<u>Feasibility item 6:</u> Main Linac active alignment/beam based feedback/stabilization

Possible technical implementation, R&D program until 2010

C. Hauviller

CERN

CLIC stabilization requirements

- Mechanical stabilization requirements:
  Quadrupole magnetic axis vibration tolerances:

	Final Focus quadrupoles	Main beam quadrupoles
Vertical	0.1 nm > 4 Hz	1 nm > 1 Hz
Horizontal	5 nm > 4 Hz	5 nm > 1 Hz

- Main beam quadrupoles to be mechanically stabilized:
  - A total of about 4000 main beam quadrupoles
  - 4 types
  - Magnetic length from 350 mm to 1850 mm

- Mechanical stabilization might be On at some quads and Off of some others

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The Stabilization Working Group

- Stabilization work for CLIC started beginning of the century, then stopped at CERN due to LHC priority.

  Kept alive at LAPP.
- Stabilization considered as a critical item with associated resources 18 months ago.

- Working group established beginning 2008 in the framework of the CLIC Technical Committee
  - Collaboration between institutes
  - Face-to-face meetings every 3 months
  - Chairman: Claude Hauviller

Organization

- Collaboration: Laboratories participating (to-date):
  - LaViSta (LAPP, Universite de Savoie-SYMME)
  - CERN (EN, TE, BE)
  - JAI- Oxford University
  - CEA-DSM-IRFU-SIS
  - PSI
  - Information from DESY, SLAC,…
  - Contacts with universities
- Extra financing through FP7

MONALISA IRFU/SIS

Tasks defined in the mandate

- Demonstrate 1nm quadrupoles stability above 1Hz *(Linac) (going below 1Hz would be appreciated)*
- Demonstrate or provide evidence of 0.1nm stability above 4Hz *(Final Focus)*
  - *Differences compared to previous studies*
    - *0.1 nm is beyond what we have shown*
    - *apply stabilization in an accelerator environment (e.g. 2BTS)*
    - *achieve 1nm with realistic equipment (a complete system), not simple elements on a special table*
    - *verify performance with (two) different methods*

- Characterize vibrations/noise sources in an accelerator
- Compatibility with pre-alignment
- Sensitivity to relaxed specifications

Remarks

- Active vibration control is not yet a mature technology.
- Activity should be defined as R&D but with CLIC engineering as objective.
- It will take time to achieve the final objective but a work plan has been agreed in March 2008 with CDR as an important milestone
- Most of the collaborators have background on vibrations but not on the specific field of stabilization.

Approach

- Competency center: understand the subject in depth
- Build a knowledgeable team
- Use the existing know-how spread in many places:
  - Previous theses (in particular Montag, Redaelli, Bolzon,…)
  - Work done in the labs: Low emittance Light sources, FEL, ILC,…
  - Work (mainly) in the universities on satellites and radiotelescopes
- Apply to realistic mock-up(s)
- Create a reference web site:

http://clic-study.web.cern.ch/CLIC-Study/CLIC_Stabilisation/Index.htm

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Actions list (keywords)

- Sensors
- Characterize vibrations/environmental noise sources in an accelerator
- Actuators
- Feedback
- Overall design + analysis
- Integrate and apply to Linac

Sensors

<u>Program of work</u>

– Develop and test sensors

– Qualification with respect to EMC and radiation

– Calibrate by comparison.

  - Interferometer to calibrate other sensors
  - Create a reference test set-up (at CERN)

– State of the art of sensor development and performances (to be updated on a yearly basis)

Prepared by C. Collette

Ground motion sensor review

Table of Contents

Sensors

How to measure vibrations/ dynamic displacements with amplitudes of 0.1 nm?

- **Seismometers** (geophones) Velocity
- **Accelerometers** (seismic - piezo) Acceleration

Streckeisen STS2
x,y,z
2*750Vs/m
120 s -50 Hz
13 kg

Guralp CMG 3T
x,y,z
2*750Vs/m
360s -50 Hz
13.5 kg

Guralp CMG 40T
x,y,z
2*800Vs/m
30 s -50 Hz
7.5 kg

Guralp CMG 6T
x,y,z
2*1000Vs/m
30s-80Hz

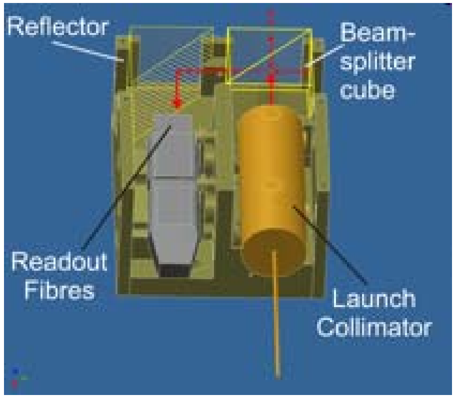
Eentec SP500
z
electrochemical
2000Vs/m
60 s -70 Hz
0.750 kg

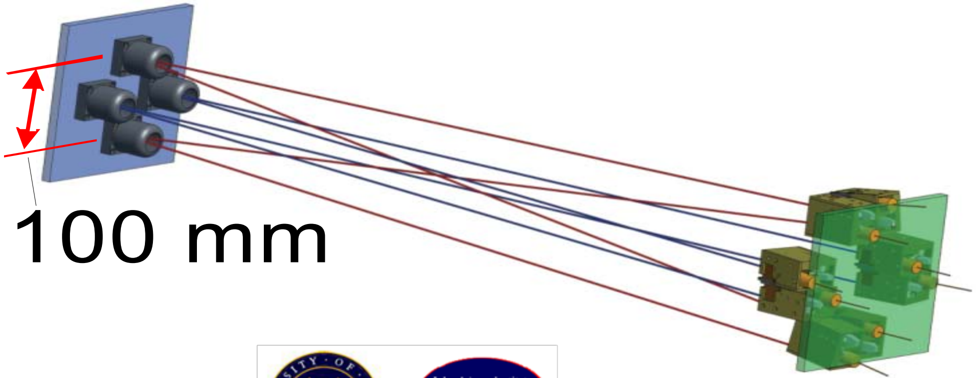
PCB 393B31
z
$1.02 Vs^2/m$
10 s -300 Hz
0.635 kg

Improved performances
Lab environment

Sensors

- **Optical sensors**
  - Vibrometer
    Supplier Polytec; at CERN
    Under performances qualification but lab is too noisy!
  - Interferometer (measures displacement)
    - Industrial products under study at CEA-IRFU (Renishaw, Attocube)
    - Low cost “Optical transducer” under development with precision of 1nm at 1Hz Compact Straightness Monitor MONALISA at Oxford





Sensors

Characterization for low intensity signals:

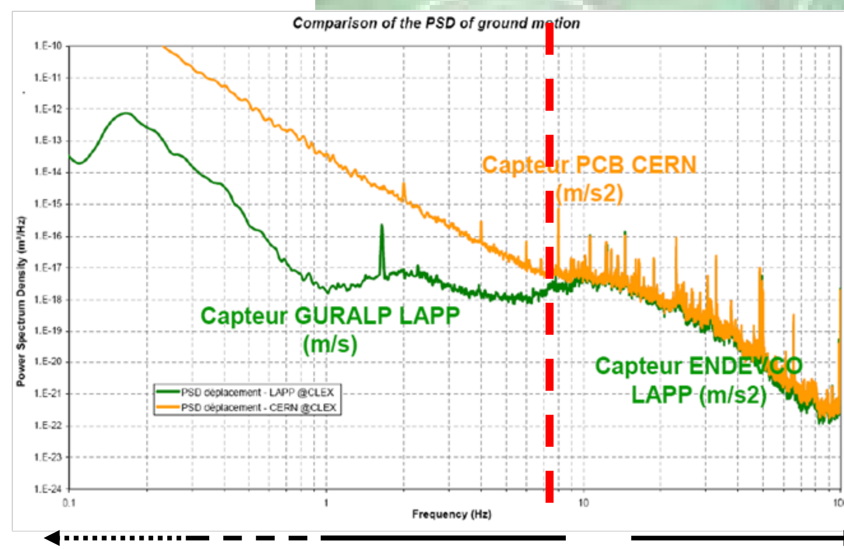
Which sensor?
Quality of its measurement?

Sensitivity + resolution

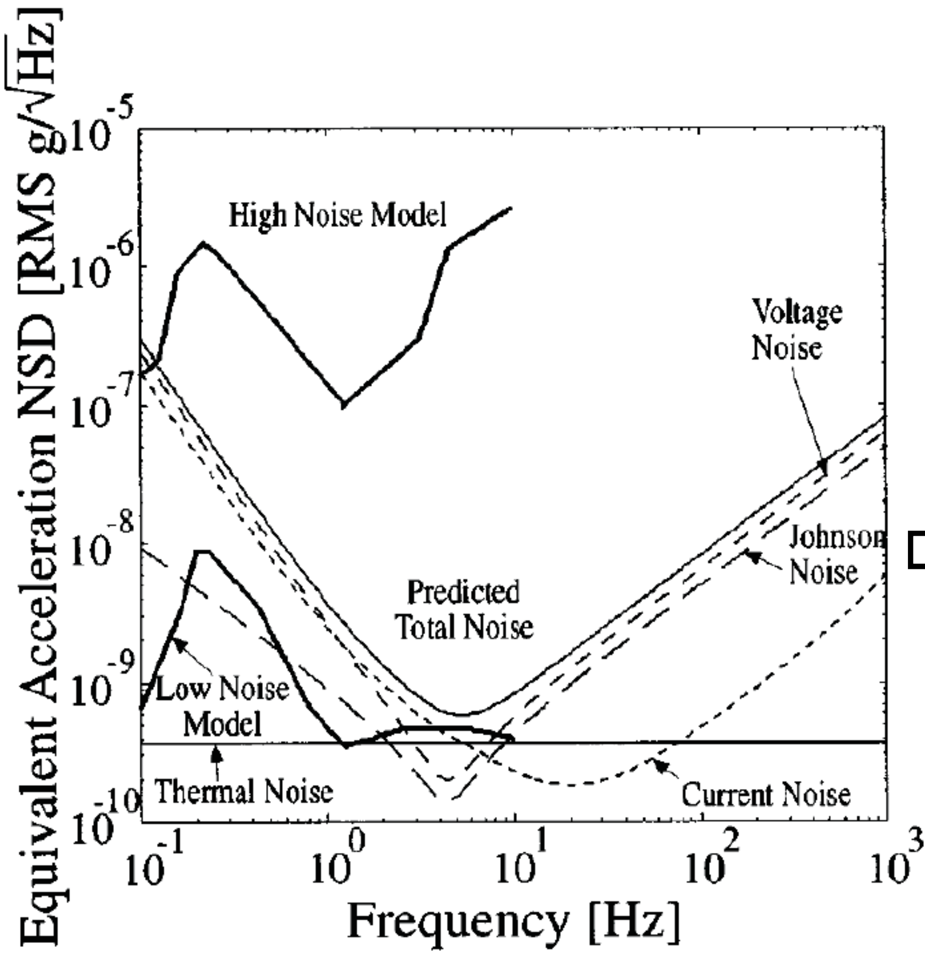
Cross axis sensitivity

Noise level, « self noise » measurement (ex. blocking the seismic mass or by coherence)

Signal processing: Resolution, filtering, window, FFT, DSP, integration, coherence



Sensor noise Sources



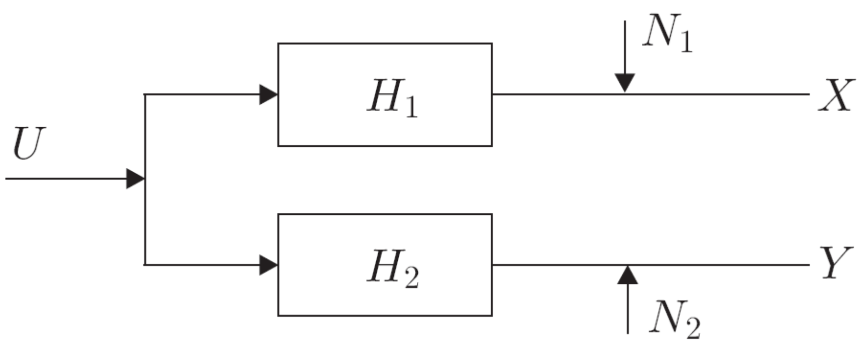
A. Bertolini et al. *Review of scientific instruments, 69:2767-2772, 1998.*

⇨ **We need a technique to evaluate the overall measurement noise**

Sensor noise Detection

C. Montag*. PhD thesis, Hamburg University, 1996.*

Two geophones side by side:



$$\begin{cases} X(\omega) = H_1(\omega)U(\omega) + N_1(\omega) \\ Y(\omega) = H_2(\omega)U(\omega) + N_2(\omega) \end{cases}$$

$$\begin{cases} \Phi_{ss} = H^2\Phi_{xx} \\ \Phi_{nn} = \Phi_{yy} - H^2\Phi_{xx} \end{cases} \Rightarrow \begin{cases} \sigma_s(\omega) = [\int_\omega^\infty \Phi_{ss}(\nu)d\nu]^{1/2} \\ \sigma_n(\omega) = [\int_\omega^\infty \Phi_{nn}(\nu)d\nu]^{1/2} \end{cases}$$

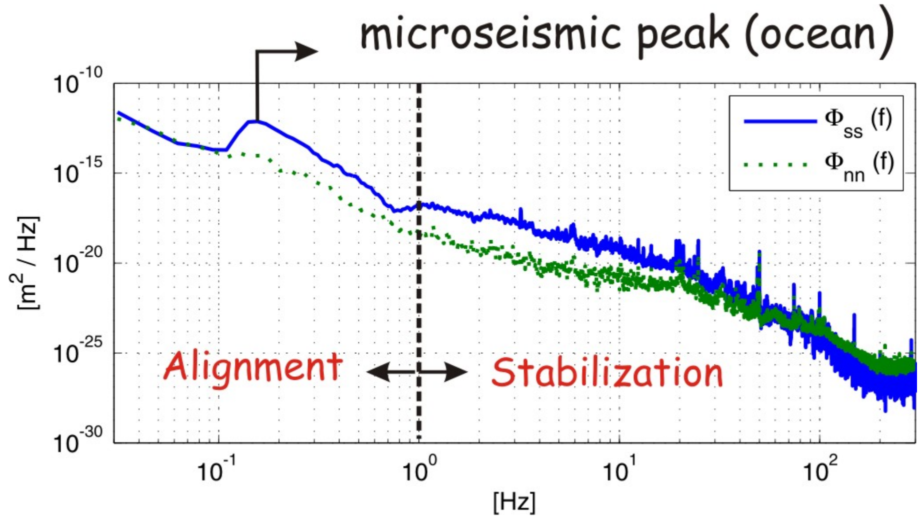
where $H(\omega) = \frac{\Phi_{xy}}{\Phi_{xx}}$

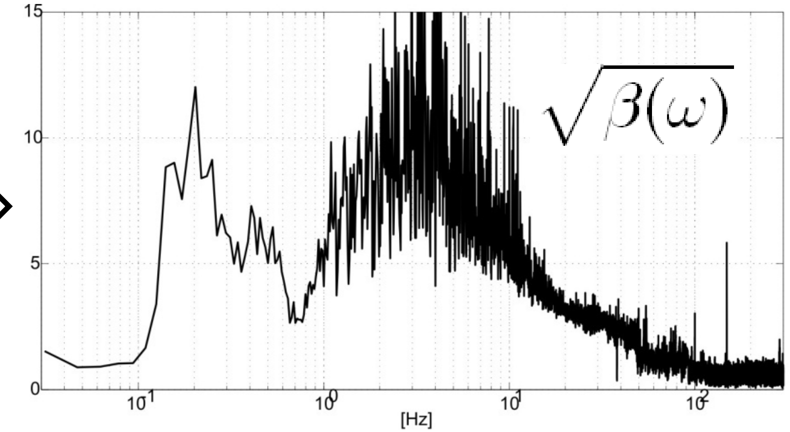
Signal to noise spectrum ratio: $\beta(\omega) = \frac{\Phi_{ss}}{\Phi_{nn}}$

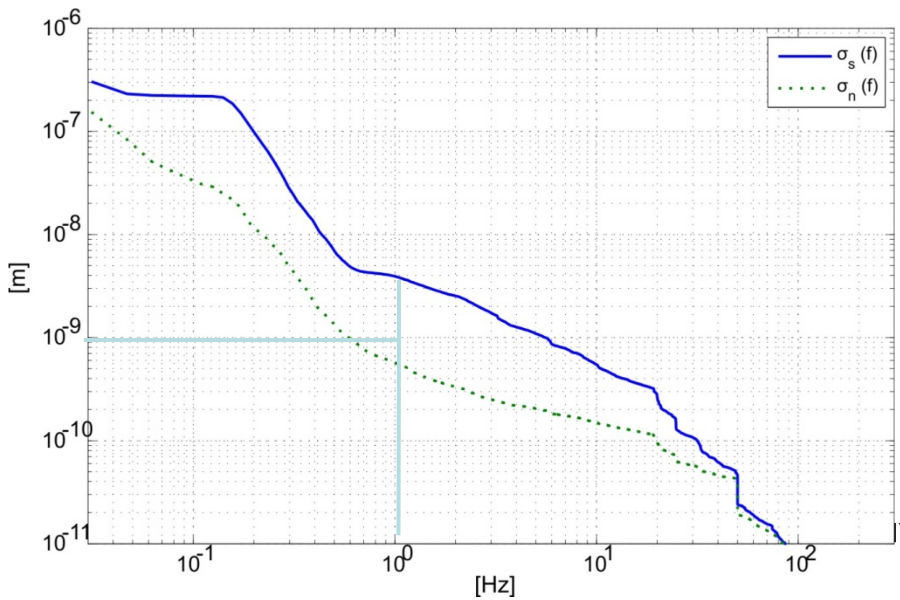
Prepared by C. Collette

Sensor noise detection

Guralp CMG 40T, LHC tunnel (summer 2008)







