European Organization for Nuclear Research

R&D ON STABILIZATION

MBQ: FROM CDR TO TECHNICAL IMPLEMENTATION PHASE

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** Associate ULB

K. Artoos, ACE 6, Geneva 2nd February 2011

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Collaboration

CERN is collaborating on the stabilization of accelerator components with the following institutes:

Active **S**tructures **L**aboratory
Department of Mechanical Engineering and Robotics
Université Libre de Bruxelles (ULB), Belgium

Institut de **R**echerche sur les lois **F**ondamentales de l'**U**nivers
CEA (Commissariat à l'énergy atomique)
Saclay, France

Laboratories in **A**nnecy (France) working on **VI**bration **STA**bilisation

Outline

- Requirements (reminder)
- Strategy stabilisation MBQ
- Status and results for feasibility demonstration CDR
- Strategy after CDR + some first results!

Requirements

3992 CLIC Main Beam Quadrupoles:

Four types :

Mass: ~ 100 to 400 kg

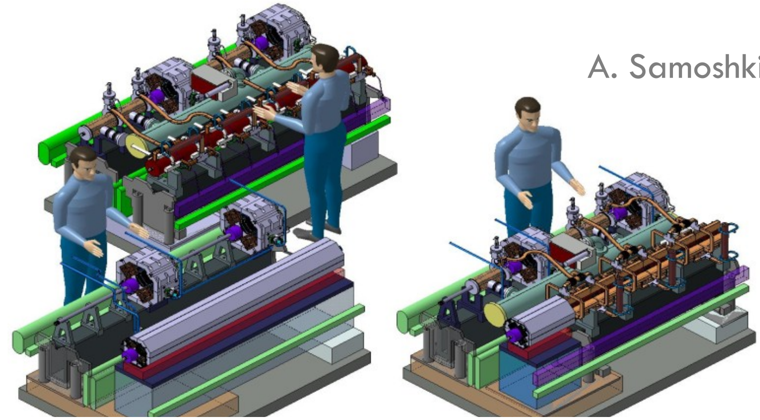
Length: 500 to 2000 mm

Stability (magnetic axis):

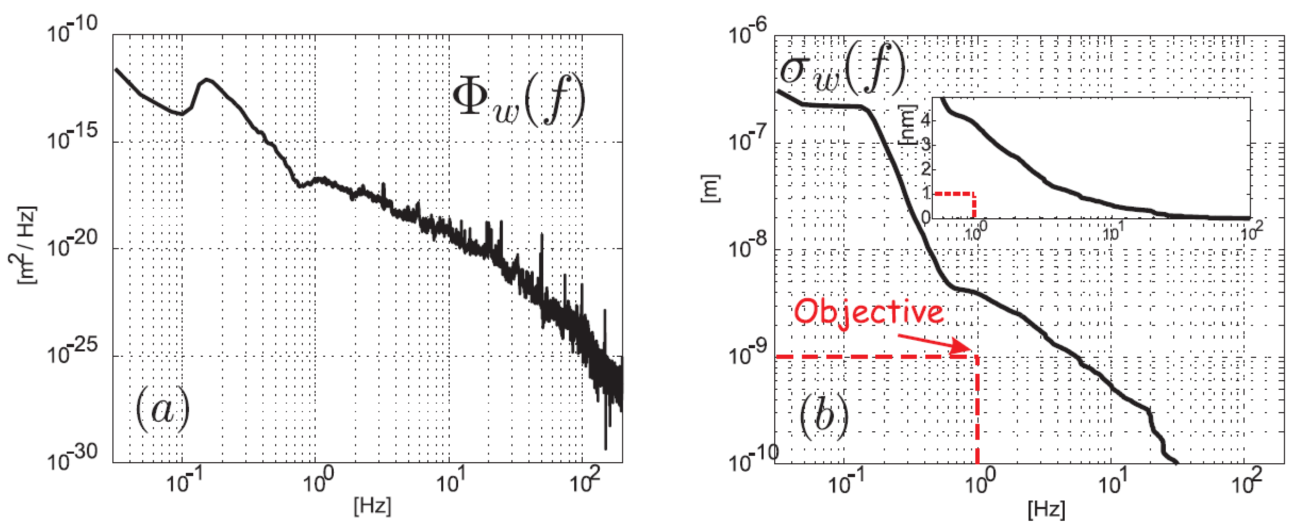
$$\sigma_x(f) = \sqrt{\int_f^{\infty} \Phi_x(\nu)\, d\nu}$$

	FF	MBQ
Vert.	**0.2 nm > 4Hz**	**1.5 nm > 1 Hz**
Lat.	**5 nm > 4 Hz**	**5 nm >1 Hz**

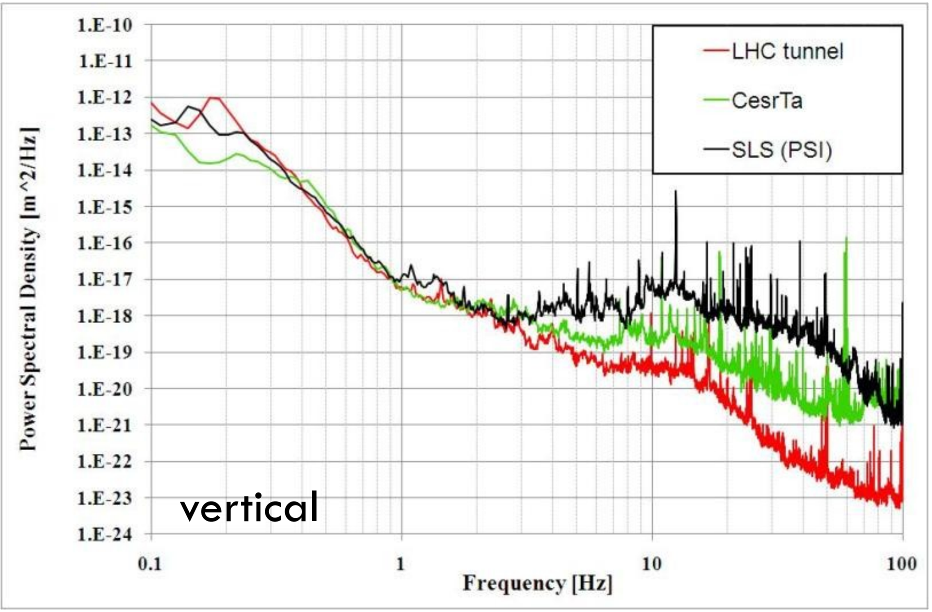
A. Samoshkin

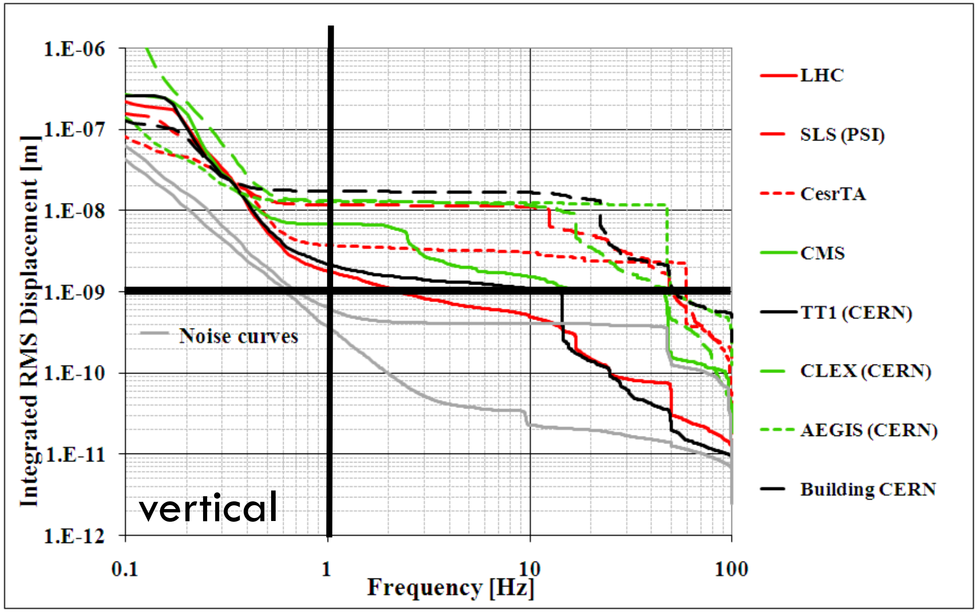


Type 4: 2m, 400 kg Type 1: 0.5 m, 100 kg



Characterisation vibration sources

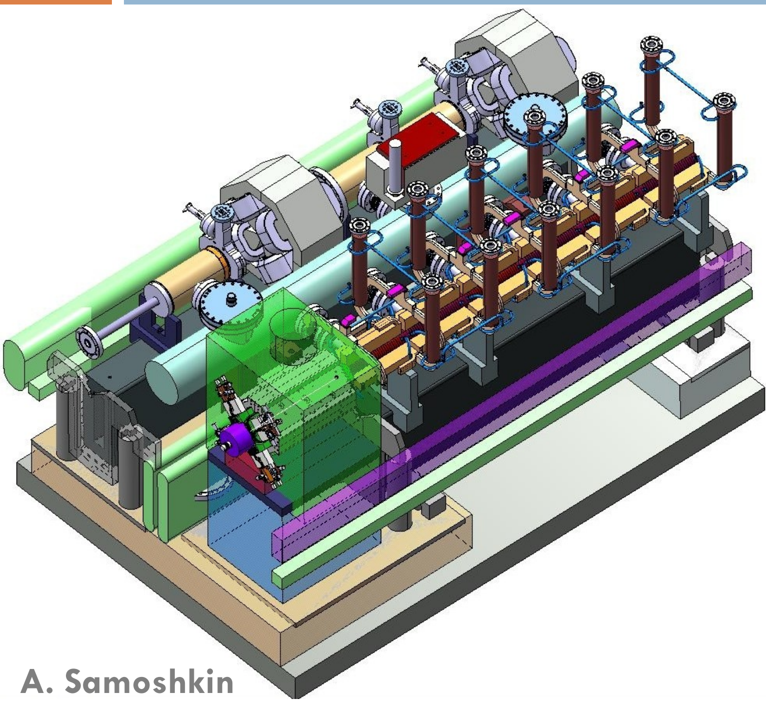




Running accelerator in deep tunnel comparable to LHC:

- **Between 2 and 5 nm** ground vertical integrated R.M.S. Displacement
- Amplitude to be reduced by **factor 4-5** in frequency range **1-20 Hz**
- **Above 20 Hz** contribution to integrated RMS is **small**
- **Environment should be part of strategy**

Other requirements



A. Samoshkin

<u>Stiffness-Robustness</u>

- Applied forces (water cooling, vacuum pipes,…
- Compatibility alignment
- Uncertainty
- Transportability

<u>Available space</u>

Integration in two beam module

620 mm beam height, width~470 mm

<u>Accelerator environment</u>

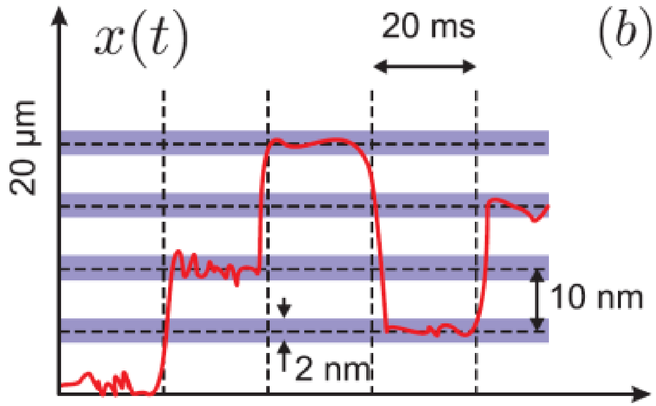
- High radiation
- Stray magnetic field

Additional objectives MBQ

« Nano-positioning» proposal

Modify position quadrupole in between pulses (~ 5 ms)

Range ± 5 µm, increments 10 to 50 nm, precision ± 1nm

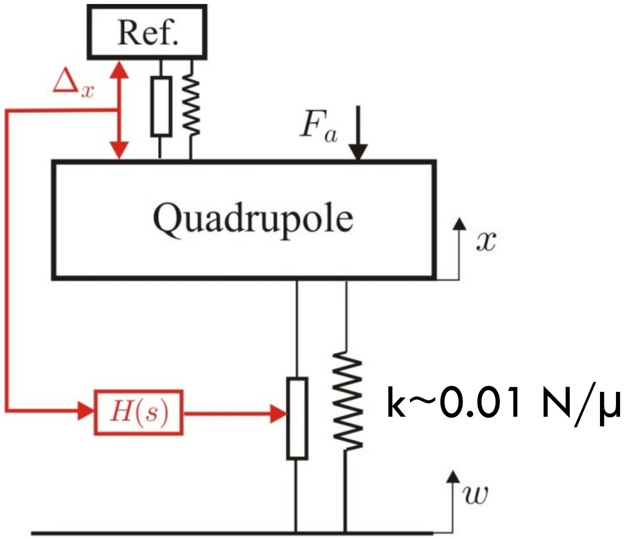


- In addition/ alternative dipole correctors
- Might increases time to next realignment with cams

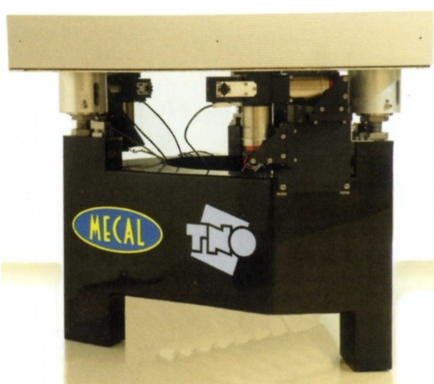
Comparison existing s.o.a. active stabilisation strategies

