Monolithic folded pendulum sensor for present and future interferometric detectors of gravitational waves

F. Travasso, F. Barone, G. Giordano, F. Marchesoni, H. Vocca

GEMMA (Gravitational-waves, ElectroMagnetic and dark MAtter) Physics Workshop

4-7 June 2018

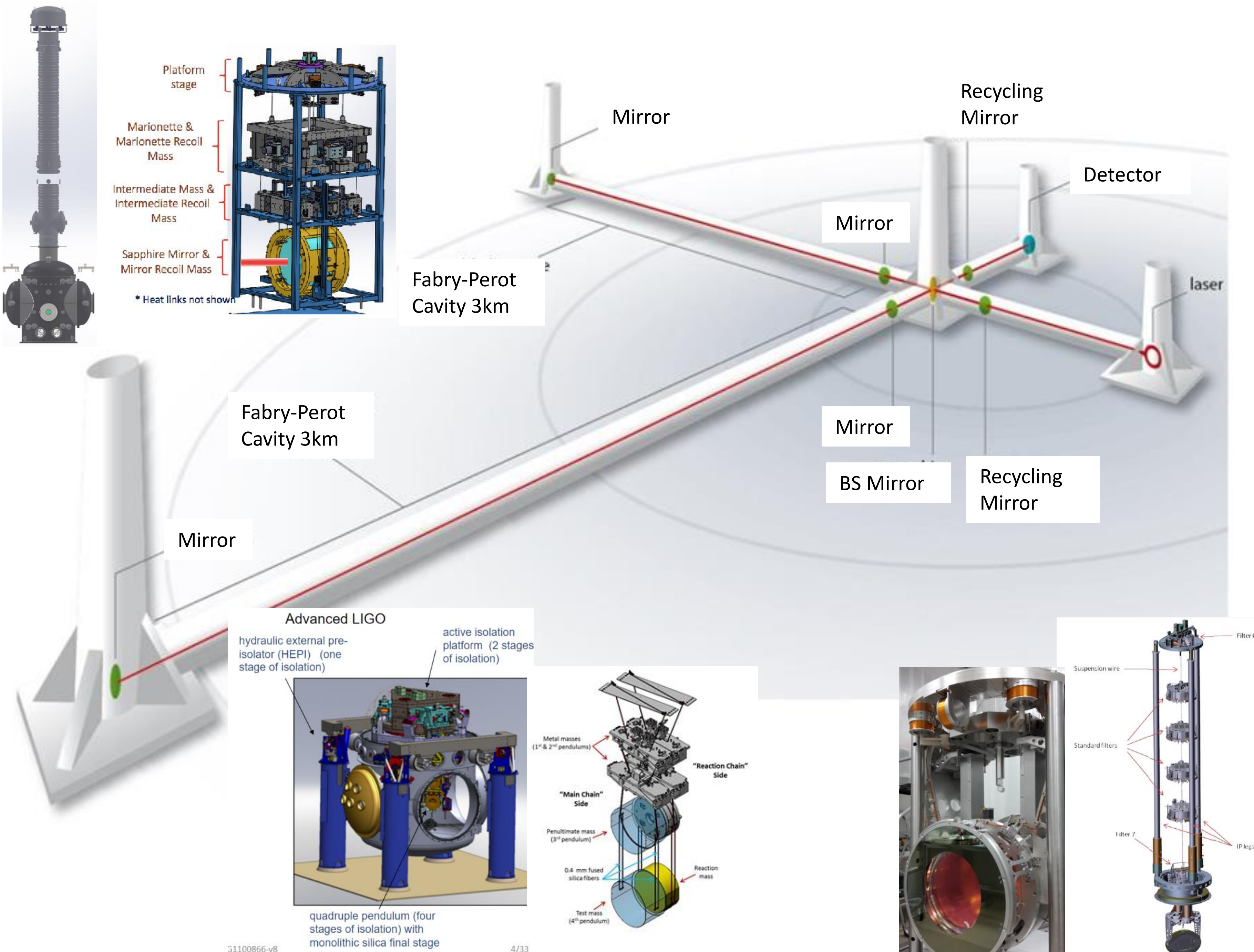
UNISA Applied Physics Group

DIPARTIMENTO DI FISICA E GEOLOGIA
Università degli Studi di Perugia

INFN
Istituto Nazionale di Fisica Nucleare

Outline

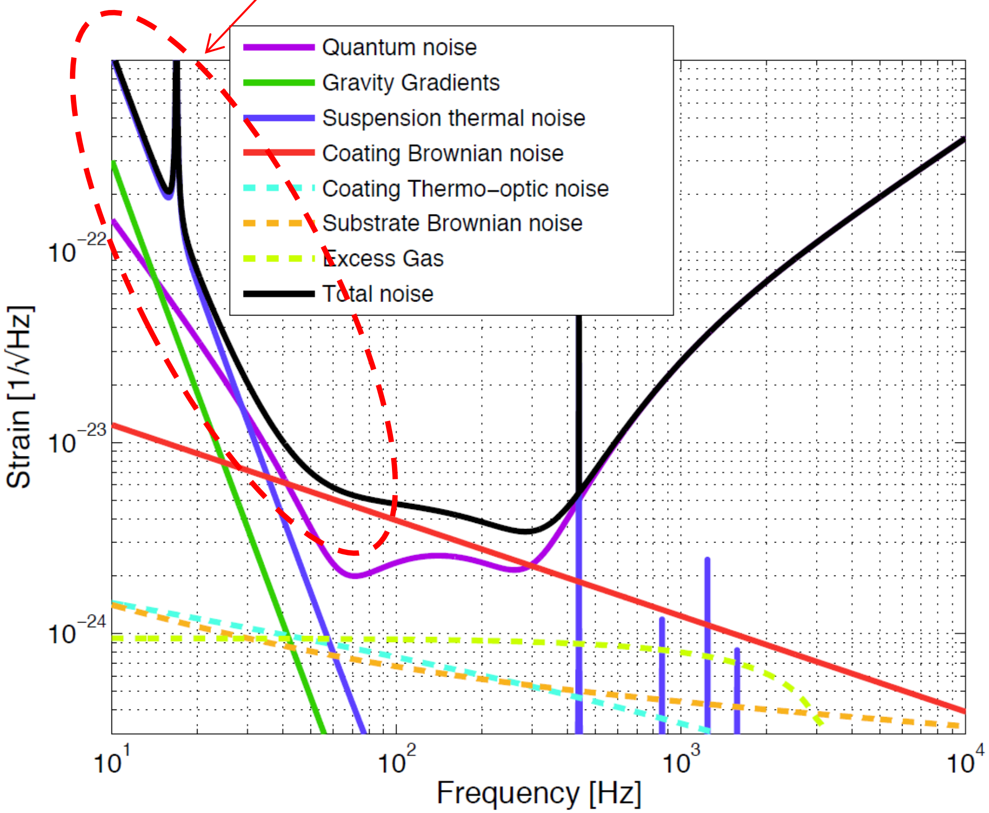
- Motivation
- Brief description of the sensor (not the topic of this talk)
- Axial and angular performances of UNISA sensor at low temperatures (main topic of the talk)
- Conclusion and next steps



Platform stage
Marionette & Marionette Recoil Mass
Intermediate Mass & Intermediate Recoil Mass
Sapphire Mirror & Mirror Recoil Mass
* Heat links not shown
Mirror
Recycling Mirror
Detector
Mirror
laser
Fabry-Perot Cavity 3km
Fabry-Perot Cavity 3km
Mirror
BS Mirror
Recycling Mirror
Mirror
Advanced LIGO
hydraulic external pre-isolator (HEPI) (one stage of isolation)
active isolation platform (2 stages of isolation)
quadruple pendulum (four stages of isolation) with monolithic silica final stage
G1100866-v8
4/33
Metal masses (1st & 2nd pendulums)
"Reaction Chain" Side
"Main Chain" Side
Penultimate mass (3rd pendulum)
0.4 mm fused silica fibers
Reaction mass
Test mass (4th pendulum)
Filter 0
Suspension wire
Standard filters
Filter 7
IP legs

Seismic noise

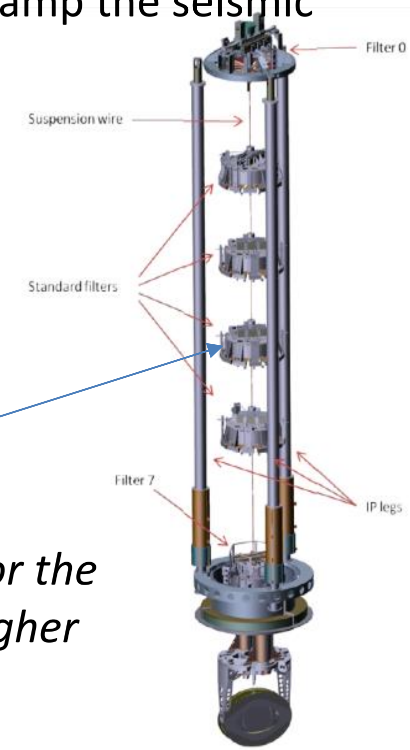
Limited by quantum noise, suspension thermal noise, seismic noise, newtonian noise



Seismic noise reduction

Passive damping system: (e.g Super Attenuator in Virgo and Kagra) chain of heavy pendulum in series: noise reduction ~ $1/(f_0)^{2n}$

Active damping system: (in all the GW detectors) hierarchical control of the suspension chain to damp the seismic noise: inertial sensors



Pendulum

Natural mechanical filter for the signals with a frequency higher than its resonance mode

Kagra detector

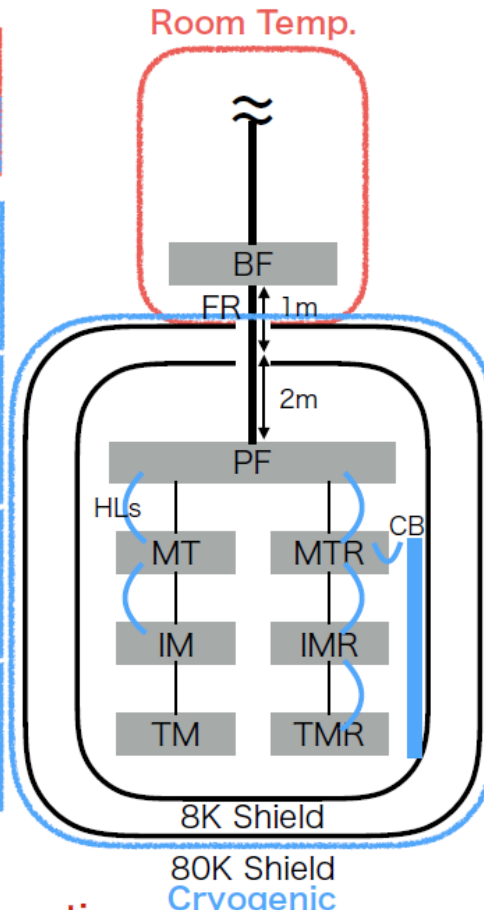
FR:Fishing Rod
Maraging Steel

HLs:Heat Links
99.9999% purity of Al

MT:Marionet
SUS316 + Cu
11K

IM:Intermediate Mass
SUS316
10.5K

TM:Test Mass
Sapphire
11.5K



BF:Bottom Filter
293K

PF:Plat Form
SUS316 + Cu

MTR:Marionet Recoil Mass
SUS316 + Cu
10.5K

IMR:Intermediate Recoil Mass
SUS316

TMR:Test Recoil Mass
NSSC130S

CB:Cooling Bar
99.9999% purity of Al
6K

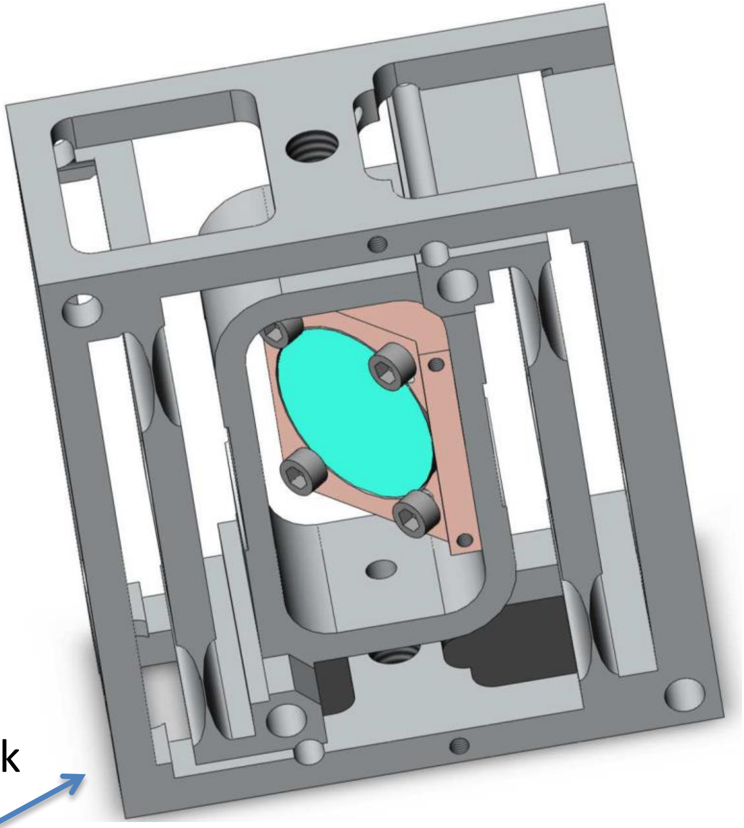
※Without laser absorption

Inertial sensors able to operate in a large range of temperature, with optimized masses and tunable resonance modes (frequency bands and sensitivities)

Desirable features for a sensor

For an effective implementation of a mechanical sensor some parameters have to be taken into due consideration:

- Dynamics,
- Directivity (axial and angular)
- Sensitivity
- Optimizable in size and weight
- Tunable in resonance modes (frequency bands and sensitivities)
- UHV and CRYO compatibility in a large range of temperature



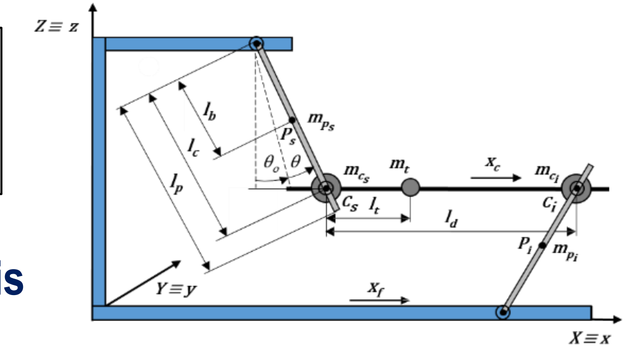
Classical mechanical sensors are not able to globally satisfy the whole set of the above requirements: generally operating in force feedback, they are characterized by large weights and sizes coupled to lack of UHV and cryogenic compatibility.

Different is the case of folded pendulum monolithic oscillators that is a native seismometers

UNISA Sensor description

First Property: a Folded Pendulum is dynamically fully equivalent to a second order system.

$$H(s) = \frac{X_c(s) - X_g(s)}{X_g\,(s)} = \frac{X_{output}(s)}{X_g(s)} = \frac{-(1-A_c)\,s^2}{s^2 + \frac{2\pi f_o}{Q(f_o)}\,s + 4\pi^2 f_o^2}$$



Second Property: The folded pendulum resonance frequency is equivalent to that of a spring-mass oscillator.

$$f_o = \frac{\omega_o}{2\pi} = \frac{1}{2\pi}\sqrt{\frac{\left[\left(m_{p_s}-m_{p_i}\right)\frac{l_p}{l_c}+\left(m_{c_s}-m_{c_i}\right)\right]\frac{g_{eq}}{l_c}+\frac{k_\theta}{l_c^2}}{\left(m_{p_s}+m_{p_i}\right)\frac{l_p^2}{3l_c^2}+\left(m_{c_s}+m_{c_i}\right)}} = \frac{1}{2\pi}\sqrt{\frac{K_{g_{eq}}+K_{e_{eq}}}{M_{eq}}} = \frac{1}{2\pi}\sqrt{\frac{K_{eq}}{M_{eq}}}$$

Equivalent Gravitational Elastic Constant ≡ $K_{g_{eq}}$ <=> 0

Equivalent Elastic Constant ≡ $K_{e_{eq}}$ > 0

$$k_\theta = \frac{C_{s1}\cdot E(T)at^2}{16\left[1+\sqrt{1+C_{s2}\left(\frac{2a_x^2}{a_y t}\right)}\right]}$$

Note: suitable combinations of physical and geometrical parameters allow in theory to setting the resonance frequency to 0 Hz (ideal inertial mass), in practice to frequencies < 60 mHz.