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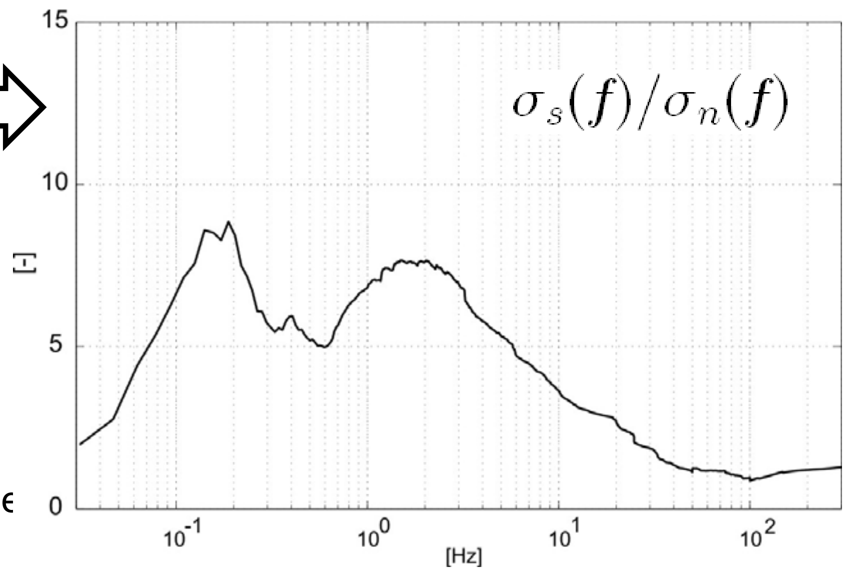
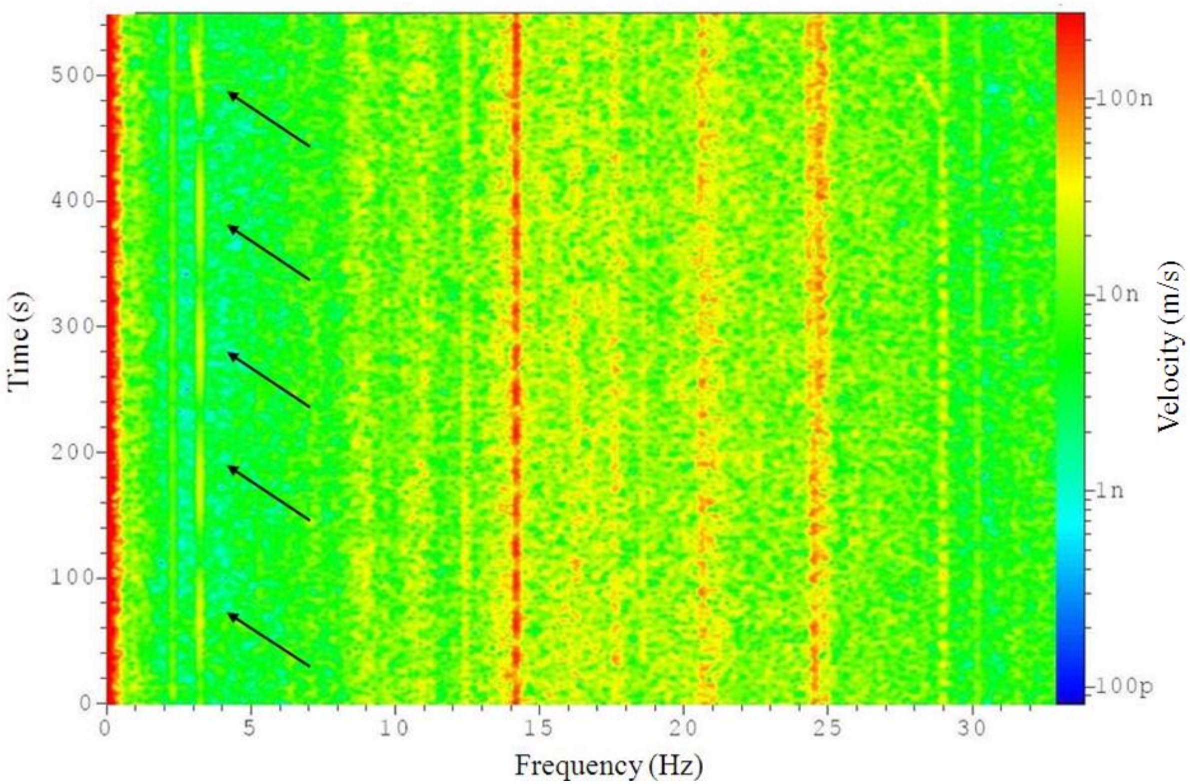


Sensor
Signal processing

- Resolution, filtering window, FFT, DSP, …

Need to establish a standard of measurement !



Vertical vibrations in the LHC tunnel
Intermittent excitation at 3Hz partly hidden by the averaging

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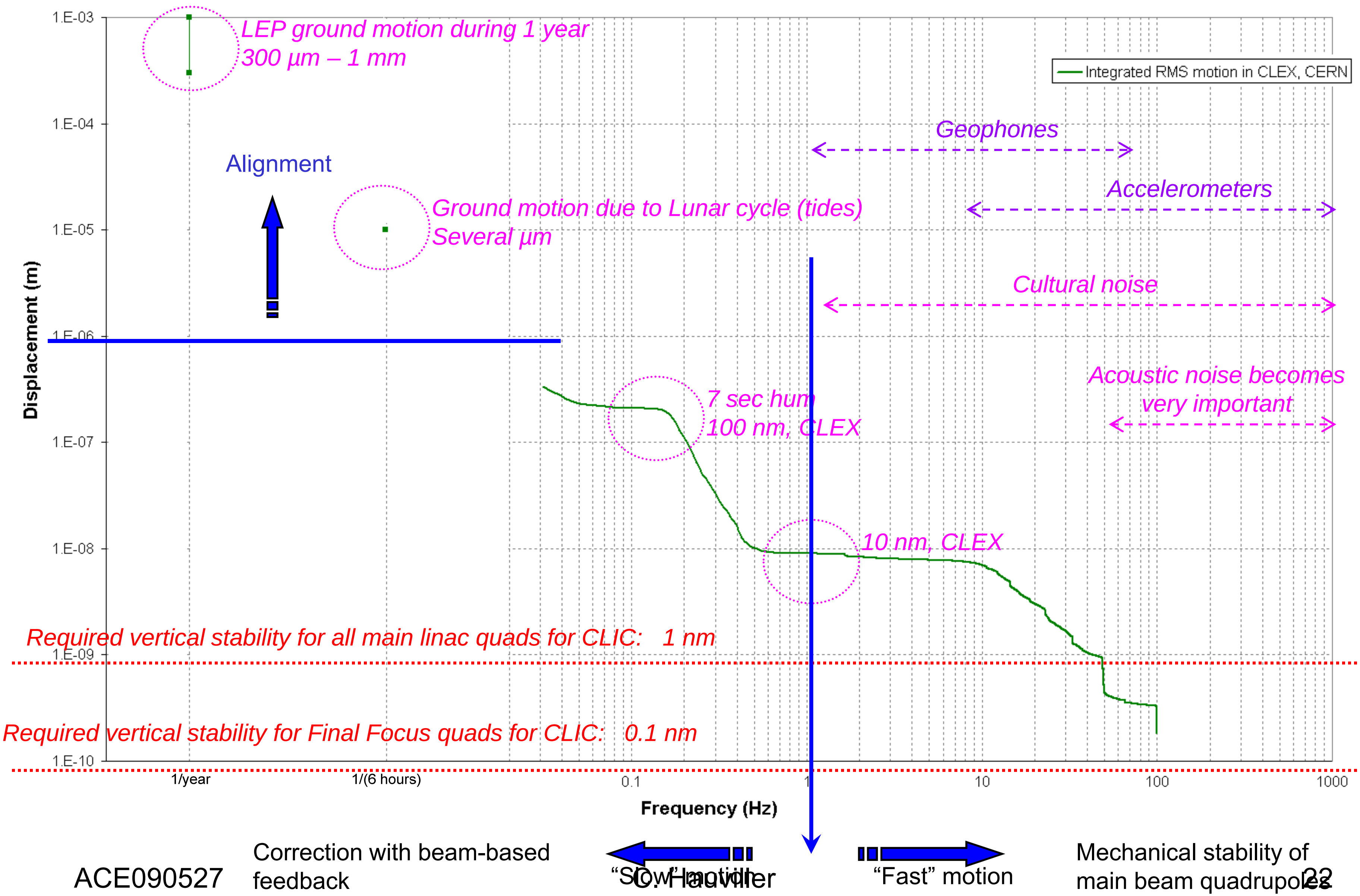
Characterize vibrations/noise sources in an accelerator and detectors

- <u>Program of work</u>
  - Summary of what has been done up to now (several studies done by DESY, SLAC, LAViSta, CERN)

    Large number of measurements done for years in many places including third generation light sources. Critical analysis of the results based on sensors and methodologies. Pertinence for CLIC ? Qualification of labs (quiet enough?)
  - Additional correlation measurements to be done at LHC over distances of ~ 1000m and in a long building on the surface

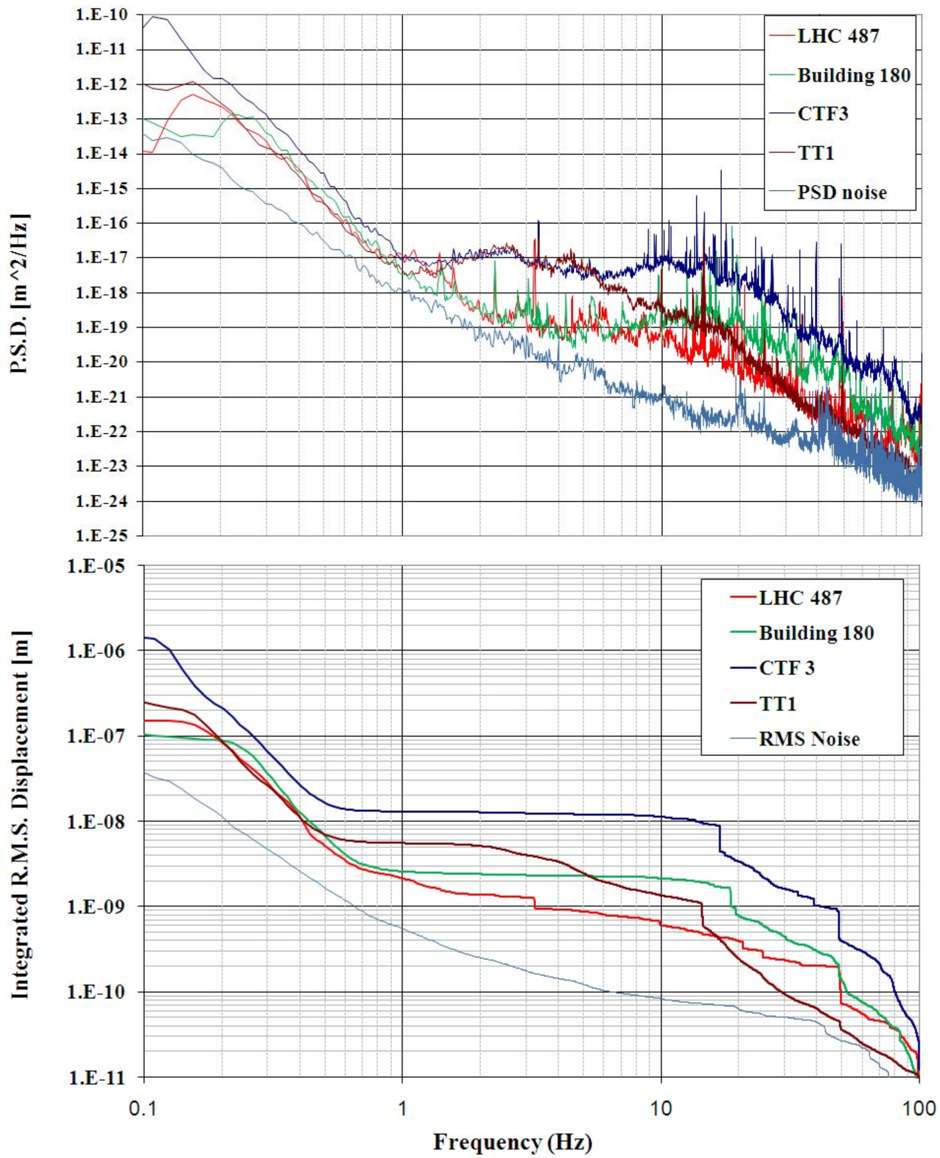
    Done and analysed.
  - Continue measurements in CLEX environment at different installation phases, at "quiet lab", at PSI, at CesrTA,…

Environmental vibration levels – orders of magnitude, CERN site



Vibrations on CERN site

- LHC tunnel
- Surface building
- CTF3
- “Quiet lab”
(under installation in TT1)

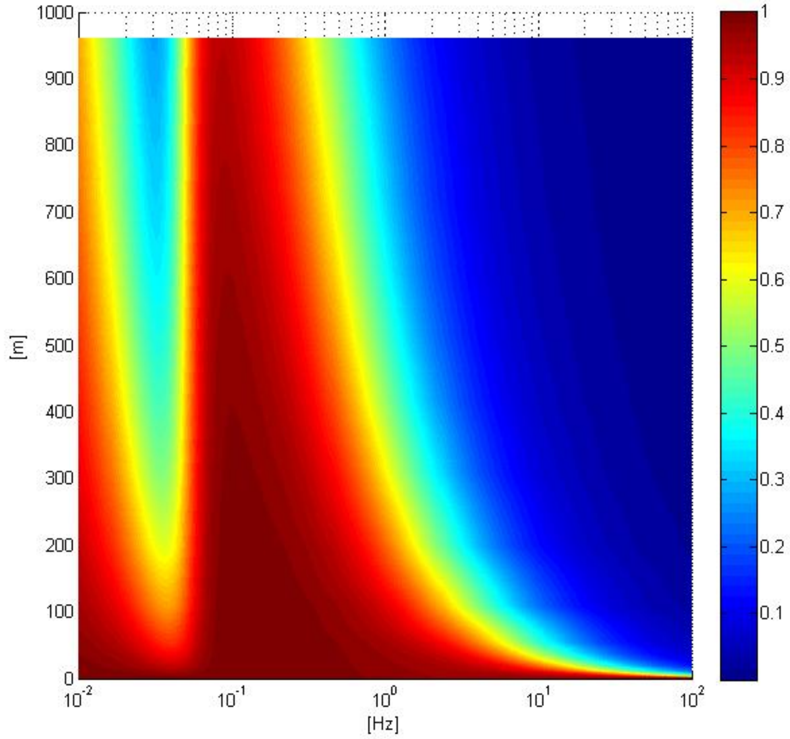


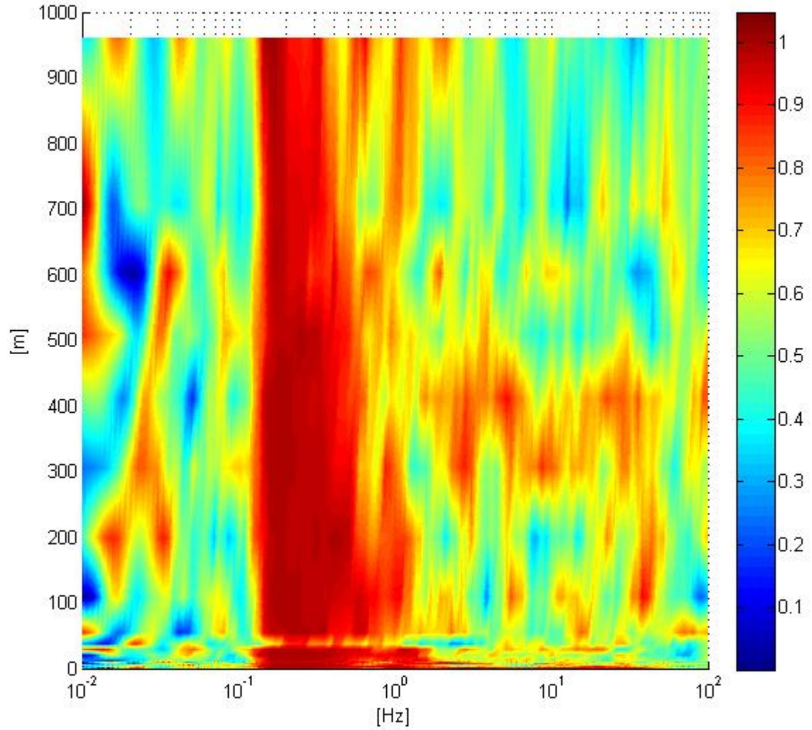
Correlation over long distances in LHC tunnel

Prepared by C. Collette

Coherence using a theoretical model (ATL law)

Calculated from measurement (2008)





➔ 3D ground motion model to be considered for the alignment

Actuators

Program of work

- State of art of actuators development and performances (to be updated on a yearly basis)

- Develop and test various damping techniques (passive and active)

State of art of actuators development

Table of Contents

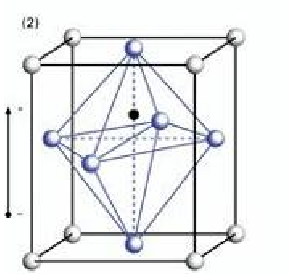
Actuators

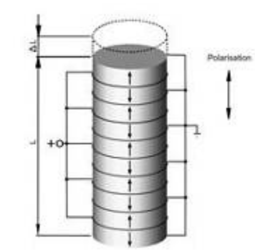
Usable actuators with 0.1 nm resolution?

Resolution but also movement reproducibility?

Friction
Guiding systems with **friction** → Real resolution limited to 1 µm (0.1 µm)

<u>Solution under development:</u>
Piezo actuators PZT
(sensitive to shear)





Actuators

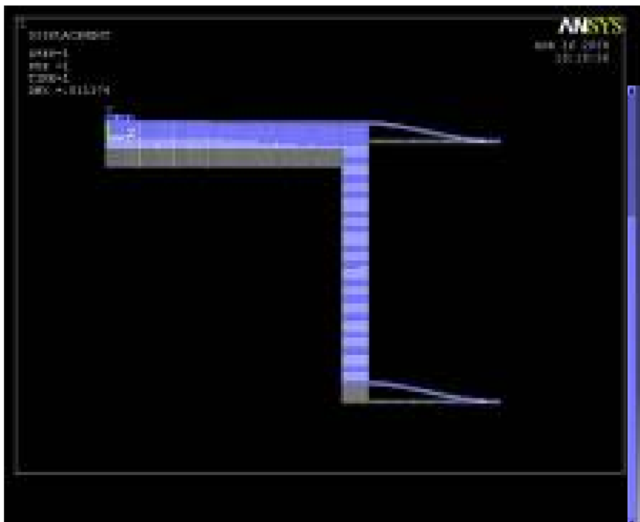
Usable actuators with 0.1 nm resolution?

