THE CLIC STABILITY STUDY
- Stabilizing Accelerator Magnets to the Sub-nm Level -

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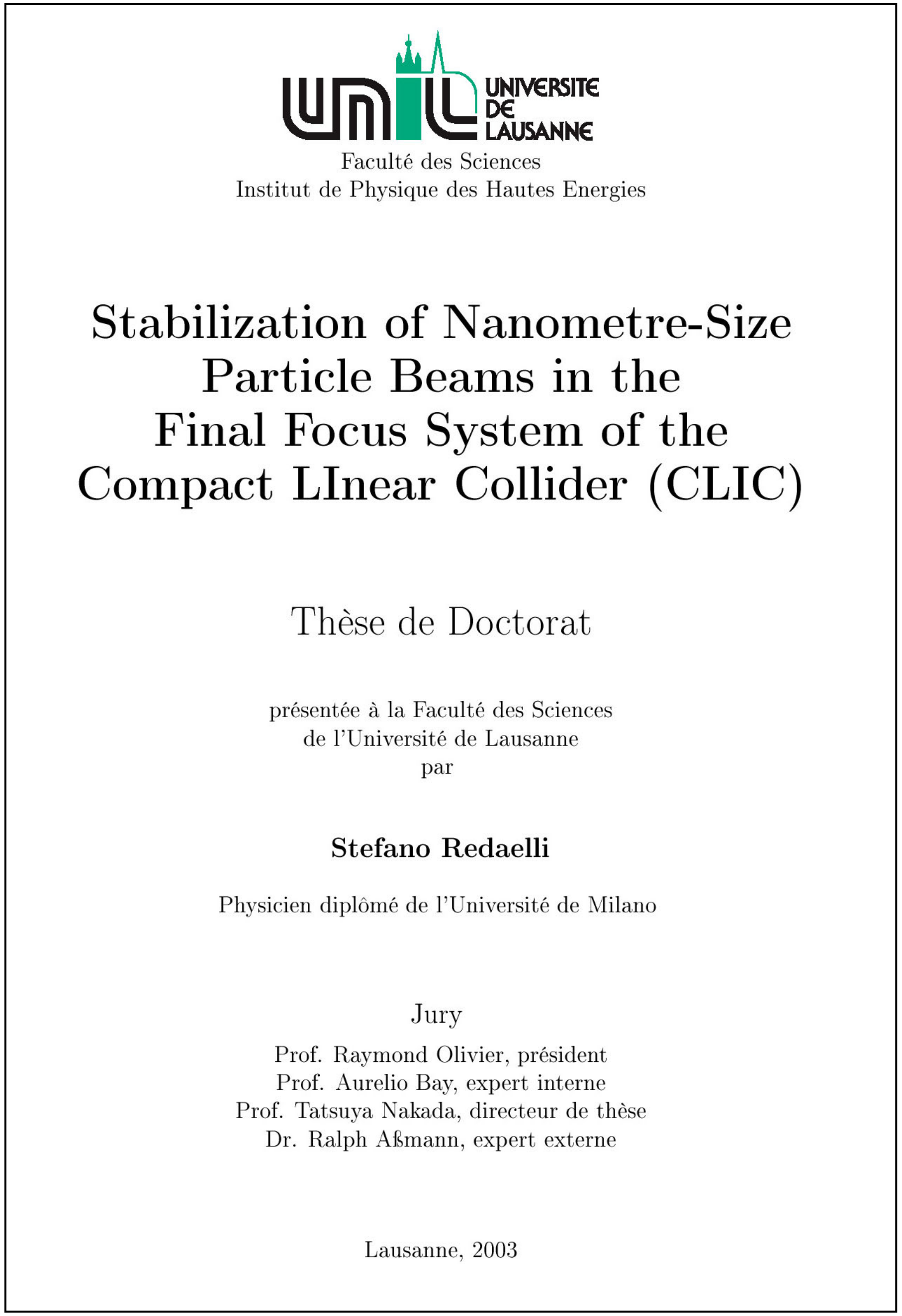

UNIVERSITE DE LAUSANNE

Faculté des Sciences
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Stabilization of Nanometre-Size Particle Beams in the Final Focus System of the Compact LInear Collider (CLIC)

Thèse de Doctorat

présentée à la Faculté des Sciences
de l'Université de Lausanne
par

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Prof. Raymond Olivier, président
Prof. Aurelio Bay, expert interne
Prof. Tatsuya Nakada, directeur de thèse
Dr. Ralph Aßmann, expert externe

Lausanne, 2003

Results published in:

Various conference papers.

PhD thesis by S. Redaelli (stefano.redaelli@cern.ch)

Journal papers under preparation!

The promise of linear colliders: Small beam sizes!

Like a human hair...

Machine	σ_x^* [nm]	σ_y^* [nm]	$\sigma_x^* \cdot \sigma_y^*$ [cm^2]
LEP	300000	3000	$9.0 \cdot 10^{-6}$
SLC	1700	900	$1.5 \cdot 10^{-8}$
FFTB		70	
TESLA	553	**5**	$2.8 \cdot 10^{-11}$
JLC/NLC	235	**3**	$7.5 \cdot 10^{-12}$
CLIC	60	**0.7**	$4.3 \cdot 10^{-13}$

1 nm = size of water molecule

SLC cross-section vs LEP:

Factor 600-1000

Where is the feasibility limit?
(collide nm-size beams)

Values for $\sigma_{x/y}^*$

- characterize perf of whole collider
- cannot be addressed in test facilities
- feasibility must be shown in *simulations fully based on measured parameters*

What is important for luminosity stability?

1) $$L_0 = \frac{N_e^2 \cdot N_b \cdot f_{rep}}{4\pi \; \sigma_x^* \cdot \sigma_y^*} \cdot H_D$$ with $$\sigma_y^* = \sqrt{\beta_y^* \cdot \varepsilon_y}$$

Stability of emittance
Stability of optics

Emittance contributions: $$\gamma\varepsilon_y \approx \gamma\varepsilon_y^{DR} + \Delta\gamma\varepsilon_y^{Design} + \Delta\gamma\varepsilon_y^{Linac} + \Delta\gamma\varepsilon_y^{FF}$$

= 0

Perfectly **straight trajectory** (centered in all quadrupoles, structures and sextupoles along straight line)

> 0

Imperfect environment (magnet alignment errors, diagnostics errors) produces **not-straight trajectory** (dispersion, wakefields)

2) Beam-beam overlap at interaction point:

Vertical separation between beams denoted by Δ_y

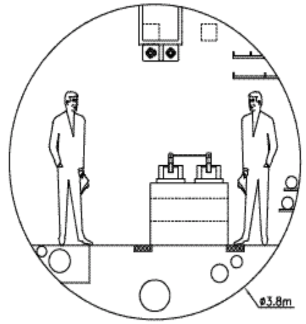
$$L \approx L_0 \cdot e^{-\left(\Delta_y^2 / 4\sigma_y^2\right)}$$

Δ_y mainly from movement of last focusing quadrupole (1-to-1 transformation)

Requirements for mechanical stability:

Linac quadrupoles

Number	1300 for each of two linacs
Field	200 T/m
Transverse size	0.15 x 0.11 m (width x height)
Length	0.46 - 2.08 m
Weight	69 - 312 kg
Goal	1.3 nm (vertical) rms uncorrelated motion above 4 Hz



Both linac and beam delivery are critical!

CLIC stability study:

Demonstrate feasibility of nano-metre size colliding beams!

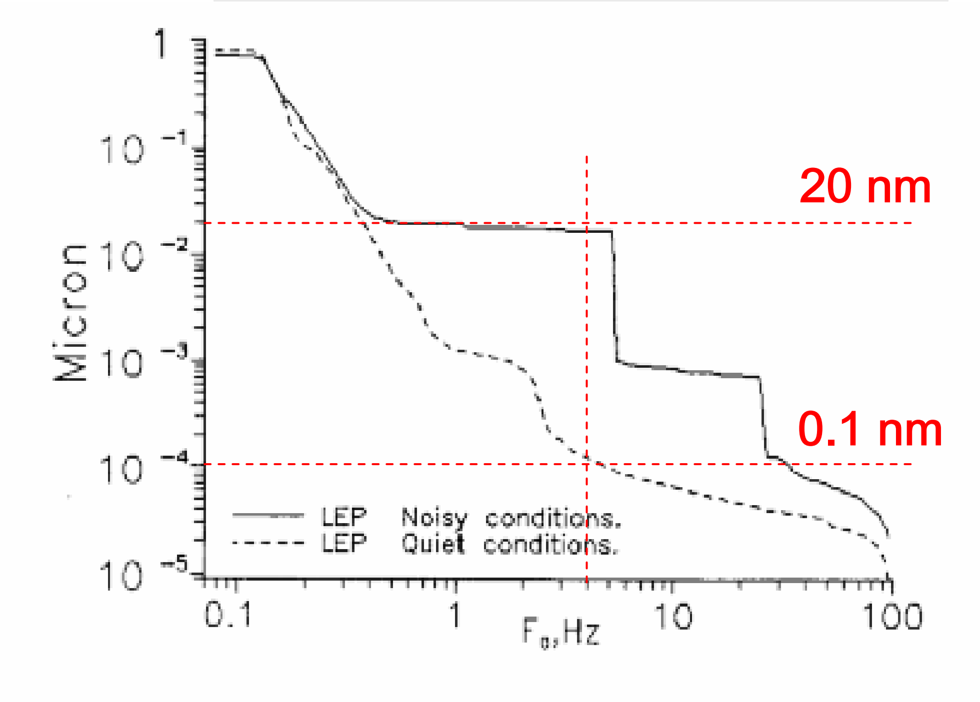
(magnet vibration, feedback, time-dependent luminosity)

Final focus quadrupoles

	Short	Standard
Number	2	2
Field	388 T/m	450 T/m
Transverse size	4.3 cm (outer rad.)	2.0 cm (outer rad.)
Length	3.5 m	4.75 m
Weight	250 kg	50 kg
Distance to IP	4.3 m	2.0 m
Goal	4.0 nm (horiz.), 0.2 nm (vert.) rms uncorrelated motion above 15 Hz	

Cultural noise and natural ground motion:

Measurements in the LEP tunnel



From [36]. 1993.

