Sapphire Fibers: Effect of Surface Roughness on Thermal Conductivity

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LIGO-G030205-00-Z

LCGT: Mirror Suspension Schematic

- Required Mirror Temperature: ~20K

- Required Medium Mass Temperature: ~10K

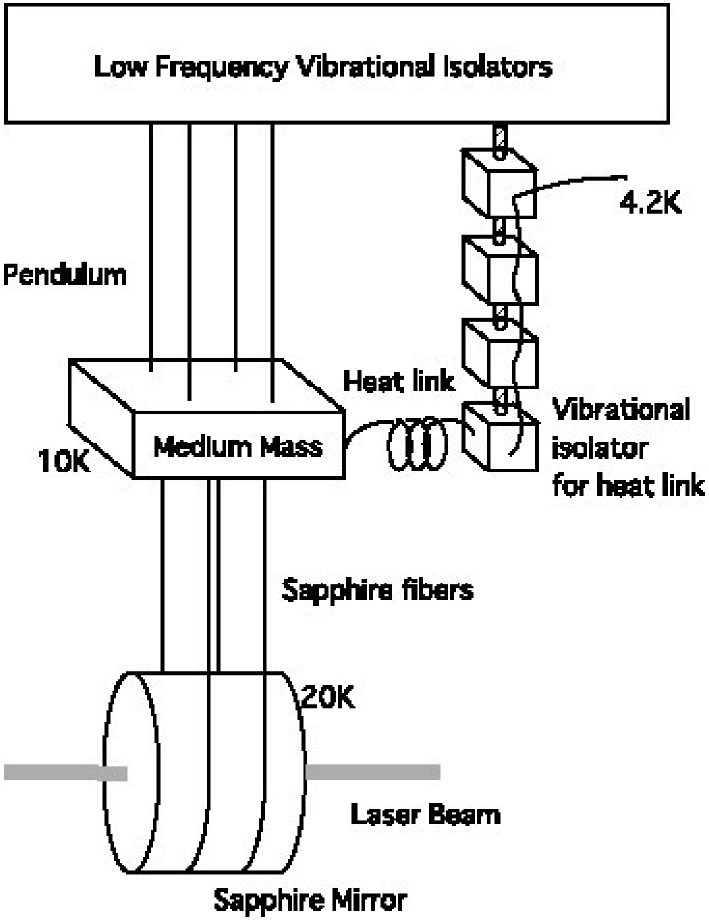
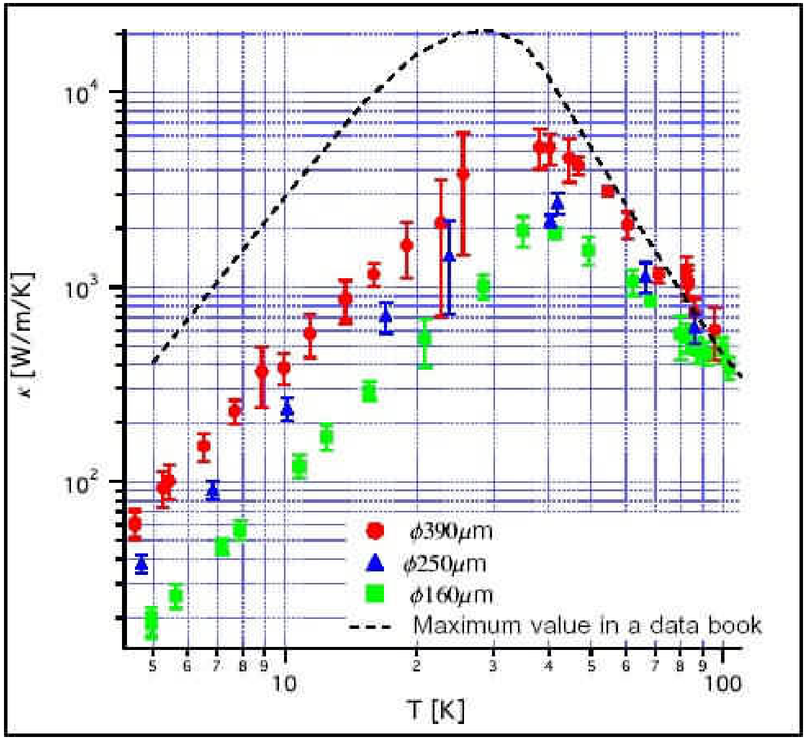


Image provided by T. Tomaru.

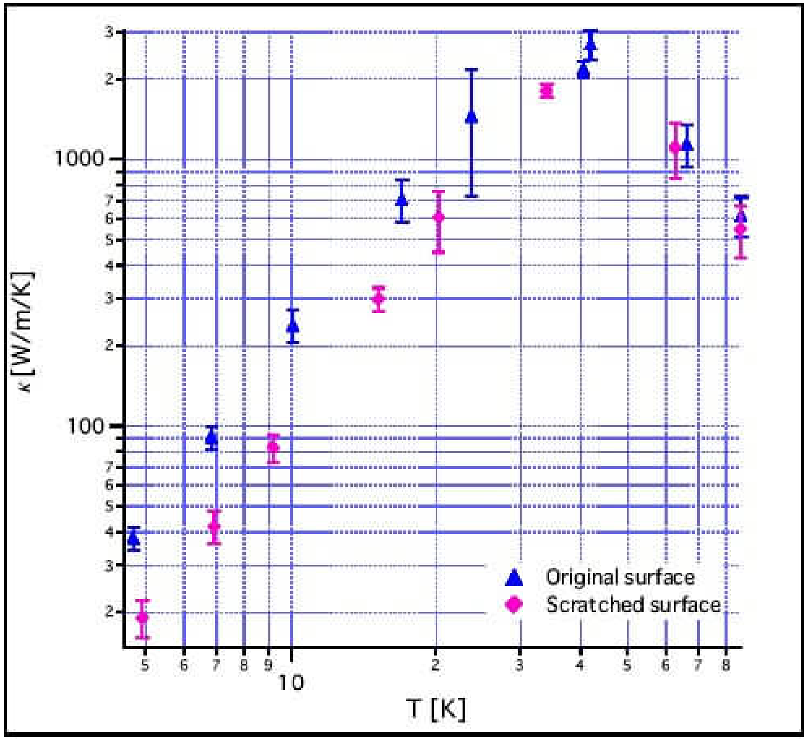
LIGO

Size and Surface Effects: Tomaru et al

Thermal conductivity spectra for different fiber diameters…



The thermal conductivity was observed to decrease by a factor of ~2 after scratching the fiber by hand…