C. Collette
S. Janssens

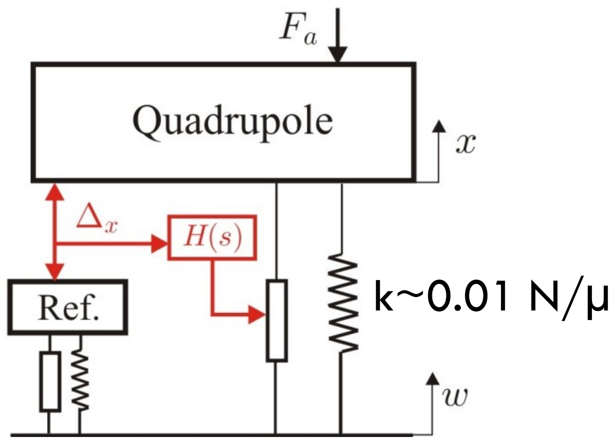
IR on payload



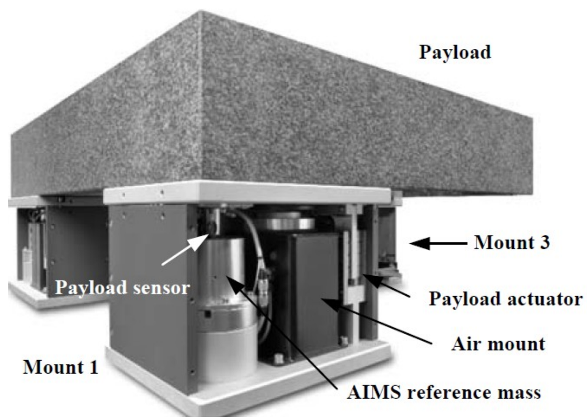
2009: Lithography WO 084,966 A1



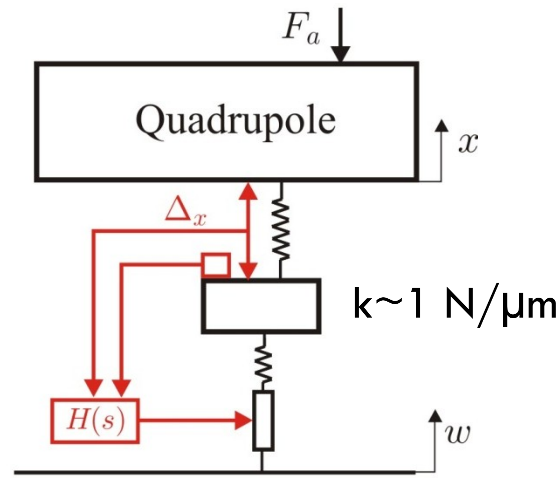
IR on the ground



2007: US 2007/003,5074 A1

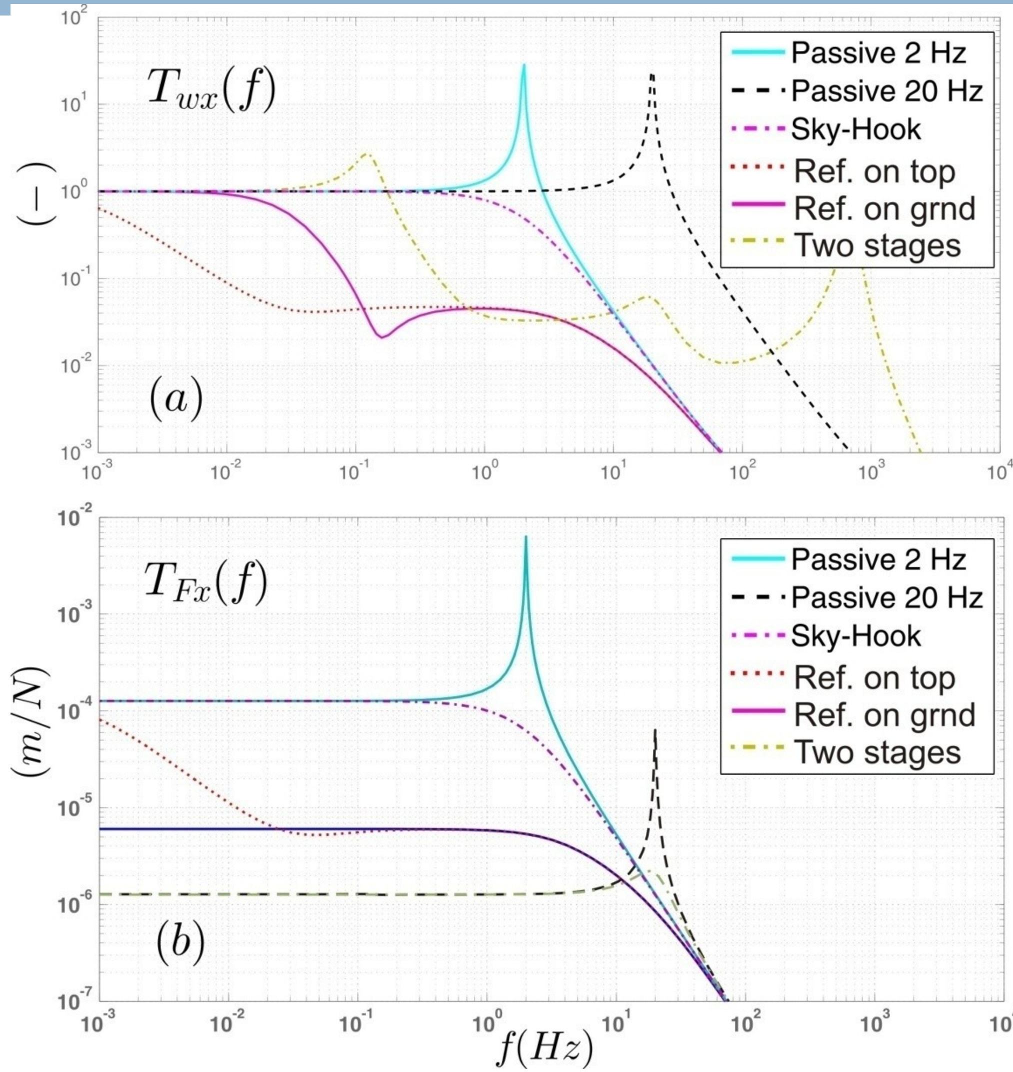


Two stages



1994: Proc. SPIE vol. 2264

Comparison existing S.O.A. stabilisation strategies



C. Collette

S. Janssens

(Without noise curves)

Comparison Active Isolation

Very Soft (1 Hz)

- Pneumatic actuator
- Hydraulic actuator

TNO+AIMS
k~0.01 N/µm

Soft (20 Hz)

- Electromagnetic in parallel with a spring
- Piezo actuator in series with soft element (rubber)

TMC k~1 N/µm

Stiff (200 Hz)

- Piezoelectric actuator in series with stiff element (flexible joint)

Piezo k~100-500 N/µm

COMPARISON

Very Soft (1 Hz)

+ Broadband isolation
- Stiffness too low
- Noisy

Soft (20 Hz)

+ Passive isolation at high freq.
+ Stable
- Low dynamic stiffness
- Low compatibility with alignment and AE

Stiff (200 Hz)

+ Extremely robust to forces
+ Fully compatible with AE
+ Comply with requirements
- Noise transmission
- Strong coupling

C. Collette

4 steps toward demonstration stiff stabilisation support

2010 : 4 steps toward demonstration on MBQ type 4 (+ type 1):

- **1.** Stabilisation **1 d.o.f. with small weight** ("membrane")
- **2.** Stabilisation **1 d.o.f. with type 1 weight** ("tripod")
- **3.** Stabilisation **2 d.o.f. with type 1 weight** ("quadruped")
- **4.** Stabilisation of **type 4 (and type 1)CLIC MB quadrupole proto type**

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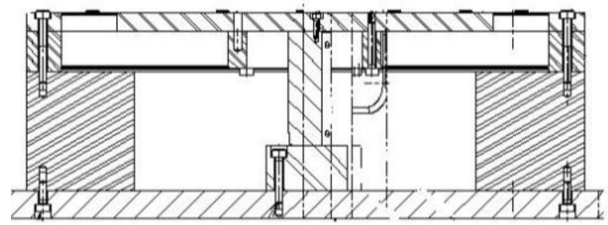
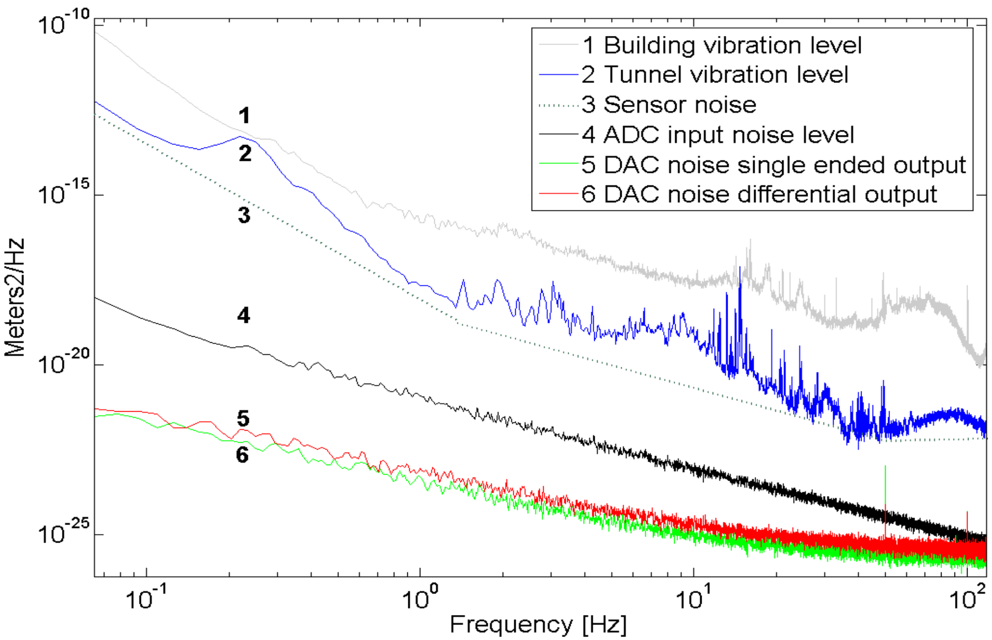
Step 1: One d.o.f. scaled set-up



$$\frac{k}{m} = \frac{k'}{m'}$$

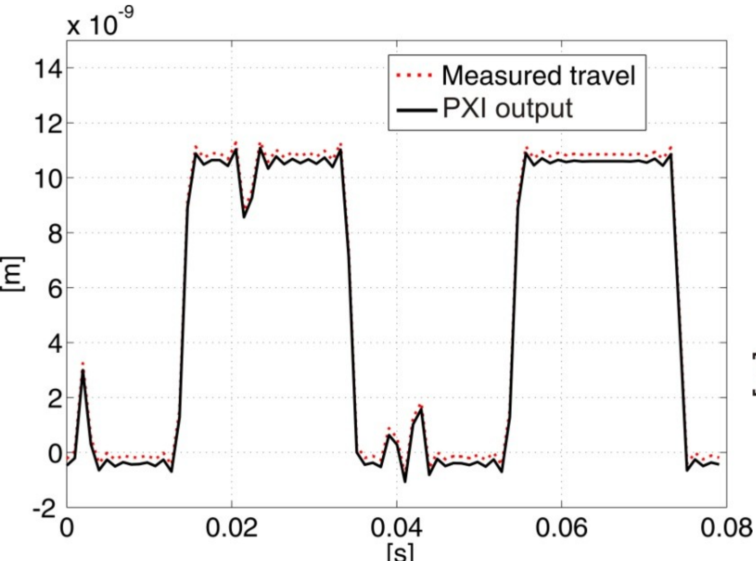


Since last ACE :

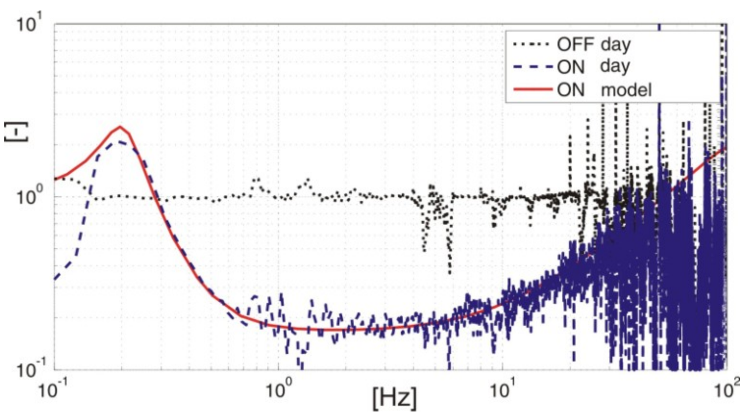
- System (sensor) modelled and fully understood
- Controller improved
- Real time behaviour improved
- Improved cabling and power supply have decreased the noise level

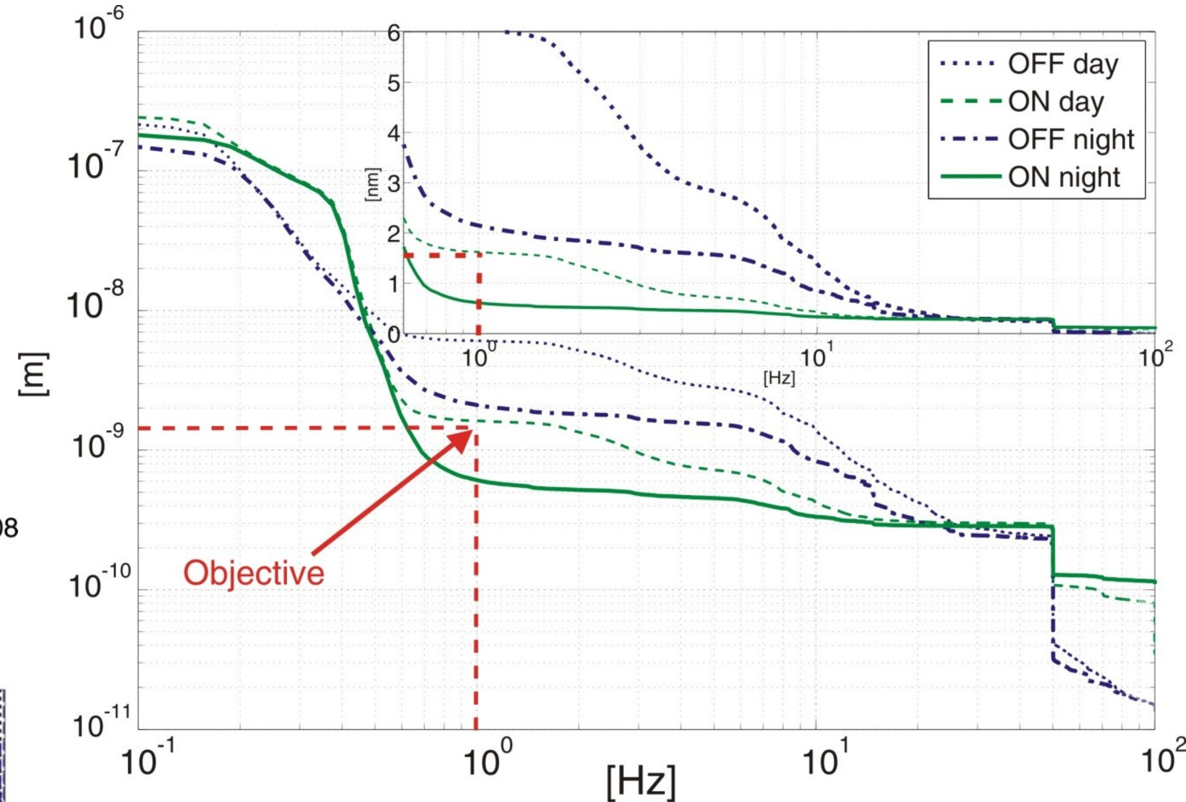
Noise study P. Fernandez Carmona

Experimental results



Objectives reached





Result: 0.6 nm at 1 Hz from 2.2 nm
day: 1.6 nm from 6.4 nm
0.44 nm at 4 Hz

4 steps toward demonstration stiff stabilisation support

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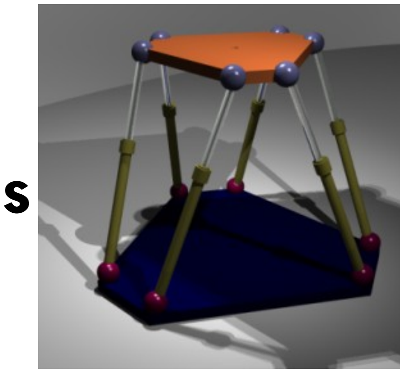
Strategy Support

