CERN Academic Training Lectures
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Technological challenges of CLIC

Sub-nanometre Stabilization of Accelerator Magnets

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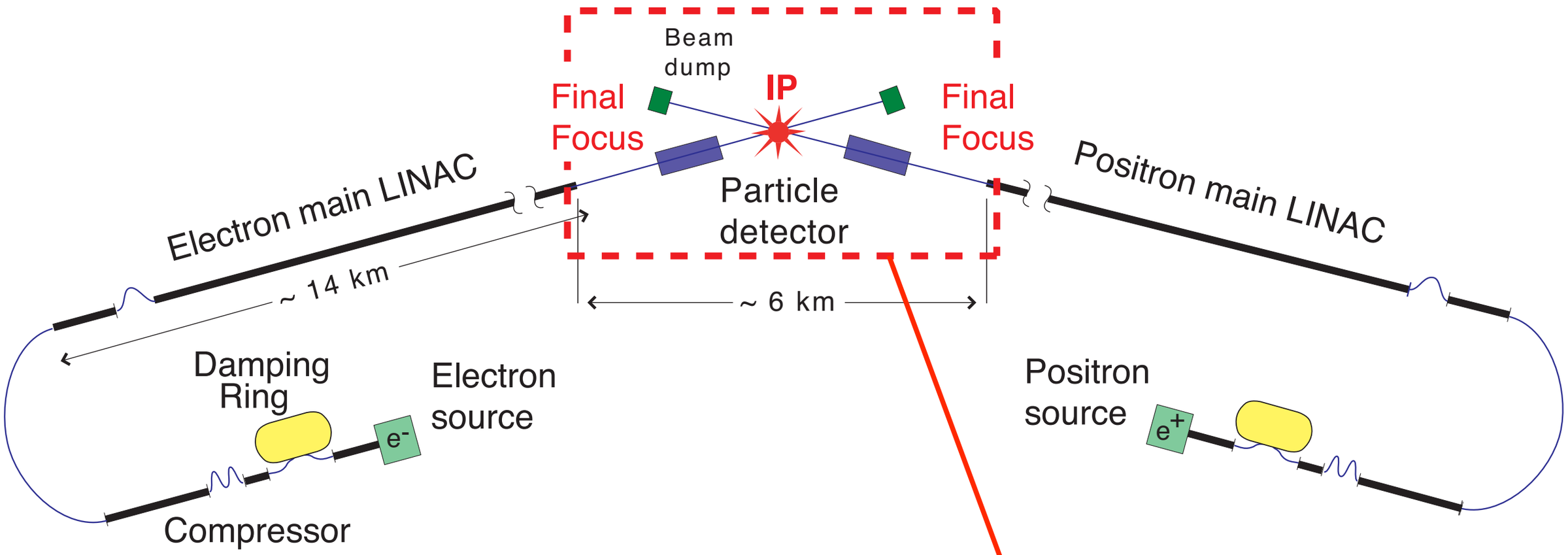
Outline

- Luminosity in a linear collider
- Perturbation of the luminosity performance
- The CLIC stability study
- Achieved magnet stability
- Outlook

The CLIC complex



Energy (c.m.)	3-5 TeV
Luminosity	0.8 x 10^{35} $cm^{-2}s^{-1}$
Repetition rate	150 Hz
Colliding beam size	60 x 0.7 nm^2
Beam area	4.2 10^{-13} cm^2
Total machine length	~ 2 x 17 km

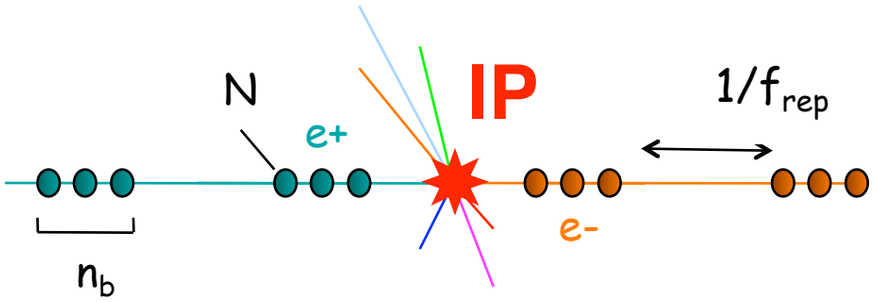
Final focus system

- Squeeze the opposing beams
- Steer beams into collision
- Beam collimation
- Beam diagnostics

Luminosity in a linear collider

Luminosity ↔ rate of interesting event:

$$N_{\text{Event}} = \sigma_{\text{interesting}} \times \mathcal{L}$$



N_e = particles per bunch
N_b = number of bunches
f_{rep} = repetition frequency
σ_x, σ_y = colliding beam sizes
P_b = beam power
H_D = Disruption factor

$$\mathcal{L} = \frac{N_e^2 N_b f_{\text{rep}}}{4\pi\sigma_x^*\sigma_y^*}\mathcal{H}_d \approx \frac{P_b}{\sigma_x^*\sigma_y^*}$$

CLIC:
$\sigma_x^* = 60$ nm
$\sigma_y^* = 0.7$ nm

The luminosity is produced by the superimposition of the opposing beams

Perturbations of luminosity performance

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

$\sigma_y^* = 0.7$ *nm*

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

⇒ *We get the optimum luminosity!*

Real world: Alignment errors of magnets / beam offsets in the RF cavities

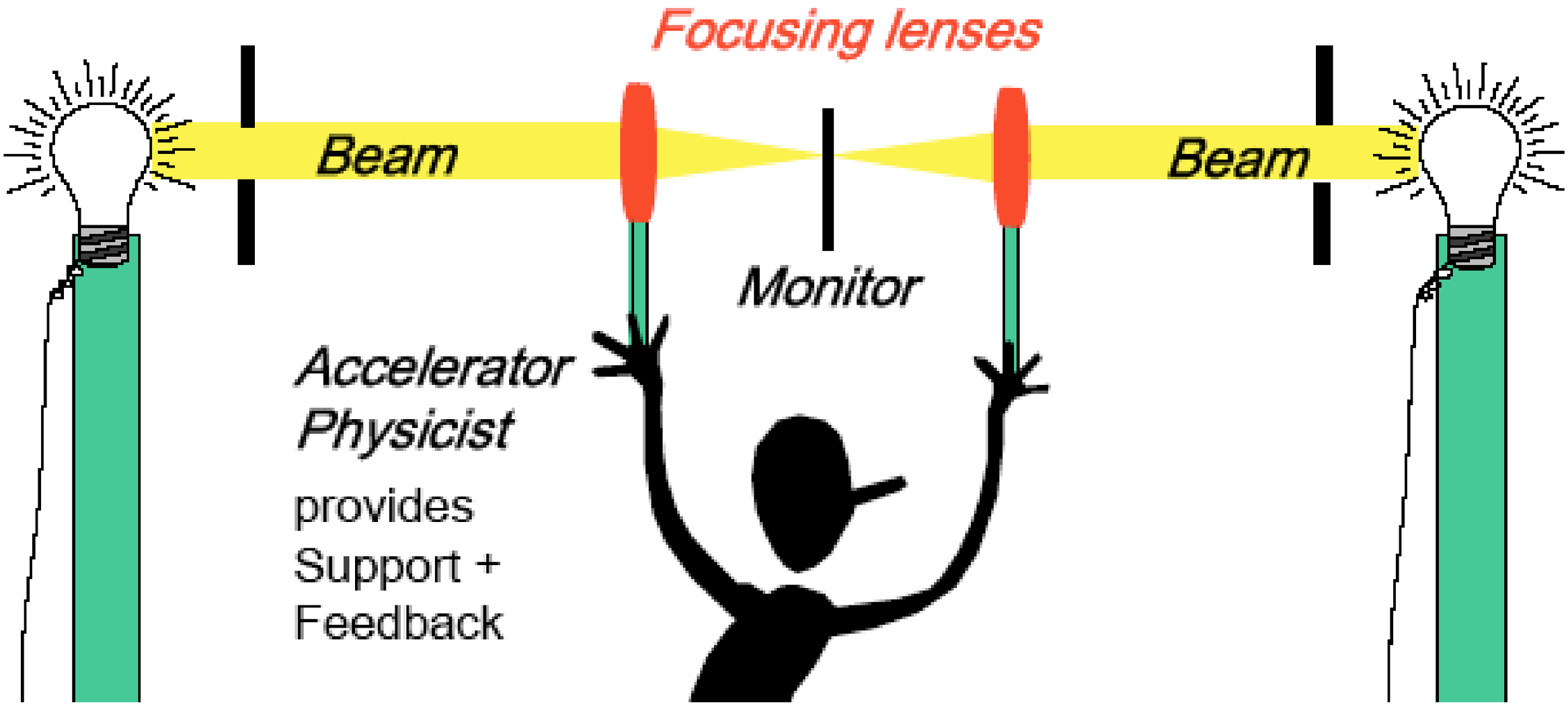
$\sigma_y^* > \sigma_{y,nom}^*$

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

⇒ *Degradation of the luminosity performance (design value)!*

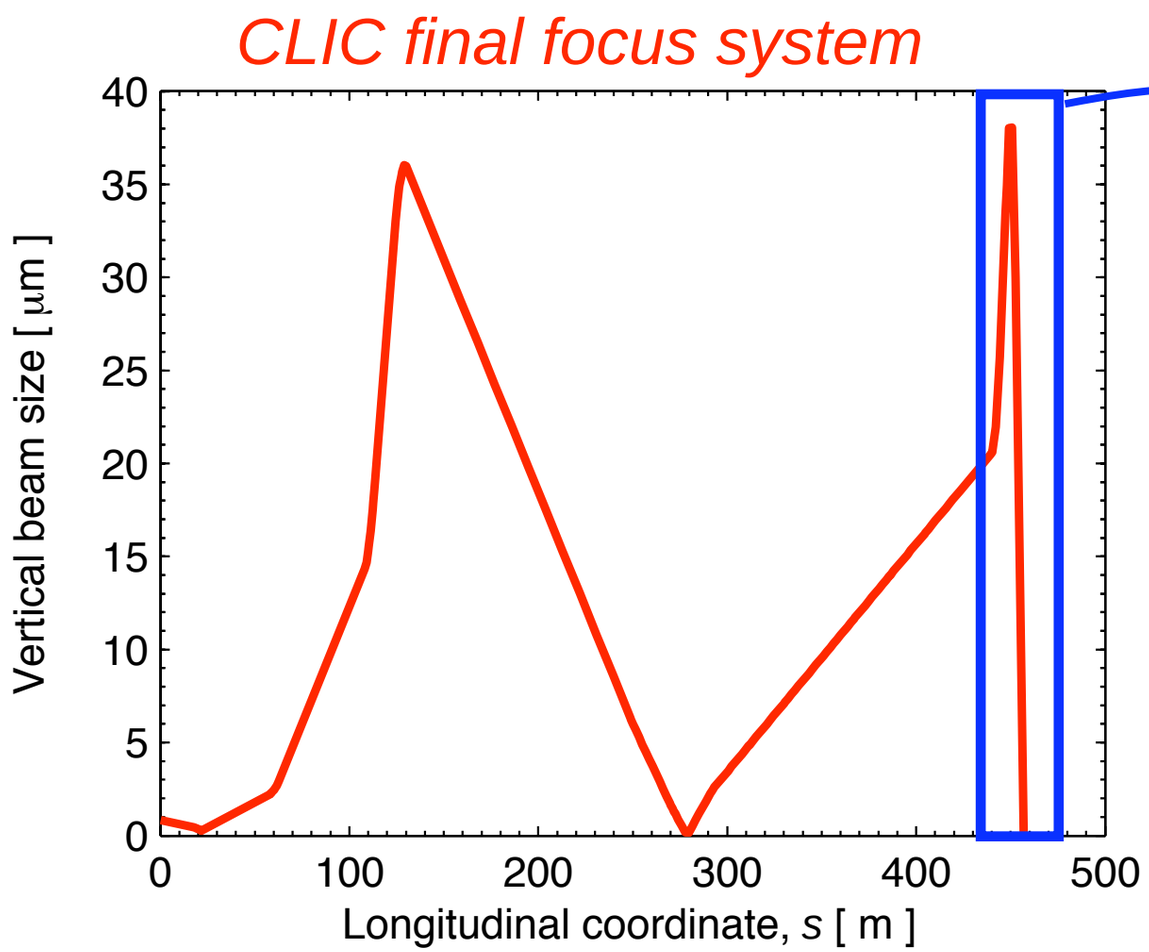
How do we produce the luminosity in CLIC?
What generates perturbations?

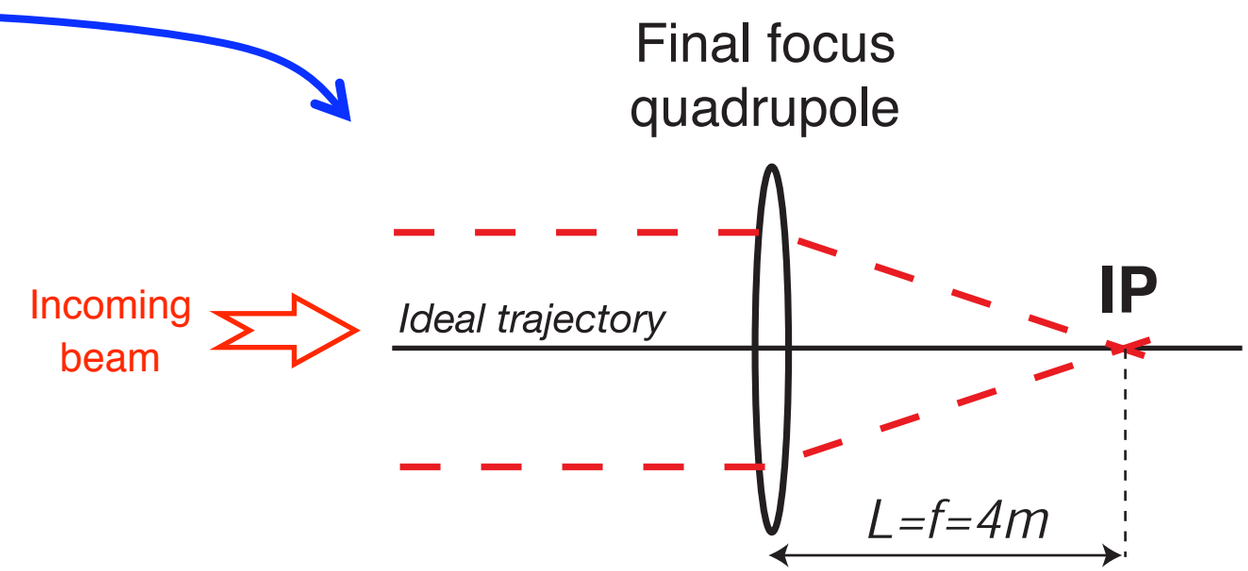
Job of the poor accelerator physicist



Picture by R. Assmann

How do we produce small beam size?

