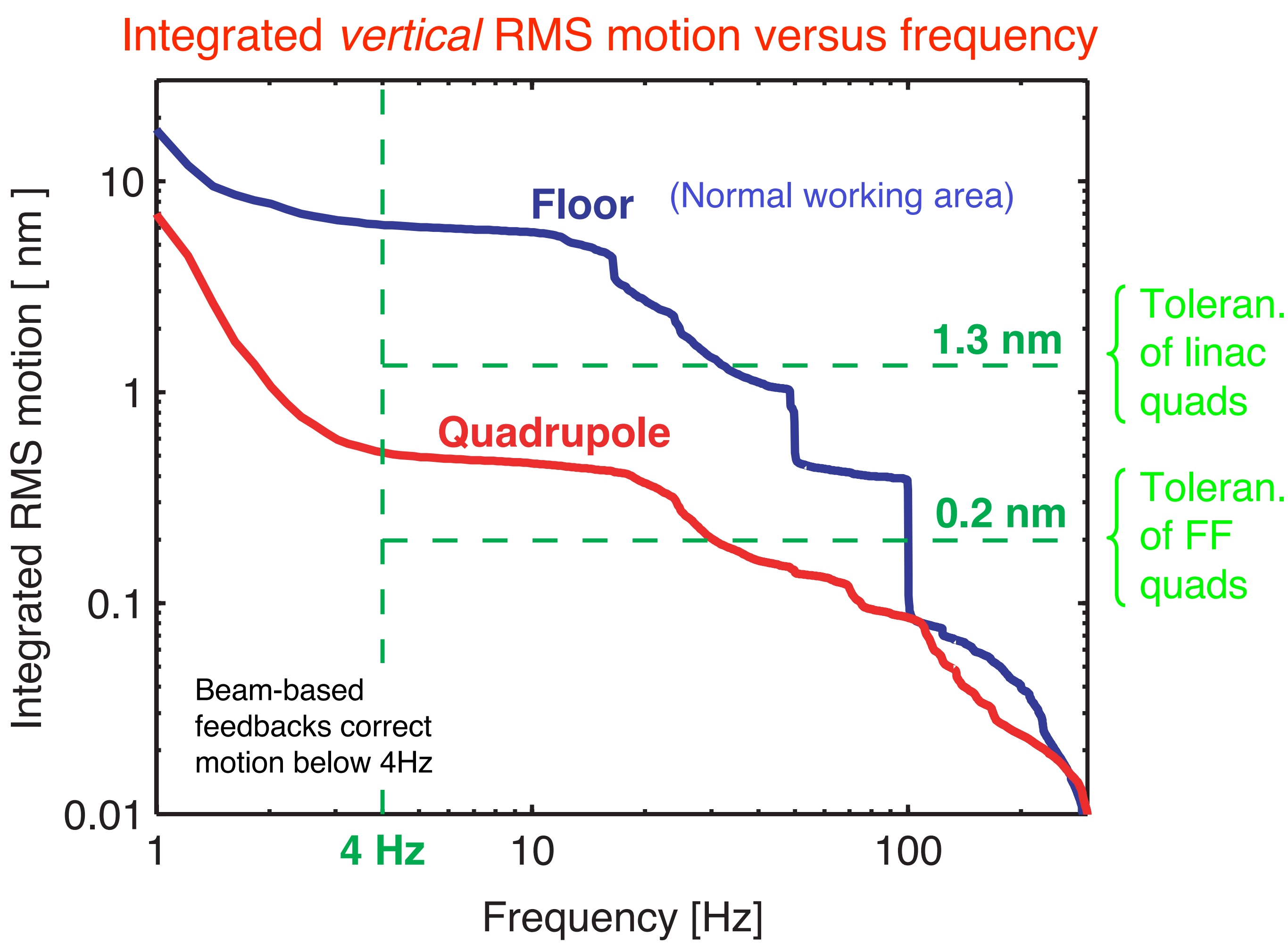
- **Passive damping** → stiff rubber
- **Active damping** → geophones / piezo crystals



This system provides a damping of 3D table vibrations!