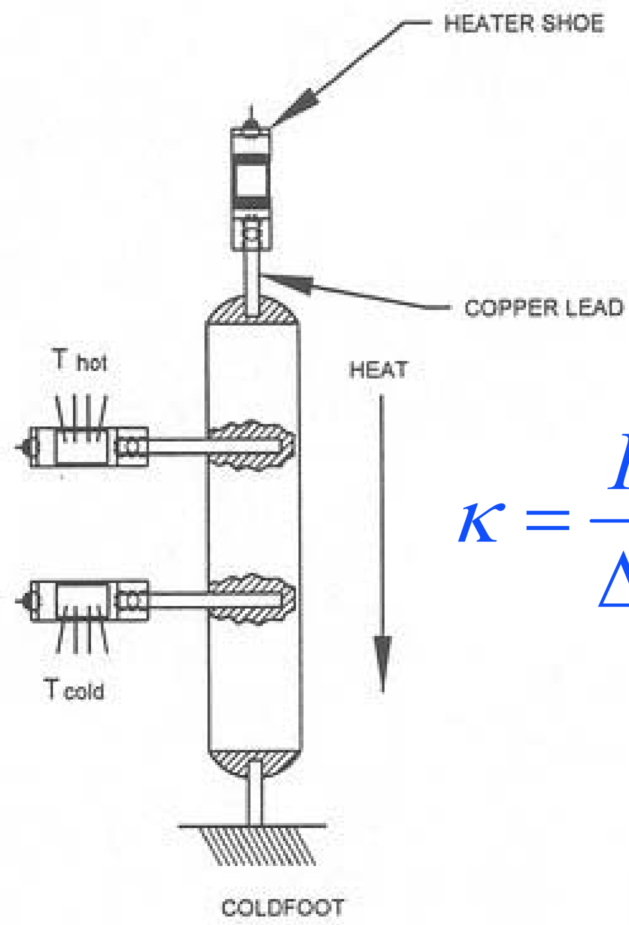
Images provided by T. Tomaru.

Thermal Conductivity Measurement: The Longitudinal Heat Flow Method

Use of Quantum Device PPMS

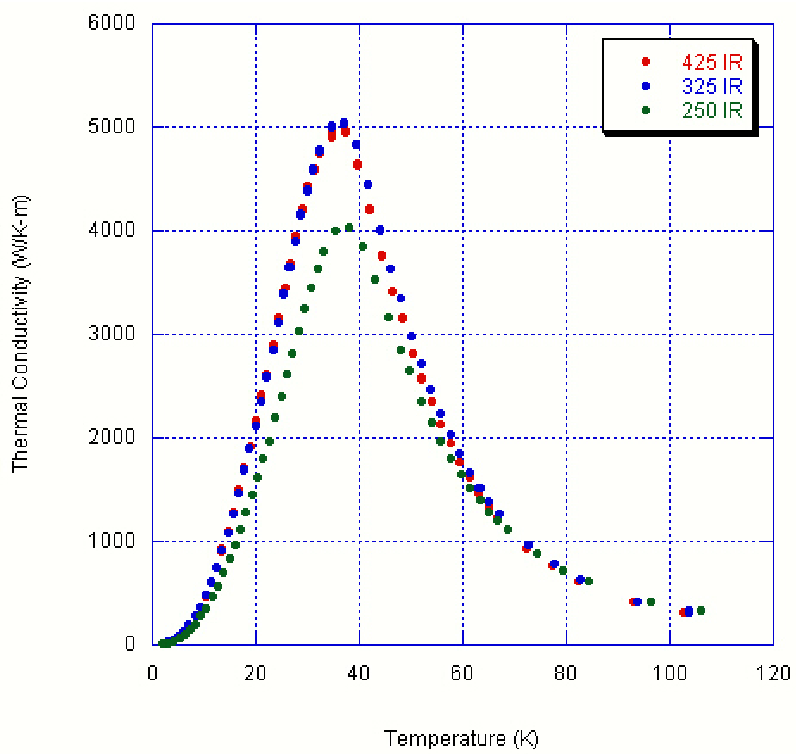
Automated measurement sequence

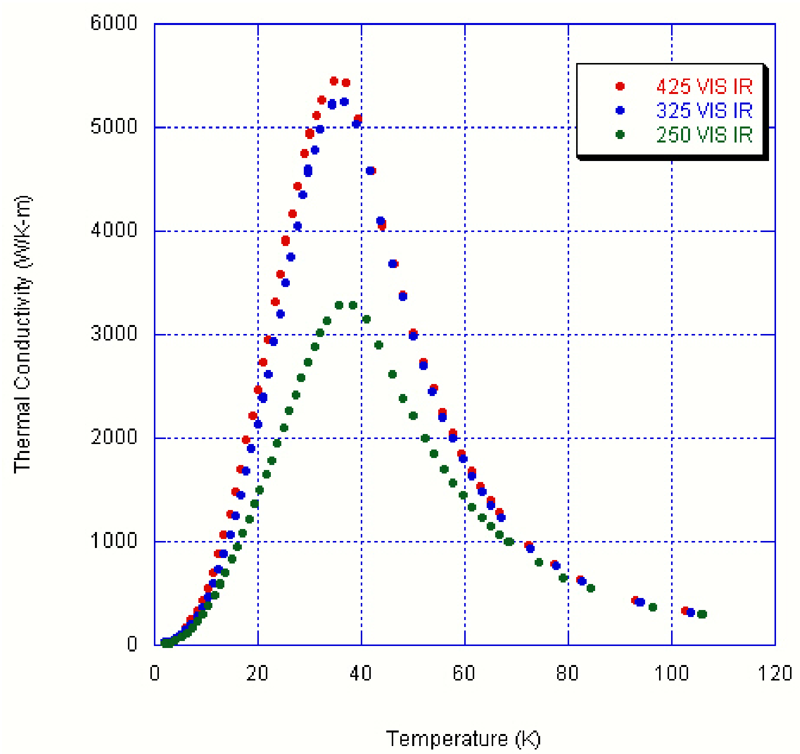
1. Apply heater pulse.
2. Wait for equilibrium.
3. Measure ΔT.
4. Repeat for different T



$$\kappa = \frac{P_{in}}{\Delta T}\left(\frac{\ell}{A_s}\right)$$

Thermal Conductivity: The Effect of Different Diameters





Note: Error bars were unavailable at the time of this presentation.

Thermal Conductivity: Expected Change With Diameter

Thermal Conductivity:

$$\kappa = \frac{1}{3} C_v \bar{v} \ell$$

Ratio of two thermal conductivity spectra:

$$\frac{\kappa_1}{\kappa_2} = \frac{\ell_1}{\ell_2}$$

Ziman defines the mean free path of a cylinder. Here, the Casimir length is equal to the diameter:

$$\ell = \frac{(1+p)}{(1-p)} \ell_c = \frac{(1+p)}{(1-p)} d$$

The thermal conductivity ratio becomes:

$$\frac{\kappa_1}{\kappa_2} = \frac{(1+p_1)}{(1-p_1)} \frac{(1-p_2)}{(1+p_2)} \left(\frac{d_1}{d_2} \right)$$

Where, p, is called the 'polish factor' and described the surface roughness' of the sapphire fiber:

$$p(\lambda) = \exp\left(\frac{-16\pi^3 \eta^2}{\lambda^2} \right)$$

If the RMS surface roughness, eta, is the same for both fibers, the ratio of thermal Conductivity spectra is the ratio of the fiber diameters:

$$\frac{\kappa_1}{\kappa_2} = \frac{d_1}{d_2}$$

Thermal Conductivity: Experiment vs. Theory

Diameter of Fiber 1 (μm)	Diameter of Fiber 2 (μm)	Ratio of Diameters	Calculated Conductivity Ratio	Difference Between Ratios
420.52	340.03	1.24	0.98	-0.26
420.52	210.00	2.00	1.20	-0.80
340.03	210.00	1.62	1.23	-0.39

Table 6: Ratio of the diameters between IR fibers.