Man passing by magnet

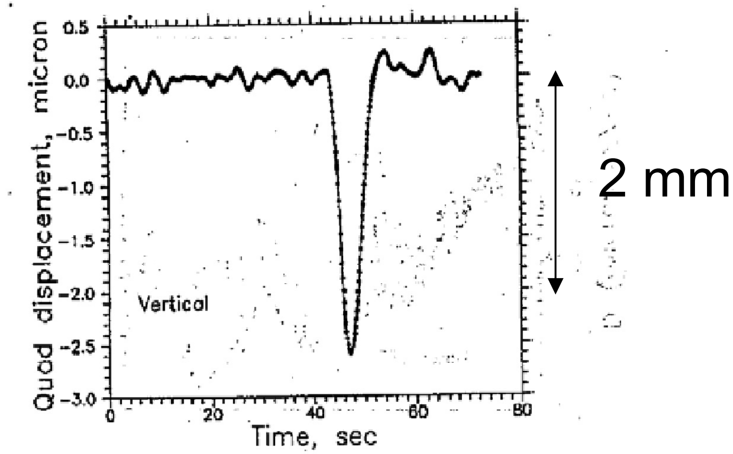


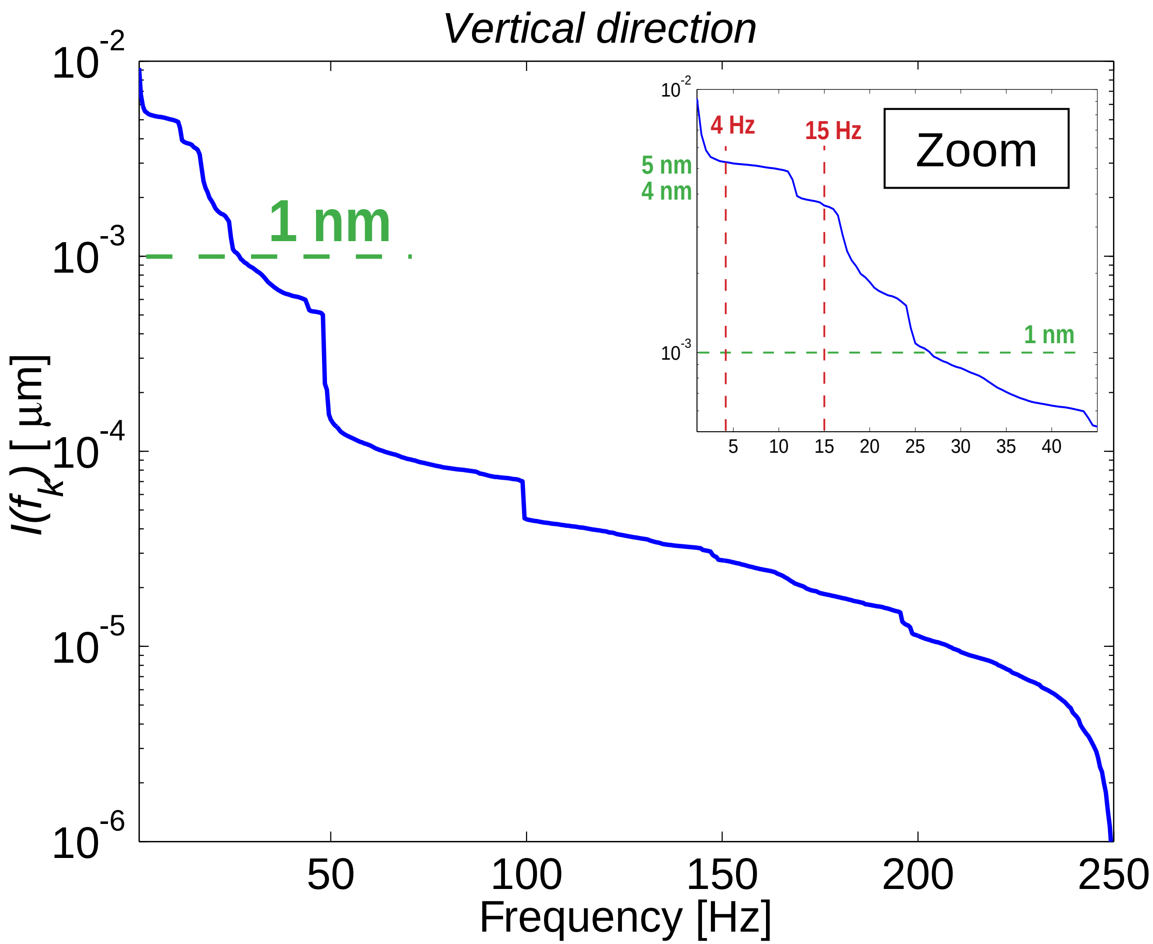
Figure 2. Low frequency vertical motion of the APS quad and effect of a man passing closely.

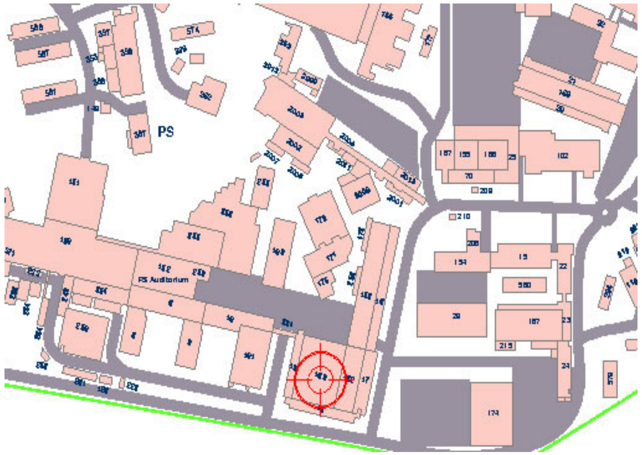
From [13].1994.

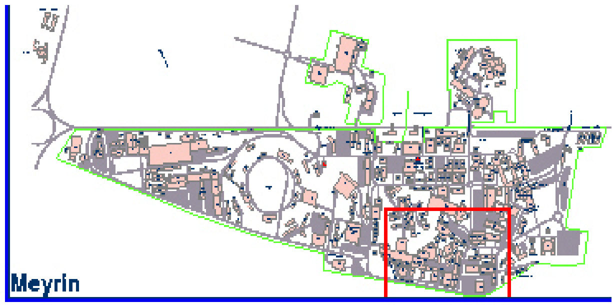
Protected environment required!

Above 4 Hz: 0.1 nm ➡ 20 nm

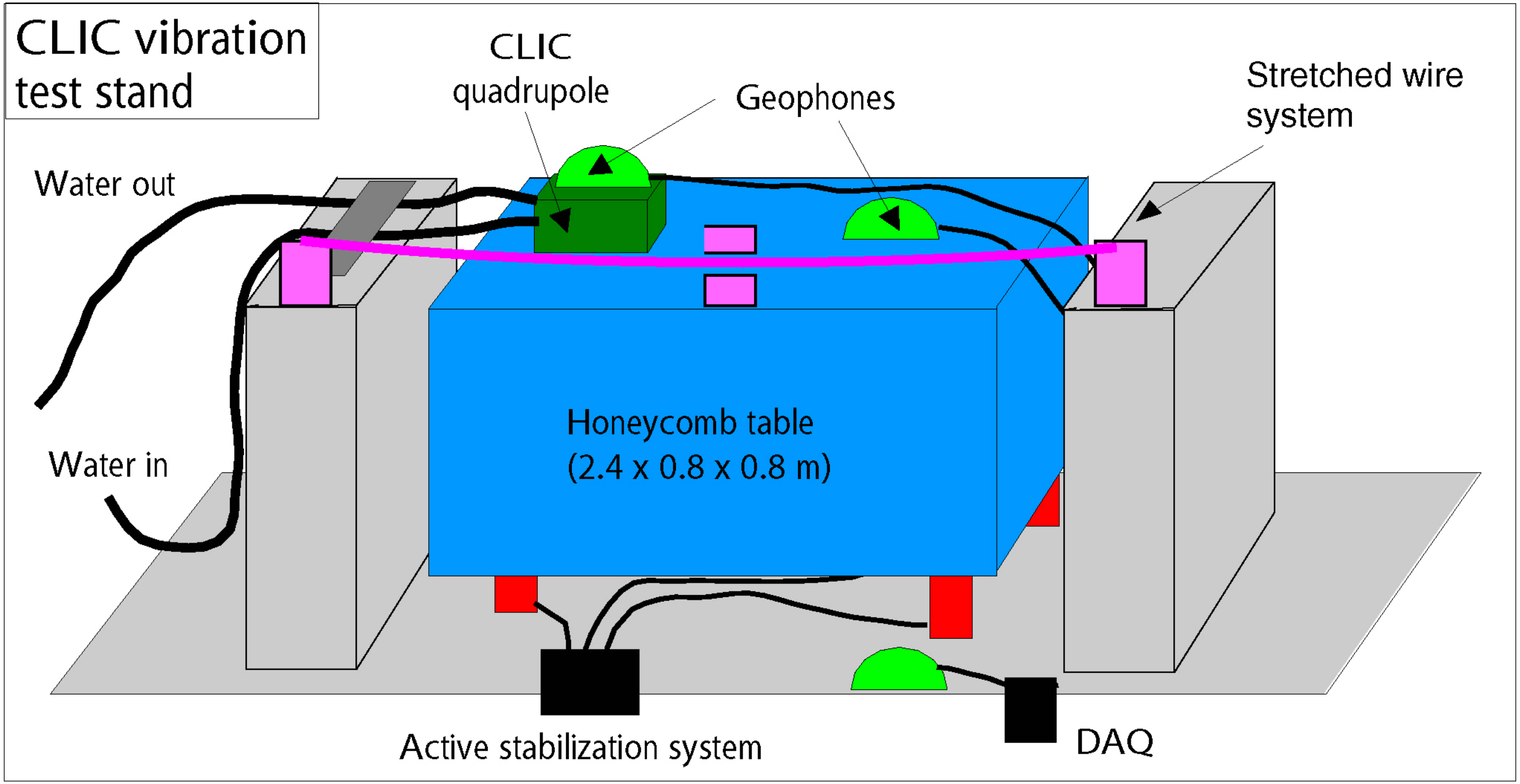
The CERN test stand: Vibration of the floor!