Barone, F., Giordano, G., Mechanical Accelerometers, J. Webster (ed.), Wiley Encyclopedia of Electrical and Electronics Engineering. John Wiley & Sons, Inc., doi: 10.1002/047134608X.W8280 (2015).

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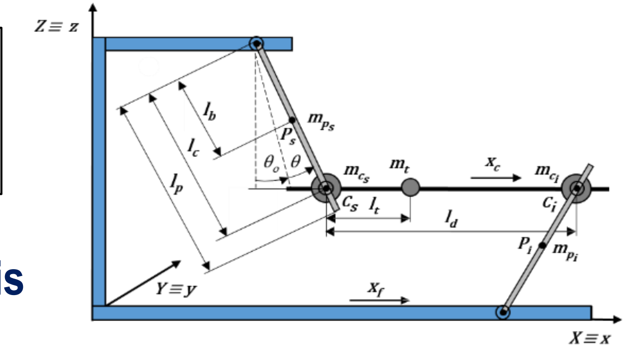

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$$f_0 \propto \sqrt{E(t)}$$

Equivalent Gravitational Elastic Constant ≡ $K_{g_{eq}}$ < = > 0

Equivalent Elastic Constant ≡ $K_{e_{eq}}$ > 0

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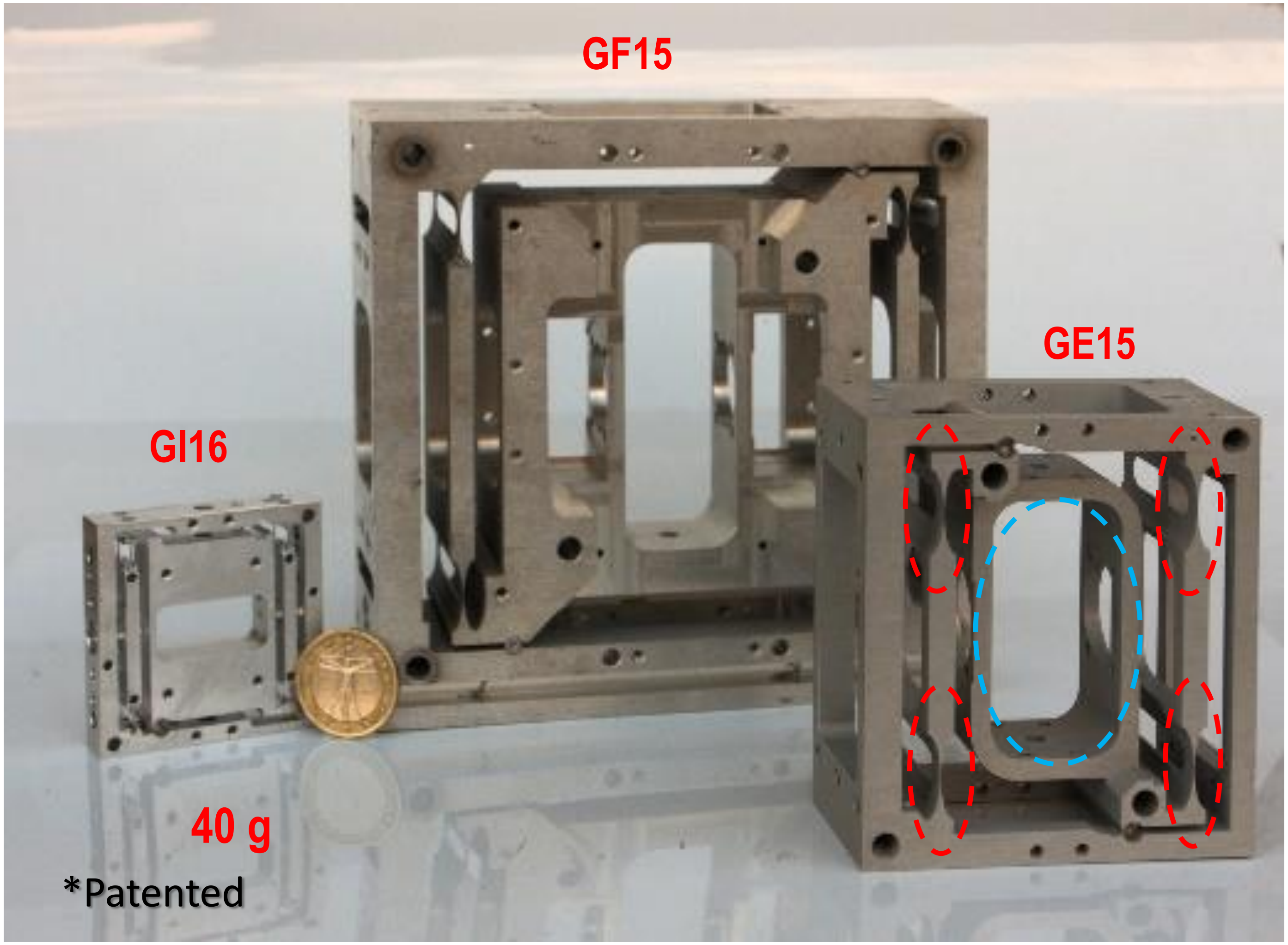
UNISA Monolithic Folded Pendulums*: GE15, GF15 and GI16

Operation: native seismometers configurable as force feedback accelerometers
Material: Al6082-T6 **Machining:** milling machining / WEDM for flexures
Main characteristics: high directivity, scalability and tunability
Design parameters: size, weight, resonance frequency and sensitivity



Resonance Frequency
Tunable: 60 mHz ÷ 10 Hz

Frequency Band
1μHz ÷ 1 kHz

Quality Factor
Q > 16000 (UHV),
Q > 2000 (air)
(res. frequency dependent)

Readout
LVDT, capacitive sensor, optical lever, optical fibre bundle, interferometer, etc.

Readout Noise
$10^{-14} \div 10^{-6}$ m/Hz$^{1/2}$

Vertical Folded Pendulum

For a full description: F. Barone, G. Giordano, Proc. SPIE 10599, 1059925, doi: 10.1117/12.2296376

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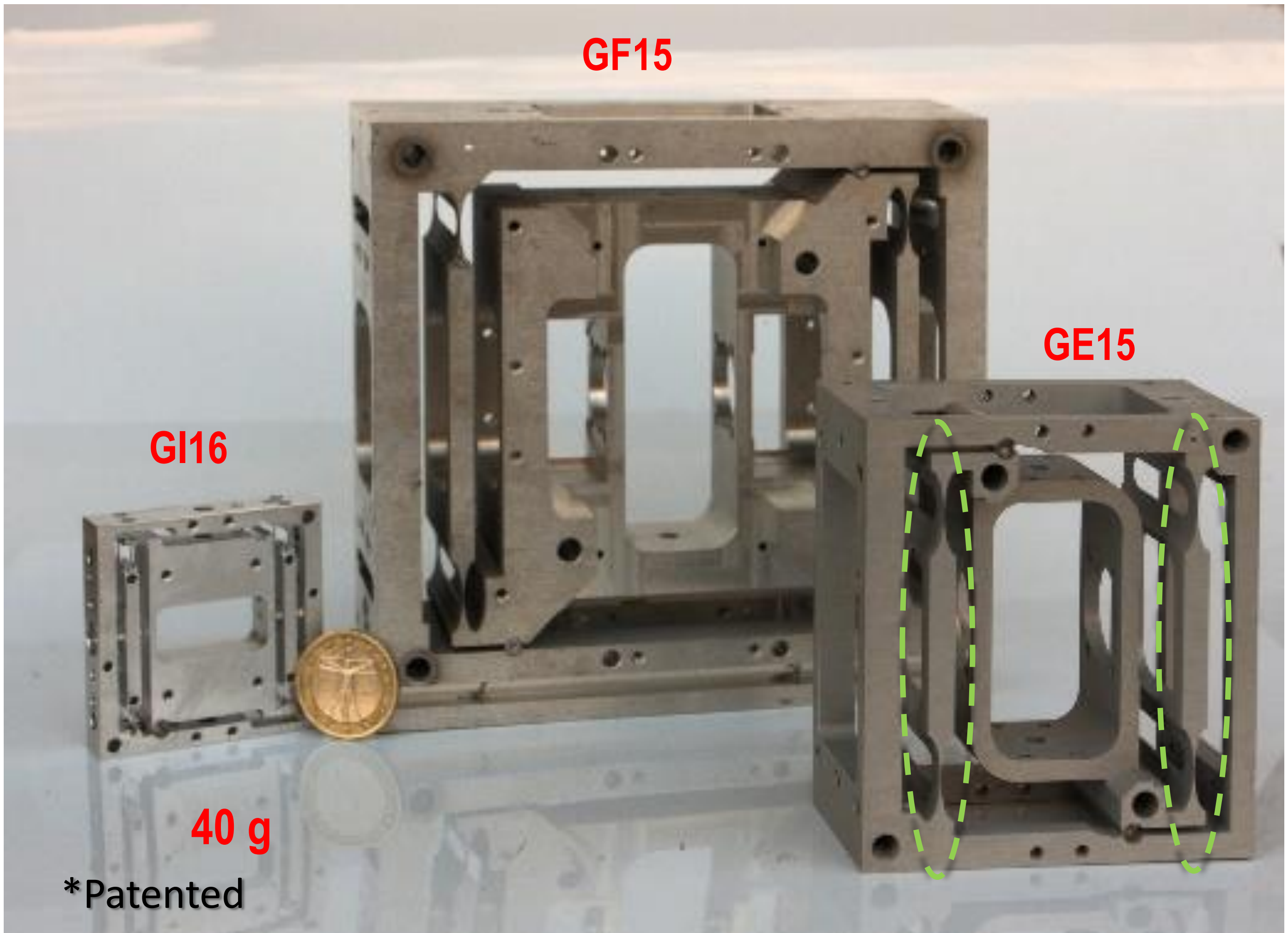

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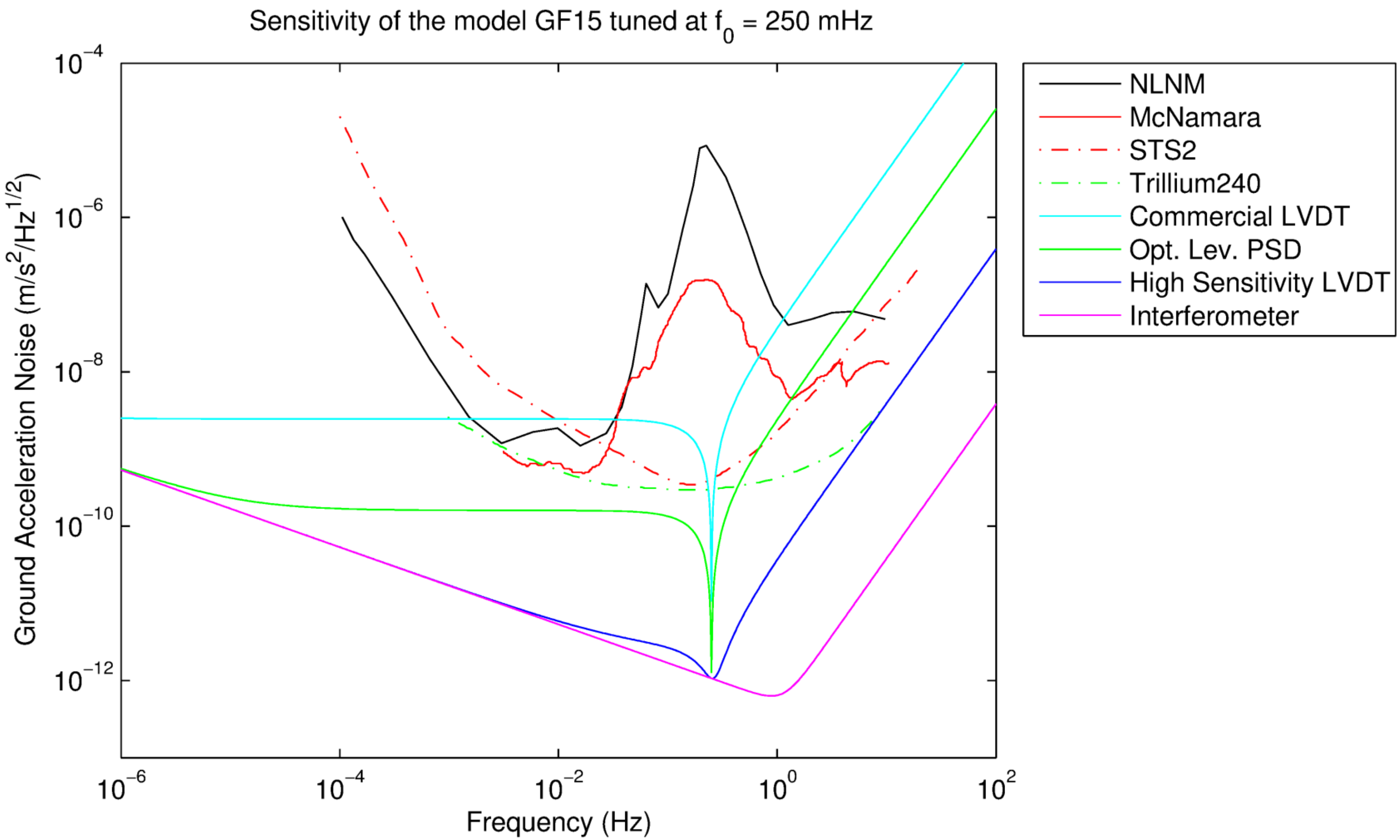
Sensor Sensitivity with different read-out systems



Without taking into account any electronic noise of the read-out system: it isn't a fundamental noise

Common Aluminum Alloy properties

Density of Aluminum

- Aluminum has a density around one third that of steel or copper making it one of the lightest commercially available metals. The resultant high strength to weight ratio makes it an important structural material allowing increased payloads.

Strength of Aluminum

- Pure aluminum doesn't have a high tensile strength. However, the addition of alloying elements like manganese, silicon, copper and magnesium can increase the strength properties of aluminum and produce an alloy with properties tailored to particular applications.
- Aluminum is well suited to cold environments. It has the advantage over steel in that its' tensile strength increases with decreasing temperature while retaining its toughness. Steel on the other hand becomes brittle at low temperatures.

