Study of vibrations and stabilization at the sub-nanometre scale for CLIC final doublets

Laboratories in **A**nnecy working on
Vibration **Sta**bilization

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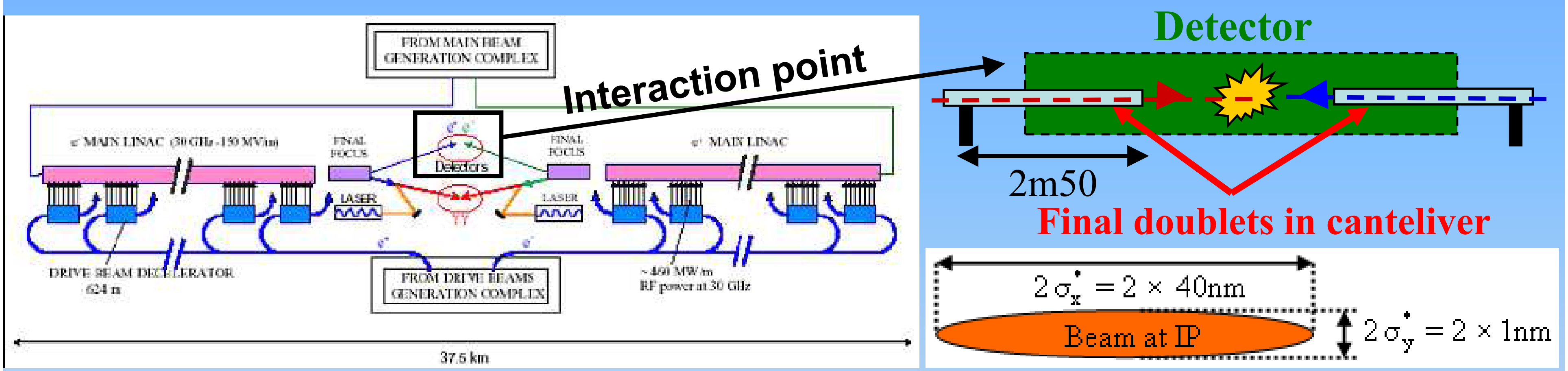
Nanobeam 08, Novosibirsk

Context

CLIC Linear Collider (~2019): New generation of the circular LHC



Vertical beam size σ_y^* at the interaction point: 1nm

Tolerance of vertical relative positioning between the two beams to ensure the collision with only 2% of luminosity loss: 1/10nm

Below 5Hz:

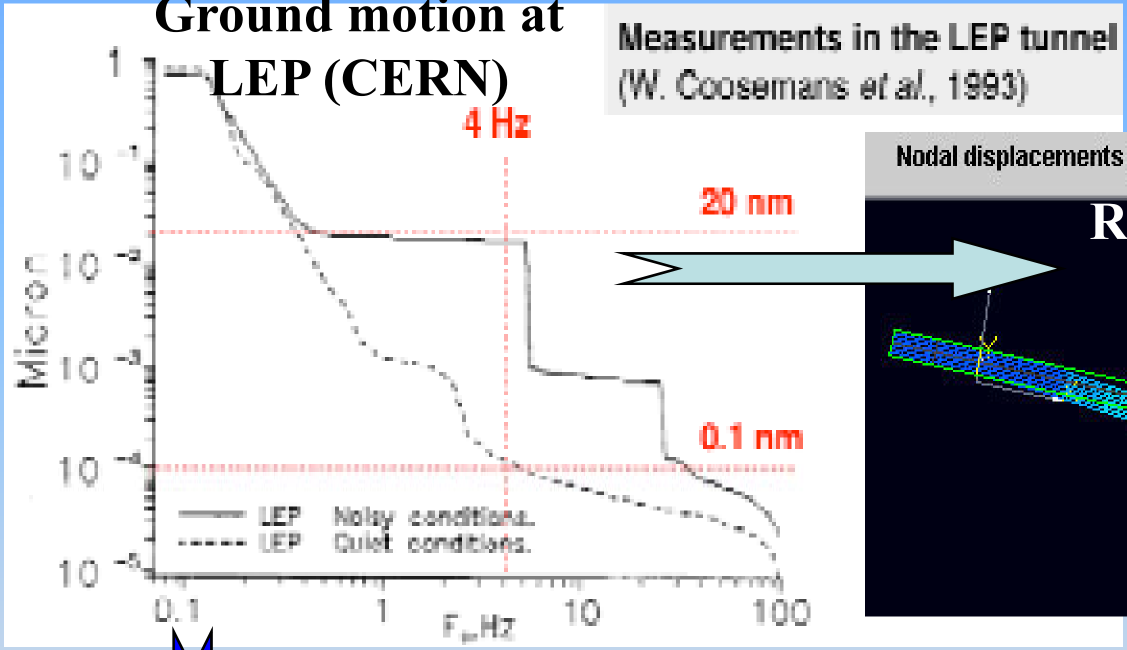
Beam position control with deflector magnets efficient

Above 5Hz:

Need to control relative motion between final doublets

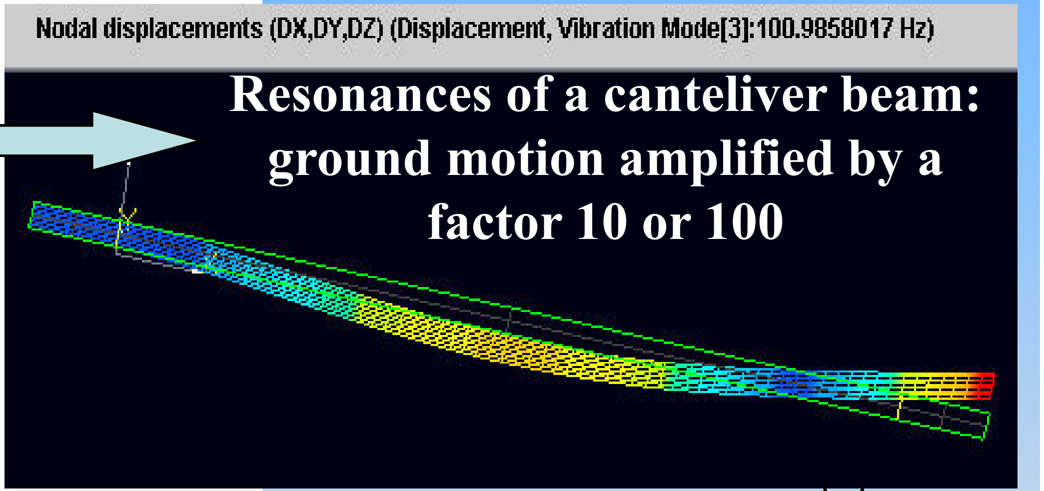
Context

Major source of vibrations: ground motion



Ground motion at LEP (CERN)

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



Resonances of a canteliver beam: ground motion amplified by a factor 10 or 100

Specifications to control FD relative motion (>5Hz)

Active stabilization of FD down to 1/10nm

Ground active isolation and active rejection of FD resonances

Context

LAViSta (Laboratories in Annecy working on Vibrations Stabilization)