Diameter of Fiber 1 (μm)	Diameter of Fiber 2 (μm)	Ratio of Diameters	Calculated Conductivity Ratio	Difference Between Ratios
420.00	340.00	1.24	1.04	-0.20
420.00	250.00	1.68	1.55	-0.13
340.00	250.00	1.36	1.48	0.12

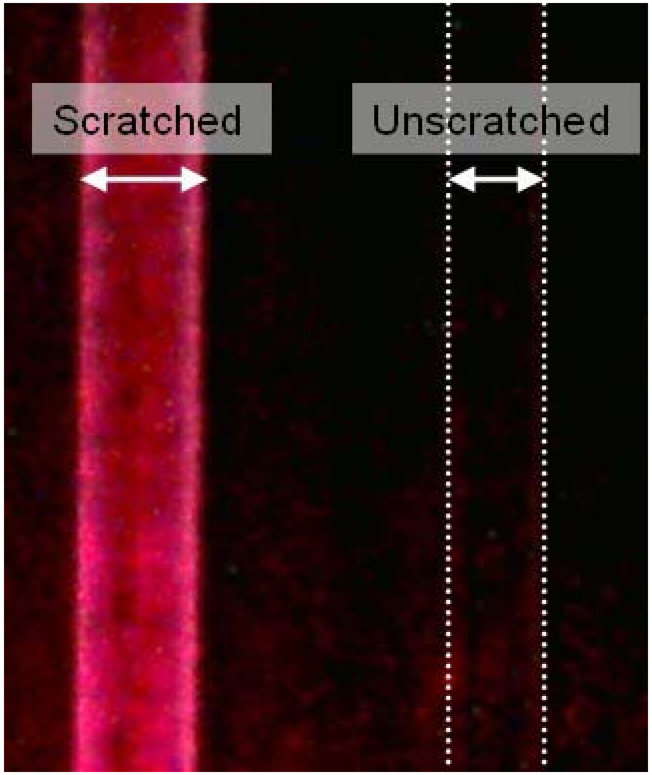
Table 7: Ratio of the diameters between VIS IR fibers.

Could it be roughness ?

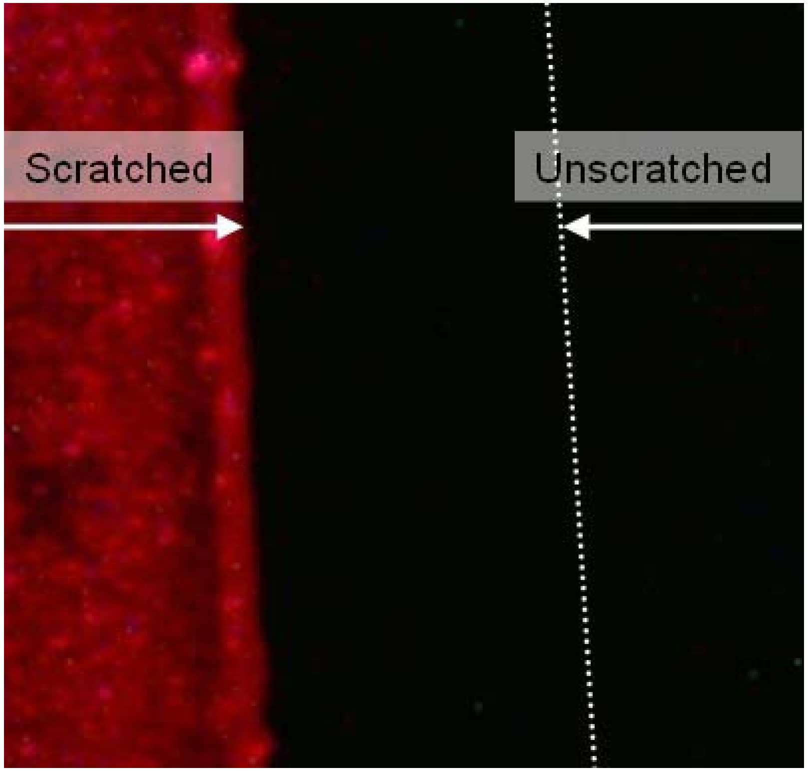
- If the RMS surface roughness is < 1nm, then a difference in RMS surface roughness on the order of only 1-2Å between samples can cause measurable deviations in the ratio of the conductivity spectra.

Sapphire Fibers: Scratching the Surface

Optical Images – Laser Reflecting off surface



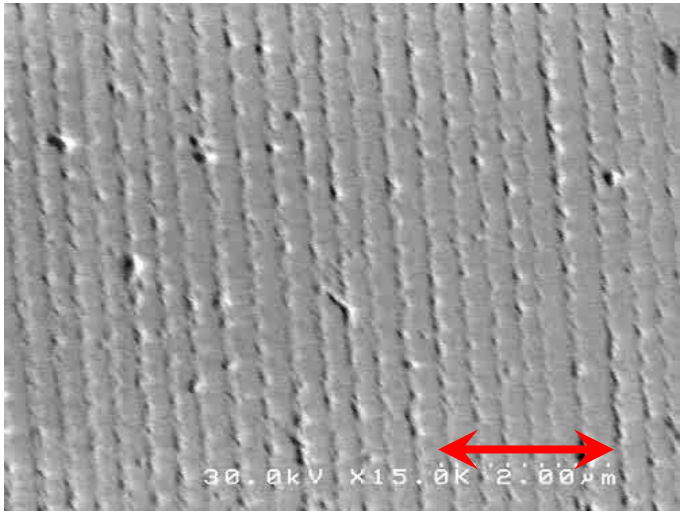
325μm IR Fiber Comparison (60x Magnification)



325μm IR Fiber Comparison (200x Magnification)