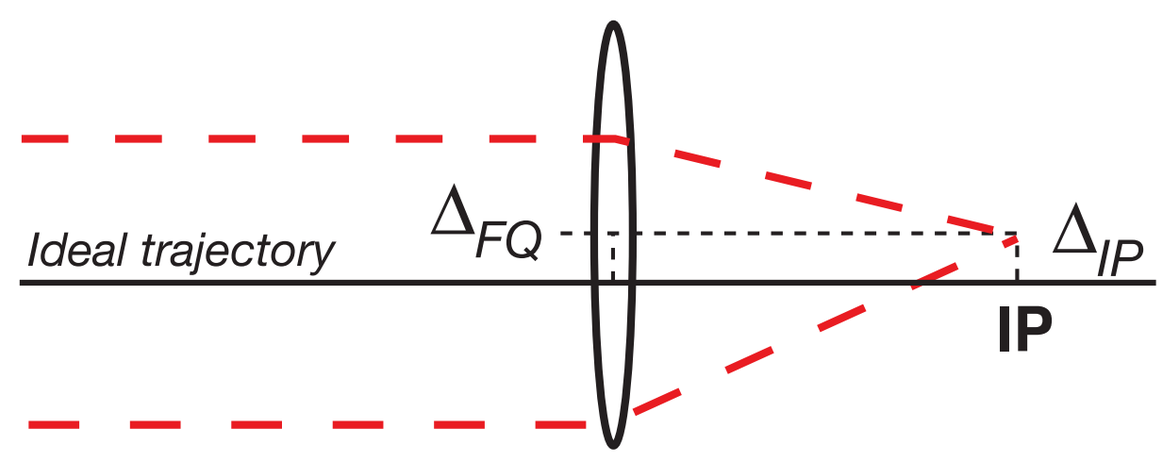




Actually, two quadrupoles are used to squeeze both horizontal and vertical size!

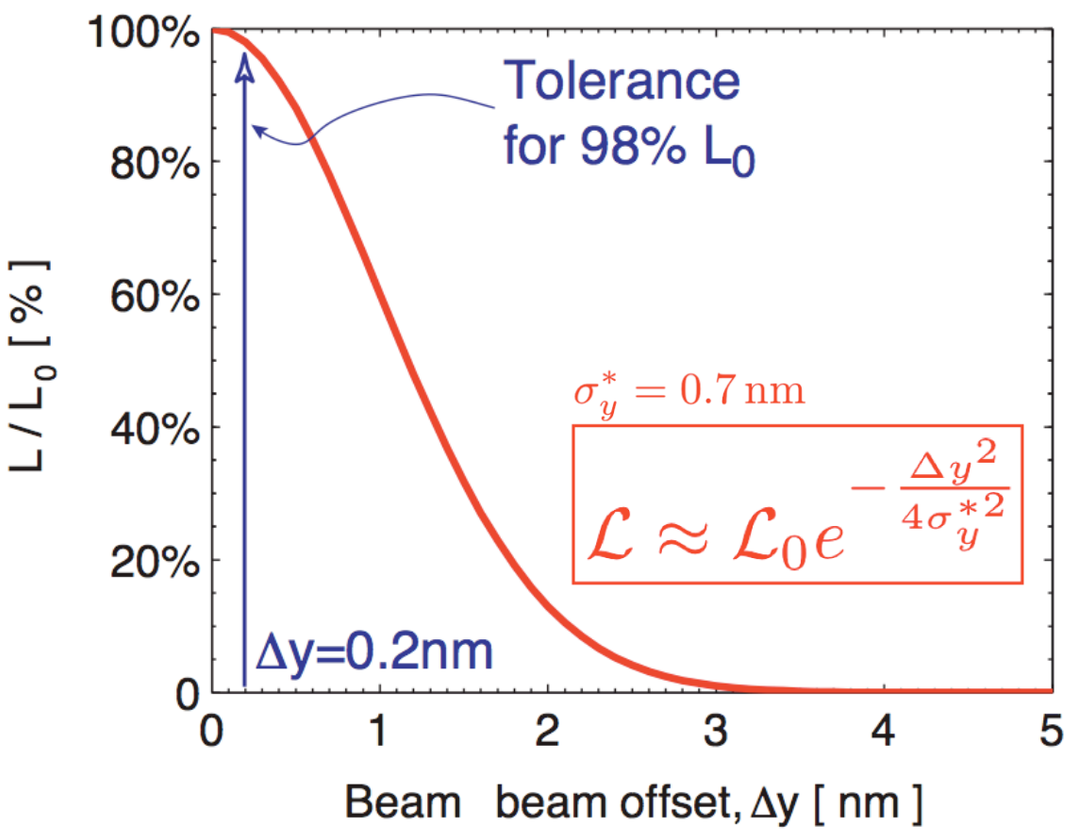
Nanometre size beams are produced in the focal point of the quadurpole "lens"

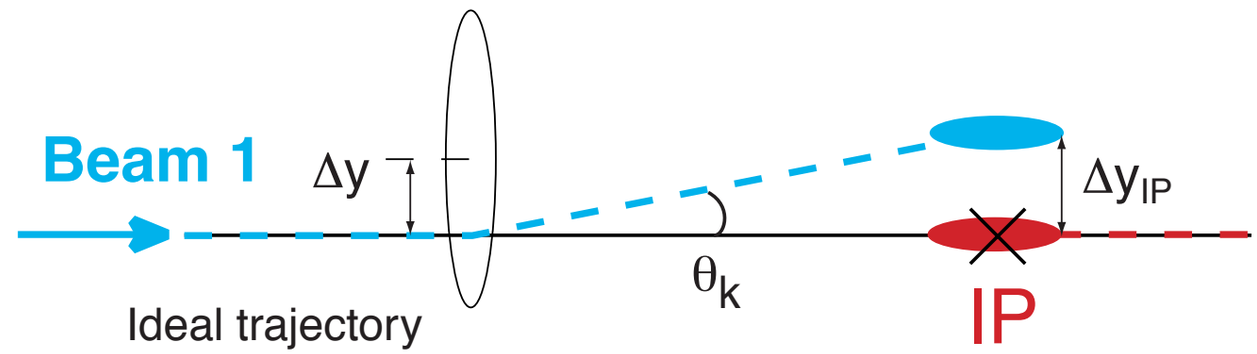
→ *the "nanobeams" at the IP move as the quadrupoles*



Tolerance for luminosity reduction

Luminosity decreases exponentially with the relative beam-beam offset!





$\Delta y^{quad} \approx \Delta y^{IP}$

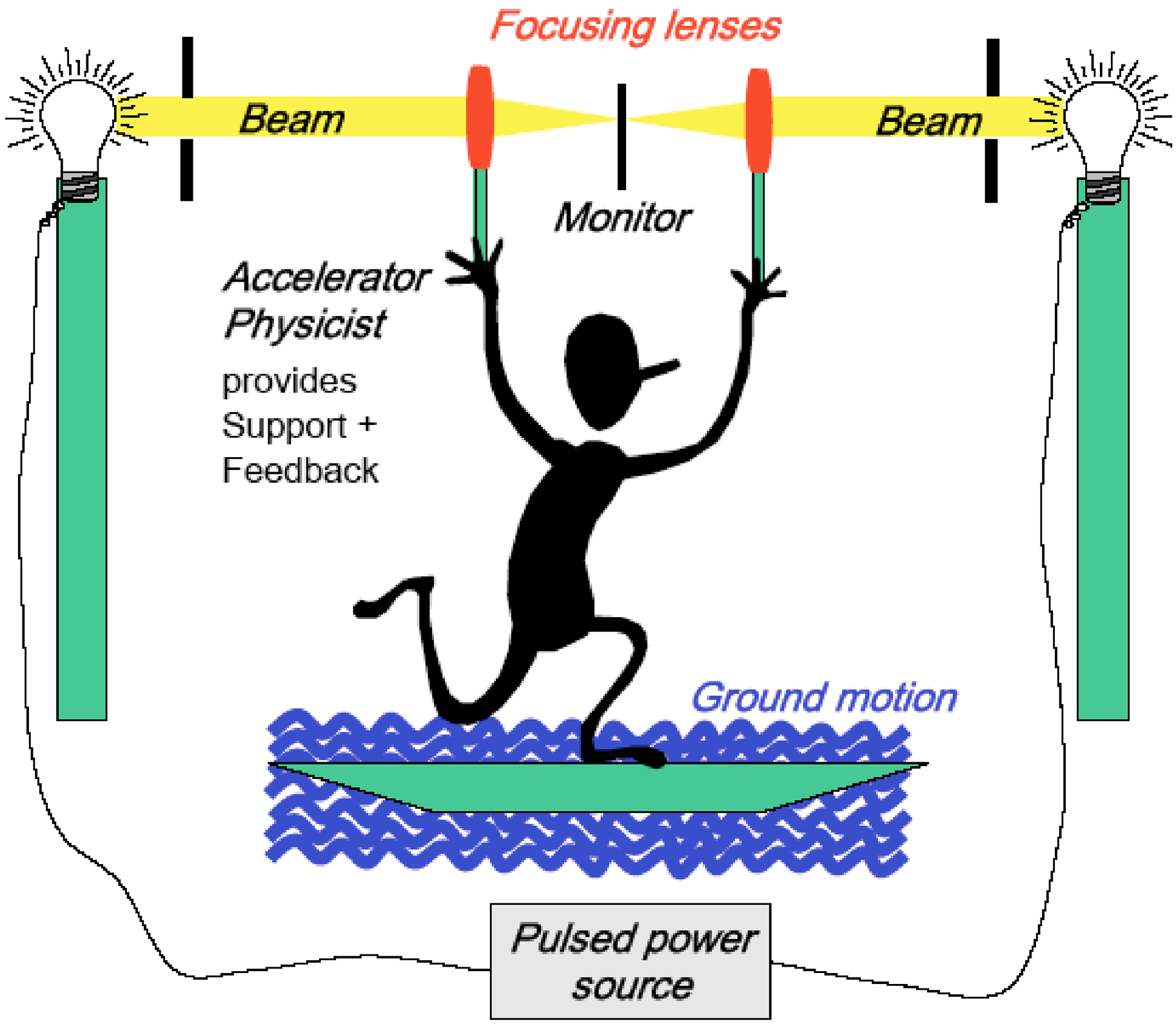
→ *Sub-nanometre tolerances for the bulk magnet!*

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

$\sigma_x = 100 \times \sigma_y$

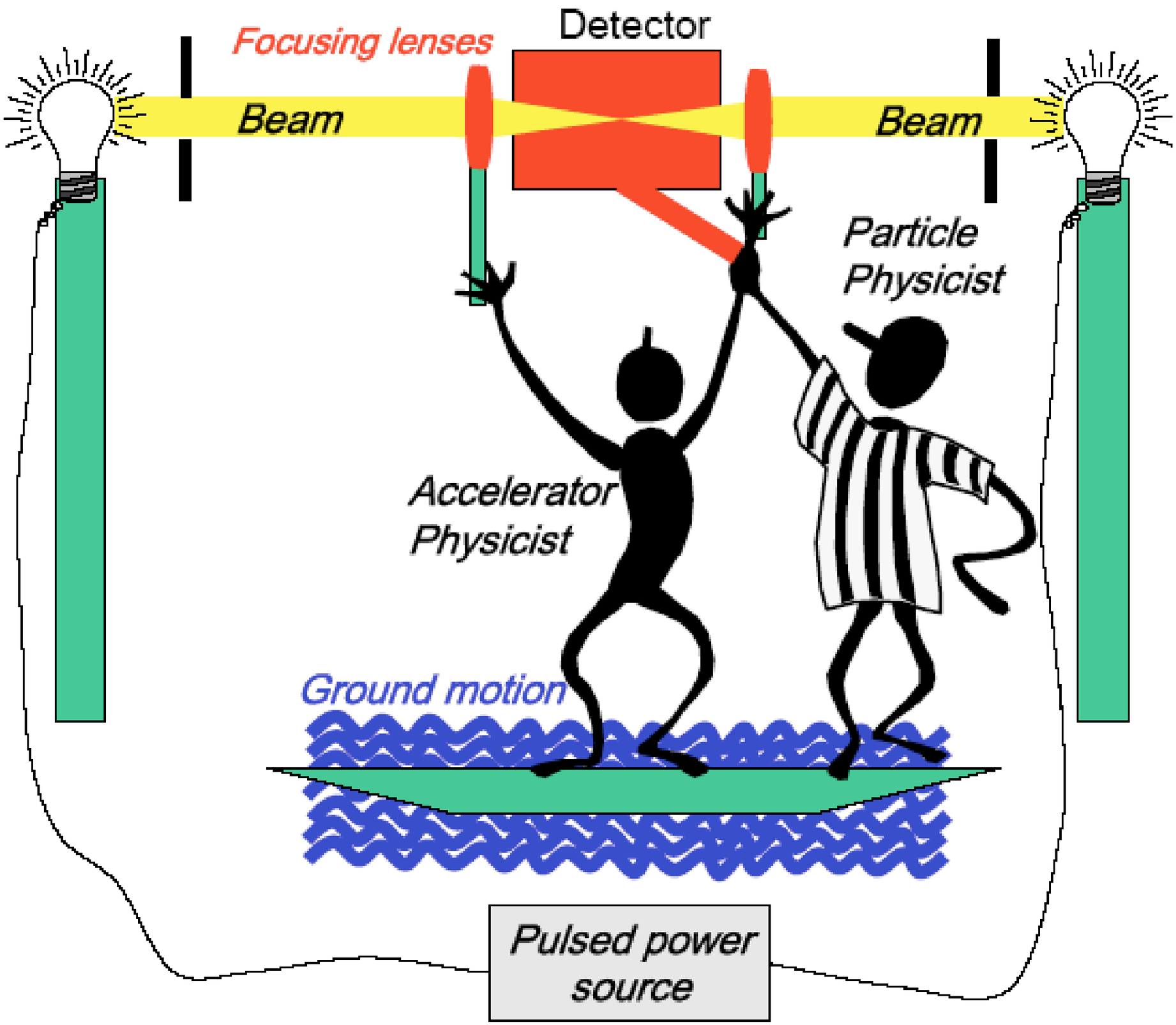
Why do magnets move??