✓ **Partnership between 2 laboratories in Annecy for mecatronics**

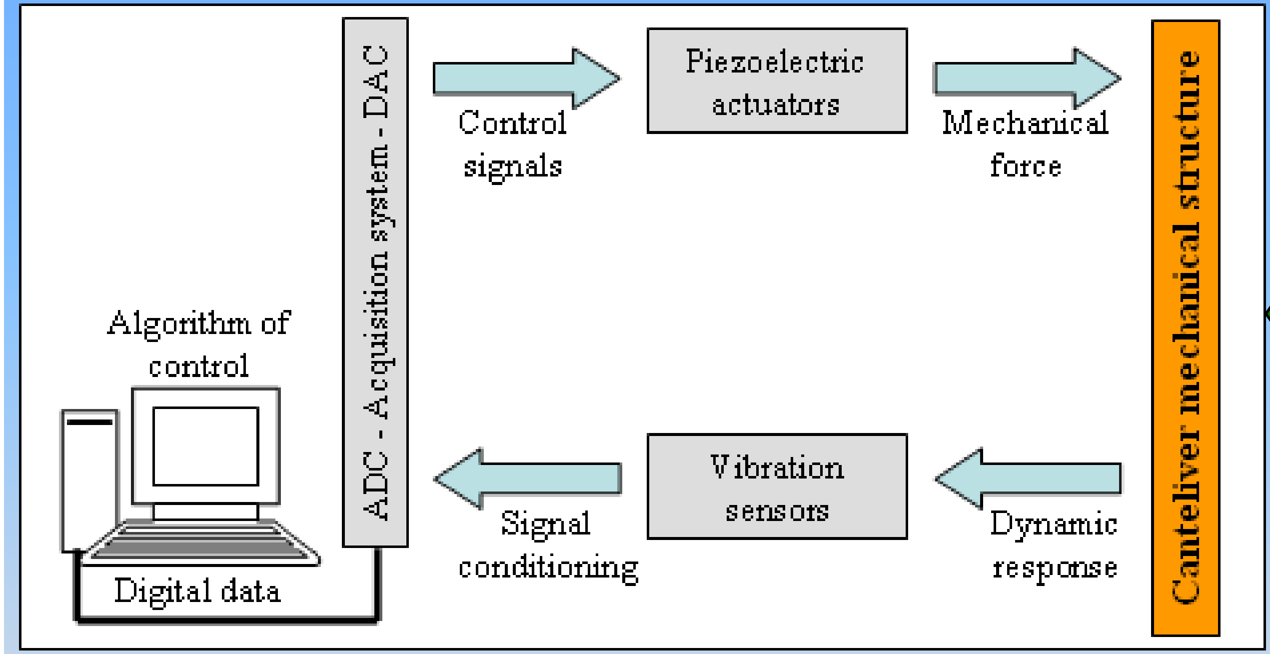
- LAPP (Particle Physics)
- SYMME of Polytech' Savoie engineering school (automatics)

✓ **Since 2004: Study on active rejection of resonances of linear collider final doublets**

- Continue work done by CLIC team from 2001 to 2003 (work only on ground isolation)
- 10 international workshops and meetings in different countries

Context

✓ **Development and simulation of a prototype for active rejection**



Sources of vibration
Ground motion, acoustic noise

✓ **Since 2006: Study of supports for the final doublets of ATF-2**

- ➢ Partership with laboratories in Japan (KEK) and France (LAL and LLR)
- ➢ Application of the R&D developed at LAPP on a real machine

Overview

1. **Feasibility study of sub-nanometre measurements**
2. **Vibration study of a canteliver beam at high frequencies**
3. **Feasibility study of final doublets active stabilization down to 1/10nm for f> 5Hz**
    - ✓ **Active isolation from the ground: commercial system**
    - ✓ **Active rejection of canteliver beam resonances: home-made**
4. **Conclusion and future prospects**

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Feasibility study of sub-nanometre measurements

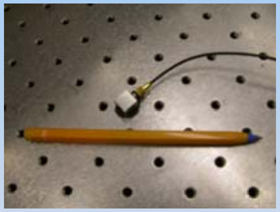
Vibration sensors acquired by LAVISTA team

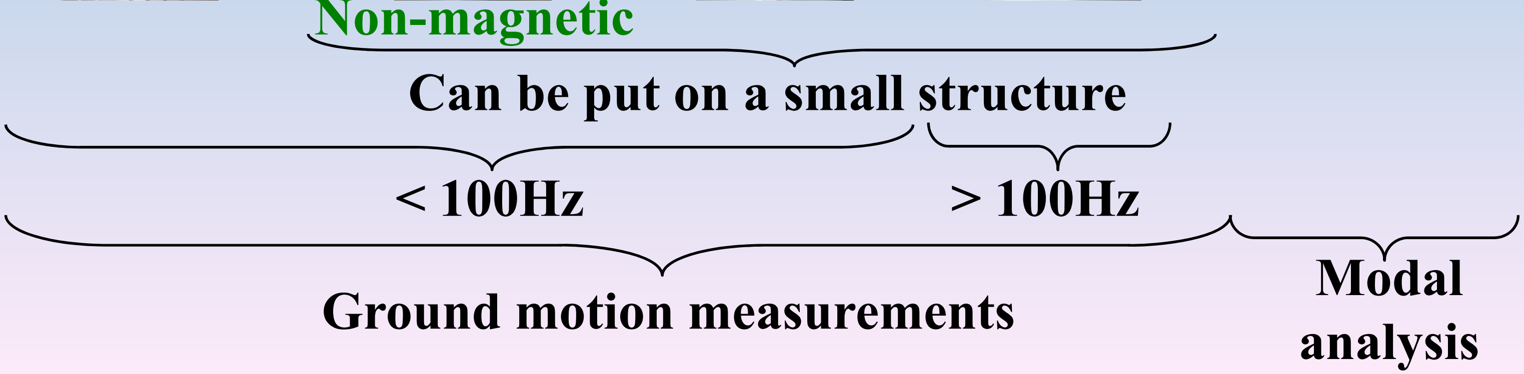
Type of sensors	**Electromagnetic geophone**	**Electrochemical geophone**	**Piezoelectric accelerometers**		
Model	GURALP CMG-40T	SP500-B	ENDEVCO 86	393B12	4507B3
Company	Geosig	PMD Scientific	Brüel & Kjaer	PCB Piezotronics	Brüel & Kjaer
Sensibility	1600V/m/s	2000V/m/s	10V/g	10V/g	98mV/g
Frequency range	[0.033; 50] Hz	[0.0167; 75] Hz	[0.01; 100] Hz	[0.05; 4000] Hz	[0.3; 6000] Hz
Measured noise (f > 5Hz)	0.05nm	0.05nm	0.25nm >50Hz: 0.02nm	11.19nm >300Hz: 4.8pm	100nm

Sub-nanometre measurements









Non-magnetic

Can be put on a small structure

< 100Hz

> 100Hz

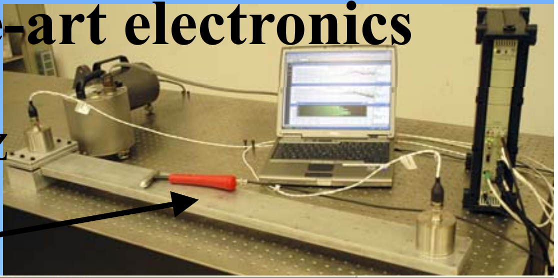
Ground motion measurements

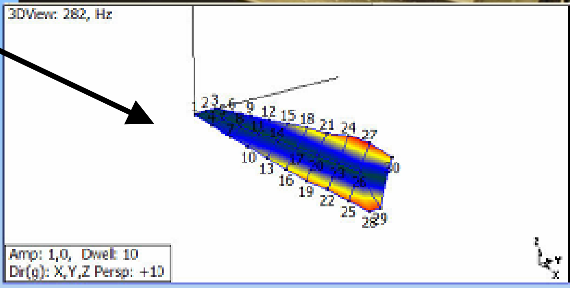
Modal analysis

Feasibility study of sub-nanometre measurements

Acquisition system acquired by LAVISTA team

✓ **Data analysis: PULSE system with state-of-the-art electronics**





- ➢ Real time acquisition of all sensor types: [1;15k]Hz
- ➢ Modal analysis with impact testing hammer
- ➢ 16/24 bits with amplifiers of variable gains
  → Good resolution and high *signal* to *ADC noise* ratio

✓ **Active rejection: DAQ PCI6052E without integrated electronics**

Signal conditioning

Same positive points than PULSE system

DAQ PCI6052E

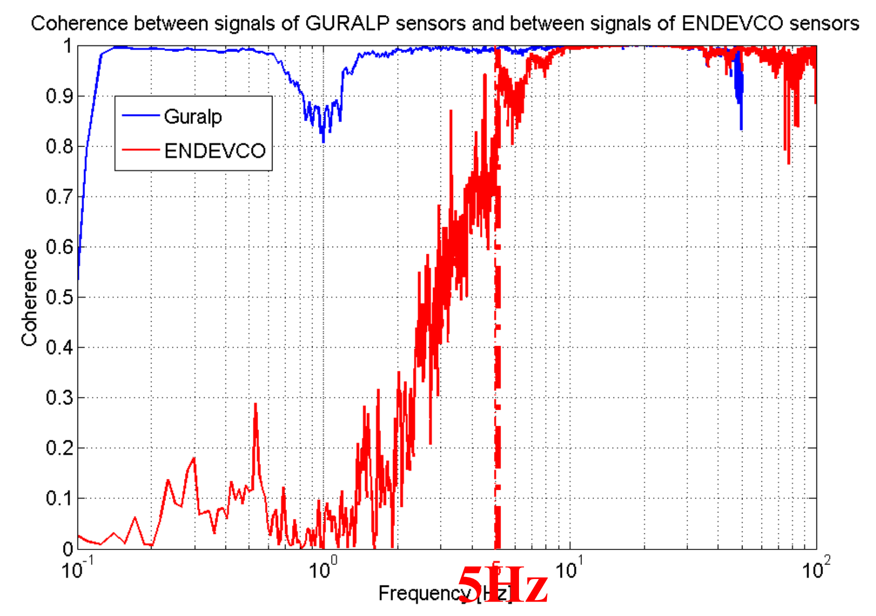
- ➢ Active HP and LP filters and amplifiers
- ➢ AC/DC, Single-ended/Differential

