Suspensions and Cryogenics for the HF and LF Interferometers

Fulvio Ricci

presentation dedicated to the memory of our friend *Stefano Braccini*

and
based on the contributions of several physicists of the ET team

F Acernese, F Barone, S Braccini, A Chincarini, R De Rosa, P Falferi, J Franc, F Frasconi, G Gemme, A Gennai, M Lorenzini, E Majorana, R Nawrodt, G M Perciballi, R Poggiani, P Puppo, D Rabeling,S Reid, S Rowan, M Tonelli, J F J van den Brand………and many others…..

Talk outline

- Upper part suspensions for the seismic noise attenuation for both
  - ✓ET-LF Interferometer and ET-HF Interferometer
- Last stage Suspension
  - ✓for ET-HF Interferometer
  - ✓for ET-LF Interferometer
- Local control issues
  - ✓ Local Sensors and Actuators
- Cooling constraints for the ET-LF Interferometer
  - ✓ cryo-fluid and cryo-generator
- Conclusion

Assumption

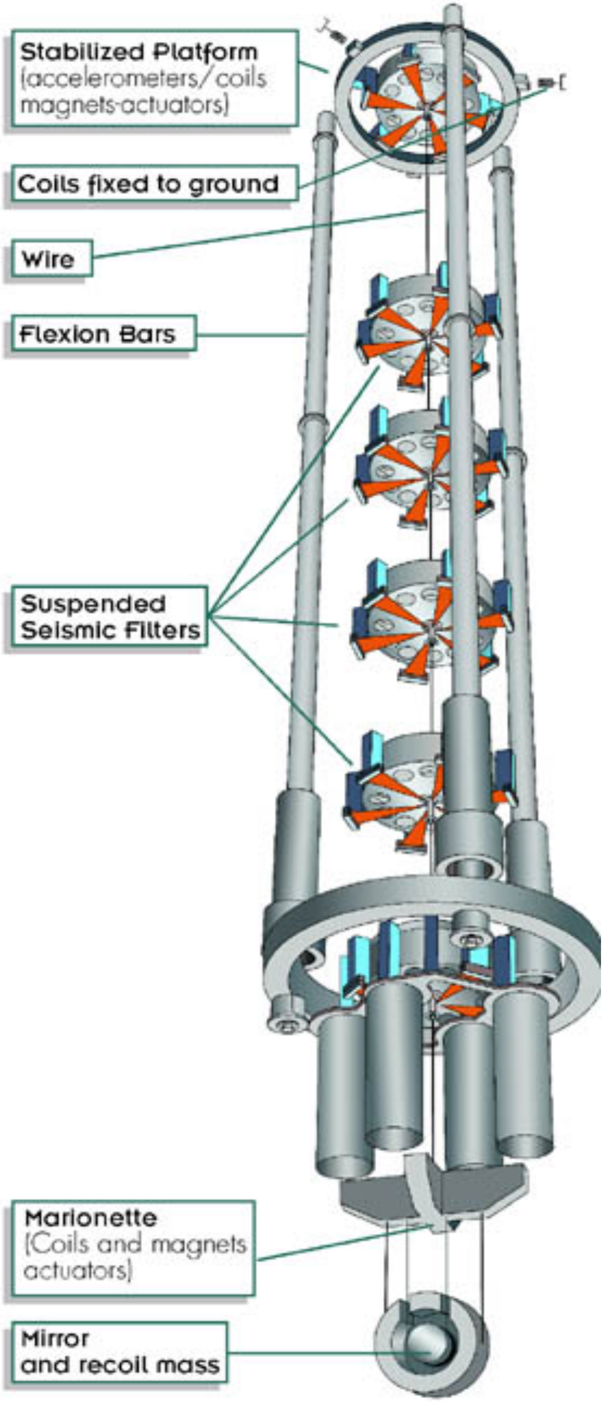
- Two independent interferometers
  - Main advantages:

    Maximize the sensitivity in the entire frequency bandwidth

    Commissioning and data taking activity in parallel

Consequence

- Double design
  - Two kinds of seismic attenuator chains
  - Two different payloads

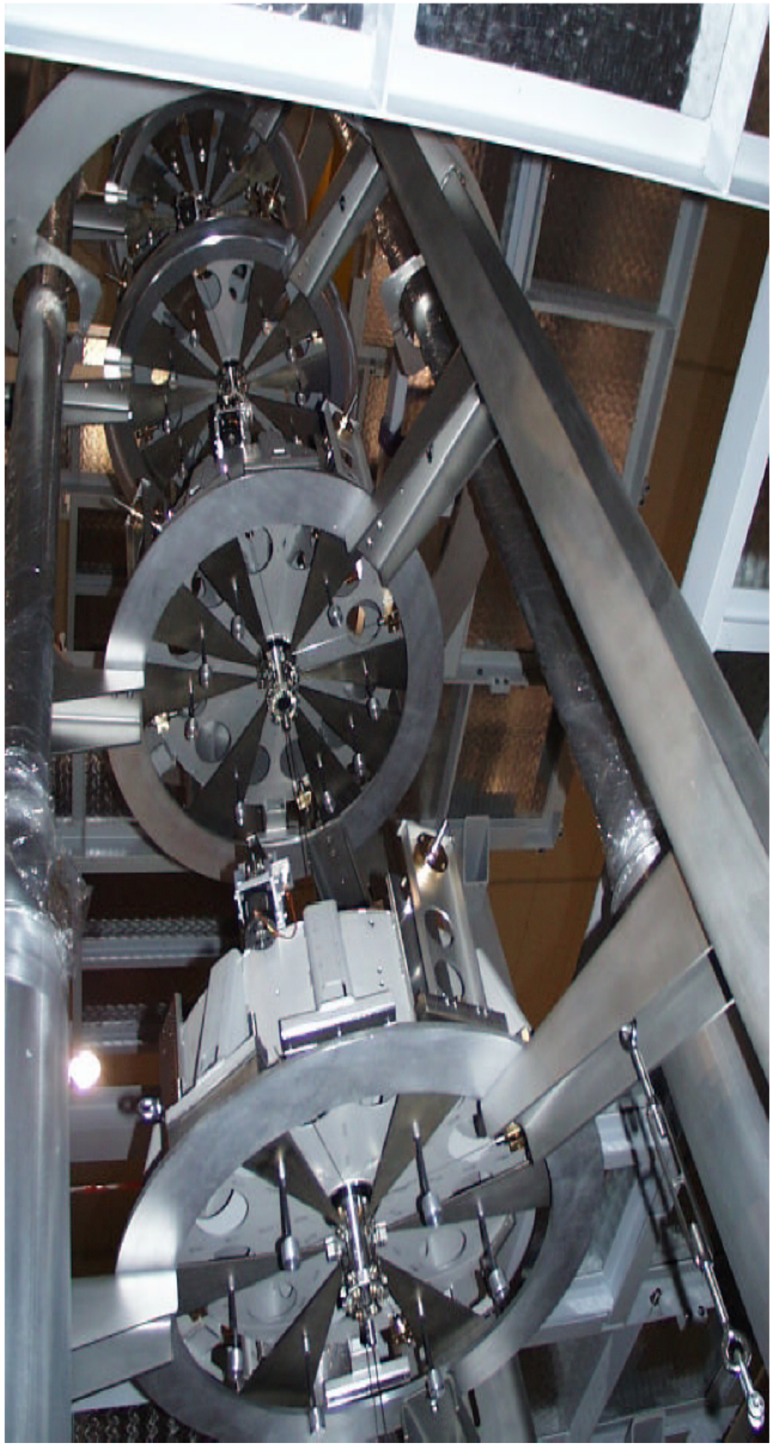


Upper part of the suspension for the seismic noise reduction

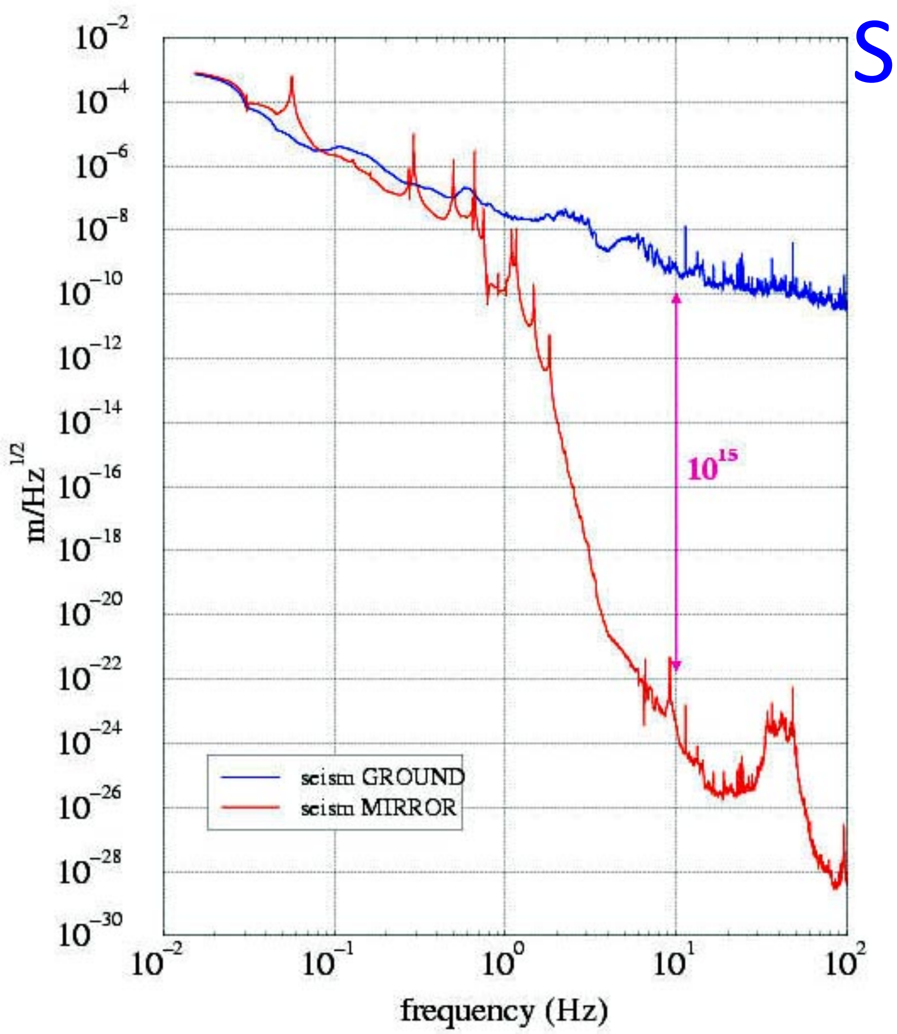
-First Stage: Inverted pendulum

-Five Pendulum Stages

- Suspension Last Stage:
Marionette and
Reaction mass for
Control

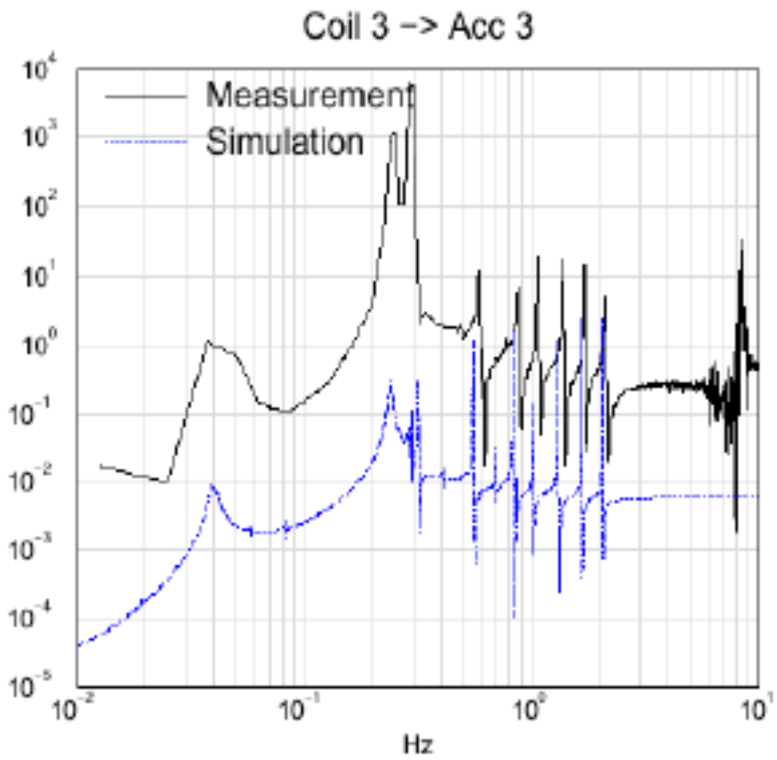


Starting point: VIRGO data



Suspended Mirror motion
compared to the
seismic motion

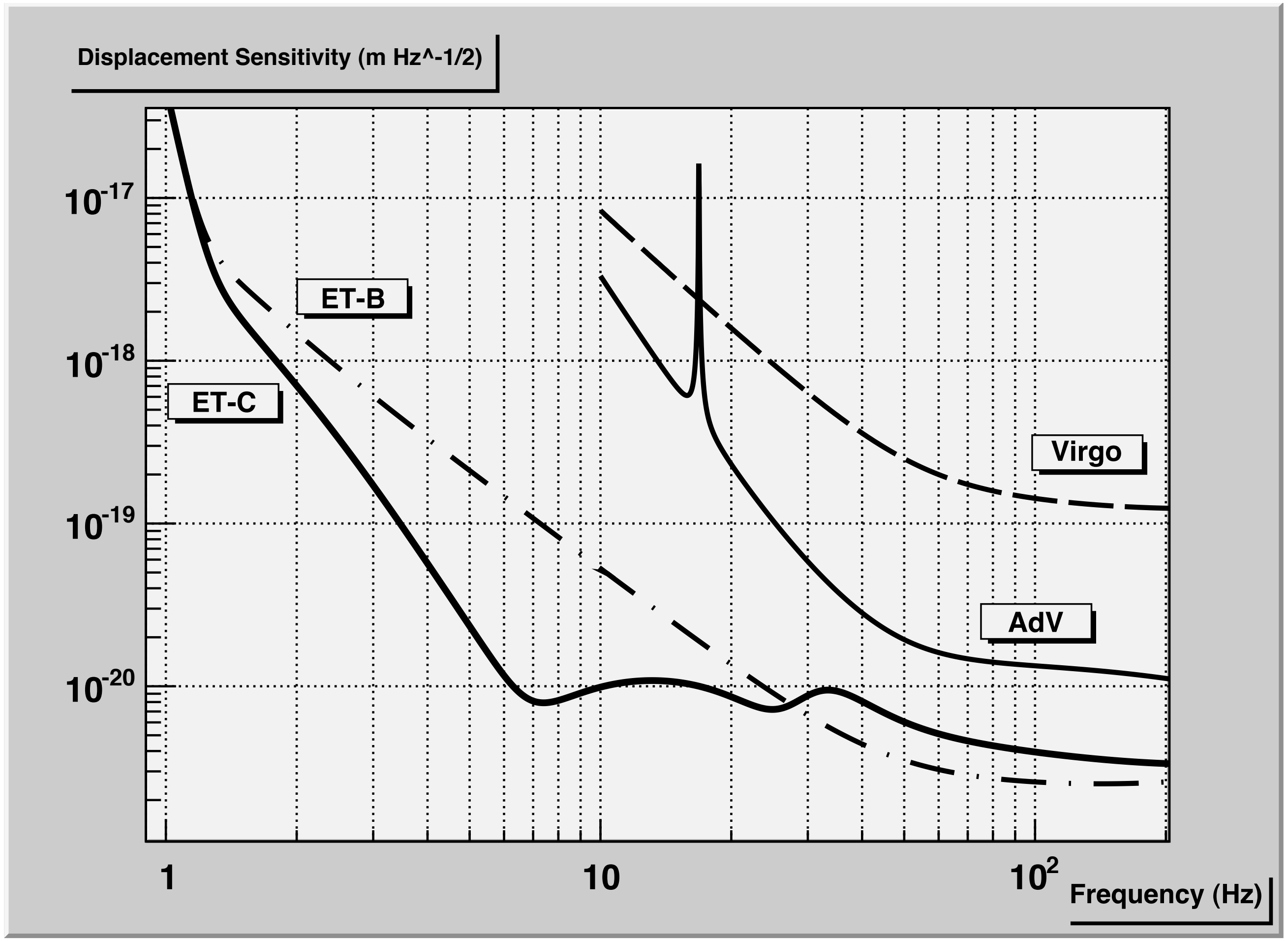
Attenuation derived
by combining
the contribution of each filter



Single stage attenuation

Ballardin G. et al : Rev. Sci. Inst. 72, 3635 (2001)

Seismic vibration transfer function requirements



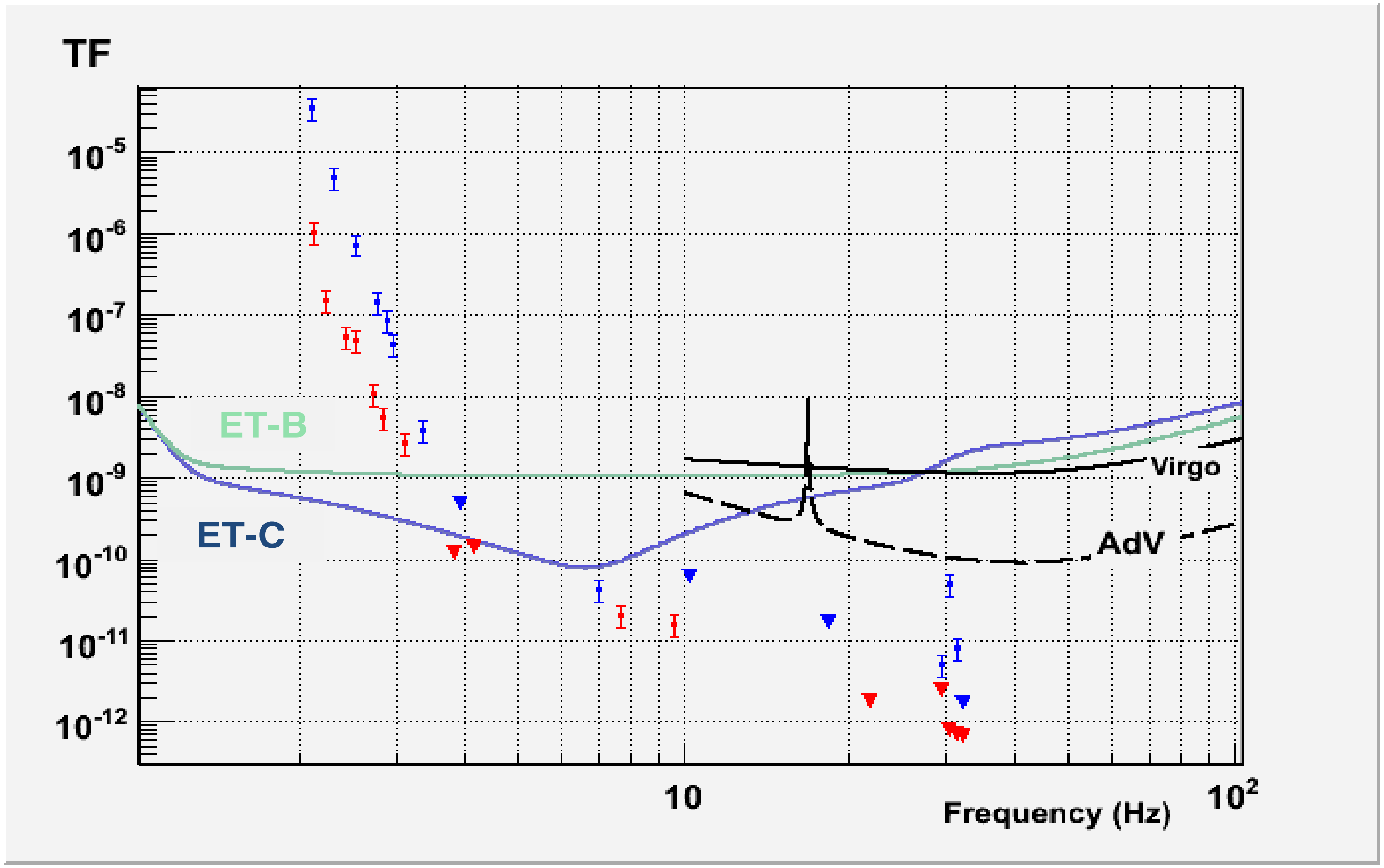
The curves represent the displacement sensitivities of the different instruments referred to different seismic noise level (VIRGO site seismic noise and Kamioka mine seismic noise.

The seismic noise will be at least a couple of orders of magnitude smaller in underground environment.

ET is less demanding in terms of seismic attenuation at high frequency.