Sources of magnets vibrations



Picture by R. Assmann

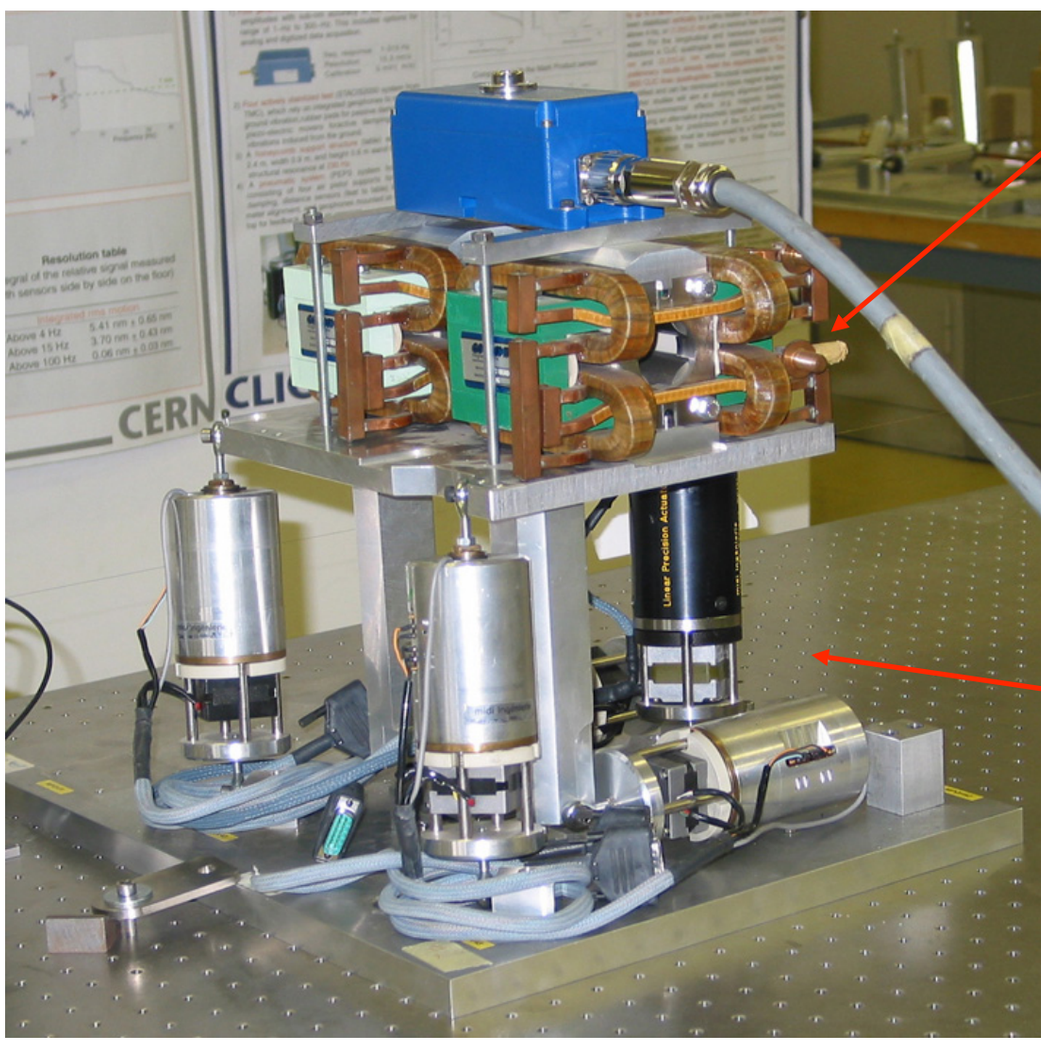
Sources of magnets vibrations

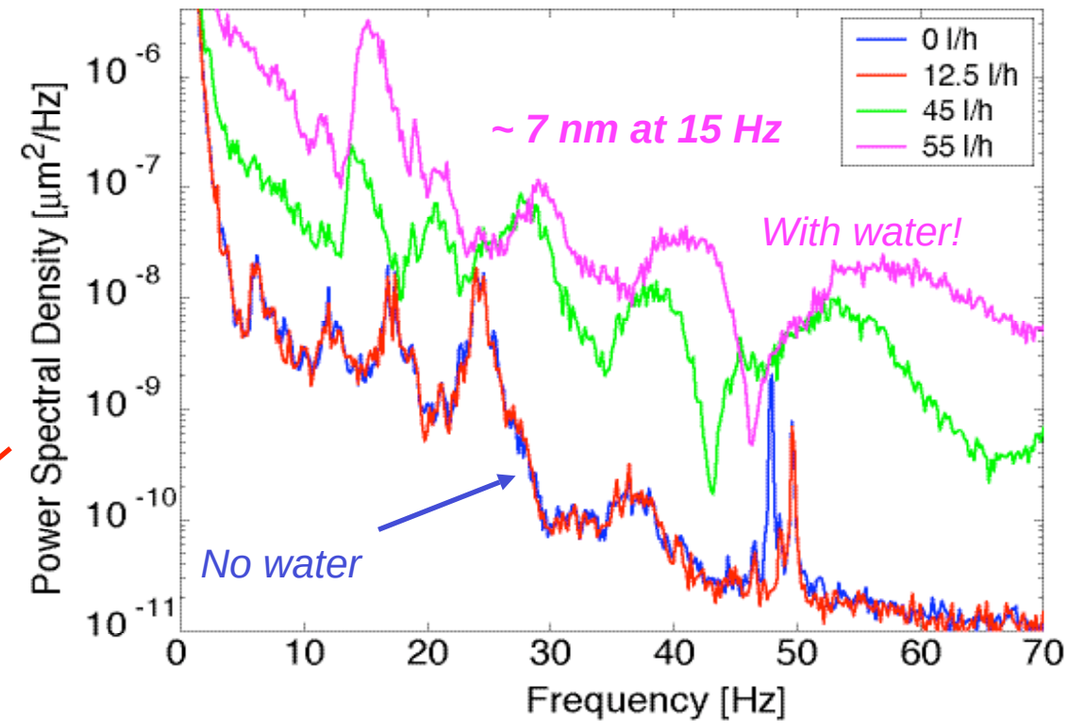


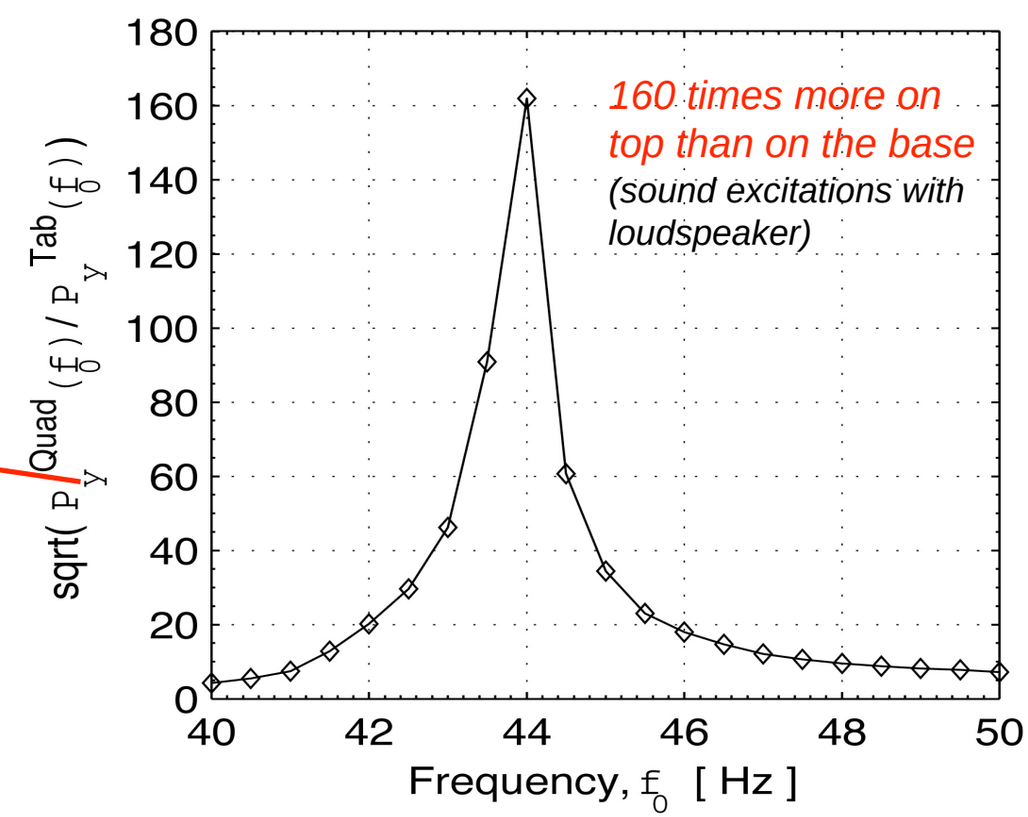
Picture by R. Assmann

What perturbs the quadrupole motion?

- *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





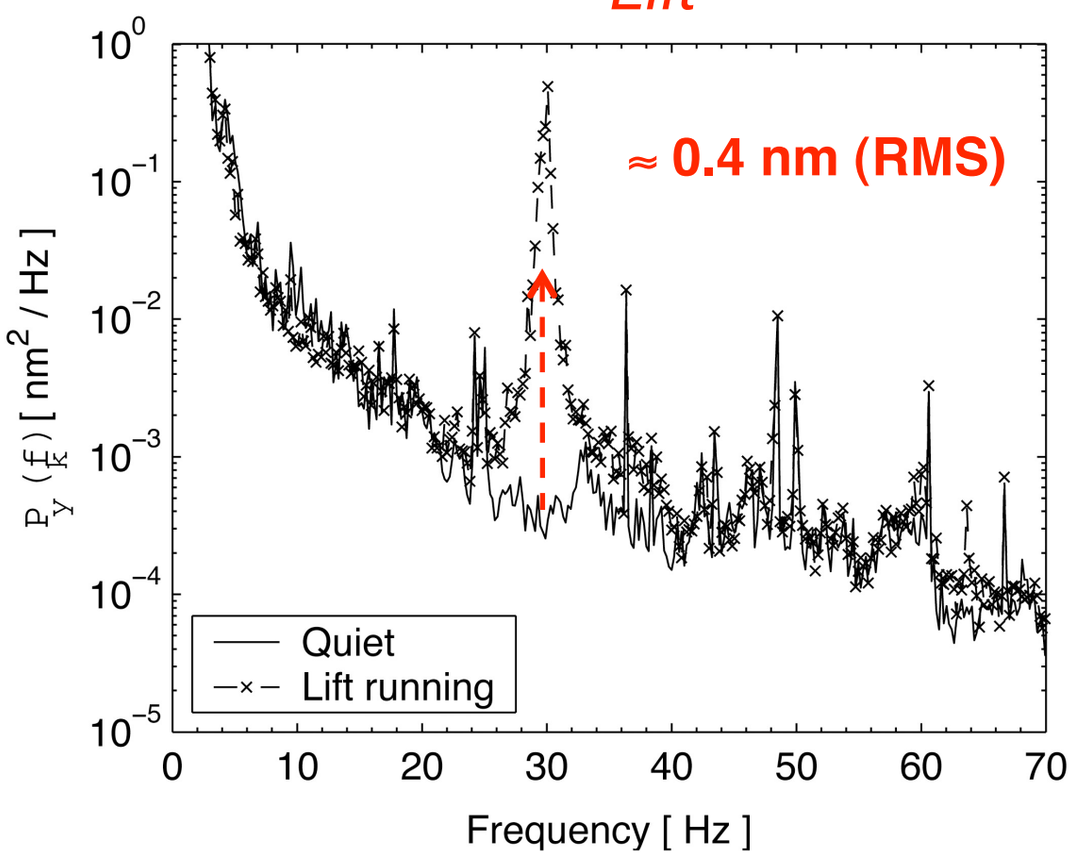


What perturbs the quadrupole motion?

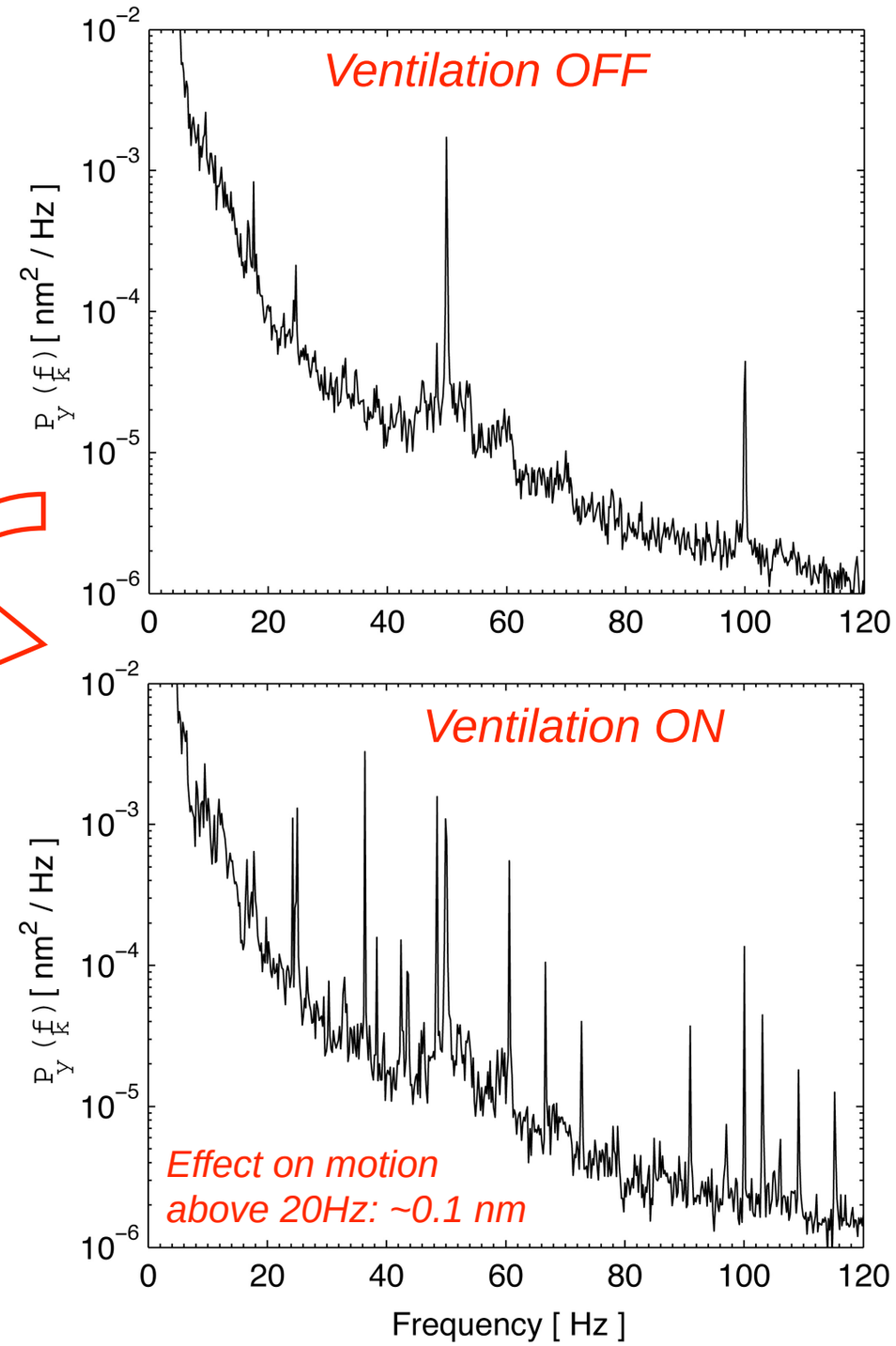
Noise in the quiet LHC tunnel:

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

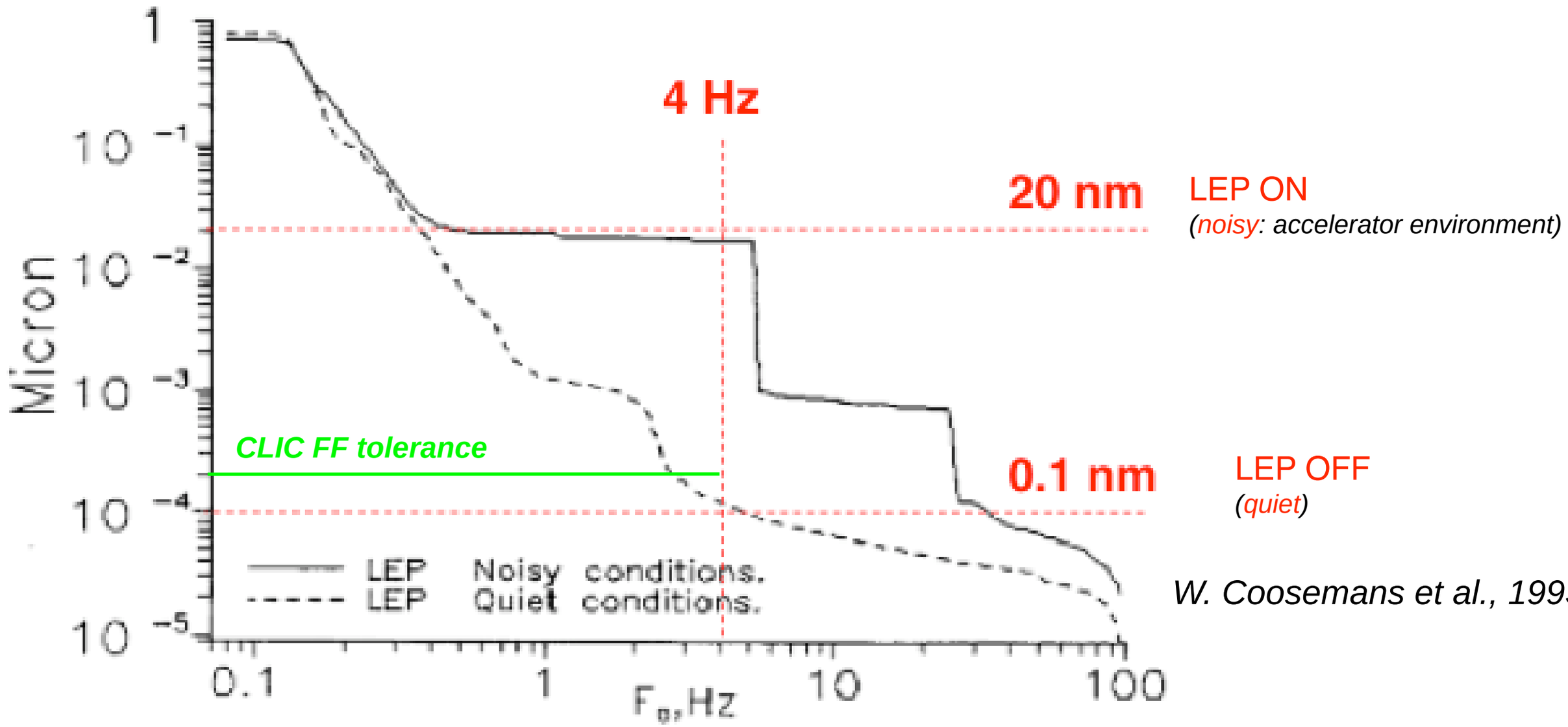
Lift



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



What perturbs the quadrupole motion?



W. Coosemans et al., 1993

Ground motion and accelerator environment are the main sources of motion

The CLIC stability study

Demonstrate the **feasibility of colliding nanometre-size particle beams** in a *real accelerator environment* for future linear colliders like CLIC.

*CLIC tolerance: **0.2 nm** RMS above 4 Hz*

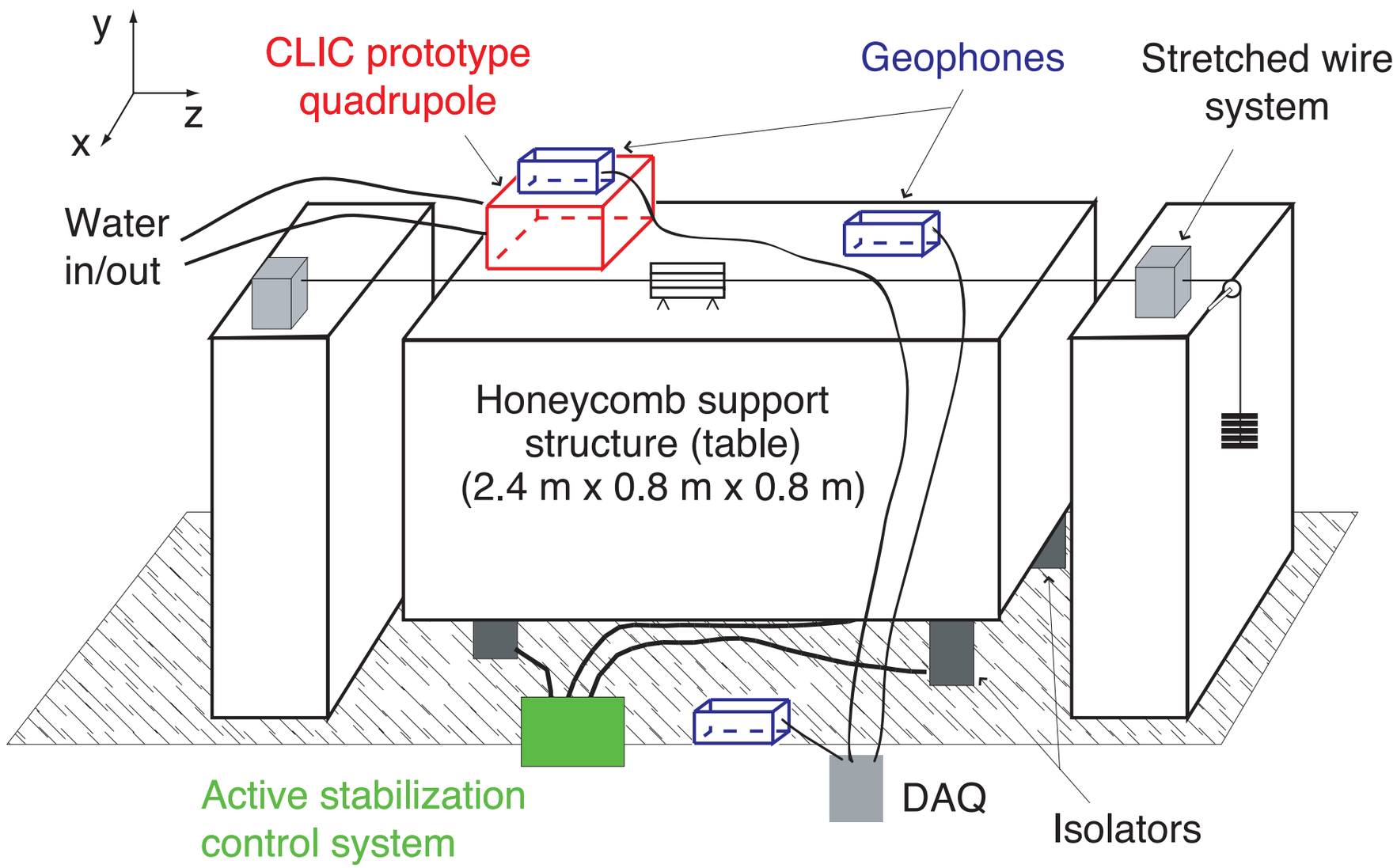
Our approach → Use state-of-the-art stabilization devices to stabilize CLIC prototype quadrupoles in a *normal working environment*
(Different approaches pursued in other laboratories in previous years!)

Steps towards feasibility demonstration *(first phase of our study)*:

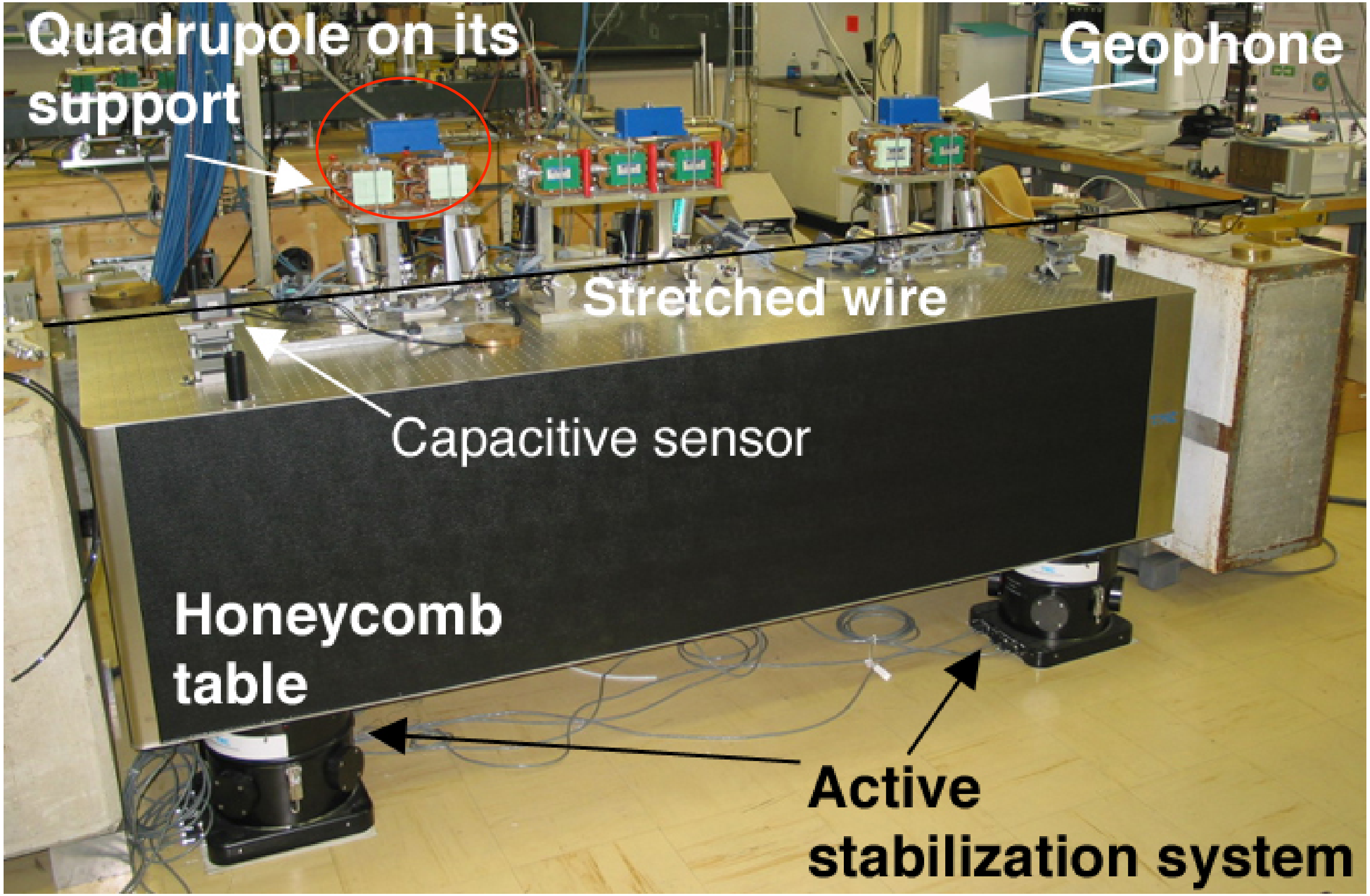
I. Establish vibration measurements with sub-nanometre accuracy
II. Investigate modern techniques for stabilizing accelerator magnets
III. Predict the performance of CLIC achievable with the measured magnet stability

CLIC stability people: *R. Assmann, W. Coosemans, G. Guignard, S. Redaelli, D. Schulte, F. Zimmermann, I. Wilson*

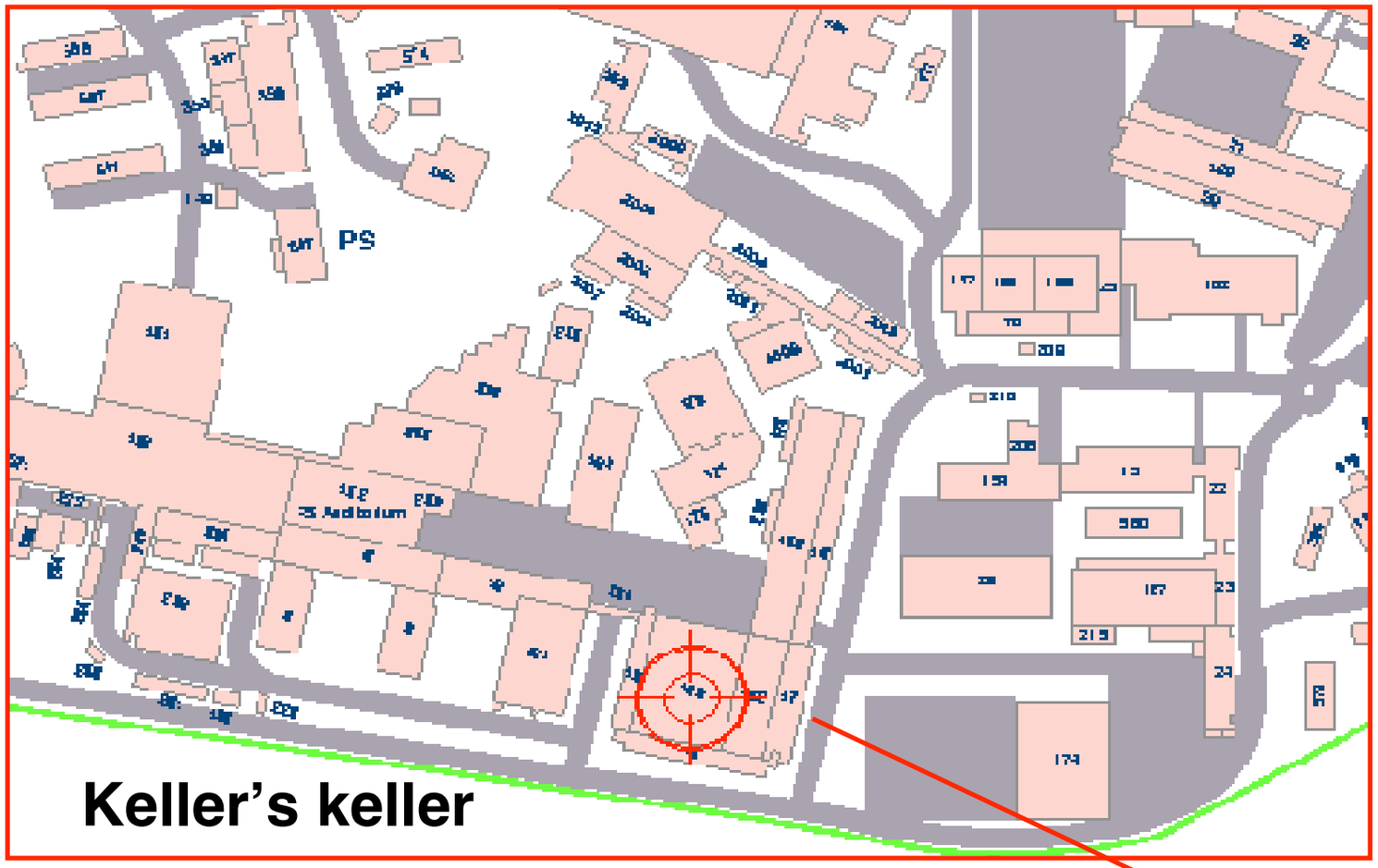
Our experimental test stand



Vibration measurements	→	Geophones (3 types)
Objects to stabilize	→	Prototypes of CLIC accelerator magnets
Support structure	→	Honeycomb table (min. resonance above 230 Hz)
Active/passive damping	→	Two systems (soft and stiff)
Alignment/inclination	→	Stretched-wire system (WPS) / accelerometers
Systematic effects	→	Water on/off; loud speakers; alignment support