- ➢ Compatible with our algorithm
- ➢ Low level card: very fast

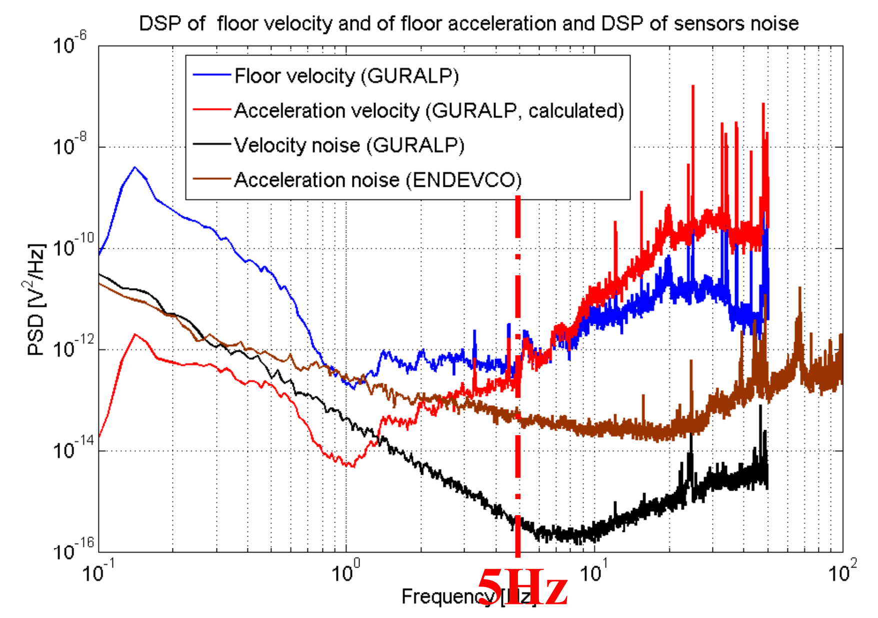
Feasibility study of sub-nanometre measurements

Evaluation of velocity sensors (GURALP CMG-40T) and accelerometers (ENDEVCO 86) for ground motion measurements between 0.1Hz and 100Hz

Coherence between sensors



Ground velocity and acceleration



✓ **At low frequencies (<5Hz):**

- ➢ High ground velocity
- ➢ Low ground acceleration

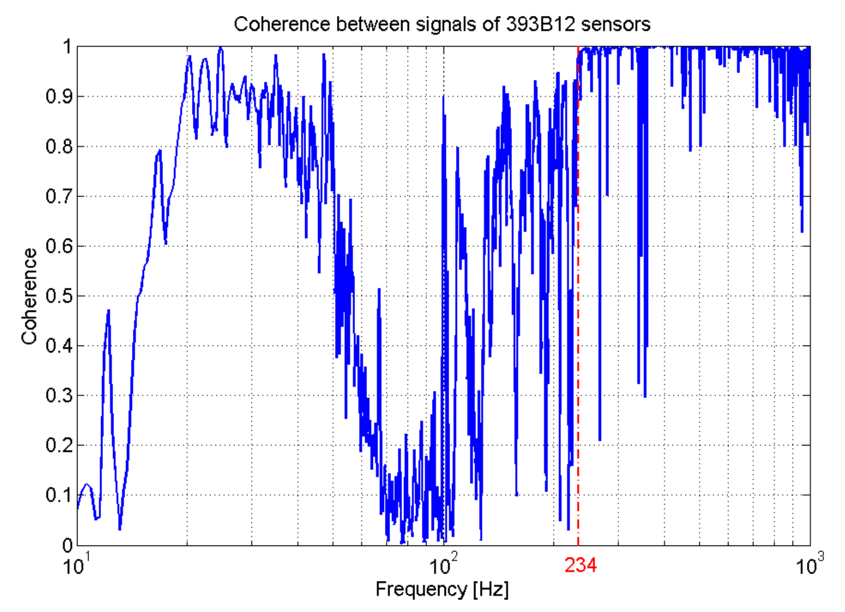
Velocity sensors:
GM measurements
possible < few Hz

Accelerometers:
GM measurements
> few Hz

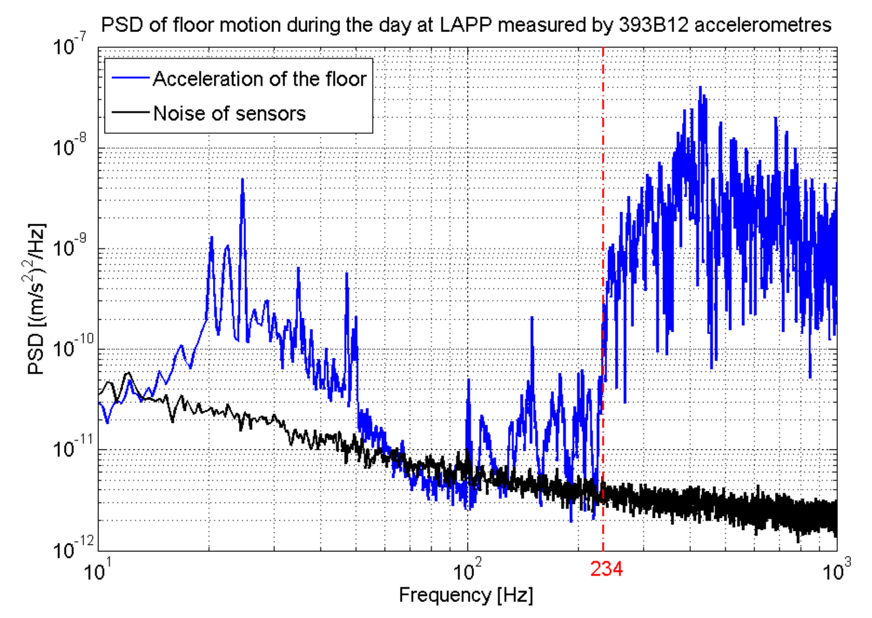
Feasibility study of sub-nanometre measurements

Evaluation of the 393B12 accelerometers for ground motion measurements at high frequencies (>300Hz)

Coherence between sensors



Ground acceleration



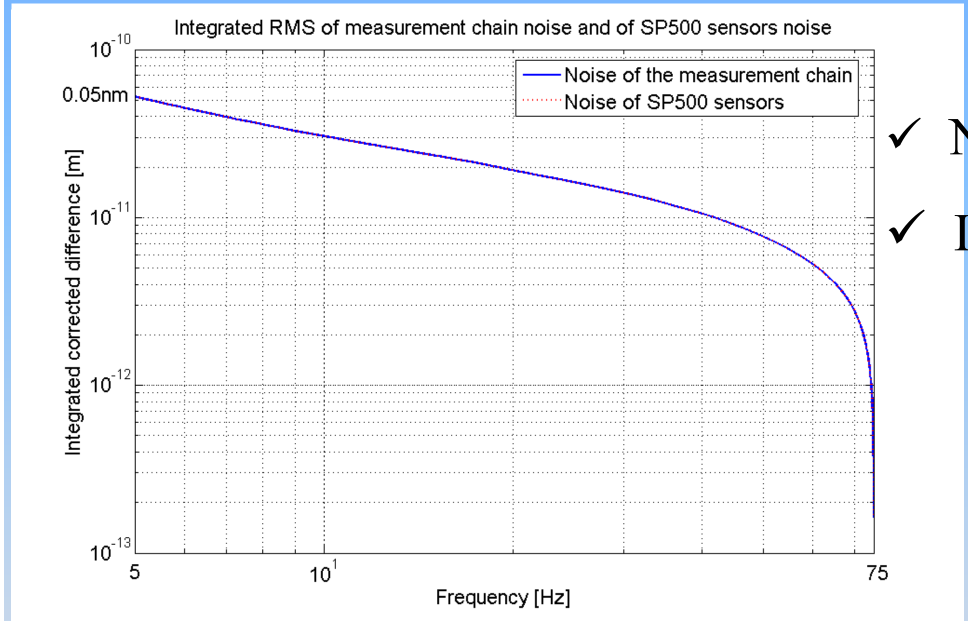
✓ **At high frequencies (f > 300Hz):**

- ➢ High ground acceleration
- ➢ Low sensors noise

Accurate measurements of ground motion at high frequencies with the 393B12 accelerometers