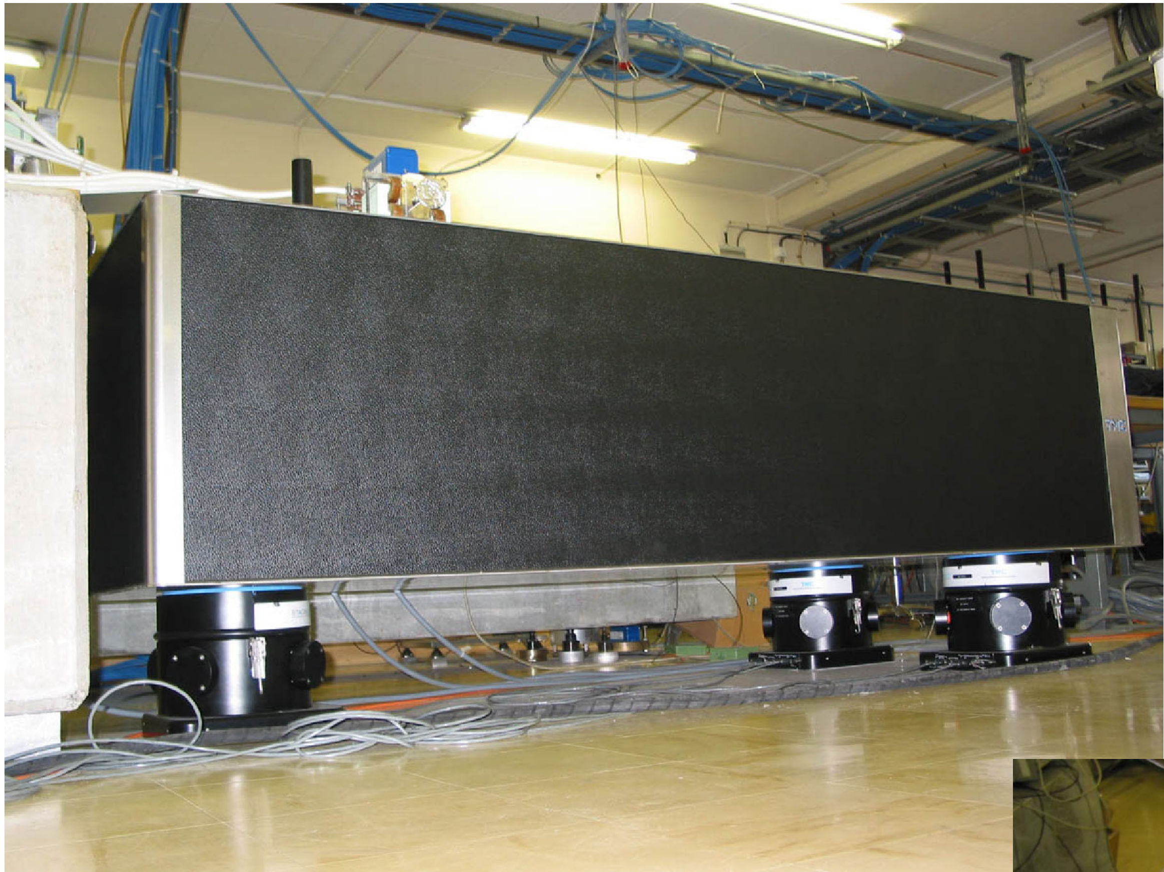




Site **suitable for active stabilization**: not too noisy, not too quiet.



Vibration damping:	Two systems (rigid or soft)
Cooling water:	on/off
Vibration:	Geophones
Alignment:	Stretched wire system
Support platform:	Lowest resonant frequency > 230 Hz



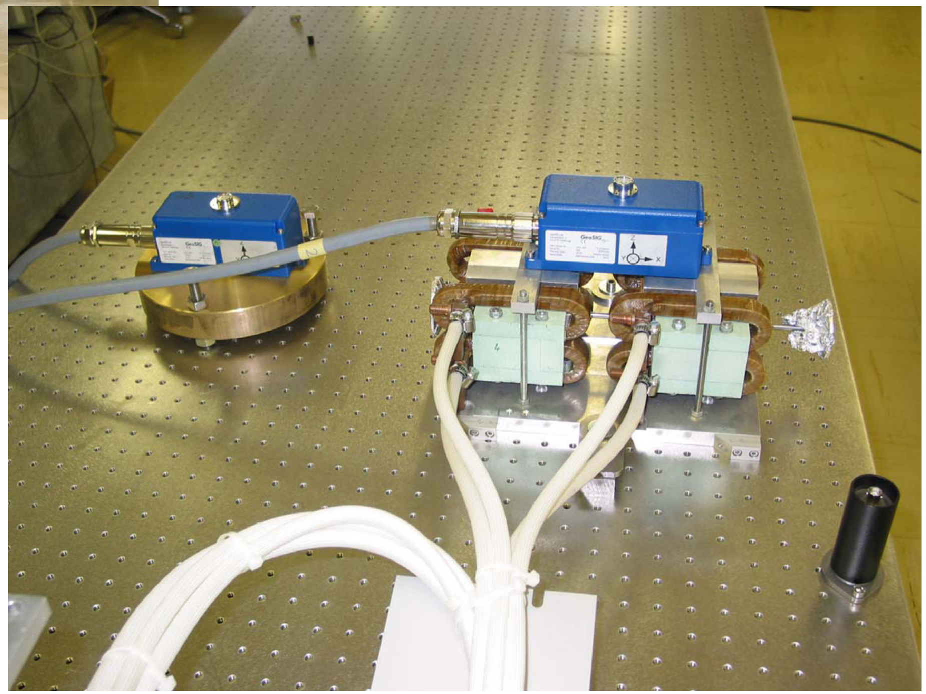
STACIS 2000 (TMC)

Rubber damping

Active feedback circuit on ground motion

Measure ground motion

Actuators: piezos



Rigid system

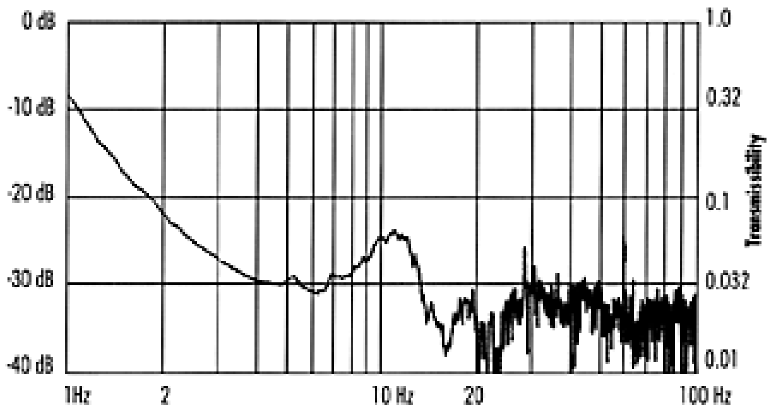
Industrial stabilization equipment

TMC

STACIS™ 2000

Active Piezoelectric Vibration Control System

Vertical transmission:



Performance Specifications:

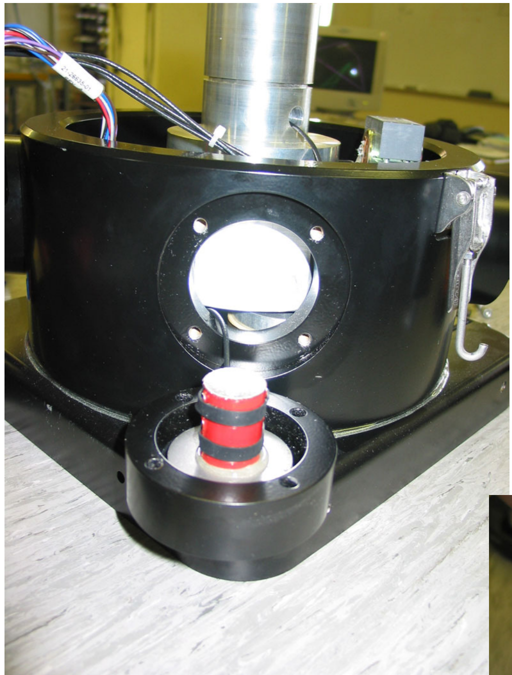
Active degress of freedom	6
Active bandwith	0.3 to 250 Hz
Resonant frequency (active):	0.4 Hz
Transmissibility at resonance:	< 1.1
Isolation above 2.0 Hz:	> 90 %
Setting time after a 10 lb. (4.5 kg) step input: (10:1 reduction)	0.3 second
Internal noise:	<0.1 nm rms
Operating load range per isolater: (different passive mounts required)	400 - 4500 lb. (182 - 2045 kg)
Isolator overload safety factor:	> 2:1
Number of isolaters:	3 or 4
Maximum displacement:	950 μ inches (24 μm)
Stiffness (1000 lbs./454 kg mass): (typical middle capacity isolater)	40,000 lbs./in (73×10^3 N/m)
Magnetic field emmited	< 0.02 micro-gauss broadband rms