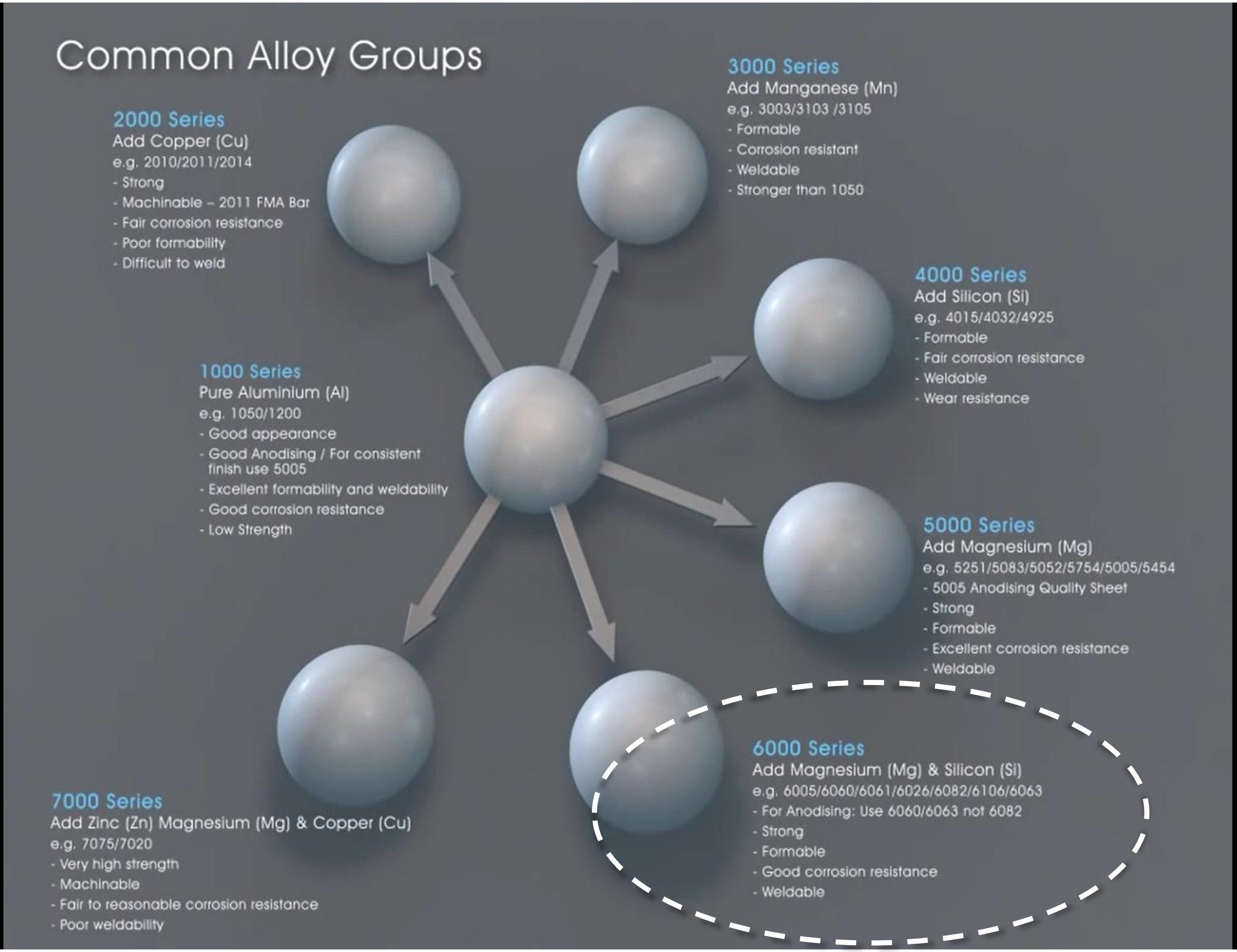
Corrosion Resistance of Aluminum

- When exposed to air, a layer of aluminum oxide forms almost instantaneously on the surface of aluminum. This layer has excellent resistance to corrosion. It is fairly resistant to most acids but less resistant to alkalis.

Thermal Conductivity of Aluminum

- The thermal conductivity of aluminum is about three times greater than that of steel. This makes aluminum an important material for both cooling and heating applications.

AA6082-T6



T6: heat-treated and then artificially aged

AA6082-T6: Strong with a good corrosion resistance for working outdoors (*approved for marine applications)*

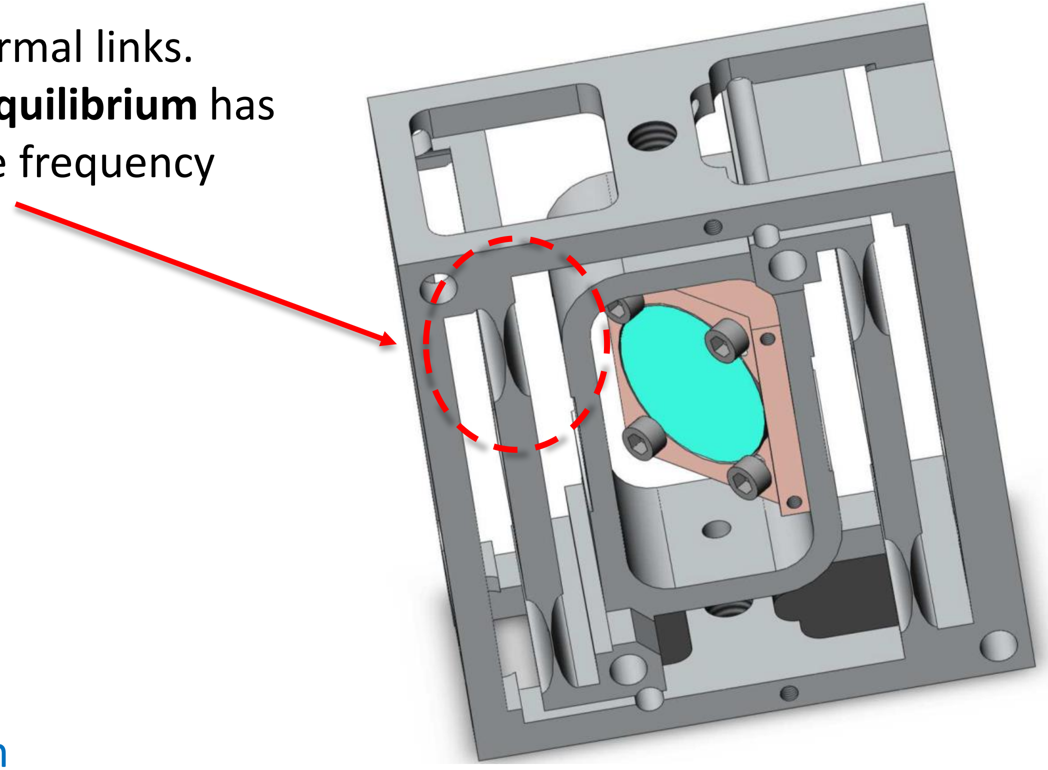
Why cryogenic measures?

- Characterizing the low temperatures sensor performances: *could the sensor work in a large range of temperature (3-300K)*? (*Done*)
- Characterizing the sensor and its main limits: *is it possible to improve it?* (*Done*)
- Measuring its performance as a tilt-meter at low temperature (*Done*)
- Optimizing sensor parameters to different environments and uses (*Next steps*)

Sensor thermalization

The 8 joints (thickness 0.1mm) are bad thermal links.
The time necessary to reach the **thermal equilibrium** has been determined measuring the resonance frequency change according to :

$$f_0 \propto \sqrt{k_\theta} \propto \sqrt{E(T)}$$



Measurement system

Customized Cryomech PT405 pulse tube to have low seismic noise and very low recoil losses

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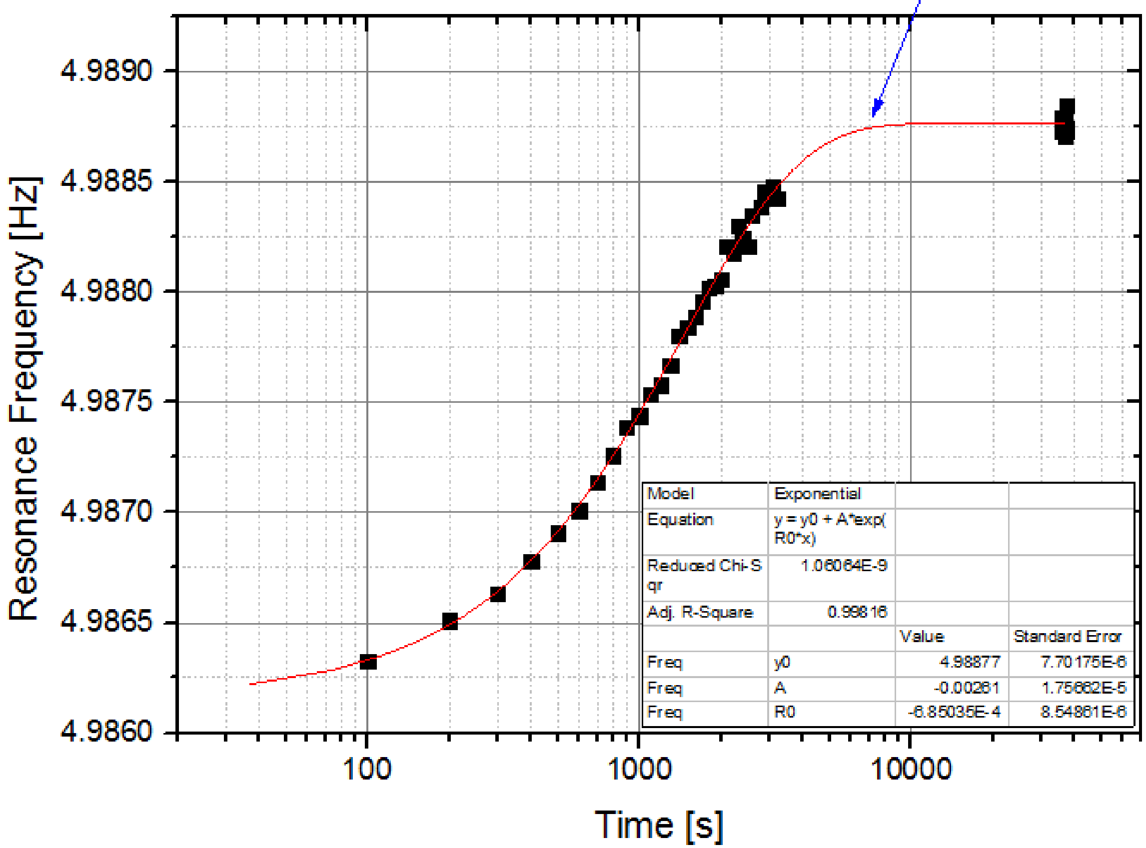
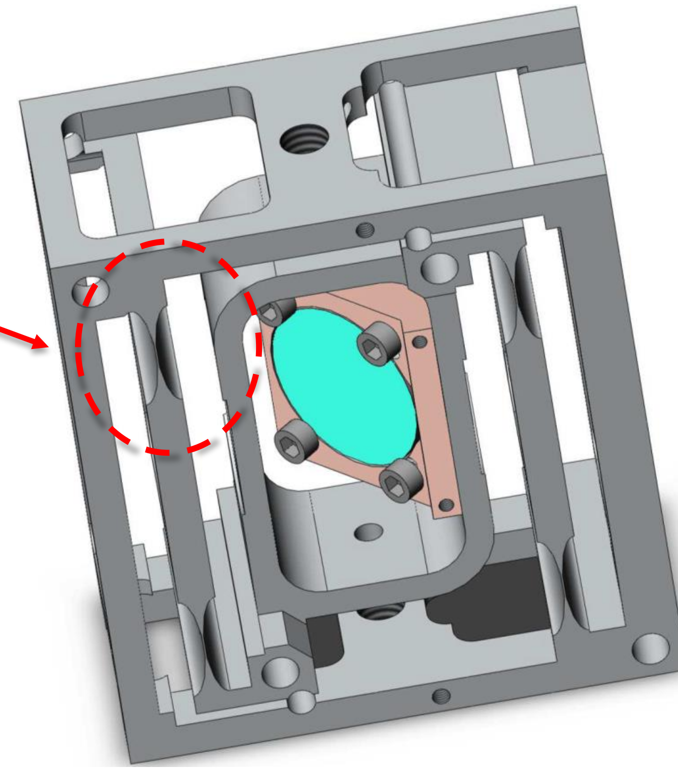
τ = 1/2hour => Thermal equilibrium in 2hours

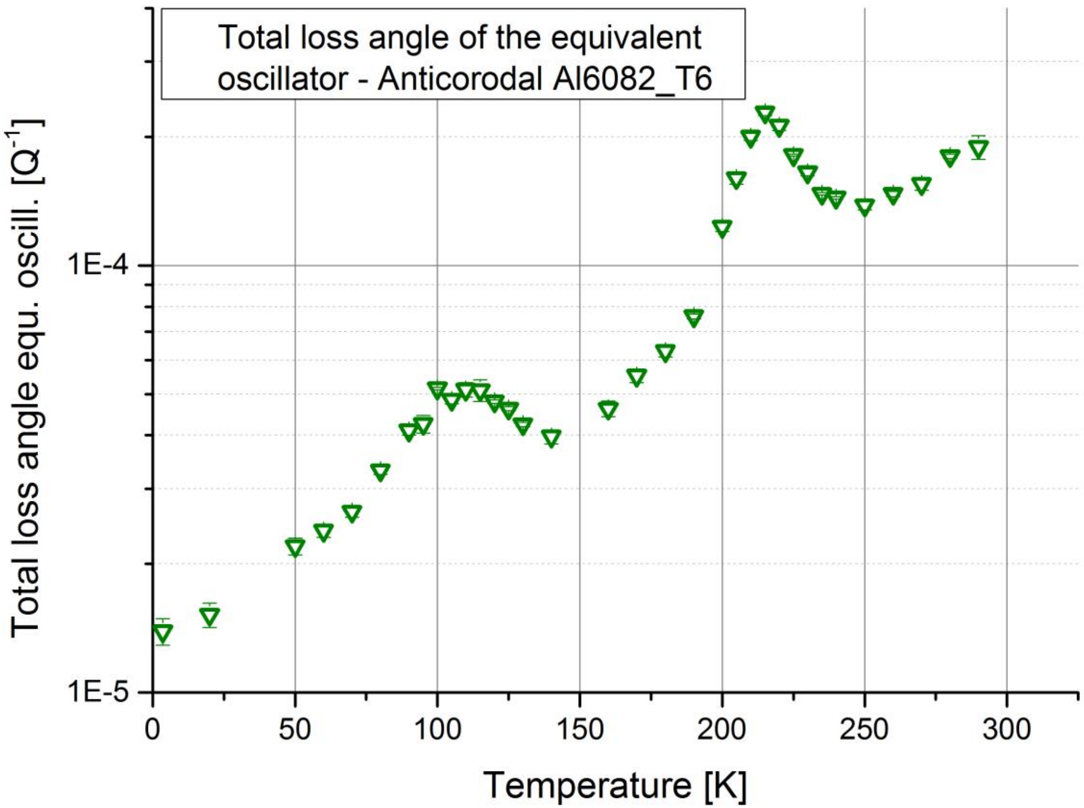




Alternative result

The time to reach the thermal equilibrium (τ) at the different temperatures can be used to evaluate the change of the **thermal conductivity** of the material with the temperature