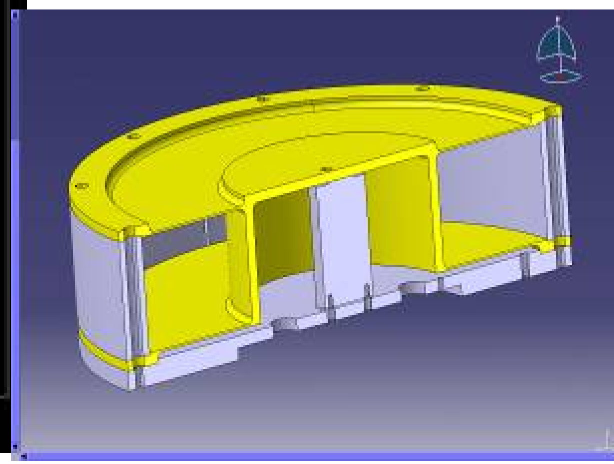
Solution under development: Piezo actuators PZT

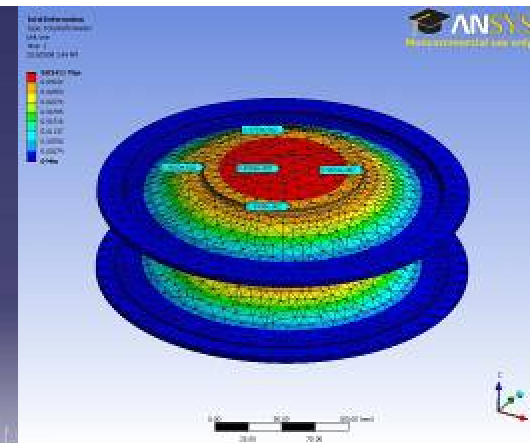
+ flexural guides

+ feedback capacitive sensor

0.1 nm 100 N Calibration bench flexural guides







But only for few kg and rigid objects....

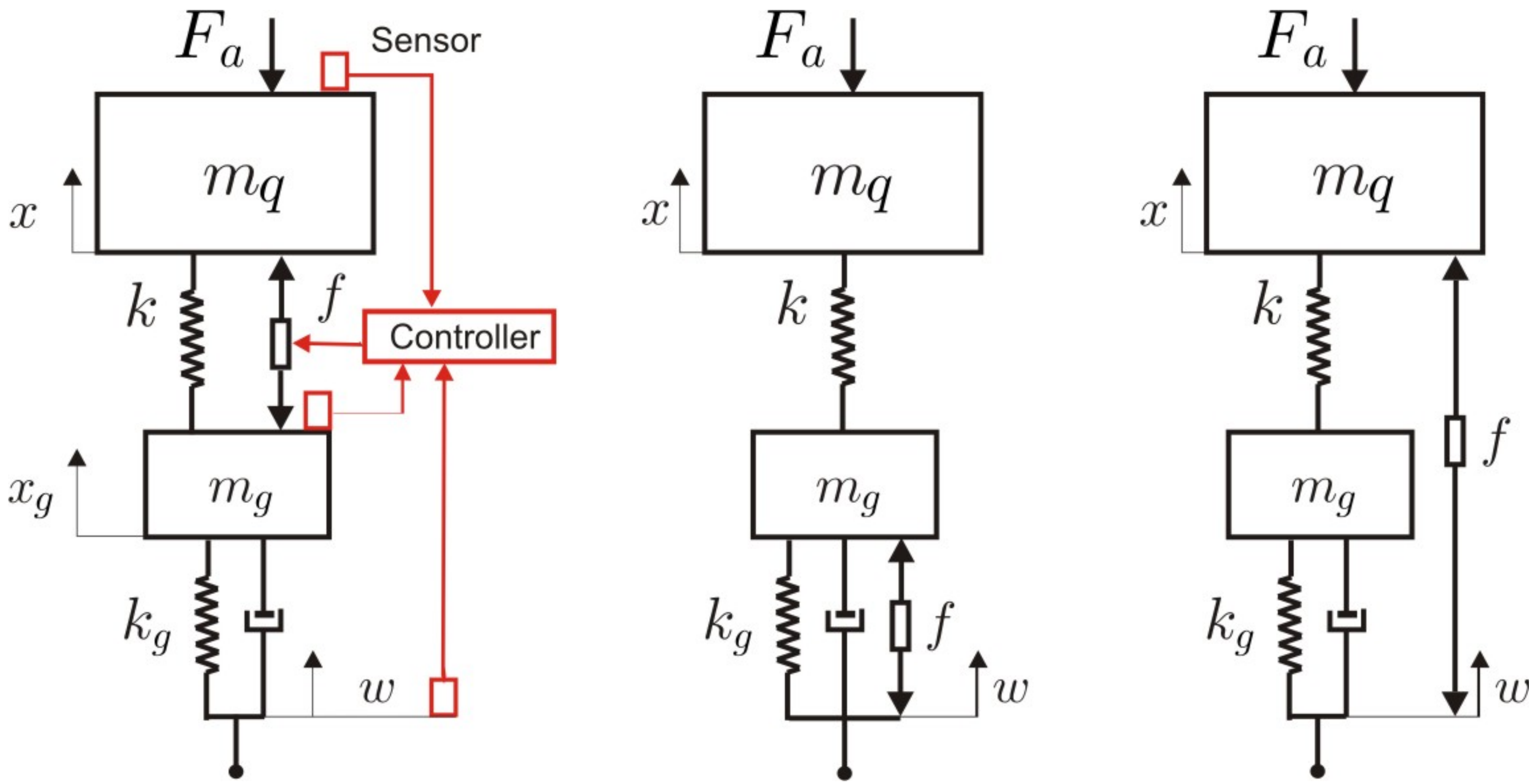
Techniques to be developed for heavier (up to 400Kg) and larger structures (up to 2 meter long)
Moreover, possible range up to many microns.

Feedback

Program of work

- Develop methodology to tackle with multi degrees of freedom (large frequency range, multi-elements)
  - *LAViSTa demonstrated feasibility on models*
  - *Similar problems elsewhere like the adaptative optics of the European ELT*
- Apply software to various combinations of sensors/actuators and improve resolution (noise level)
  - *High quality acquisition systems at LAViSTa and CERN*

Stabilization strategies



Similar in size ELT project

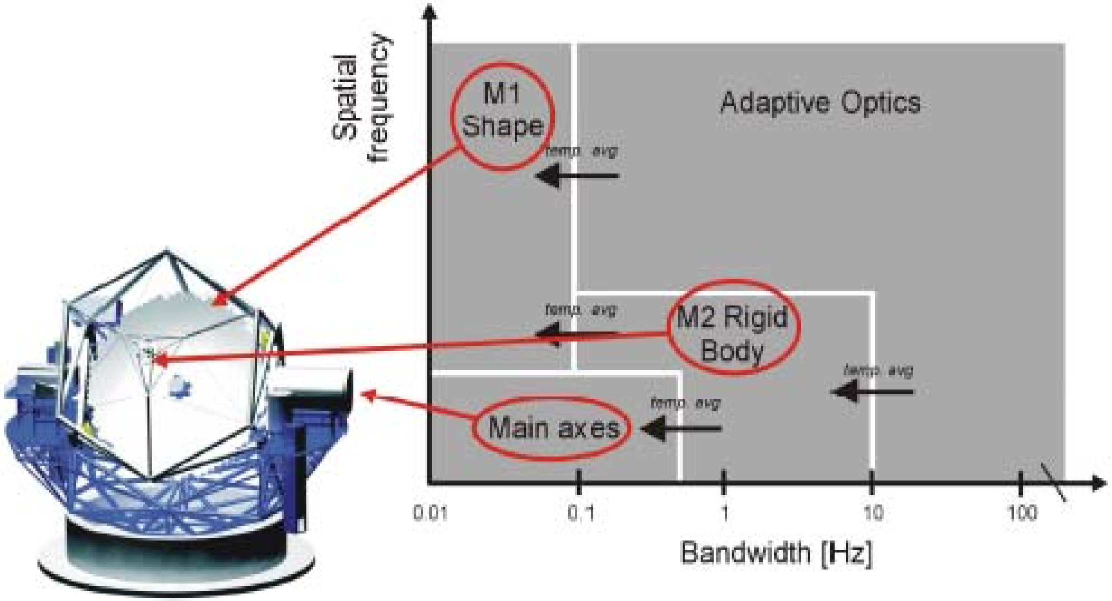


Figure 3: Temporal and spatial frequency distribution of the various control layers of a large telescope (adapted from [8]).

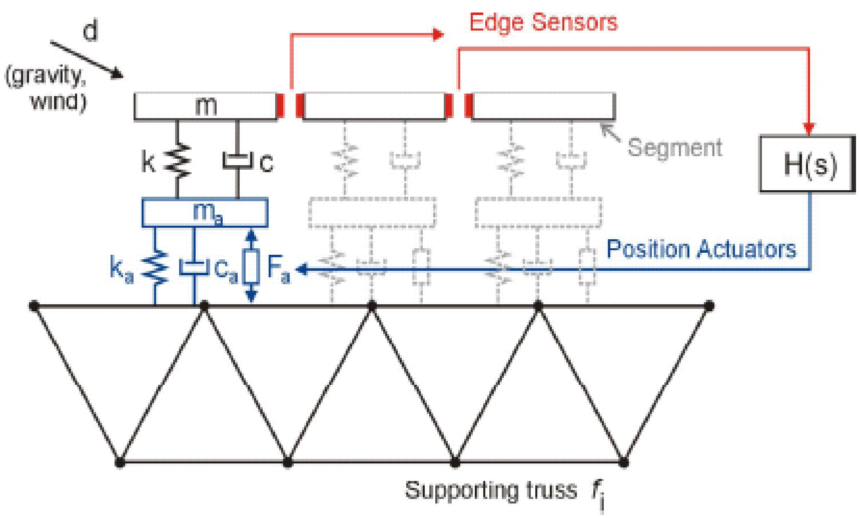


Figure 4: Co-phasing strategy of segmented mirrors. Every segment is equipped with 3 position actuators.

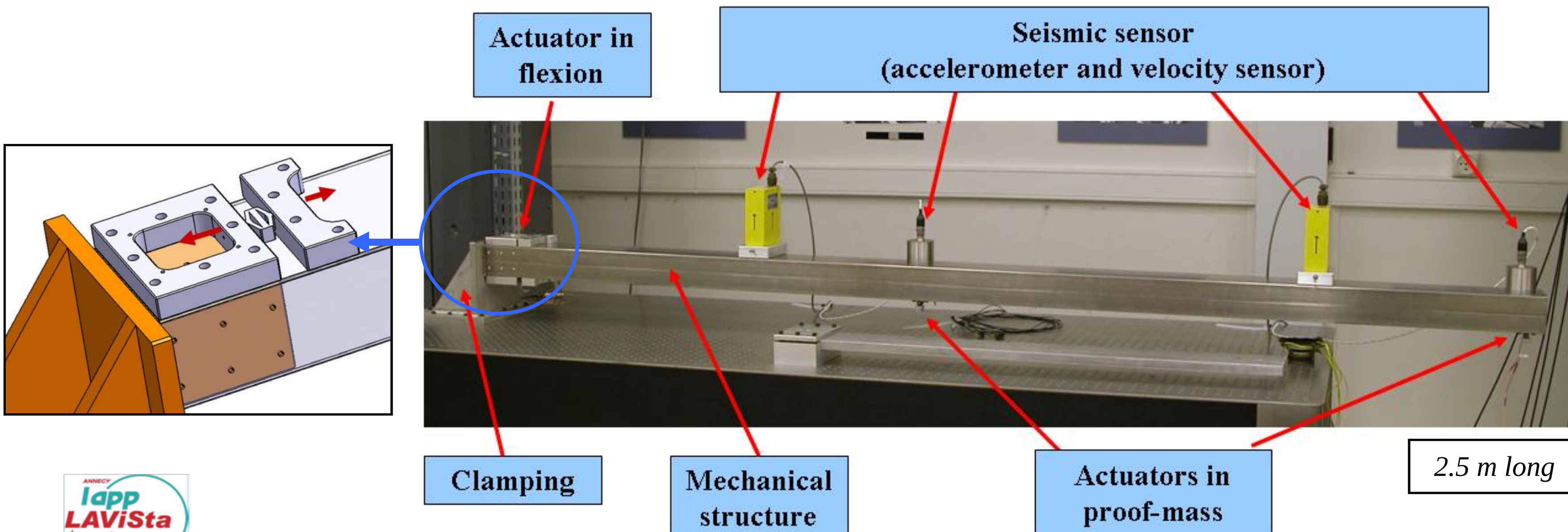
2952 actuators
5604 sensors

A. PREUMONT et al.
(To be presented to the Smart09 - July 2009)

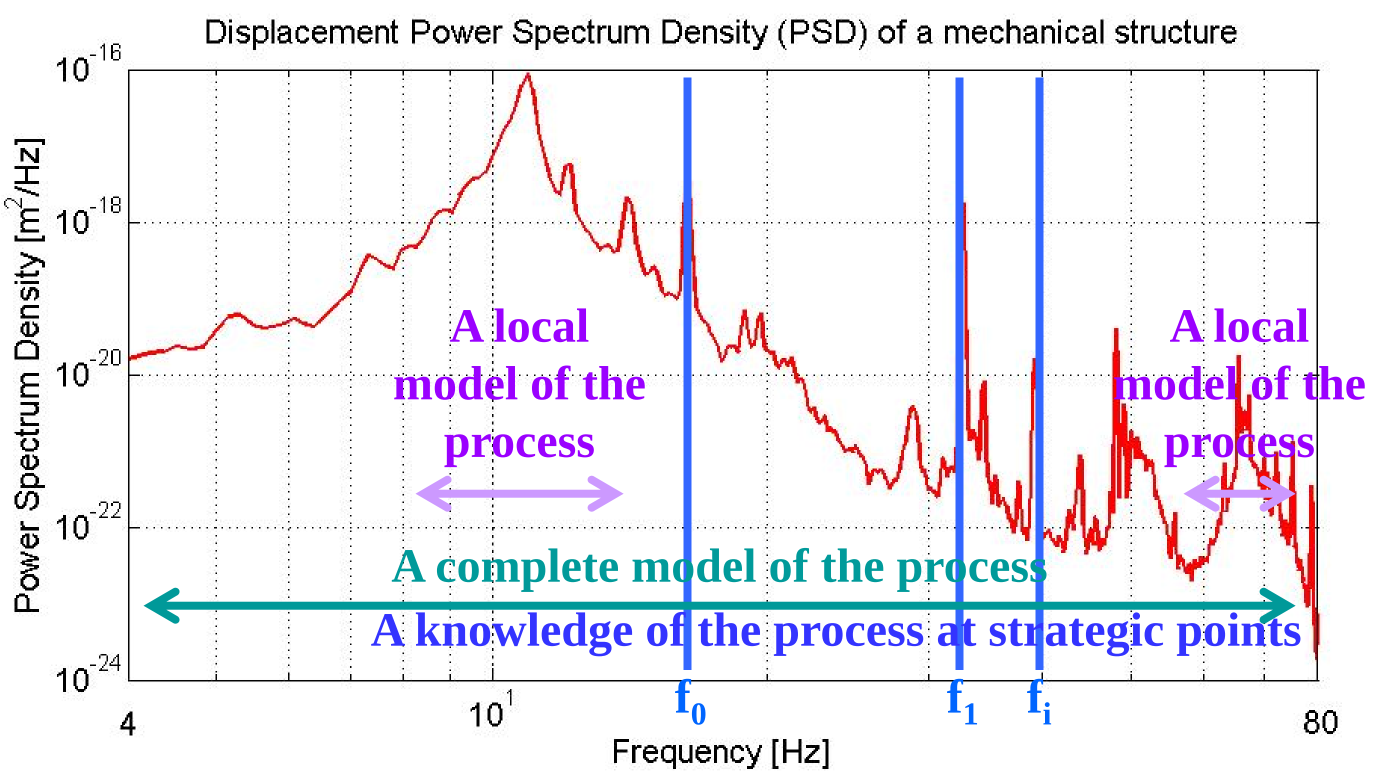
Feedback

Active rejection of canteliver beam resonances: home-made

Mechanical structure and its instrumentation



Feedback



1 - A knowledge of the structure at strategic points : ***for lumped disturbances***

2 - A local model of the structure : ***for the disturbances amplified by eigenfrequencies.***

3 - A complete model of the structure : ***for the entire structure***

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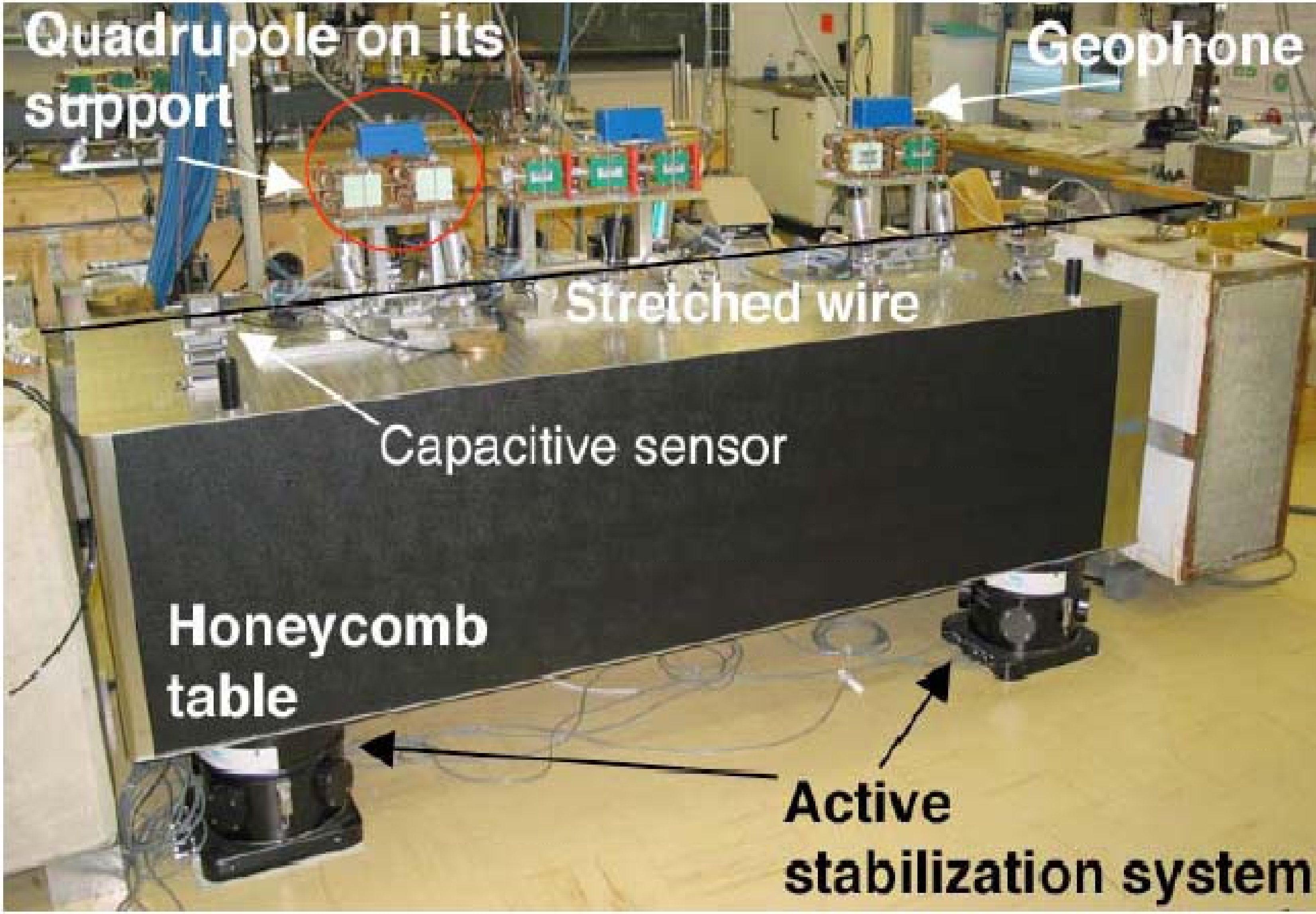
Overall design