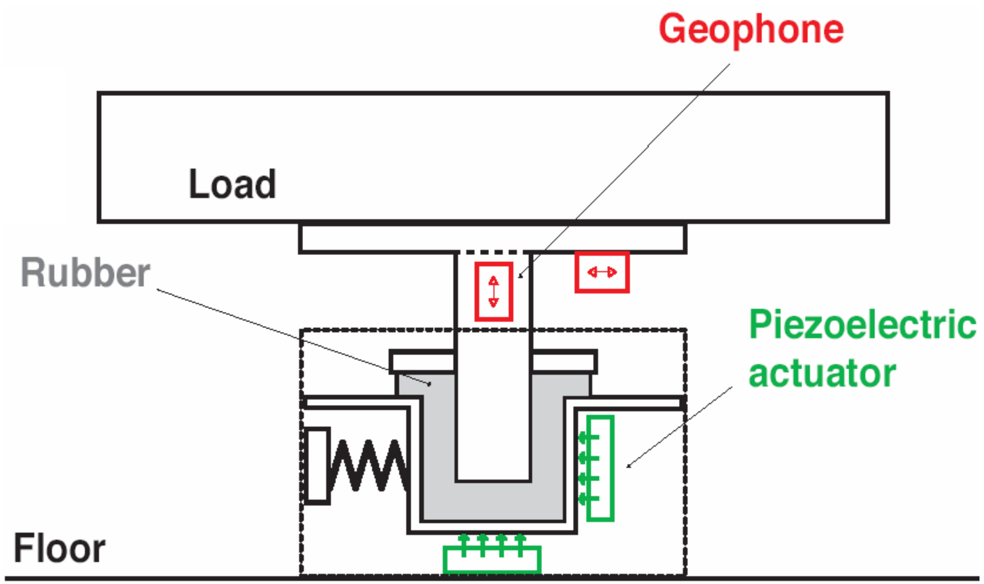
Dimensional, Evironmental and Utility Requirements:

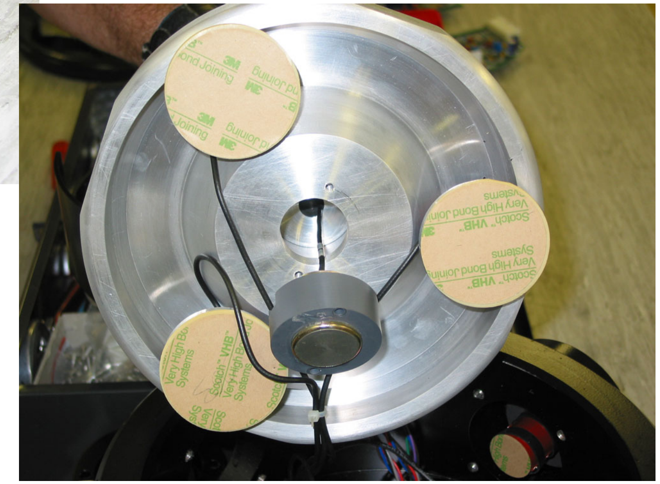
Isolater size:	11.75" w x 12.5" d x 10.25" h (300 x 320 x 260 mm)
Isolater weight:	75 lb. (34 kg)
Controller size:	17" w x 10" d x 6.5" h (432 x 254 X 165 mm)
Temp., operating:	50° to +90°F(10 to 32°C)
Temp.,storage:	-40° to 255°F(-40 to 125°C)
Humidity, operating:	76° F dewpoint(maximum)
Power required	100, 120, 230 or 240 volts; 50/60 hz; < 600 watts,CE compliant
Floor displacement:	<950 μ inches (24 μm)
Floor level:	level within 0.005"/foot (0.4mm/m) and coplanar withing 0.03" (0.76)

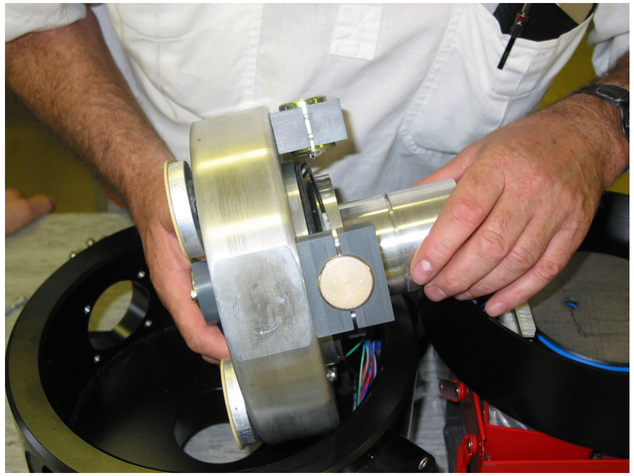
Options: TMC laminated stainless steel platforms, frames and "risers," leveling devices, and earthquake restraints

Functional sketch



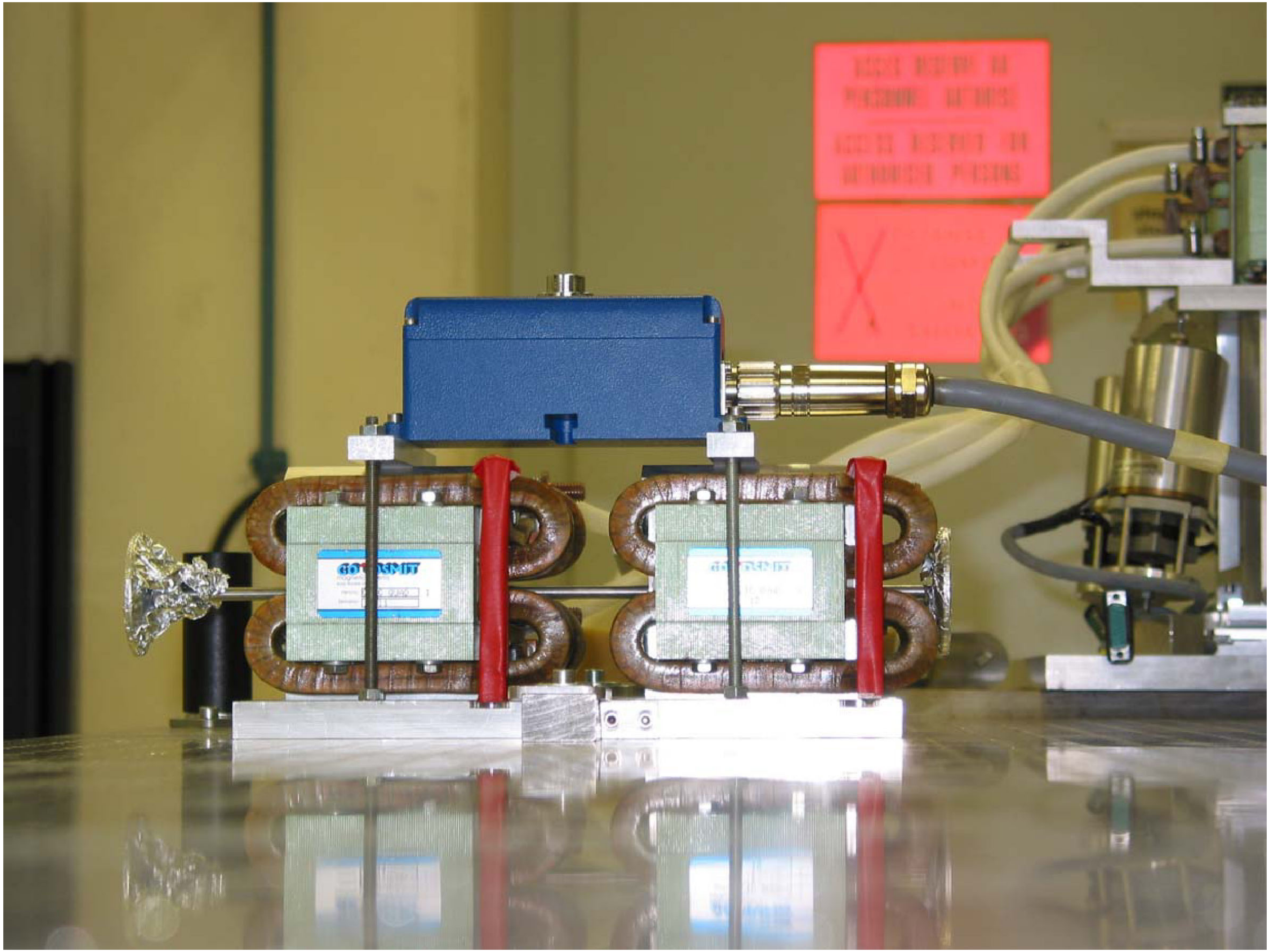






Includes: Passive damping (high frequency)

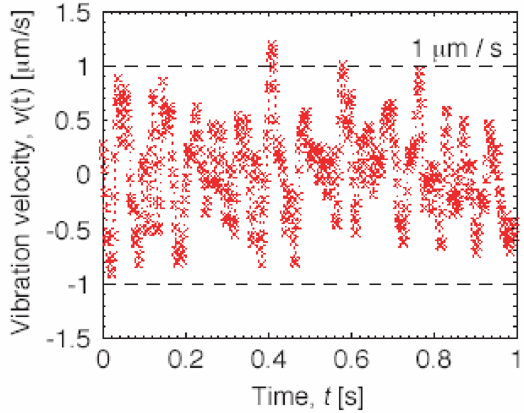
Active damping (low frequency resonance)



Frequency analysis of vibration data

We measure discrete vibration velocities

$$v(t_n) = v(t_0 + n\Delta t)$$



Fourier transform of the velocity

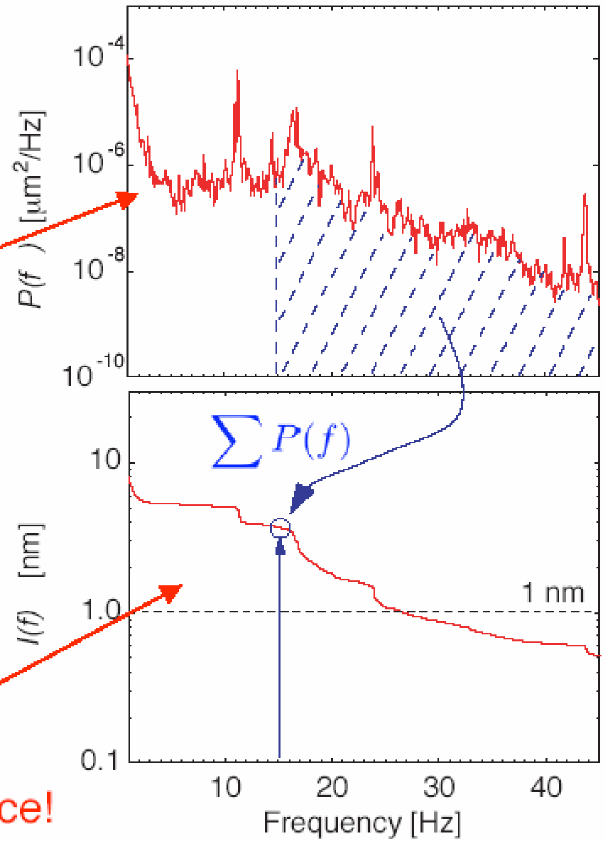
$$\tilde{v}(f) \equiv \Delta t \sum_{n=1}^{N} v(t_n) e^{-2\pi i \frac{kn}{N}}$$