Cryogenic performances – Loss Angle



Measurement method

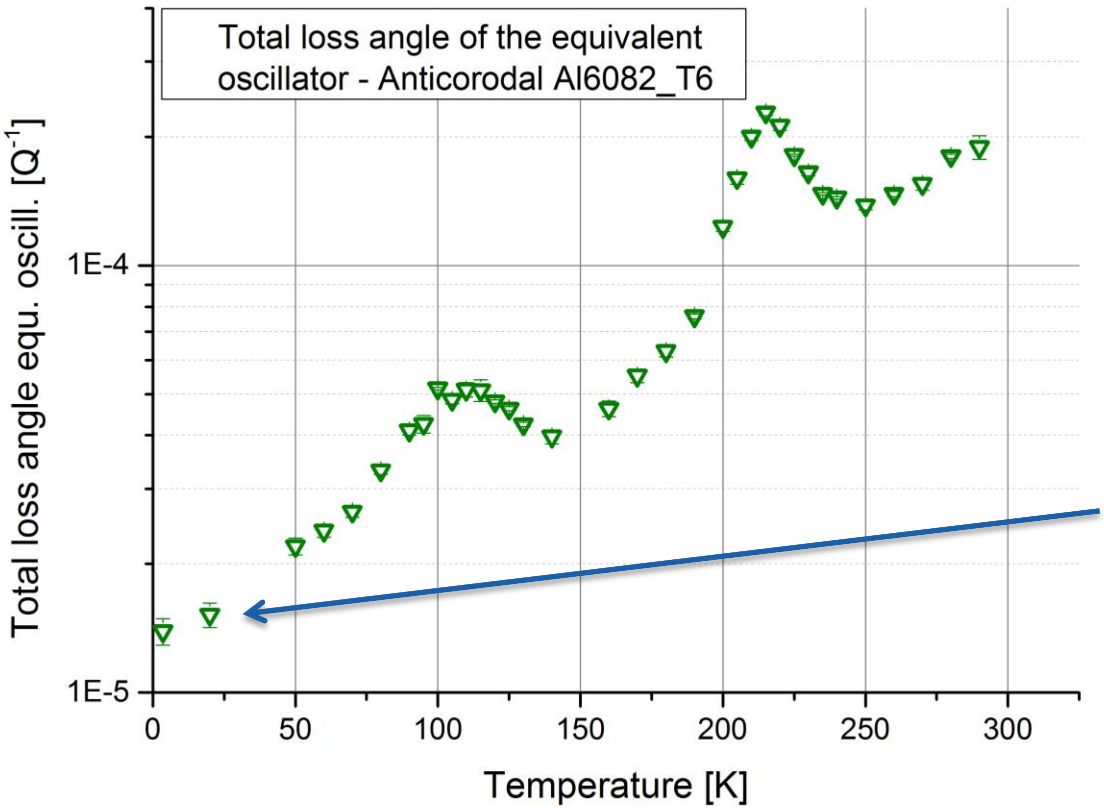
- Excite the resonance mode of the oscillator/sensor
- Measure the time decay, τ, of the resonance
- Evaluate the quality factor of the mode: $Q=\pi*f_0*\tau$
- Evaluate the loss angle $\varphi=1/Q$

The loss angle takes into account the energy lost in the sensor during its oscillations

The Fluctuation/Dissipation theorem links the dissipation of a mechanical system to its thermal noise and in particular states:

$$\langle x^2(f)\rangle = \frac{k_b T}{\pi^3 f}\frac{\varphi}{m f_0^2}$$

Cryogenic performances – Loss Angle



The performances if the sensor increase at low temperature: **the lower the φ the better the thermal noise**

The Fluctuation/Dissipation theorem links the dissipation of a mechanical system to its thermal noise and in particular states:

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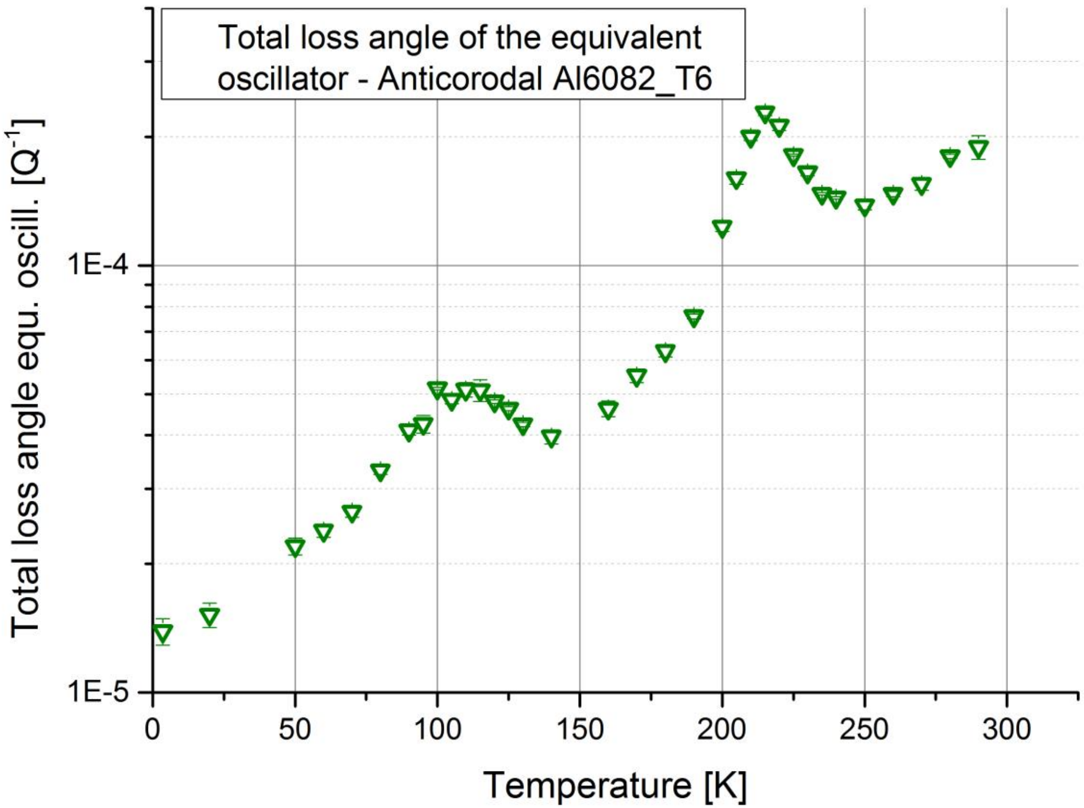
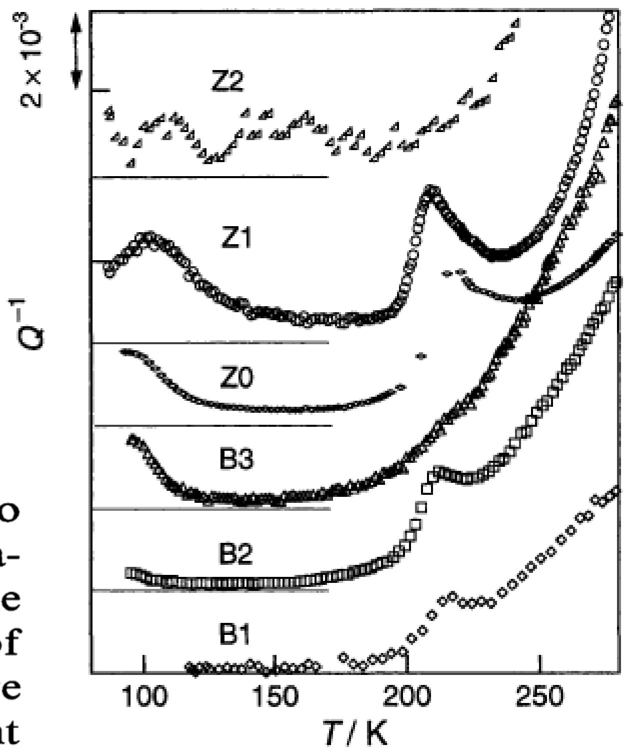
Cryogenic performances



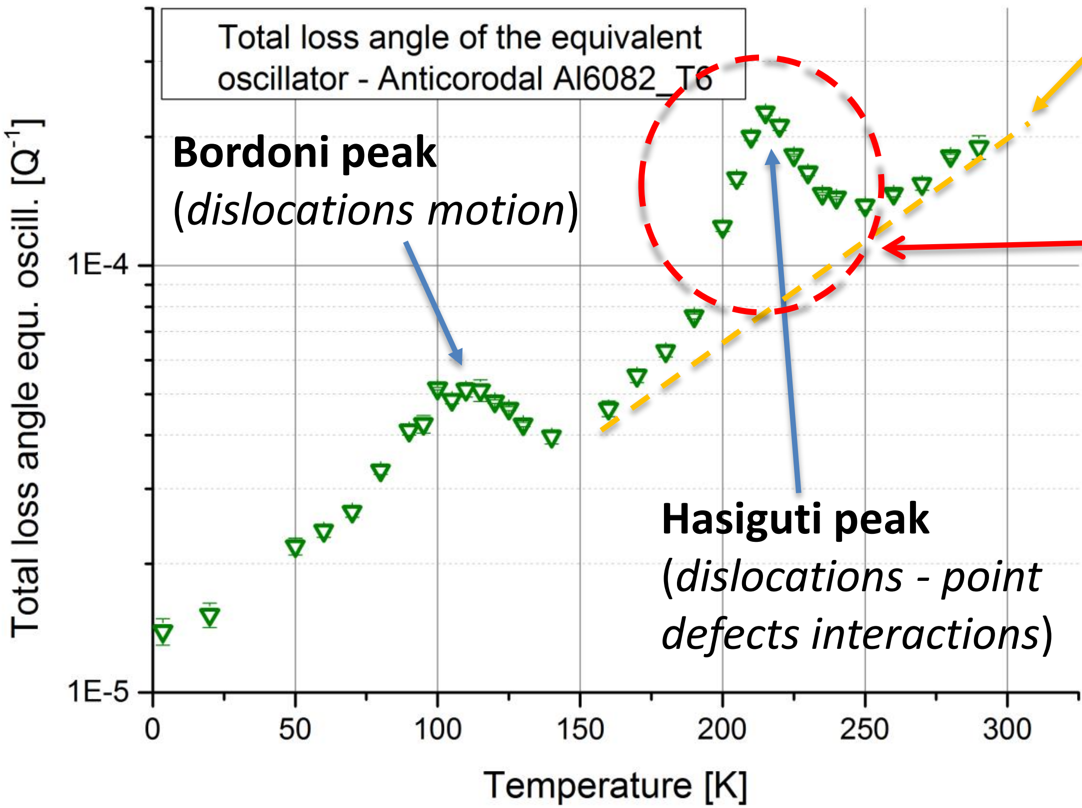
In literature



Materials Transactions, JIM, Vol. 40, No. 6 (1999), pp. 498 to 507

Cold-worked pure fcc metals are known to exhibit two types of internal friction peaks below room temperature, the Bordoni peaks and the Hasiguti peaks[(1)–(3)]. The former are generally attributed to intrinsic motion of dislocations over the Peierls barrier, while the latter are considered to be due to dislocations combined with point defects such as vacancies introduced by cold-working.

Cryogenic performances



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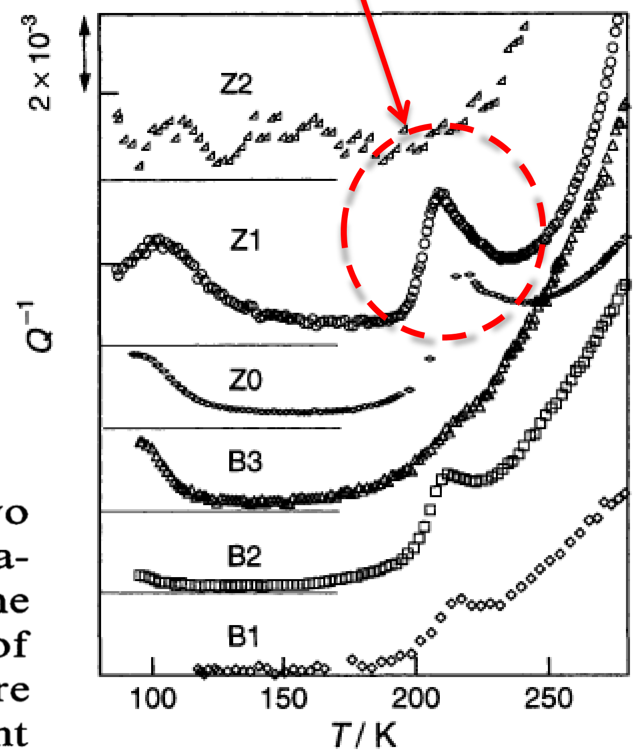

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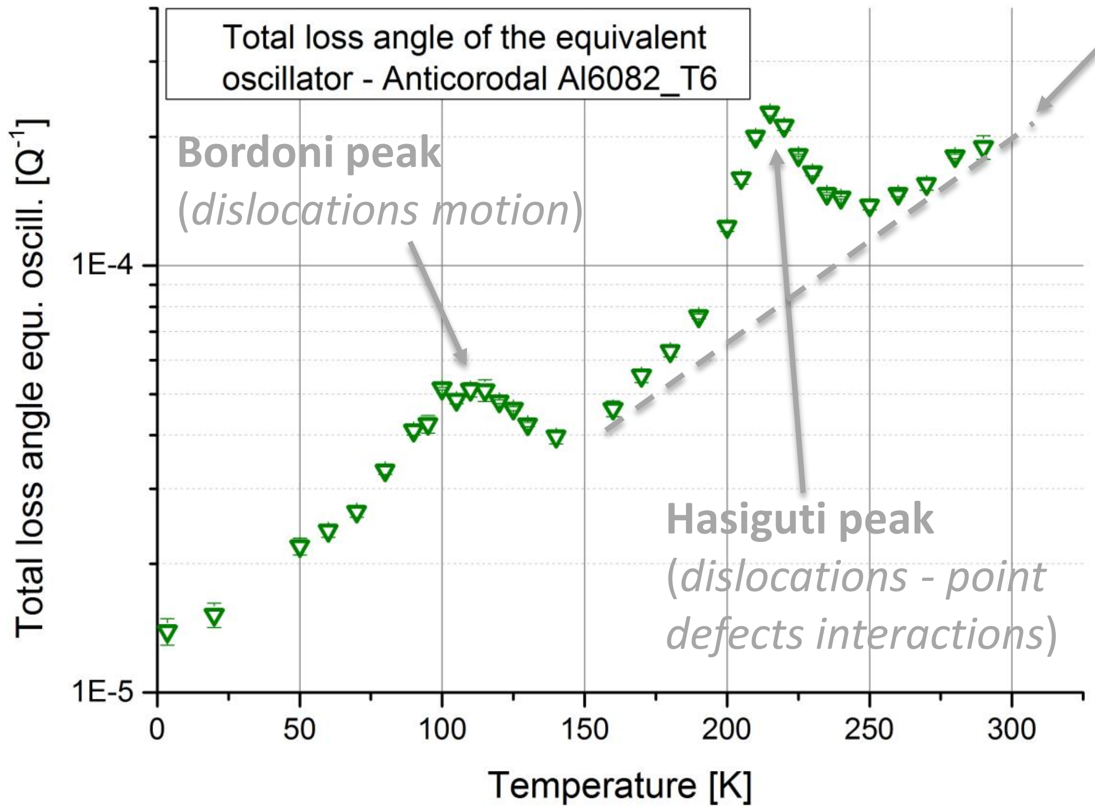


Exponential damping background (*viscous plastic deformation – grain boundary relaxation*)

MAIN RESULTS

Sensor performances (*Q vs. T*): sensor suitable in a large range of temperature and its performances improve with the temperature decreasing (Best Q ~ $7*10^4$)

No extra losses: no clamping dissipations, no structural problems, no recoil losses (sensor design)

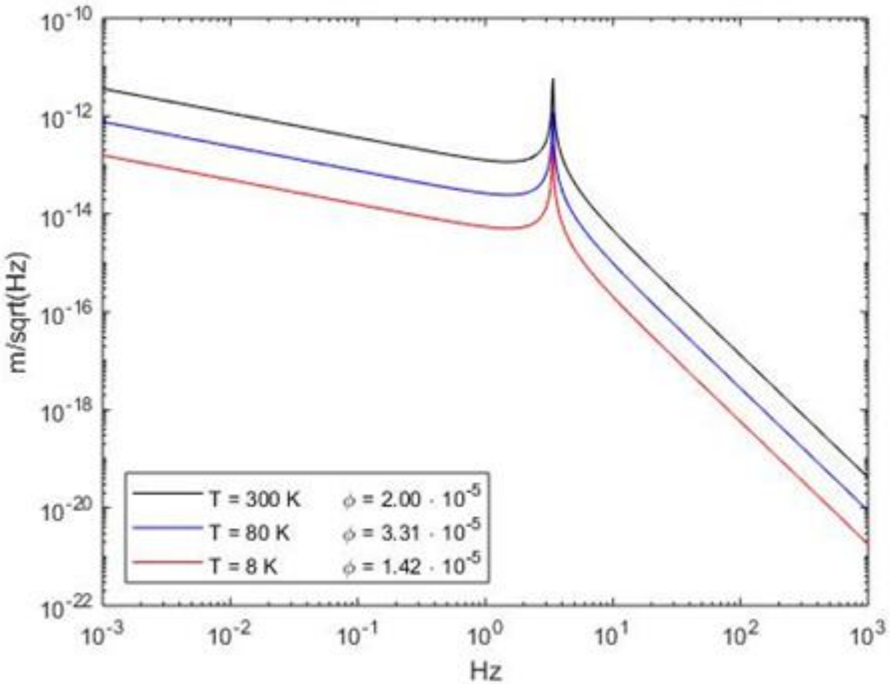
Material as main limit: a possible improvement of the sensor could be reached using a better materials like the Al5056* that exhibits an internal friction of one order of magnitude lower than Al6082 + or could be obtained just replacing the joints: all the stresses are concentrated in the elastic hinges => **the sensor can be easily optimized**