Vertical stabilization of a CLIC prototype quadrupole

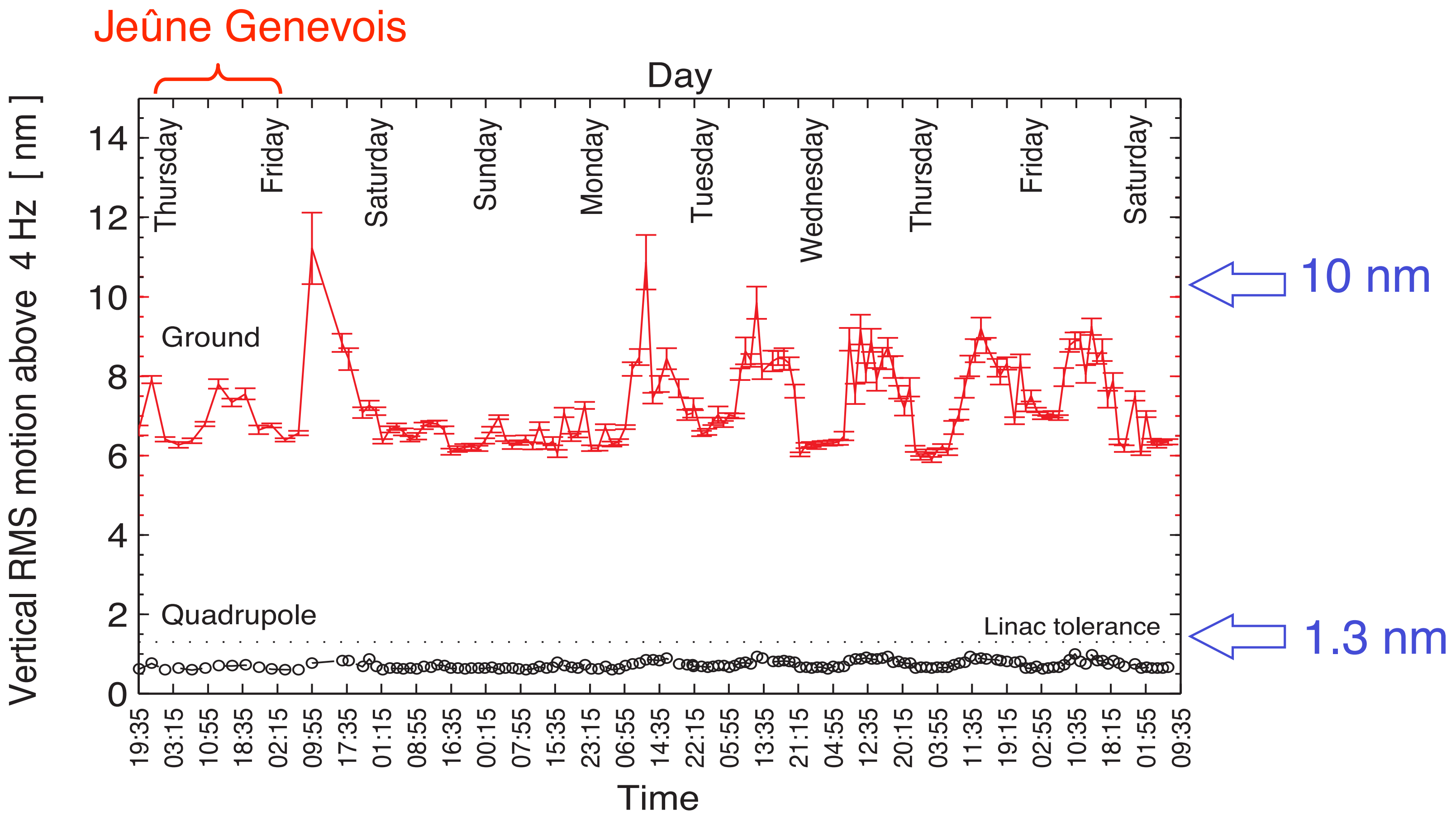




CLIC prototype magnets stabilized to the sub-nanometre level !!

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 (~15km x 2) **10 µm** (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 µm** tolerance is within reach!
   - Stabilization ($f >$ 4Hz) 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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