Super-Attenuation Measurements on VIRGO

Acernese F. et al. , Astropart. Phys. 33, 182 (2010)



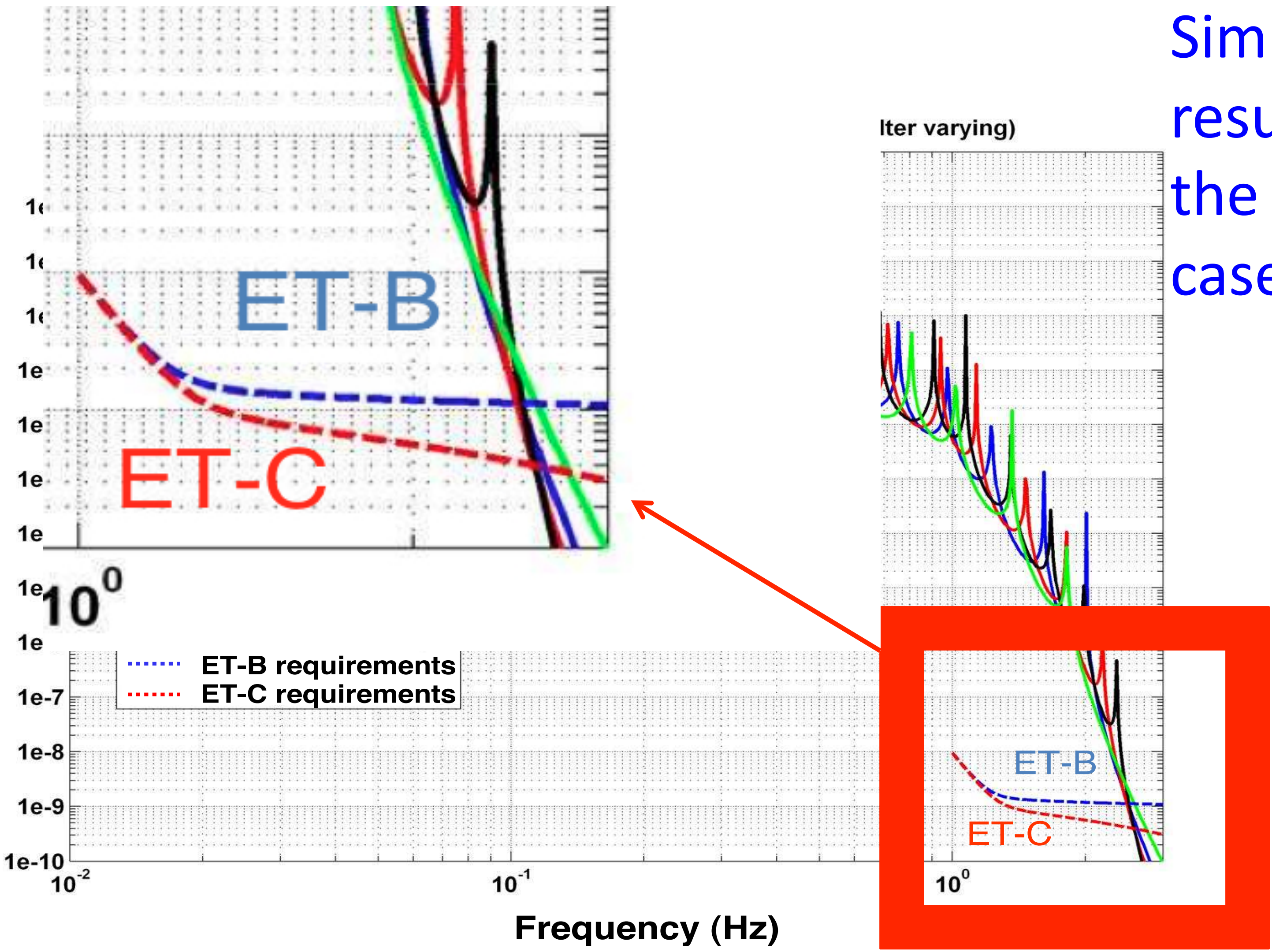
Red points: *measurements where a vertical excitation of the top stage is applied*.

Blue points: measurements with the excitation in horizontal direction.

Triangles ➔ upper limits

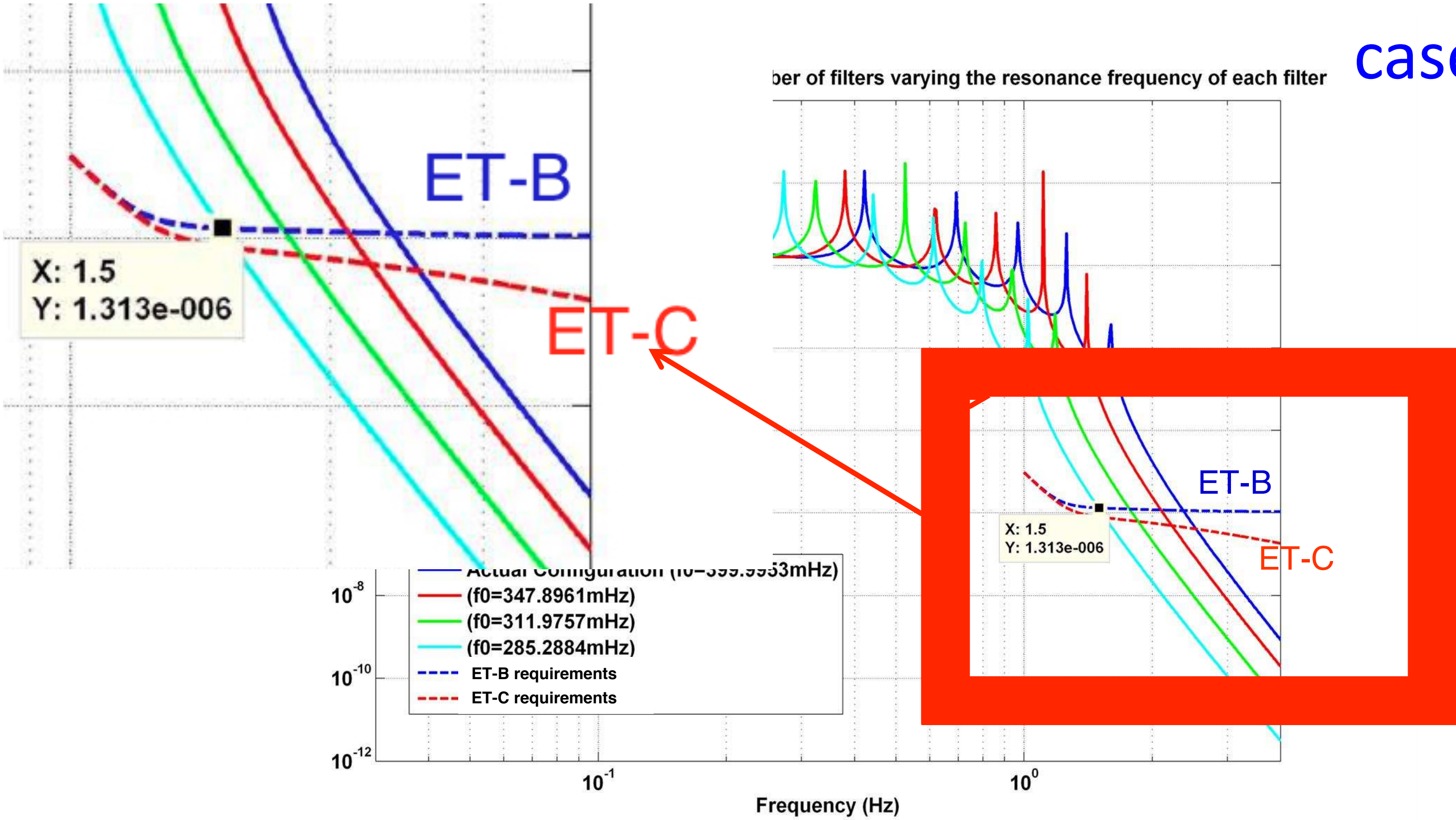
Bars ➔ direct measurements of the signal at the level o the mirror

Simulation results for the two ET cases I



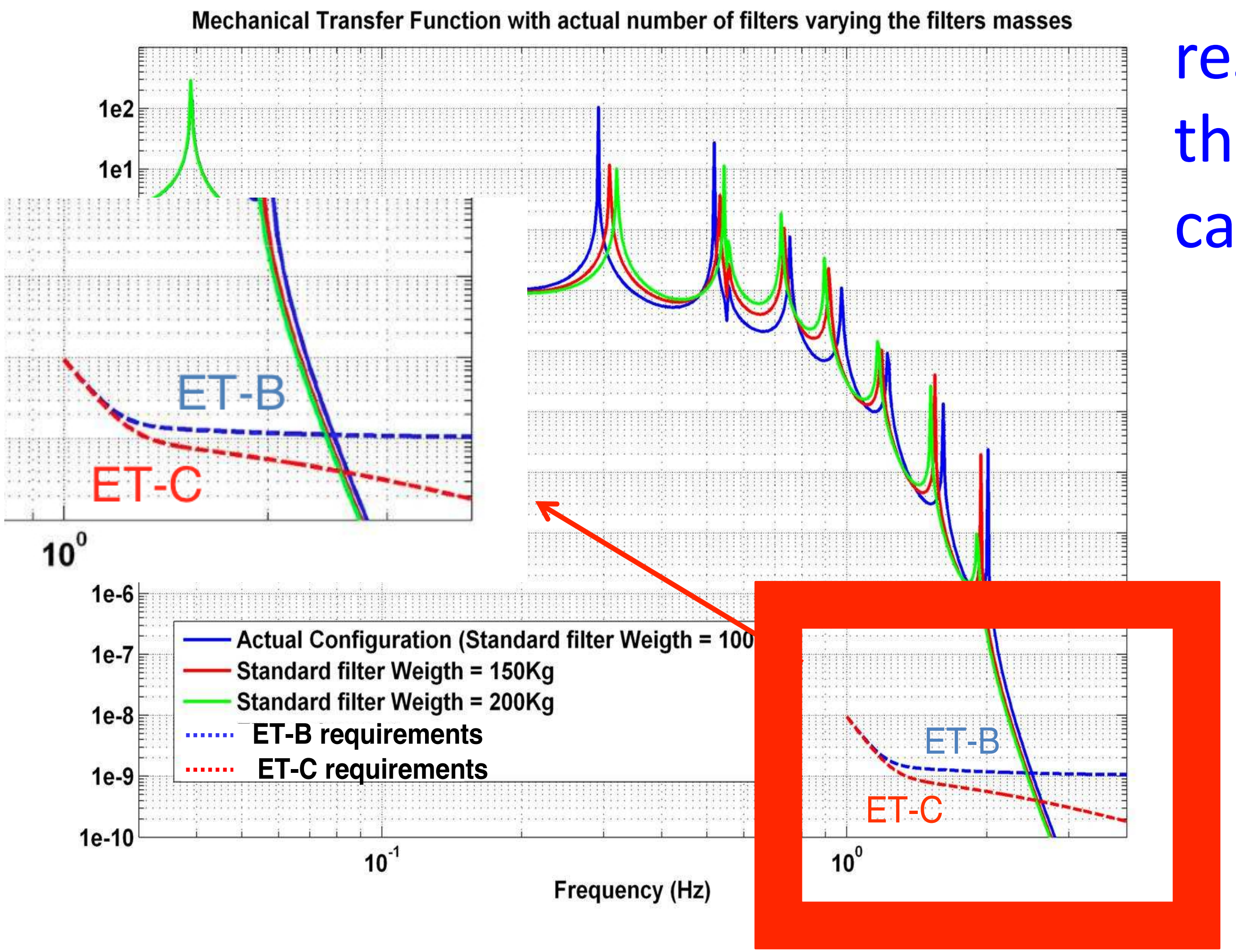
Simulation results of the SA horizontal transfer function with the present chain length (9 m). Changing the number of (“equal-spaced”) filters the resulting horizontal transfer function is compared with the ET requirements (for High Frequency—ET-B and ET-C). Adding or removing filters along the chain length do not have remarkable role in the positioning **of the cross-over frequency with the requirements**

Simulation results for the two ET cases II



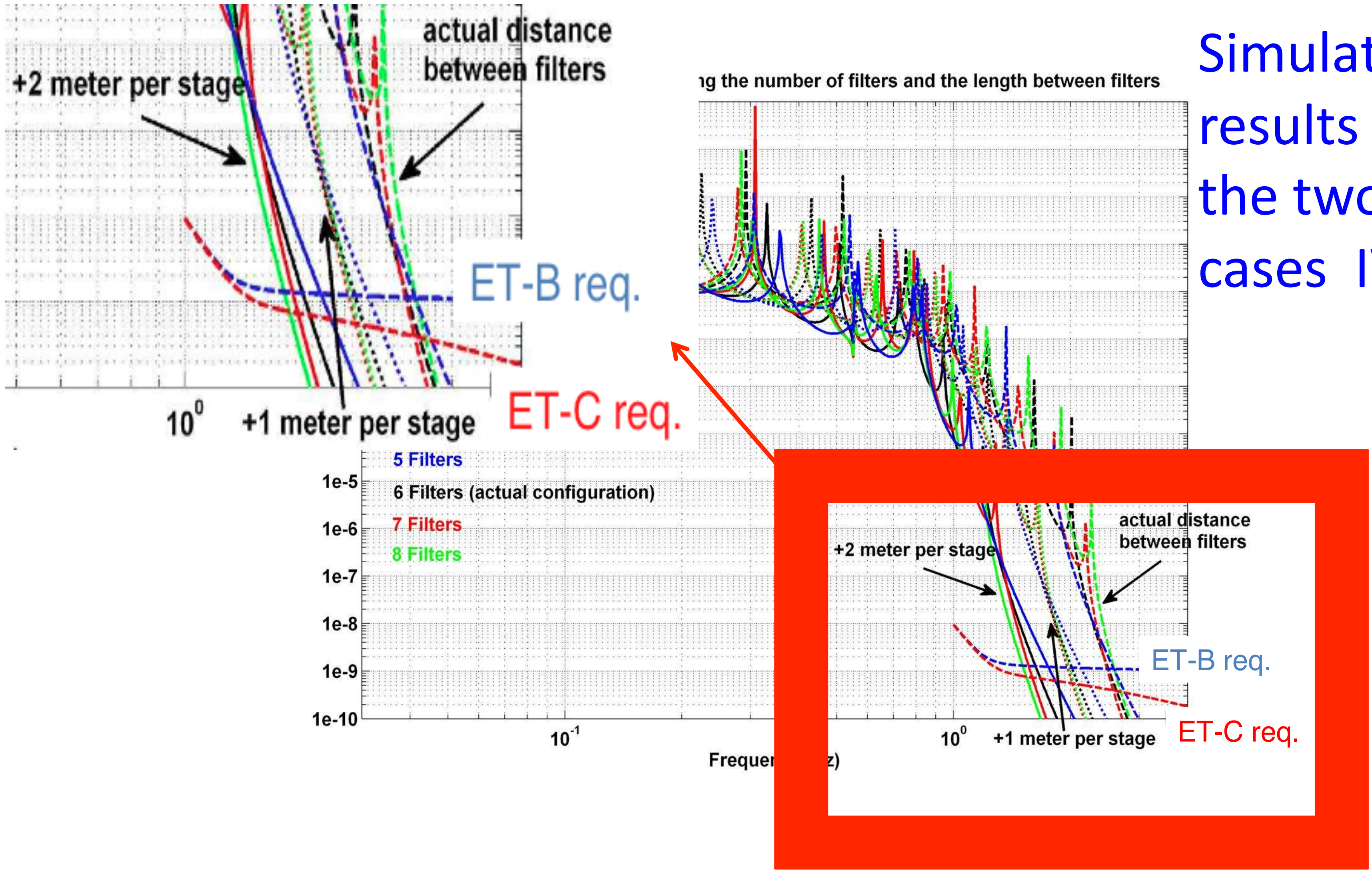
Vertical Transfer Function of the SA considering the six stages (as it is now, i.e. with the pre-isolator or “Filter Zero” plus other five mechanical filters). The different curves have been obtained changing the filter vertical resonant frequency. With filters working around 300 mHz it is possible to move the cross-over below2 Hz.

Simulation results for the two ET cases III



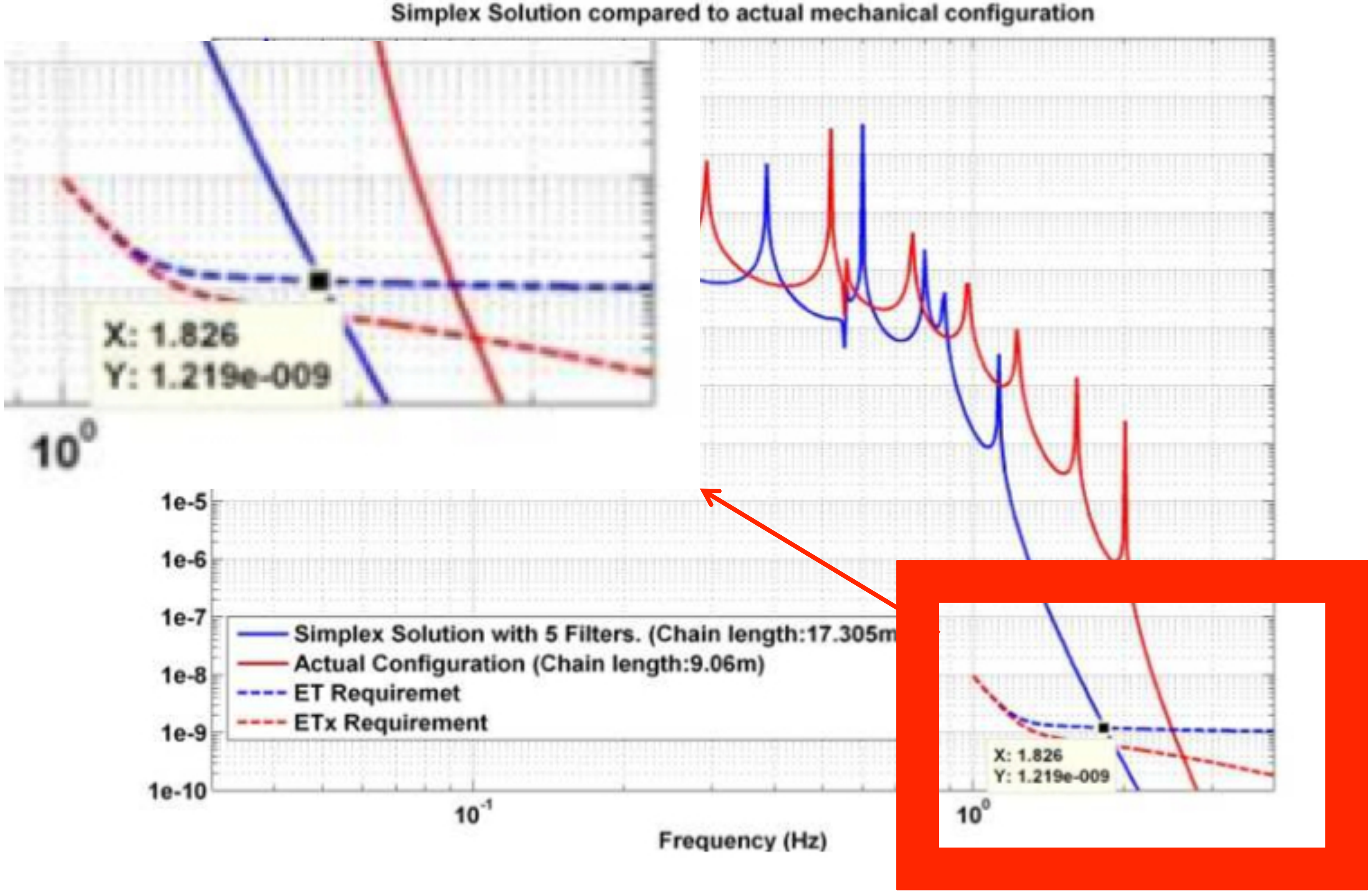
The horizontal transfer function of the present SA (6 filters weighting 100 kg each one for a total length of about 9m) is compared with the same transfer function changing the mass of each filter (150kg and 200 kg). Also in this case the cross-over frequency with the ET requirements is not remarkably affected by the change of the filter mass.