+ *Internal Friction in Metallic Materials - A Handbook*

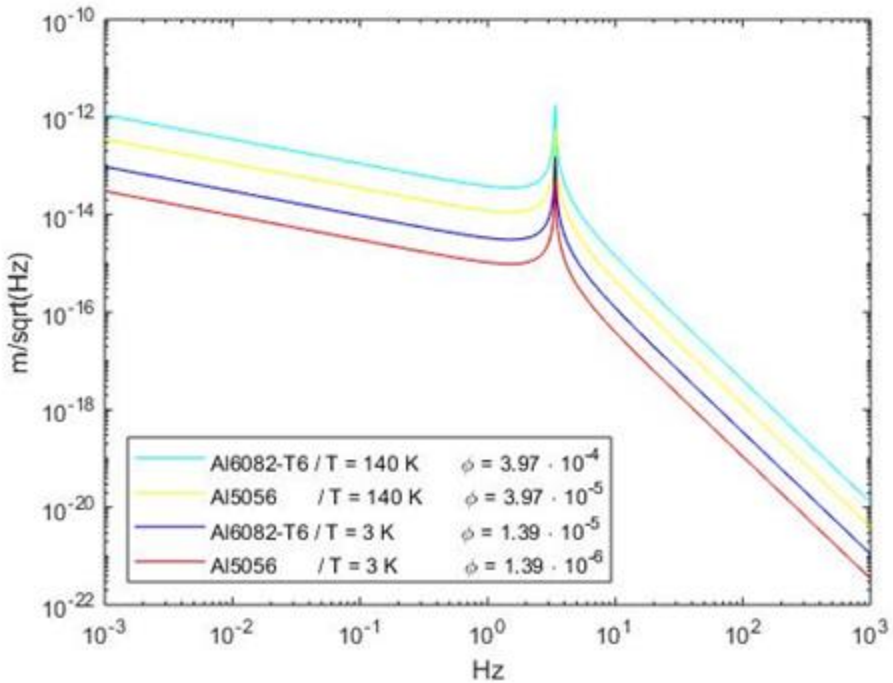
*Al5056 is the material used for the cryogenic resonant bars *(Auriga: T=0.1K, $f_{0.1}$=920Hz, $Q_{0.1}$~$4*10^6$ - Ref: Auriga webpage*

Sensor thermal noise

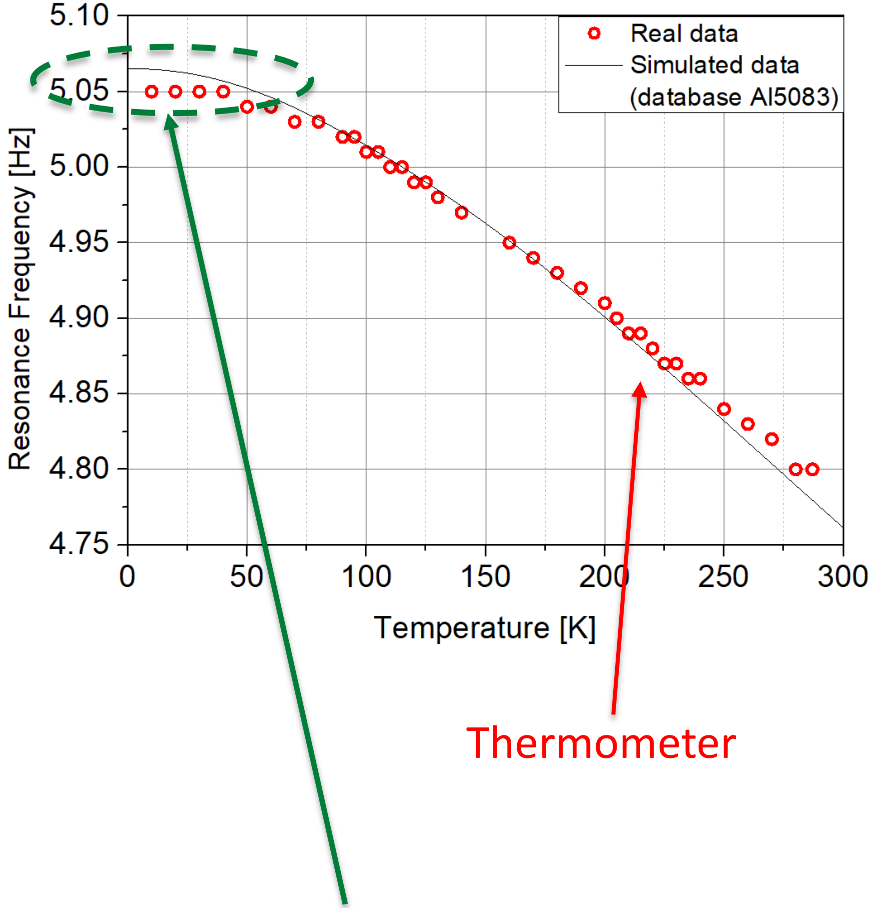
Improving of the sensor sensitivity (thermal noise as main limit) due to the improving of the loss angle φ (reduced internal losses) with the temperature



Improving of the sensor sensitivity (thermal noise as main limit) due to the improving of the material



Frequency vs Temperature



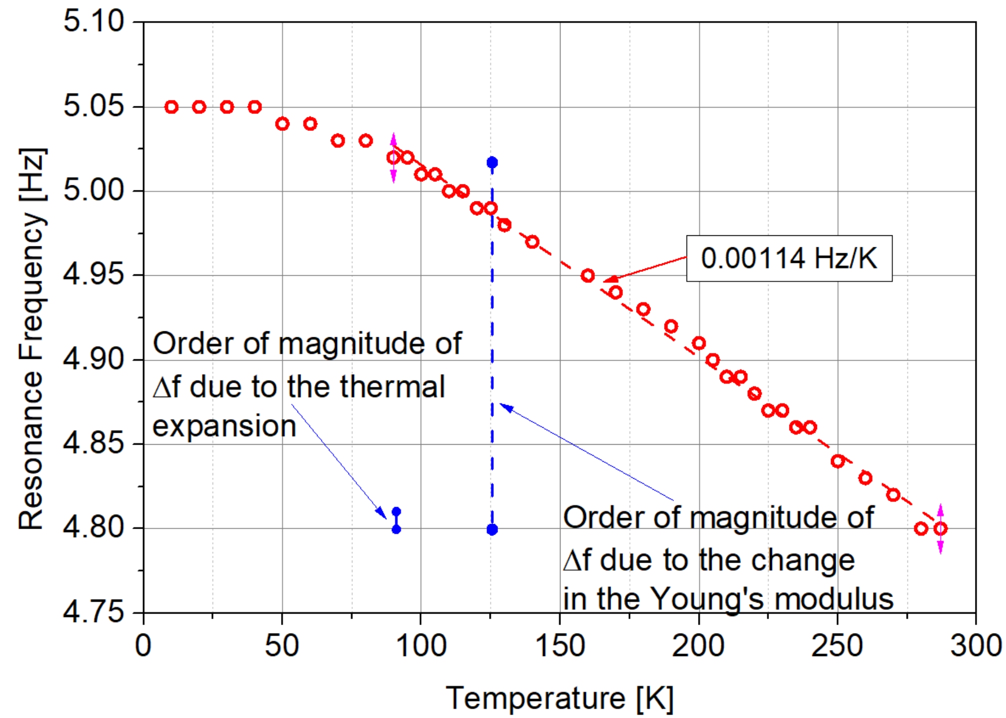
Frequency is **not sensitive** to temperature changes => tilt-meter in cryogenics (see next slides)

http://reference.lowtemp.org/alkappa.html

Alternative result

In literature there are no data for the AA6082 elastic modulus at low temperature: these are the first organized data that we can use to extrapolate the Young's modulus

$$\left[f_0 \propto \sqrt{k_\theta} \propto \sqrt{E(T)}\right]$$



Frequency vs Temperature

The frequency linear trend means a quadratic trend for the Young's modulus $\left[f_0 \propto \sqrt{k_\theta} \propto \sqrt{E(T)}\right]$

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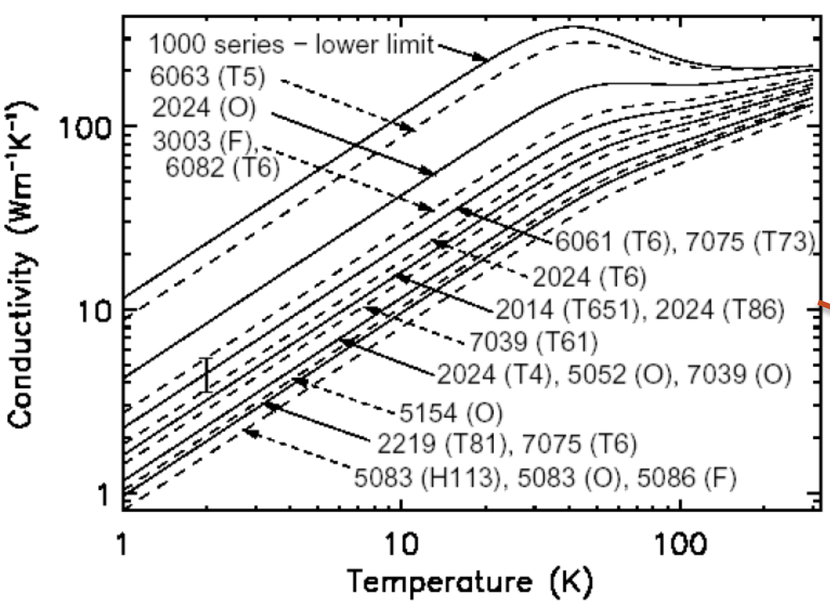
…with a good definition using the conductivity data



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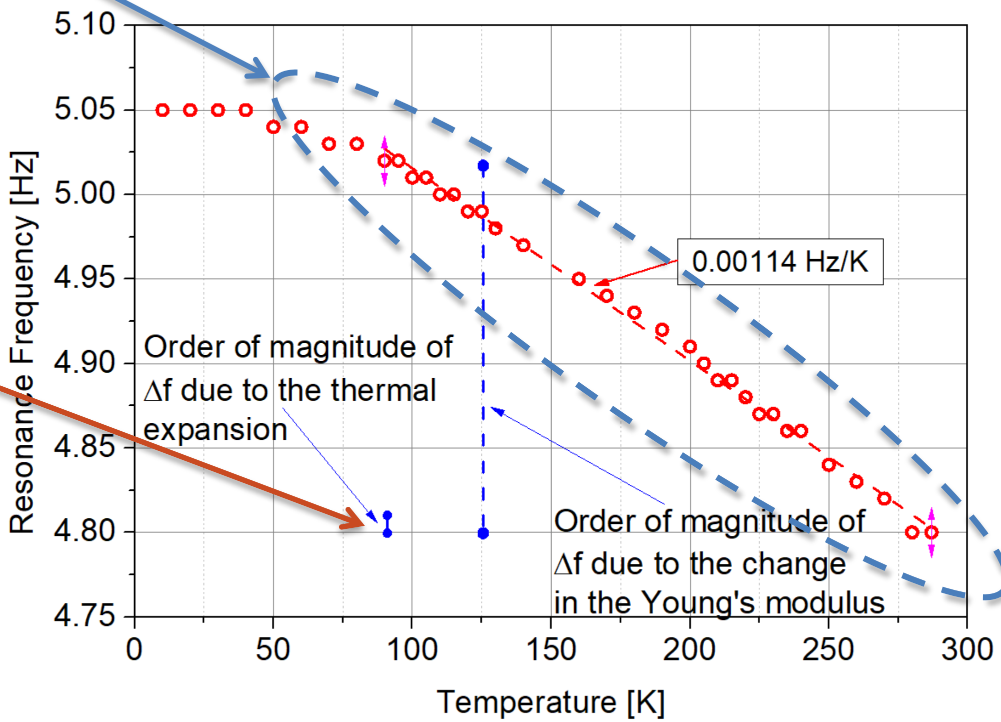
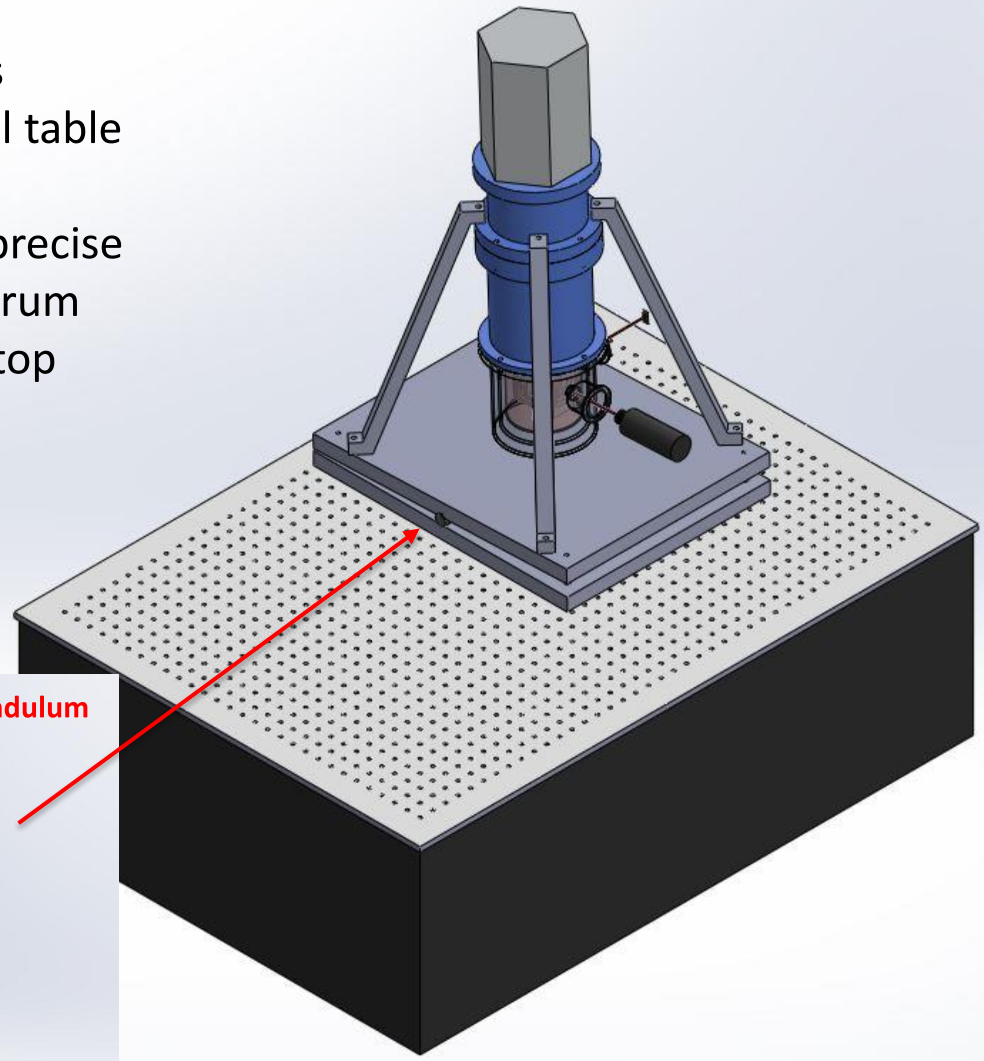