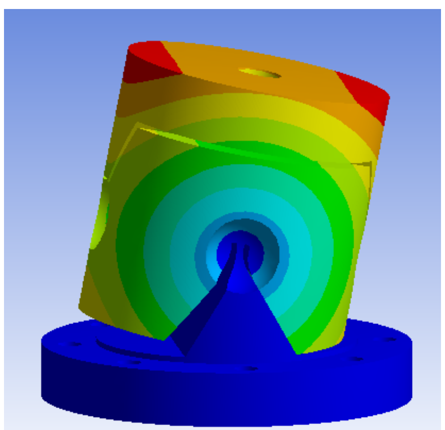
- Stiff structure
- At least four d.o.f.
- Precise motion
- Repeatability
- 0.1 nm resolution vertically

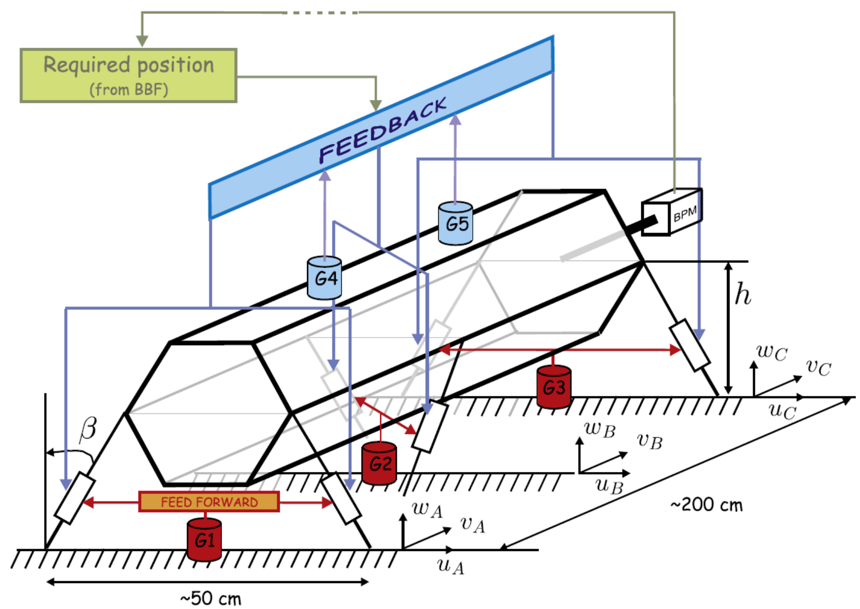
Parallel structure

Stiff piezo actuators

Flexural hinges







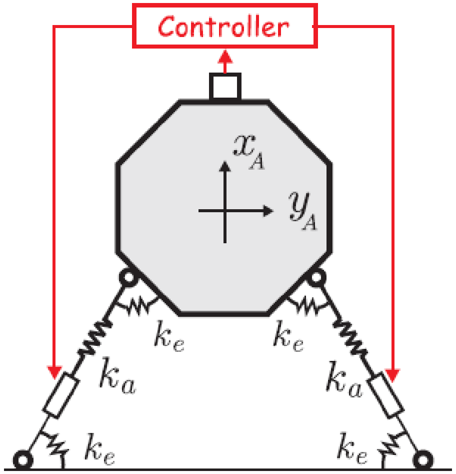
Sensors : Seismometers “to get started”

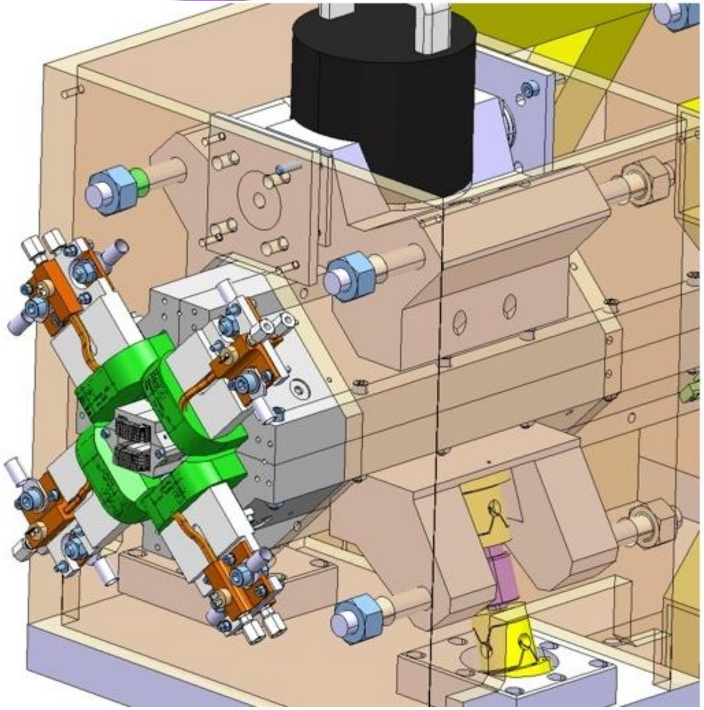
Strategy Support

Structural stiffness	↔	Induced stresses in piezo
Inclination	↔	Resolution, structure stiffness, forces
Number	↔	# D.O.F. , COST Resonant frequency Solution 4 types

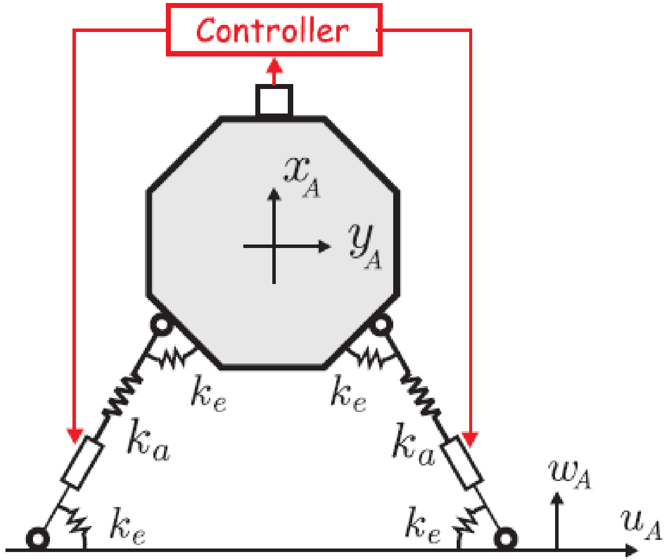
Block longitudinal
Block roll

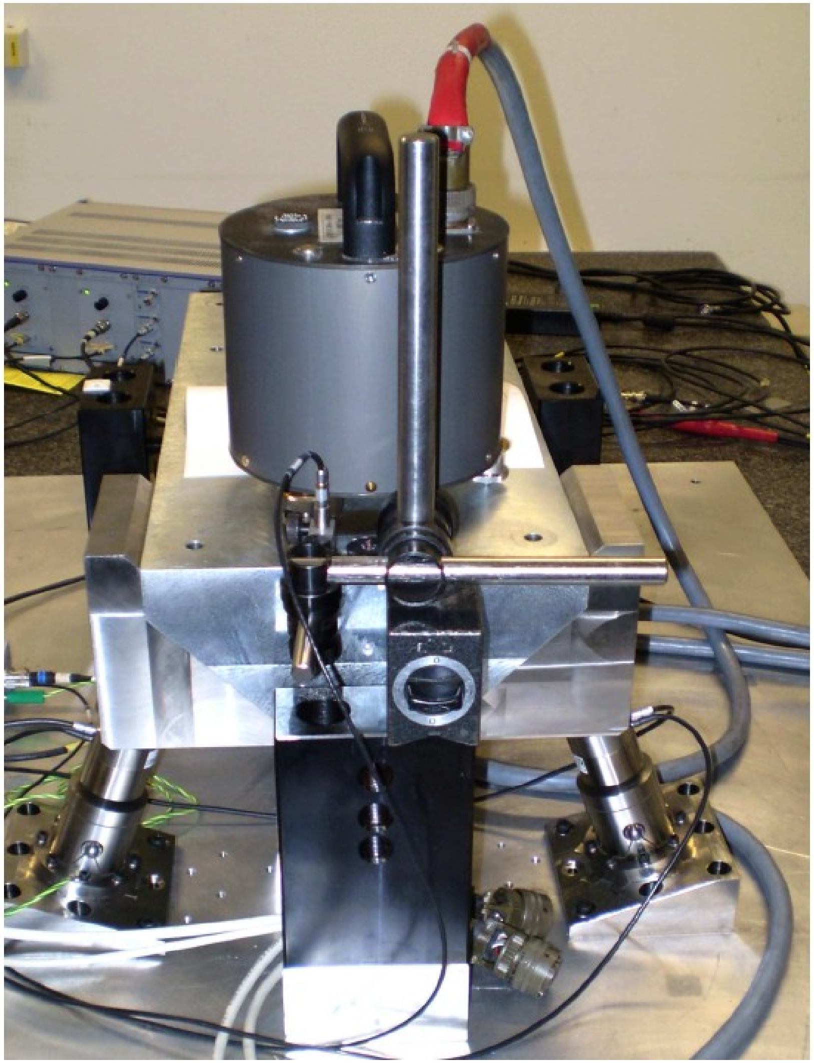
X-Y flexural guide





Step 3: 2 d.o.f. with type 1 mass

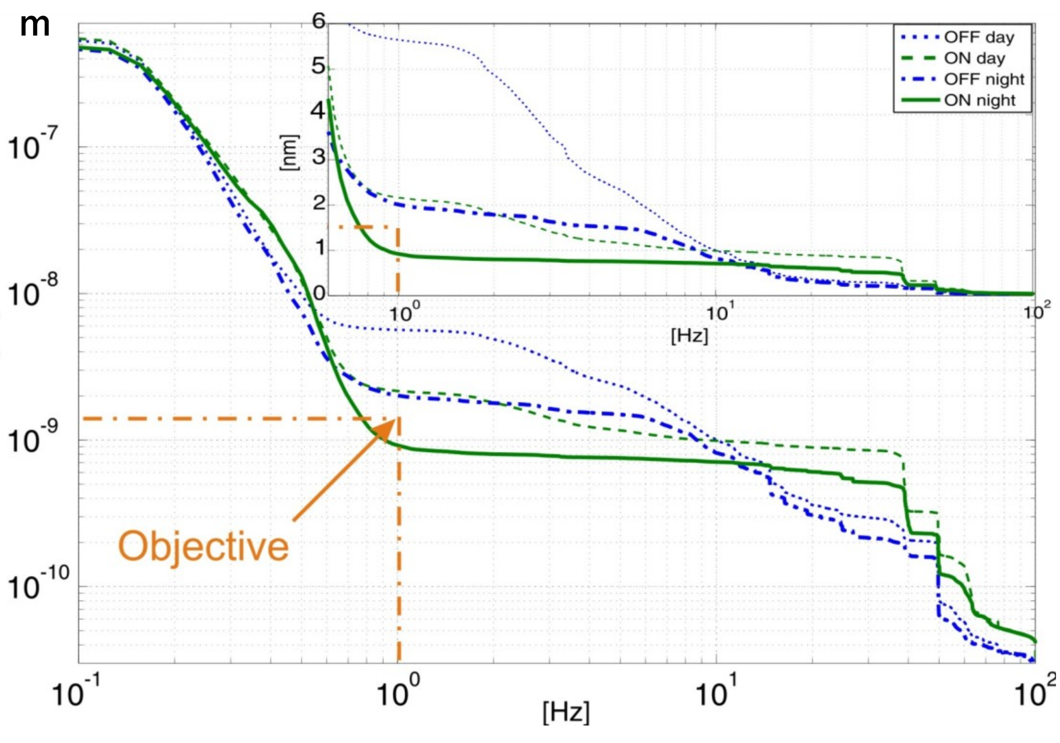


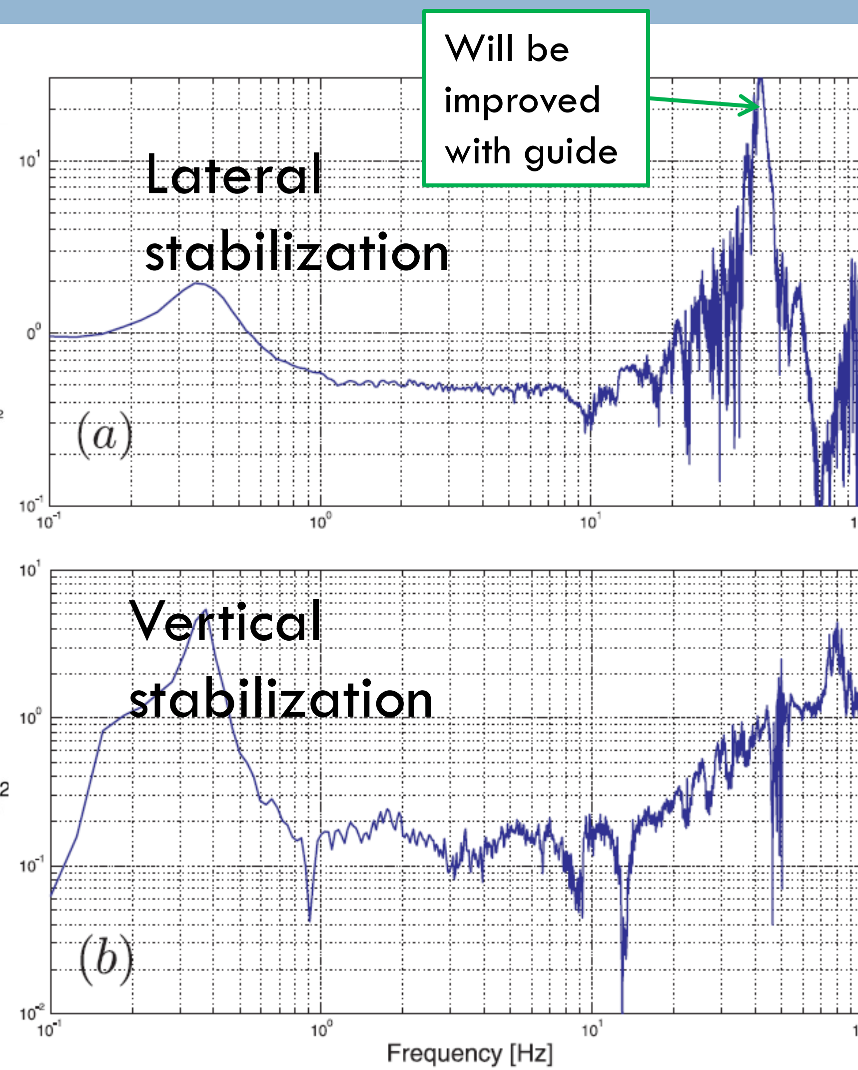


Objectives:

- Validate the strategy and controller in 2 d.o.f. Type 1
- Validate flexural hinge design
- Validate Mounting and assembly issues
- Validate nano positioning in 2 d.o.f.