Simulation results for the two ET cases IV

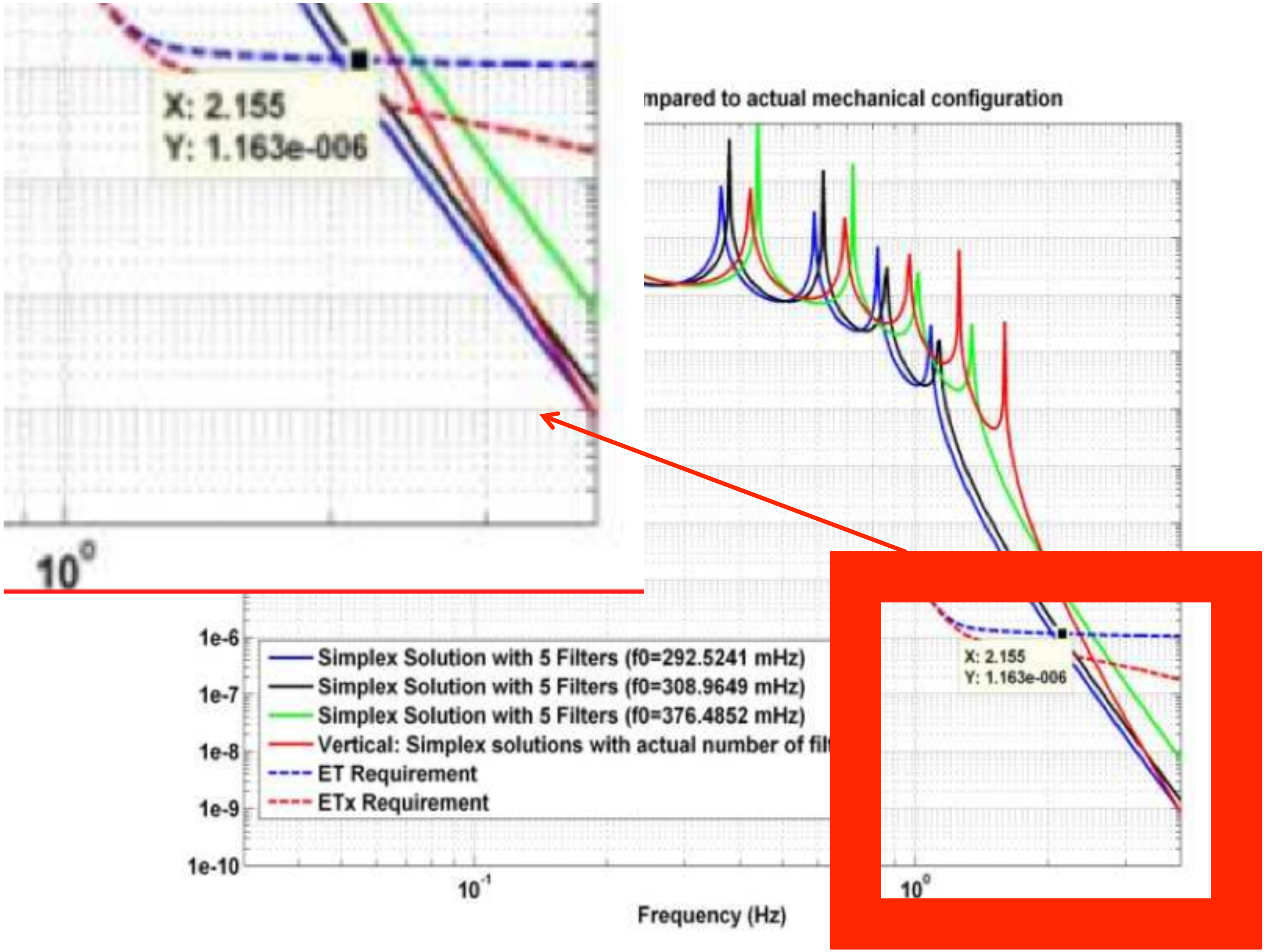


Simulation results for different configurations. The horizontal transfer function of the SA is plotted changing the number of filters and keeping fixed their relative distances (”equal-spaced” geometry) along the chain (changing, as a consequence, the full length of the SA).

The proposed reference solution for the SA configuration of the Einstein Telescope.



The proposed reference solution for the SA configuration of the Einstein Telescope.



Conclusions on the Upper suspension I

- *ET-HF interferometer*

a Virgo-like Superattenuator can be used as seismic isolation system:

- ✓ the attenuation performance is compliant with the ET requirements;
- ✓ the construction technology is well tested ;
- ✓ the control strategy has been refined during over 10 years activity

Conclusions on the Upper suspension II

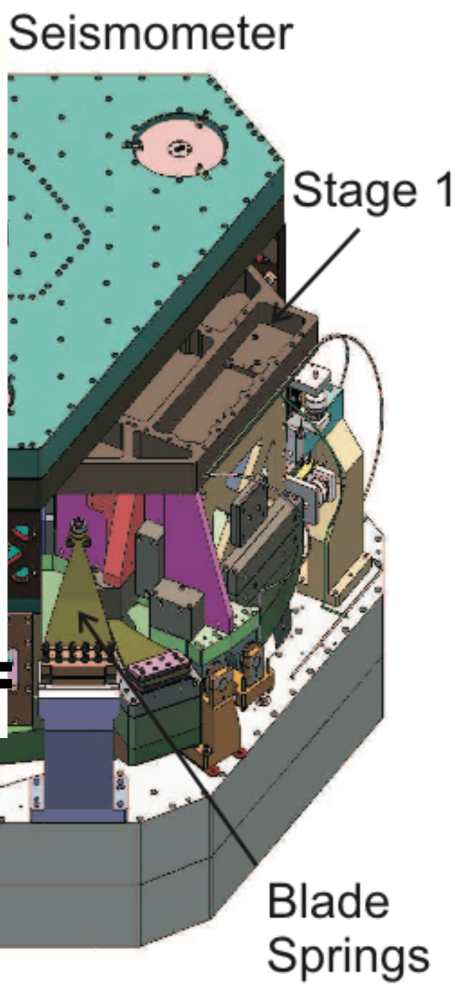
- *ET-LF Interferometer*

Super-attenuator 17 m tall with 6 stages (filters) in ”equal-spaced” configuration

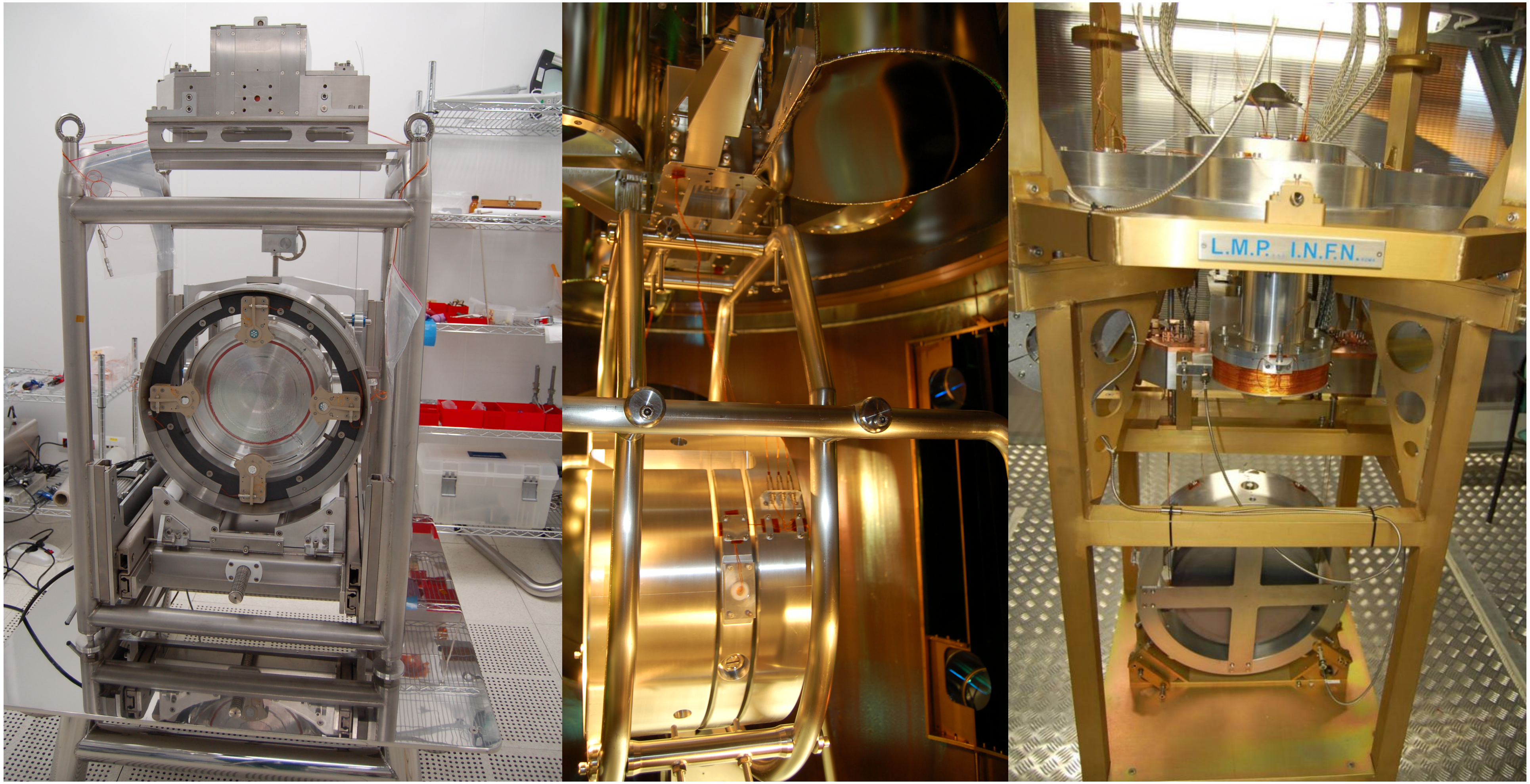
- ✓ filter tuning with a vertical cut-off around 300 mHz
- ✓ with this set-up a suspension system with a conservative cross-over frequency around 1.8 Hz (compliant with ET requirements) can be built.

Developments and alternative approaches

NIKHEF at work on GAS springs: credit J. van den Brand



The last stage of the suspension



Payload mechanical Issues

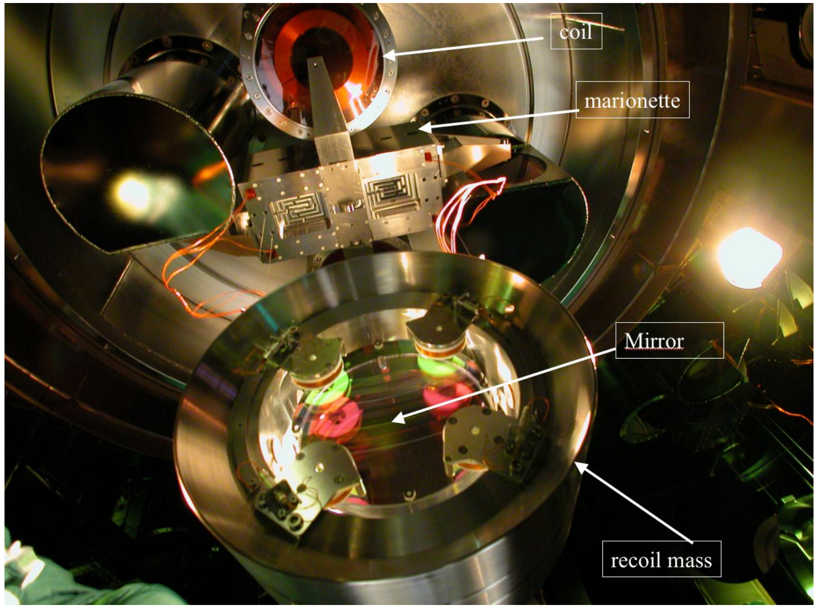
- *Large Masses:*
  - ✓ reduce the recoils (good for suspension thermal noise)
  - ✓ increase the violin mode frequencies (advantage for the pay control)
  - ✓ reduce the vertical modes ((trouble for the pay control)
  - ✓excess thermal load for ET-LF
- *Wire Length Increment*
  - ✓reduce the pendulum frequencies (advantage for susp. thermal noise)
  - ✓ reduce the violin modes (trouble for the pay control)
  - ✓ reduce the vertical modes trouble for the pay control)
- *Wires Diameter Increment*:
  - ✓ increment of the wire sections (more efficient cooling for ET-LF)
  - ✓ reduce the violin mode frequencies (trouble for the pay control)
  - ✓reduce the dilution factor (trouble for suspension thermal noise)

Two different payloads

ET-HF

- Marionette : 400 kg
- Reaction Mass: 200 kg
- Mirror (Suprasil): 200 kg
- Mirror Diameter 62 cm
- Mirror thickness 30 cm

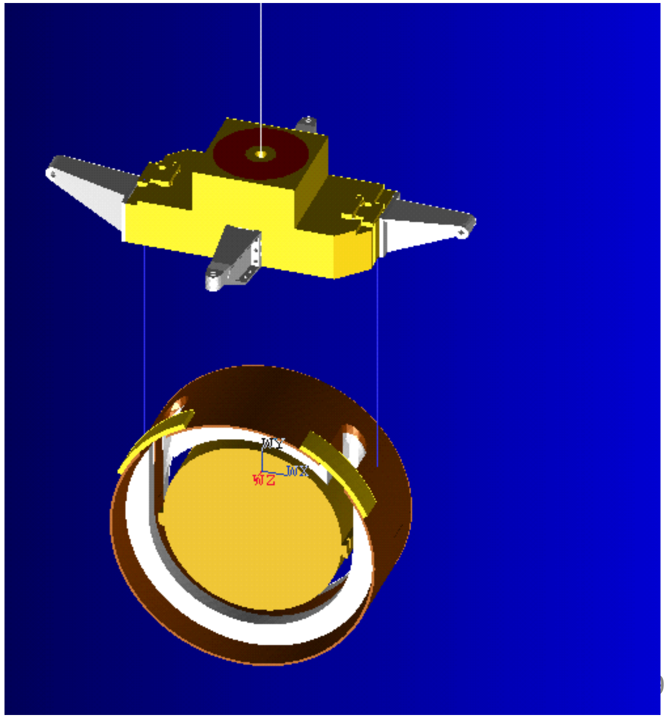
Overall payload weight: 800 kg



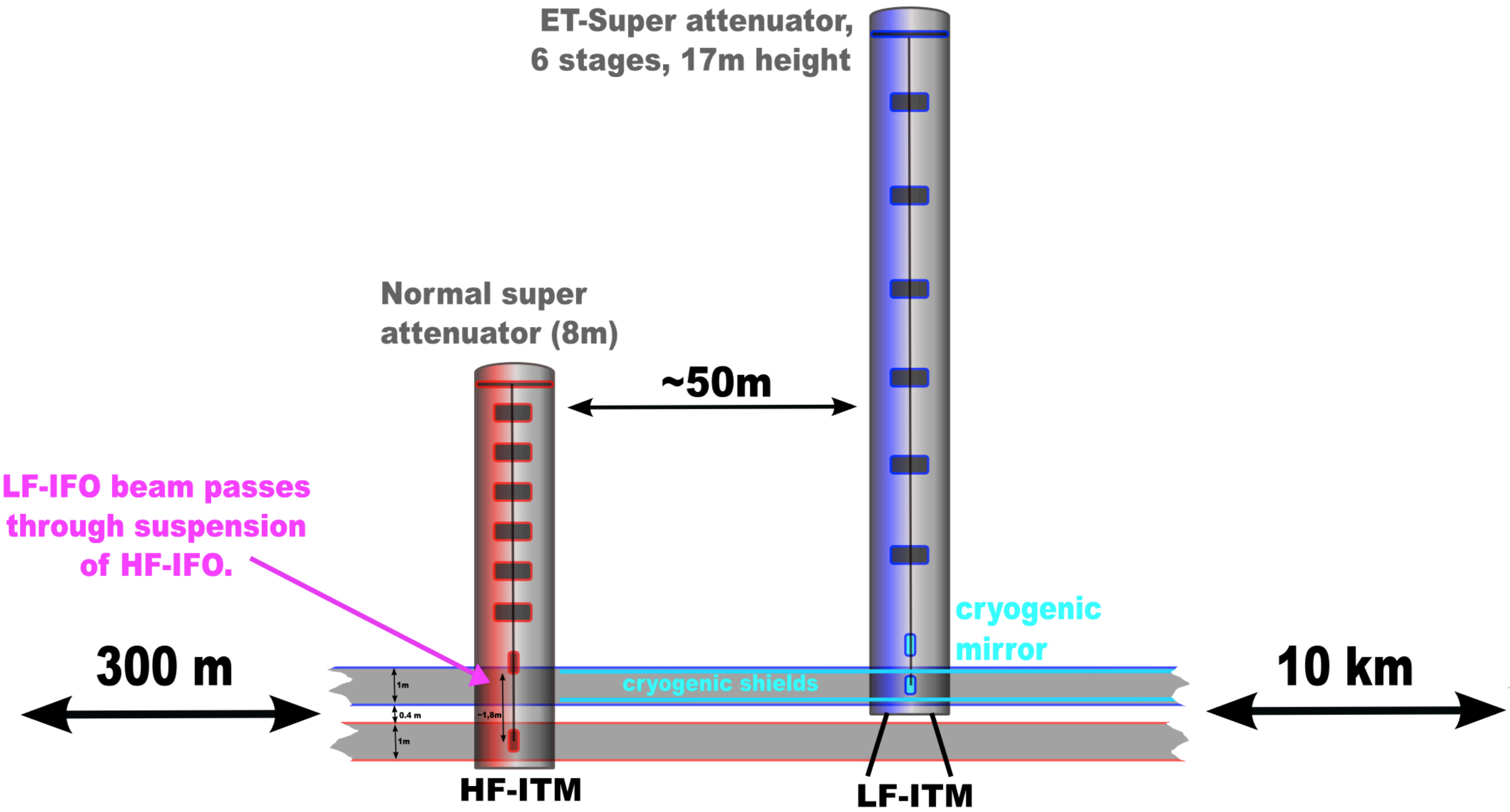
ET-LF

- Marionette : 422 kg
- Reaction Mass : 211 kg
- Mirror (Silicon): 211 kg
- Mirror Diameter 45 cm
- Mirror thickness 57 cm

Overall payload weight:844 kg

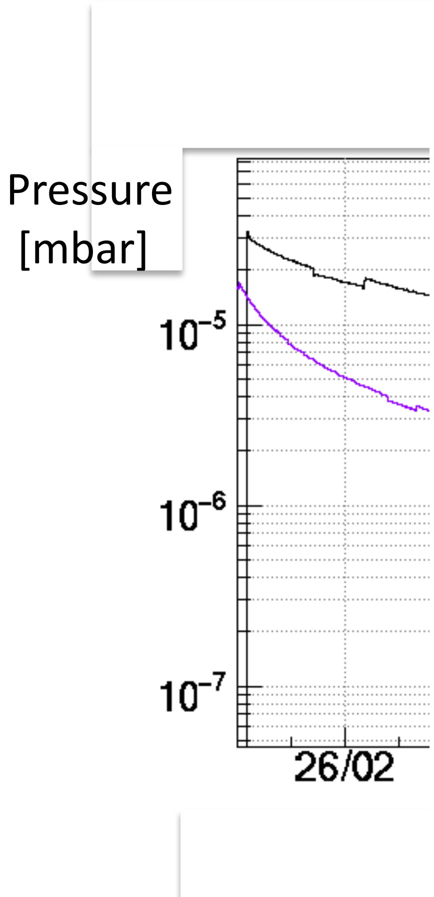


ET-HF payload



Material   nt.

Dielectric re

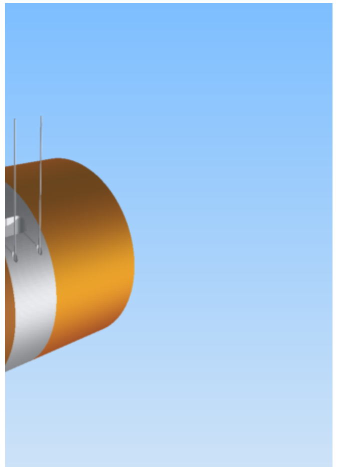


Approximate outgassing rates to use for choosing vacuum materials or calculating gas loads

(All rates are for 1 hour of pumping)

Vacuum Material	Outgassing Rate *(torr liter/sec/cm²)*
Stainless Steel	6×10^{-9}
Aluminum	7×10^{-9}
Mild Steel	5×10^{-6}
Brass	4×10^{-6}
High Density Ceramic	3×10^{-9}
Pyrex	8×10^{-9}

Vacuum Material	Outgassing Rate *(torr liter/sec/linear cm)*
Viton (Unbaked)	8×10^{-7}
Viton (Baked)	4×10^{-8}