Program of work *(as defined in March 2008)*

- Linac (a demonstrator mock-up will be built)
  - Compatibility of linac supporting system with stabilization (including mechanical design): eigenfrequencies, coupling between girders, coupling of mechanical feedback with beam dynamics feedback,…
  - Design of quadrupole (we have to stabilize the magnetic axis) mock-up will have “real” physical dimensions and all mechanical characteristics but not the field quality required by CLIC

Mock-up built in 2004 (S. Redaelli)

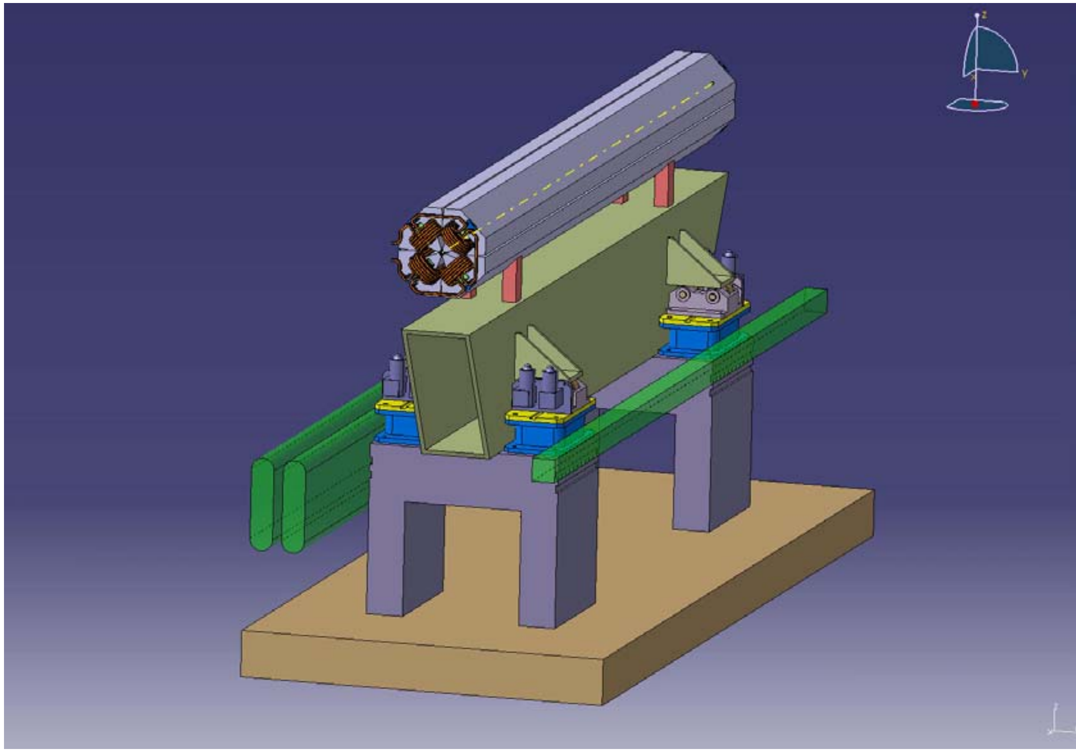


Main Beam Mock-up

Work launched within the collaboration

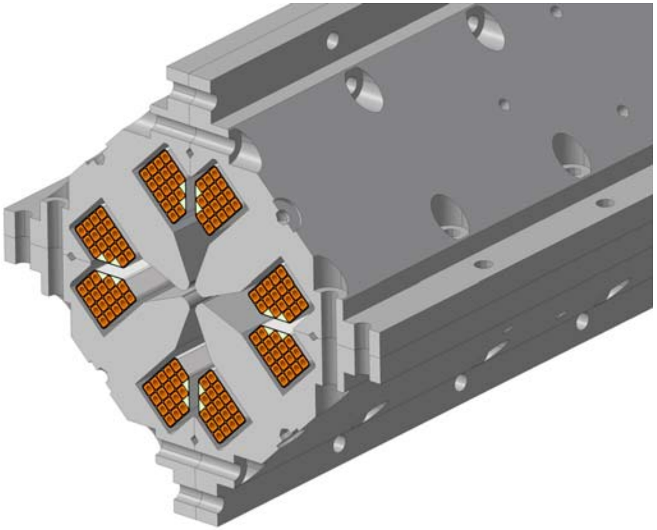
- **Functionalities**
  - Demonstrate stabilization in operation:
    - Magnet powered, Cooling operating
    - Configurations
      - 1- Stand-alone
      - 2- Integrated in Module
      - 3- Interconnected
    - Accelerator environment

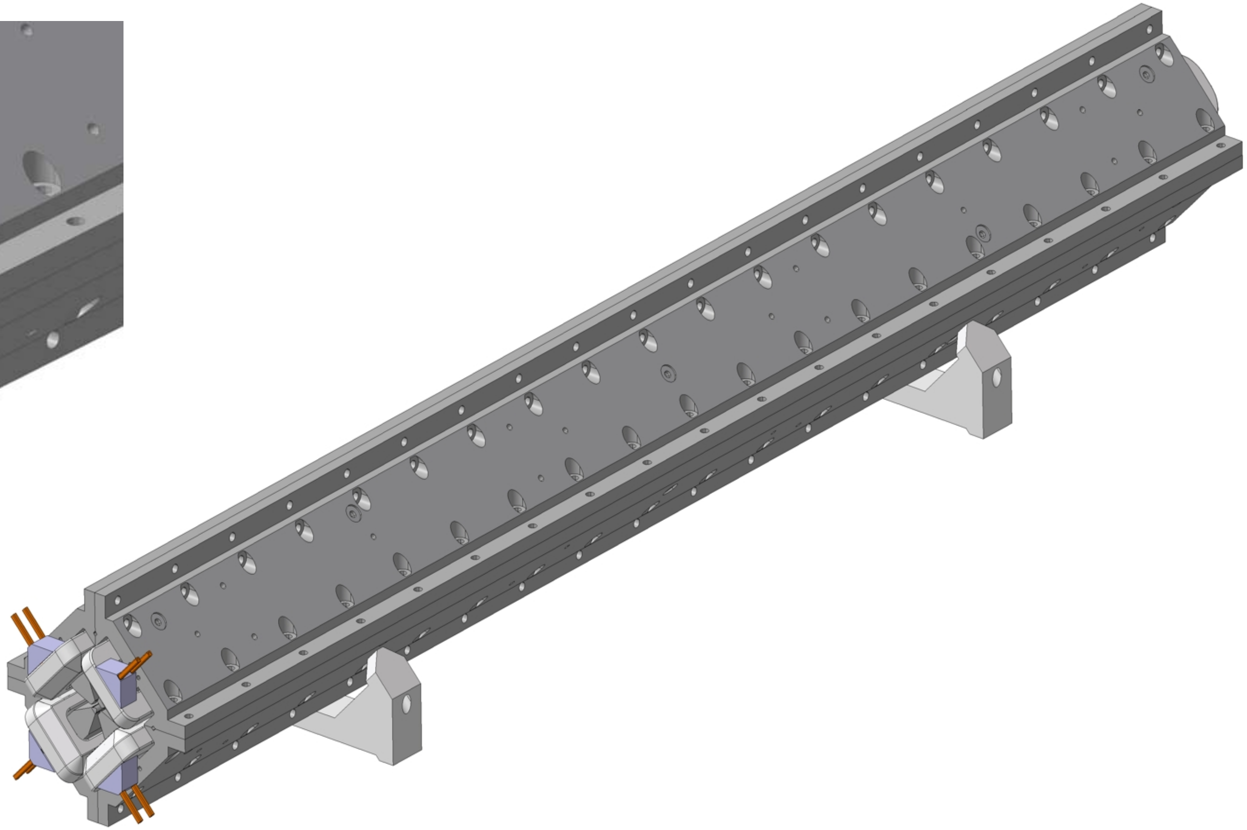
- **Parts / Measuring devices**
  - Floor (damping material)
  - Support
  - Pre-alignment
  - Stabilization
  - Magnet
  - Vacuum chamber and BPM
  - Independent measurement



Main beam quadrupole

- Under final design.
- Plain material (incompatible with corrector magnet)
- Assembly methods to be tested (accuracy of some microns!)



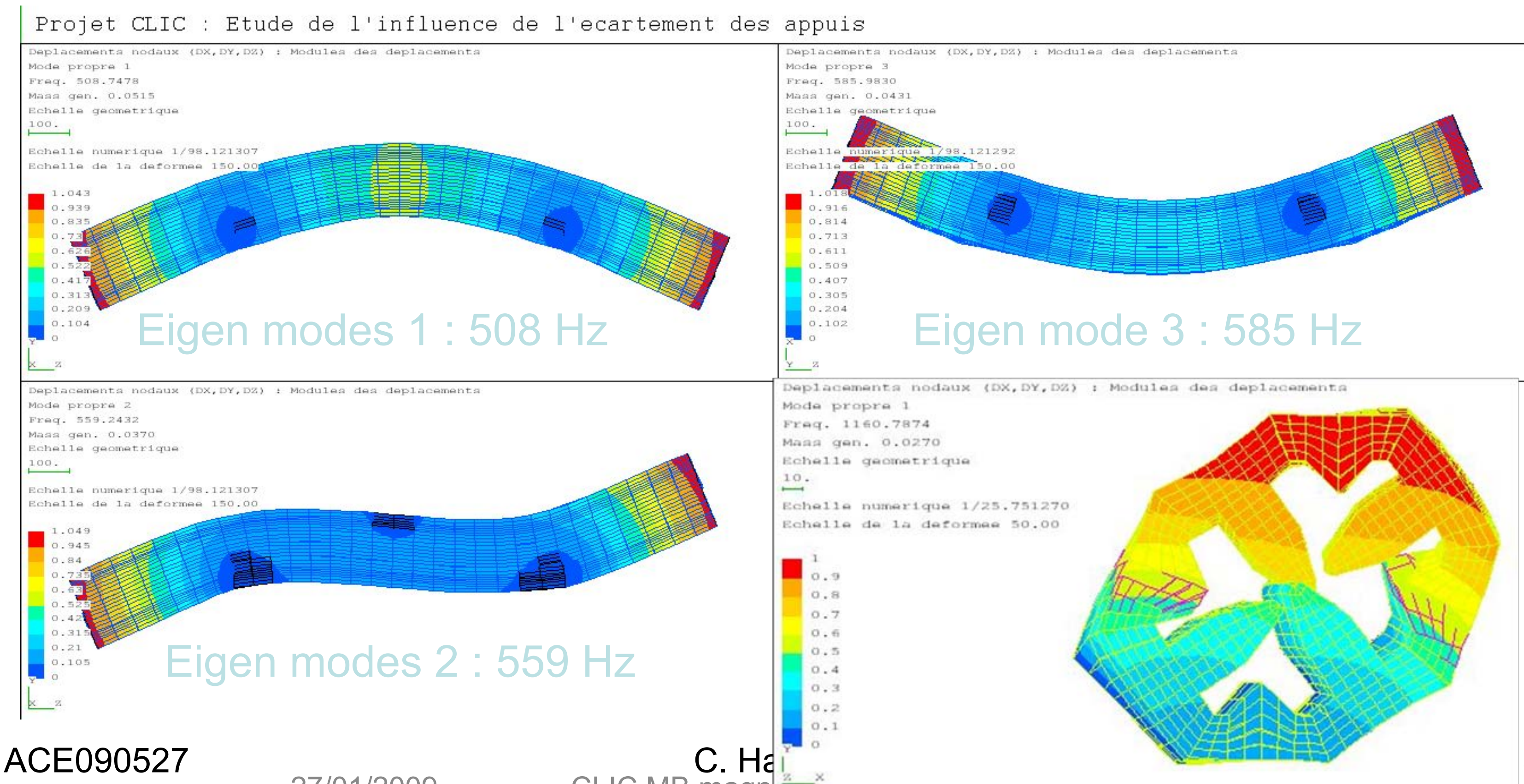


ACE090527

Main beam quadrupole
Dynamic behaviour (analysis+test)

(Guillaume Deleglise LAPP)

- Length 1500 mm, 4 lateral supporting lines (d=350 mm)

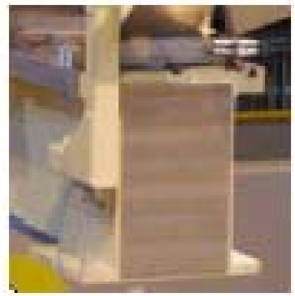


Girder Design – Geometry and Supports

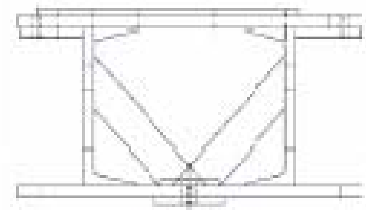
- A box-type cross section is preferable for high stiffness in flexure (both directions) and torsion.
- Full-length welds, gussets and plate stiffeners can significantly increase the overall stiffness.


SPring-8


Boomerang

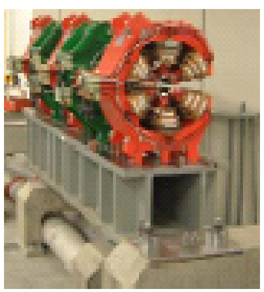

Diamond


CLS

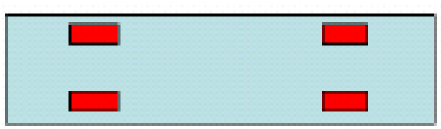

APS

- Unsupported length of the girder should be kept as small as possible (SPring–8 girders are supported at six points).

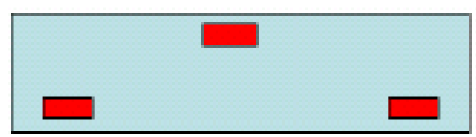
CLS

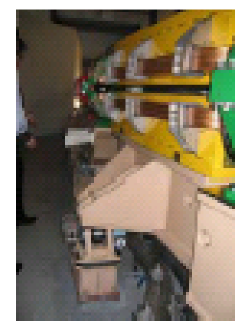


Supports at Airy Points



3–Point Support

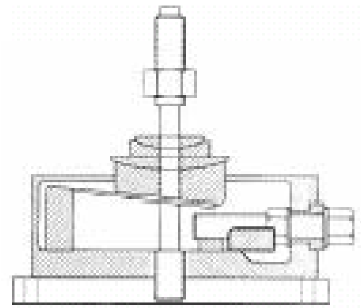



Boomerang

Girder Design - Alignment Mechanisms

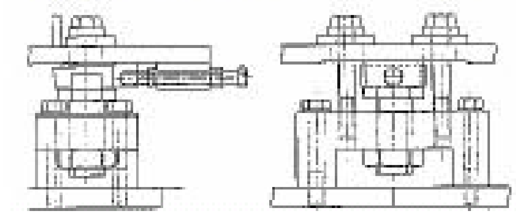
Threaded Rod

Threaded Rod with Lateral Adjustments (APS)

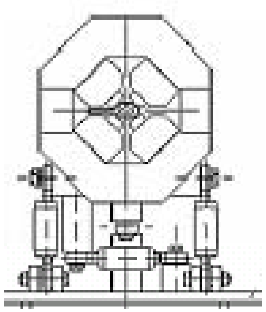


Wedge Jack (APS)

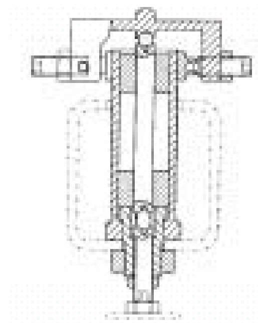
http://www-group.slac.stanford.edu/met/IWAA/TOC_S/PAPERS/KTsum02.pdf



SPring-8 Alignment



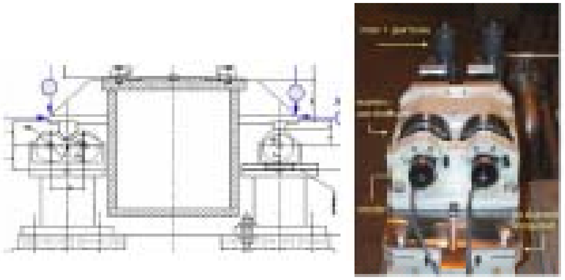
Six-Strut System



Cartridge Adjuster (CEBAF)*

Motorized Jack (ESRF)

http://accelconf.web.cern.ch/AccelConf/e00/PAPERS/WEP4A17.pdf



Cam Mover (SLS)

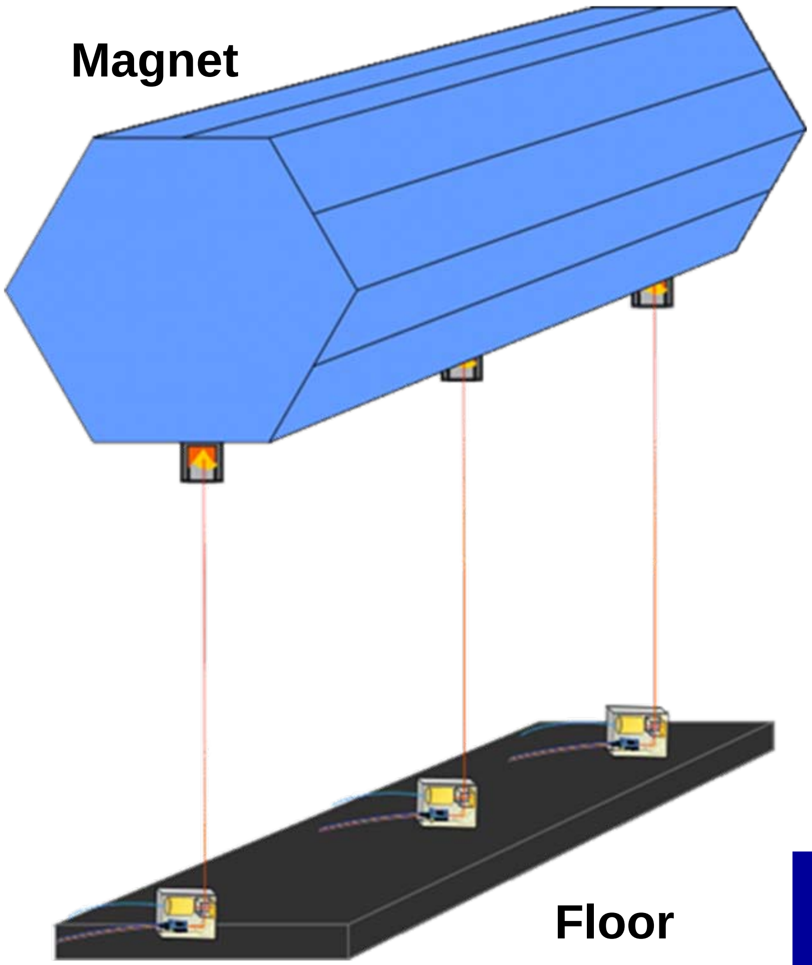
Upgraded in NSRRC 32 Hz for 10 tons

* Other Concepts [1994] http://www-group.slac.stanford.edu/met/IWAA/TOC_S/Papers/RRula95a.pdf