Stabilization in 2 d.o.f.

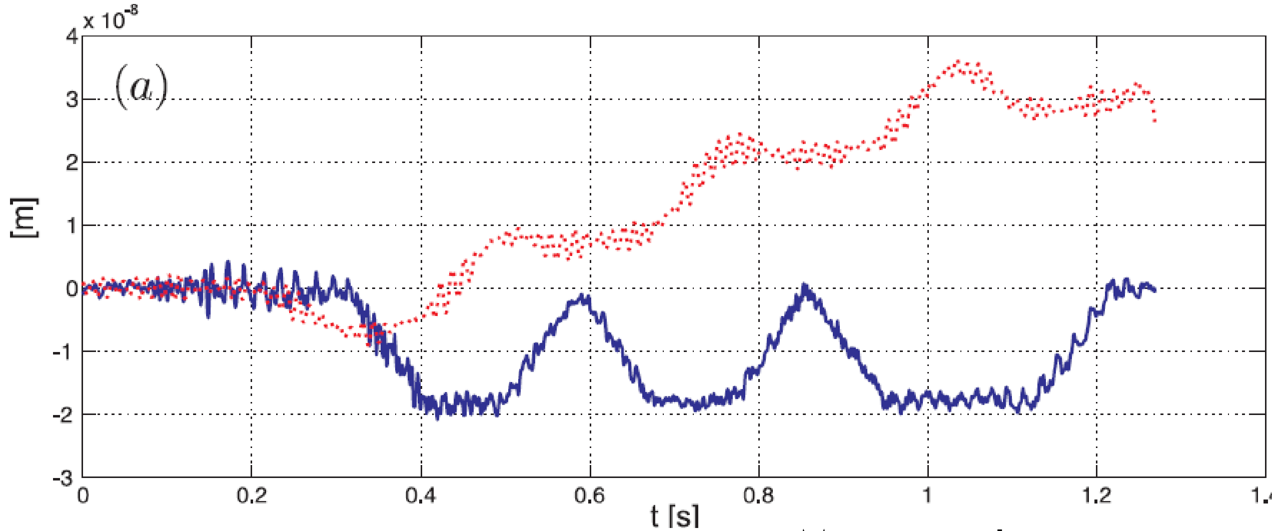


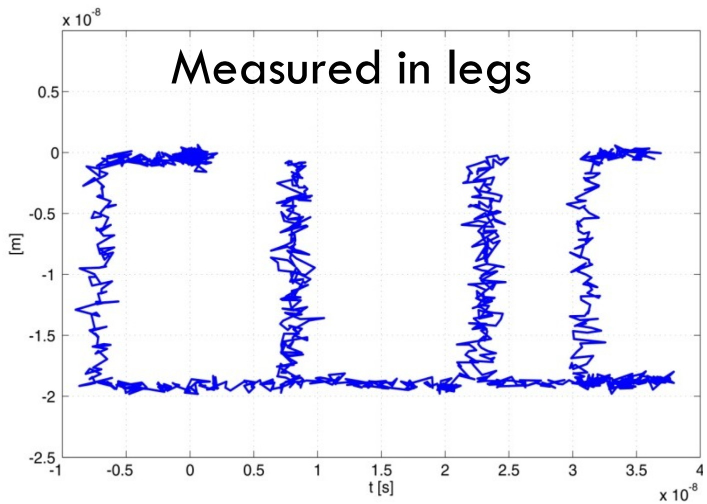


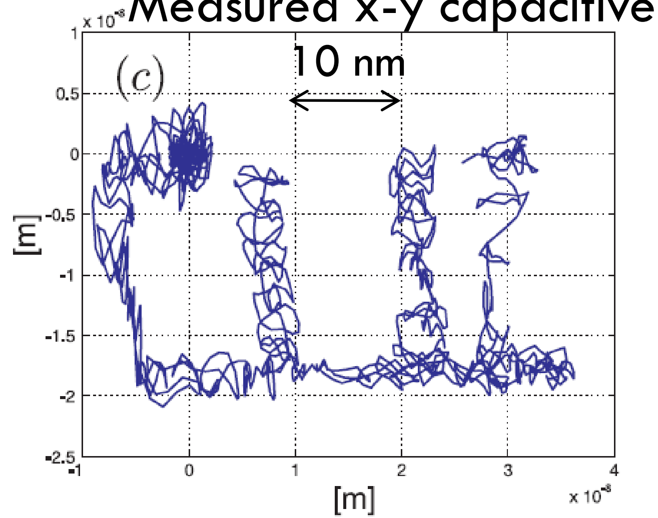
0.9 nm at 1 Hz

Can be improved still.

Positioning in 2 d.o.f.



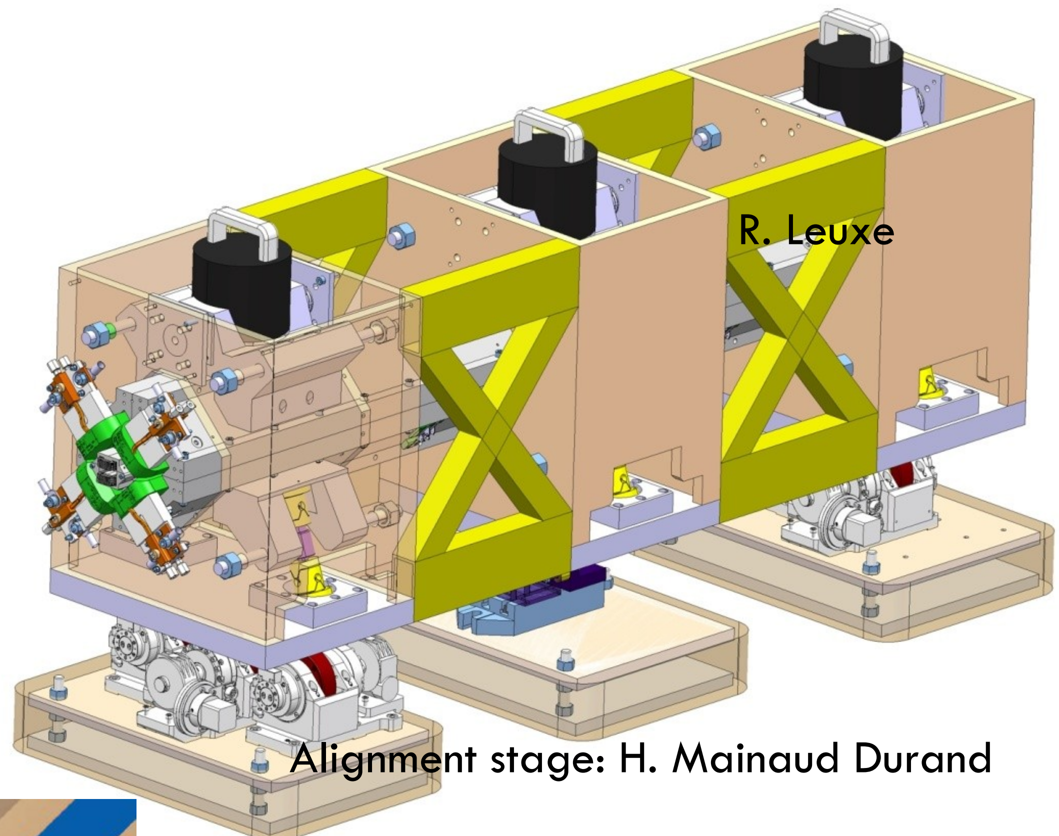


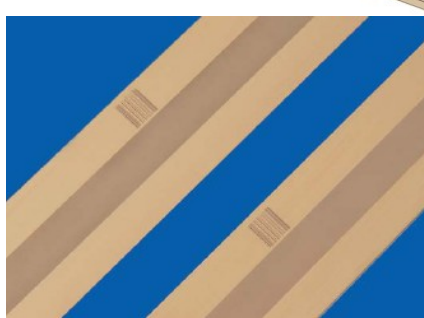


Concept drawing

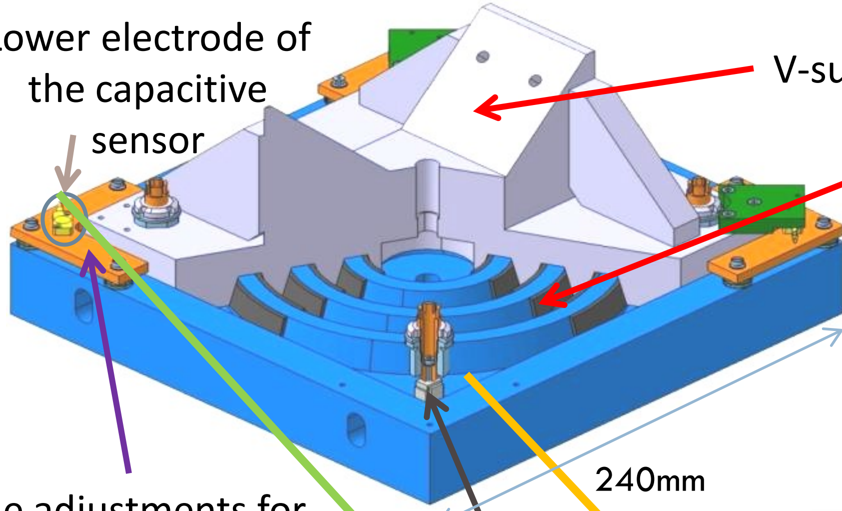
Type 4

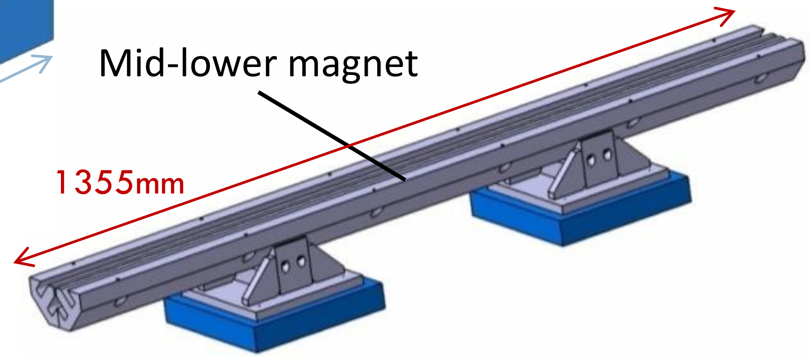
- Stiff intermediate girder between alignment and stabilisation
- Lockable in longitudinal direction (transport)
- Introduce x-y nanometrology
- Optical encoders would allow a hardware zero position

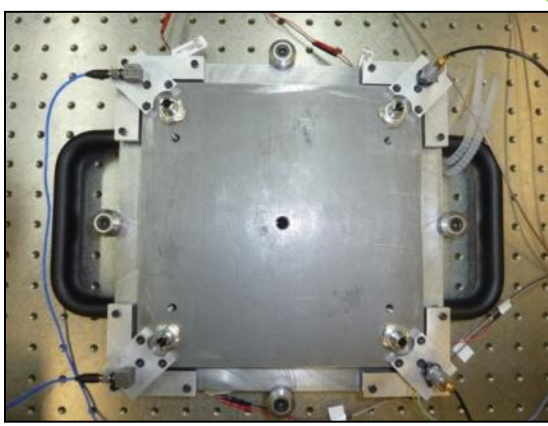


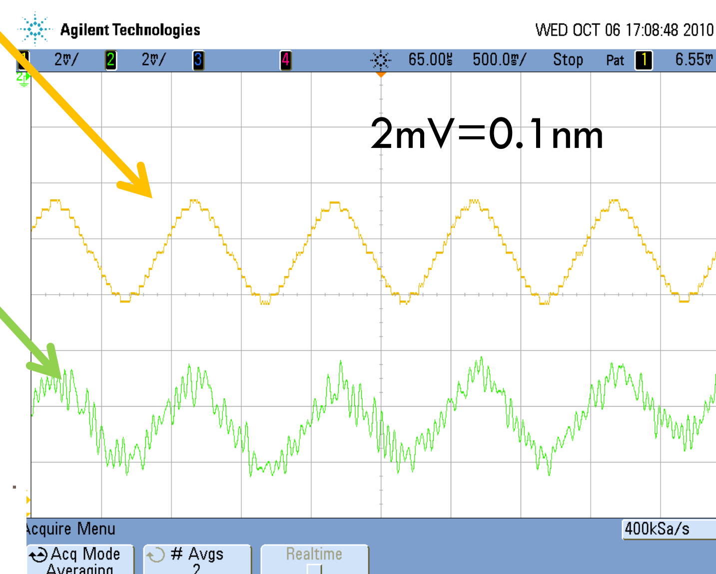


Lavista development Status: changed to stiff support option









Next step: add feedback

Conclusions CDR for MBQ

With STRATEGY **STIFF** stabilisation support based on parallel piezo actuator structure:

- We DEMONSTRATED in a **model** and on **test benches**
- the **technical feasibility** to stabilise better than the required level at 1Hz in two d.o.f., from levels that were characterised in a running accelerator in a deep tunnel (LHC). This **with commercially available components.**
- We demonstrated **nano positioning** in two d.o.f.
- We have a **concept design of the stabilisation support** based on the validated actuator pair with flexural hinges.
- Compatible with module requirements and alignment and robust against external forces
- We did **not yet demonstrate** this in an accelerator environment
- We did **not yet demonstrate** this with a complete system (magnet, alignment,...)