Feasibility study of sub-nanometre measurements

Noise of the measurement chain used for active rejection: Non-magnetic SP500 sensors and DAQ PCI6052E noise



- ✓ Noise of the measurement chain
- ✓ Internal noise of SP500 sensors

} ~ same

➔ Noise of PCI6052E system very low compared to noise of SP500 sensors

⇩

Efficient signal conditioning

➔ Integrated noise of SP500 sensors from 5Hz to 75Hz: 0.05nm

Sensors and instrumentation answering CLIC specifications for active rejection of vibrations (1/10nm for f>5Hz)

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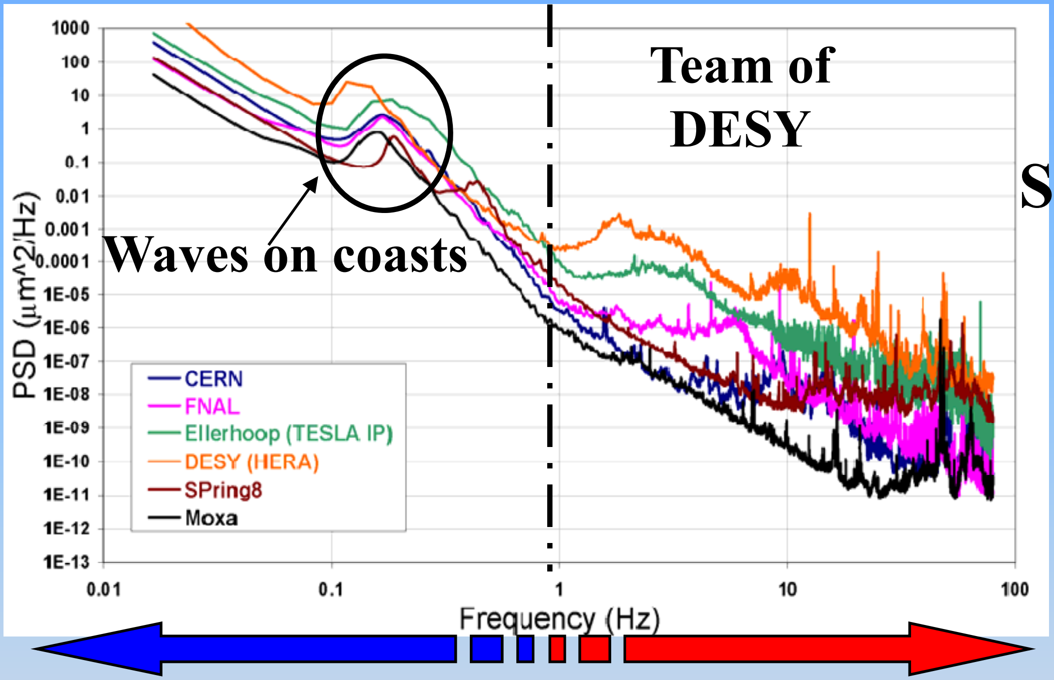
   - ✓ **Active isolation from the ground: commercial system**
   - ✓ **Active rejection of canteliver beam resonances: home-made**

4. **Conclusion and future prospects**

Vibration study of a canteliver beam at high frequencies

- ✓ **Ground motion: decreases with frequency**



Team of DESY

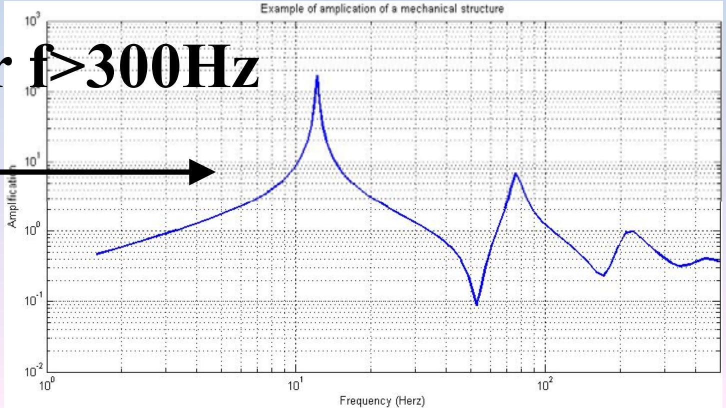
Waves on coasts

Effect of the earth

Cultural noise

Studies focused until now on highest motions (below 300Hz)

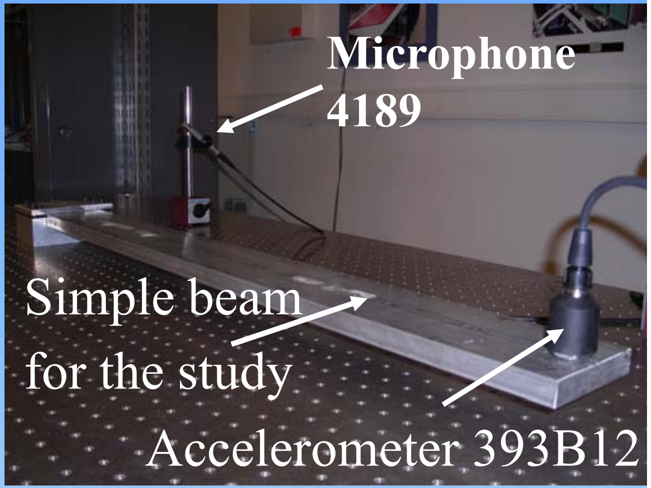
- ✓ **Vibration study of a canteliver beam for f>300Hz**
  - ➢ Amplification at resonances
  - ➢ **Impact of acoustic noise**

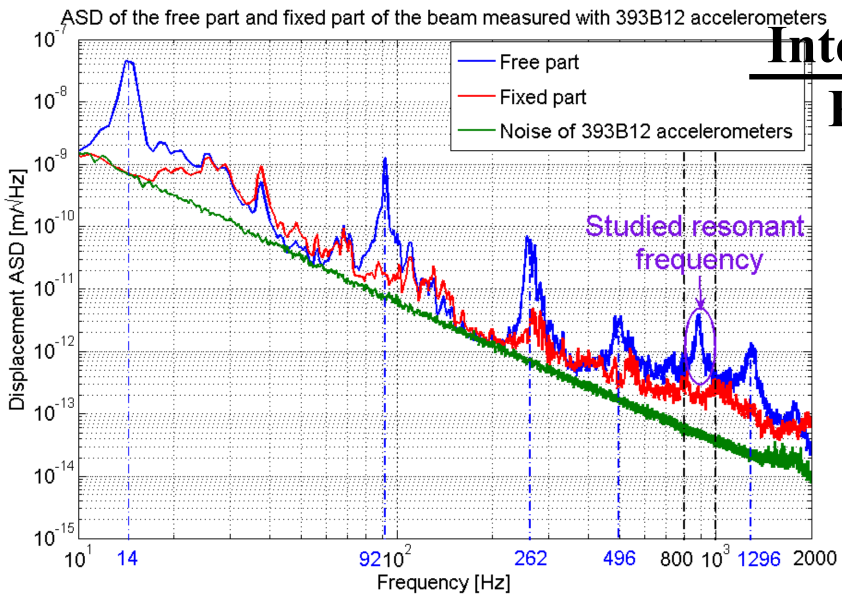


Vibration study of a canteliver beam at high frequencies

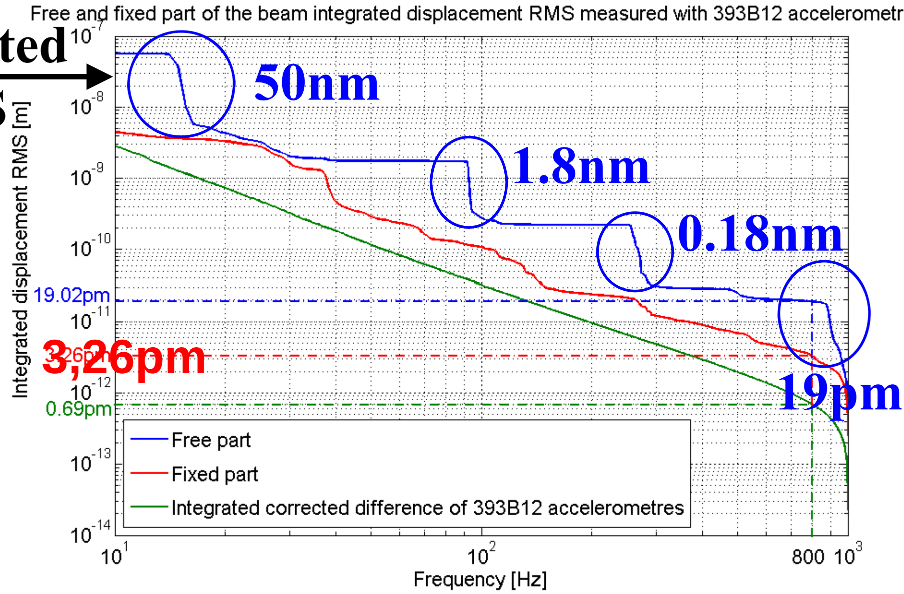
- ✓ Study done on the bandwidth [800; 1000] Hz of a resonance at 881Hz
  - ➢ Floor displacement very low: 3.26pm
  - ➢ Beam displacement: 19pm