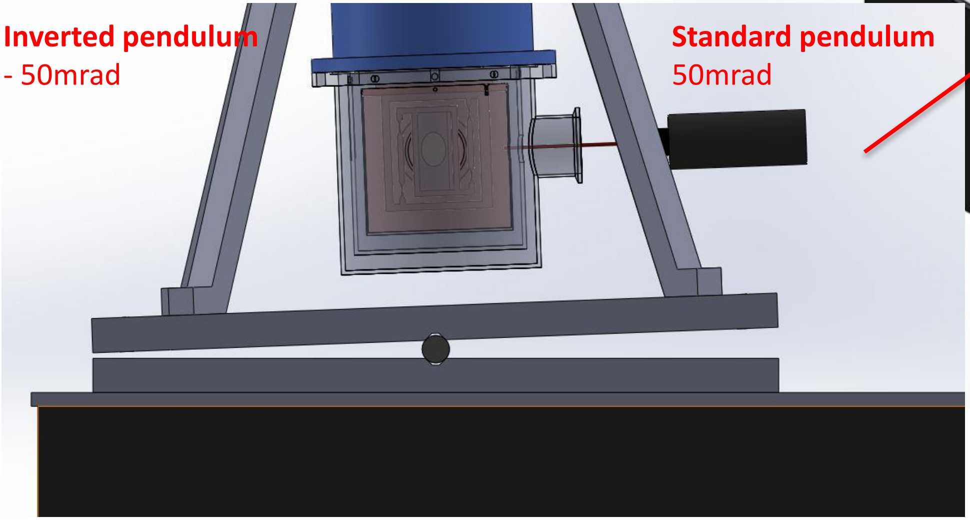
Tilt measurements

Measurement set-up

- One aluminum plates, thick 25mm, is strongly screwed on a massive optical table
- A second aluminum plate is strongly screwed at the first plate but with a precise inclination thanks to a cylindrical fulcrum
- The Pulse Tube is tightened on their top

The system was designed and realized in order to minimize the recoil losses



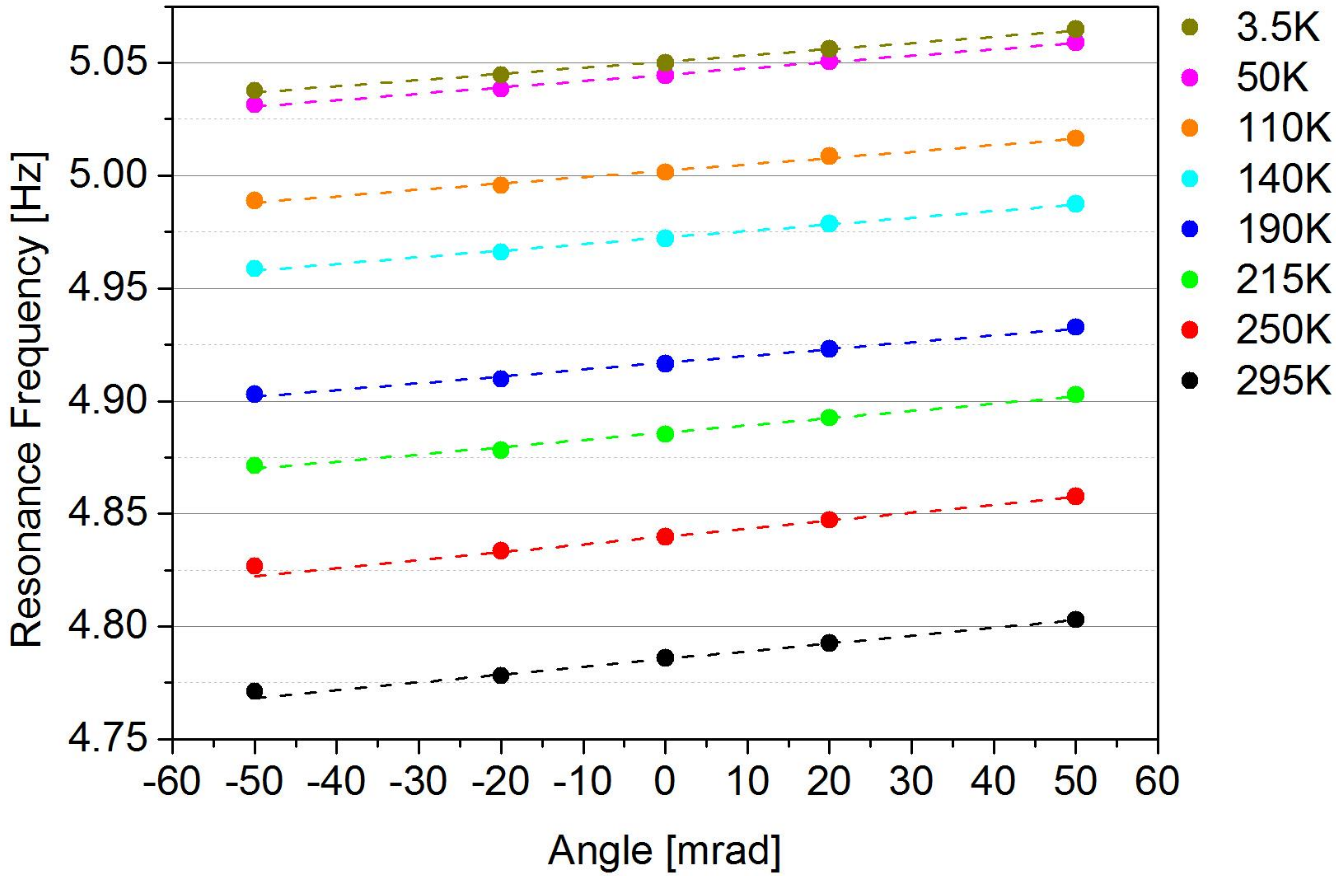


Angular dependency of sensor resonance frequency

As predicted by the model for this folded pendulum, the resonance frequency shows a linear dependence on the pitch angle for small angle from the horizontal => to measure the angular motion we can measure the change of resonance frequency: due to its asymmetric response, it is possible to know the direction of the change of angle

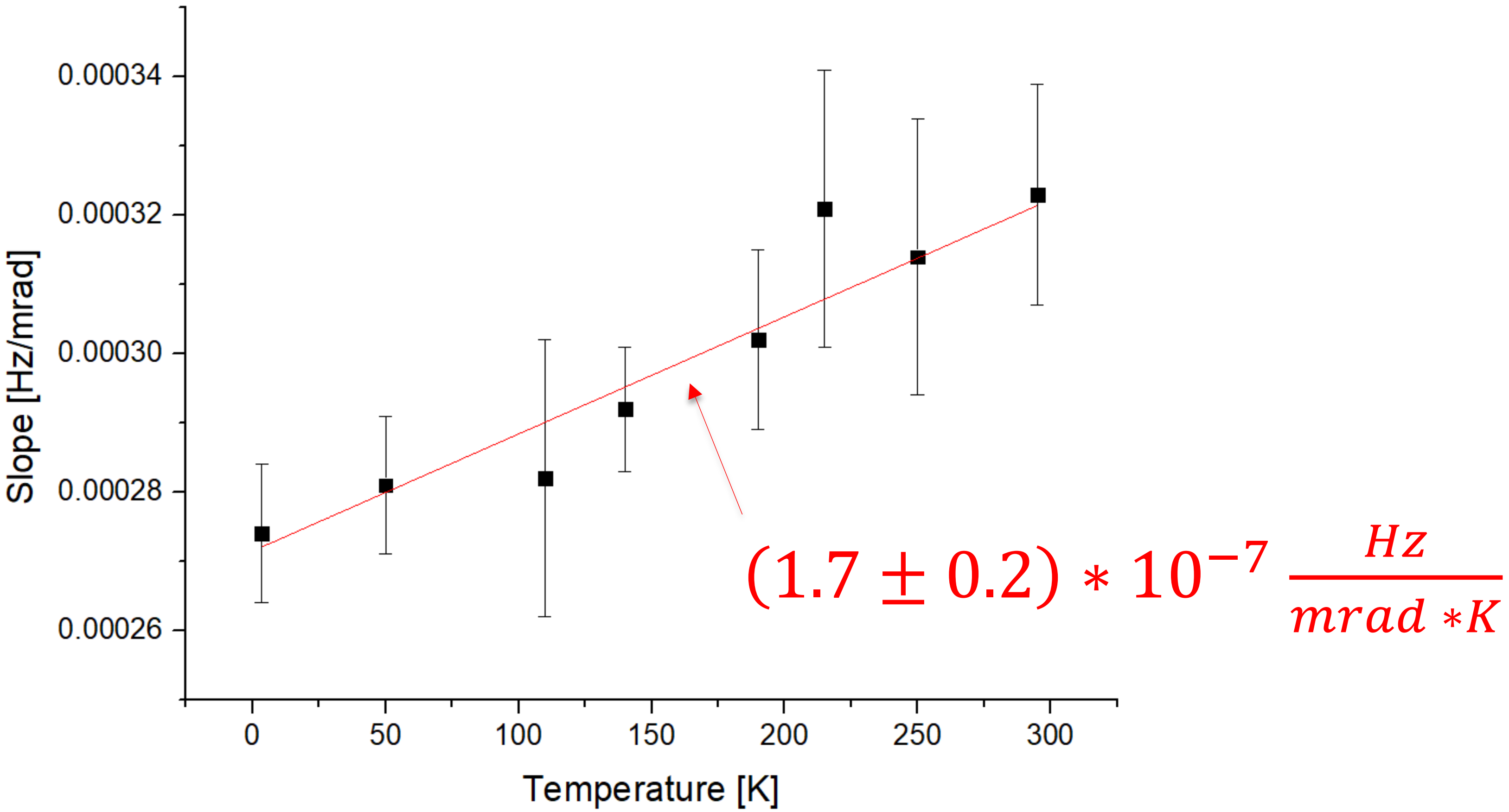
It easy to decouple the axial motion and the angular motion of the sensor:

- for the former we have to measure its oscillations
- for the latter we have to measure it change of resonance frequency

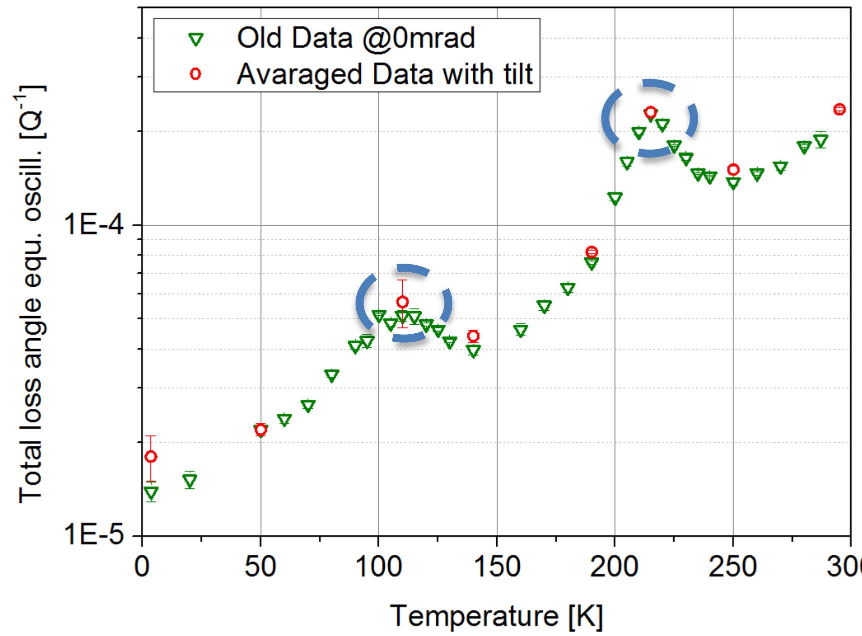


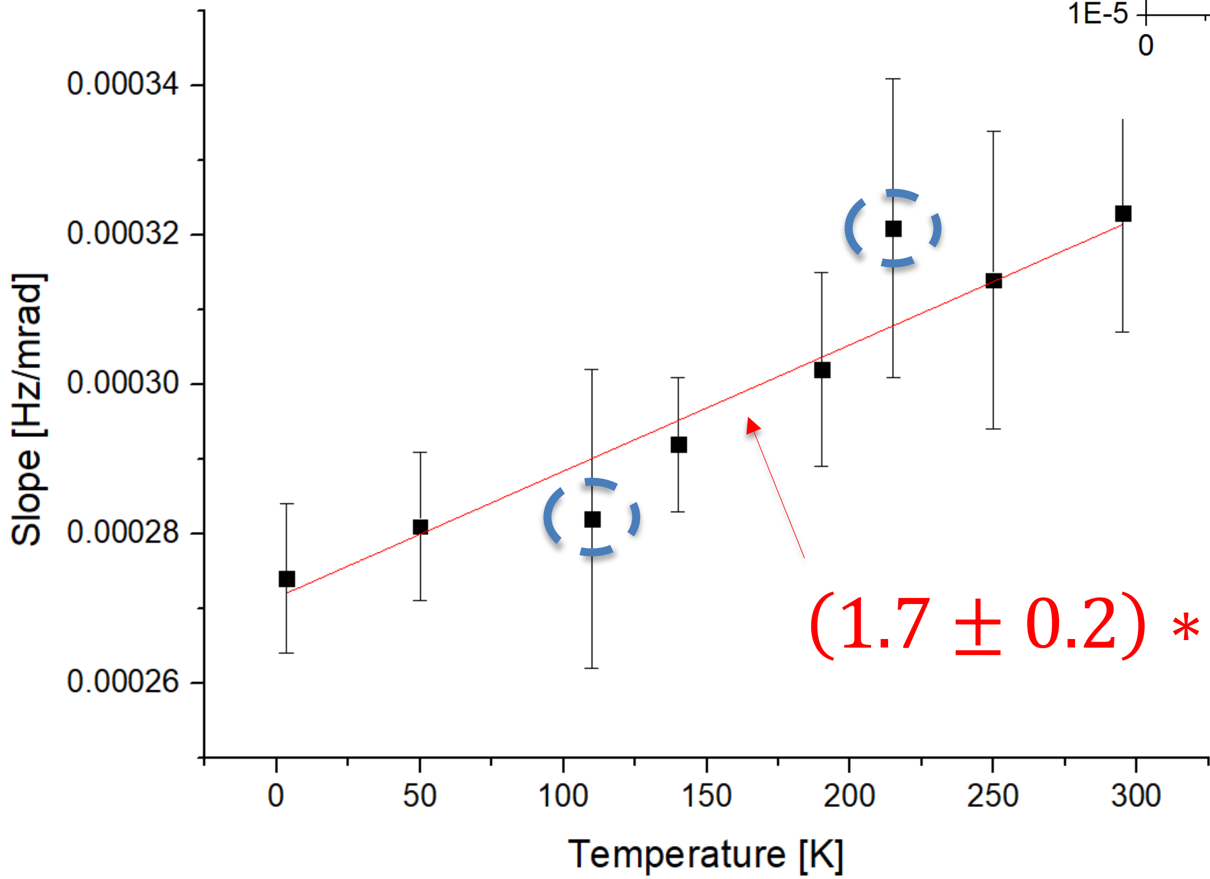
Slopes of the Freq.vs.Angle @ different temperatures

The resonance frequency versus tilt slopes appear to be linearly dependent on the temperature.
This gives the possibility to calibrate the sensor response to extrapolate the angular information using it as a tilt-meter.