Monitoring CLIC magnet 2010

- Test several points along the magnet
  - at first independent DMs
- Compare readings with accelerometers
  - on the magnet
  - and on the floor

Paul Coe / Oxford (TILC'08)



Integrate and apply to Linac

Program of work *(as defined in March 2008)*

- A mock-up should be ready to provide results by June 2010 with several types of sensors including interferometers (intermediate milestones to be defined accordingly). The mock-up should perform better than required for main linac in order to "provide evidence" for final focus requirements.
- Mock-up to be integrated in CLEX (important to have the stabilization together with the alignment) or in other accelerators
- Beam experiment in CESRTA (storage ring)
  - 1st step (June 2009): excite a quad with narrow band and measure the beam blow-up (BPM equipped with BBQ)
  - 2nd step: install a full mock-up

Global alignment / stabilization strategy for main linac magnets

- Once / year

  Mechanical pre-alignment => *0.1 mm*

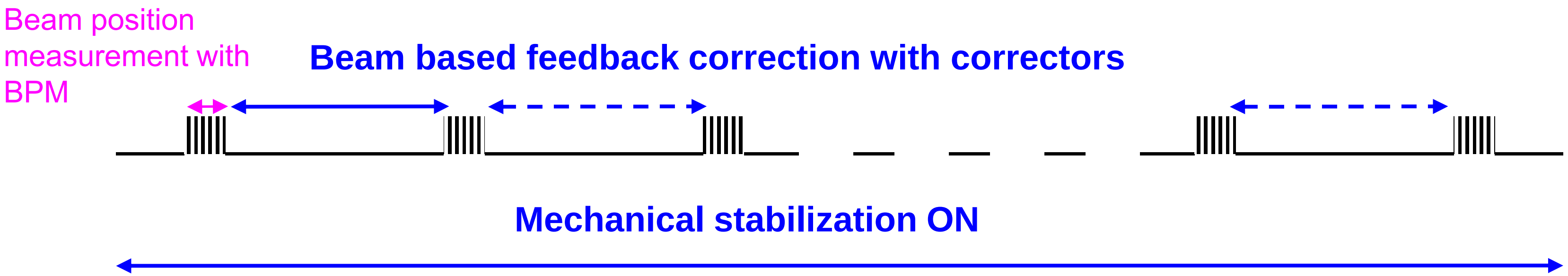
- Once / few weeks

  Active pre-alignment using HLS, WPS, RASNIK => +/- *10 μm* on a sliding window of 200 m

- Once / couple of hours

  Beam based active alignment with movers – complex procedure => *1 μm*
  Beam based alignment with magnet correctors or actuators
  and mechanical stabilization on=> *few nm*

- “Steady state”



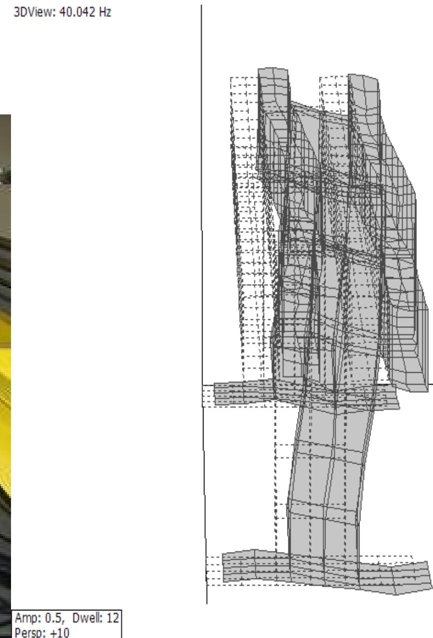
Main Beam Mock-up
Compatibility between functionalities?

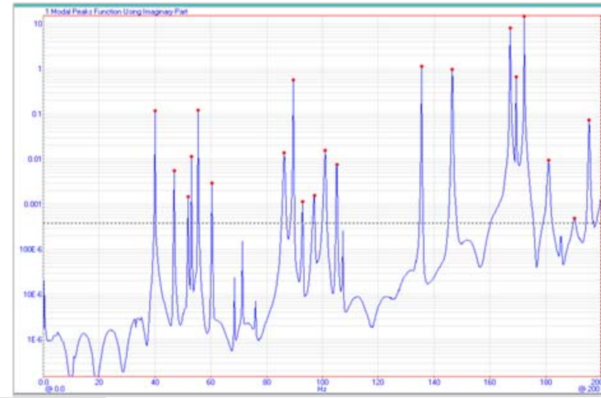
- Stabilization is better achieved with a rigid support
- Adjustable re-alignment needs a flexible support

- *To minimize the incompatibility, fix on a rigid ground, minimize the beam height, design movers, girder, magnet with "high" first eigenfrequency: a challenge!*

Support design

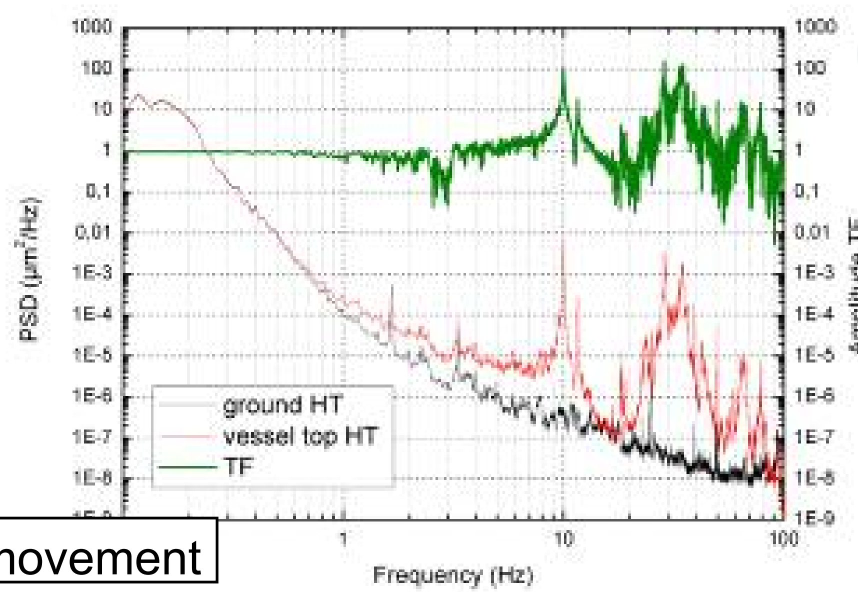
Multi degrees of freedom and several deformation modes with different structural damping





Experimental modal analysis on **CLEX** girder

Low Beta LHC

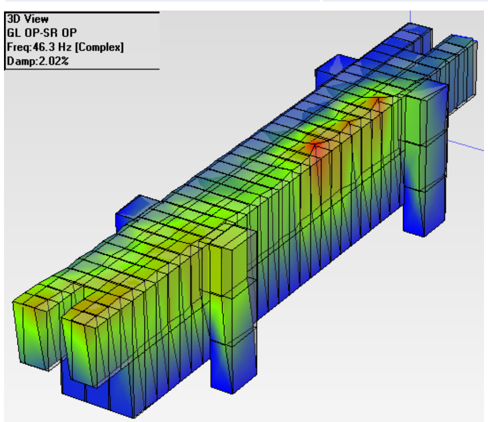


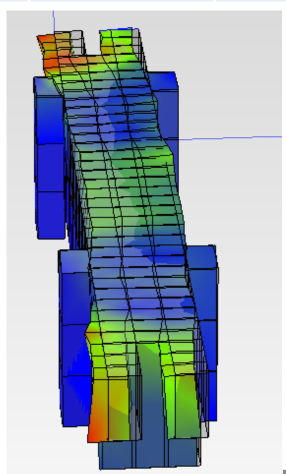
Amplification of floor movement

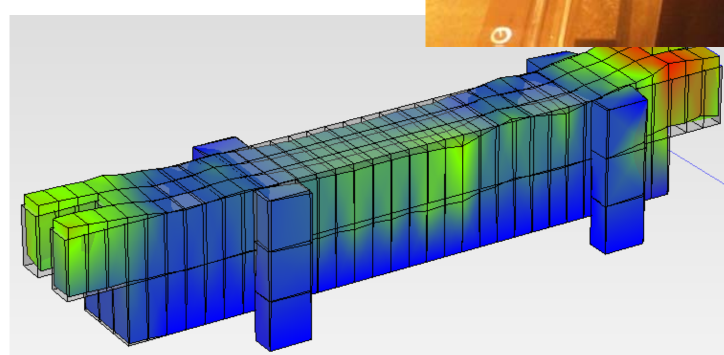
Experimental Modal Analysis

PSI – Mineral Cast Girder / Preliminary Results

Mode Shape	Installation on 4 feet		Installation on 3 feet	
	Frequency	Damping	Frequency	Damping
Lateral rigid body mode	46.3 Hz	2.0 %	37.9 Hz	1.6 %
Longitudinal rigid body mode	56.4 Hz	1.2 %	60.3 Hz	1.4 %
Vertical rigid body mode	81.2 Hz	2.4 %	75.8 Hz	2.3 %
First lateral bending mode	129 Hz	0.5 %	108 Hz	0.9 %
First vertical bending mode	147 Hz	1.3 %	153 Hz	0.8 %







Overall design

Accelerator environment

• Mechanical coupling via beam pipe, cooling pipe, instrumentation cables,...

• Vibrations inside the structure to be stabilized:

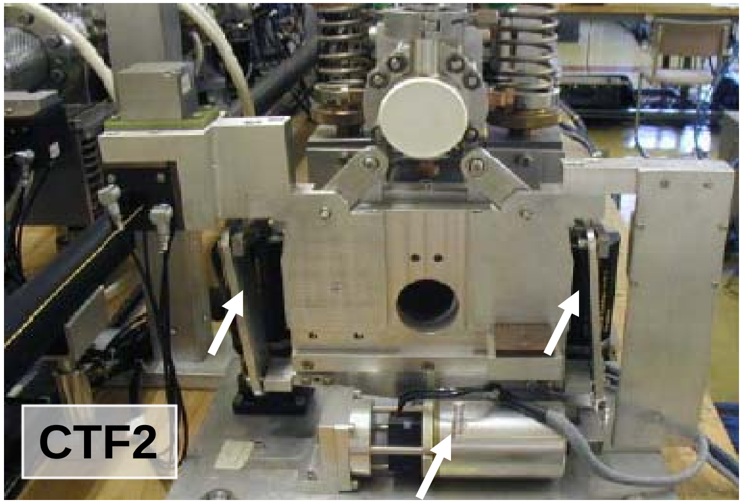
- Cooling water circuit
- Inter pulse alignment with stepper motors

•Radiation

-Radiation level at CLIC not yet estimated

-Radiation damage effects on electronics:

Total dose
Displacement
Single event error



Beam experiment at CESRTA

- 1st phase: Demonstration of nm-sensitivity for beam motion observation
- 2nd and 3rd phase: demonstration of quad stabilization on a nm-level

- Installation of high sensitivity electronics onto an existing BPM at CESR: BBQ electronics. (M.Gasior et al. (CERN); successfully used for tune diagnostics at CERN, FNAL, BNL
- Using CESR with low emittance beams (order of micrometers)
- Optimization of this electronics for very low frequencies: 10 Hz – 100Hz; observation of beam spectra; selection of narrow frequency window with lowest beam eigen-motion
- Controlled low amplitude beam excitation through current modulation of a corrector dipole.
- Trying to obtain a reasonable signal to noise ratio for beam oscillations of nm-size (expected measurement time: 15 minutes)

Contents

- Organization
- Actions
  - Sensors
  - Characterize vibrations/environmental noise
  - Actuators
  - Feedback
  - Overall design + analysis
  - Integrate and apply to Linac
  - Final Focus
- Conclusion

Some words on the Final Focus

- No dedicated full mock-up for FF will be done before CDR, but special features to be integrated in the Linac mock-up
  - Integration of all the final focus features: types of supporting structures, coupling with vertex detector, forward detectors,…
  - Small mock-ups for FF (cantilever) being developed
  - Main features being studied by MDIWG to define inputs to the future program:
    - Type of magnet : permanent or/and superconductors
    - Type of supporting structures: cantilevered beams or connected through the experiment
- A subject for the CLIC/ILC collaboration, presently around ATF2

ATF2 by LaVista

A way to avoid amplification!

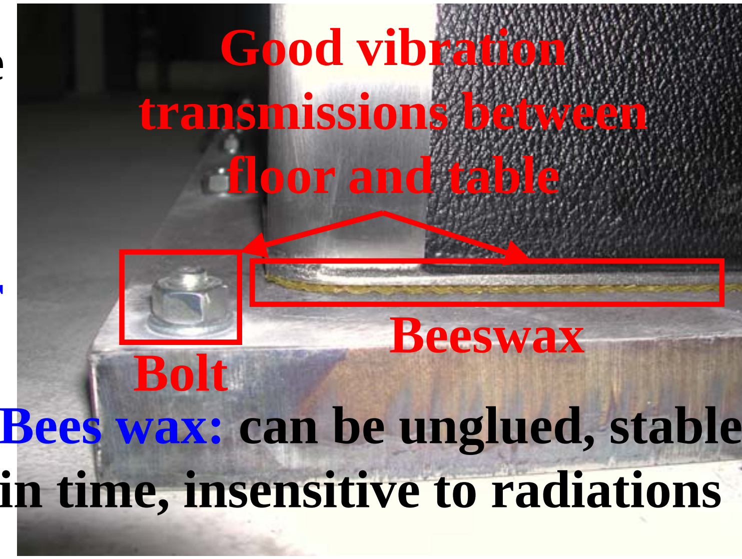
Table fixed on one entire face to the floor

Honeycomb table

Bees wax

3 steel plates bolted to the floor

Space between plates to move the table with slings



Bees wax: can be unglued, stable in time, insensitive to radiations

Evolution of resonances with masses simulating FD weight

GURALP geophones (0.033Hz - 13Hz)

ENDEVCO 86 accelerometers (13Hz - 100Hz)

Microphone of type 4189

FF mock-up proposal (2011)

Brett Parker
(PAC'08)

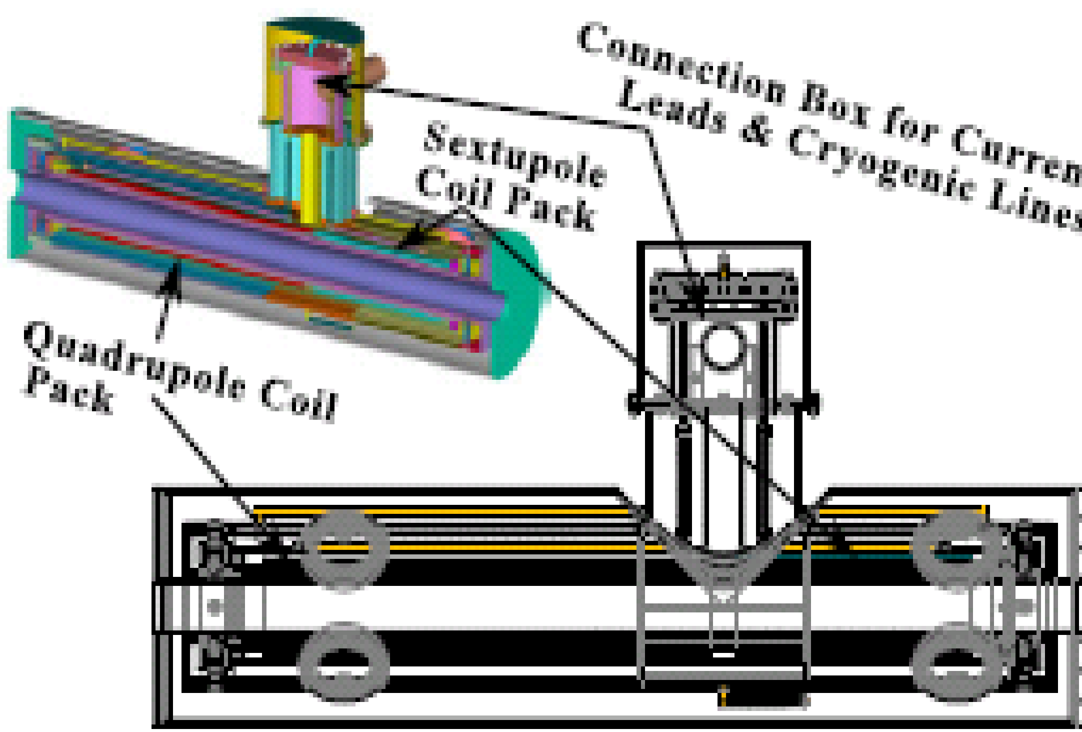


Figure 3: ATF2 Magnet Cryostat Overview.

Conclusion

MONALISA IRFU/SIS

The Stabilization Working Group is up and running.

Actions plan is in place.