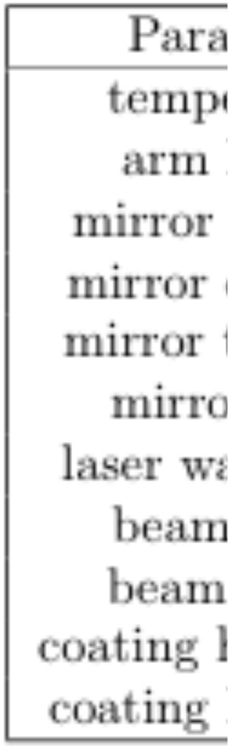
mass

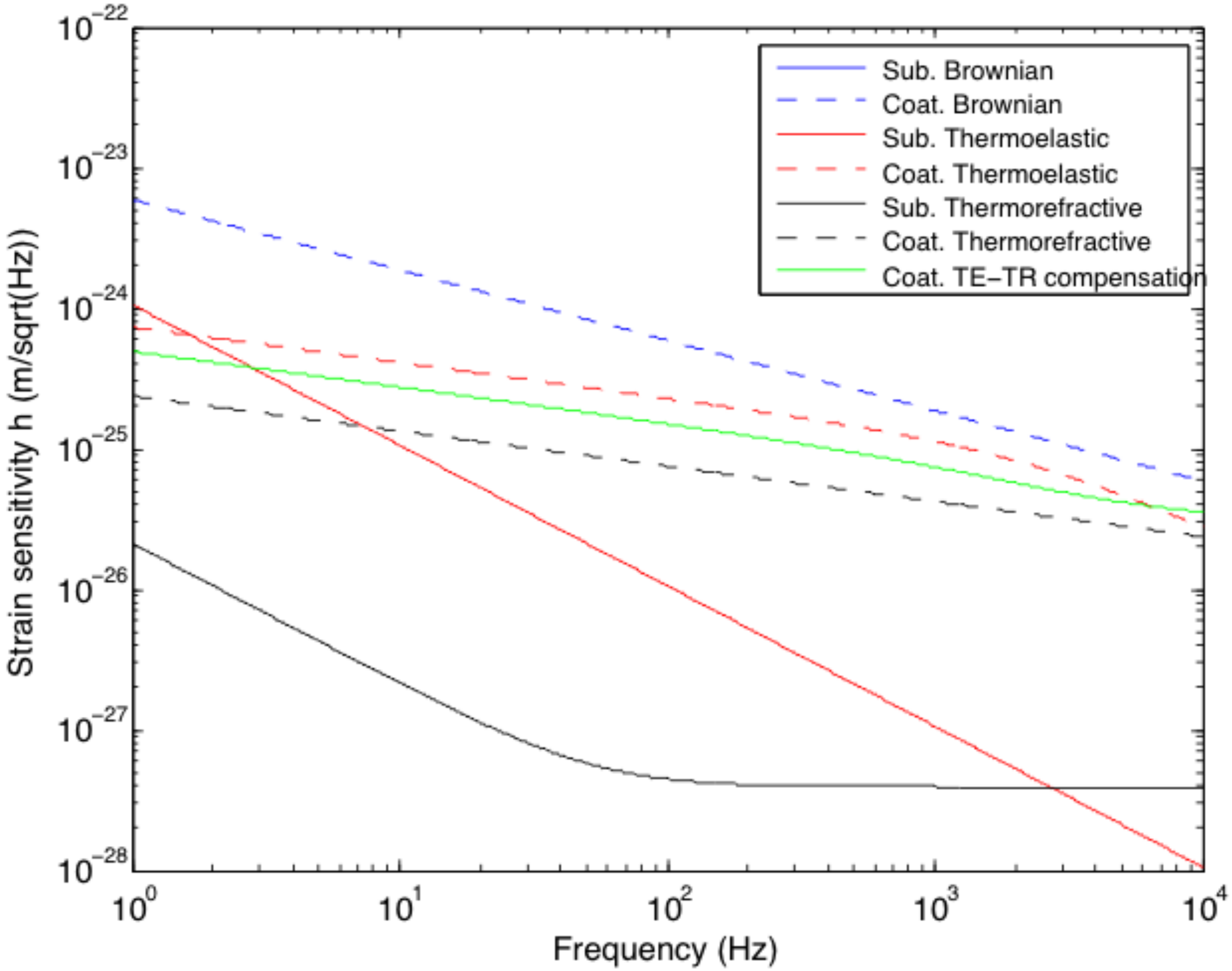
ium

plastic

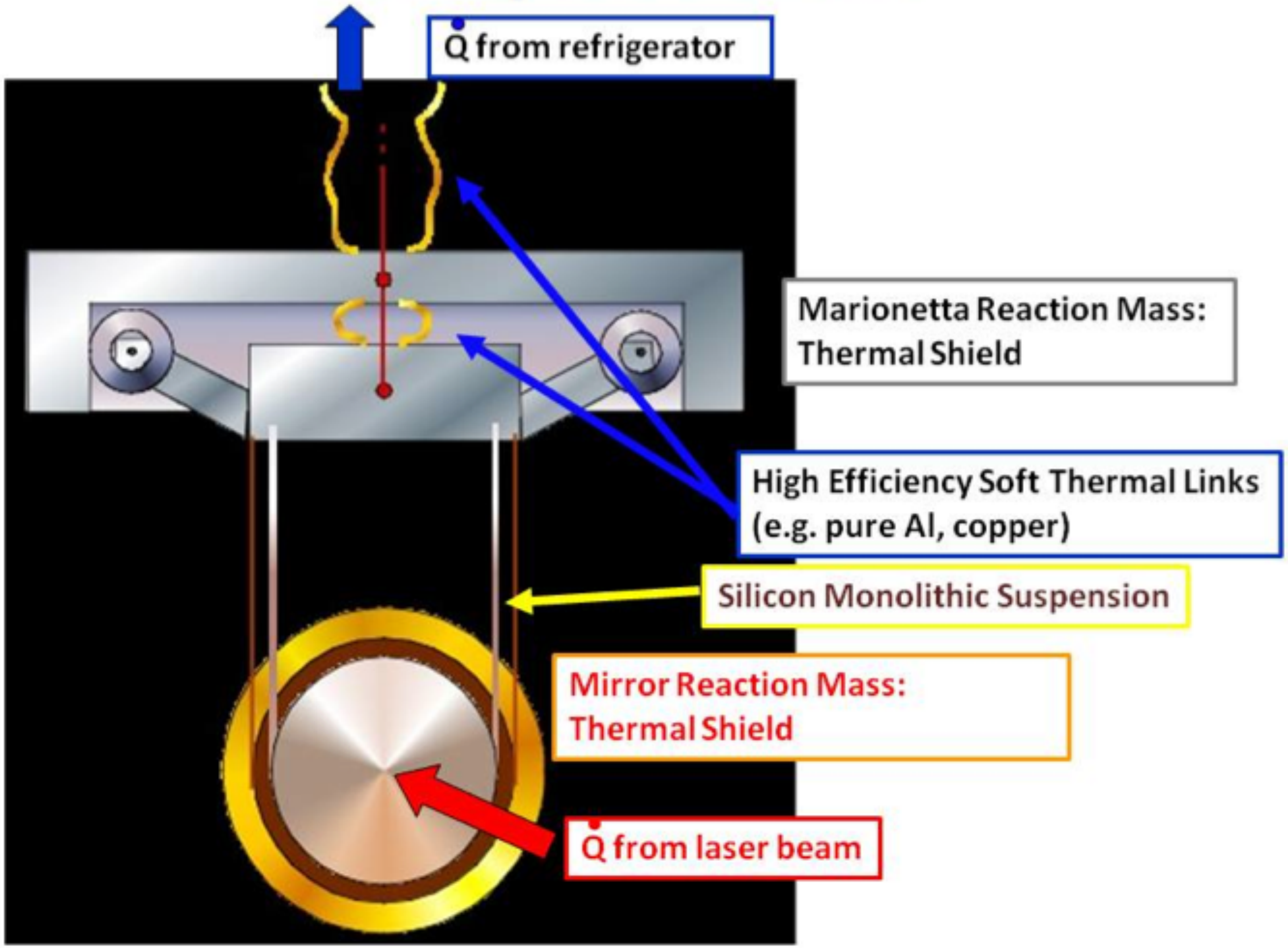
The time evolution of the vacuum pressure
for metal (purple) and dielectric RM of the payload (text carried on a VIRGO tank)

Mirror thermal noise contributions in the ET-HF case

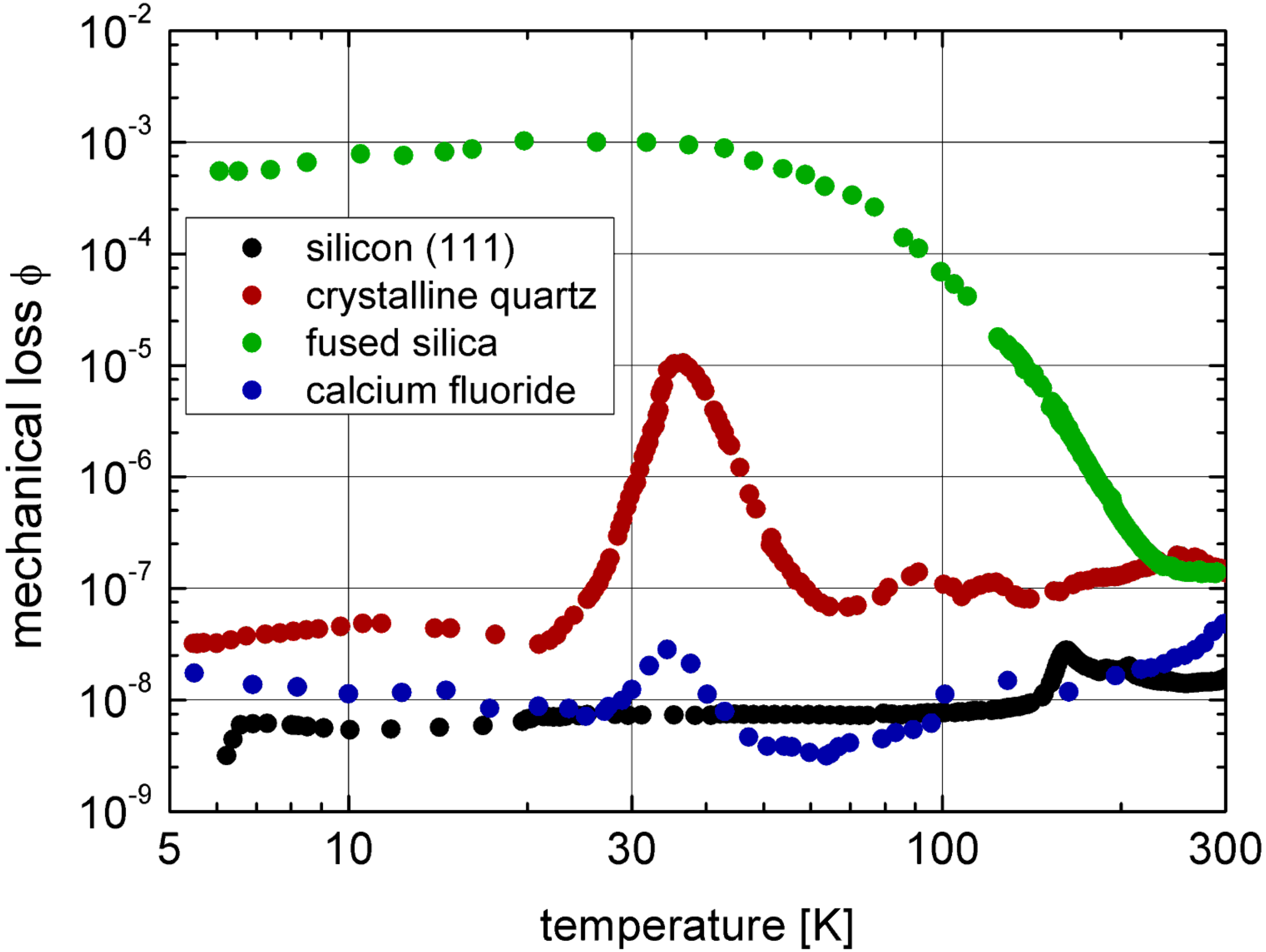




ET-LF payload



Mirror bulk loss



Thermal noise – Material Choice

- Two main candidates

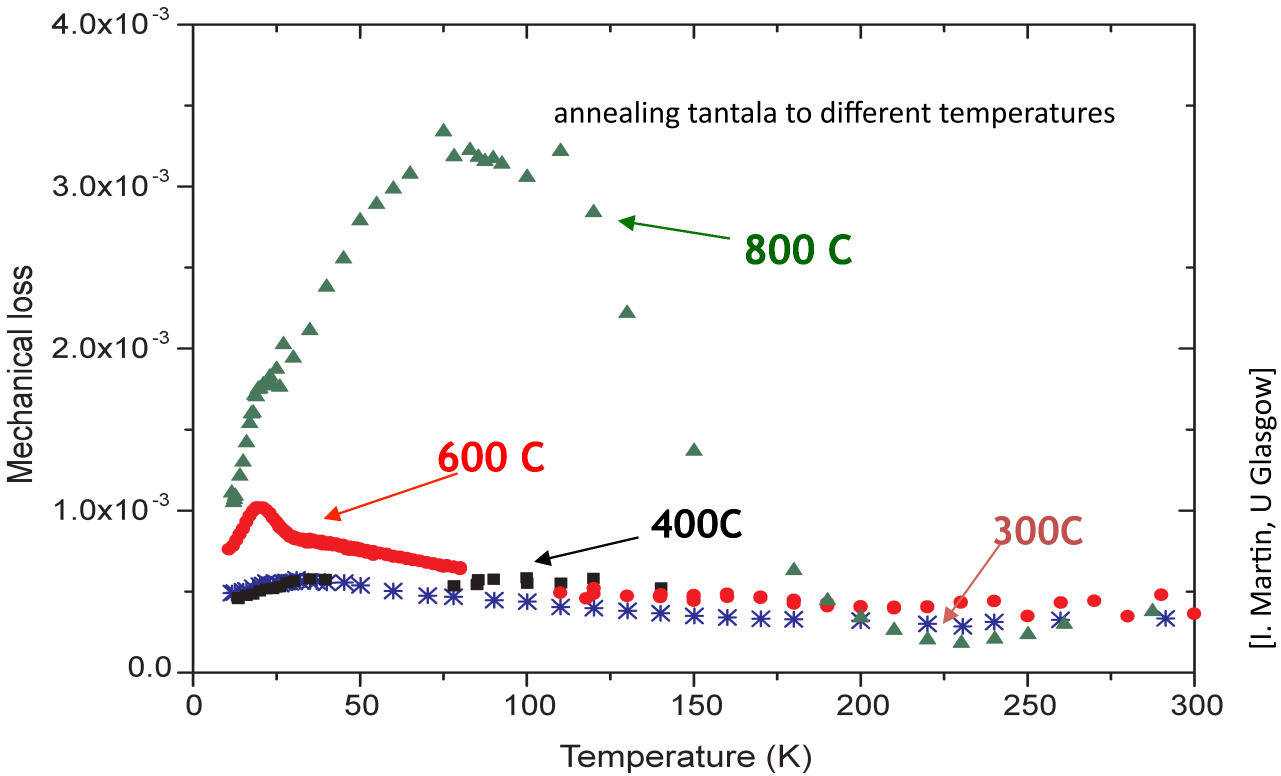
Credits to R. Nawrodt

	Sapphire	Silicon
mechanical loss	++	++
mechanical strength	+(+)*	++
optical material	+	o
thermal conductivity	++	++
polishing	-	+
size availability	-...+	+...++ (semicond. industry)

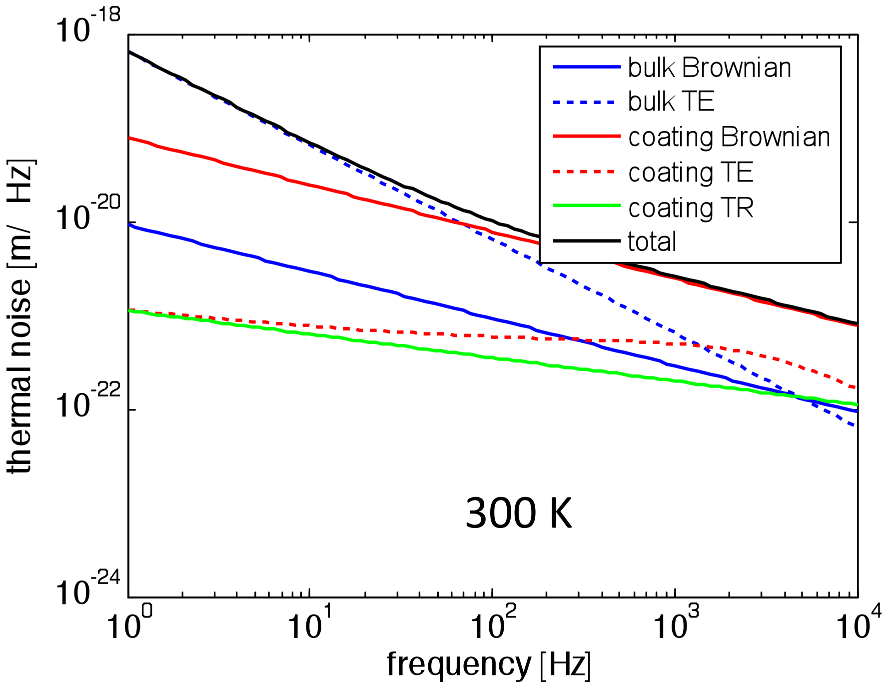
* Bonding method should require further R&D: strength might not be higher enough

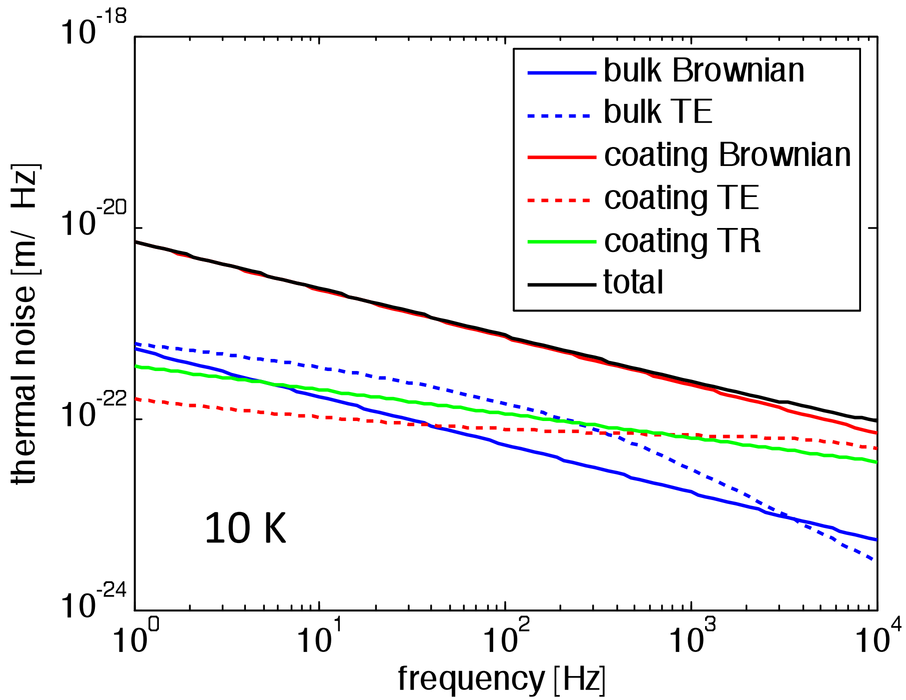
Mirror thermal noise – Coatings

- Coating thermal noise dominates all other thermal noise sources of the mirrors in current detectors (coating = amorphous)
- R&D ongoing effort to understand loss mechanisms