Power spectral density of *displacement*

$$P(f) = \frac{2\Delta t}{N} \frac{|\tilde{v}(f)|^2}{(2\pi f)^2}$$

Physical picture: Integrated RMS motion

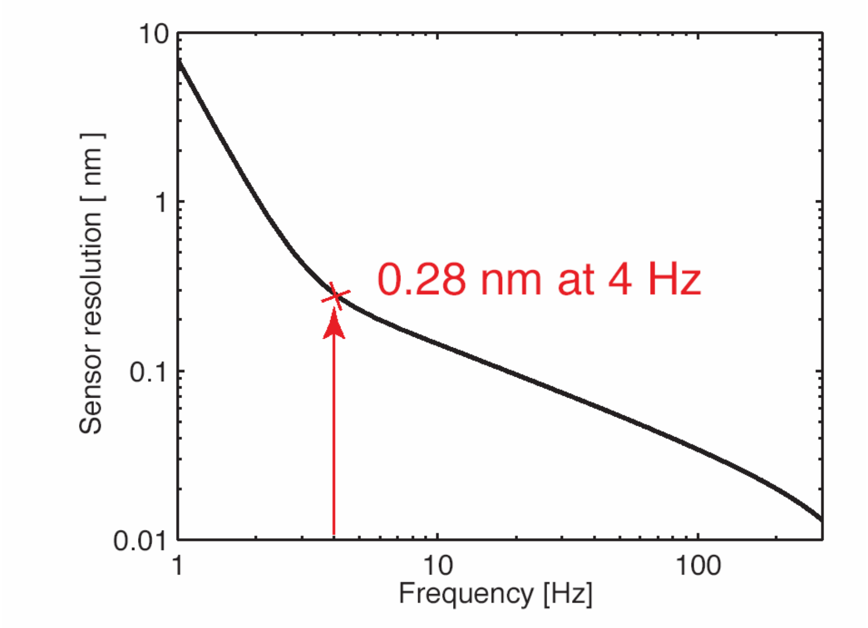
$$I(f_k) = \sqrt{\frac{1}{N\Delta t} \sum_{k'=k}^{\infty} P(f_{k'})}$$



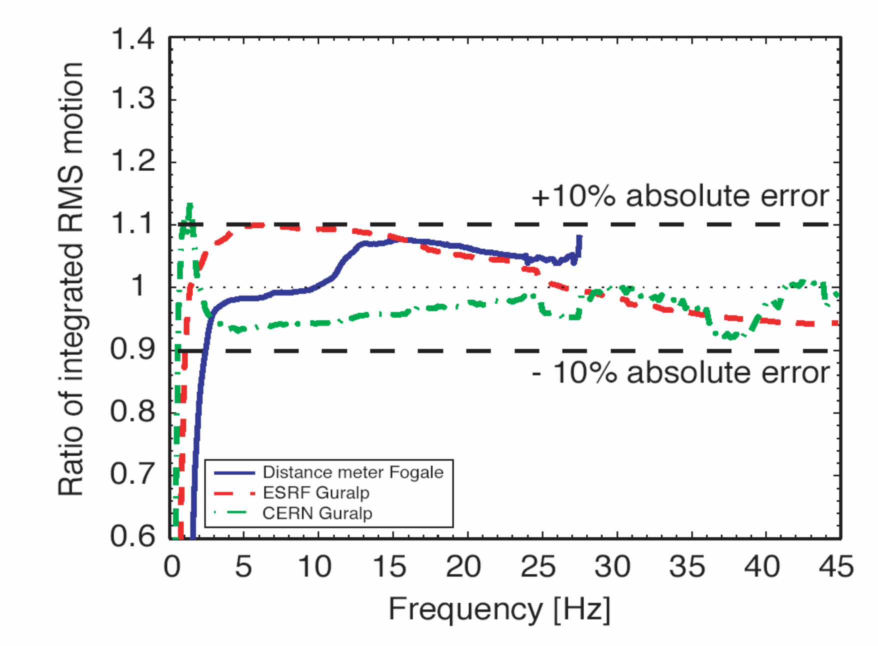
This is what matters for the CLIC performance!

Determination of resolution and accuracy

Resolution
(two sensors side by side)



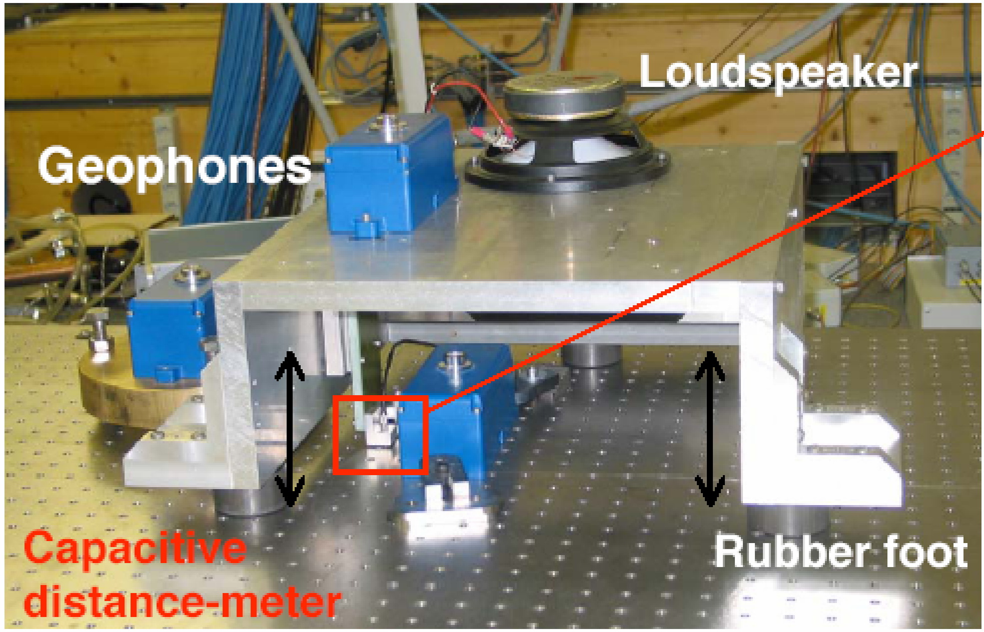
Accuracy
(different measurements)

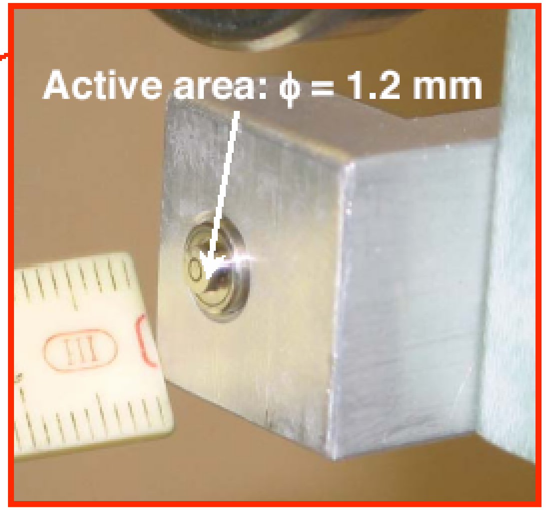


1 nm is measured within 10% absolute error!

Result also relying on direct distance measurements (absolute distance versus velocity)

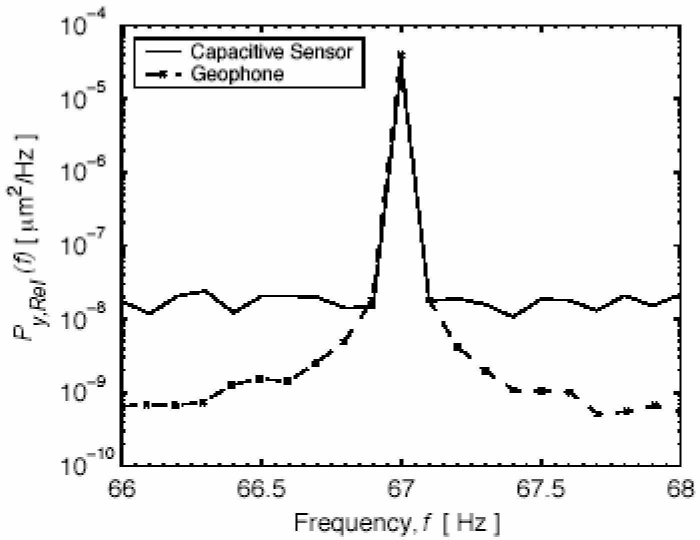
Comparison between geophones and capacitive distance-meter