N.B.: Measured integrated noise: 0.69pm





Integrated RMS



Vibration study of a canteliver beam at high frequencies

Simulation thanks to a loudspeaker of a pump inducing
higher ground motion and higher acoustic noise

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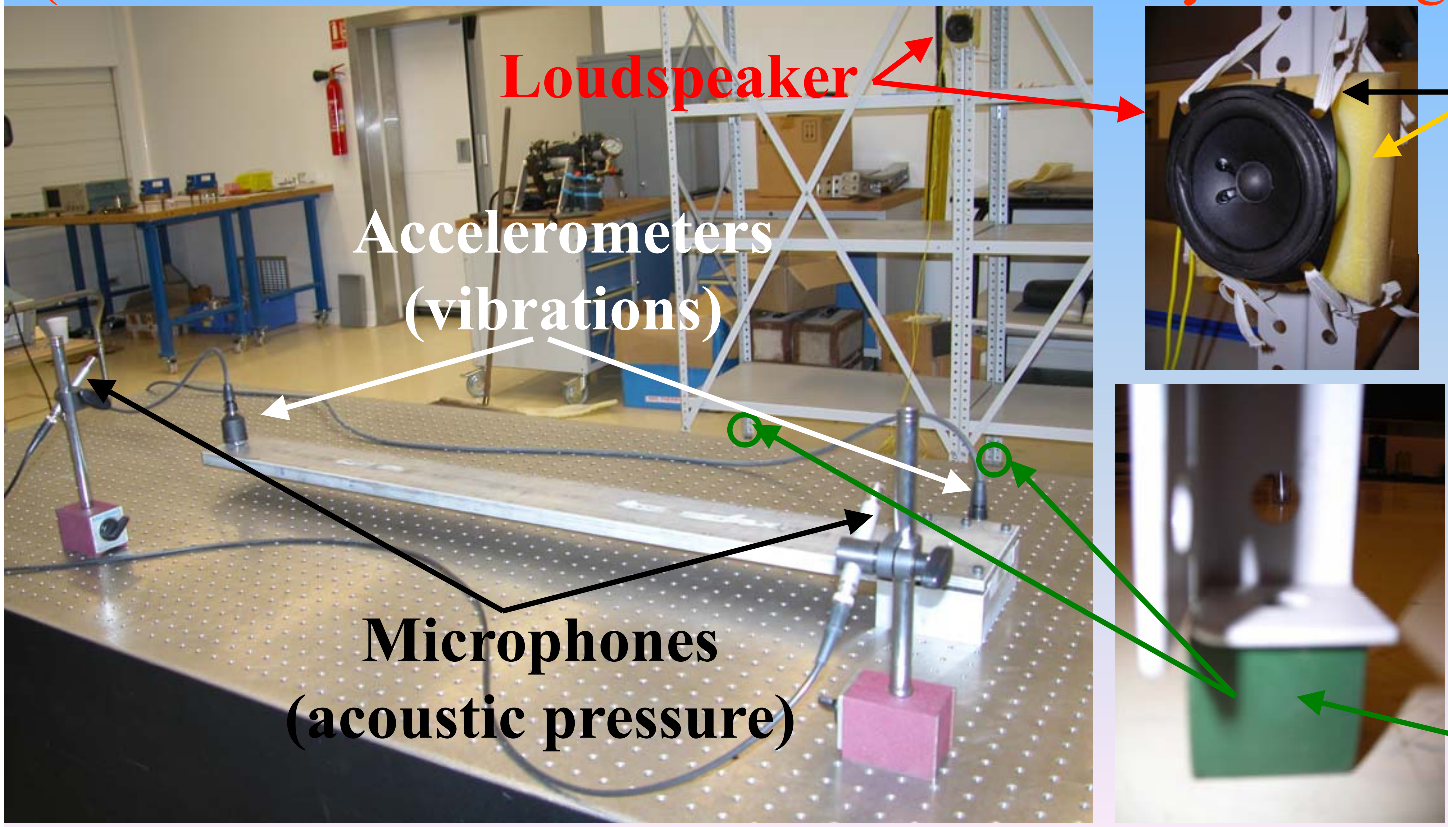
Loudspeaker: sinusoidal noise at 881Hz of different levels

(the vibrations of the membrane mechanically induce ground vibrations)

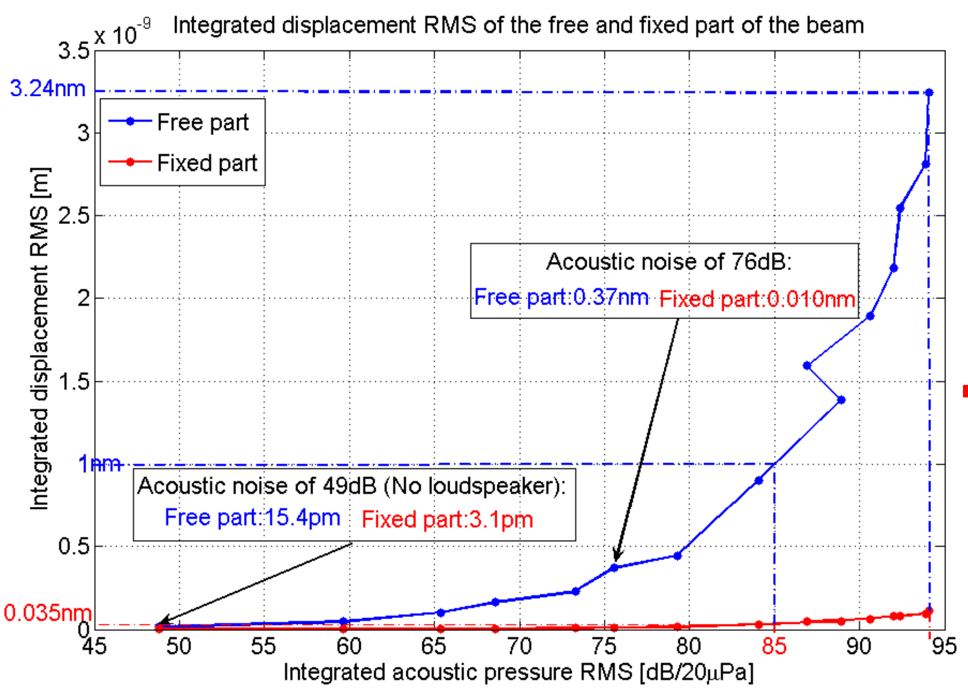


Passive damping:

Isolation of the loudspeaker from the ground not to excite it too much mechanically

Vibration study of a canteliver beam at high frequencies

- ✓ ***Displacement* VS *Acoustic pressure* integrated in [800; 1000]Hz**



Acoustic noise: 49dB to 76dB

→ **Clamping:** 3.1pm to 10pm

- ➢ Factor 3 of amplification

→ **Beam: 15.4pm to 0.37nm**

- ➢ **Exceed tolerances (1/10nm)**
- ➢ **Factor 24 of amplification**

- ✓ **Displacement of the beam: factor 24 of amplification**
  - ➢ **Factor 3 due to the displacement of the clamping**