Mirror thermal Noise – silicon case

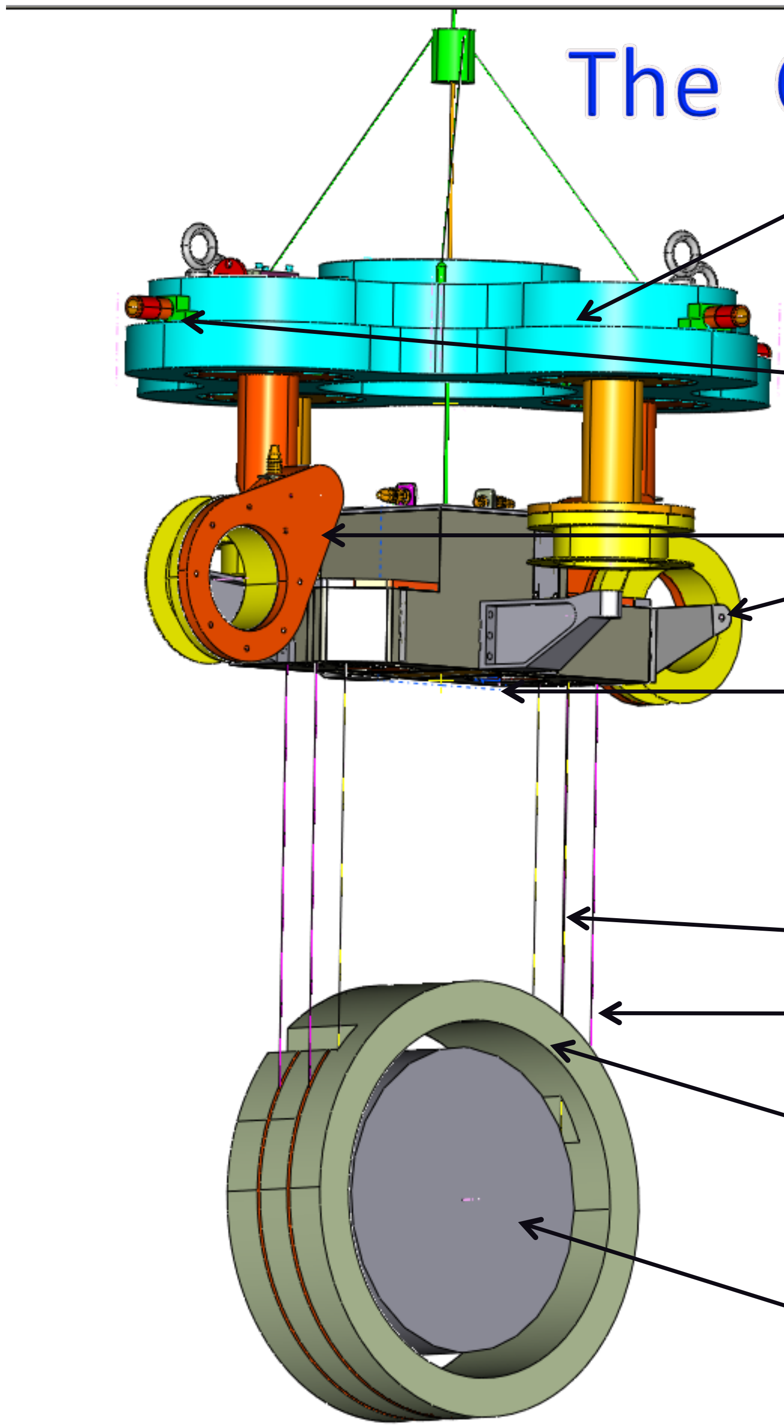




Coating 18 doublets, Ta_2O_5:TiO_2, SiO_2

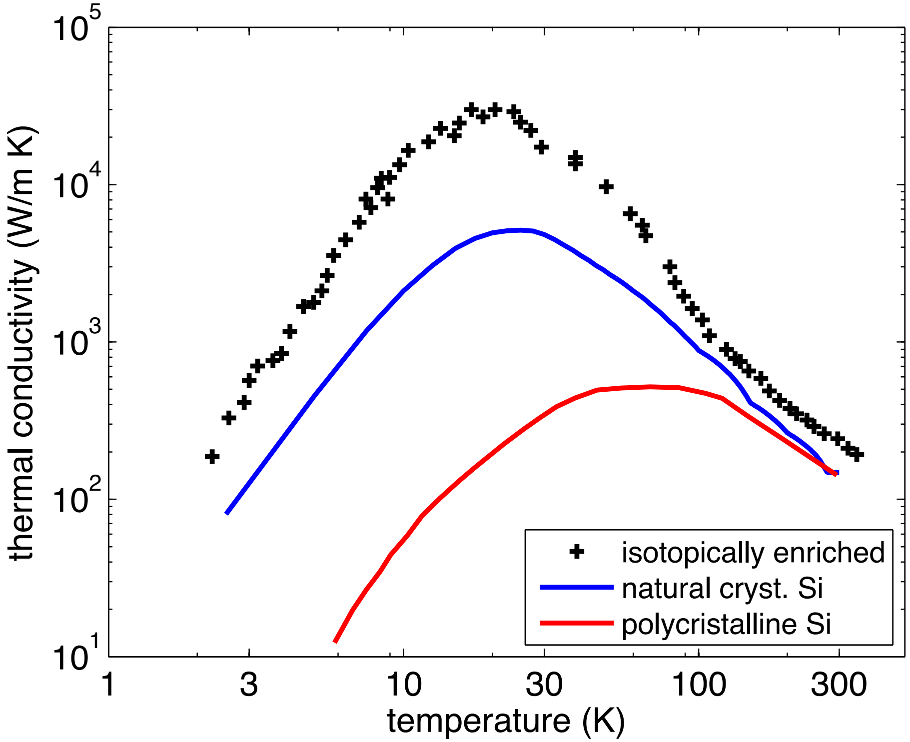
Beam diameter w= 90 mm

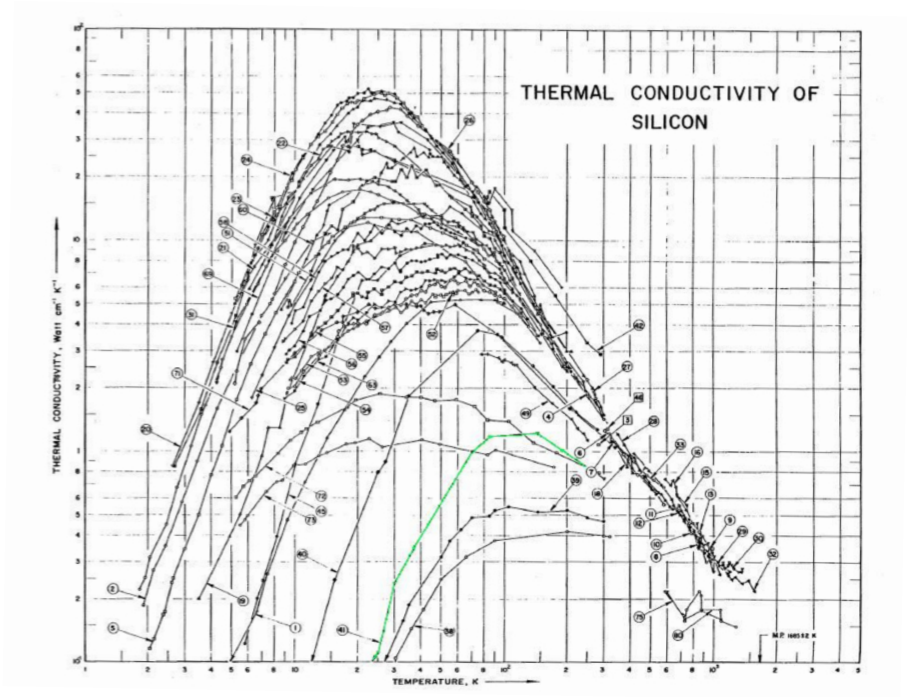
The Cryogenic Payload



- **Marionetta Reaction Mass (MRM)**
- **Ti alloy cable (low thermal conductivity) Ti-6Al-4V**
- **LVDT sensor**
- **Coil actuator**
- **Marionetta**
- **Mirror silicon Wires**
- **Reaction Mass high conductive wires**
- **Reaction Mass**
- **(Dielectric material)**
- **Silicon mirror**

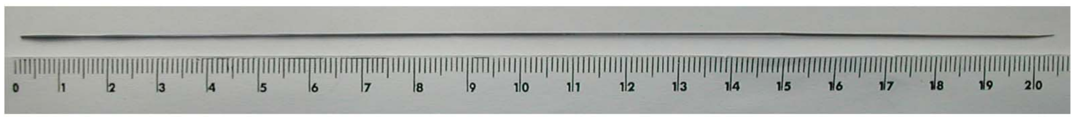
Silicon fiber : the thermal conductivity



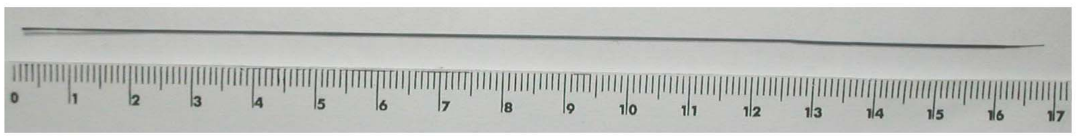


Silicon sample prepared by micropulling

Pure Si L ≈ 21 cm

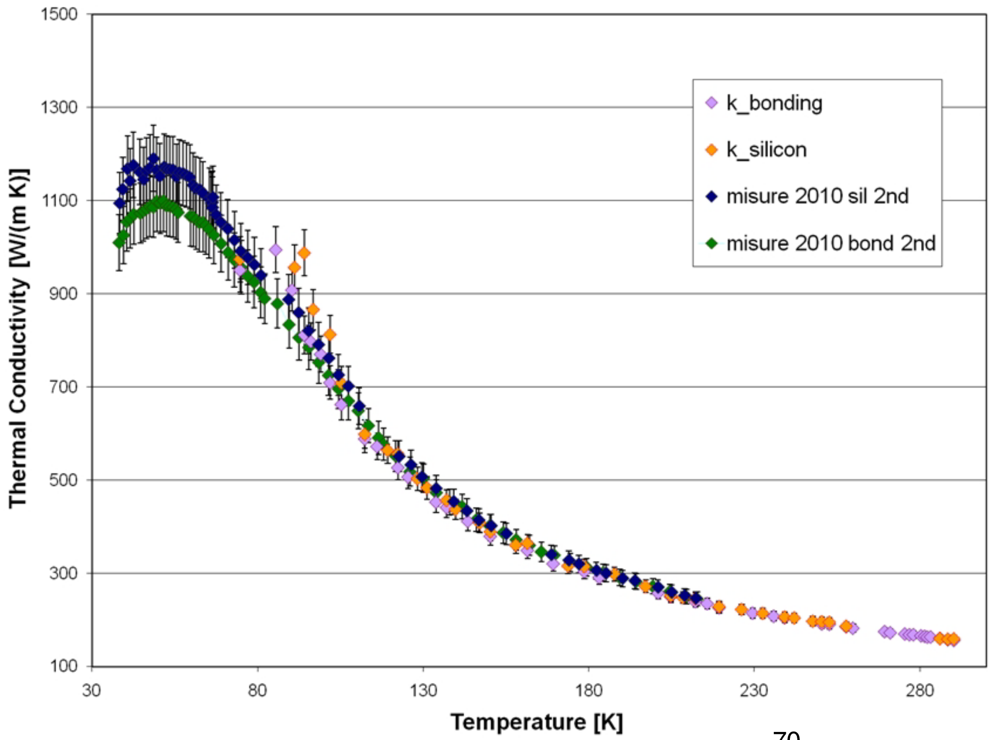


Pure Si L ≈ 17 cm

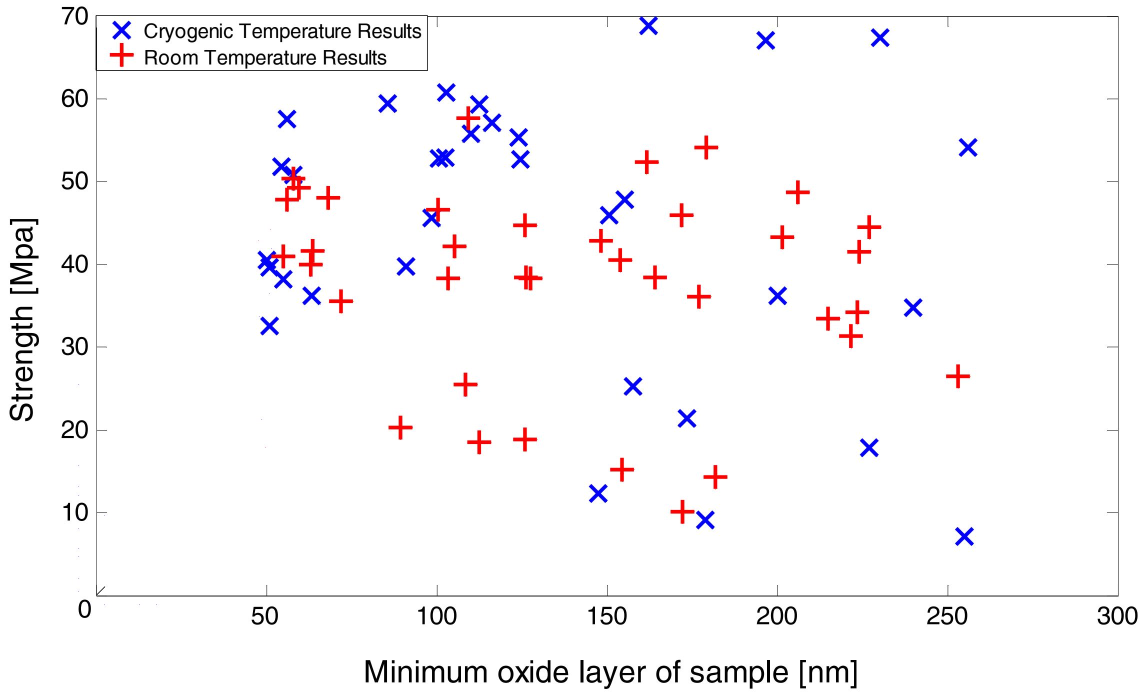


R&D is required:
Fiber payload
~ 60/70 cm long

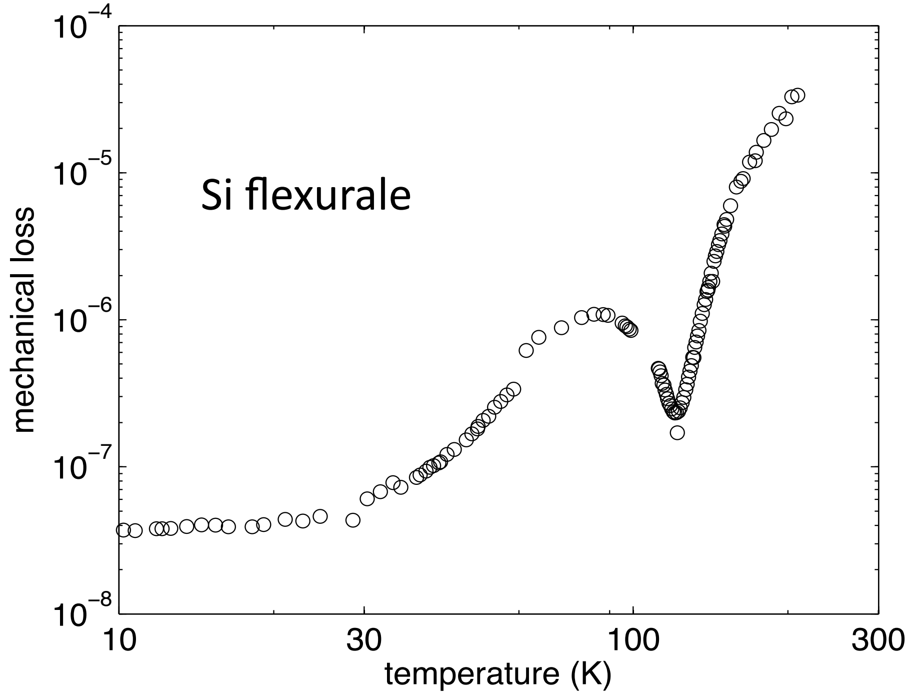
Silicon Bonding: Thermal conductivity and strength