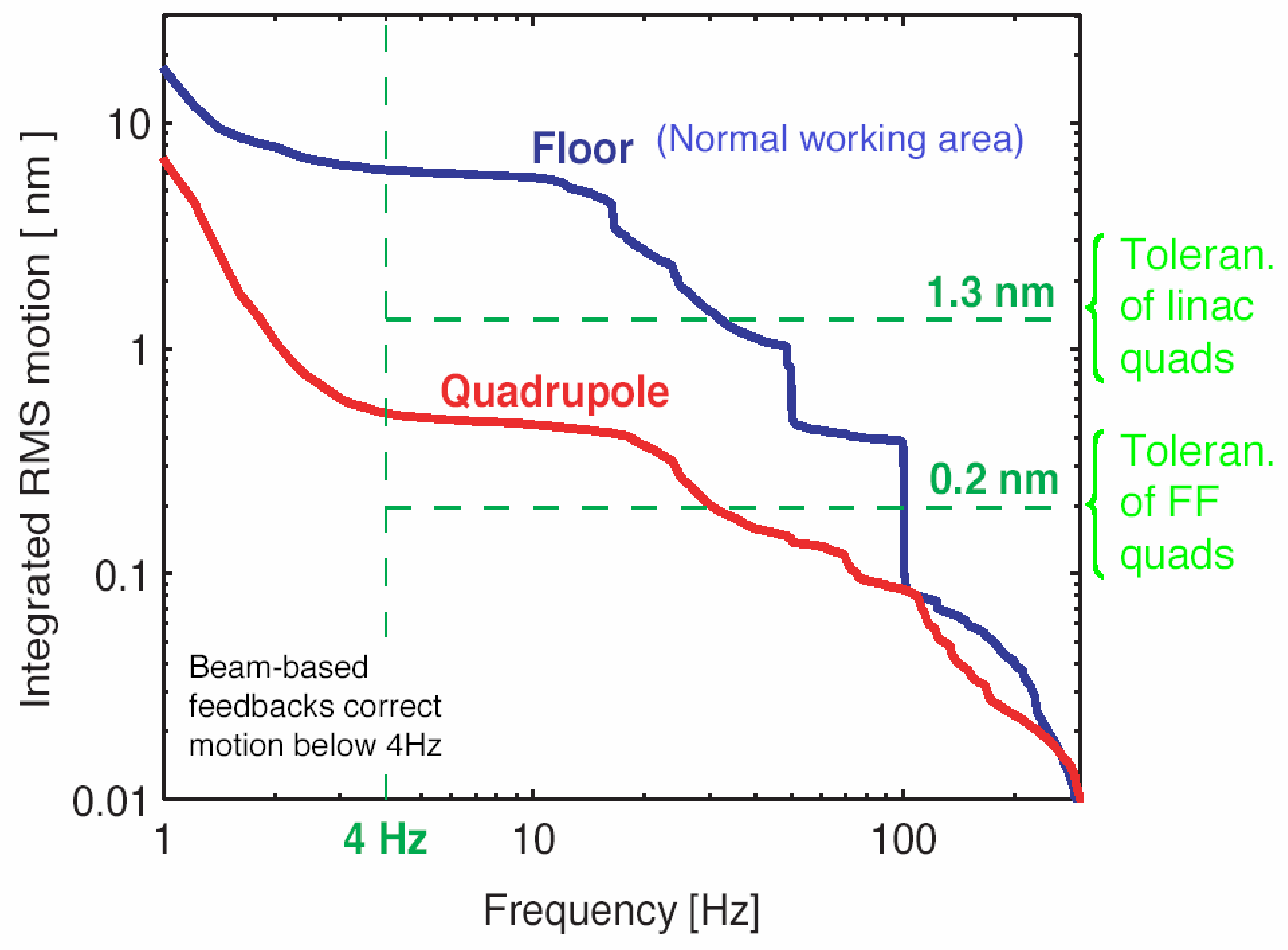


W. Coosemans and S. Redaelli, paper submitted to NMI (2004).

- Different **physics mechanisms**
  - ✓ oscillating coils
  - ✓ electric capacity
- Vertical relative motion between platform and supporting table (stabilized)
- Excitation with loudspeaker



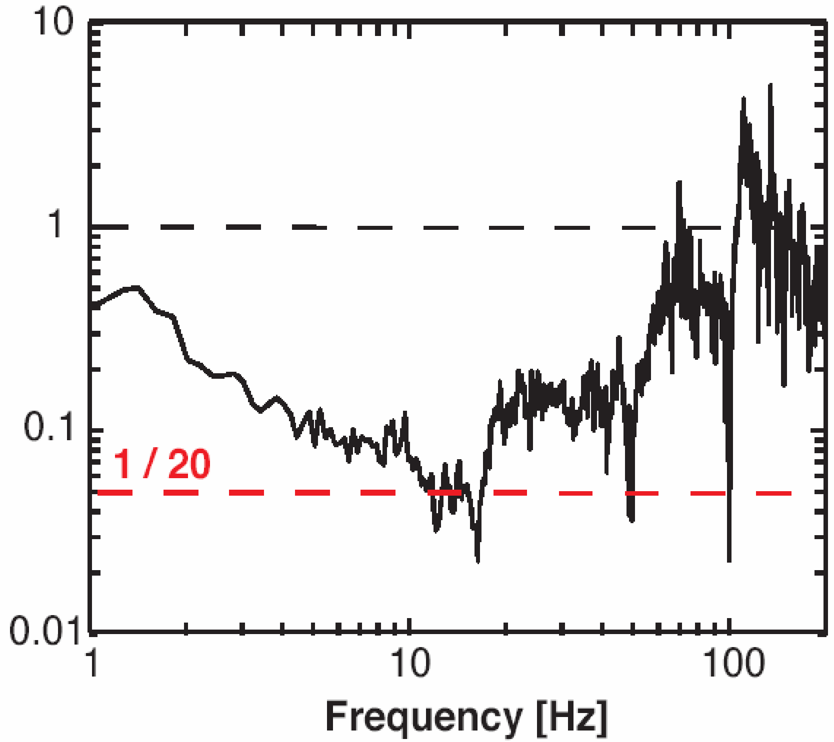
Stabilization of the CLIC prototype quadrupole



Best performance

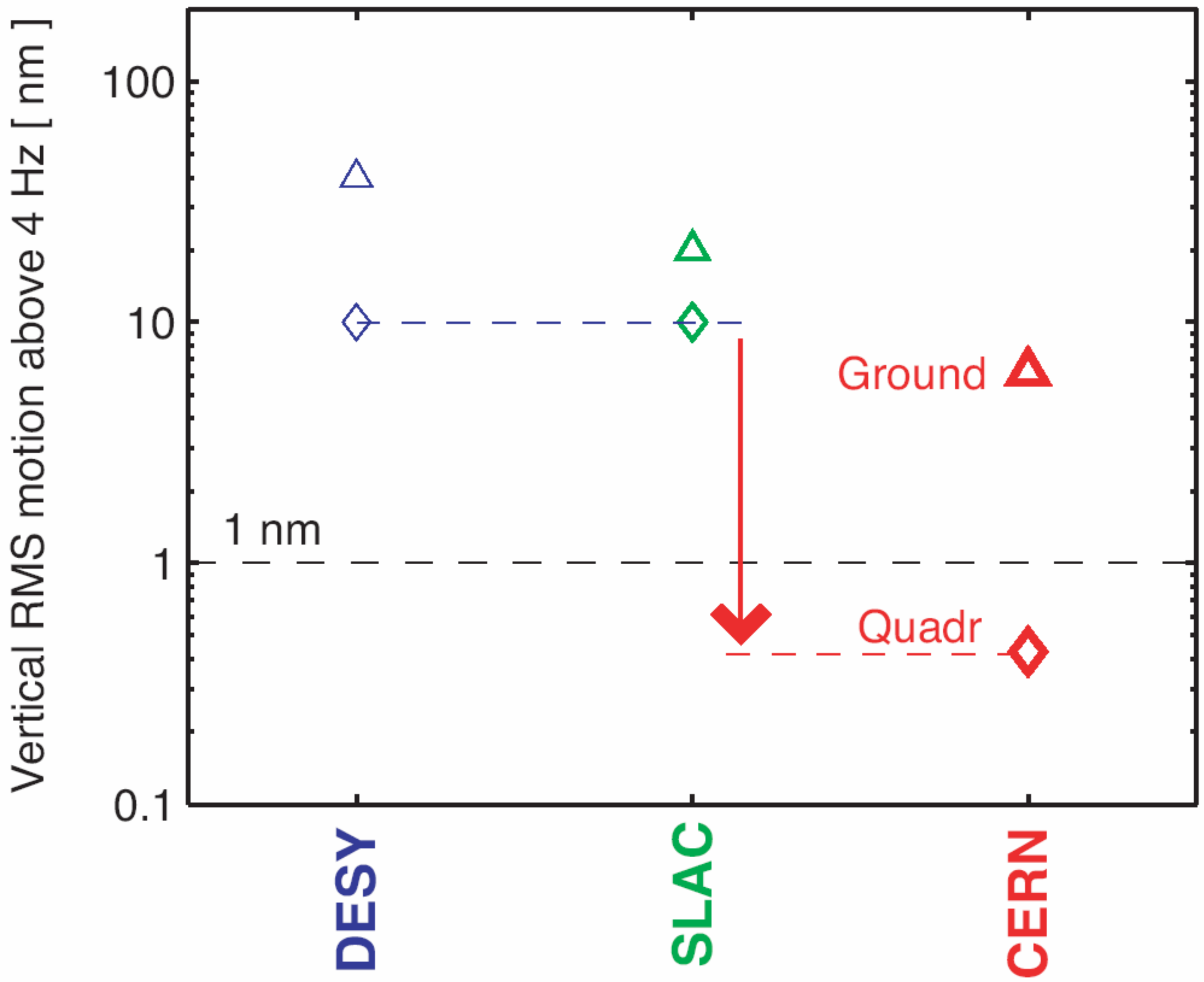
RMS vibrations above 4 Hz

	Quad [nm]	Ground [nm]
Vertical	**0.43**	**6.20**
Horizontal	**0.79**	**3.04**
Longitud.	4.29	4.32