Quadrupole on its support
Geophone
Stretched wire
Capacitive sensor
Honeycomb table
Active stabilization system

Location of the stabilization test stand



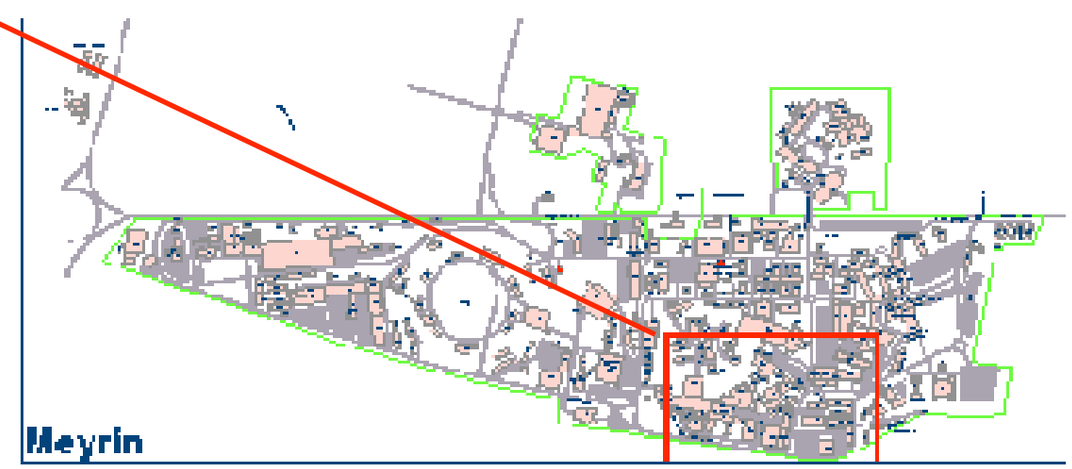
Laboratory is chosen close to streets, normal working areas, offices, workshops…

Ground motion of **up to ~ 12 nm** (RMS) above a few Hz

… we want to test stabilize magnets in a *realistic accelerator environment*!

Much more stable places exist!

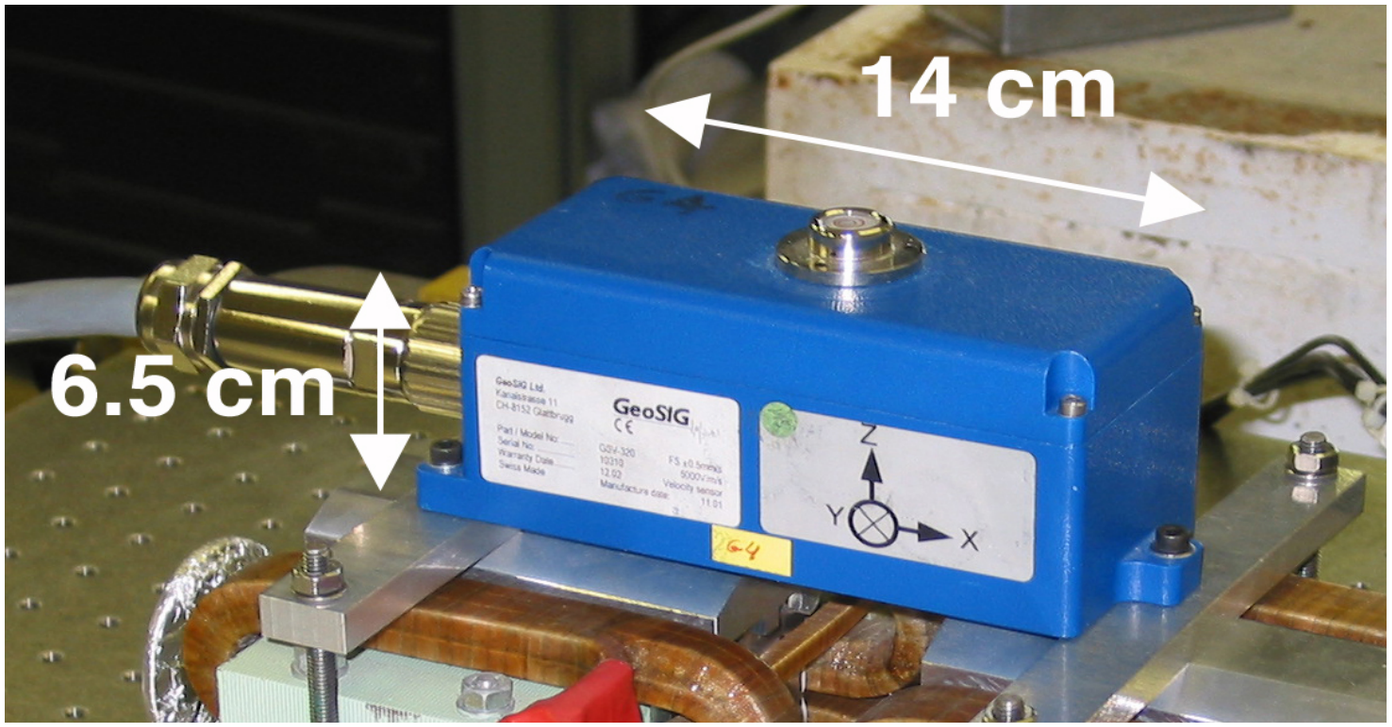
*But we want a **noisy environment** to provide a **feasibility demonstration** of required stabilization!!*

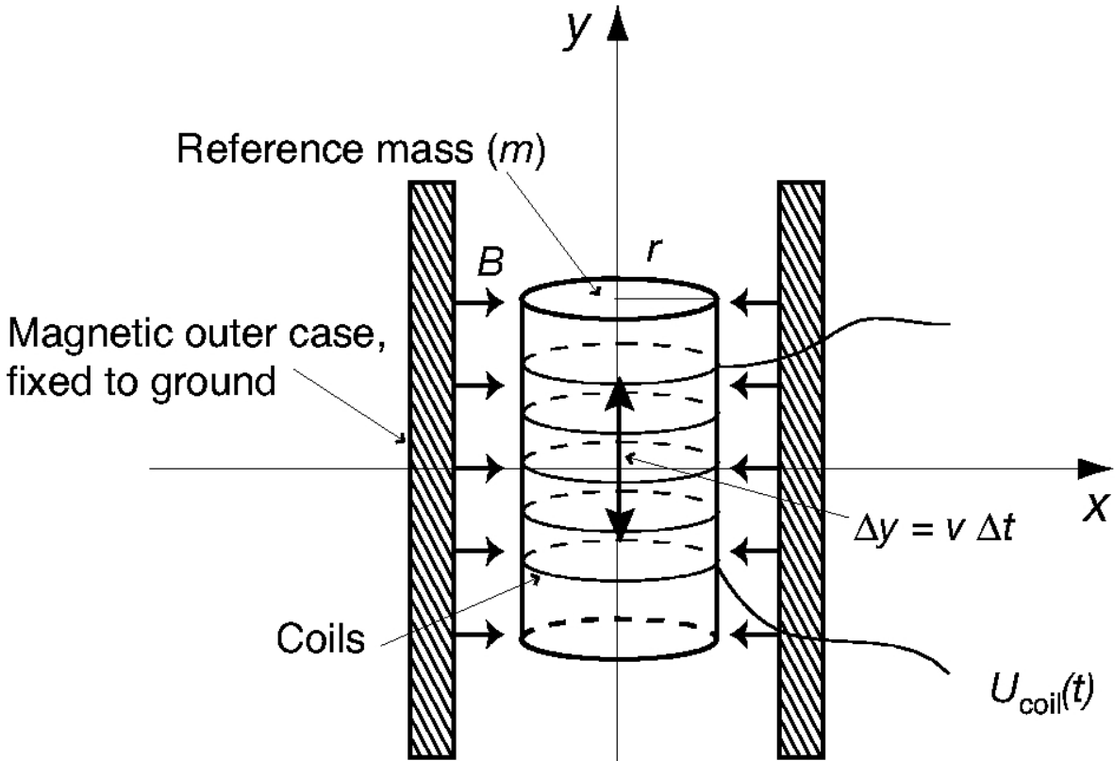


Geophones for sub-nanometre vibration measurements

Triaxial **geophones** (seismometers) are used to measure vibrations

(Measure velocities in the ~ 4Hz - 315 Hz frequency range)



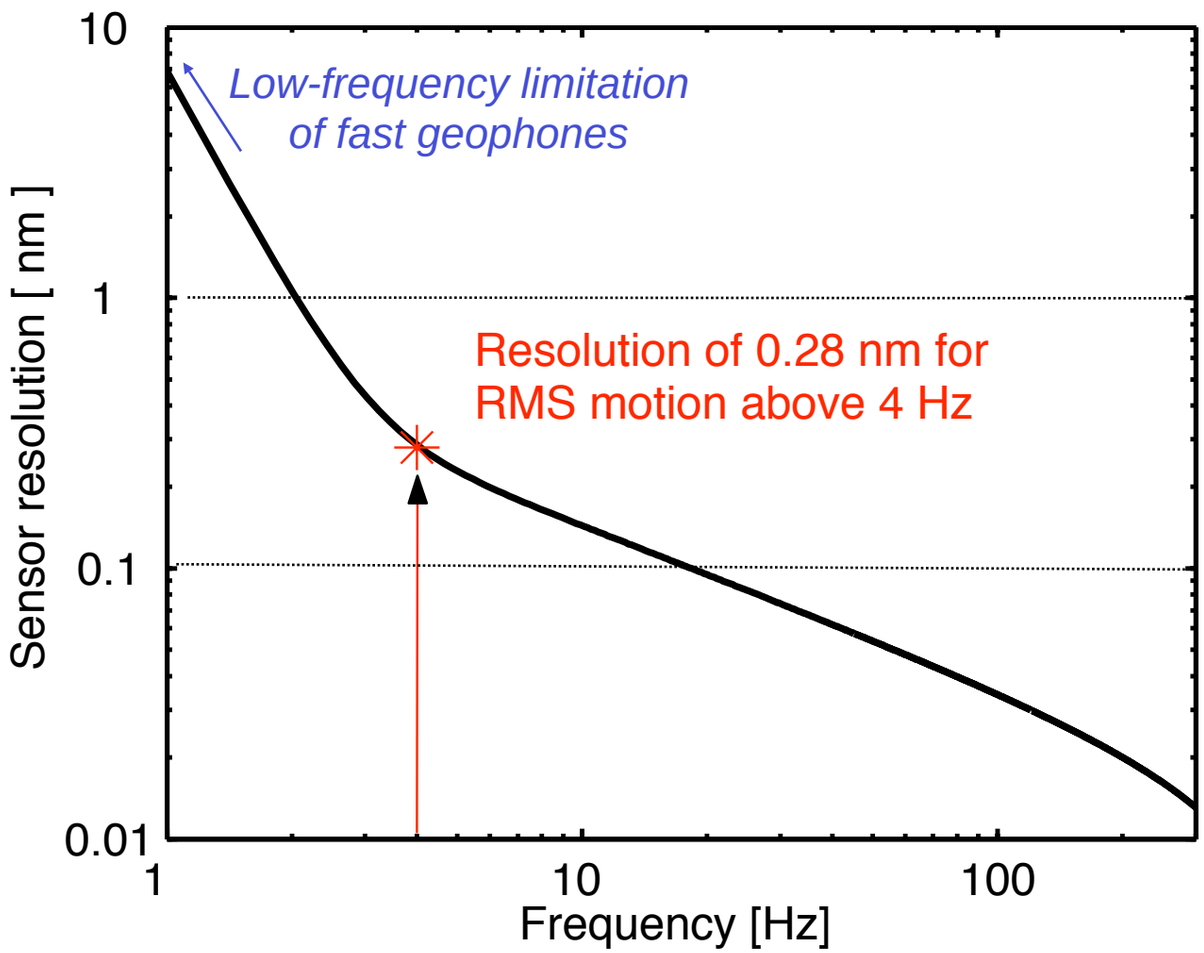


The geophone measures velocities with respect to a reference mass at rest (absolute vibration velocities)

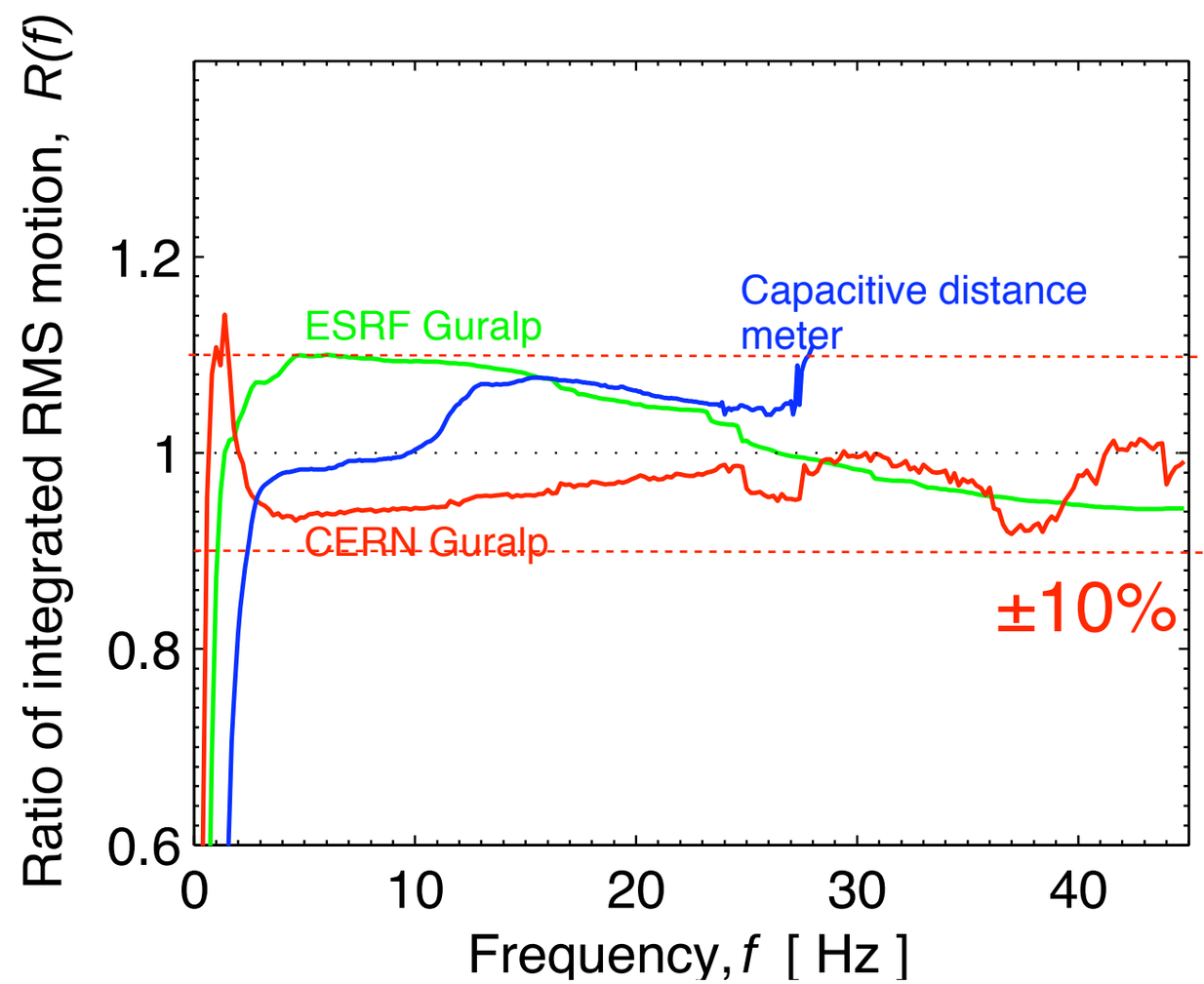
$$V_{\text{coil}} \approx -n(2\pi r_{\text{c}} B)v$$