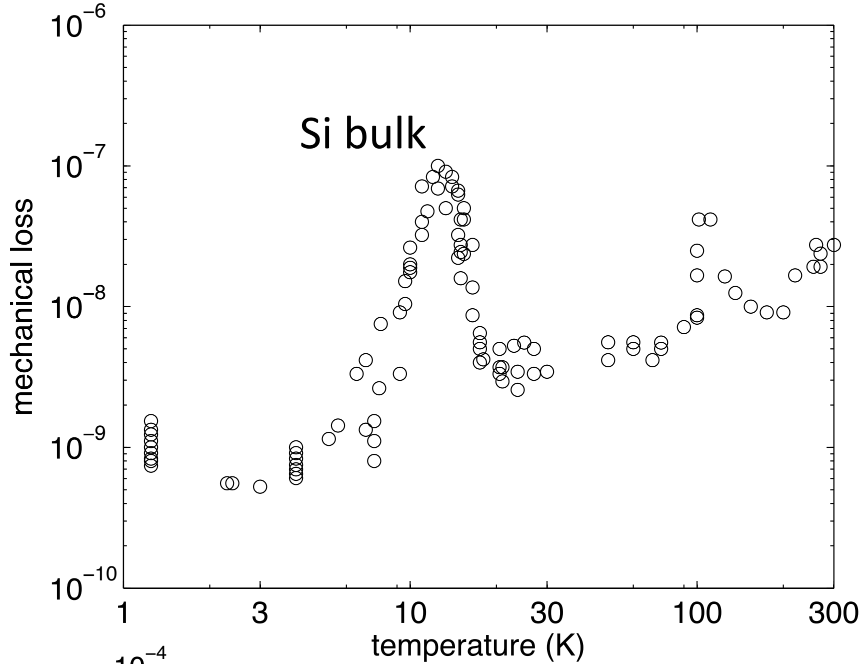


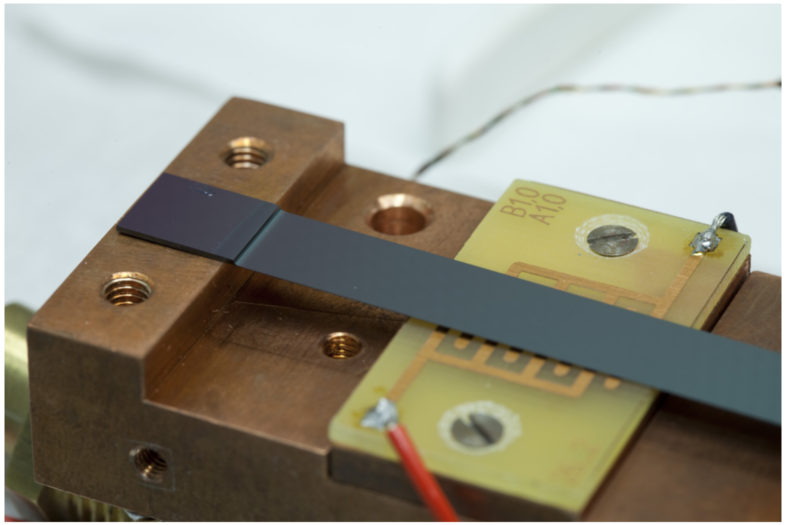
N. Beveridge talk on Thursday

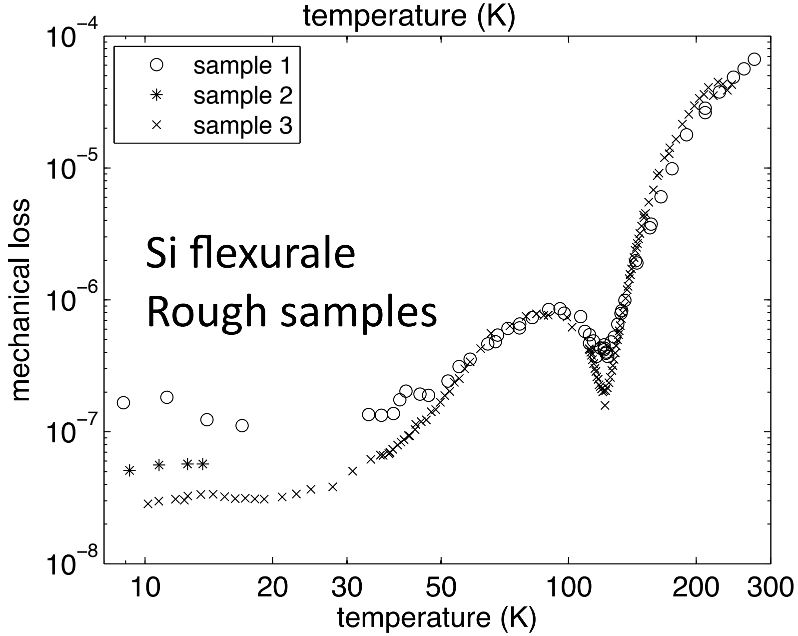


Silicon acoustic losses

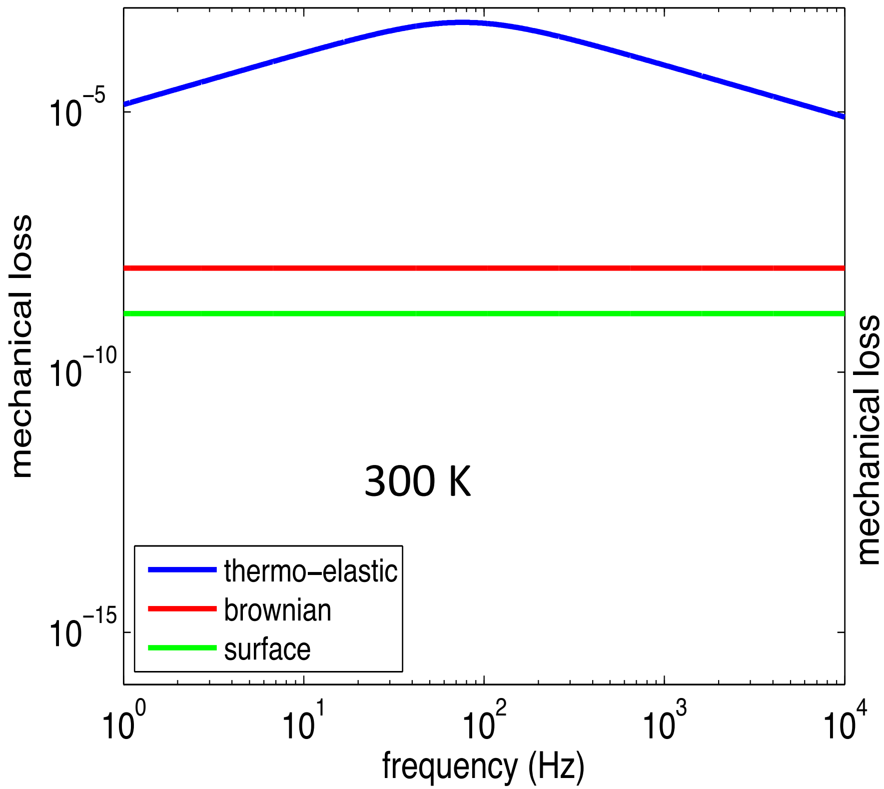


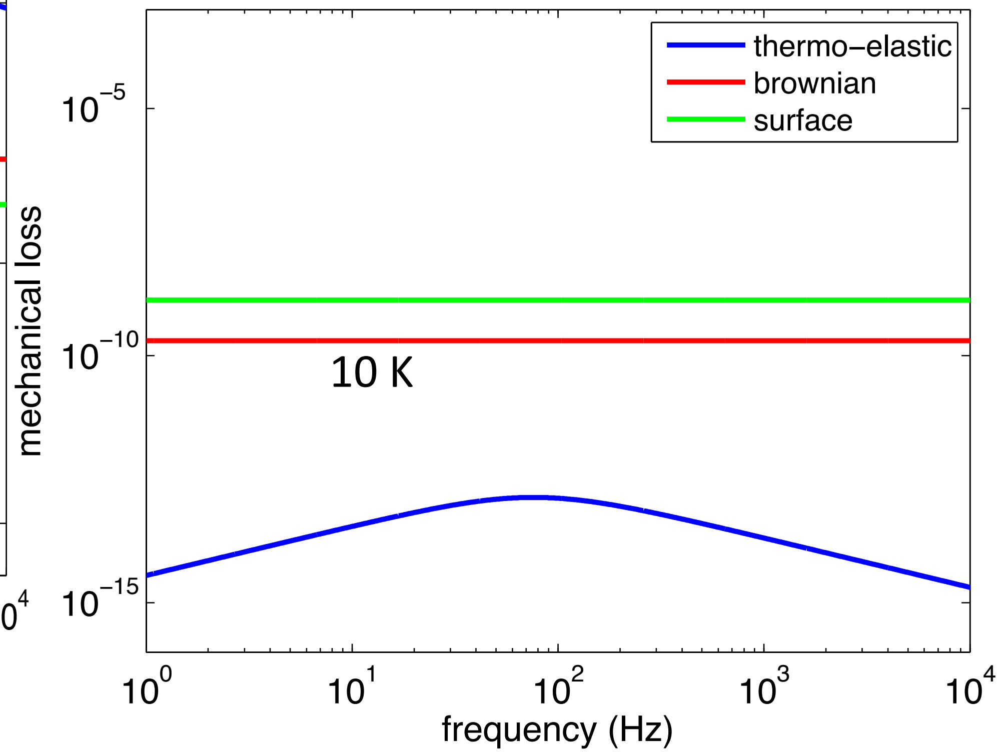




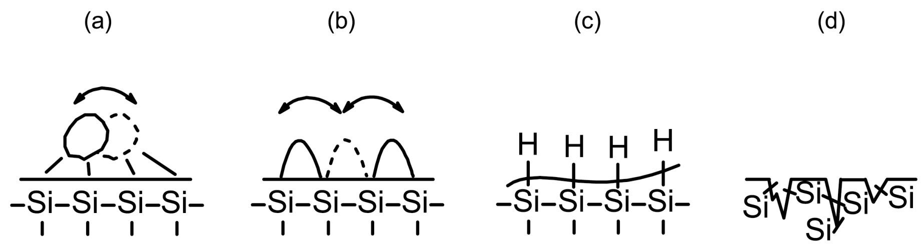


Acoustic loss contributions vs temperature



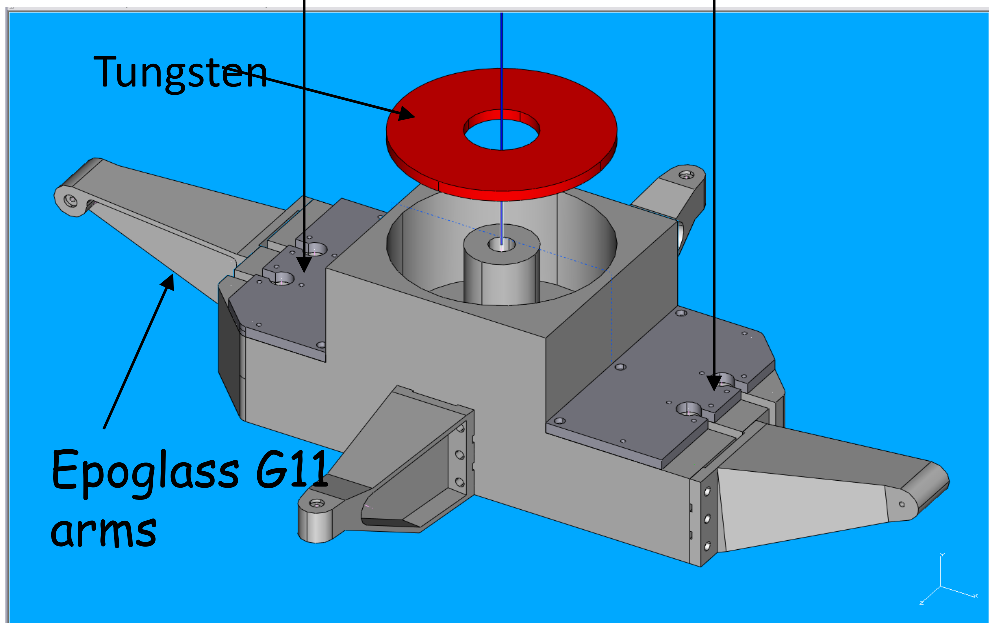


Surface loss mechanisms

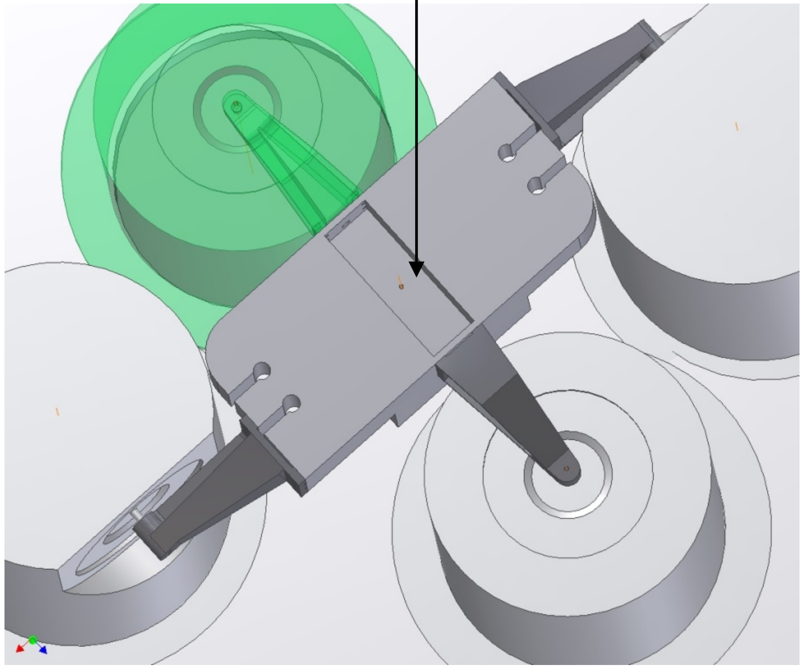


Marionette for the cryogenic environment

•Body in amagnetic Steel (AISI316L)
•Tungsten (or CuW) insert
• Epoglass arms G11 (suitable for cryo applications)
•Copper plate to clamp the suspension wires and the thermal links

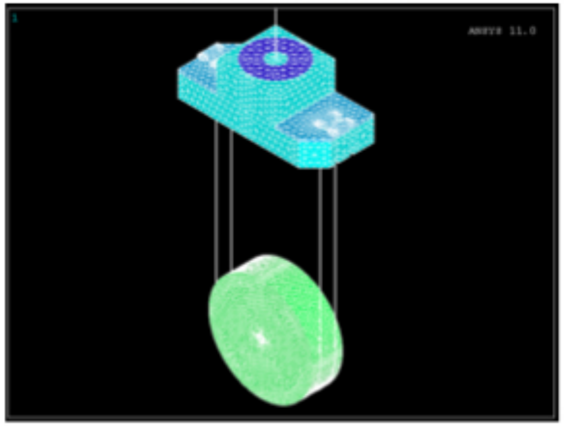


Mass for balancing the marionette by an electric motor



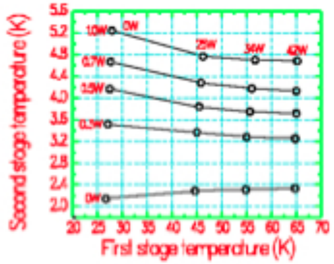
Thermal Simulation

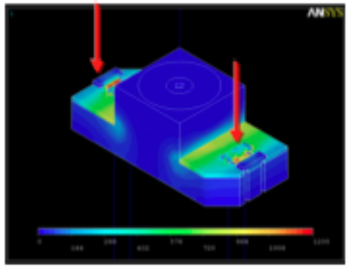
The model



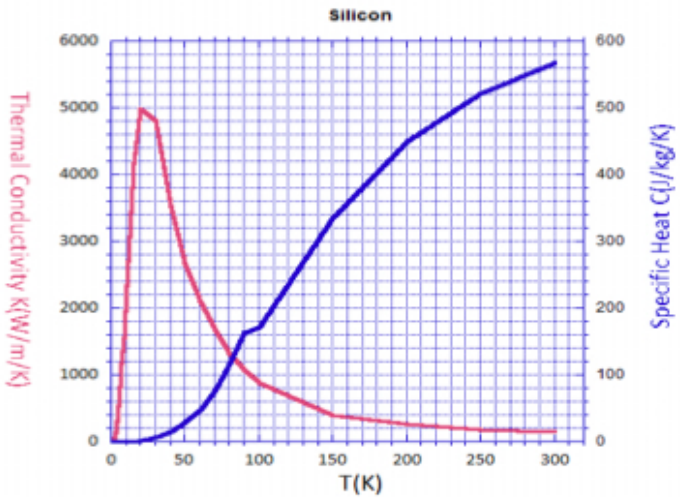
Boundary Conditions

•Cryocooler Second stage link to the marionetta

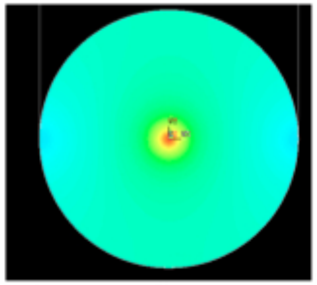




P_{cooler} depends on the temperature (Cryomec PT curve used) with 2 coolers the extracted power at 5 K is 1 W



Laser power on the mirror

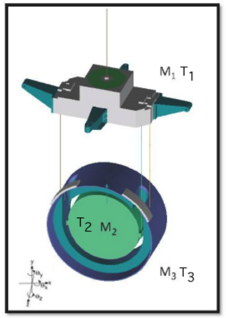


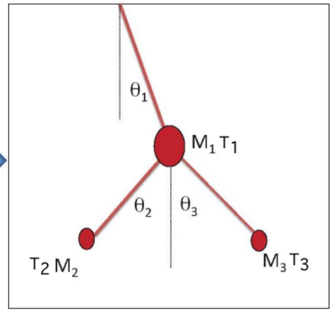
Gaussian beam

P_{abs}= 1W

The power absorbed by the coating is dominant

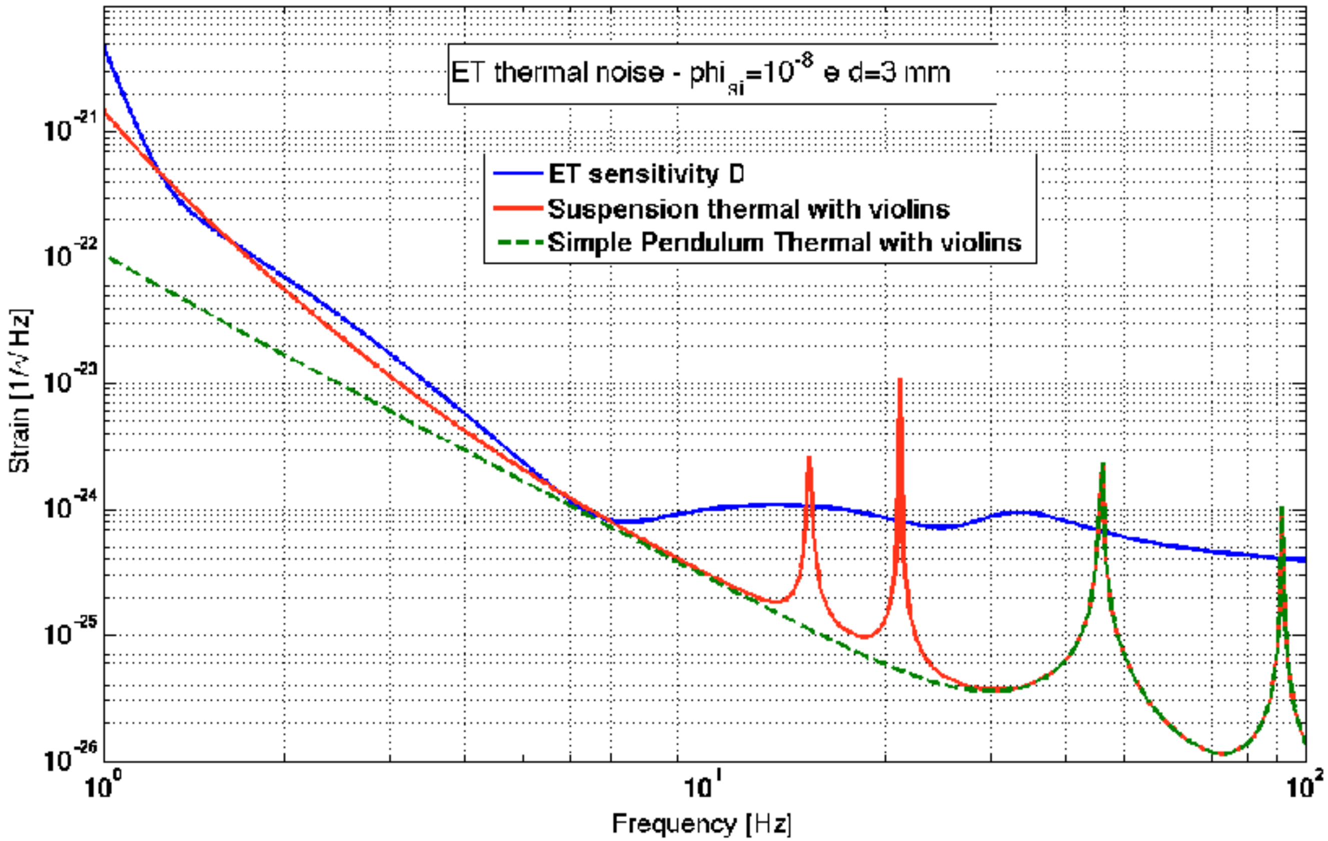
Starting point:
- termalised system at 10 K
- laser power on
- surrounding system at 10K





ET-LF suspension thermal noise

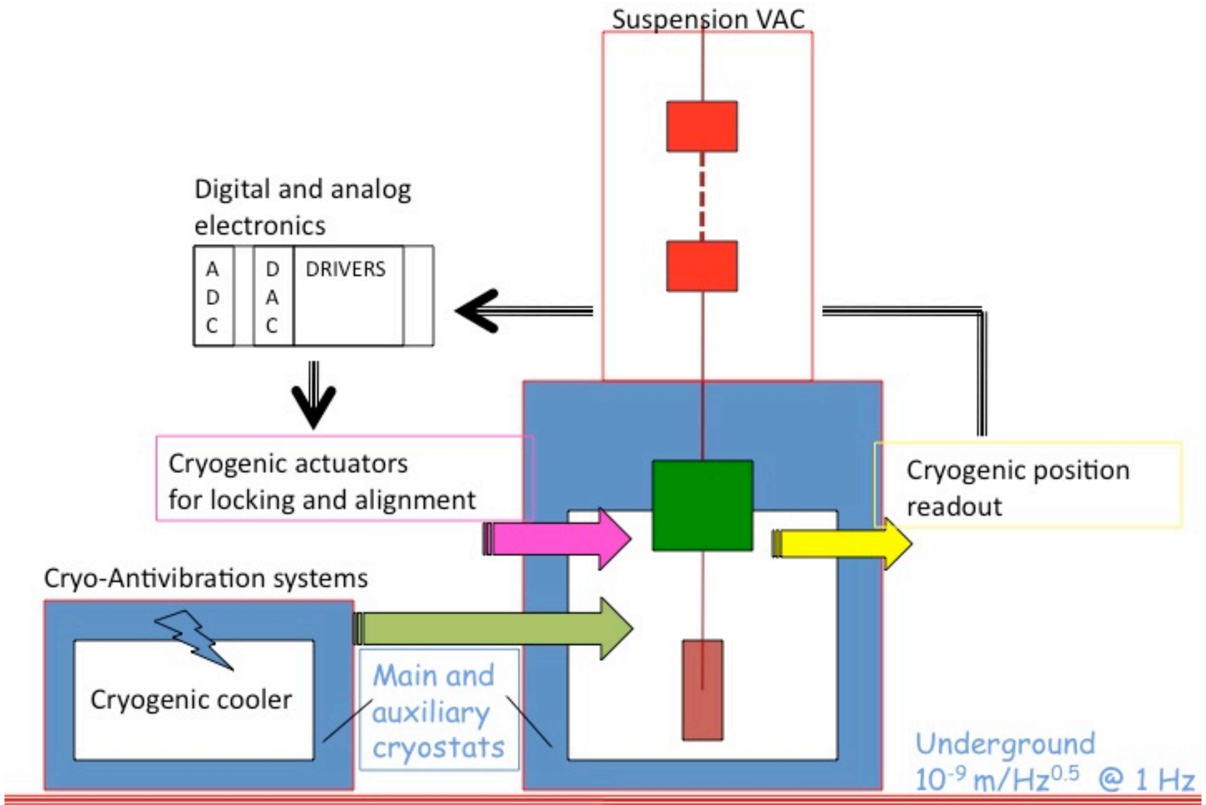
Based on the model,
which includes coupled oscillators at different temperatures



Suspension control: sensors and actuators

Coil - Magnet actuators: design according to constraints given by locking.