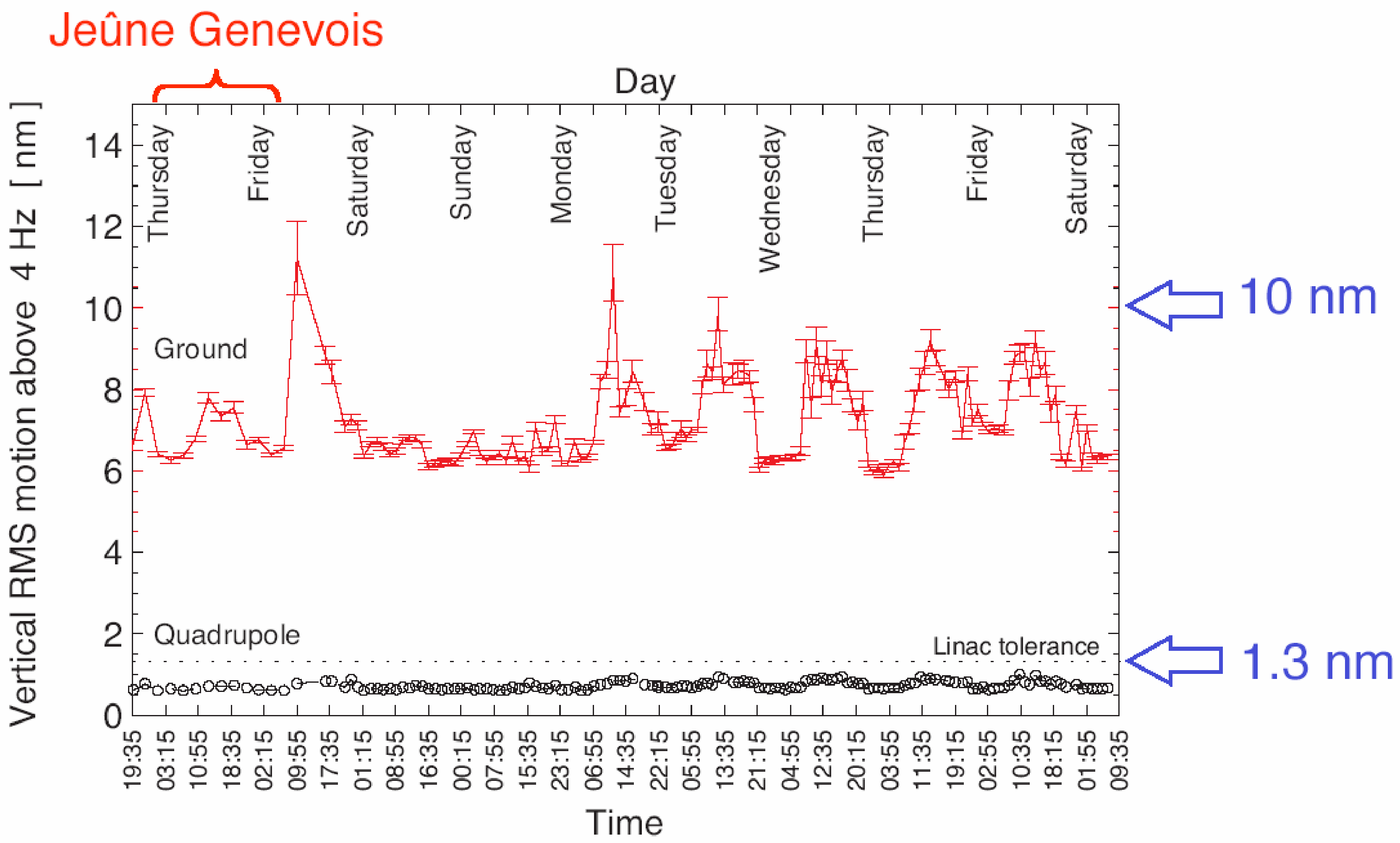
Transmission ground to magnet

Progress in the field



(s-band)

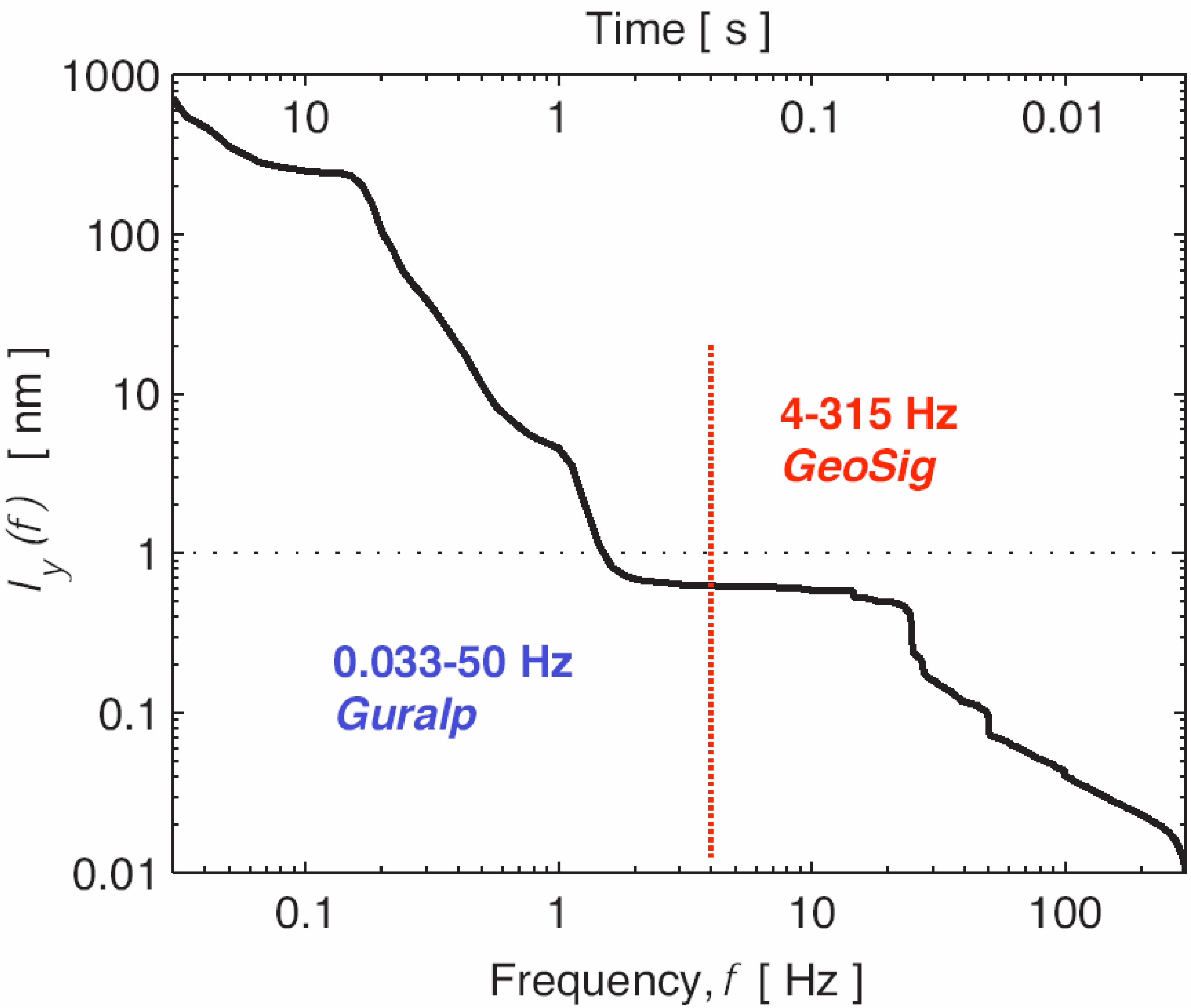
Stability with time (10 days)



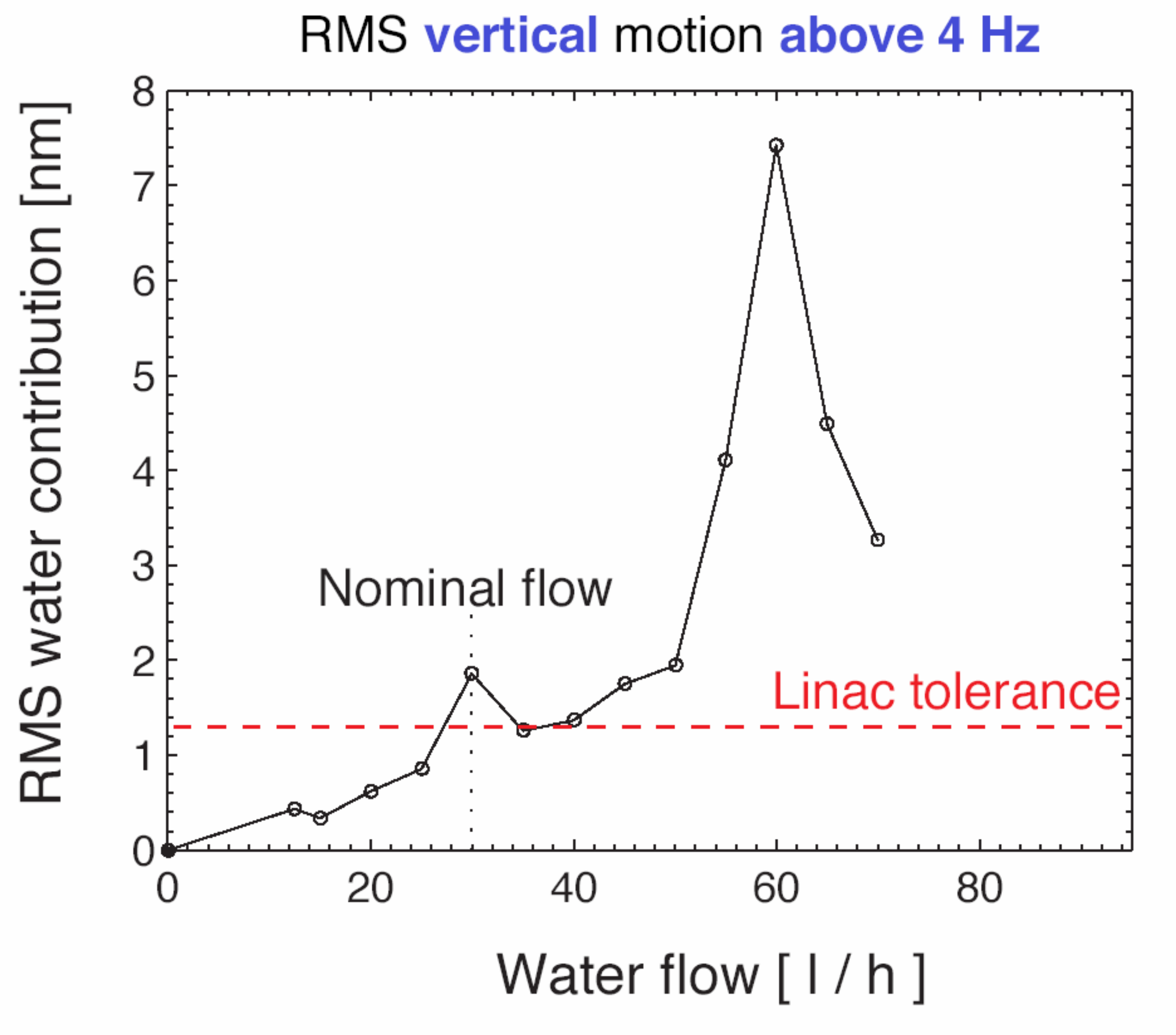
Long term motion:

Integrated RMS motion in vertical direction (above cut-off frequency)

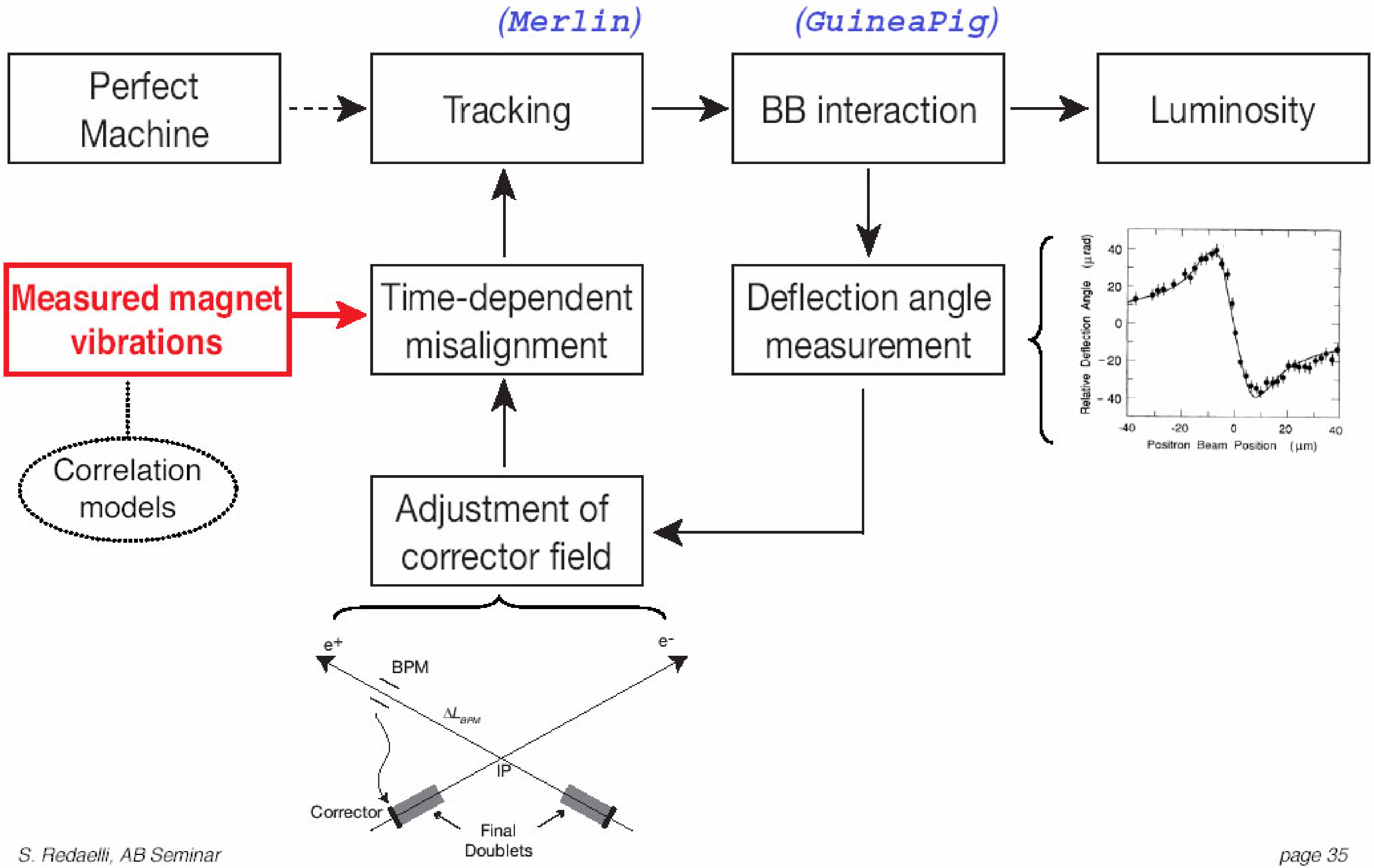
Imagine motion below cut-off is filtered out (long term motion): Corrected by beam-beam feedback!



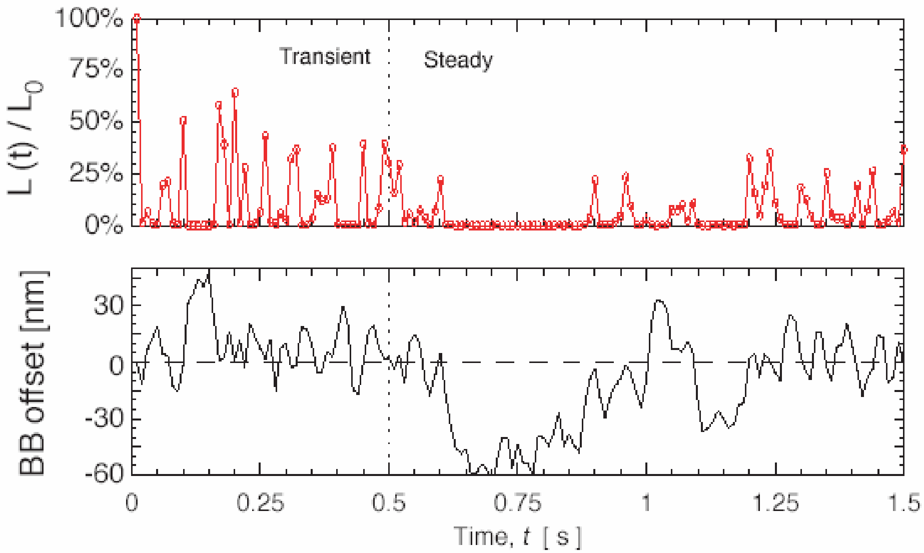
Effect of cooling water:



Scheme of time-dependent luminosity simulations



Example of simulation results

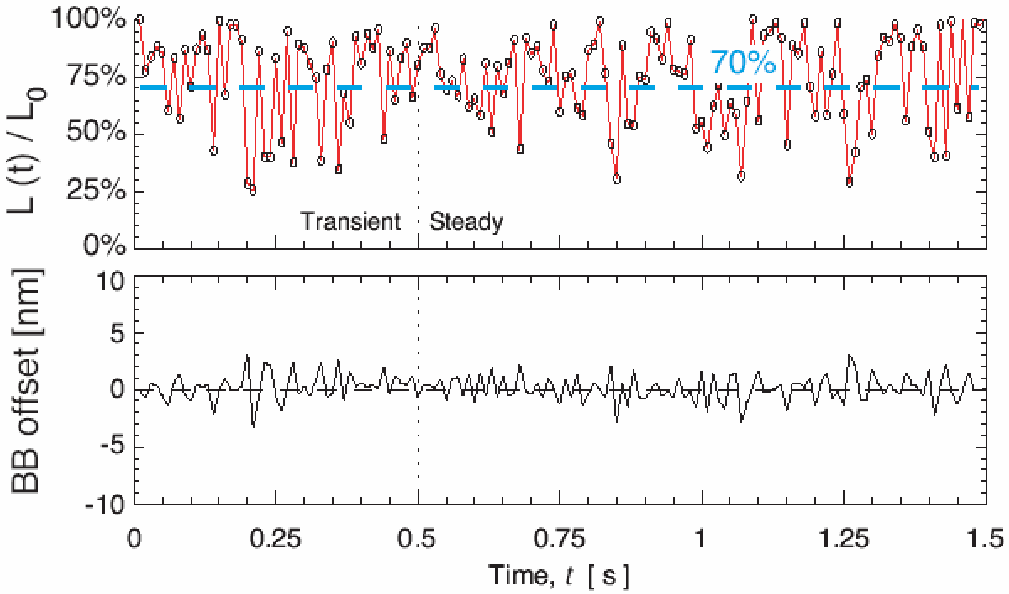


Without stabilization (ground)

No significant luminosity is produced!

With stabilization:

~ 70 % of the luminosity is steadily maintained!



Luminosity performance:

Input spectra	$\langle \mathcal{L} \rangle / \mathcal{L}_0$
CLIC test stand	
Ground, no stabilization	$(\mathbf{6.07 \pm 0.50})\%$
Stiff stabilization system	$(\mathbf{68.97 \pm 0.72})\%$
Soft stabilization system	$(50.08 \pm 1.52)\%$
Cooling water, with stabilization	$(68.01 \pm 0.83)\%$
Alignment support, with stabilization	$(50.26 \pm 0.66)\%$
Empty LHC tunnel (quiet site, no stab.)	$(64.86 \pm 1.42)\%$
ESRF site (noisy site, no stab.)	$(0.49 \pm 0.10)\%$

➔ Reasonable performance with present technology for quadrupole stabilization (FF)!

Conclusion

CLIC stability study has shown the **feasibility to stabilize accelerator magnets to sub-nm**!

Stabilization to sub-nm can be maintained for long periods of time!

Several **systematic effects** have been studied in more or less detail!

Luminosity performance is decent (70%) with present technology!

Now:
- ➔ Adapt technologies to the specific accelerator requirements (radiation, magnetic fields, sources of noise).
- ➔ Complete view of systematics and possible perturbations.
- ➔ Realistic FF magnet prototypes with stabilization.
- ➔ Integration into experimental detector environment, etc.

LAPP/Annecy is picking up our effort (see next talk)...

Modern technology can help us building linear colliders that looked too ambitious just a short while ago!