Deliverables and R&D

- **Main deliverables (Eucard):** Type 4 mock-up 09/2011

  Implementation CDR baseline — Type 1 and 4 Test modules/ CLEX 2012

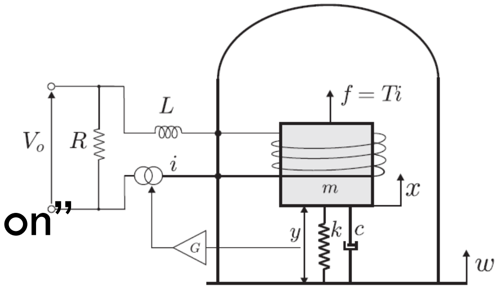
- **Continued R&D:**
  - **Increased performance**: Interaction with BBF, stability and ratio increase RMS displacement, sensor development
  - **COST reduction**: e.g. Electronics, number of actuators, x-y sensors
  - **Compatibility components accelerator environment:** sensor development, research + qualification
  - **Overall system analysis:**, sensitivity to change of requirements, again interaction with integrated luminosity simulations, characterisation components and vibrations sources, compliance
  - **Pre-Industrialised, operational system:** Reliability, distributed control system, series production

5 points summary:

Mature technology

Sensor R&D

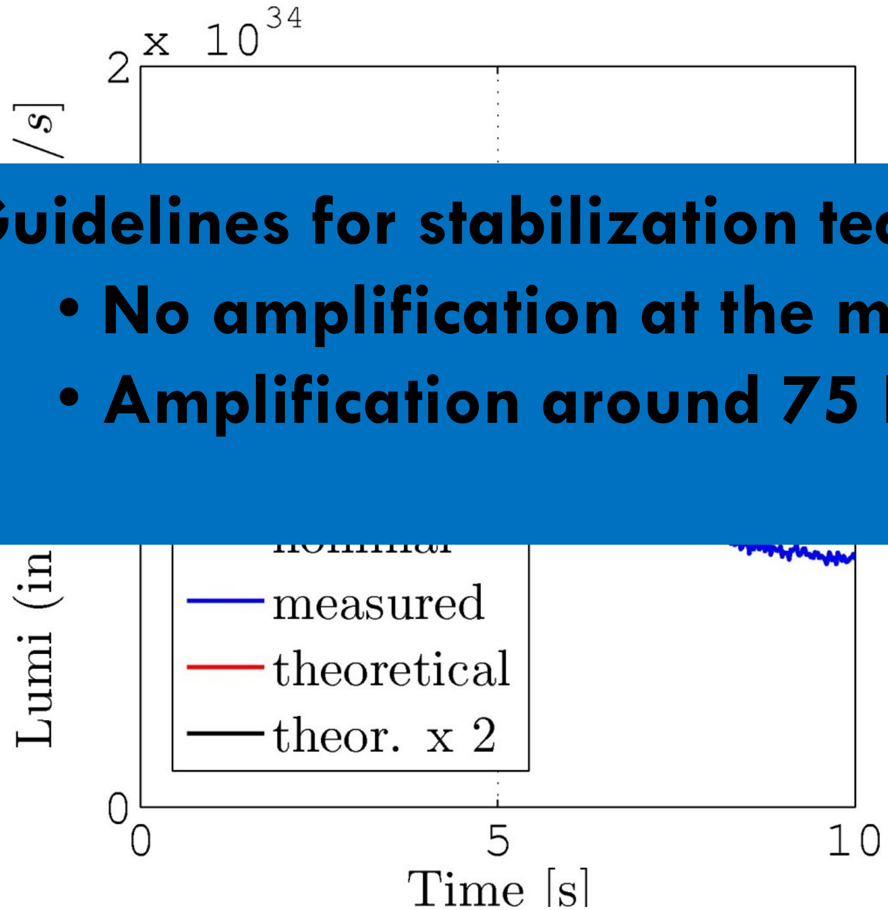
- Increase performance
  - Increase RMS ratio
  - Increase resolution
- Adapt to Daniel's "Favorite Transfer Function"
- Decrease Costs
- **Make compatible with Accelerator environment**



- <u>Modify Standard seismometer</u>
  - Use mechanics
  - Implemented other displacement sensors
- <u>Development of a new sensor</u>

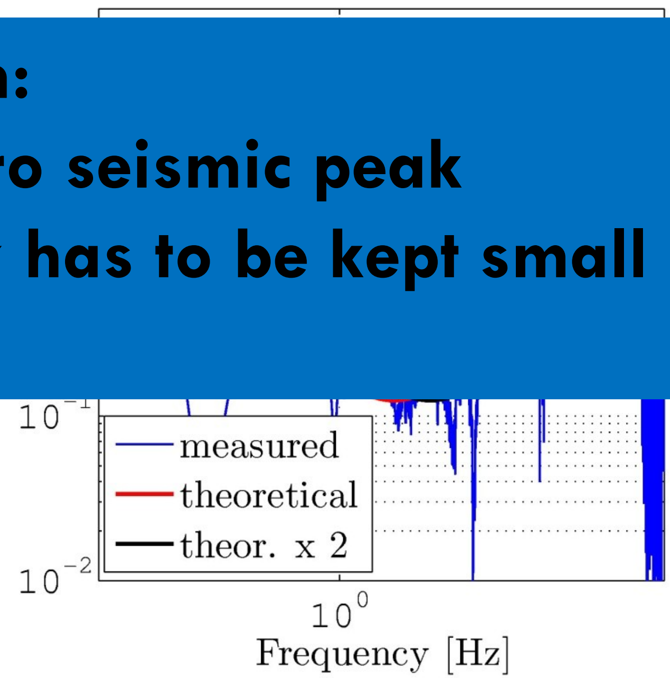
- <u>Investigate Eentec Electro chemical seismometer</u>

Interaction with BBF team



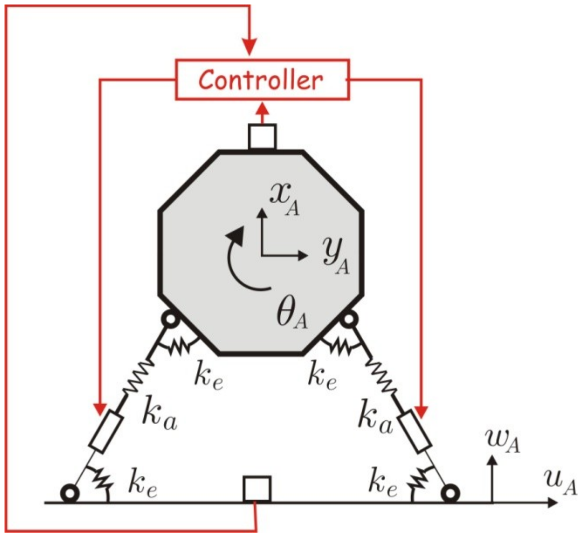
Guidelines for stabilization team:

- **No amplification at the micro seismic peak**
- **Amplification around 75 Hz has to be kept small**



Slide courtesy of **J. Pfingstner and J. Snuverink**
Beam physics meeting 12-01-2011

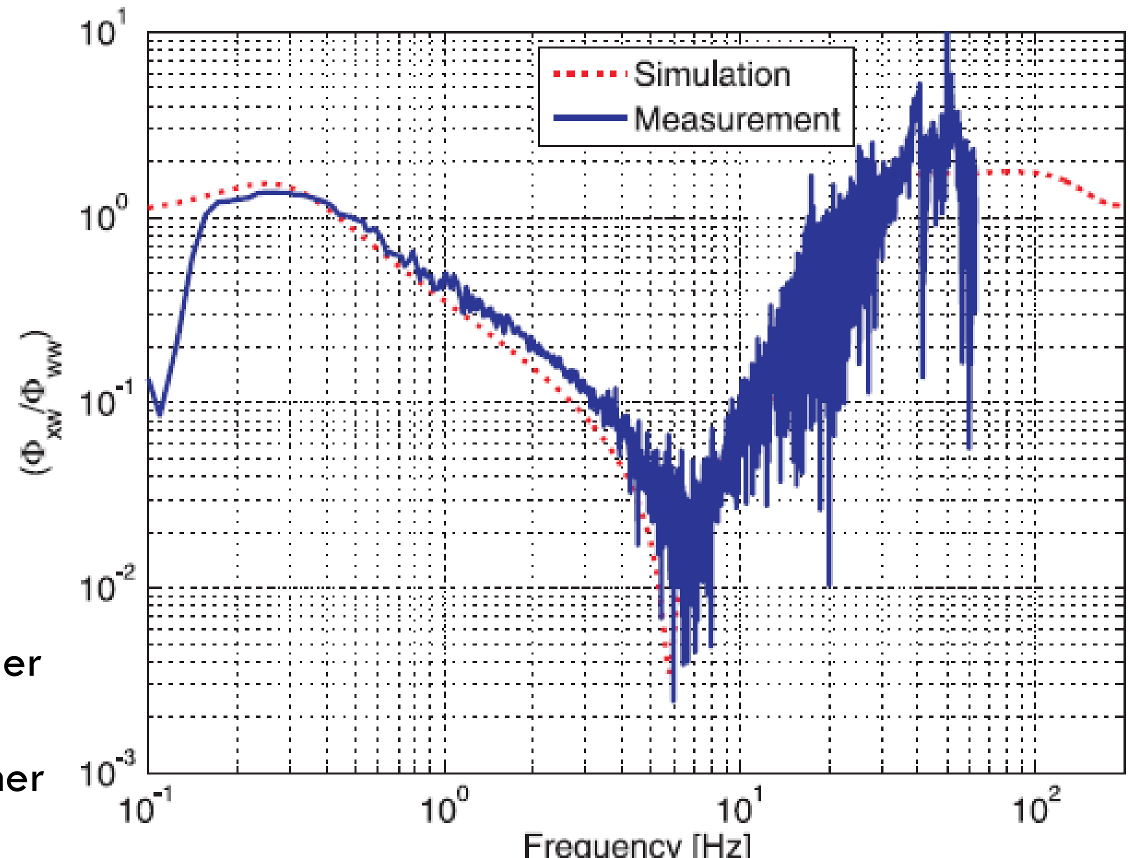
Feedforward Feedback



- Reduced peak at low frequency
- Reduced peak at high frequency

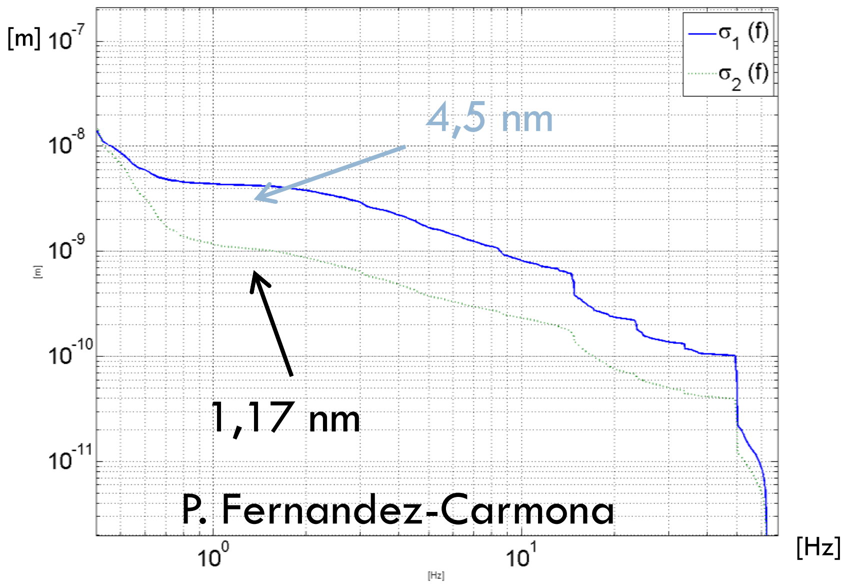
⇒Tested by J. Snuverink and J. Pfingstner

Request to increase stabilization to higher frequency

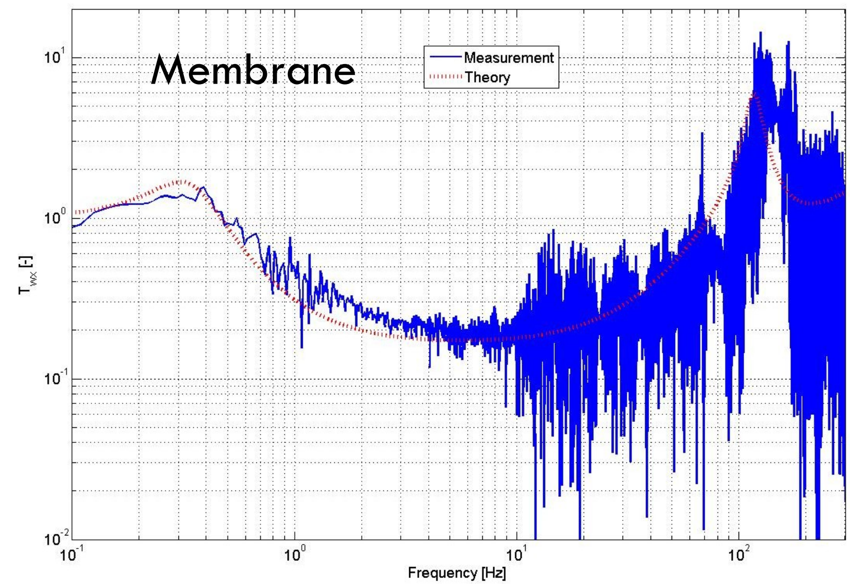


S. Janssens

Analog control research

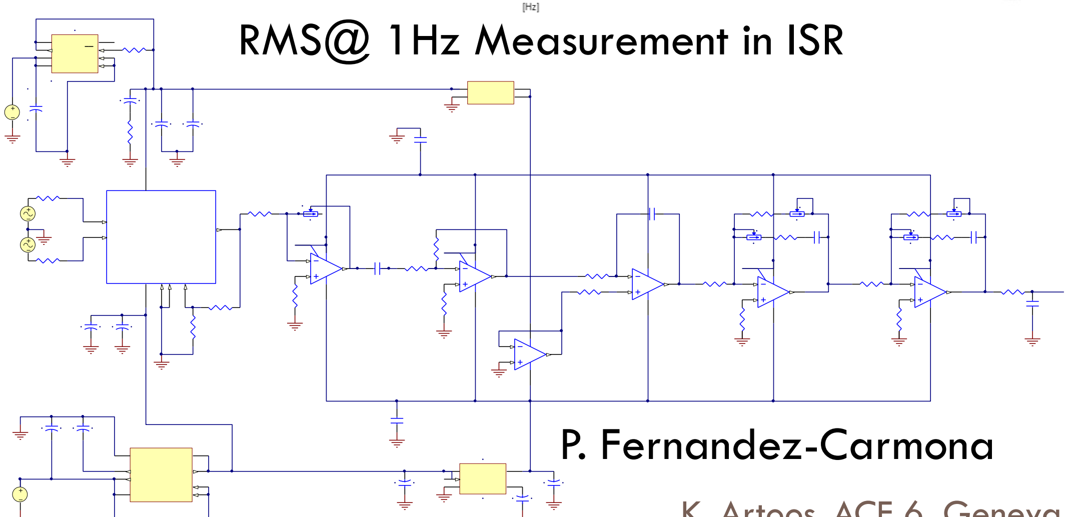


RMS@ 1Hz Measurement in ISR



Measured Transfer function

- \+ Low noise
- \+ Low cost
- \+ Small volume
- \+ Lower phase delay
- \+ Less sensitive to single events
- \+ Low power consumption
- \- Limited flexibility



P. Fernandez-Carmona

Analog control research

Power ≈20mW
Cost ≈100CHF
Volume ≈0.15 l

Power ≈80W
Cost ≈15000CHF
Volume ≈13 l

Conclusions technical implementation

Short term deliverables are defined in EUCARD.