    → **Factor 8 due to the acoustic noise**

→ **Conclusion: High impact of acoustic noise up to at least 1000Hz**

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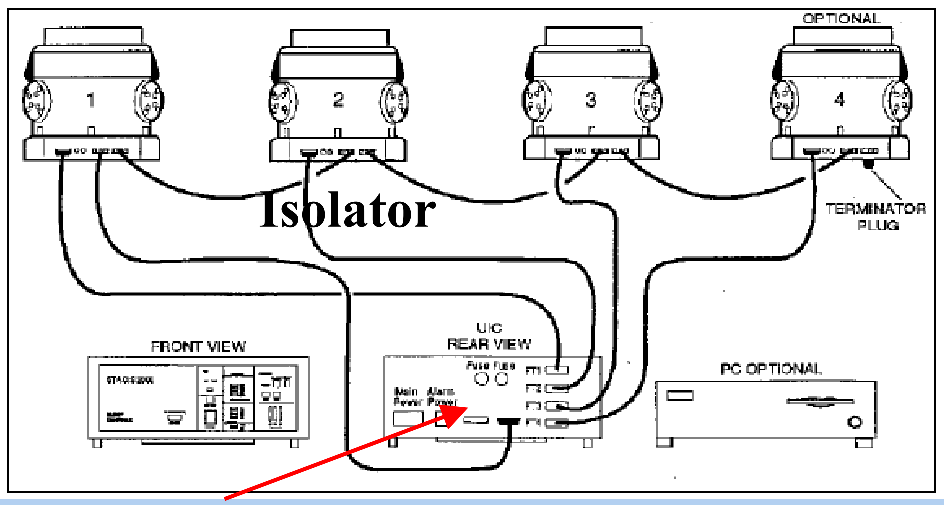
4. **Conclusion and future prospects**

Active isolation from the ground: commercial system

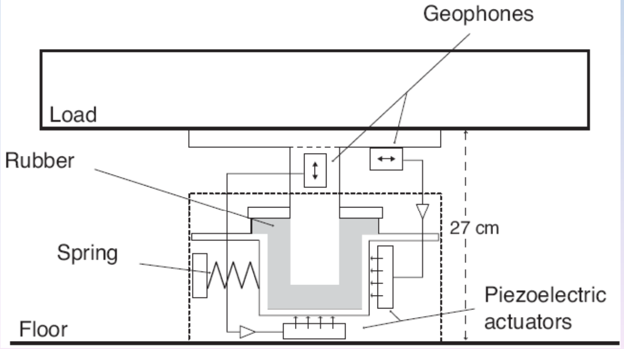
Presentation of the STACIS commercial system

Honeycomb table



Isolator

Controller :
Control actuators from geophone data



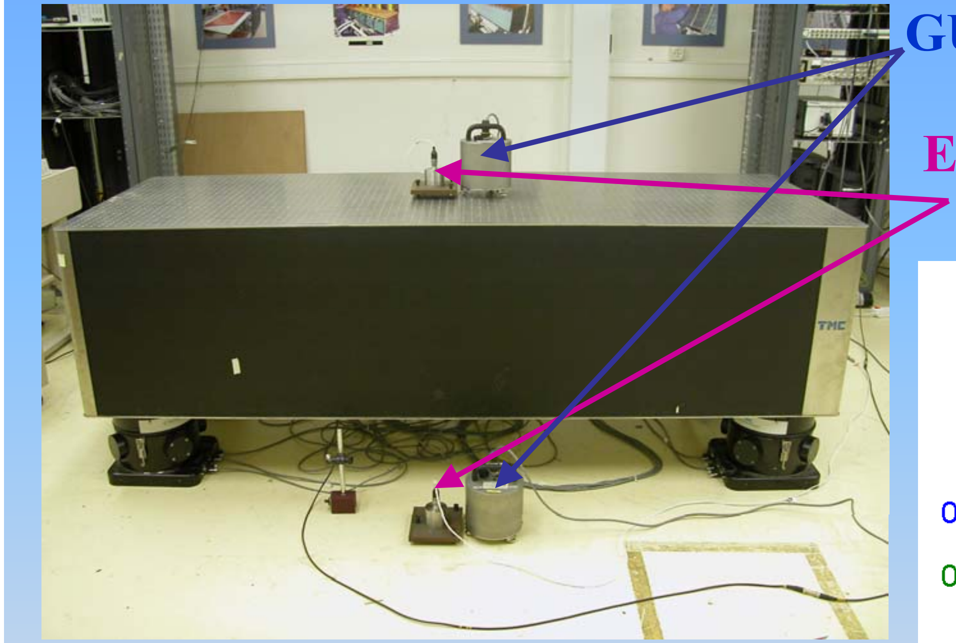
Isolator:

- ✓ Elastomer: **Passive isolation**
- ✓ 1 geophone / 1 vertical actuator
- ✓ 2 geophones / 2 horizontal actuators

} **Active isolation**

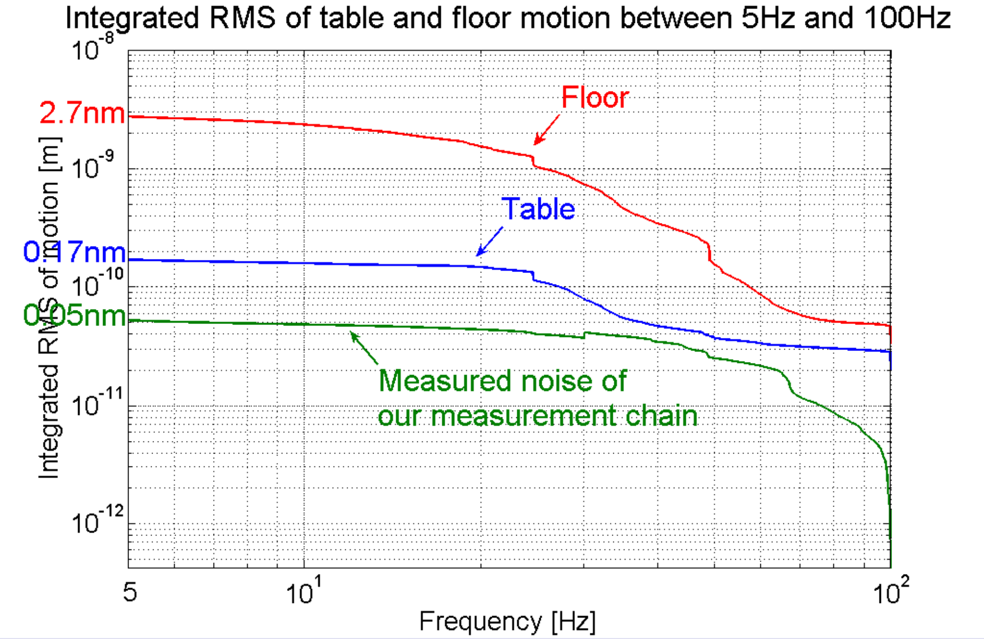
Active isolation from the ground: commercial system

Measured performance of the system from 5Hz to 100Hz



GURALP CMG-40T geophones (5Hz - 50Hz)

ENDEVCO 86 accelerometers (50Hz - 100Hz)



➔ **Factor 16 of damping between 5Hz and 100Hz down to 0.17nm**

➔ **Feasibility of active isolation from the ground down to the sub-nanometre level above 5Hz proven**

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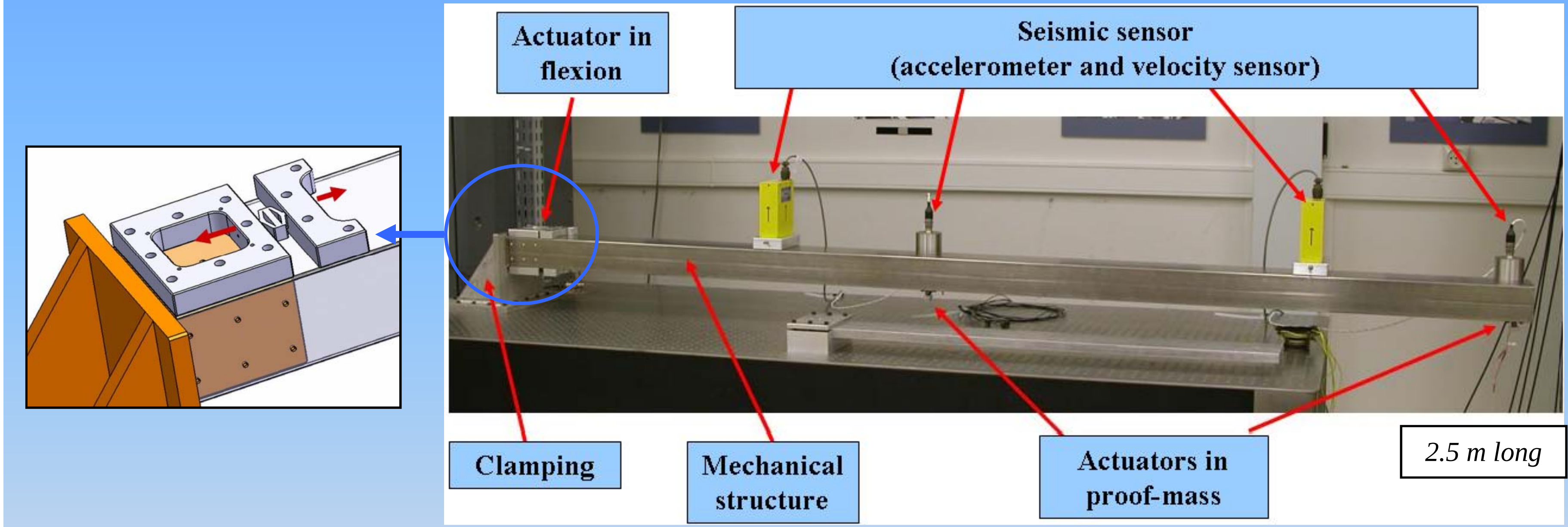
   - ✓ **Active rejection of canteliver beam resonances: home-made**