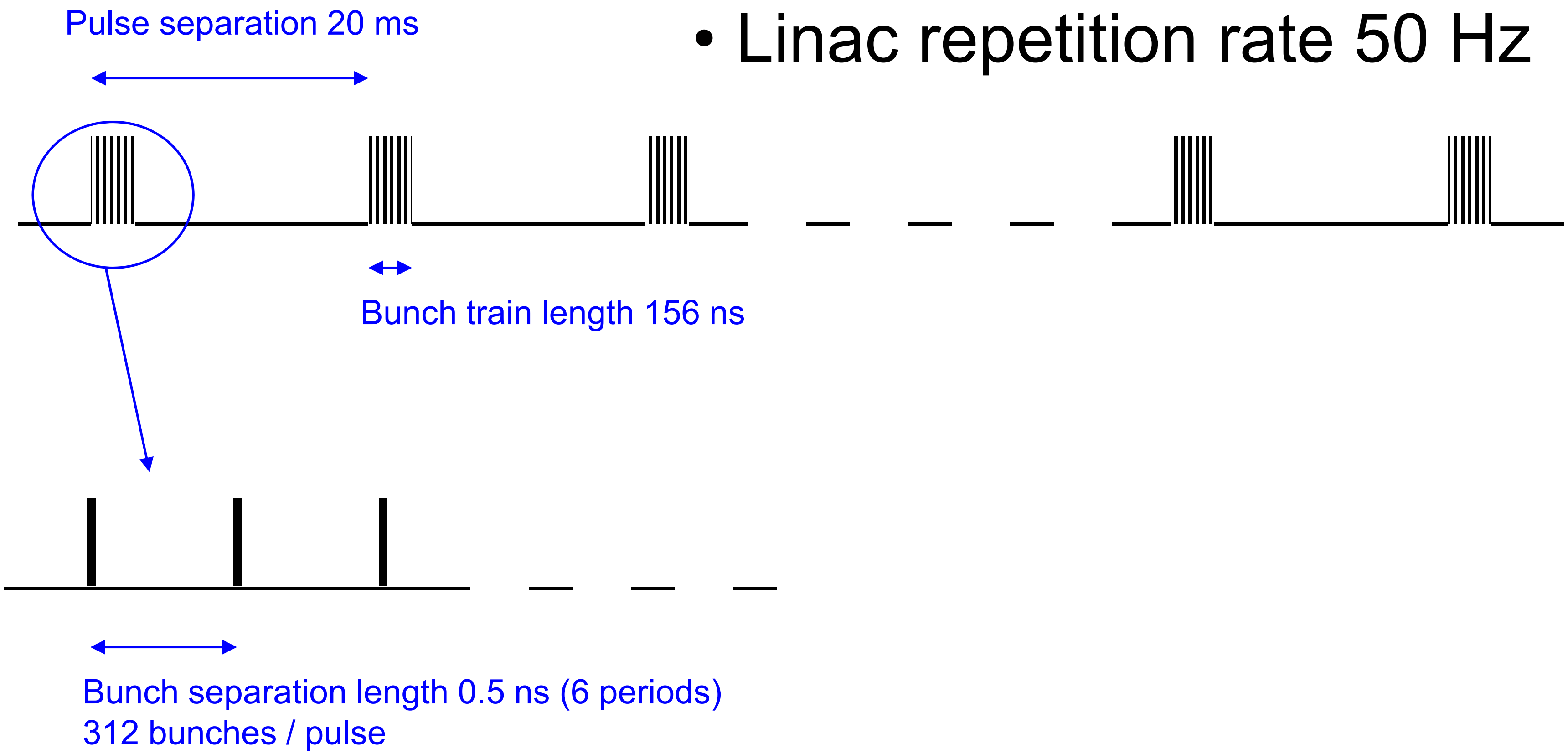
A pragmatic approach with a deadline in 2010:
a full scale demonstrator with an MB quadrupole built and qualified.

No prototyping work on the FF before 2010, but involvement of CLIC study in ATF2 work

Back-up slides

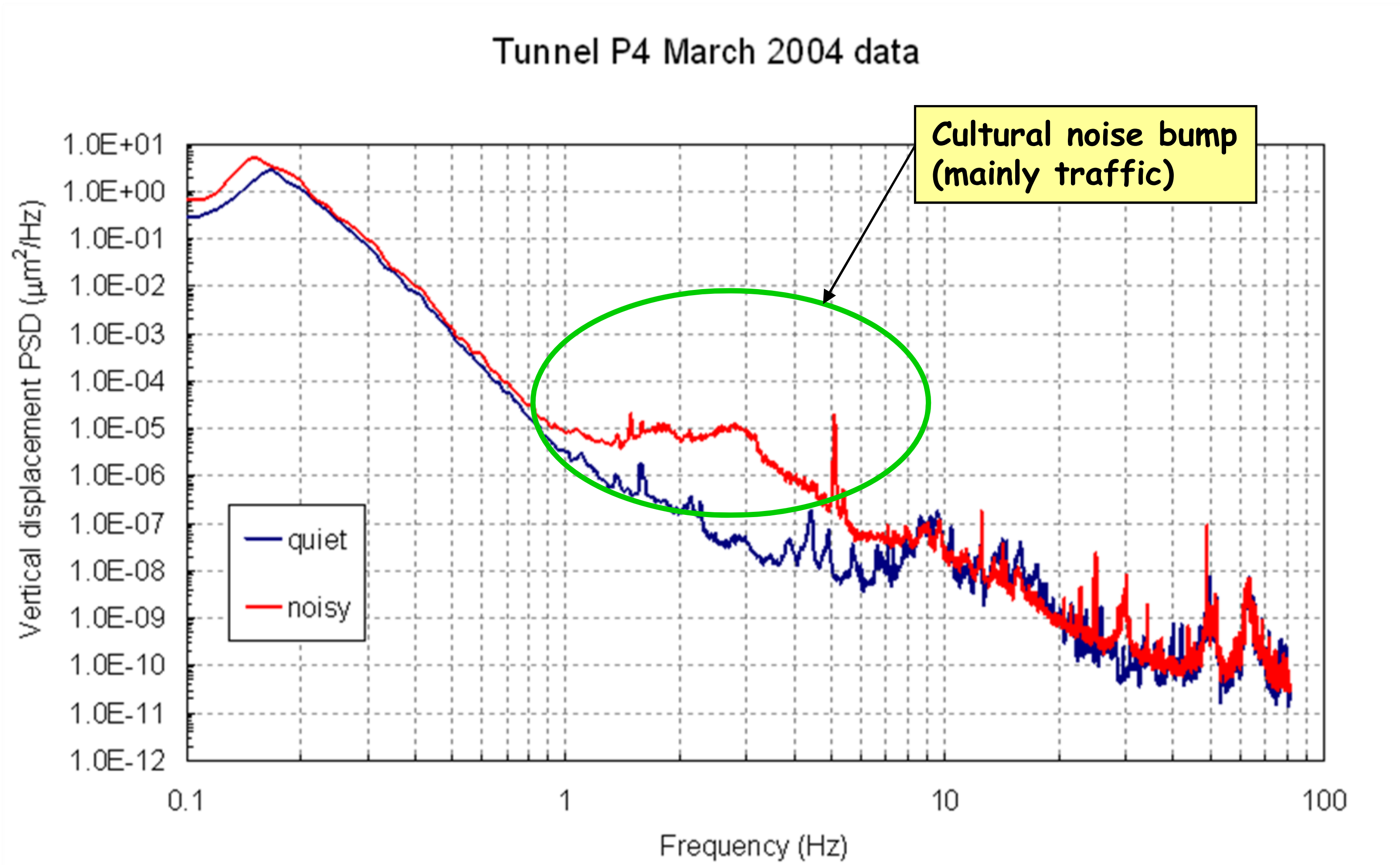
CLIC standard operating mode

- Main linac RF frequency 12 GHz
- Linac repetition rate 50 Hz



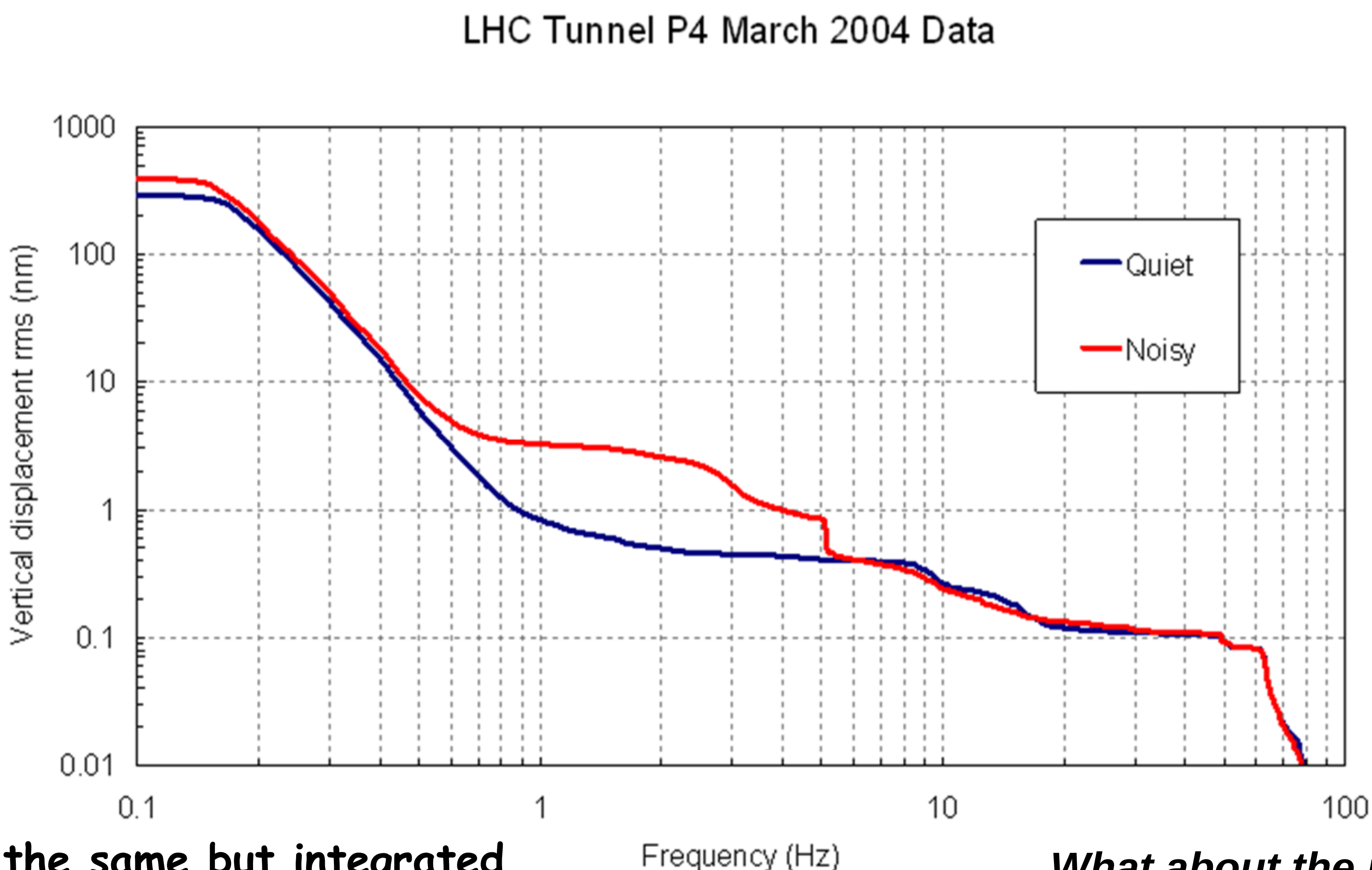
Characterize vibrations/noise sources in an accelerator

DESY's fast seismic motion studies @ CERN – LHC Tunnel P4 Noisy vs Quiet



Characterize vibrations/noise sources in an accelerator

DESY's fast seismic motion studies @ CERN – LHC Tunnel P4 Noisy vs Quiet

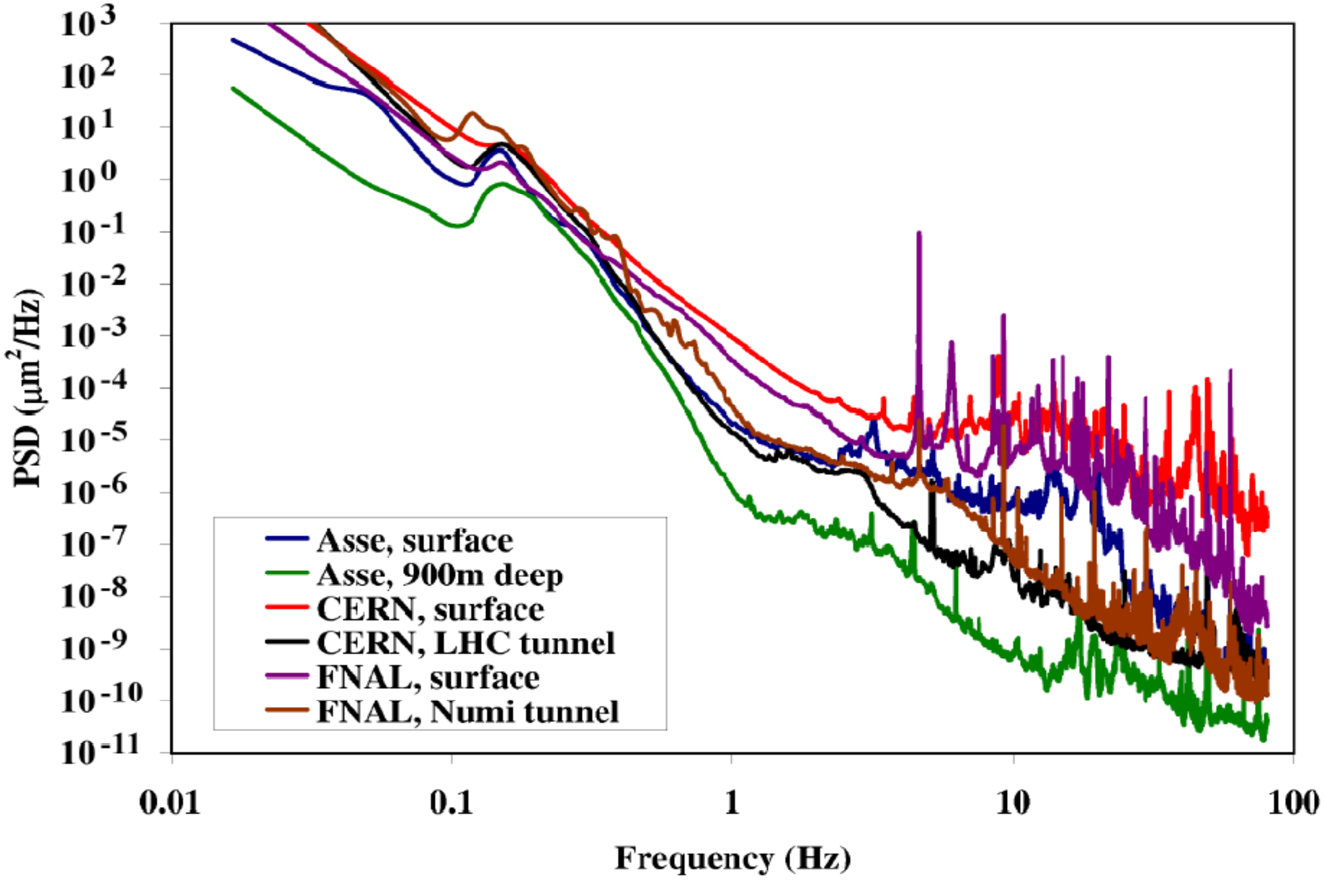


… the same but integrated

What about the peaks!

Characterize vibrations/noise sources in an accelerator

Influence of the sites / depth

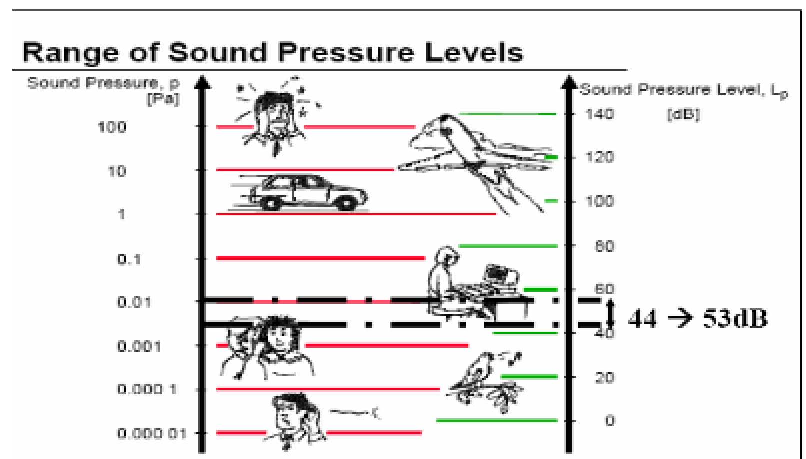


CLEX

Characterize vibrations/noise sources in an accelerator

Acoustic noise

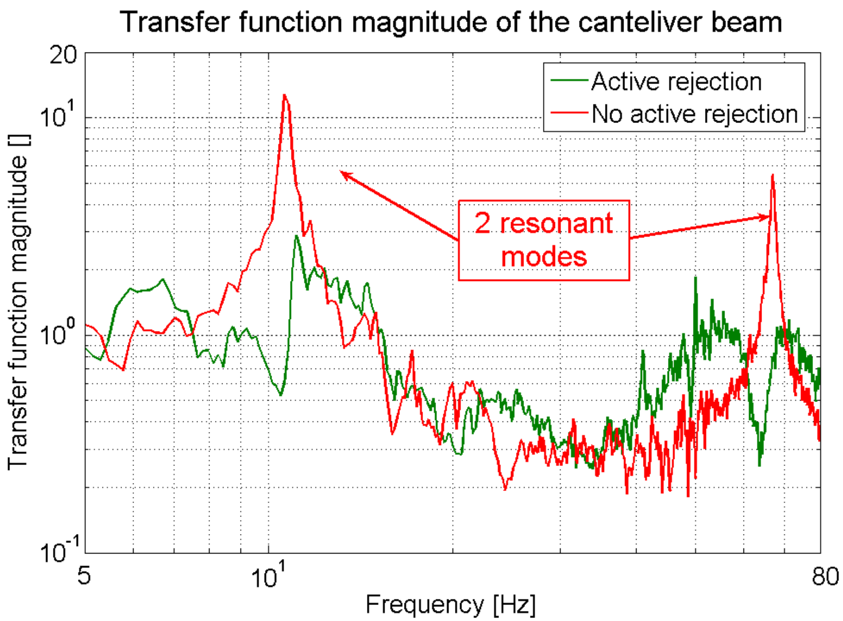
Acoustic noise = air pressure waves
Acoustic noise as dominant source de vibration > 50 Hz



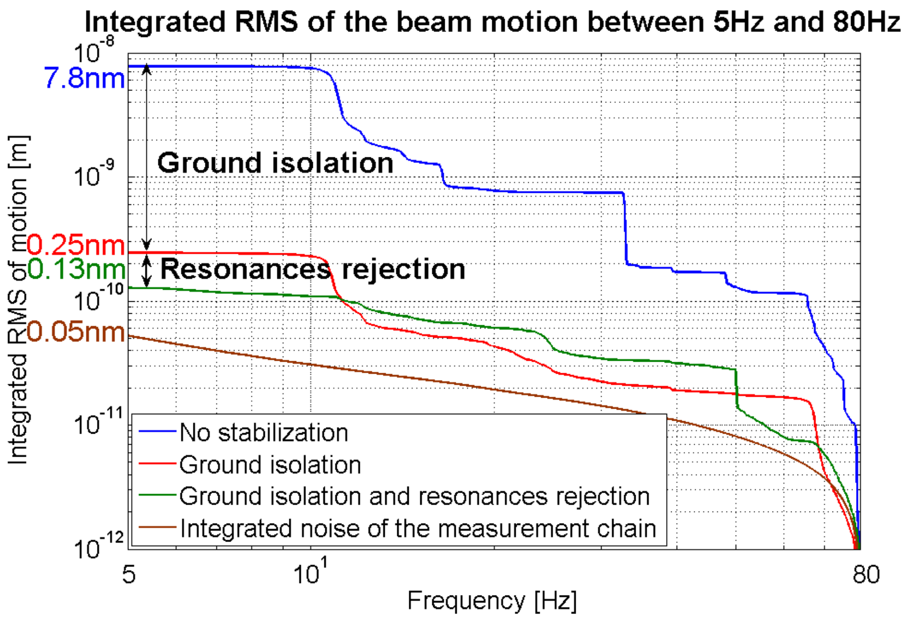
For high frequencies > 300 Hz, movements > tolerances may be induced