Sensor calibration to the sub-nm level

Resolution *inferred from the comparison of close-by sensors*



Calibration *assessed by comparing with other kinds of sensors*

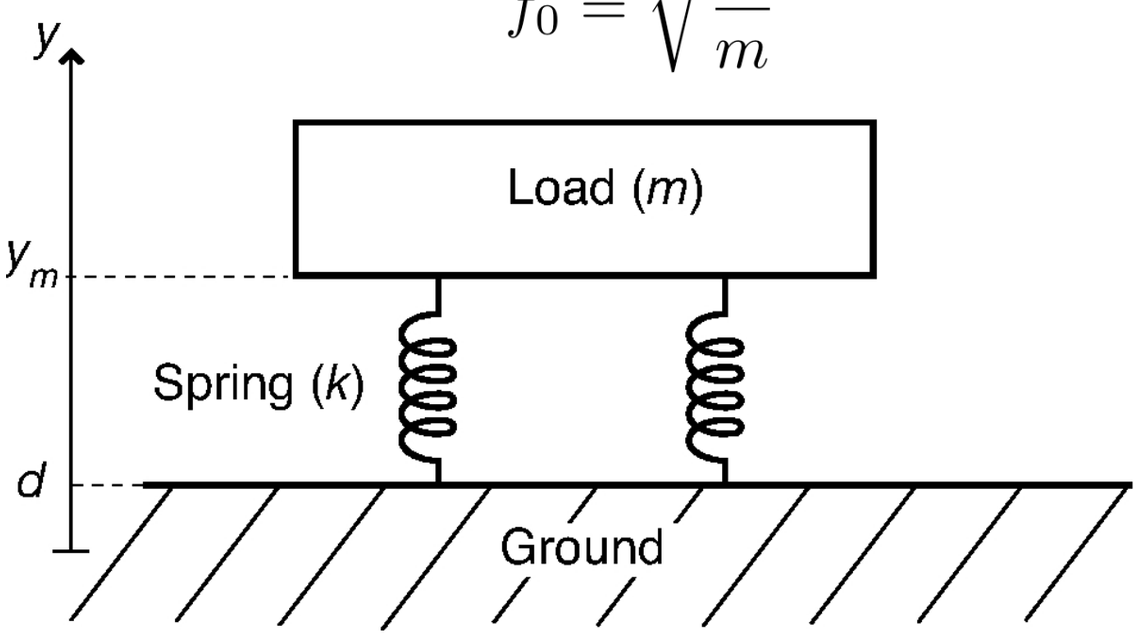


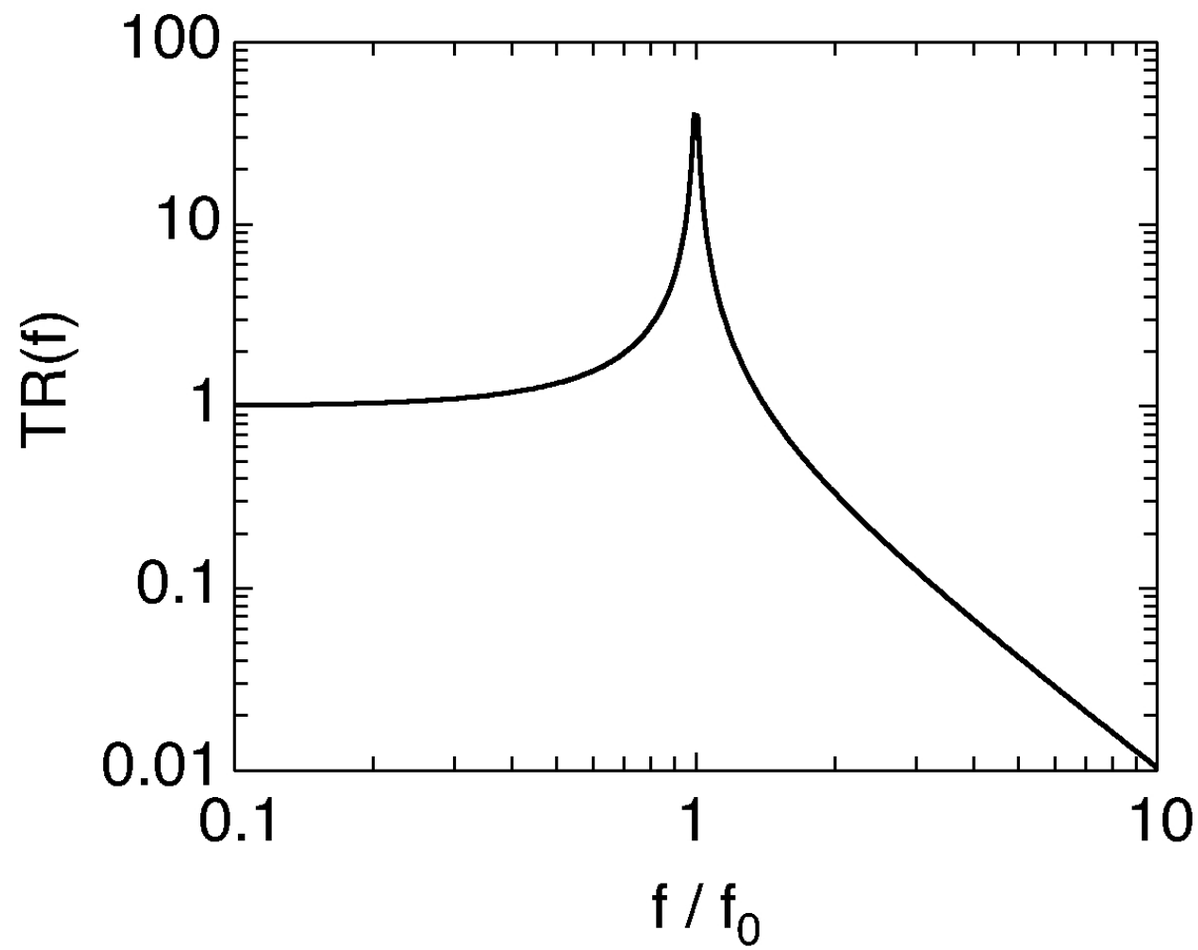
We believe that 1 nm is 1 nm within 10%!

(good accuracy within the frequency range of interest)

Passive stabilization - Mass/spring system

$$f_0 = \sqrt{\frac{k}{m}}$$

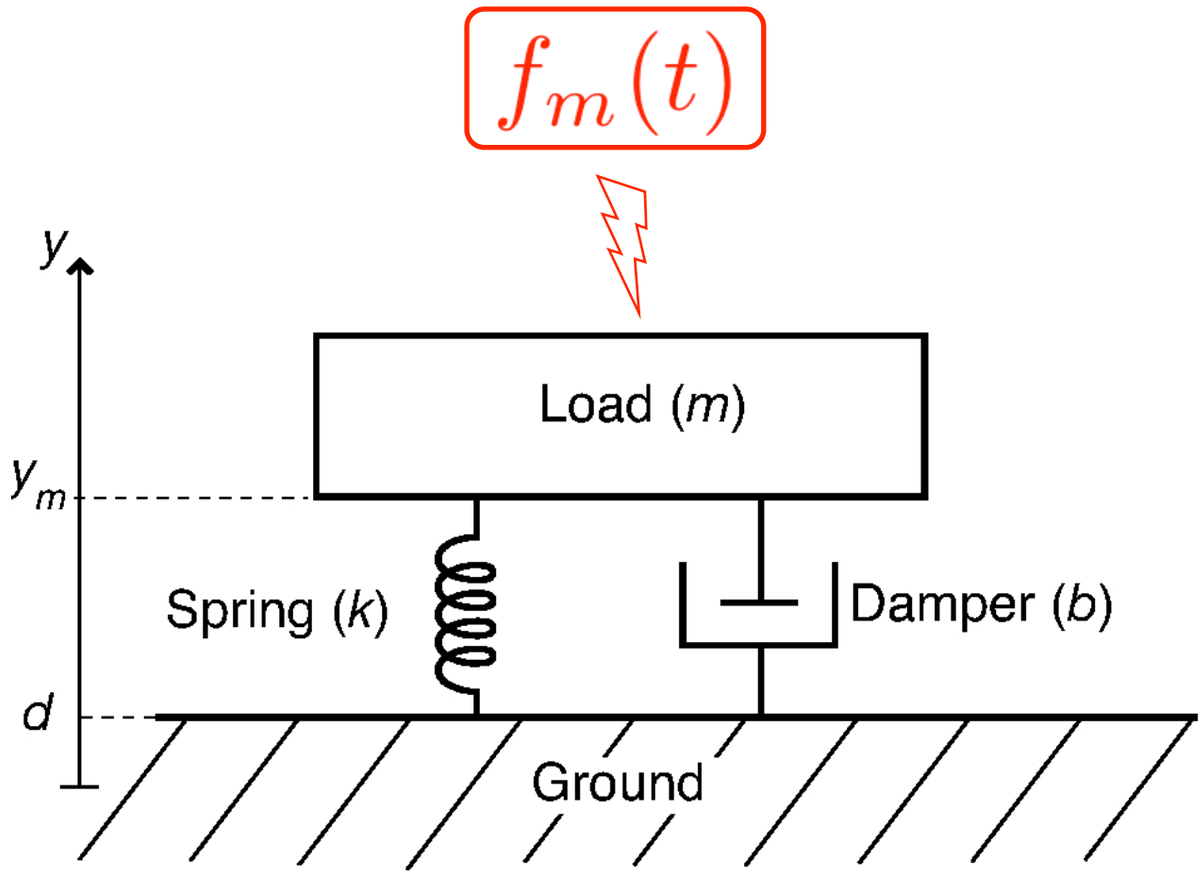


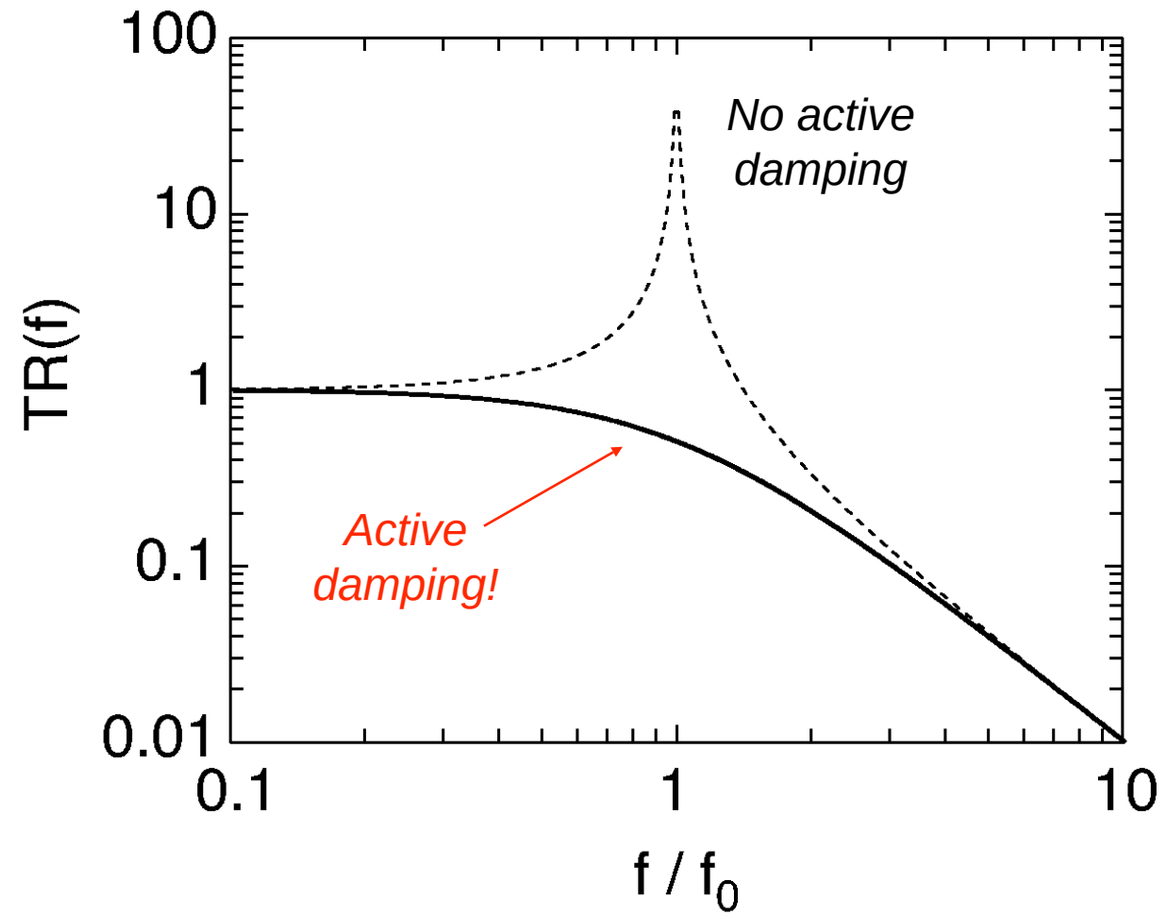


- Coupled motion below f_0
- Good damping above f_0
- Resonant amplification at $\sim f_0$

Active damping *required to counteract amplification of motion around the resonance frequency!*