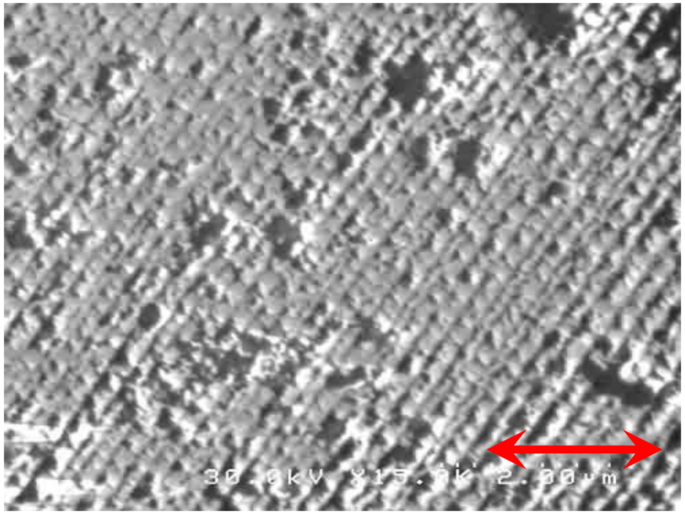
Sapphire Fibers: Scratching the Surface

SEM Images – 2.00µm Scale



2.00µm

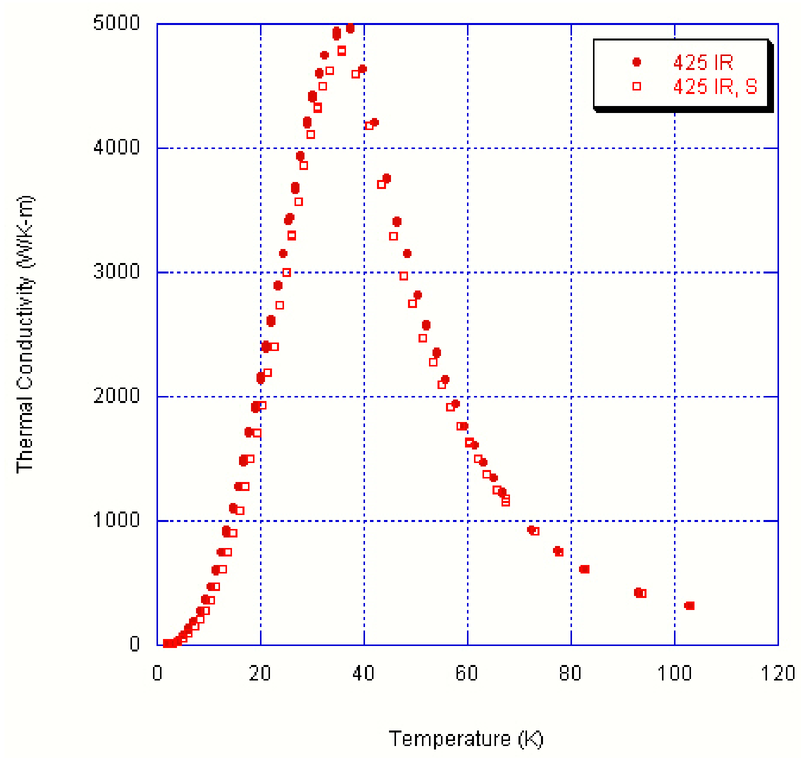
325µm IR Fiber – Before Sand-Blasting

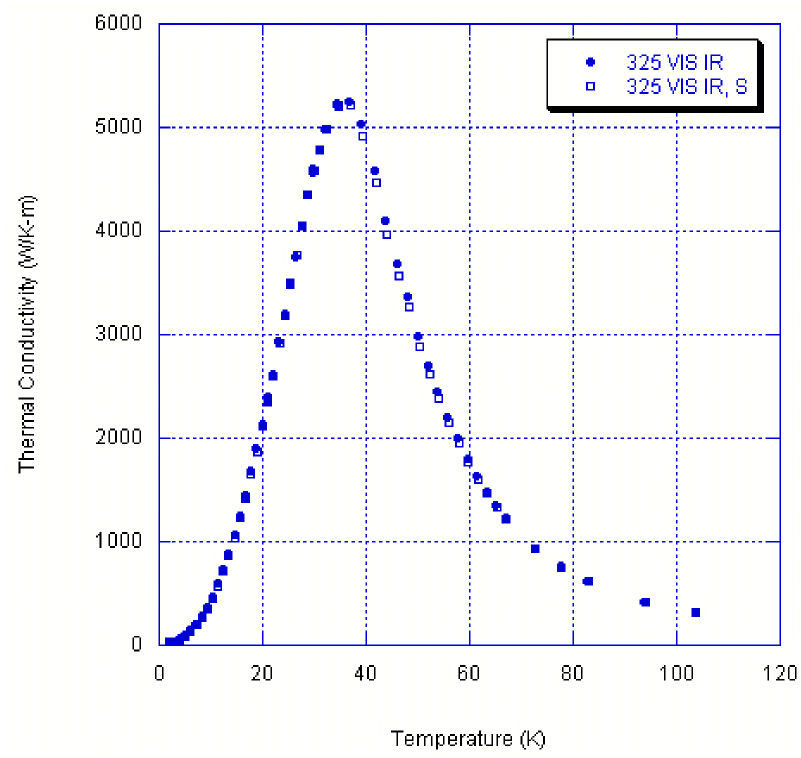


2.00µm

325µm IR Fiber – After Sand-Blasting

Thermal Conductivity: The Effect of Surface Roughness