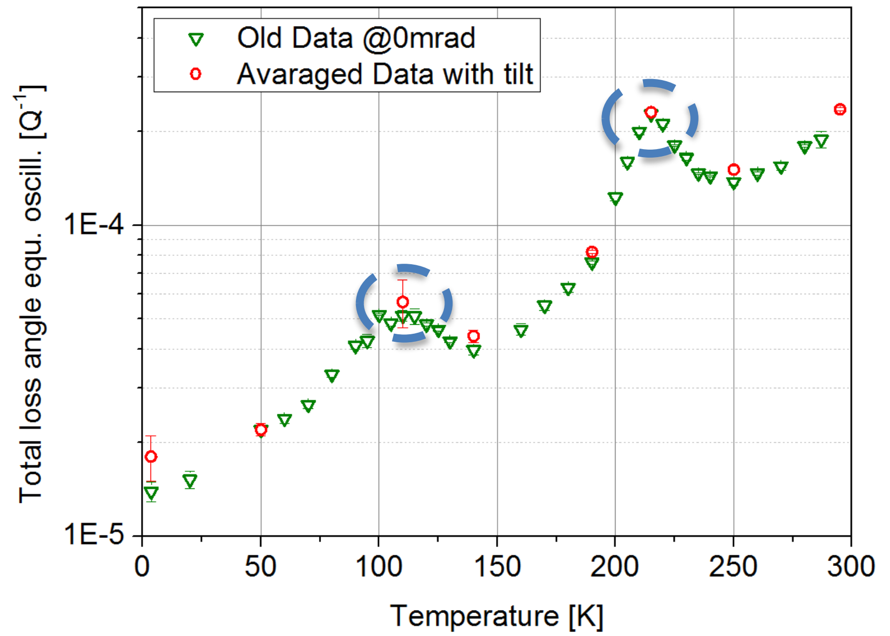
NOTE: the points far from the linear fit are the points with the maximum dissipation: a better definition in temperature is needed

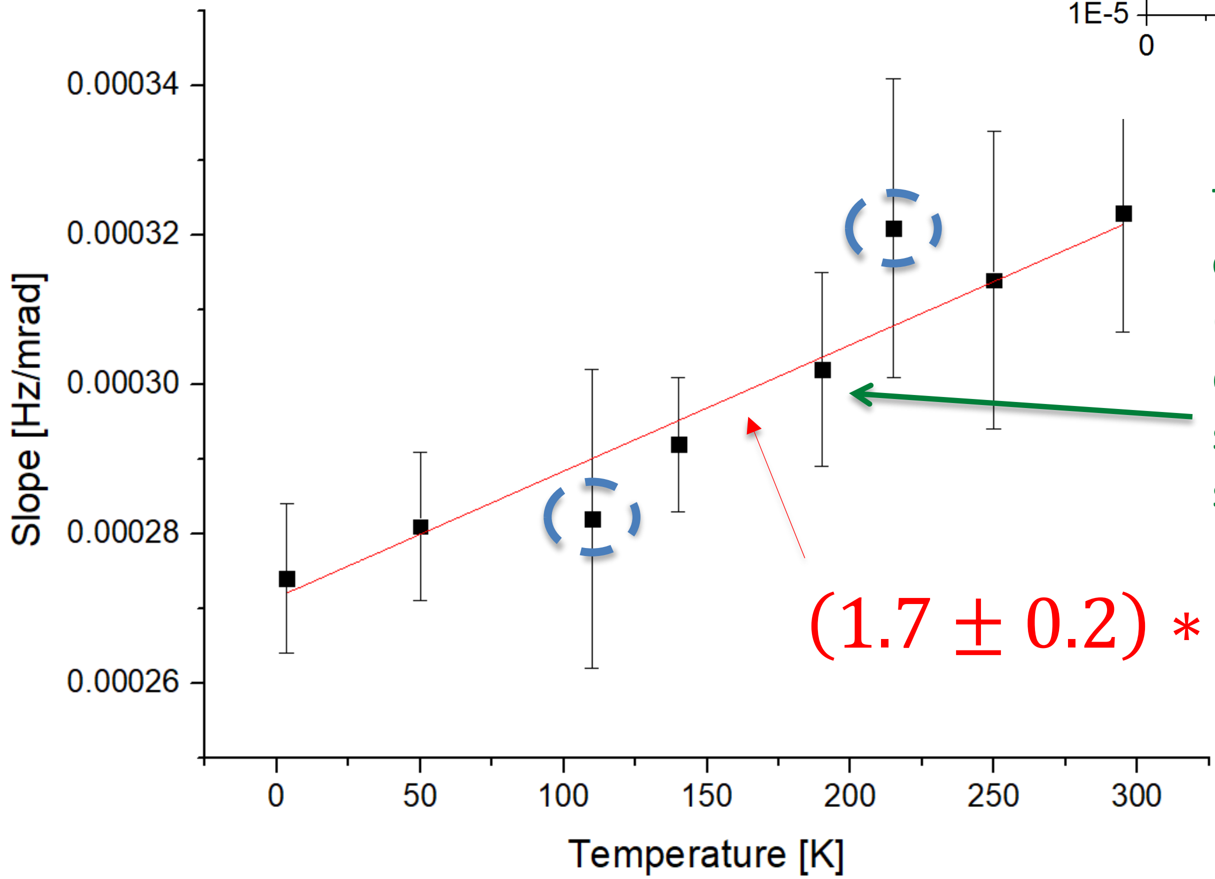




$$(1.7 \pm 0.2) * 10^{-7} \frac{Hz}{mrad * K}$$

NOTE: the points far from the linear fit are the points with the maximum dissipation: a better definition in temperature is needed





The sensor tested is **not optimized** as angular sensor (almost symmetrical distribution of the masses: see slide 10) and that means a slope around **3*10^{-4}Hz/mrad**

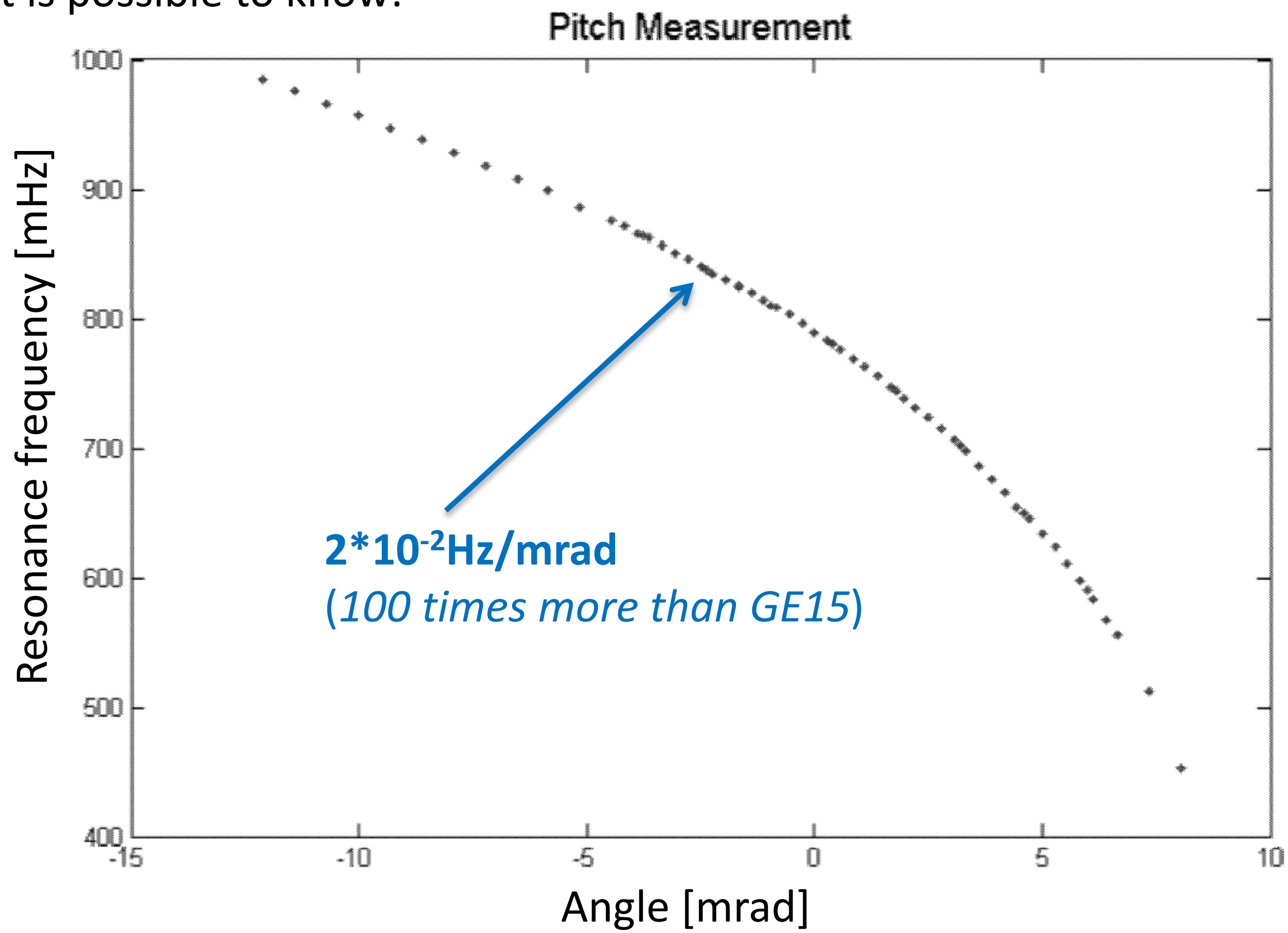
$$(1.7 \pm 0.2) * 10^{-7} \frac{Hz}{mrad * K}$$

Resonance frequency @ T_{room} for an optimized angular sensor

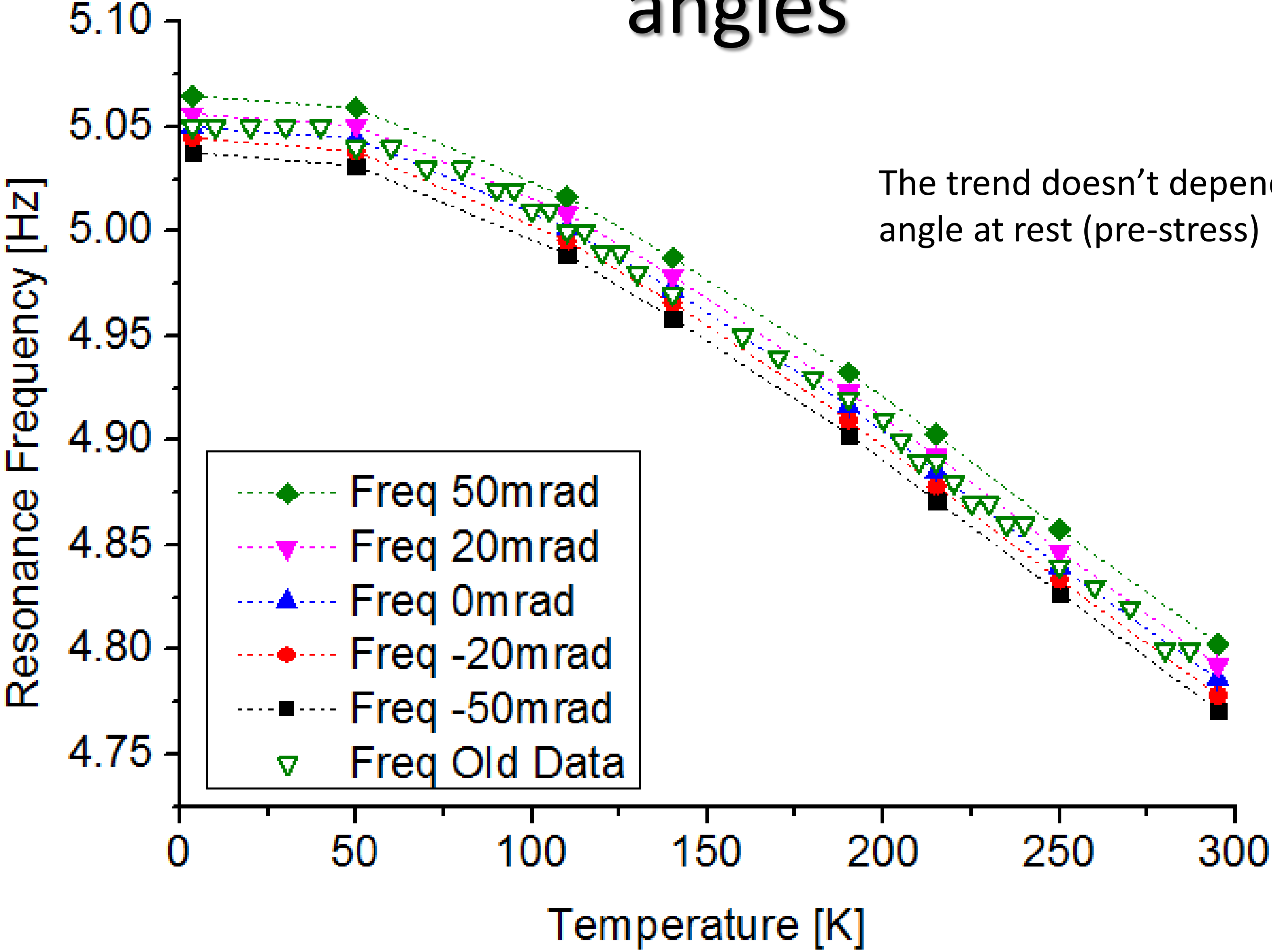
For an optimized angular sensor, its change in frequency is around 0.02Hz/mrad => acquisition time ~ 50s.

Knowing the temperature, it is possible to know:

- the static value (or the mean value for little oscillation) of the angle at rest
- slow angular drifts
- the direction of the angular motion (the sensor response is asymmetric
- the angular sensitivity can be increased by changing its working point.