Active stabilization

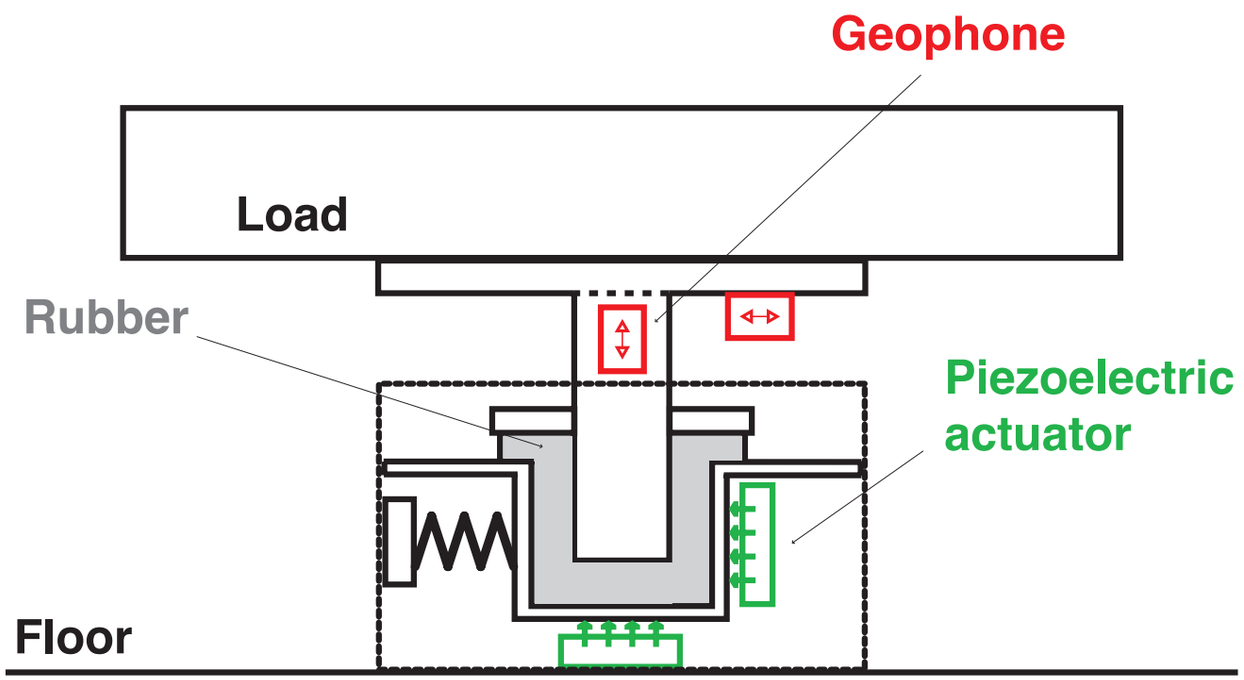




By applying a **time-dependent force** (actuator) to the system, the resonant peak can be damped. Good damping at high frequency is kept!

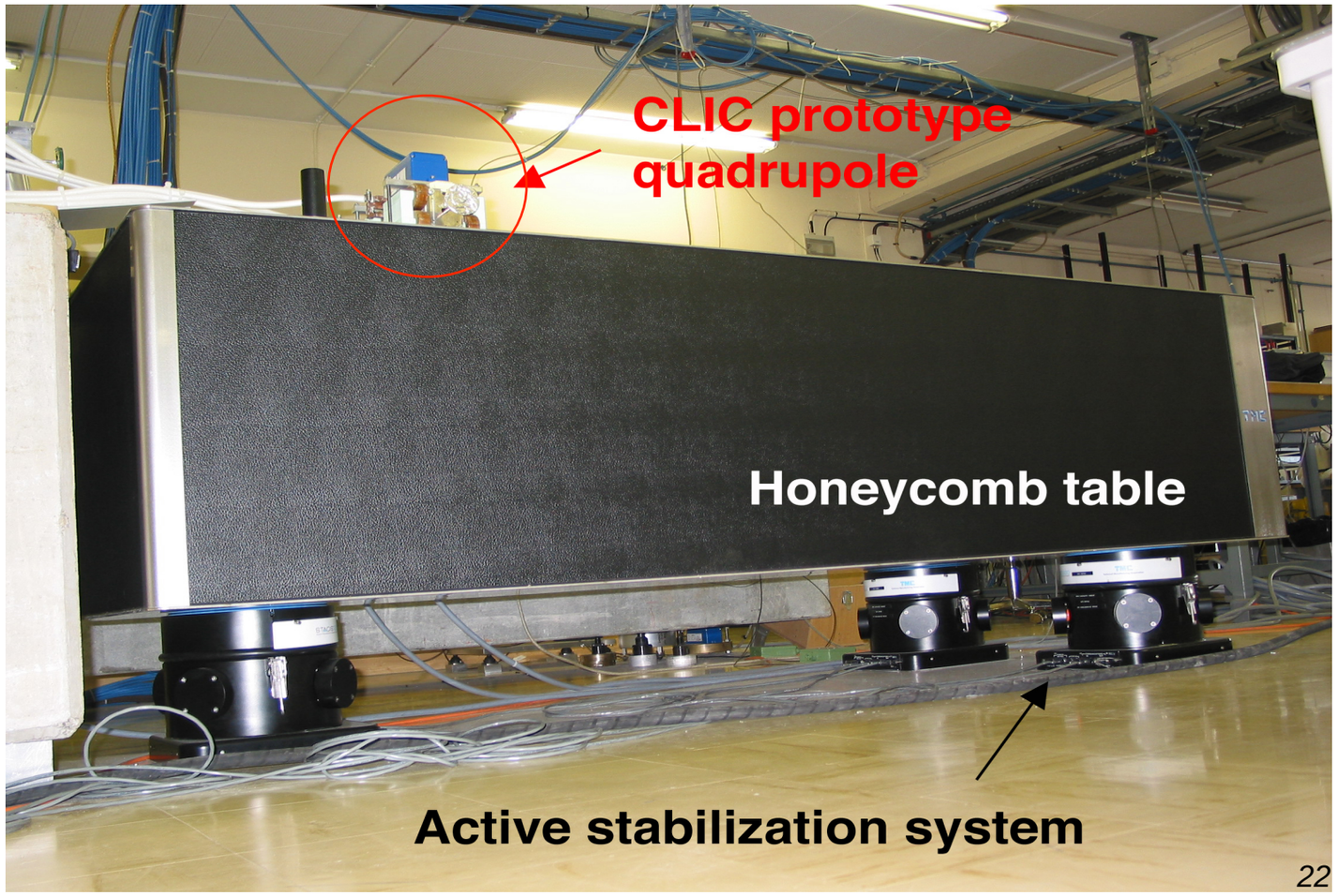
Actuator implementation depends on the type stabilization technology…

Our stabilization system

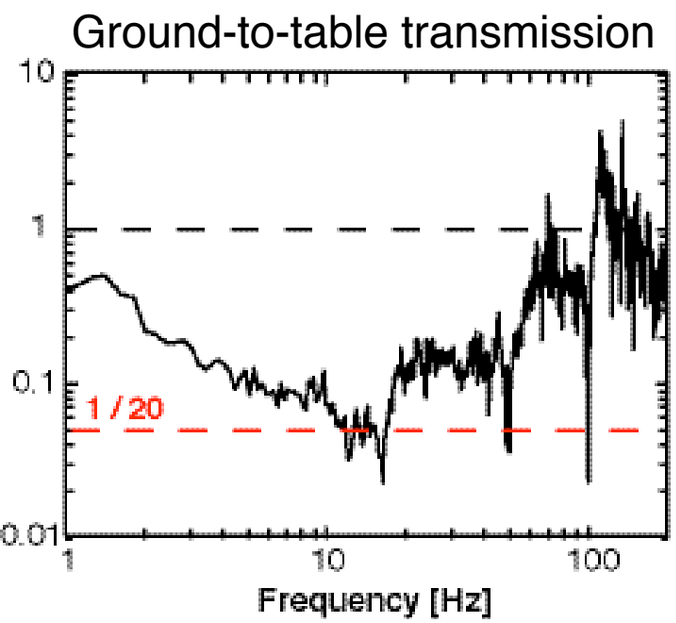


- **Passive damping** → stiff rubber
- **Active damping** → geophones / piezo-cristals

This system provides a damping of 3D table vibrations!

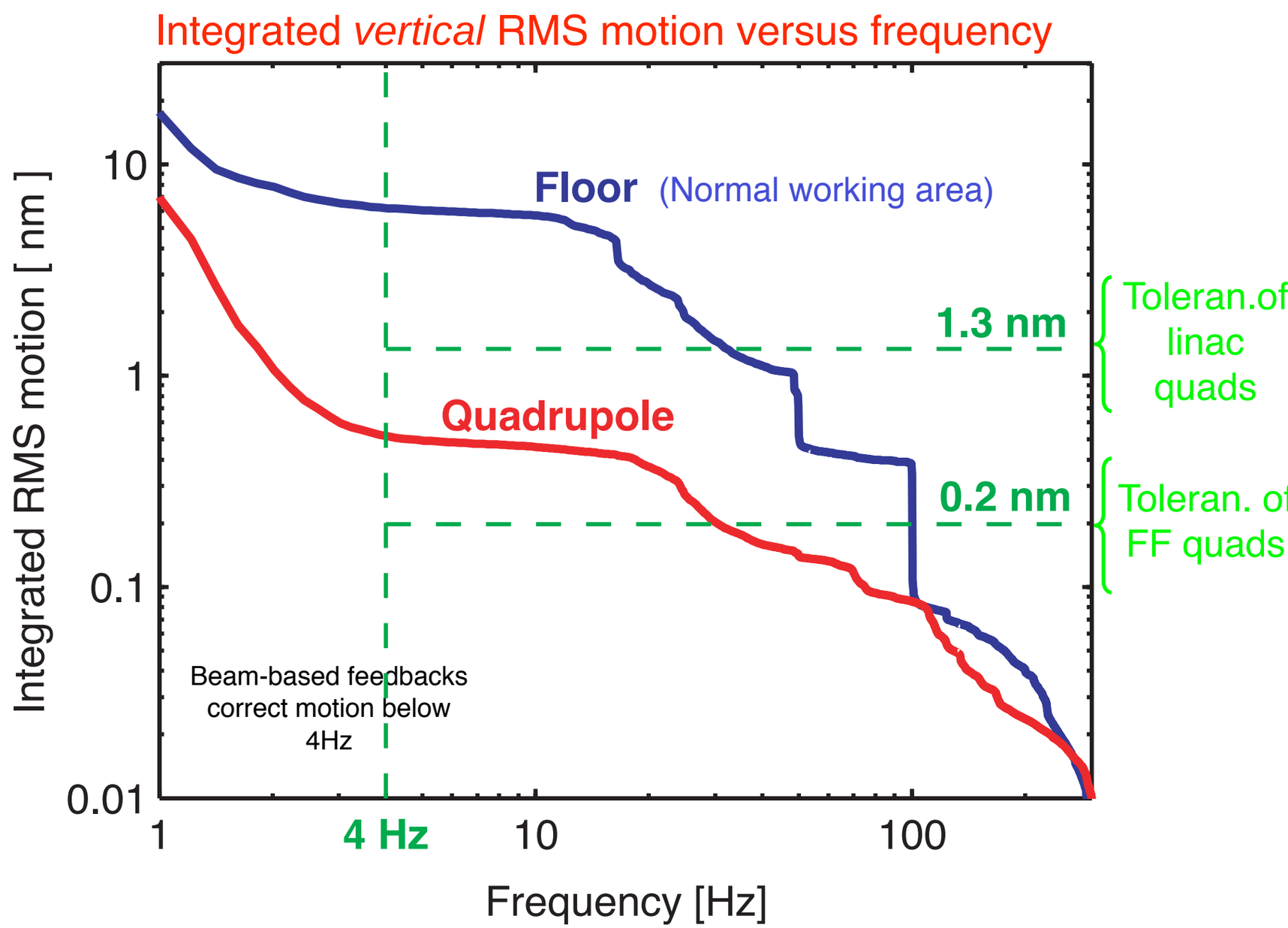


Best vertical stabilization of magnets



RMS vibrations above 4 Hz

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



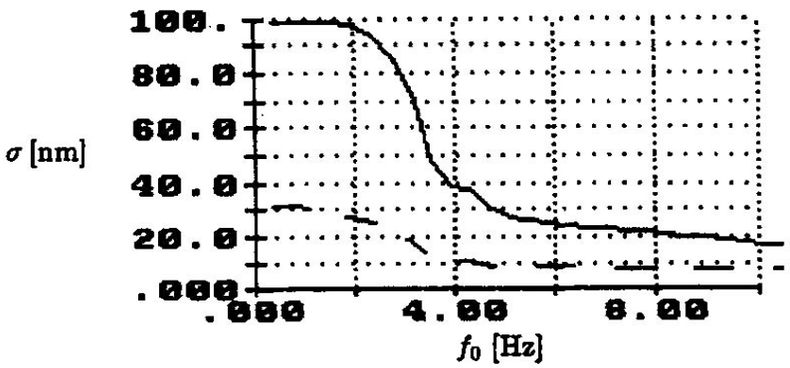
CLIC prototype magnets stabilized to the sub-nanometre level !!

Above 4Hz: **0.43 nm** on the quadrupole instead of **6.20 nm** on the ground.

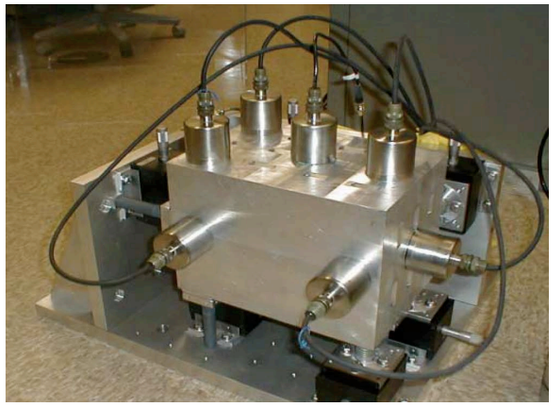
What was achieved in other laboratories?