Medium term R&D strategy summarized in 5 points.

Technical implementation after CDR has already started with regularly new results.

Integration with BBF and Luminosity simulations is now systematic.

Publications

- COLLETTE C., ARTOOS K., KUZMIN A., JANSSENS S., SYLTE M., GUINCHARD M. and HAUVILLER C., Active quadrupole stabilization for future linear particle colliders, *Nuclear instruments and methods in physics research section A,* vol.621 (1-3) pp.71-78 (2010).
- COLLETTE C., ARTOOS K., GUINCHARD M. and HAUVILLER C., Seismic response of linear accelerators, *Physical reviews special topics – accelerators and beams* vol.13 pp. 072801 (2010).
- FERNANDEZ-CARMONA P., COLLETTE C., JANSSENS S., ARTOOS K., GUINCHARD M., KUZMIN A., SLAATHAUG A., HAUVILLER C., Study of the electronics architecture for the mechanical stabilization of the quadrupoles of the CLIC linear accelerator, Journal of Physics : Conference series (Published 2010).
- ARTOOS K., COLLETTE C., FERNANDEZ-CARMONA P., GUINCHARD M., HAUVILLER C., JANSSENS S. KUZMIN A., LACKNER F., LEUXE R. and SLAATHAUG A., Stabilization and fine positioning to the nanometre level of the CLIC Main beam quadrupoles, accepted in *Physical reviews special topics – accelerators and beams* (submitted in 2010).
- In preparation: COLLETTE C., FERNANDEZ-CARMONA P., JANSSENS S., ARTOOS K., GUINCHARD M., HAUVILLER C., Inertial sensors for low frequency seismic vibration measurement, *Bulletin of the Seismological Society of America*
- submitted in 2011: COLLETTE C., FERNANDEZ-CARMONA P., JANSSENS S., ARTOOS K., GUINCHARD M., HAUVILLER C., Nano-Motion Control of Heavy Quadrupoles for Future Particle Colliders: An Experimental Validation, *Nuclear instruments and methods in physics research section A*

Publications

- ARTOOS K., COLLETTE C., GUINCHARD M., JANSSENS S., KUZMIN A. and HAUVILLER C., Compatibility and integration of a CLIC quadrupole nano-stabilization and positioning system in a large accelerator environment, *IEEE International Particle Accelerator Conference IPAC10*, 23-25 May 2010 (Kyoto, Japan).
- ARTOOS K., COLLETTE C., GUINCHARD M., JANSSENS S., LACKNER F. and HAUVILLER C., Stabilisation and fine positioning to the nanometer level of the CLIC Main beam quadrupoles, *IEEE International Particle Accelerator Conference IPAC10*, 23-25 May 2010 (Kyoto, Japan).
- COLLETTE C., ARTOOS K., JANSSENS S. and HAUVILLER C., Hard mounts for quadrupole nano-positioning in a linear collider, *12th International Conference on New Actuators ACTUATOR2010,* 14-16 May 2010 (Bremen, Germany).
- COLLETTE C., JANSSENS S., ARTOOS K. and HAUVILLER C., Active vibration isolation of high precision machine (keynote lecture), *6th International Conference on Mechanical Engineering Design of Synchrotron Radiation Equipment and Instrumentation (MEDSI 2010)*, 14 July 2010 (Oxford, United Kingdom).
- COLLETTE C., JANSSENS S., ARTOOS K., GUINCHARD M. and HAUVILLER C., CLIC quadrupole stabilization and nano-positioning, *International Conference on Noise and Vibration Engineering (ISMA2010)*, 20-22 September 2010 (Leuven, Belgique).

Publications

- COLLETTE C., JANSSENS S., ARTOOS K. and HAUVILLER C., Active vibration isolation of high precision machine (keynote lecture), *6th International Conference on Mechanical Engineering Design of Synchrotron Radiation Equipment and Instrumentation (MEDSI 2010)*, 14 July 2010 (Oxford, United Kingdom).
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- JANSSENS S., COLLETTE C., ARTOOS K., GUINCHARD M. and HAUVILLER C., A sensitiviy analysis for the stabilization of the CLIC main beam quadrupoles, *Conference on Uncertainty in Structural Dynamics*, 20-22 September 2010 (Leuven, Belgique).
- FERNANDEZ-CARMONA P., COLLETTE C., JANSSENS S., ARTOOS K., GUINCHARD M., KUZMIN A., SLAATHAUG A., HAUVILLER C., Study of the electronics architecture for the mechanical stabilization of the quadrupoles of the CLIC linear accelerator, Topical Workshop on Electronics for Particle Physics TWEPP 2010, 20-24 September 2010 (Aachen, Germany).

Spares

Deliverables

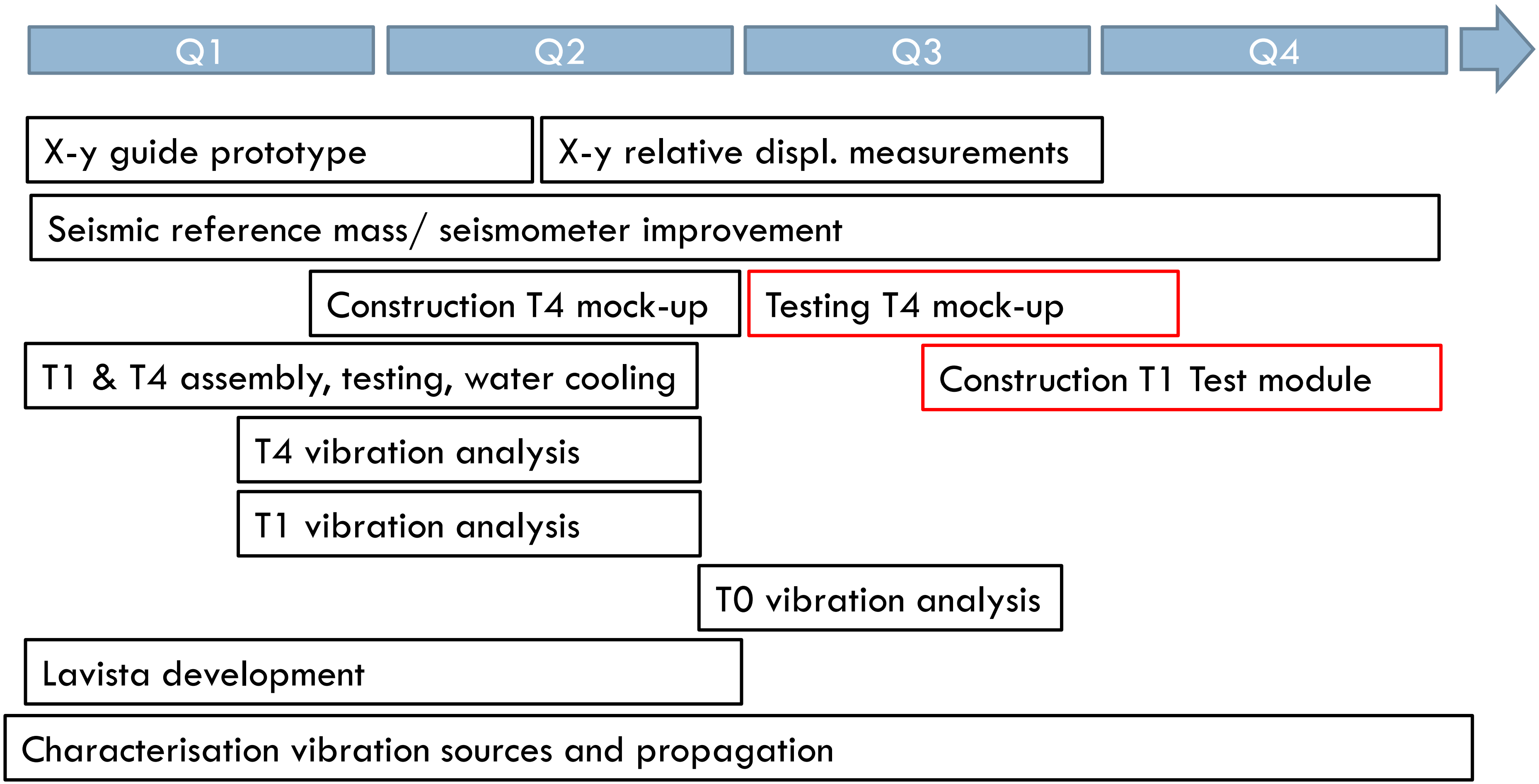
2009 -2010	**R&D Stabilisation CLIC** **CDR** **Feasibility demonstration CLIC MBQ stabilisation** **Stabilisation Working Group** ~ *DONE!* T1 concept drawing Module CDR
APRIL 2009-2013 *Final EUCARD reports 03/2013*	EUCARD WP 9.3.1 and 9.3.2 1. Mock-up type 4 (9/2011) 2. Characterisation of noise/vibration sources in an accelerator (03/'11) 3. Test module Type 1(10/'11) + 4. type 4 (05/'12) 5. CLEX: Type 1 + 6. Type 4 (12/'12) *Experiment at CEBAF (2013)*
2009-2010	Contribution exceptionelle de la France au CERN (EDMS 1009438) WP 4.7 and 4.8 LAPP (calculs et analyse vibratoire)+ CEA (interferometre) Evaluation performances 2011

Deliverables (conditions)

- 7. Further **increase performance:** stability and ratio reduction RMS displacement.
- 8. Compatibility components (**sensor/actuator/ electronics**) with **accelerator environment:** research + qualification
- 9. Compatibility with **Alignment** + external forces
- 10
  - Calibrate + characterise sensors by comparison + **independent measurement method**
  - Demonstrate stability with **independent method**
- 11. For operation in test modules and CLEX: a controller with **external communication**
- 12. State of the art report on sensor development and performances (updated yearly basis)
- 13. State of the art report on actuator development and performances (updated yearly basis)
- 14. Overal system analysis: stability, bandwidth, **sensitivity to change of specifications, interaction with BBF**
- 15. **Integration** in the module design
- 16. Faults analysis and tolerance of technical system, machine protection

Remark: CDR is the baseline during technical implementation... but with some flexibility without dispersing our activities

2011


Q1
Q2
Q3
Q4
X-y guide prototype
X-y relative displ. measurements
Seismic reference mass/ seismometer improvement
Construction T4 mock-up
Testing T4 mock-up
T1 & T4 assembly, testing, water cooling
Construction T1 Test module
T4 vibration analysis
T1 vibration analysis
T0 vibration analysis
Lavista development
Characterisation vibration sources and propagation

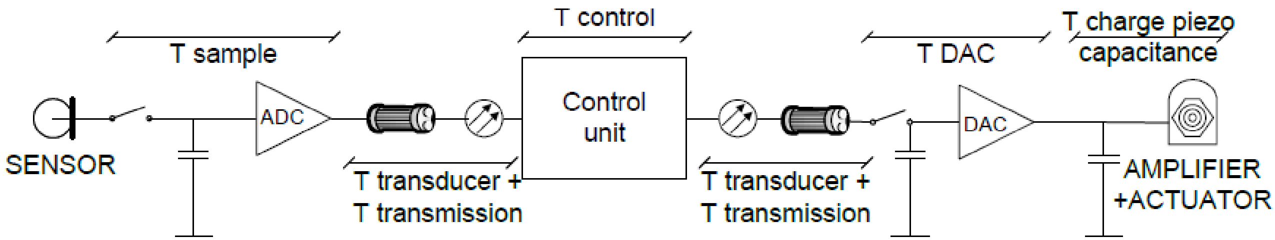
Latency Research

<u>Latency research for stabilization (Digital system)</u>

<u>Goal:</u> "Evaluate the impact of the latency on stabilization performance"

<u>Controller:</u> Experimental validation with NI PXI 8106 RT + M series acquisition with a 2D controller

"Study of the electronics architecture for the mechanical stabilisation of the quadrupoles of the CLIC linear accelerator" P. Fernandez
2010_JINST_5_C11014



P. Fernandez-Carmona

Component	ADC	Electro - optic transducer	Optic fiber transmission	Opto - electric transducer	DAC	Actuator (20nm single step)
Delay	8 µs	100 ns [6]	5 µs/Km	120 ns [6]	3 µs	1 µs

Delay	Performance
43µs	100%
80 µs	90%
90 µs	80%
100 µs	60%
130 µs	30%

Table 1

- Reduction in performance due to latency in feedback system

  ⇒ Long cables = latency problem => Localized control

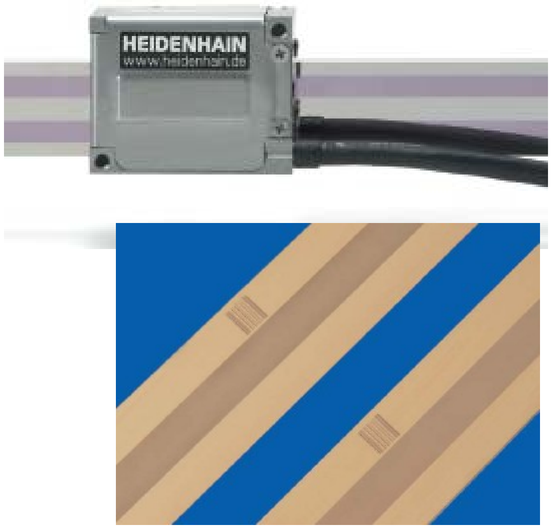
Additional objectives

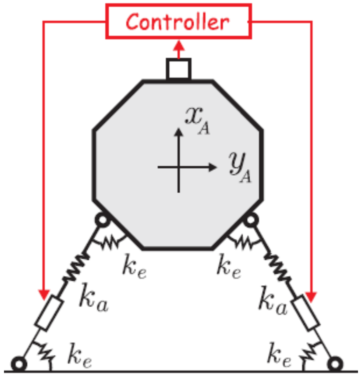
NANOMETROLOGY and introduction REFERENCE position

Measurement of the x-y displacement with respect to intermediate platform (**fiducials**):

- Instrumentation in actuator legs
- Capacitive gauges in x-y guide
- Optical linear encoders with gratings in x-y guide (Introduction hardware reference position)