Electrostatic actuators easily adapted

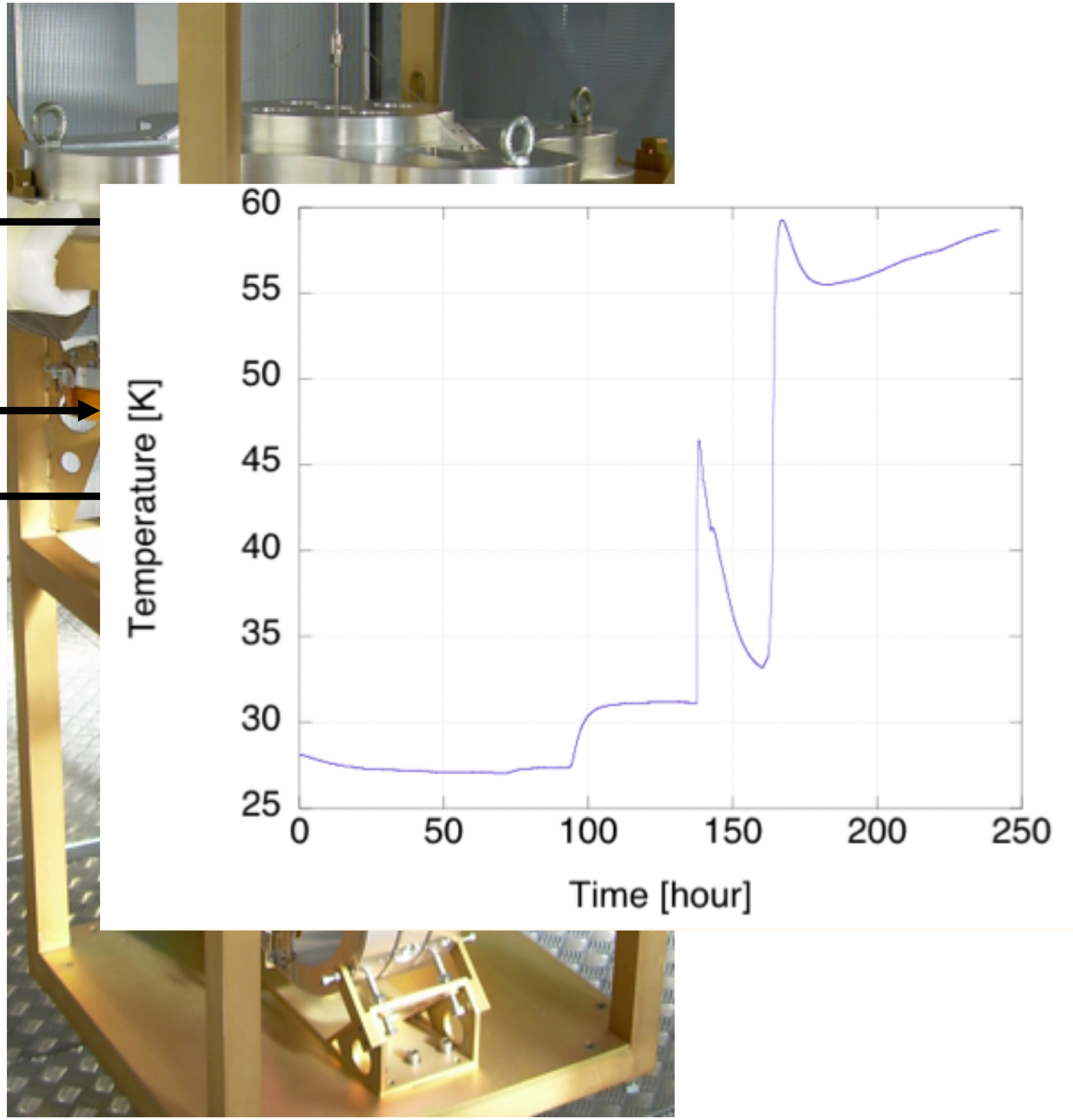


Solutions from the previous R&D experience

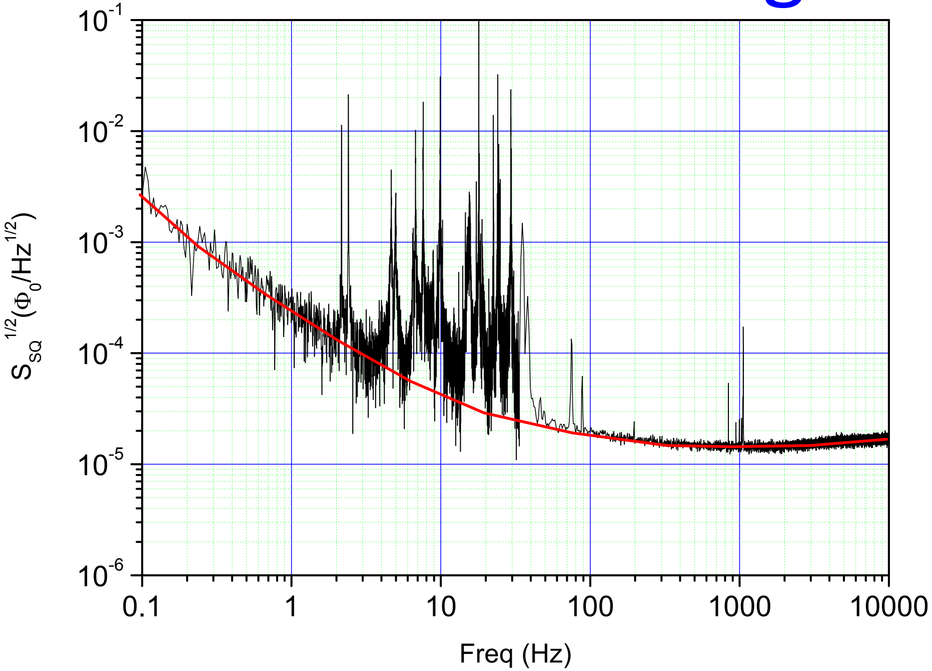
LVDT
at low temp

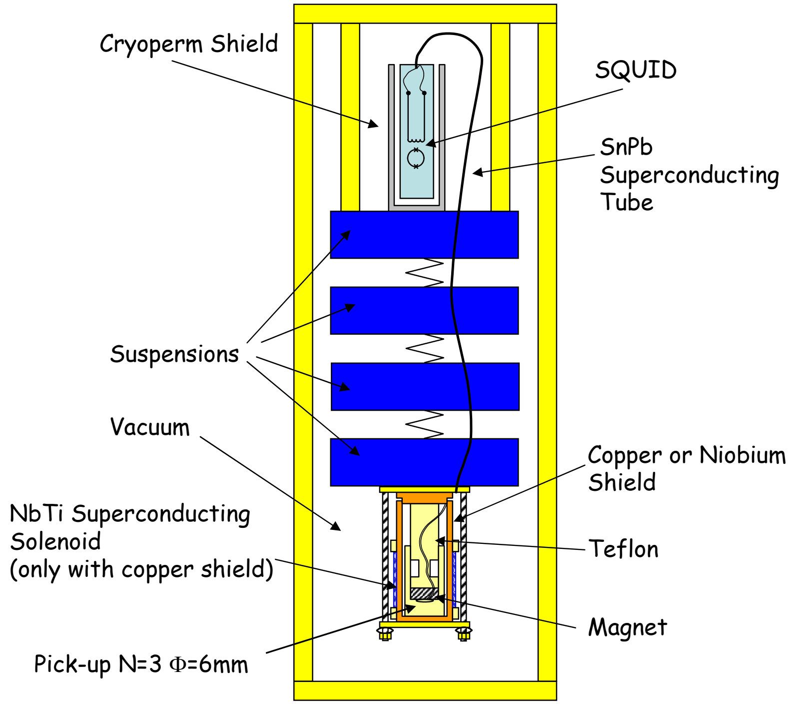
Superconducting
wires

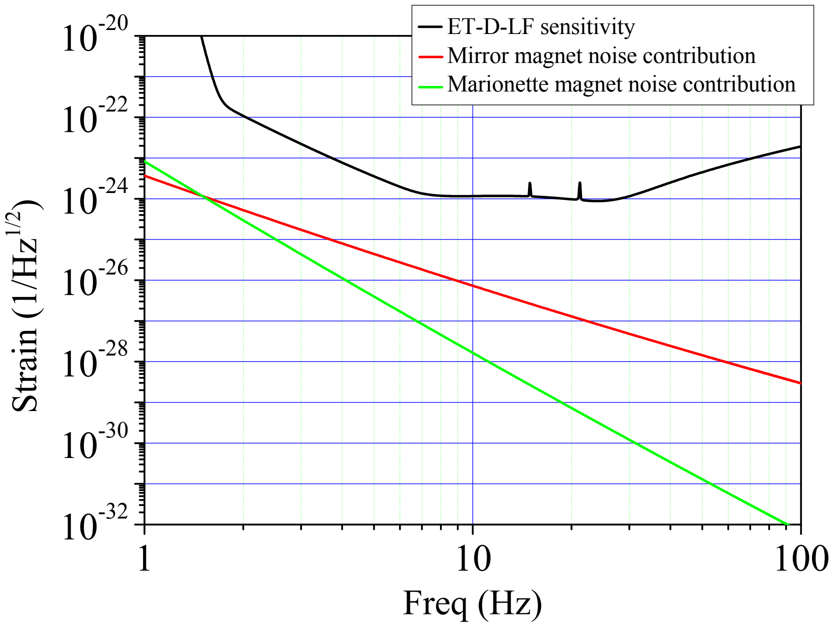
Epoglass



Coil-magnet actuation noise



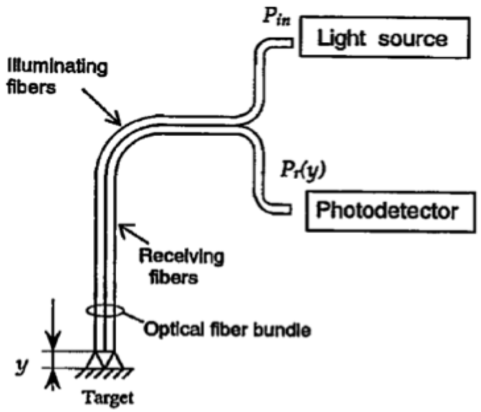


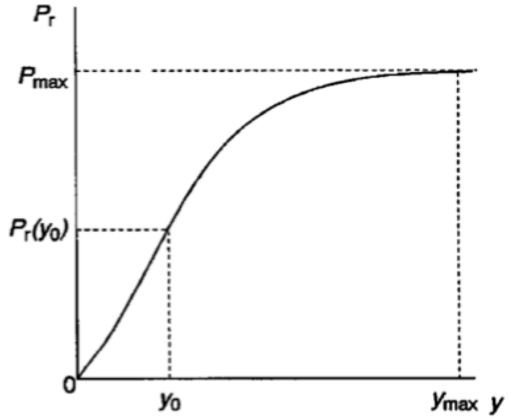


Barkausen noise measurements on a SmCo magnet at 4 K

P. Falferi Class. Quant. Grav. in press (2011)

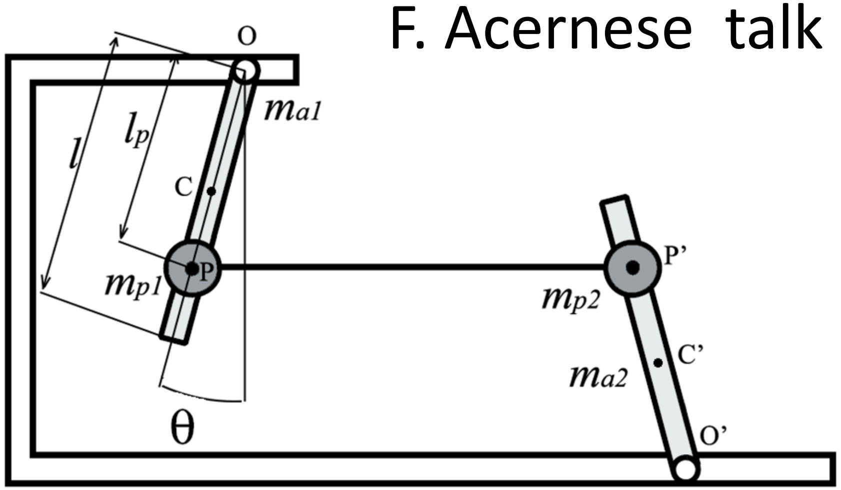
Displacement sensors at low temperature

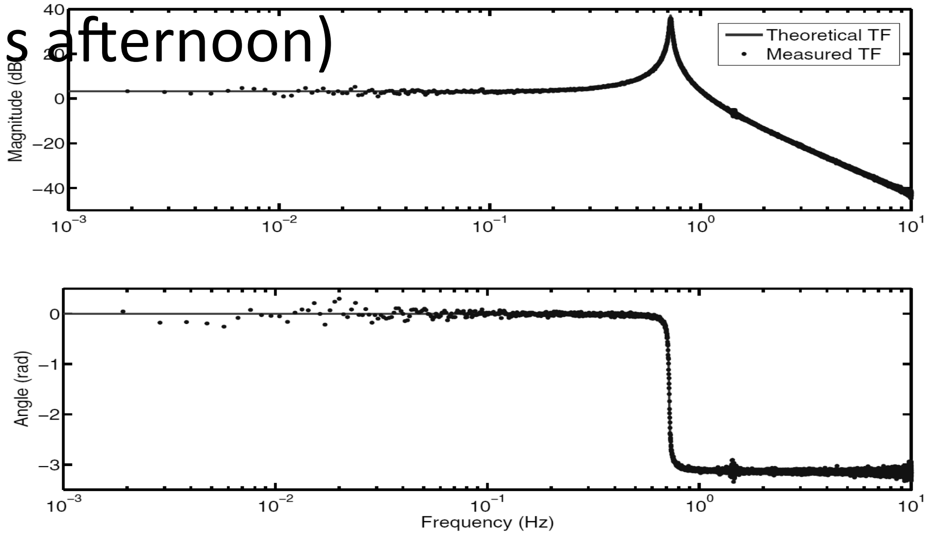




New Inertial sensors for suspension control

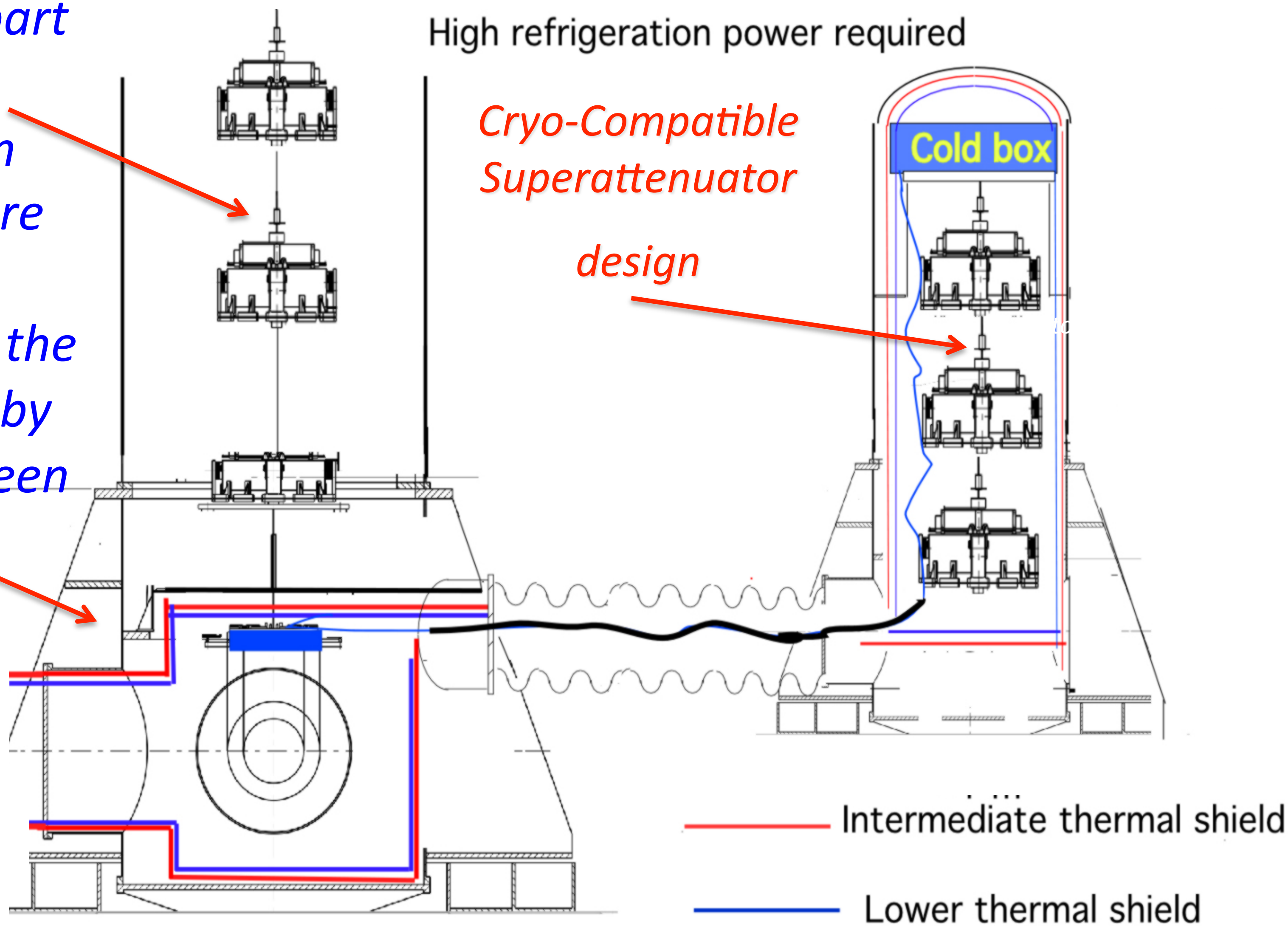
F. Acernese talk (this afternoon)





Design of the cooling system

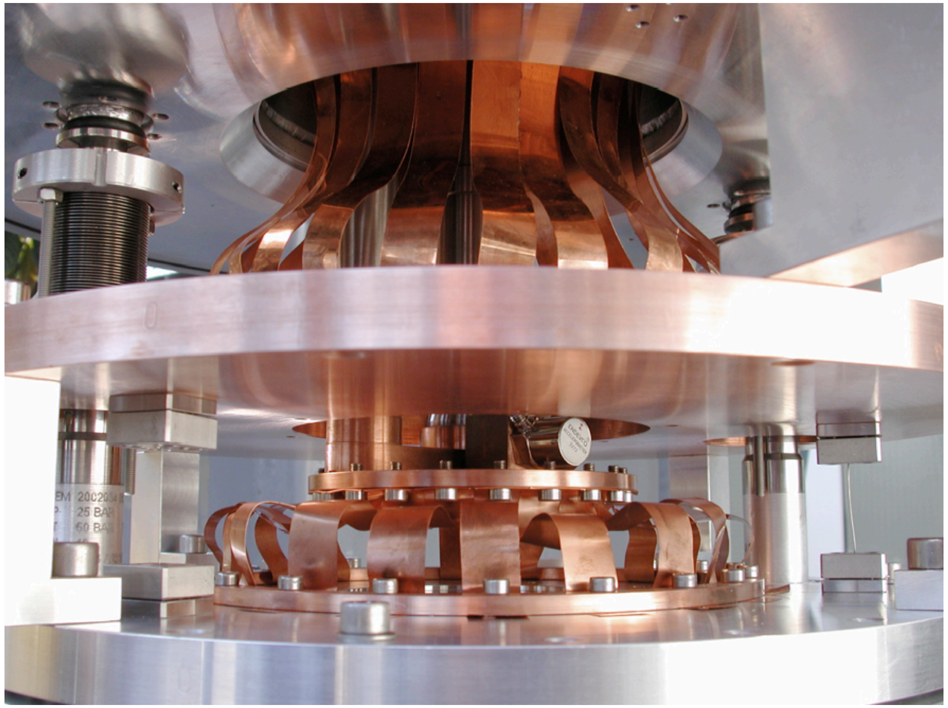
The upper part (~15 m) is at room temperature and insulated to the lower part by thermal screen



Thermal Links I

Geometries

A corona of thin beams

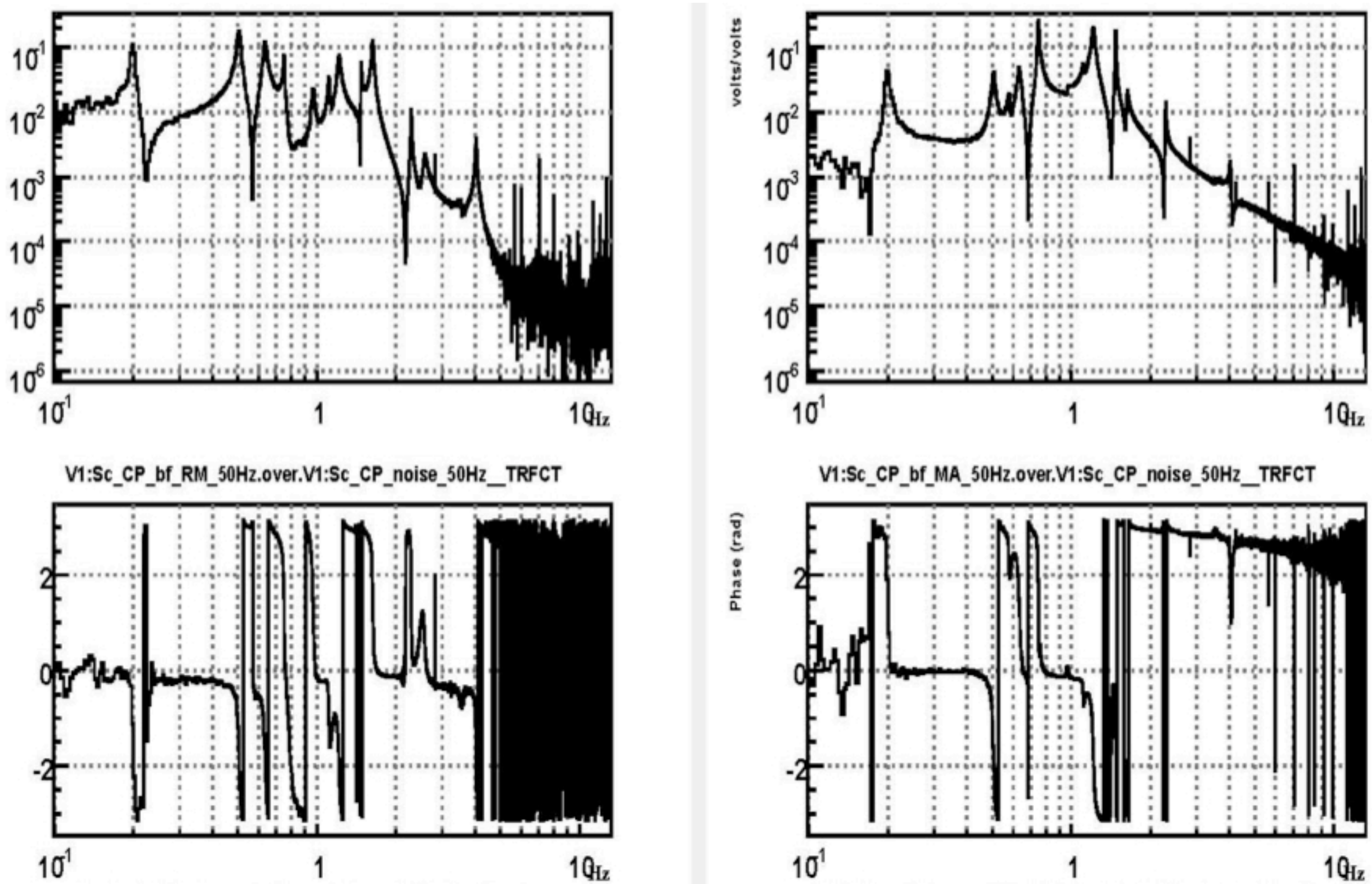


Long Braids

Thermal Links II: mechanical transfer function measurements at low temperature

P. Puppo talk next Thursday

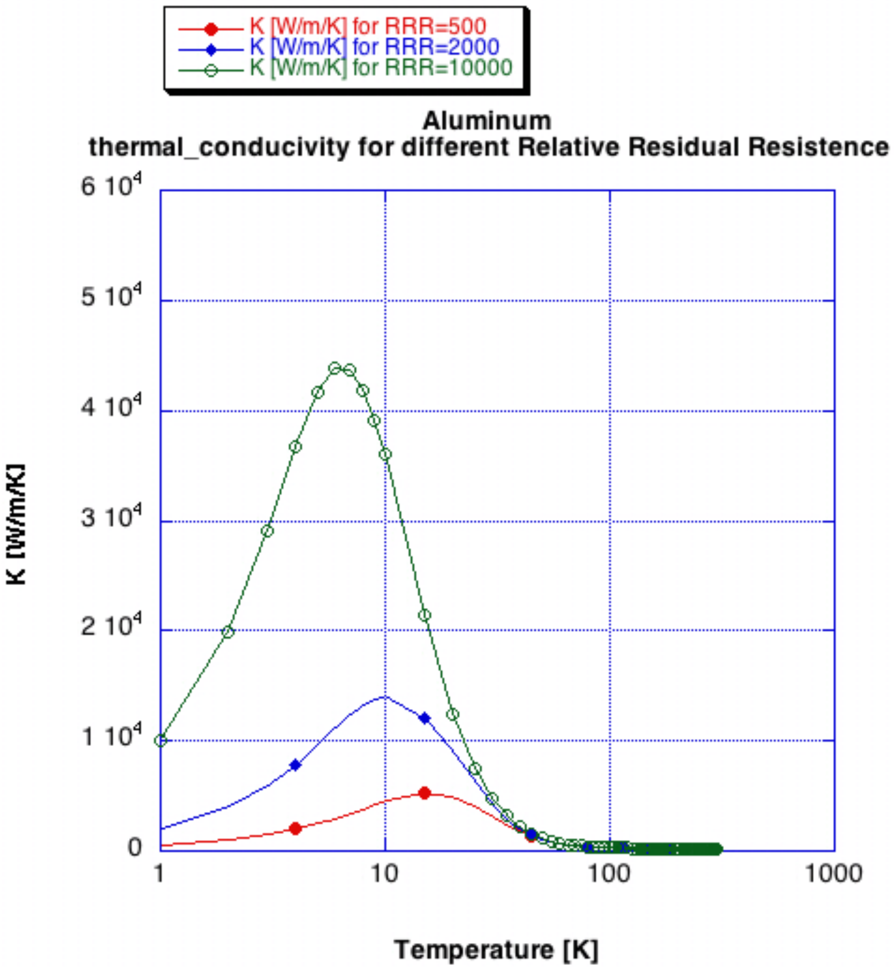
Evidence of a negligible influence of braids in the case of the torsion degrees of freedom