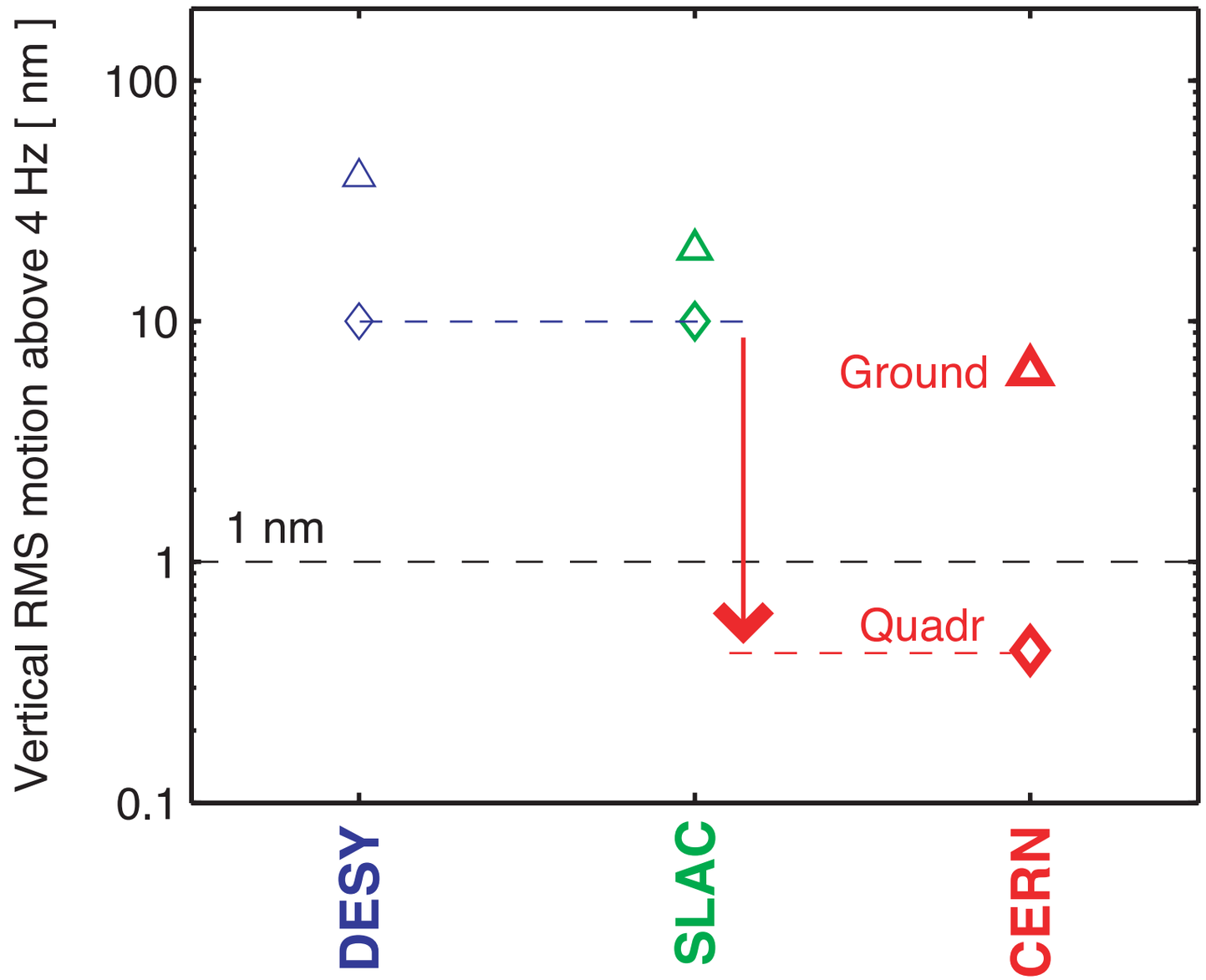
DESY: studies on magnet stabilization

C. Montag, Nucl. Instrum. Meth. A **378** (1996) 369.



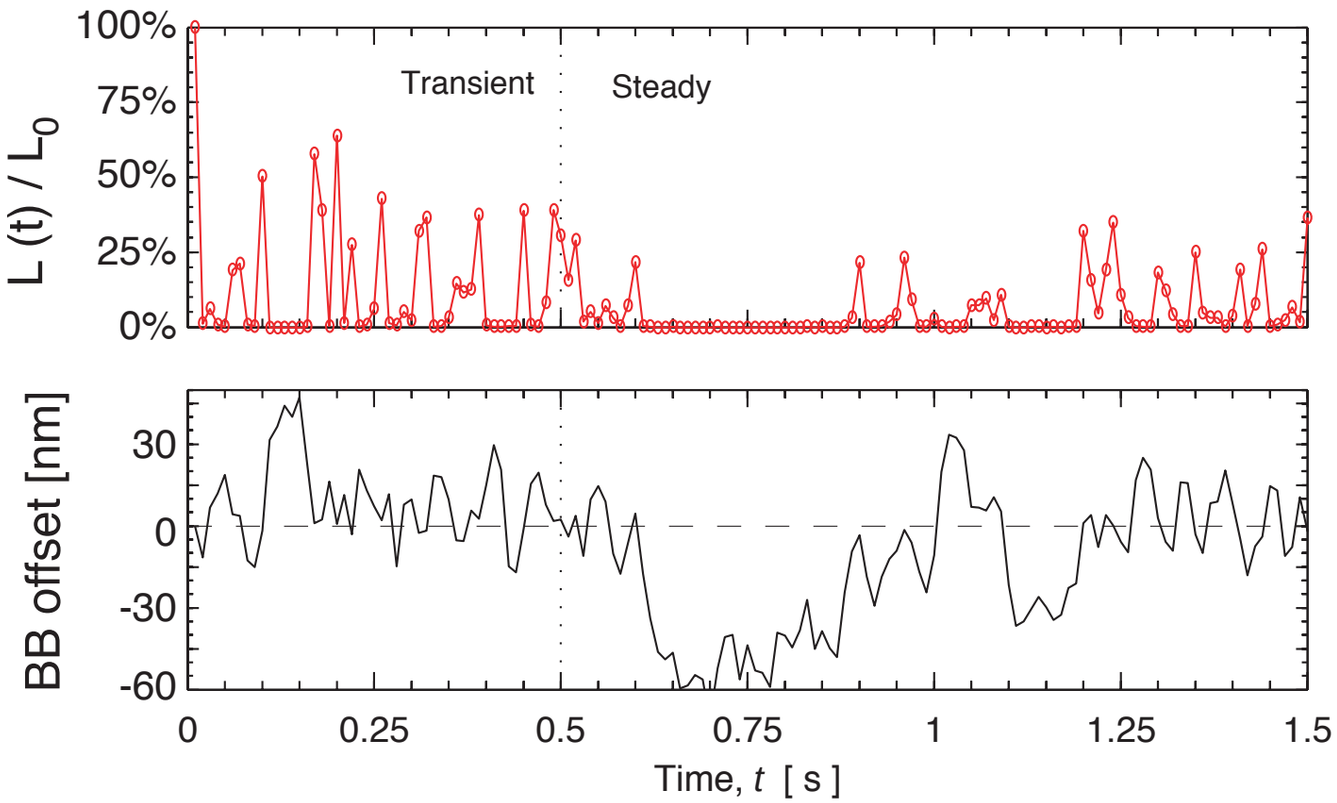
SLAC: Hand-made system to stabilize a test mass (J. Frisch et al, PAC2001)





Magnet stability was advanced from the **10 nm level** to the **0.5 nm level**!

Achieved CLIC luminosity

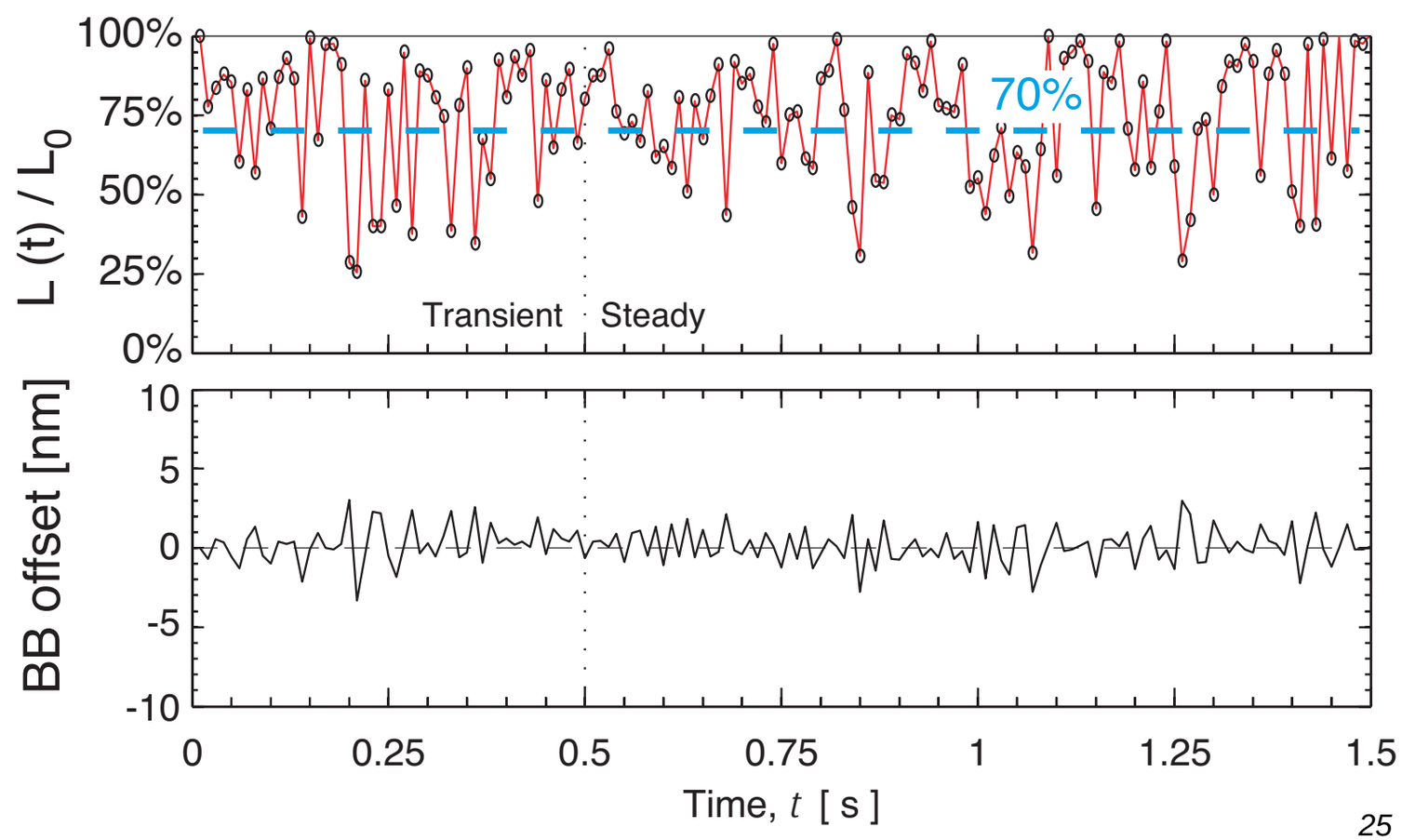


Without stabilization (ground):

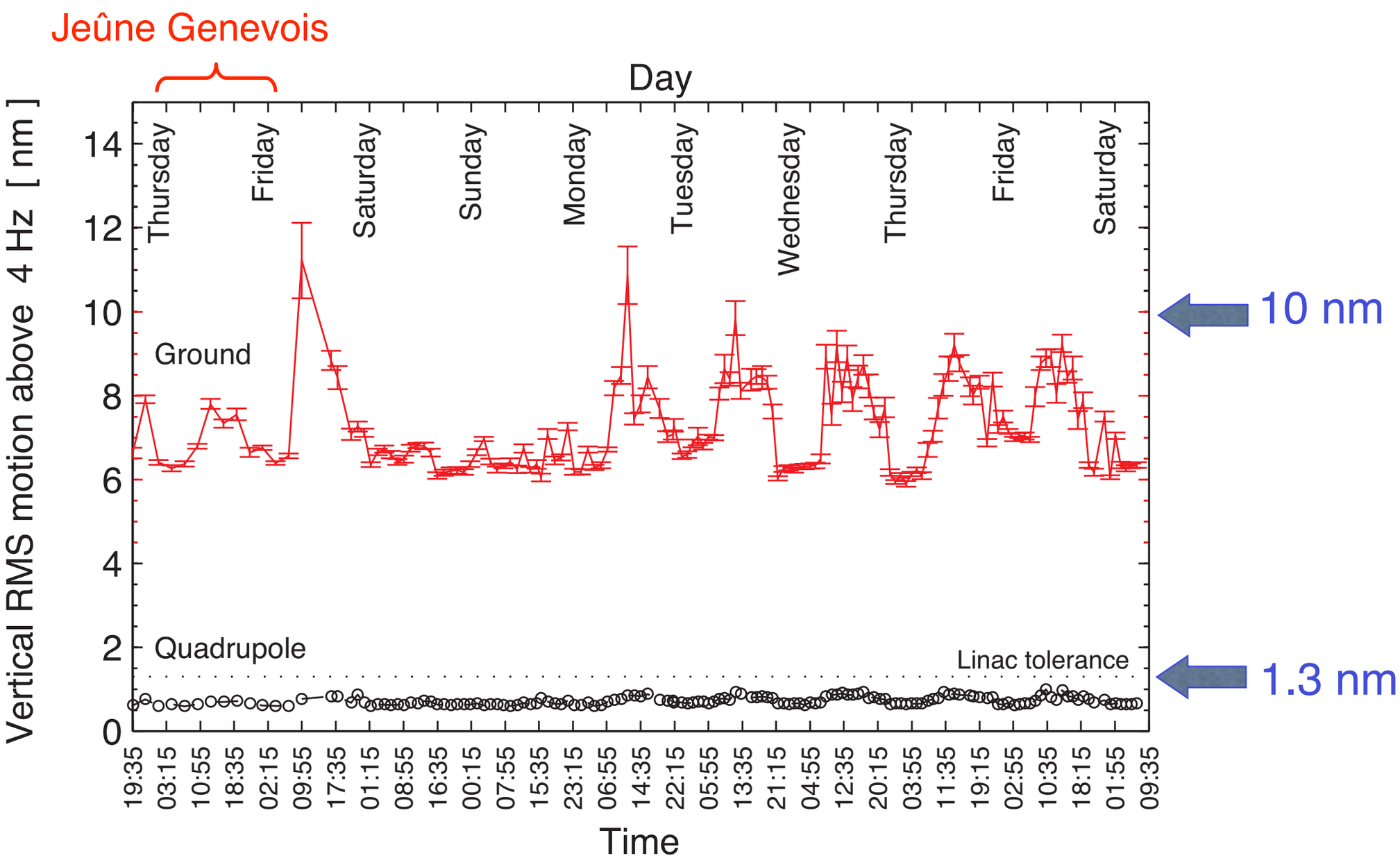
No significant luminosity is produced!

With stabilization:

~ 70 % of the luminosity is steadily maintained!



Ok, this is good. But is it ***stable***?



Quadrupole vibrations kept below the 1 nm level

over a period of 9 consecutive days!

Conclusions

- The CLIC Stability Study has brought modern stabilization technology to the accelerator field
- CERN successfully used this technology: first sub-nanometre stabilization of accelerator magnets (0.5 nm RMS above 4 Hz)
- Further improvements are required:

  Additional improvement by a factor 3-5 would be needed

  Find a technical solution to be integrated in detector region

  Optimize magnet and support design against vibrations
- We are confident that we will have the required stabilization technology in hands once it will be needed for CLIC!

Acknowledgments

O. Brüning, W. Coosemans, R. Corsini,
S. Sgobba, M. Taborelli

Presentations based on the results
achieved by the CLIC stability study team
and by the CLIC alignment team

Reserve slides

Frequency analysis of vibrations

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 accelerators!