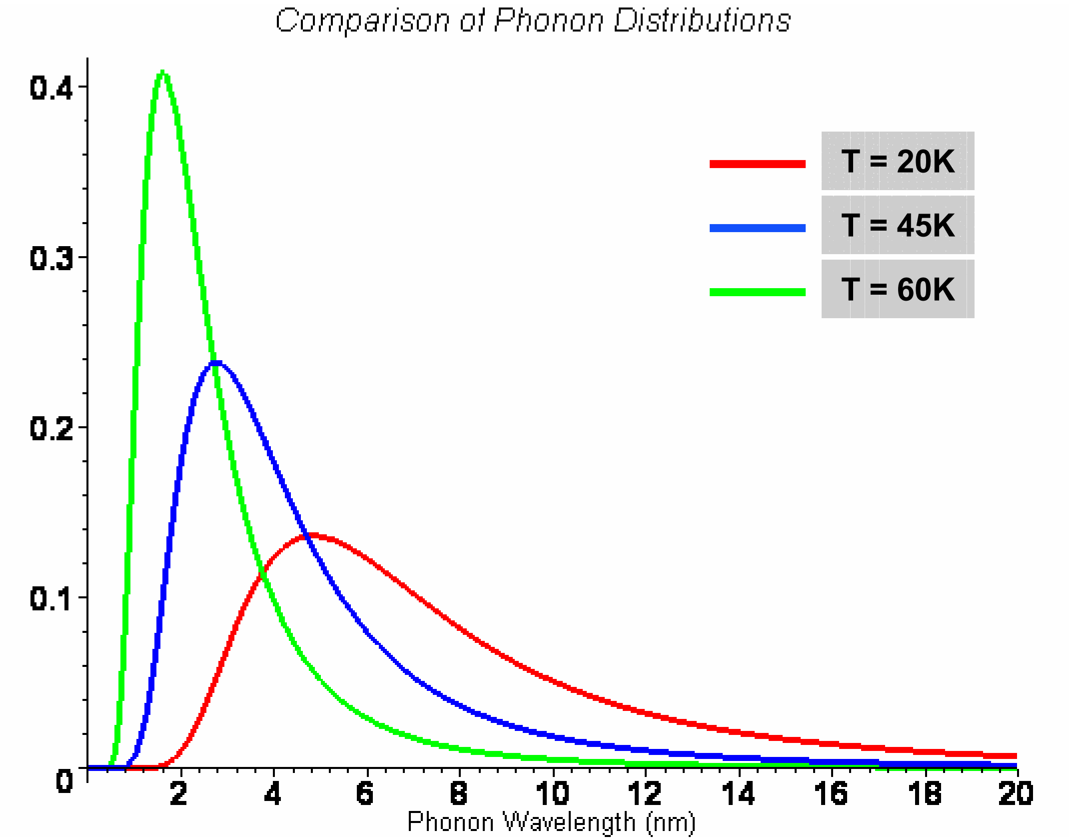




Thermal Conductivity: The Effect of Surface Roughness

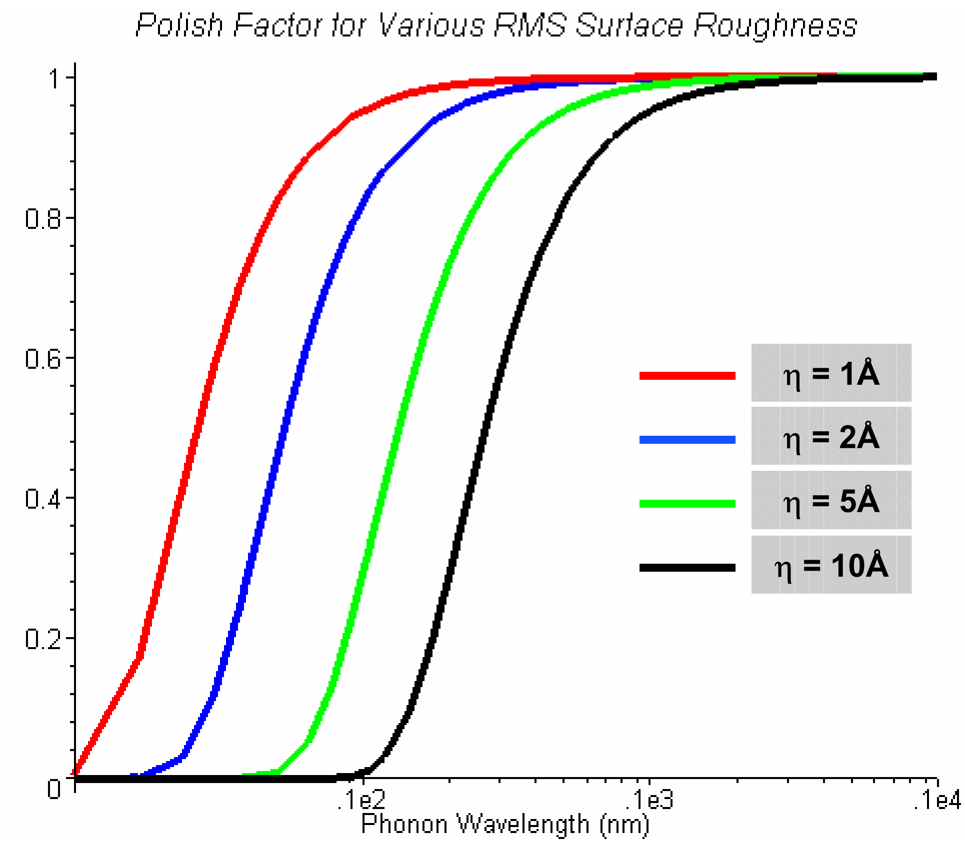
- Insignificant change in thermal conductivity spectra after increasing the surface roughness on all fibers.

Phonon Distribution Comparison

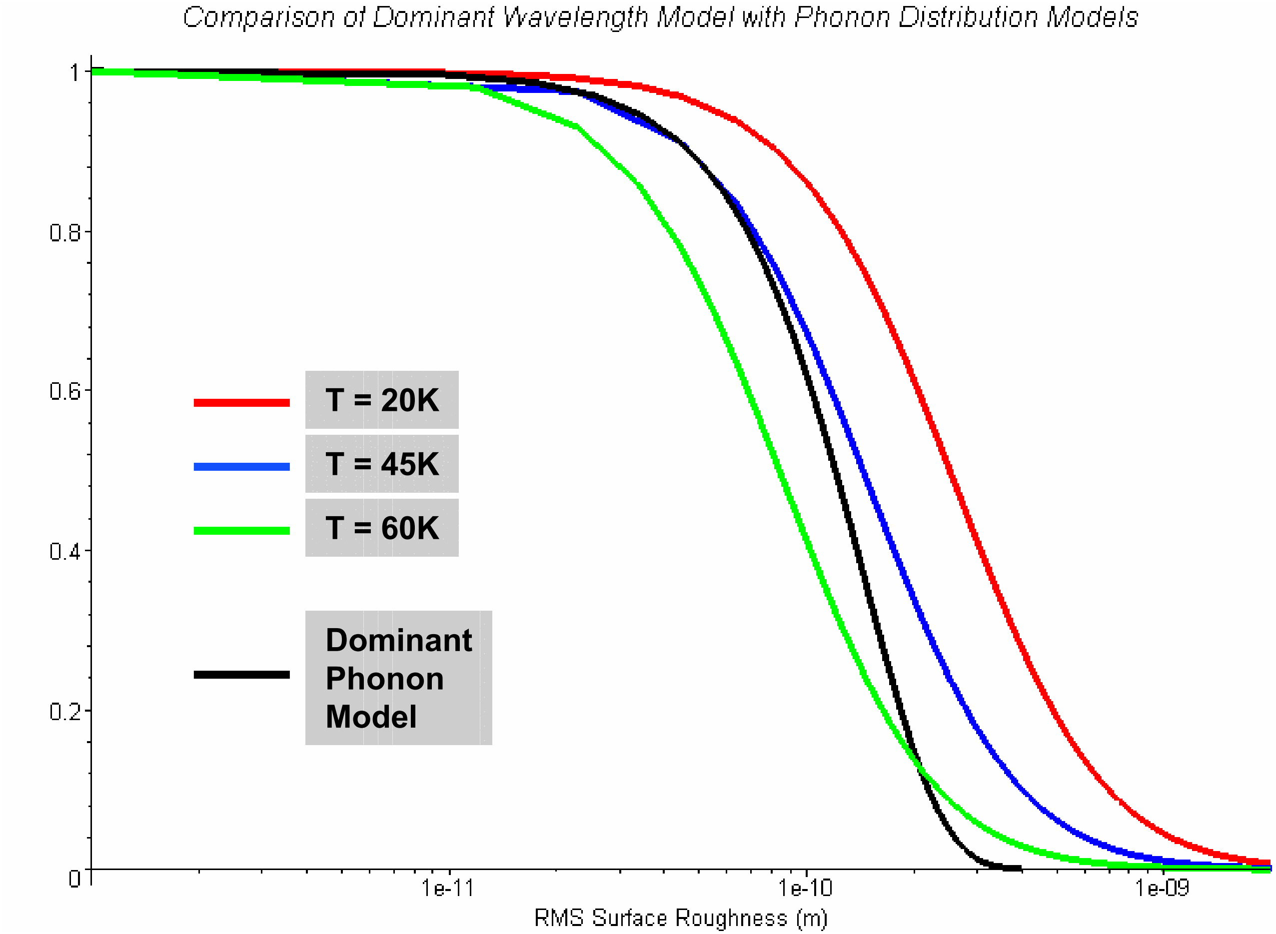


NOTE: Areas are normalized to unity.