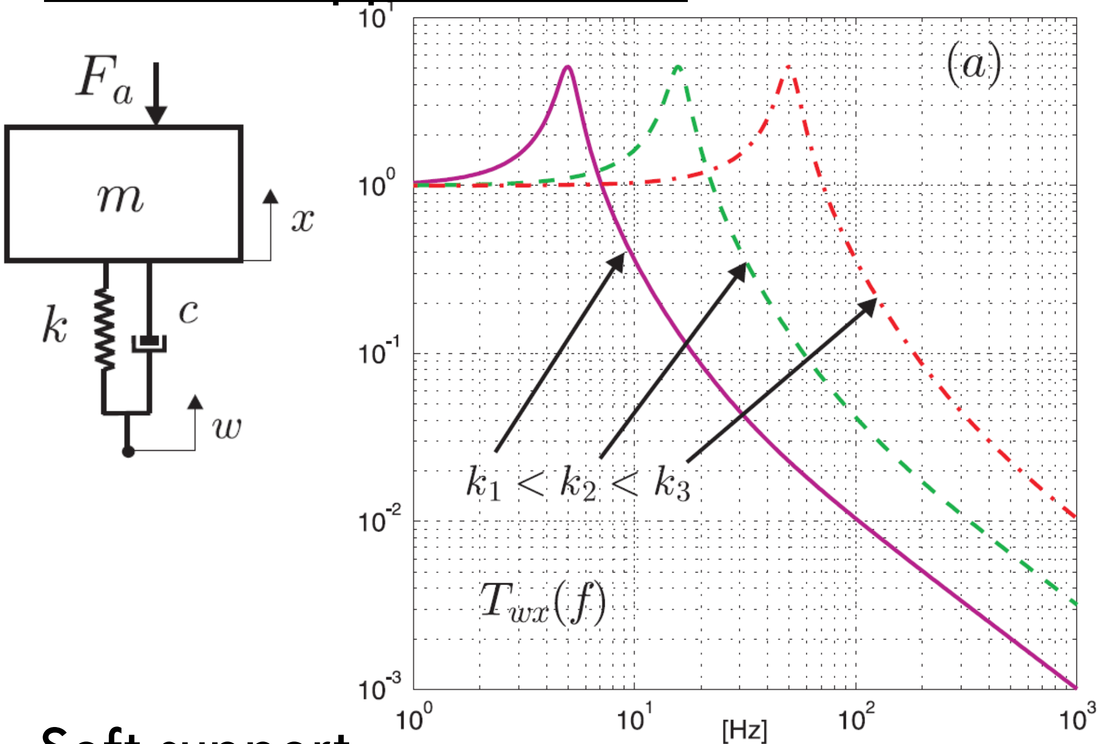
Nanometre resolution

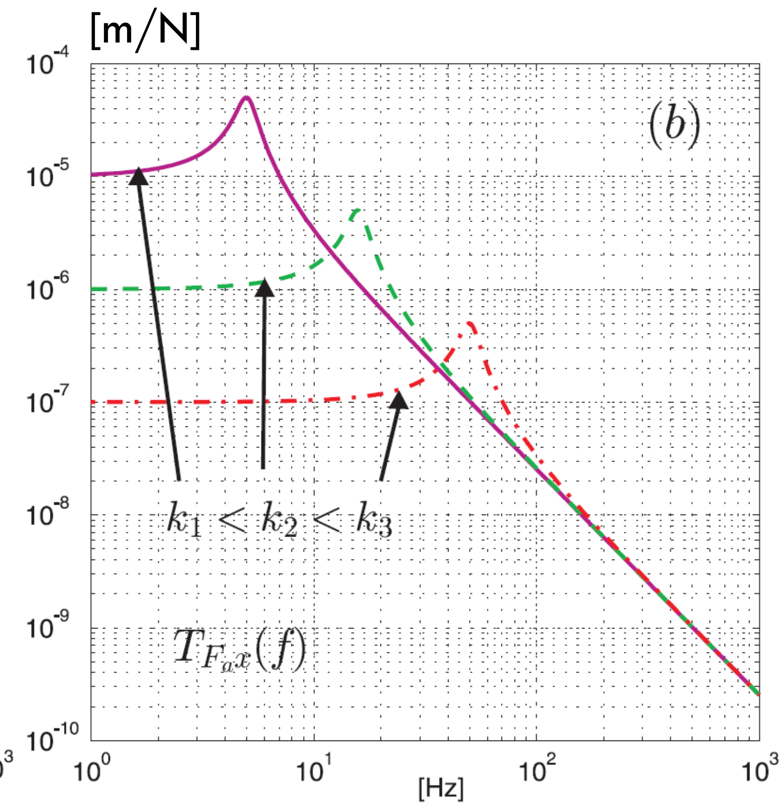




Passive Isolation Strategies

Effect of support stiffness





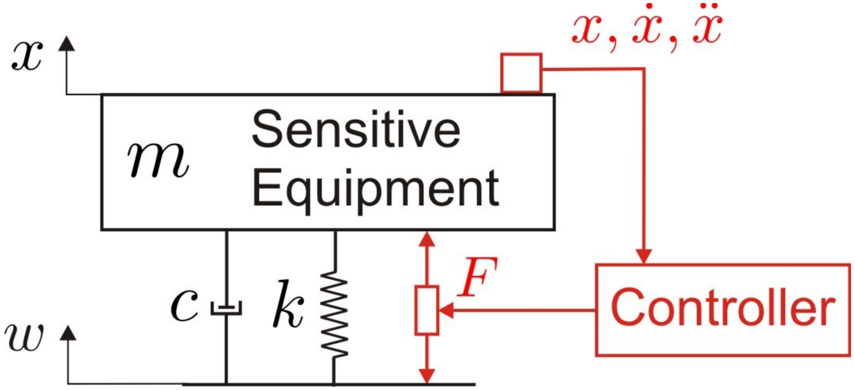
Soft support :

(i) Improves the isolation

(ii) Make the payload more sensitive to external forces Fa

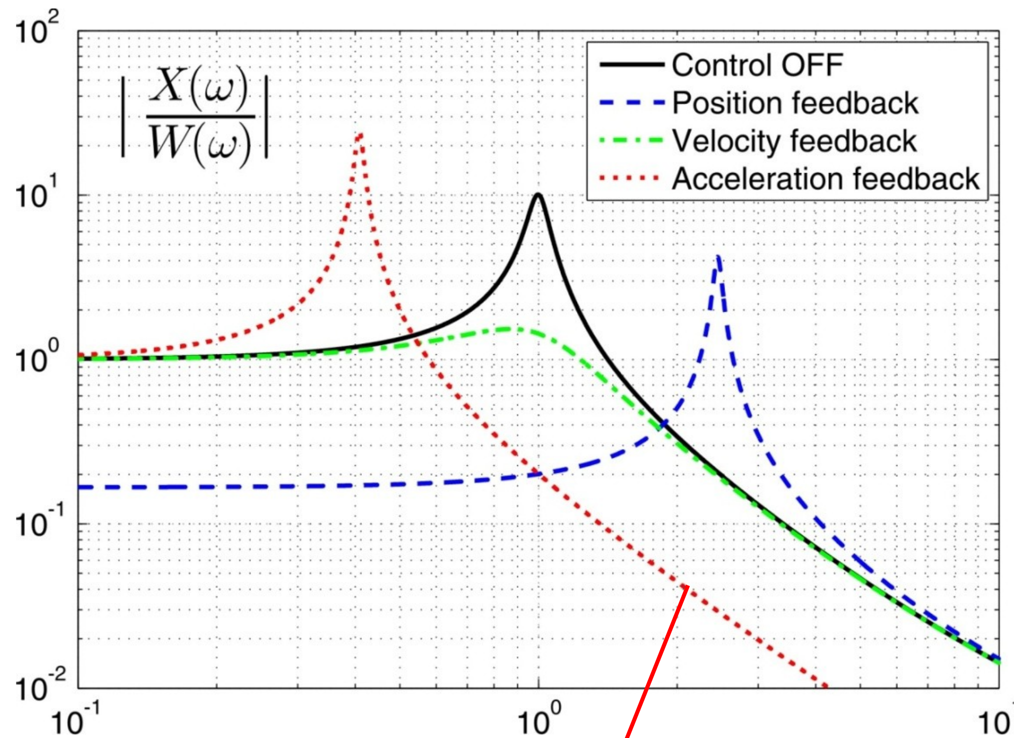
Active Isolation Strategies

Feedback control principle



$$F(t) = k_d x + k_v \dot{x} + k_a \ddot{x}$$

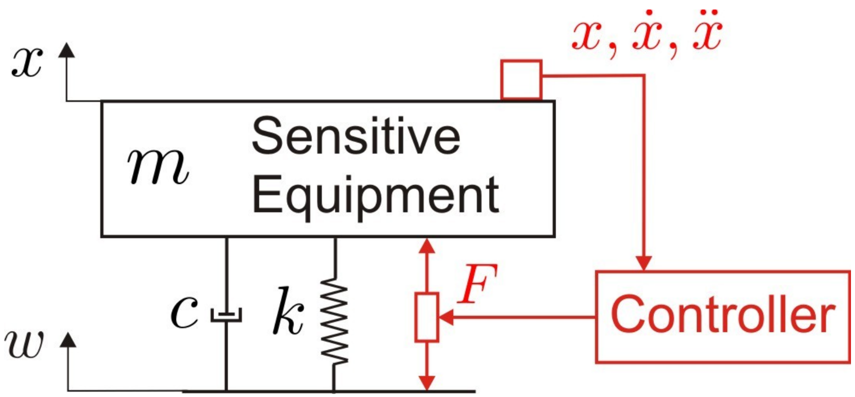
$$\frac{X(s)}{W(s)} = \frac{cs+k}{(m+k_a)s^2+(c+k_v)s+(k+k_d)}$$



Add virtual mass
(e.g. space applications)

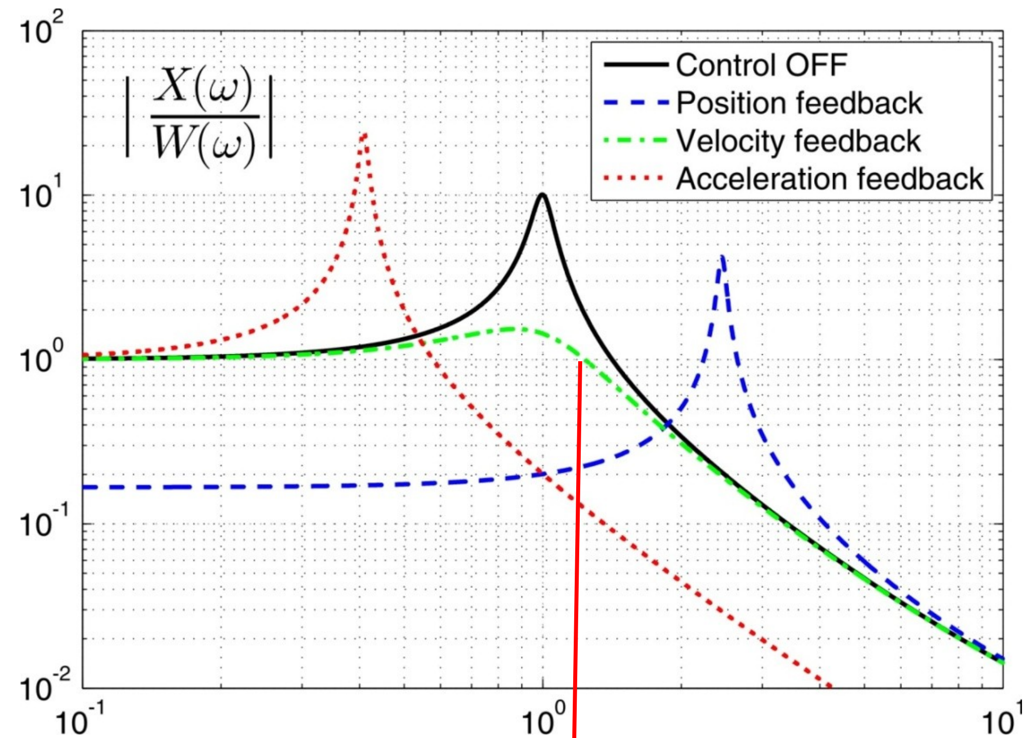
Active Isolation Strategies

Feedback control principle



$$F(t) = k_d x + k_v \dot{x} + k_a \ddot{x}$$

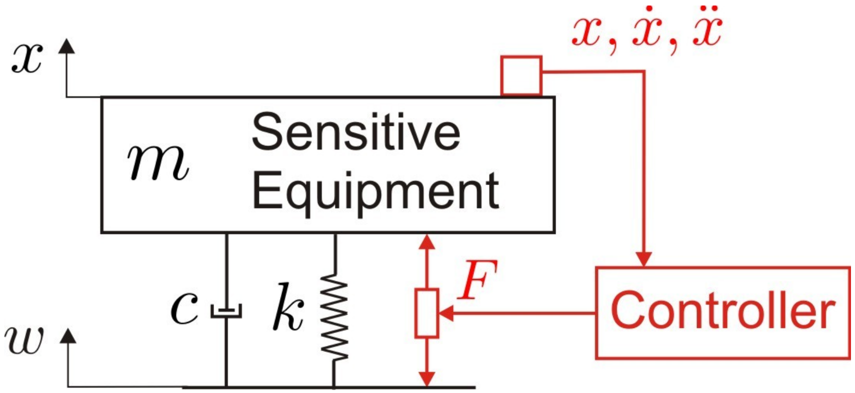
$$\frac{X(s)}{W(s)} = \frac{cs+k}{(m+k_a)s^2+(c+k_v)s+(k+k_d)}$$



Sky-hook damper
(D.C. Karnopp, 1969)

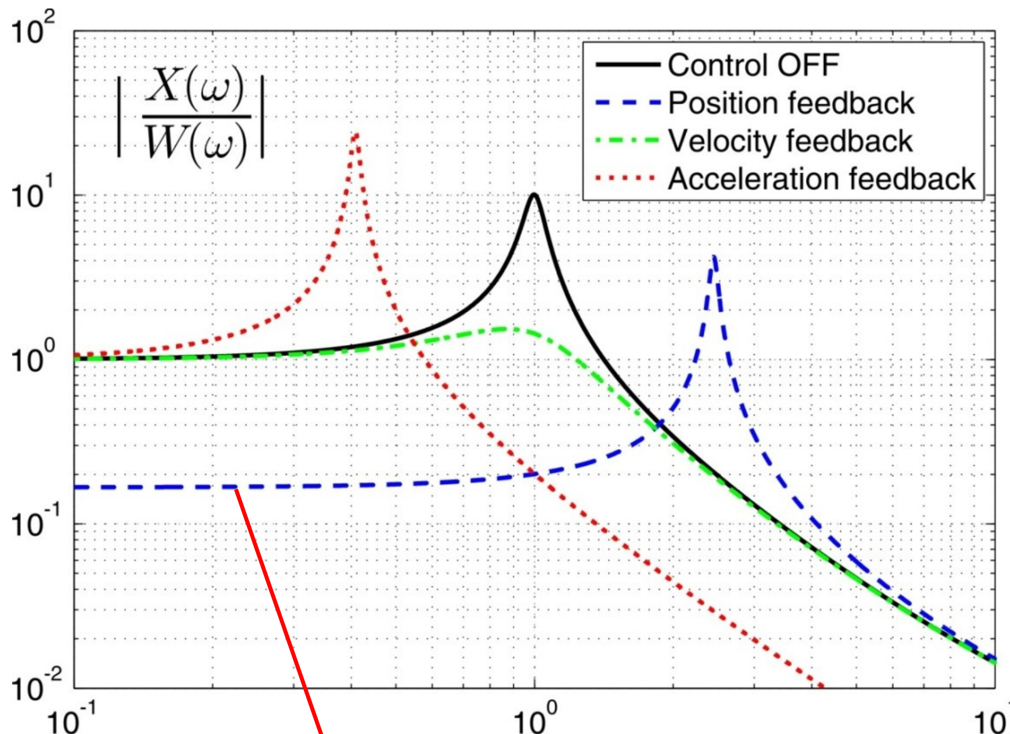
Active Isolation Strategies

Feedback control principle



$$F(t) = k_d x + k_v \dot{x} + k_a \ddot{x}$$

$$\frac{X(s)}{W(s)} = \frac{cs+k}{(m+k_a)s^2+(c+k_v)s+(k+k_d)}$$



Position feedback would be great !