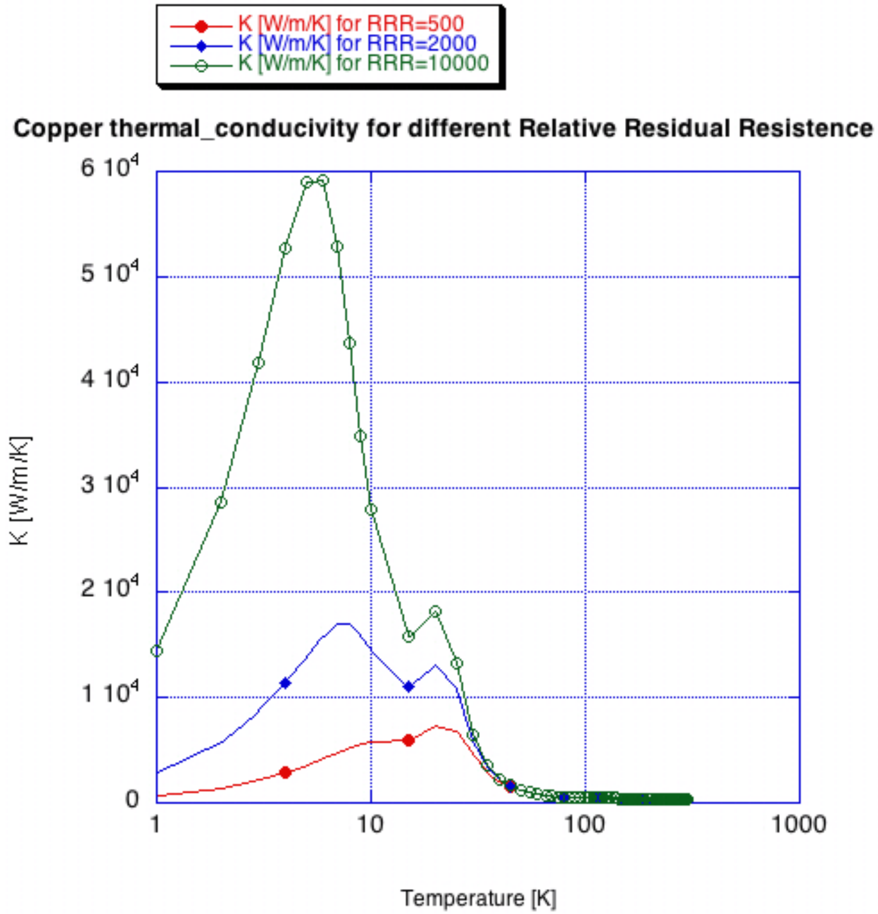


Thermal Links III

Pure Materials as aluminum and copper

RRR = $\rho_{room\ temperature} / \rho_o$ where ρ_o resid. resist. at T~0 K





Thermal Links IV

Solution for the stationary state

Use of a high purity material

k~2000 W/m/K in the range 1-10 K

Thermal link length 20 m

Thermal difference at the link ends ~ 1K

LF Int. ~200 mW ~8 wires r~1 mm

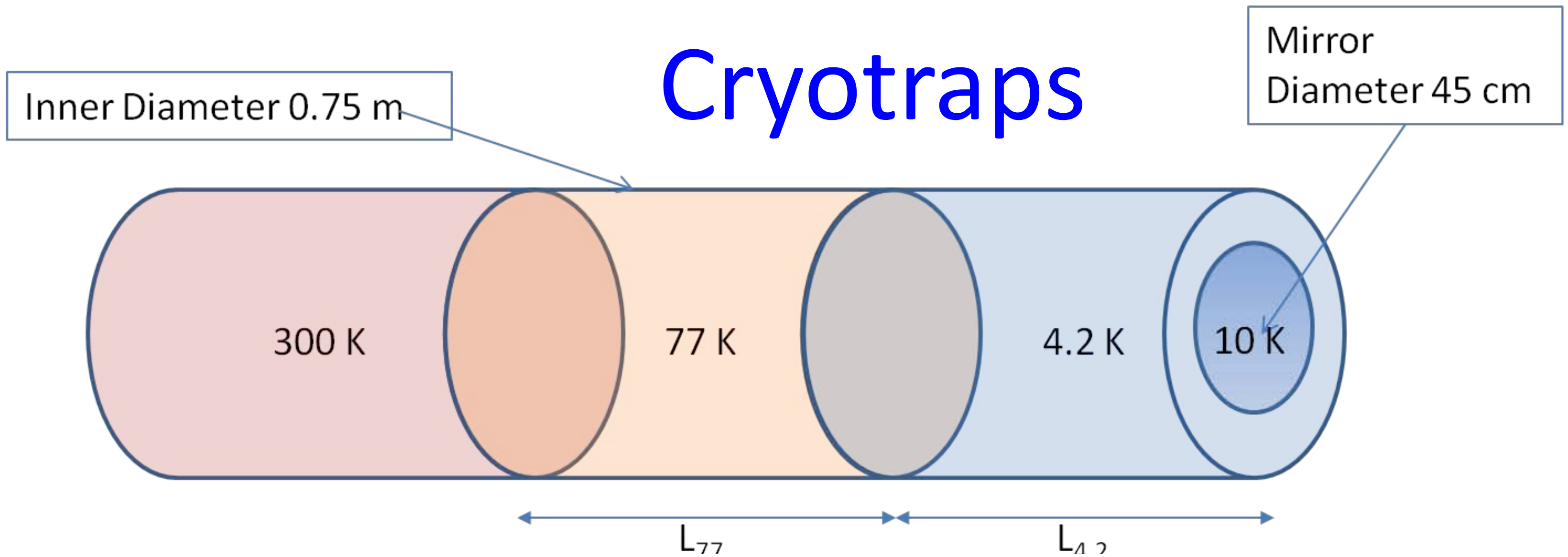
Cooling strategy: two solution analyzed

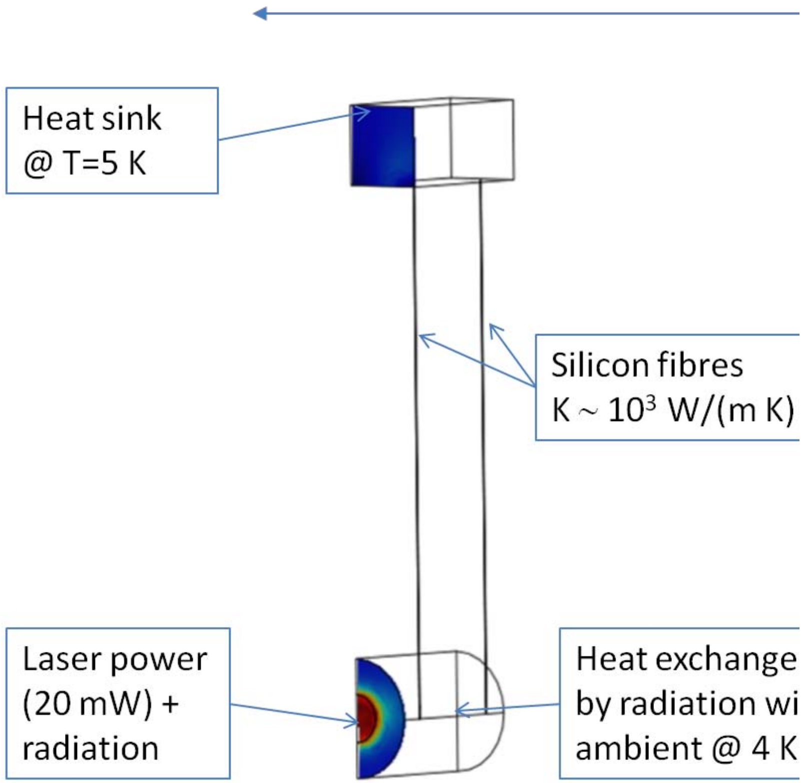
- Cryo – coolers:
  - the solution adopted in LCGT
  - reduced manpower
  - easy to use in an underground laboratory
  - *higher vibration and sound noise in the lab*
  - *lower refrigeration power*

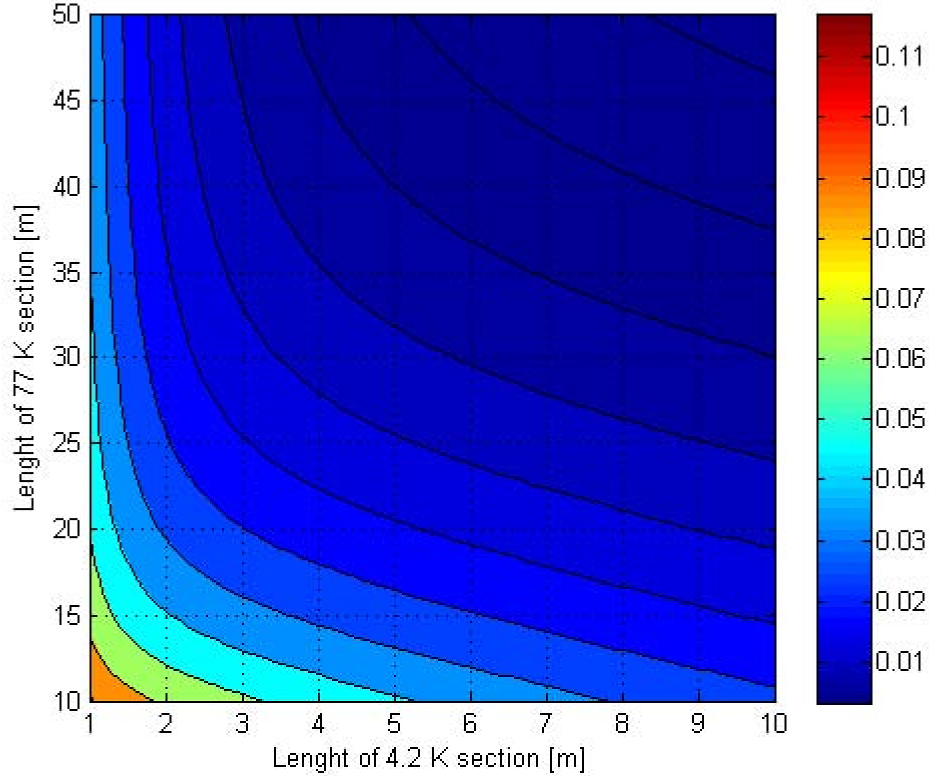
Cryo-fluids (Helium):

- technique adopted in the GW resonant detectors
- higher refrigeration power
- less noisy system
- *higher manpower*
- *safety issue in the underground laboratory*

Cryotraps





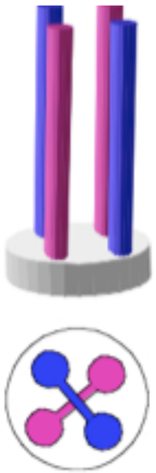


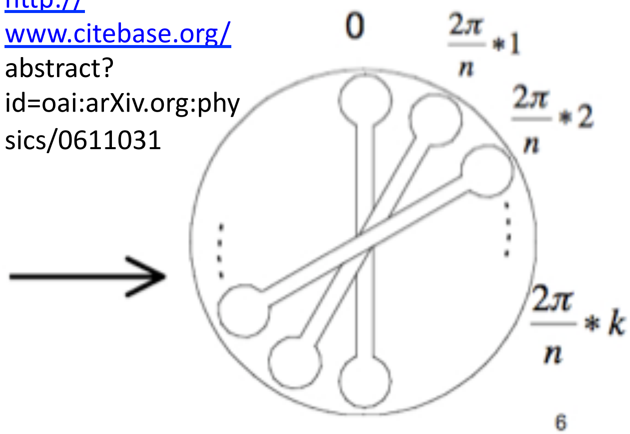
Credits A. Chincarini, G. Gemme

R&D for reducing the cryo cooler vibration

- Vibration noise of the refrigetation system (~0.01 - 0.03 mm/(Hz)$^{1/2}$) kept under control by an active system.

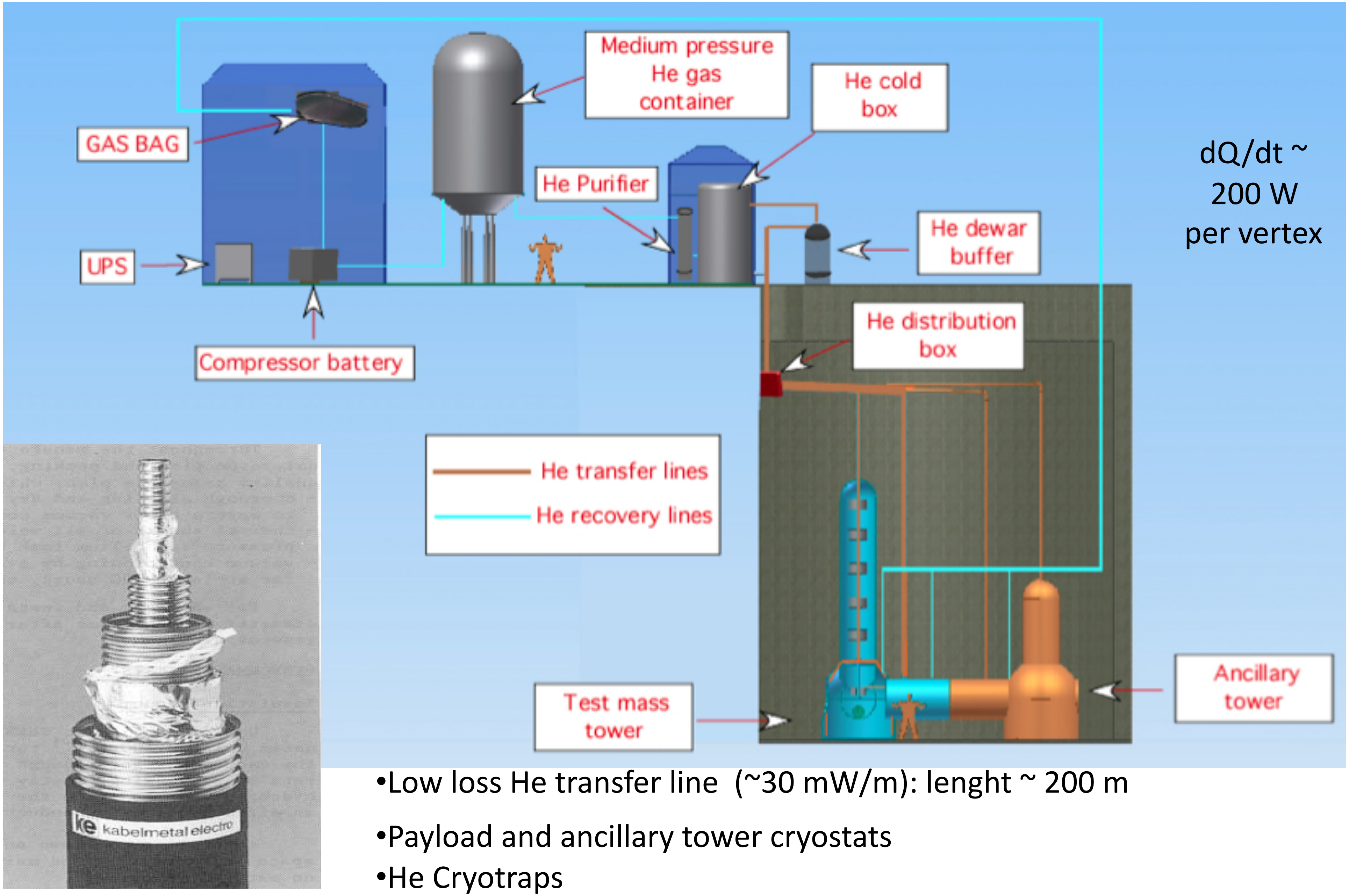
Suzuki et al. (2006) http://www.citebase.org/abstract?id=oai:arXiv.org:physics/0611031





•Improved attenuation is possible by adding to the first PT an other cryo-cooler, which operates@180º of phase

Cryofluid solution: a He plant in each vertex



dQ/dt ~ 200 W per vertex

- Low loss He transfer line (~30 mW/m): lenght ~ 200 m
- Payload and ancillary tower cryostats
- He Cryotraps

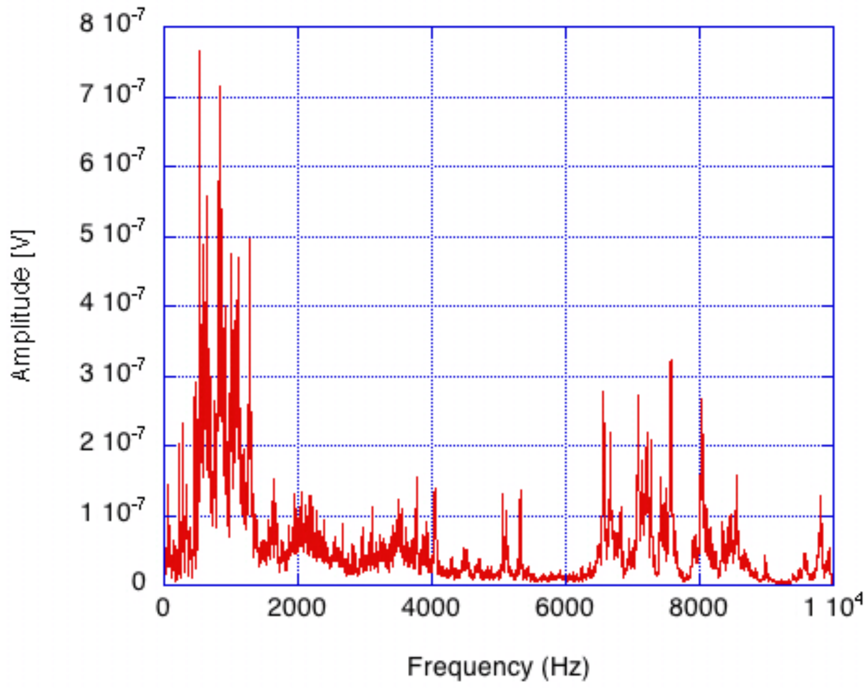
Cryofluid: R&D on the boiling problem

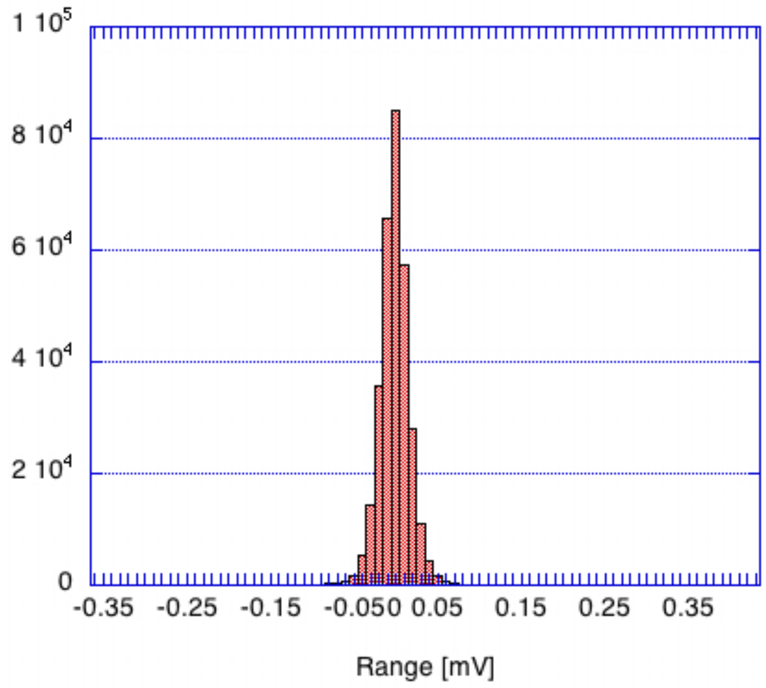
(absent in the superfluid case)

Displacement amplitude and frequency spectrum shape depend on the tank material and geometry: typical pressure fluctuation 20 dBa ➔ 2 10^{-4} Pa.
For example in the case of the GW resonant antenna Explorer x_{rms} ~ 10^{-10} m @ 4K with an evaporation rate of a liquid Helium ~2 lt/h

Example of the noise characteristics of a boiling fluid in cylindrical container

A simplest approach is to use supercritical helium at T>5.19 K (single phase status)





Conclusion

At the conclusion of the FP7- ET deign study we are confident the that ET is not any more a dream, it is a challenging project which requires R&D activity for

✓The material characterization,
✓The suspension improvement and its compatibility with the cryo temperatures
✓The development of new auxiliary sensors and actuators
✓The noiseless cooling process

This presentation is dedicated to the memory of our friend *Stefano Braccini*

It has been prepared thanks to the contributions of sevral physicists of the ET team

F Acernese, F Barone, S Braccini, A Chincarini, R De Rosa, P Falferi, J Franc, F Frasconi, G Gemme, A Gennai, M Lorenzini, E Majorana, R Nawrodt, G M Perciballi, R Poggiani, P Puppo, D Rabeling,S Reid, S Rowan, M Tonelli, J F J van den Brand………and many others