Polish Factor: Various RMS Surface Roughness



Fraction of Reflected Phonons vs. Various RMS Surface Roughness



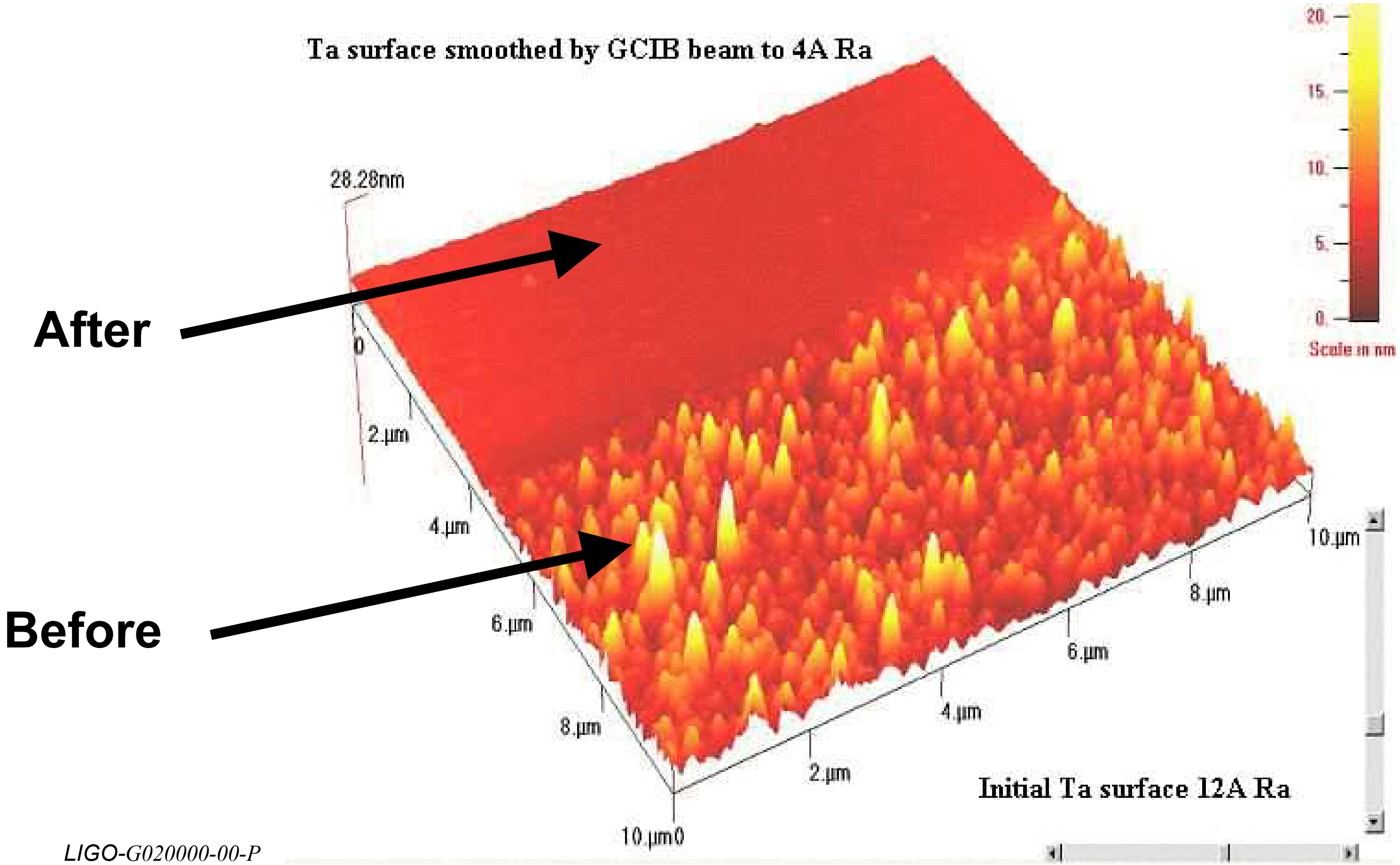
What does this mean?

- Improving the ‘polish’ of a surface has no effect on thermal conductivity until an RMS surface roughness < 1nm is achieved.

- An RMS surface roughness ~3Å allows ~35% of all phonons to be reflected from the fiber surface.

How well can we expect to polish the surface of a sapphire fiber?

Epion (a JDS Uniphase Company) claims to polish silicon wafers to ~3Å RMS.



Epion's *Ultra Smoother*™ Processing System using Gas Cluster Ion Beam (GCIB) Technology, http://www.epion.com (2002).

What's Next

1. Measure the RMS Surface Roughness using AFM (Feb-Mar 2003).

2. Contact Epion about surface polishing (Feb-Mar 2003).

3. Measure polished fibers (Mar-Apr 2003).

Up-to-Date Report

Updated progress report located at:

http://www.ligo.caltech.edu/~mhall/SapphireRoughness.pdf

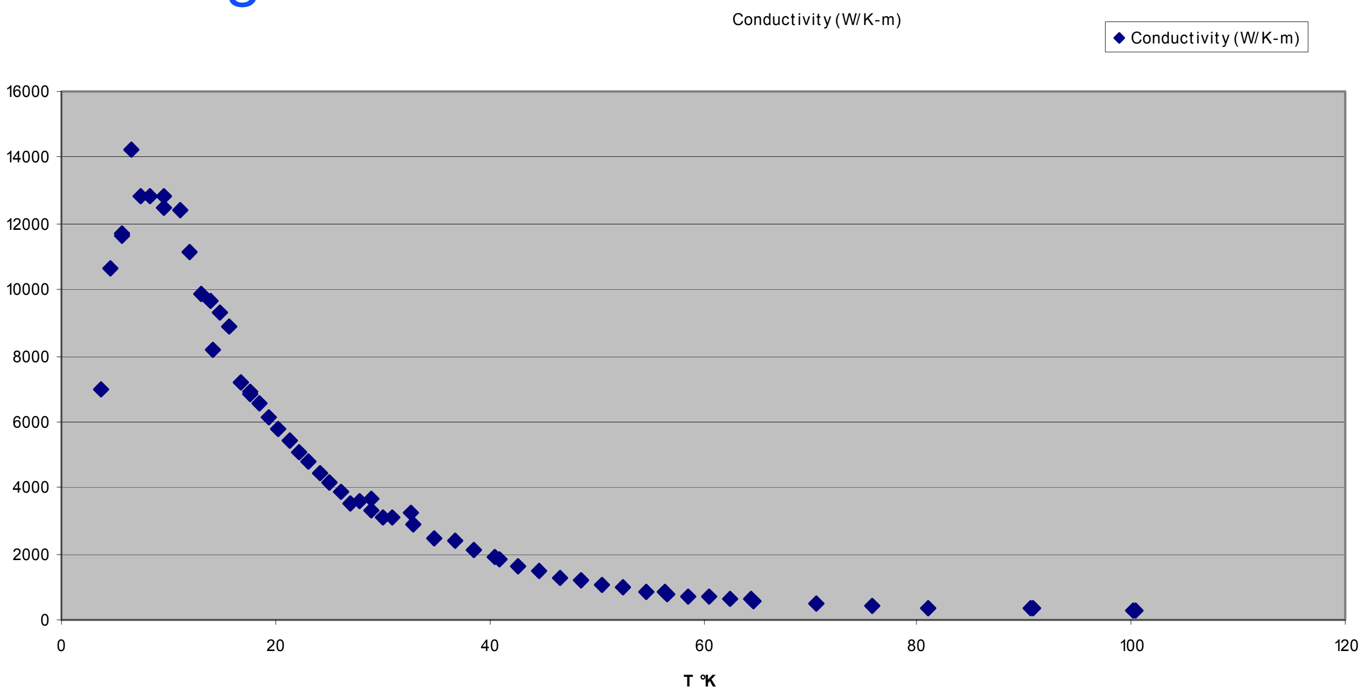
Questions, Comments, & Suggestions are welcome:

Michael Hall, mah28@drexel.edu

Al samples

Conductivity measurements, to be performed before and after baking (crystallization)