➔ How to measure it ?

Passive vs Active vibration isolation

Only active isolation can provide both:

- Isolation in a broad frequency range between 1Hz and 20 Hz

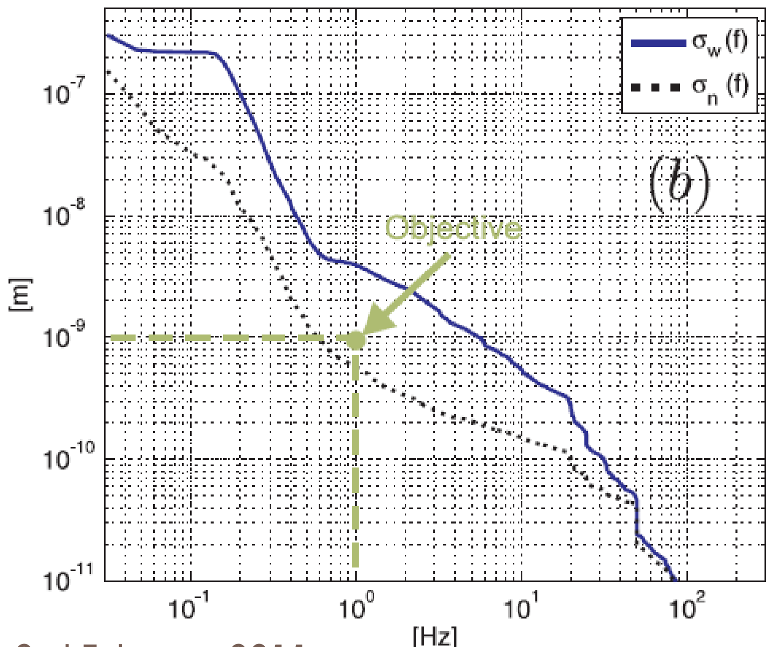
- Dynamic stiffness for robustness to disturbances and compatibility with alignment

Conditions:

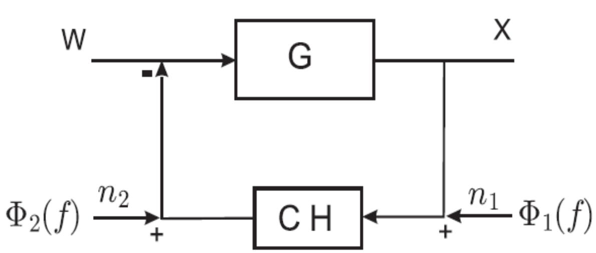
- Measure the vibrations

- Process the signal in real time

- Apply small dynamic forces



Error budgeting

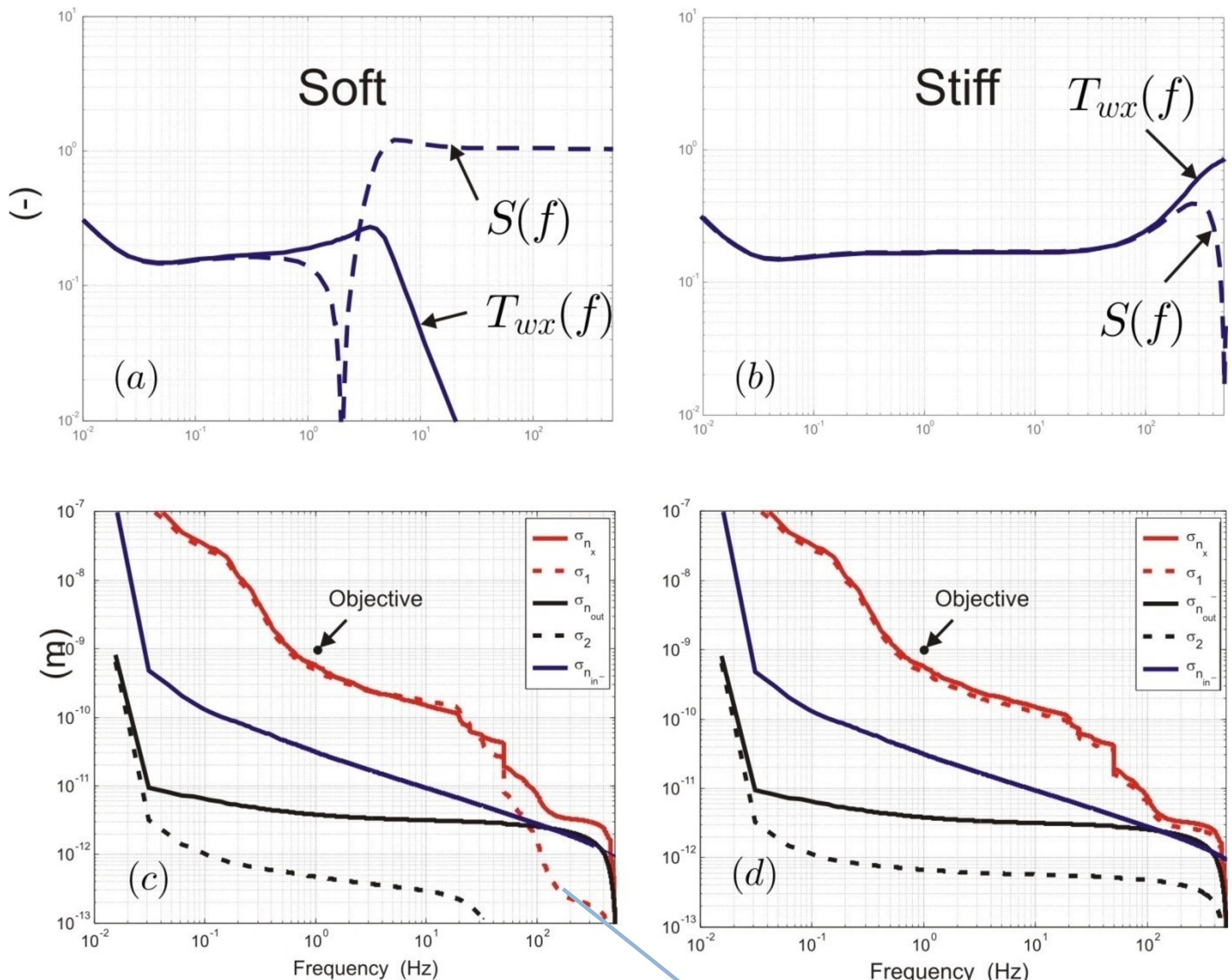


$$\Phi_n = |SKG|^2\Phi_{n1} + |SG|^2\Phi_{n2}$$

$$K = CH$$

$$S = 1/(1+KG)$$

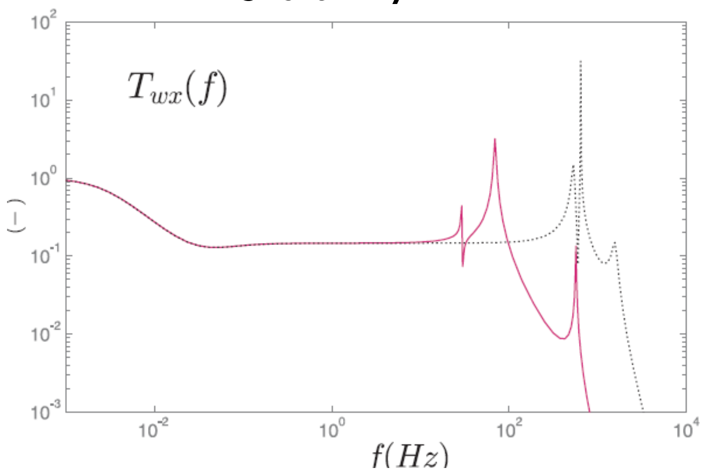
No significant difference in the noise transmission

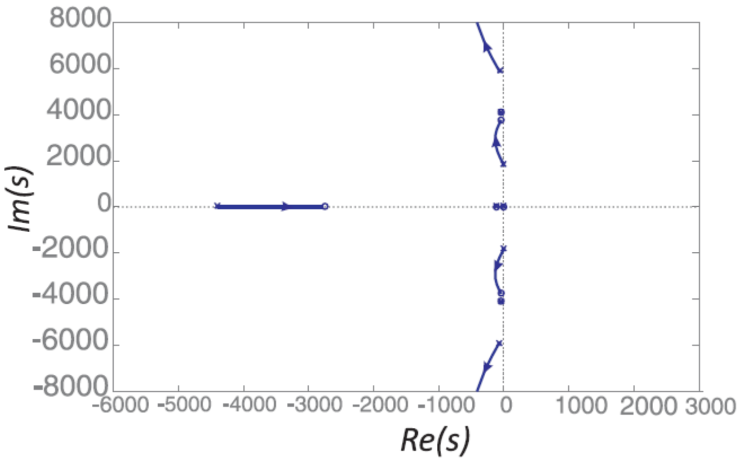


Noise reduction

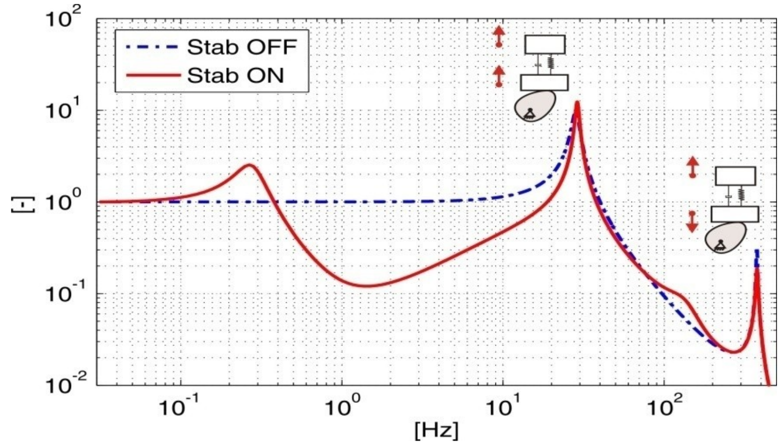
Strong coupling

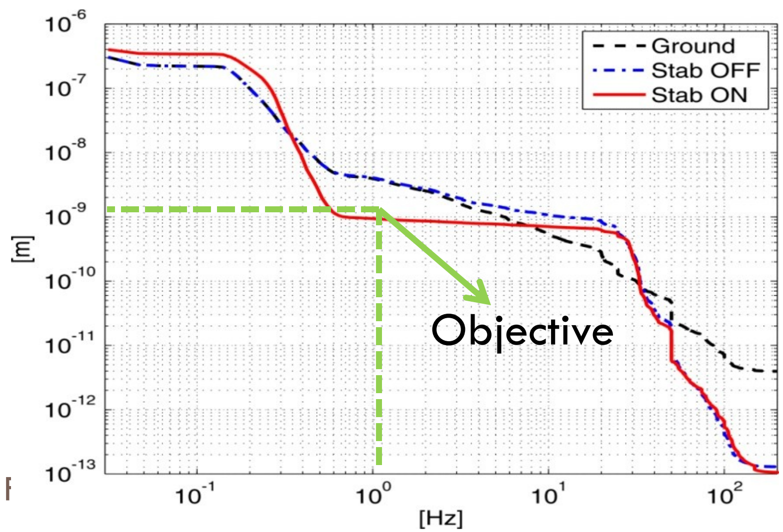
Stability



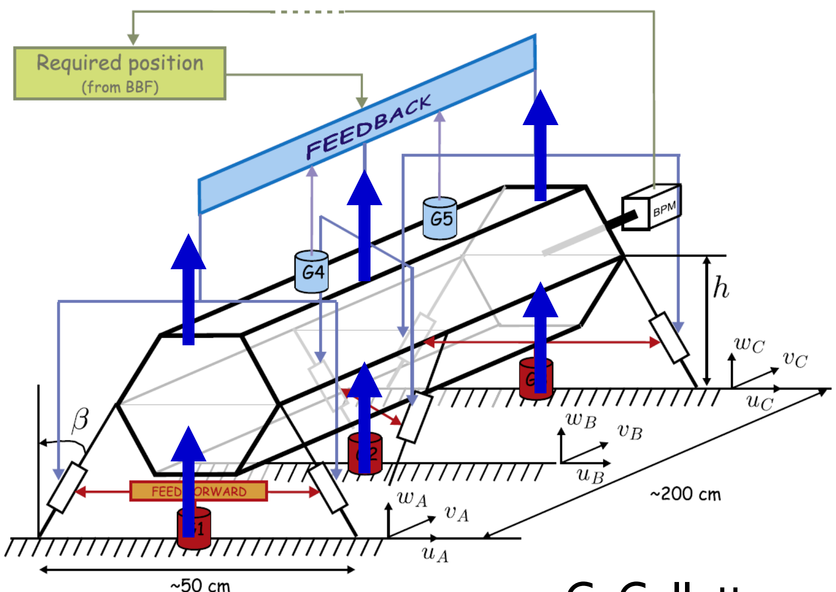


Performances





Stability of slender quadrupoles



C. Collette

$$M\ddot{\mathbf{x}} + K\mathbf{x} = k_a B \boldsymbol{\Delta} + k_a B E \mathbf{w}$$

$$K = k_a B B^T \qquad B = J^T \qquad \dot{\mathbf{q}} = J\dot{\mathbf{x}}$$

C. Collette et al, *Nucl. Instr. meth. in phys. Res. A*, vol.621 (1-3) pp.71-78 (2010).

Complete matlab program:

- Simulate vibration isolation
- Simulate positioning
- Simulate mechanics (x-y guide)