4. **Conclusion and future prospects**

Active rejection of canteliver beam resonances: home-made

Mechanical structure and its instrumentation



- ***Actuators used for active control***

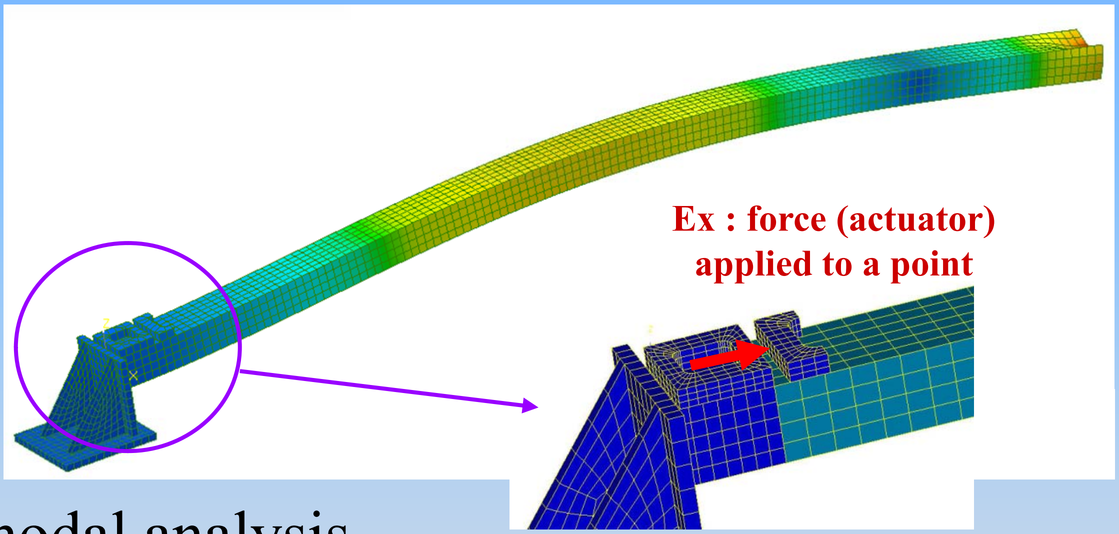
- A stacking of PZT patches -

- ✓ Force = 19.3 N
- ✓ Maximal displacement = 27.8 µm
- ✓ Resolution = 0.28 nm

Active rejection of canteliver beam resonances: home-made

Tests in simulation

✓ **Finite Element Model of the structure**



Ex : force (actuator) applied to a point

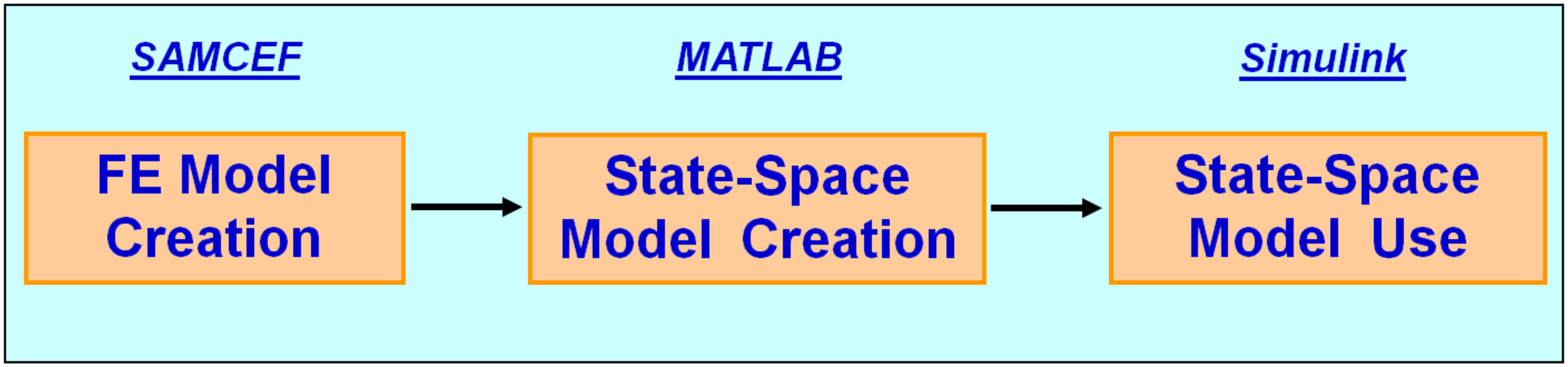
- ➢ Realize modal analysis
- ➢ Perform dynamic response computation (under external perturbation and active control)

NB: *possibility to update the structure to be as representative as possible with respect to the real set-up*

Active rejection of canteliver beam resonances: home-made

Tests in simulation

- ✓ **From the Finite Element Model to the State-Space Model**



$$\mathbf{M}\,\ddot{\mathbf{u}}(t)+\mathbf{C}\,\dot{\mathbf{u}}(t)+\mathbf{K}\,\mathbf{u}(t) = \mathbf{f}_p(t)$$

M : mass matrix

C : damping matrix

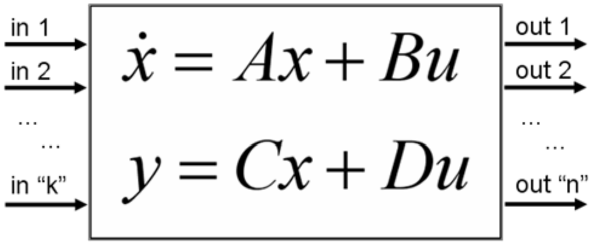
K : stiffness matrix

$$\dot{x} = Ax + Bu$$
$$y = Cx + Du$$

x : state vector

u : input vector

y : output vector



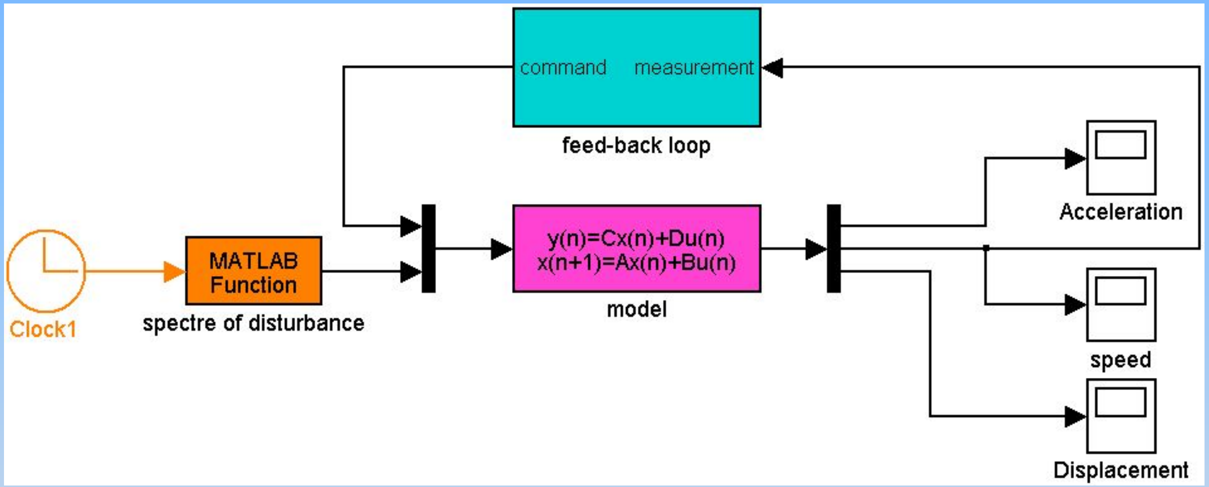
in : accel / force perturb. + force actuator