First glance at data



Related activities: accelerometers

Low frequency low noise monolithic accelerometer

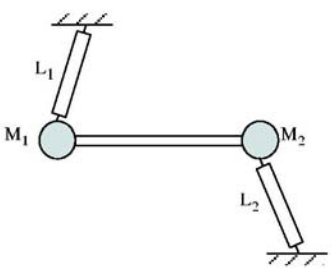
Alessandro Bertolini, Giancarlo Cella, Riccardo DeSalvo, Francesco Fidecaro, Mario Francesconi, Szabolcs Marka, Virginio Sannibale, Duccio Simonetti, Akiteru Takamori, Hareem Tariq

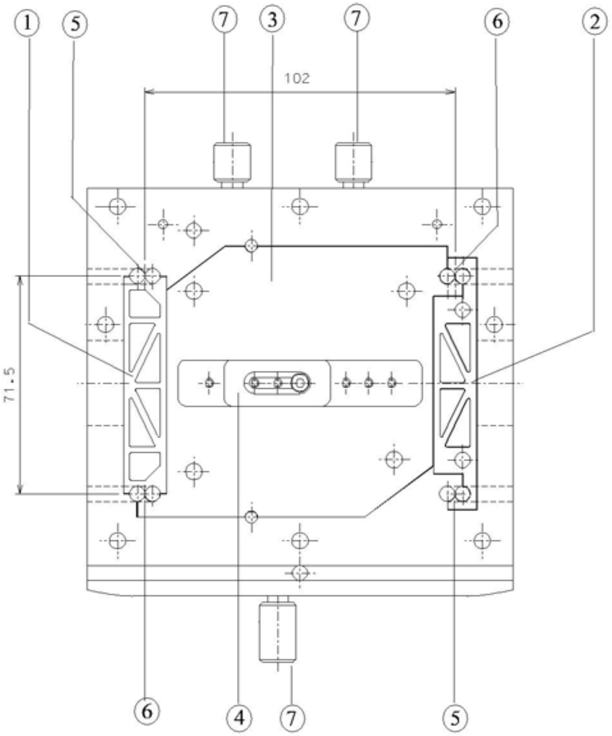
Carve mechanics out of a single metal block (Al, CuBe)

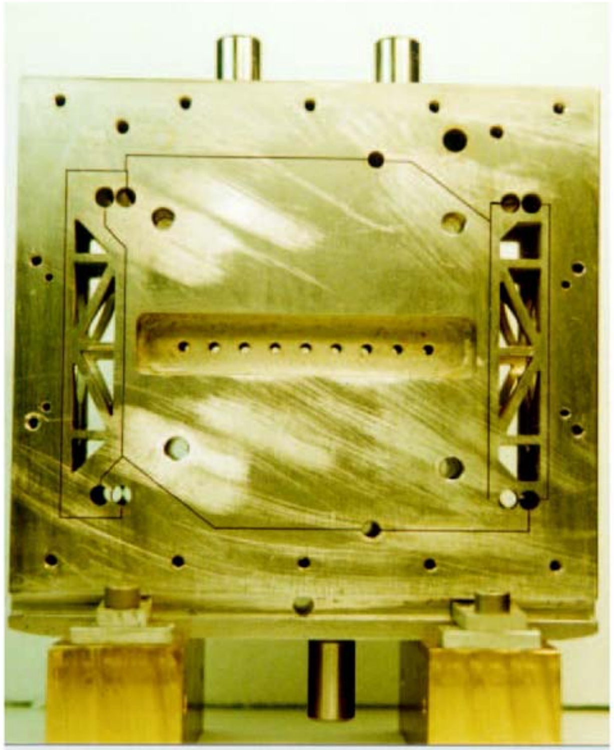
- Well defined geometry and assembly
- Limited number of parts
- Should behave nicely with temperature

Mechanical design

Pendulum + inverted pendulum





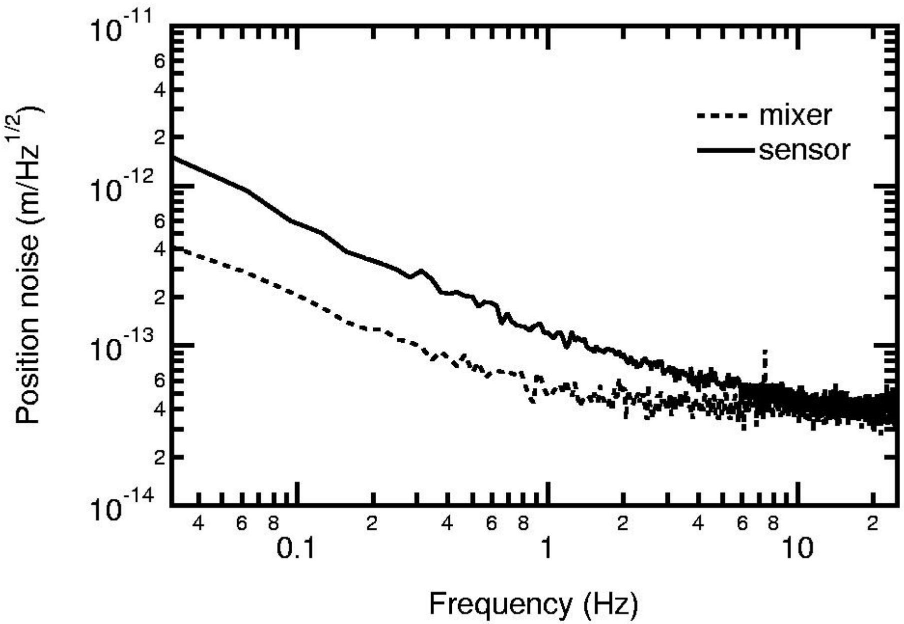


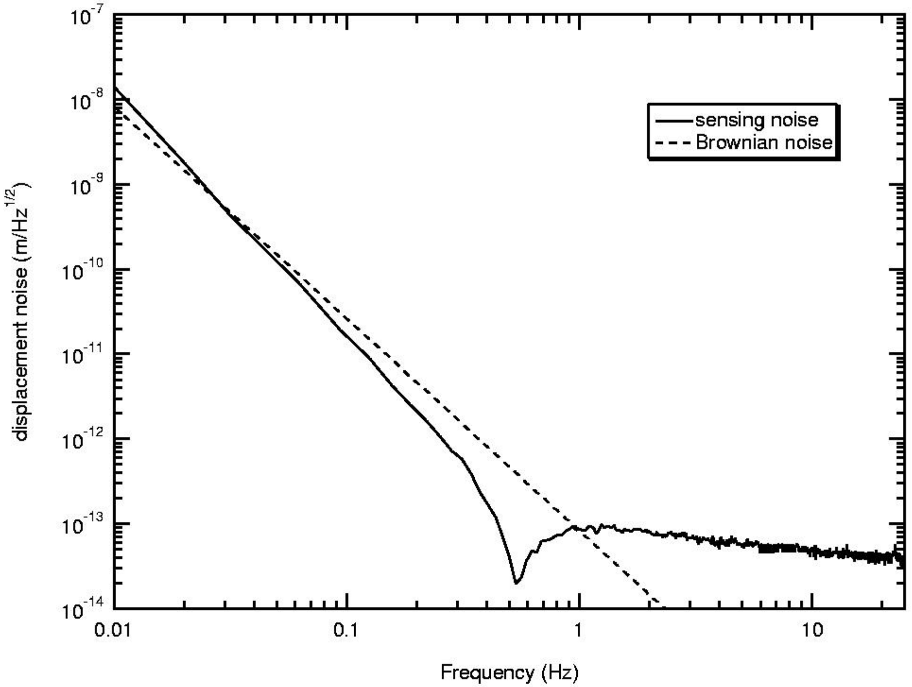
Noise

Resonant capacitive readout (100 kHz)