Feedback

Experimental test

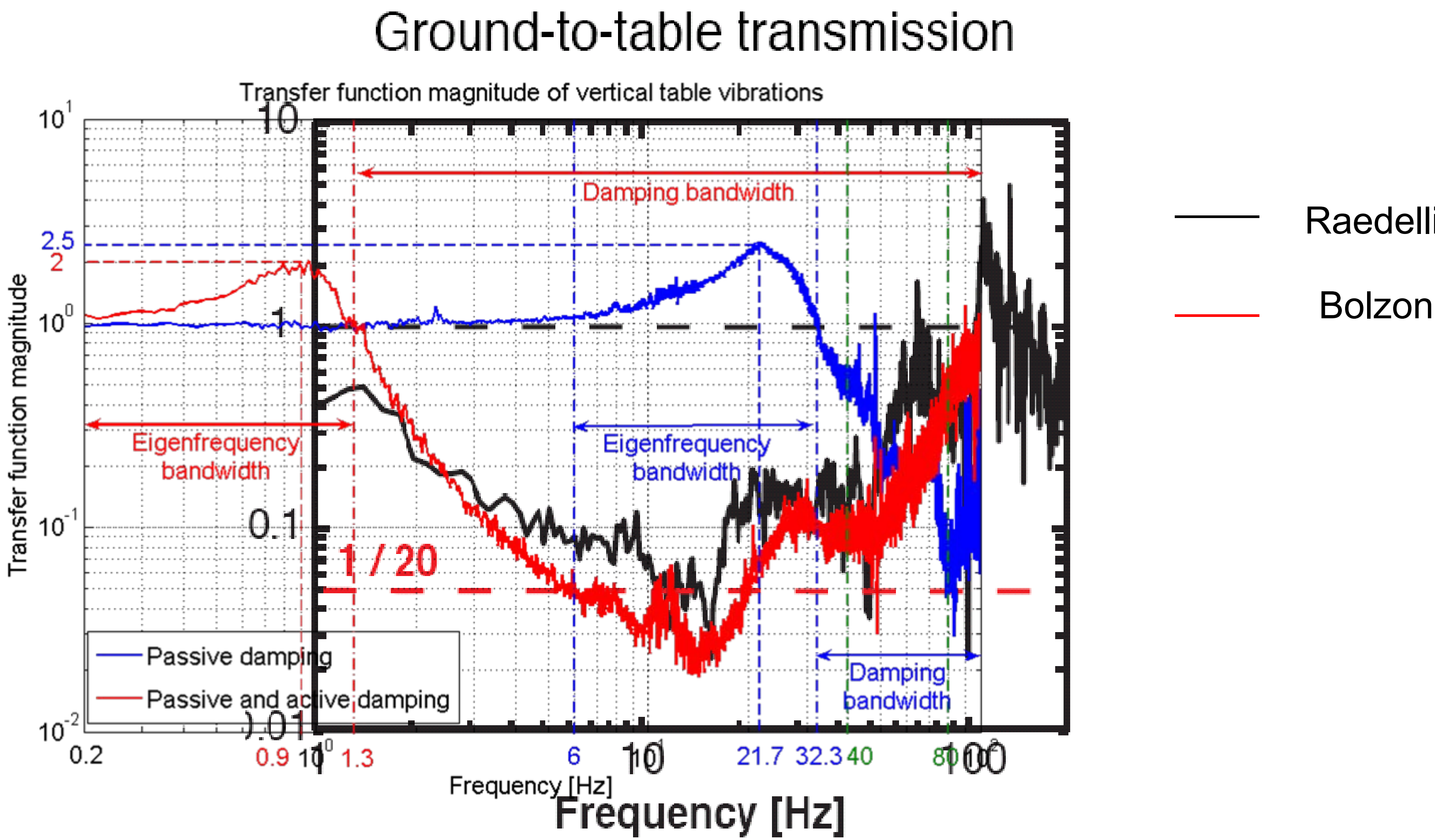


- The two first resonances entirely rejected



➔ **Factor 60 of damping between 5Hz and 80Hz down to 0.13nm**

Transfer function between ground and top of the same STACIS table according to Redaelli (at CERN) and Bolzon (at LAPP)



Definitions

- Correlation function: $$R_{xy}(\tau) = \int_{-\infty}^{\infty} x(t)y(t+\tau)dt$$

- Cross spectral density: $$\Phi_{xy}(\omega) = \int_{-\infty}^{\infty} R_{xy}(\tau)e^{-i\omega\tau}d\tau$$

- Normalized spectral density between two measurements x(t) and y(t): $$\gamma_{xy}(\omega) = \frac{\Phi_{xy}(\omega)}{\sqrt{\Phi_{xx}(\omega)\Phi_{yy}(\omega)}}$$

(the absolute value is the *coherence* and the real part is the *correlation)*

- Power spectral density of the relative motion $d(t)=x_1(t)-x_2(t)$: $$\rho(\omega, L) = \Phi_{xx}(\omega)2\{1 - Re[\gamma_{x_1x_2}(\omega)]\}$$

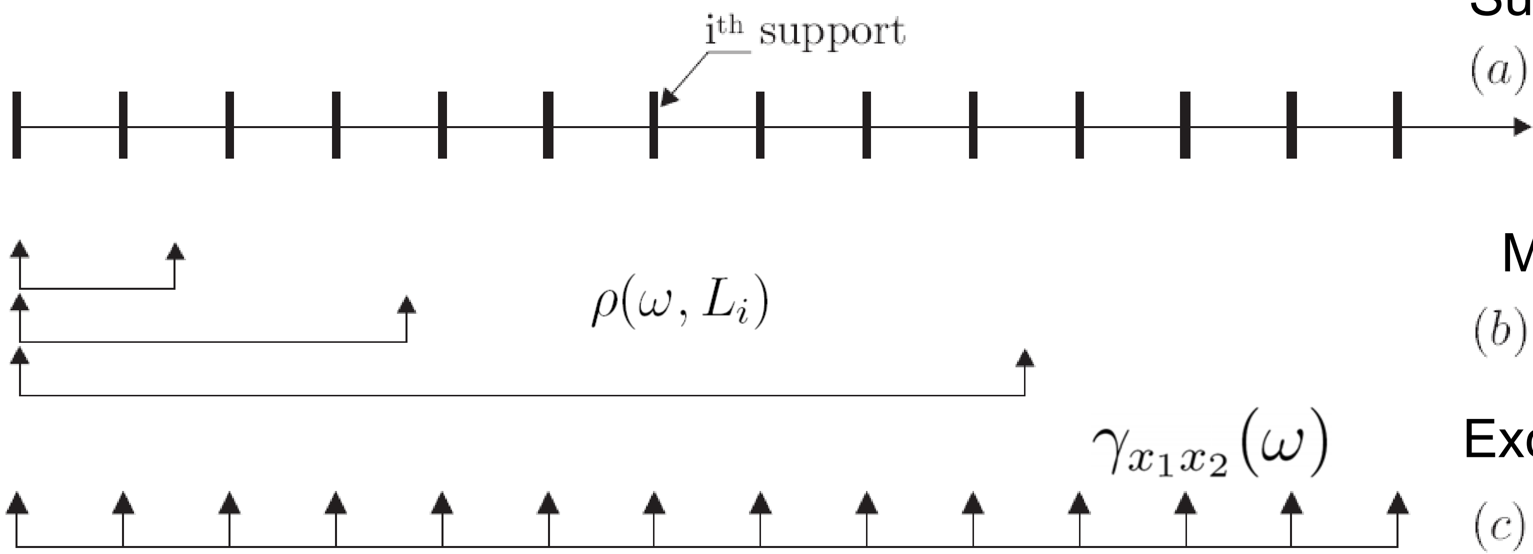
- 2D power spectral density: $$P(\omega,k) = \lim_{T\to\infty}\lim_{L\to\infty}\frac{1}{T}\frac{1}{L}|\int_{-T/2}^{T/2}\int_{-L/2}^{L/2} x(t,s)e^{-i\omega t}e^{-iks}ds|^2$$

For ATL law: $P(\omega,k) = \frac{A}{\omega^2 k^2}$ and $\rho(\omega, L) = \frac{AL}{\omega^2}$

Prepared by C. Collette

Ground motion modeling

Motivation:



Support location

Measurements (available)

Excitation matrix (objective)

Procedure:

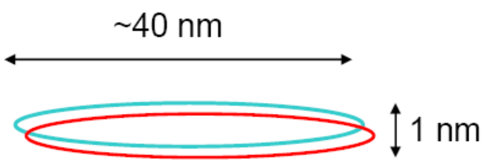
$\rho(\omega, L_i)$ for a few L_i ⇨ $P(\omega, k)$ ⇨ $\gamma_{x_1 x_2}(\omega)$ for any x_1 and x_2

Prepared by C. Collette

Quadrupole stabilization

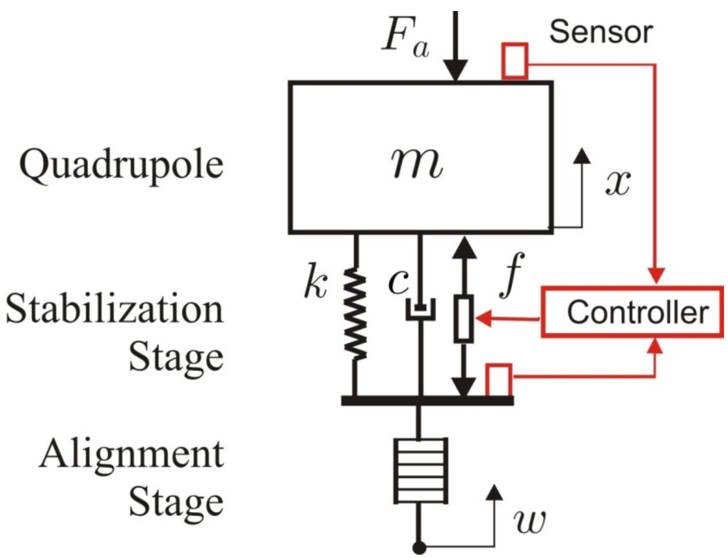
Objective:

Beam size above 1 Hz:

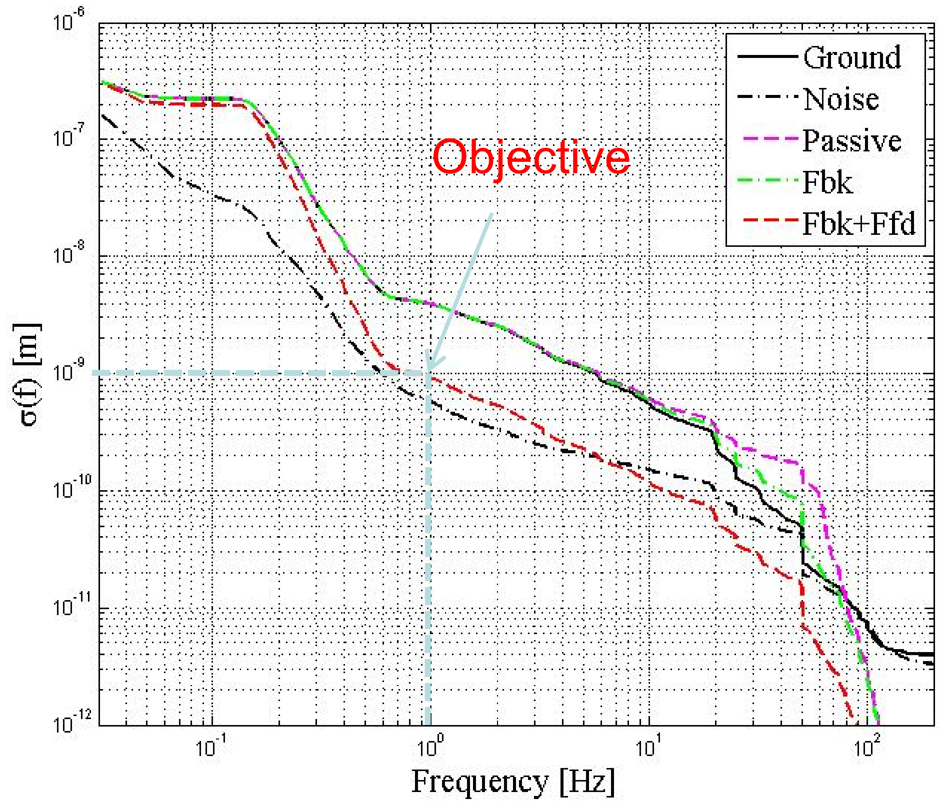


Control strategy:

Feedback + Feedforward

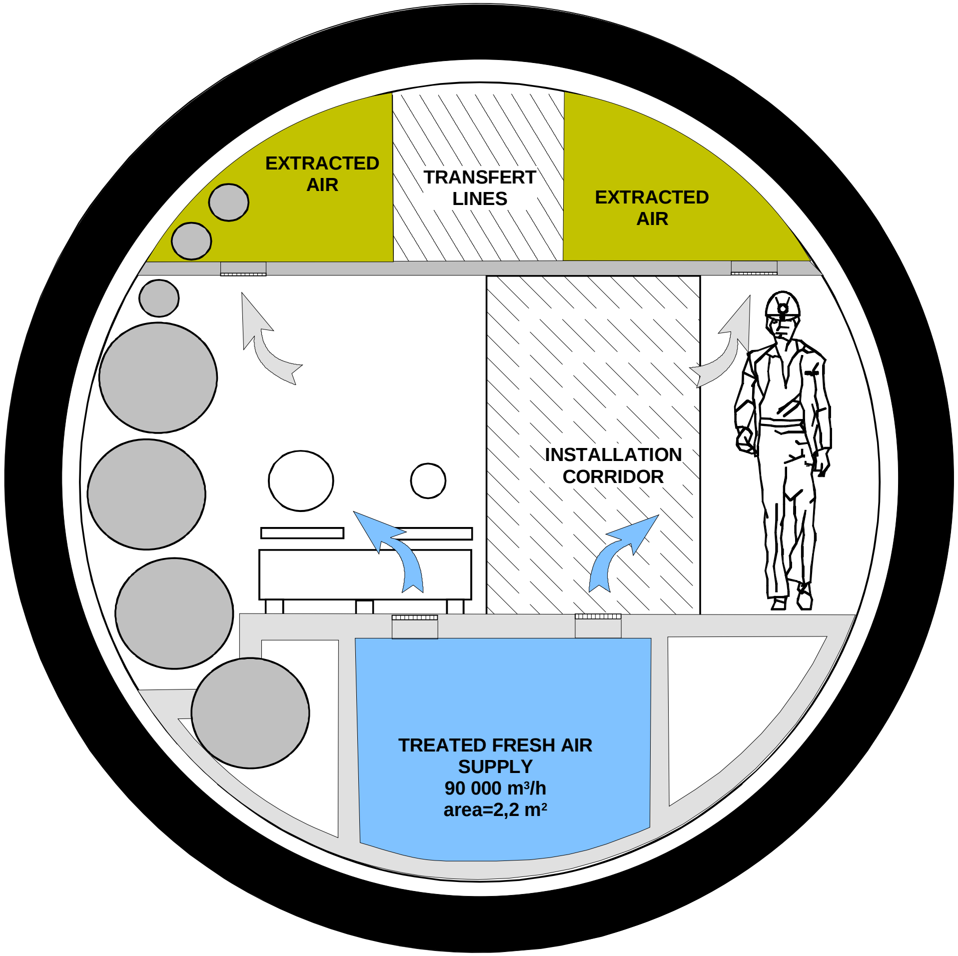


RMS integrated $\sigma(f) = \sqrt{\int_f^\infty \Phi(\nu) d\nu}$



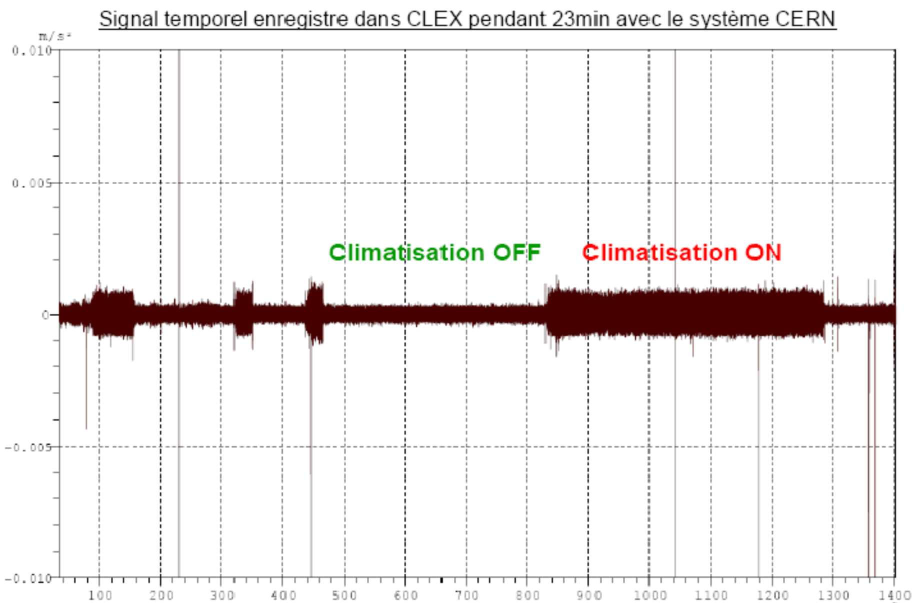
Next: Combine stabilization and micropositioning