Frequency vs Temperature @ different angles



The trend doesn't depend on the angle at rest (pre-stress)

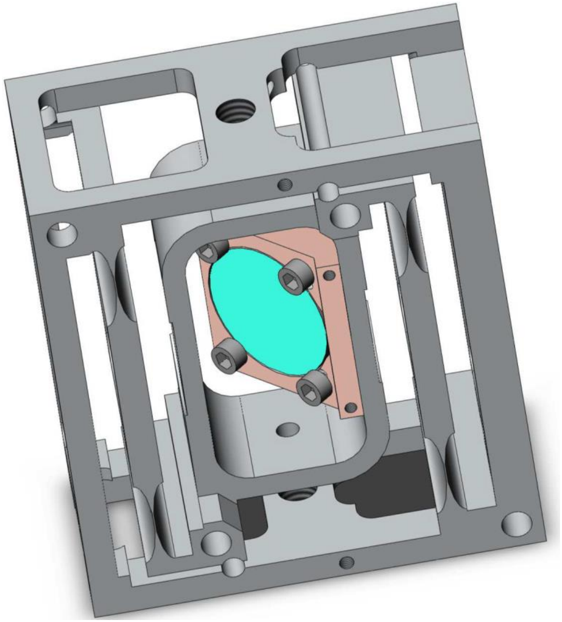
Conclusions and perspectives

- Cryogenics is not a limit for the sensor indeed its performances improve at very low temperatures
- The material is the main limit of sensor performances: new material with lower losses (e.g. Al5056) maybe only for the joints (stresses totally confined in the elastic joints)
- Next steps:

  The sensor is easily *scalable/tunable* that means that it is possible to optimize its main parameters (mass, resonance frequency, dimensions) taking into account its use, environment and position:

  - ✓ to characterize the same sensor with a lower resonance frequency (~0.1Hz) (*resonance frequency*)
  - ✓ to characterize the smallest sensor (*mass, dimensions, resonance frequency*)
  - ✓ to produce and characterize prototypes with new materials (*Q*)

Conclusions and perspectives

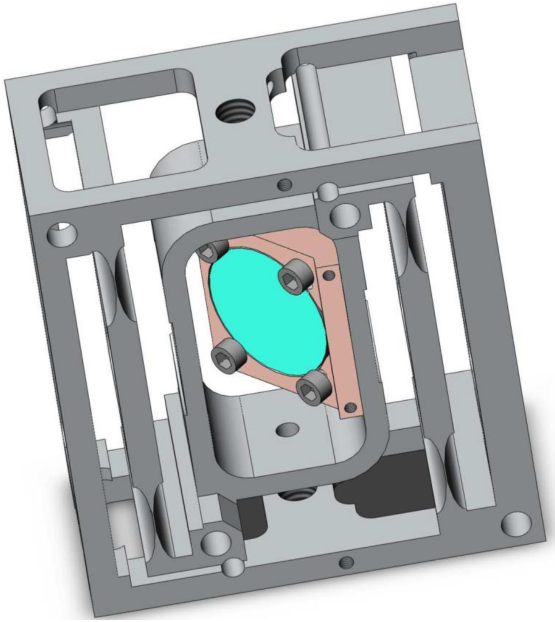


Alternative results

A positive counterpart of this analysis is that the sensor proved to be an excellent system for the study of materials: due to its peculiarities, with measures of frequency and loss angle, it is possible to extrapolate:

- Young's modulus (*Freq.vs.Temp*)
- Thermal conductivity (*Freq.vs.Time to thermalize*)
- Pre-stress effects (*Angle at rest, oscillating mass*)
- Internal losses (*Phi.vs.Temp*)

Conclusions and perspectives



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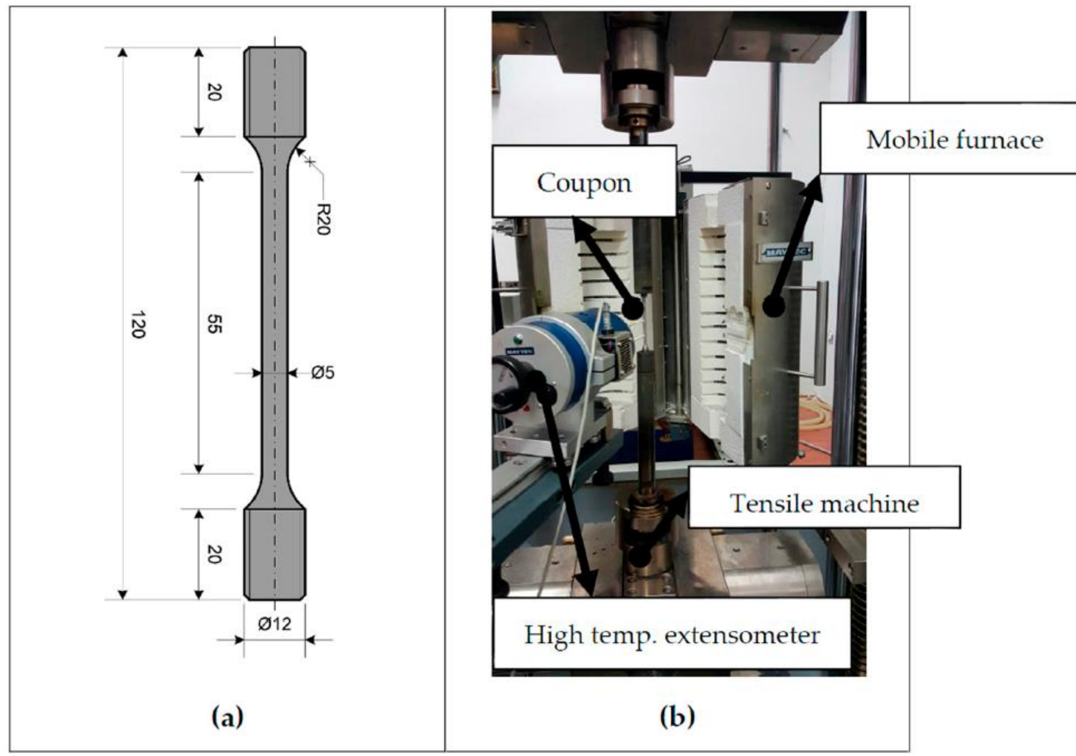


Neno Toric et al. Metals 2017, 7, 126 (doi:10.3390/met7040126)

Measures of frequency and loss angle are easier than the use of a tensile machine in cryogenics

END

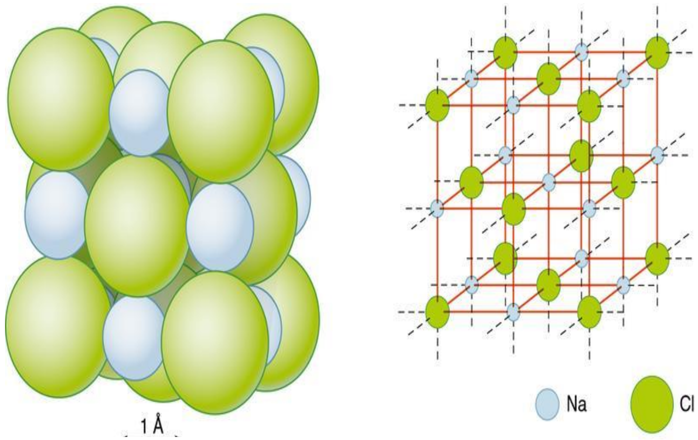
Thank you

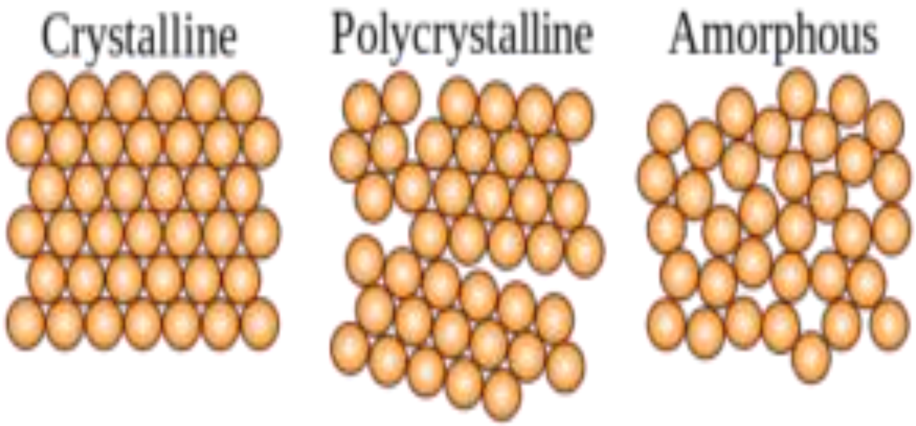
Extra Slides

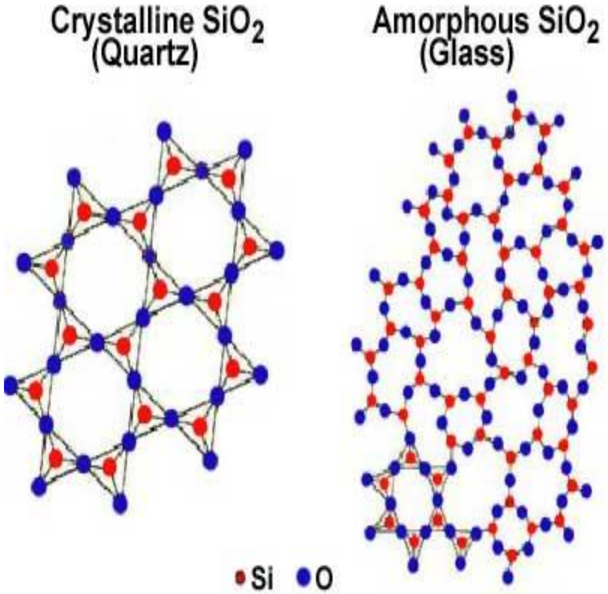
Material dissipations main sources

Materials structures

- Metal: crystalline or poly-crystalline structure
- Glasses: amorphous structures

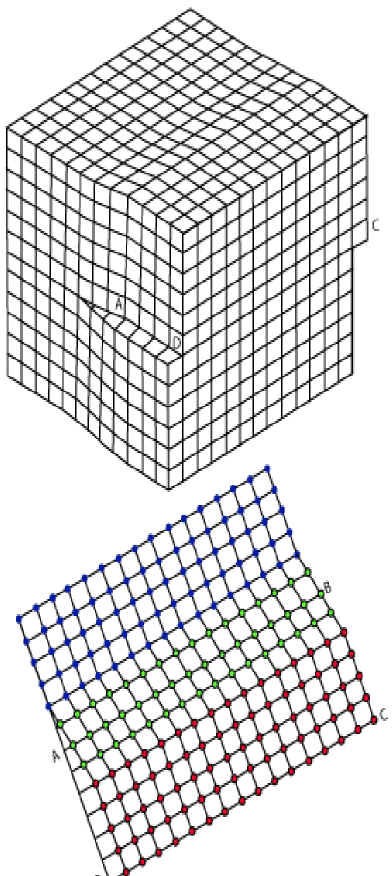


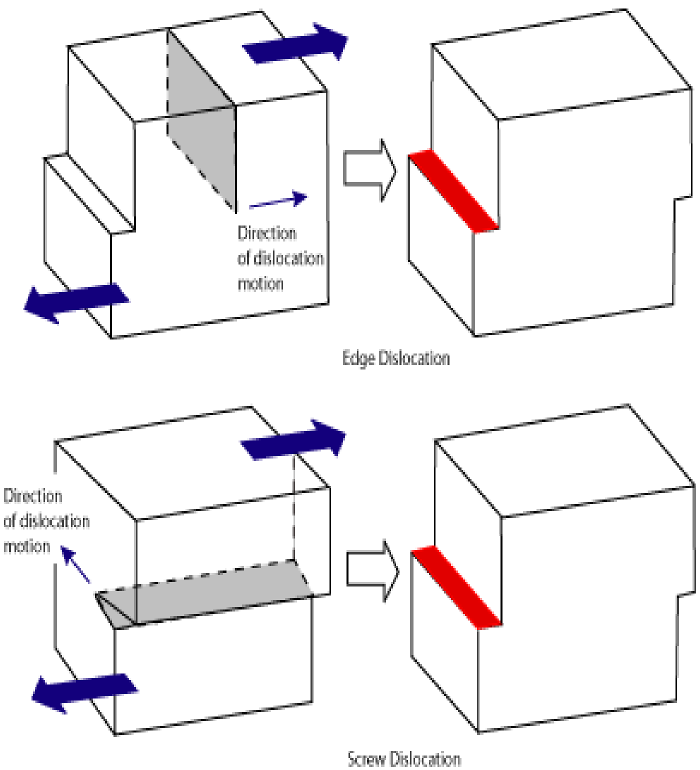




Material dissipation - Internal Friction

Defects relaxation generally means an anelastic relaxation caused by a redistribution of the defects under the action of an applied stress





https://www.nde-ed.org/EducationResources/CommunityCollege/Materials/Structure/point_defects.htm

Metals defects

A perfect crystal, with every atom of the same type in the correct position, does not exist. All crystals have some defects. Defects contribute to the mechanical properties of metals. In fact, using the term "defect" is sort of a misnomer since these features are commonly intentionally used to manipulate the mechanical properties of a material. Adding alloying elements to a metal is one way of introducing a crystal defect

- **point defects**: which are places where an atom is missing or irregularly placed in the lattice structure. Point defects include lattice vacancies, self-interstitial atoms, substitution impurity atoms, and interstitial impurity atoms
- **linear defects**: which are groups of atoms in irregular positions. Linear defects are commonly called dislocations.
- **planar defects**: which are interfaces between homogeneous regions of the material. Planar defects include grain boundaries, stacking faults and external surfaces.

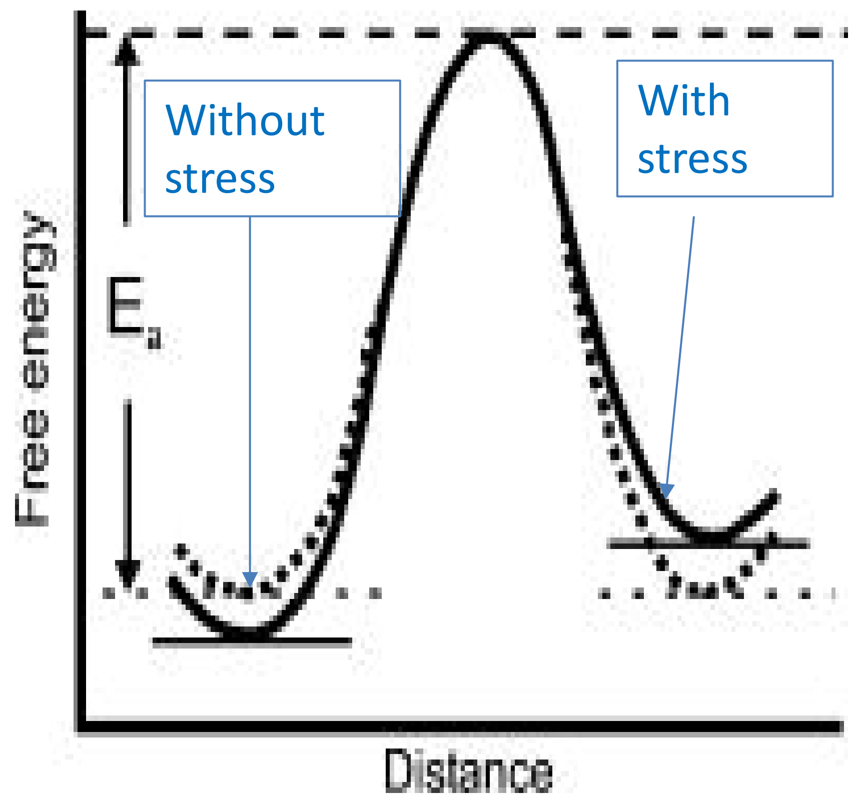
It is important to note at this point that plastic deformation in a material occurs due to the movement of dislocations (linear defects)..

https://www.nde-ed.org/EducationResources/CommunityCollege/Materials/Structure/point_defects.htm

Glasses defects

While in the crystals, defects are known to be the main sources of mechanical dissipation, in the amorphous materials the origin of dissipation remains largely elusive, in part because of the strong disparities in short and medium-range order

The dissipations are explicable in the framework of the two-level system (DWP - double well potential) where a distribution of double-well potentials can represent ther different mechanisms: "*When the glass is stressed by a mechanical wave, the solid is deformed and so the DWP is brought out of equilibrium (ADWP – asymmetric double well potential*"



Classical dissipations in aluminum

Comparing the results showed in slide 14 with the data present in literature it is possible to recognize the typical characteristics of the Aluminum Alloys: the Bordoni peak, the Hasiguti peak and the exponential trend at high temperature.

The former, usually observed at low temperatures, is generally attribute to intrinsic dislocation motion due to nucleation and sideways movement of kinks in the dislocation line over the Peierls barrier without interaction with any other defects. Its position and frequency spread depend on its microscopic structure, its deformation history, its dopant, the presence of impurity and the annealing process. The latter, also if the microscopic mechanisms are still not well known, appears to be connected with processes of dislocation motion in the presence of self-point defects (e.g. vacancies, self-interstitials). It depends on the same parameters of the Bordoni peak plus the amount and the type of defects present in the material

Other interesting things to underline are the point at 100K, maybe induced by a multi-peaks structure, the asymmetric structure of the higher peak due to multi-relaxation processes and the exponential trend at high temperature maybe due to the lower tail of the continuous damping contribution corresponding to viscous plastic deformation that generally is dominant at few hundred degrees above room temperature.

Recoil losses

Mean loss angle @ main points

For a preliminary test 8 temperatures where chosen at the main points of the Phi.vs.Temp curve:
the recoil losses are not a problem for this set-up