Works with 15 m cables

Oscillator amplitude stabilization

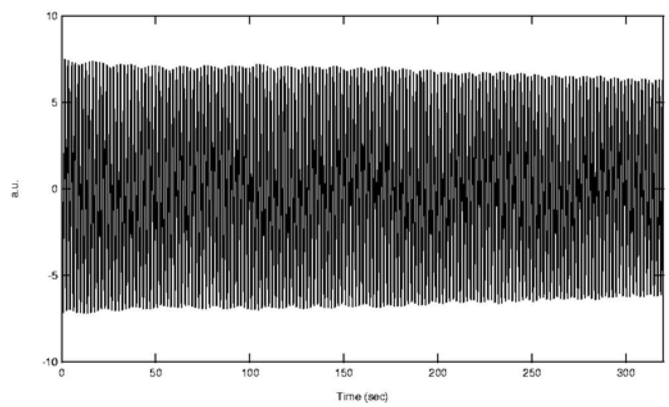


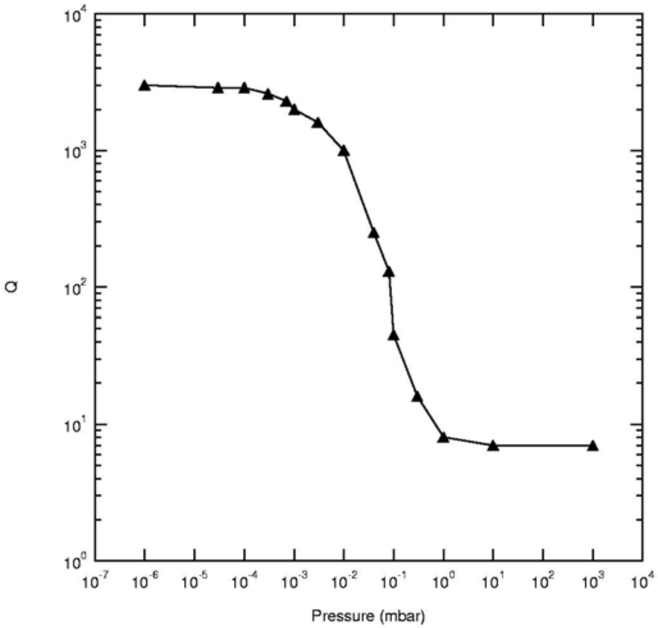


Mechanical dissipation

At beginning we thought the EDM would spoil the metal characteristics

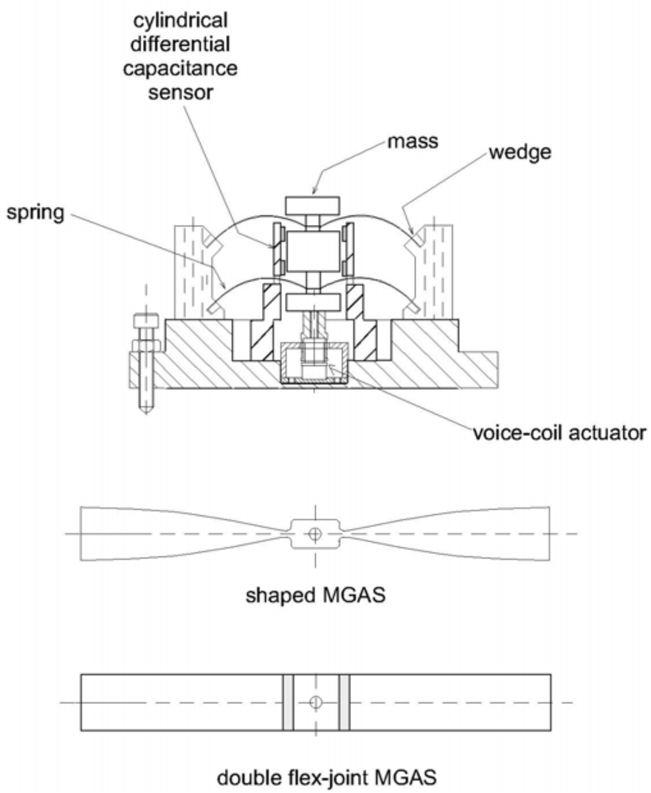
Then found cause: bad magnet





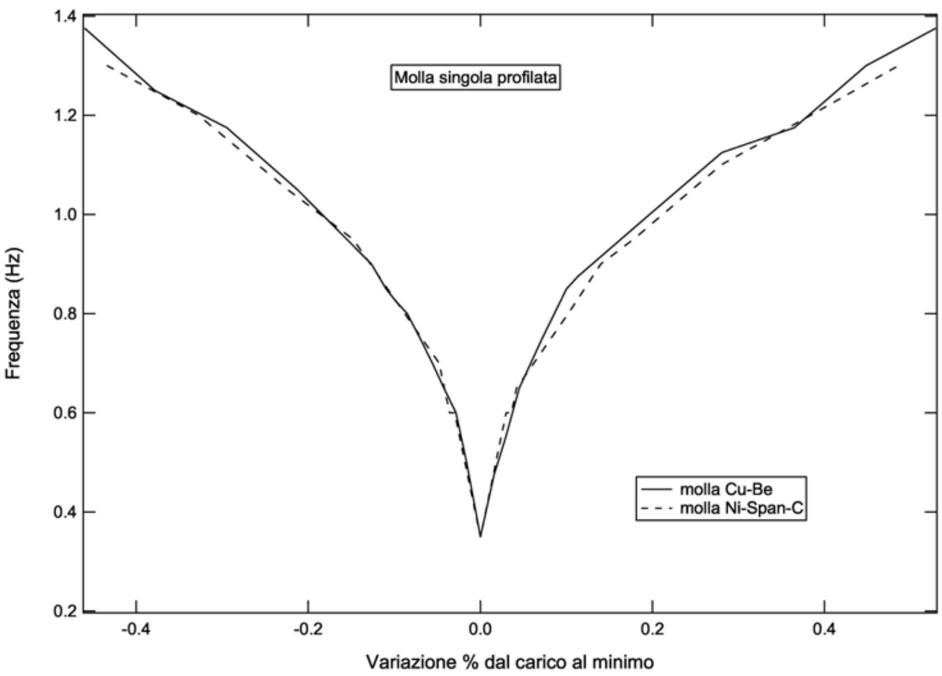
Vertical accelerometer

Based on GAS seismic filter



Resonance frequency

- Predictable spring behaviour
- Compute load as function of spring metal characteristics
- Design with capacitive sensor



Conclusions

- Work is going on, experience accumulates on many items critical for a high performance mirror suspension
- Most of the work is in line with cryogenic applications