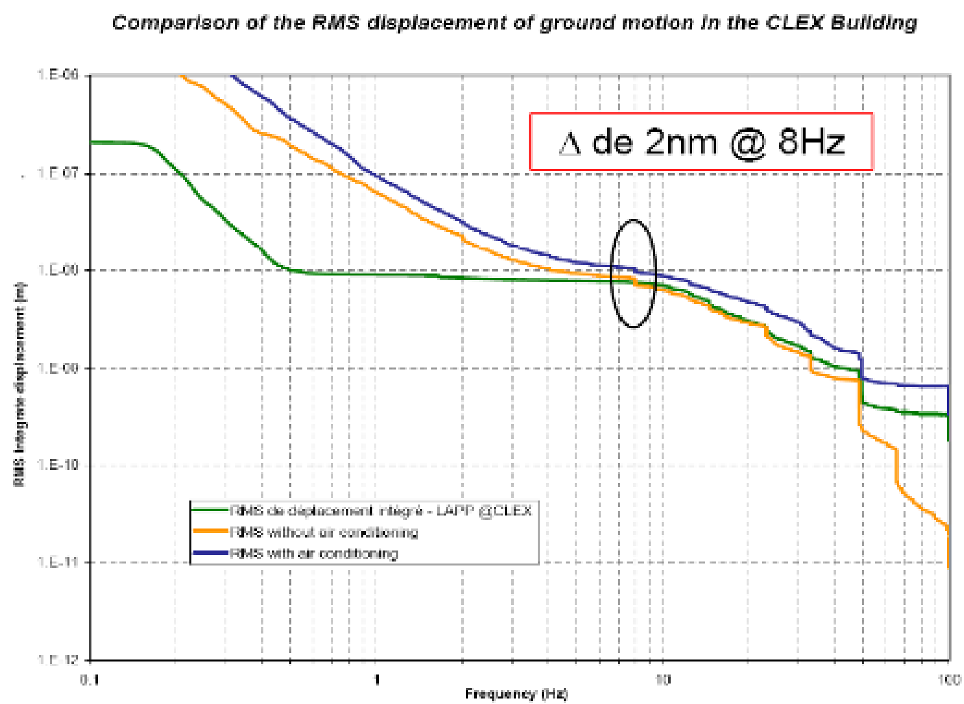
What should be avoided



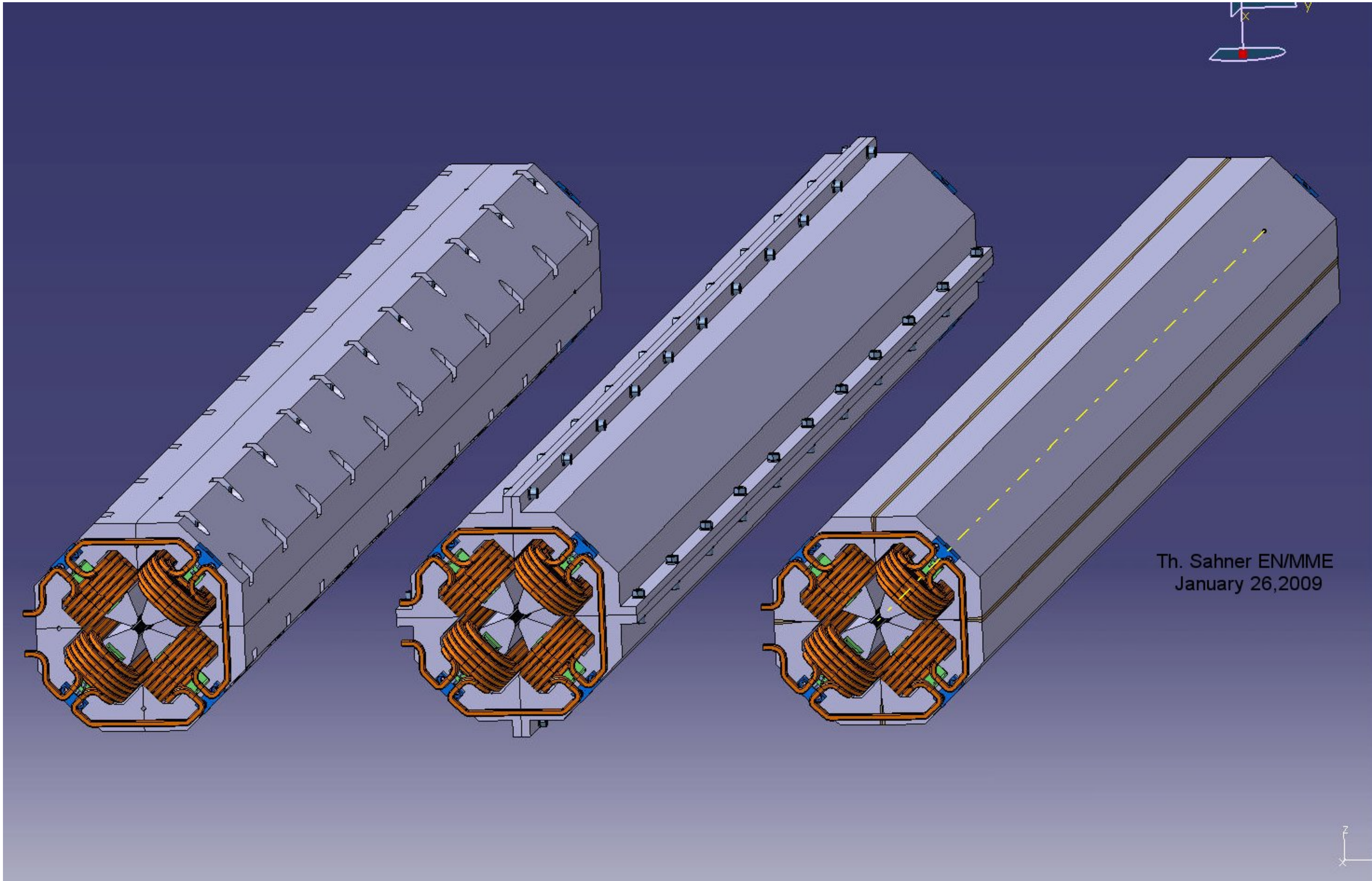
Characterize vibrations/noise sources in an accelerator

Influence of the ventilation in the CLEX building

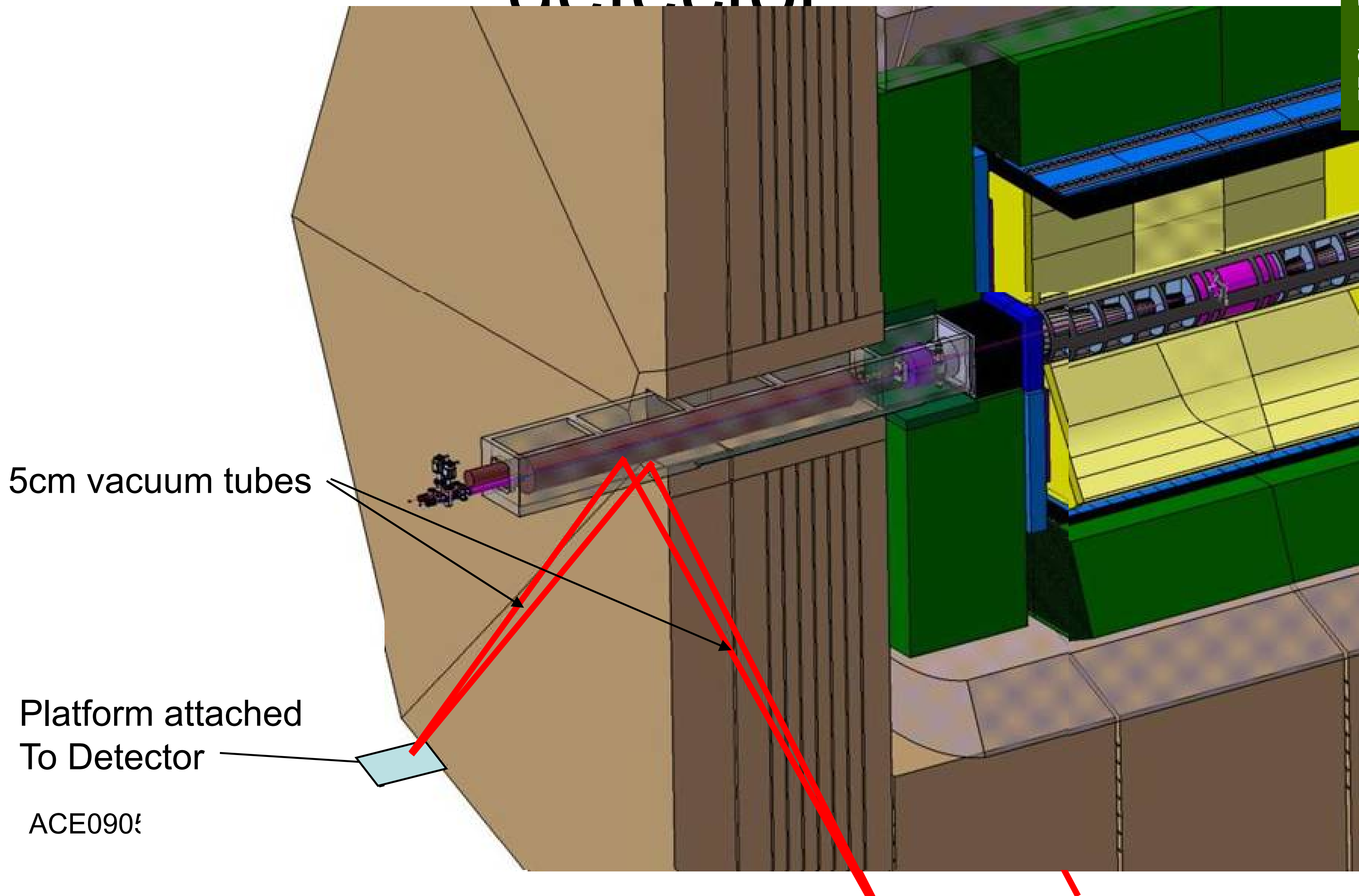




CLEX


Th. Sahner EN/MME
January 26,2009

Narrow lines favoured through detector



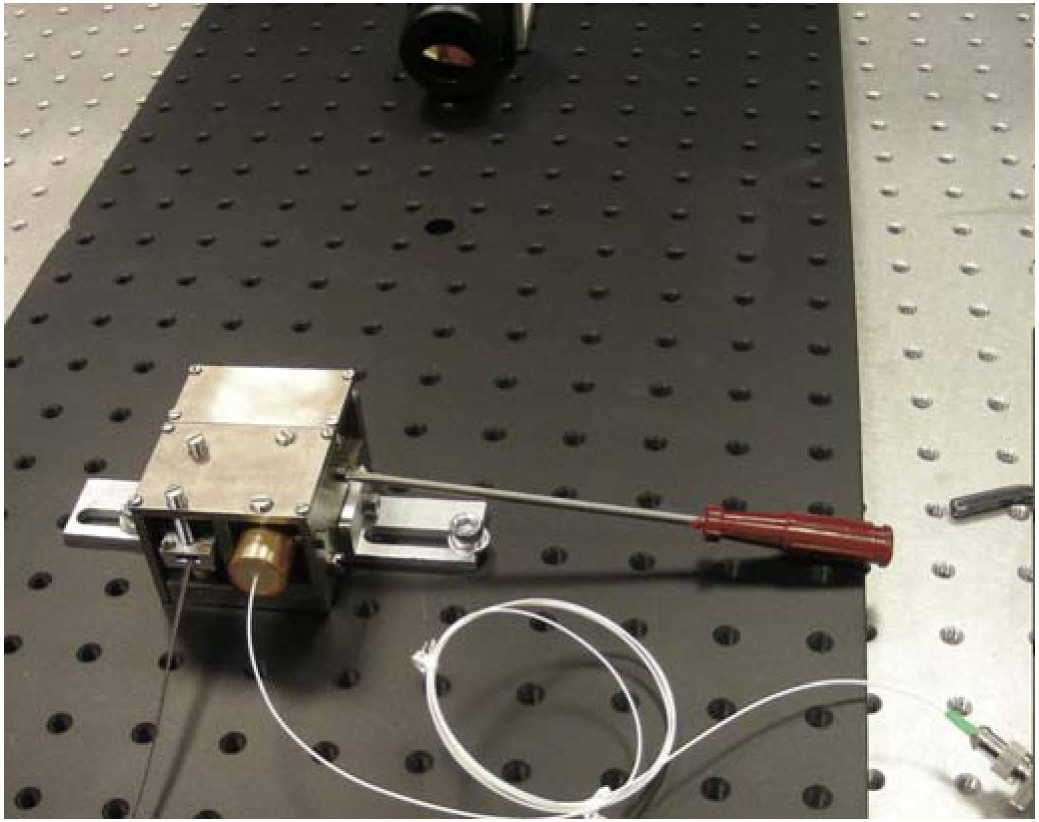
Interferometer: Distance meter

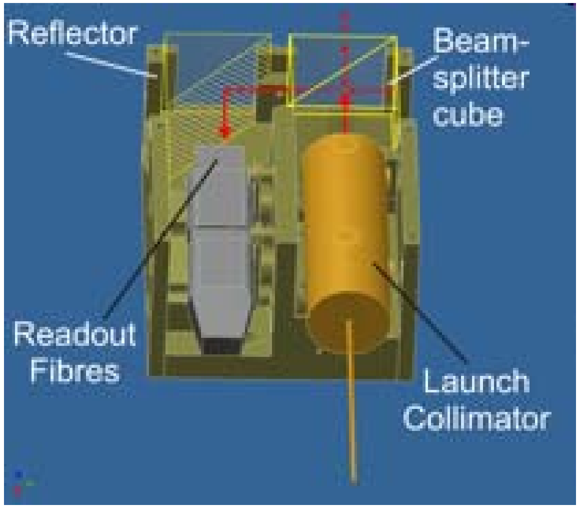
- Operates in two modes
  - Absolute Distance (< μm resolution)
  - Displacement measurement (nm resolution)

- Two modes combined
  - Displacements referred to absolute distance
  - Tolerant to interruption of measurements

Interferometer head

- Prototype tested at Oxford





Interferometry

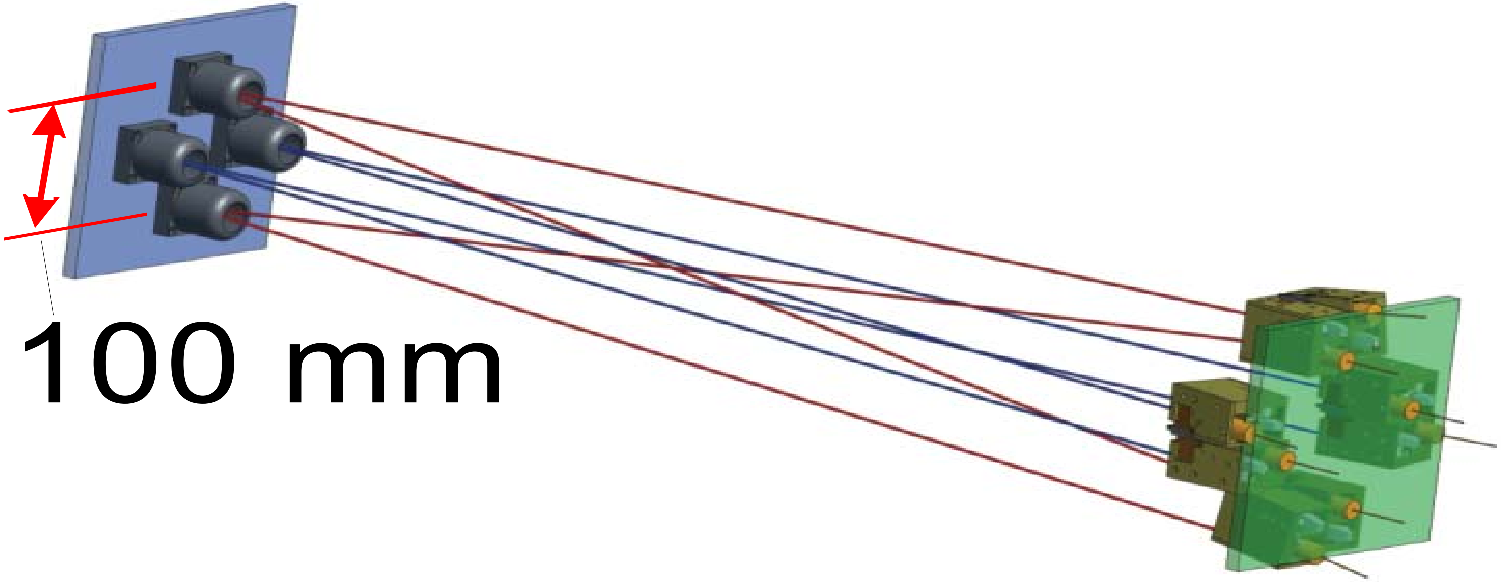
Interferometers: Make relative measurements

Interferometry

- Distance Meters measure point to point
  - Range and displacements (ε changes)
- 2 lasers reduce systematic errors of range
  - We use FSI laser and the FFI laser
- Compact Straightness monitor
  - Combines distance meters to measure object to object
    - 3 translational degrees of freedom
    - 3 rotational degrees of freedom

Instruments: CSM

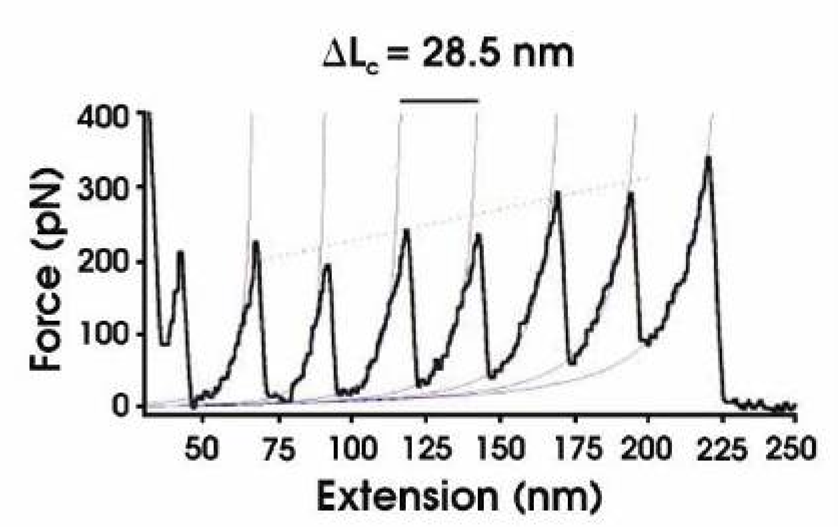
- Compact Straightness Monitor
- Example from ATF2
  - Measures plane to plane
- Internal displacements and rotations measured
- CSM always blind to 6 external DoF



Interferometry

Actuators

Stabilized structures and Piezo-actuators with resolution of 0.05 nm exist!



Fernandez Lab, Columbia University NY
Traction test on a protein

But only for few kg et rigid objects....

Techniques to be developed for heavier (up to 400Kg) and larger structures (up to 2 meter long)

Actuators

Recent calibration of the new actuator with a vibrometer

Our lab is too noisy for the nanometer range: search going on for a quieter place at CERN