out : acceleration / velocity / displacement

Active rejection of canteliver beam resonances: home-made

Tests in simulation

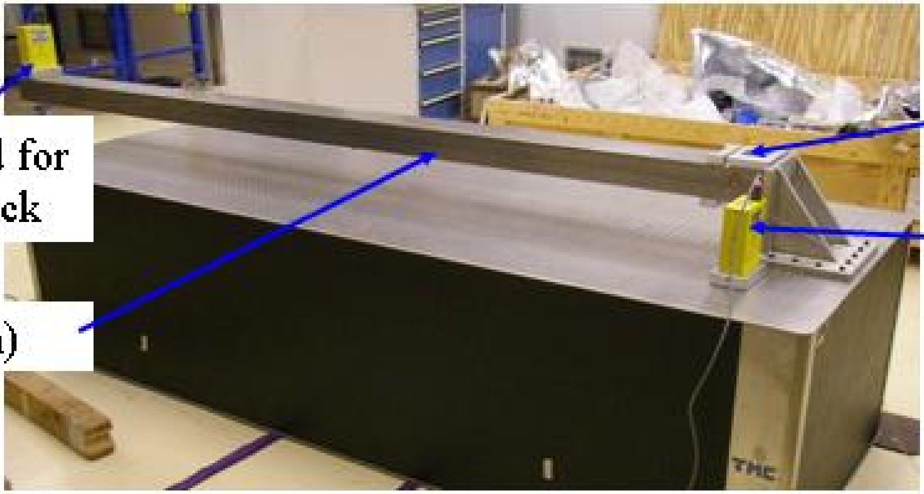
- ✓ **Integration of the State-Space Model in Simulink simulations**



- ✓ **Interests of the simulation**
  - ➢ To adjust the feedback loop
  - ➢ To increase test possibilities (multiple configurations for sensors / actuators)
  - ➢ To analyse the behavior of the entire structure

Active rejection of canteliver beam resonances: home-made

Experimental test

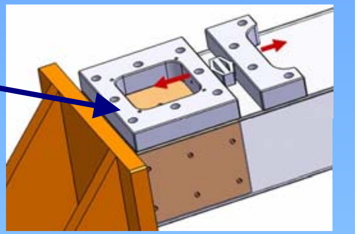


Sensor used for the feed back

Beam (2,5m)

Actuator in flexion mode

Sensor used for the reference



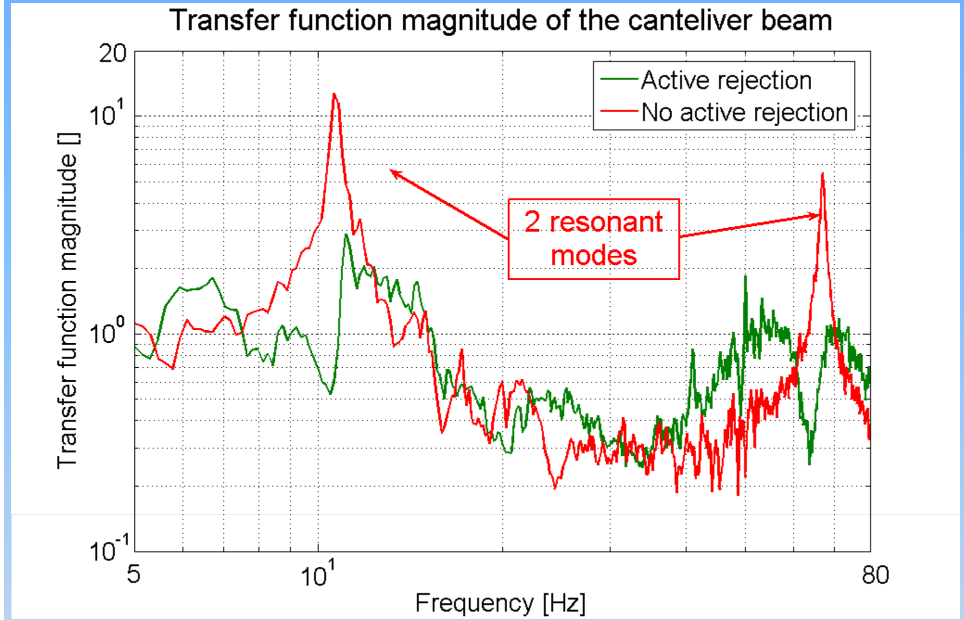
PCI6052 DAQ:
Acquisition of sensor data and control of actuator

- ✓ **Ground motion as only excitation**
- ✓ **STACIS system in parallel with our algorithm of active rejection**
- ✓ **Active rejection: the two first resonances (flexion mode)**

N.B.: Our algorithm of active rejection has been adjusted thanks to some simulations

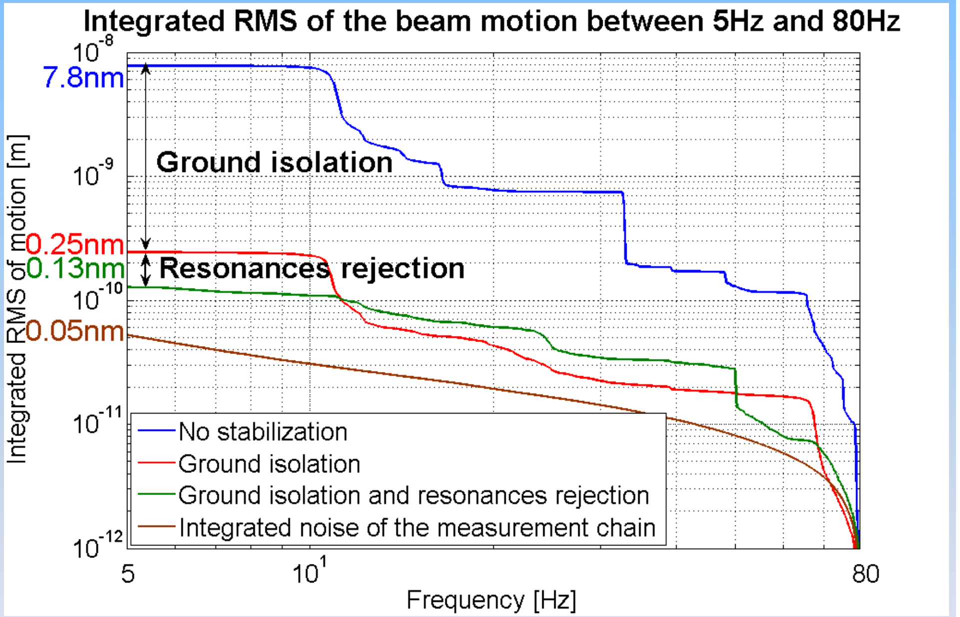
Active rejection of canteliver beam resonances: home-made

Experimental test


Transfer function magnitude of the canteliver beam

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

- **The two first resonances entirely rejected**


Integrated RMS of the beam motion between 5Hz and 80Hz

➔ **Instrumentation and algorithm efficient for an active rejection of wide vibration peaks down to the sub-nanometre level above 5Hz**

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Conclusion and future prospects

✓ Vibration sensors and instrumentation

- ➢ Ground motion measurements from low to high frequencies (0.1Hz → 2000Hz)
- ➢ Measurement chain found for active rejection of CLIC final doublets vibrations (1/10nm for f>5Hz)
- ➢ Collaboration with PMD Scientific company to test new electrochemical sensors tending toward the final specification of CLIC
- ➢ Test of small capacitive sensors with 0.1nm resolution (P75211C of PI)

✓ Vibration study of a canteliver beam at high frequencies (>300Hz)

- ➢ High impact of acoustic noise up to at least 1000Hz for CLIC FD
- ➢ Measurements to perform on canteliver magnets in an operating accelerator site

Conclusion and future prospects

✓ **Active stabilization of a canteliver beam down to the sub-nanometre level above 5Hz**

- **Feasibility of active isolation from the ground proven**
- **Active rejection feasibility of resonances proven**
- On-going study: multi-sensors multi-actuators system in order to stabilize the beam all along its length
- Stabilization to do on a more complex structure closer to the FD design

⇓

Simulations give us information about optimal location of sensors and actuators and their number

Simulations will allow us to follow the evolution of final doublets design