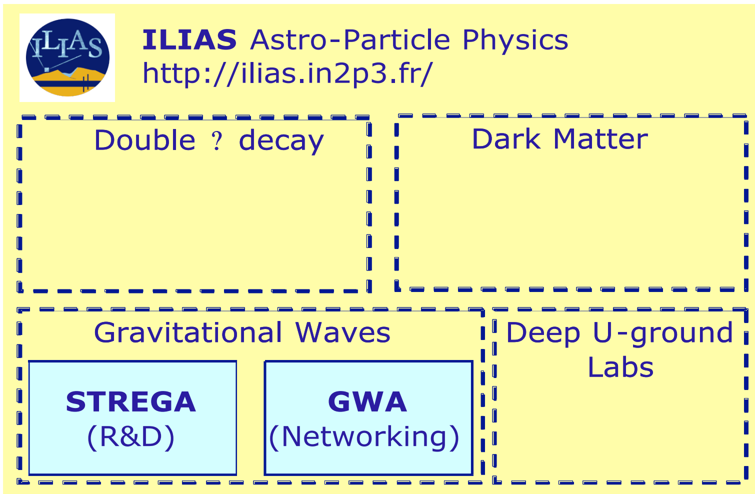
Mirror substrates and coatings for cryogenic interferometers

Stuart Reid
University of Glasgow

Overview

- Mission and objectives of STREGA:
  - Study of Thermal noise Reduction for European Gravitational wAve detectors
  - Lower thermal noise 10 times with respect to the second generation detectors
- STREGA to coordinate the efforts that many labs in different projects spend on Thermal Noise Research.



STREGA - objectives

- 3 Objectives: Materials, Cryogenics, Thermal Noise
  Selected topics

Materials		Cryogenics	Thermal Noise
M1 Mirror substrates	M2 Materials for resonators	C1 - Cryogenic top suspensions for IFOs	T1 - Direct ThNs measurement facility
M3 - Super conductive RF cavities	M4 Mirror coatings	C2 - Cryogenic system for resonators	T2 - Dynamic photo-elastic effect
M5 Mirror suspensions	M6 Cosmic Rays acoustic em.	C3 - IFOs last stage suspensions	T3 - Selective read-out for resonators

- Groups involved: Legnaro, Perugia, Florence, Urbino, Jena, Glasgow

Investigation on thermal and mechanical properties of silicon & other candidate materials e.g. SiC

- Mechanical losses
- Thermal properties
- Strength

1. Crystal orientation
2. Doping effect
3. Surface effect
4. Coatings and Diffraction Gratings
5. Bonding techniques
6. Full scale prototype

Cryogenic measurements are more time consuming than room temperature ones

The groups within M1,2,4&5 are now involved in collaborative investigations through the ILIAS project.

Legnaro – slides provided by Jean-Pierre Zendri

New materials for DUAL: the LNL activity

Material requirements:

1. High cross section (i.e. maximize Y^2/ρ)
2. High quality factor ($Q/T > 10^8$)
3. High thermal conductivity (ultra-cryogenic operation?)
4. Availability, low cost

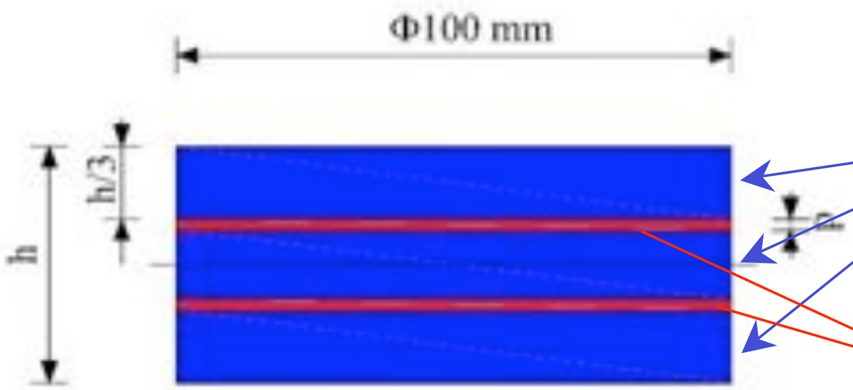
Materials presently under investigation:

	Main activity
• Silicon →	Measurement of Bonding losses
• Silicon Carbide →	Measurement of mechanical losses
• Molibdenum →	Bonding and Q measurements

Measurement of the Si bonding loss angle ϕ_{bond}

Aim of the experiment is to measure $\phi_{bond}(\omega)$ at low temperature

Sample (in preparation, March '07) h=0.9 mm <100> pure Si



silicon wafers

bonding Layer (direct bonding)

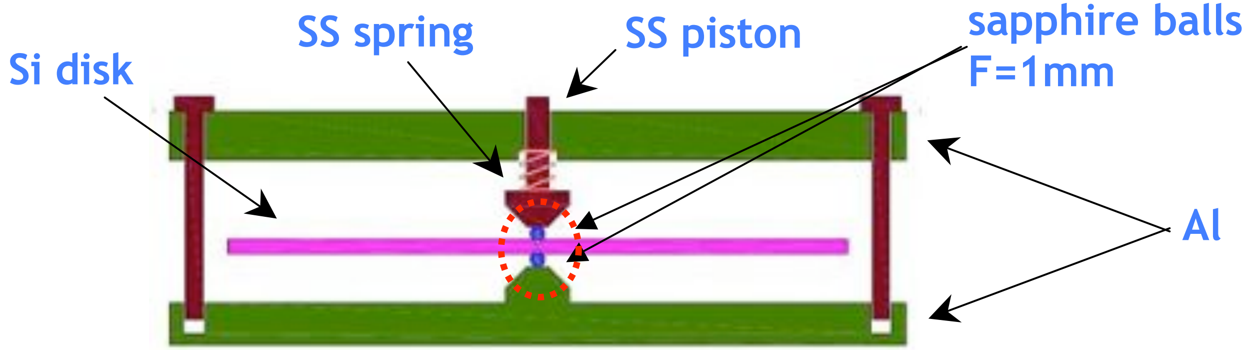
$$\phi(\omega) = \phi_{not-bonded}(\omega) + \frac{E_{bond}}{E_{tot}}\phi_{bond}(\omega)$$

Estimated by the measurement of the loss angle of a single crystal Si disc 0.9 mm in thickness

In calculation using FEM (Ansys)

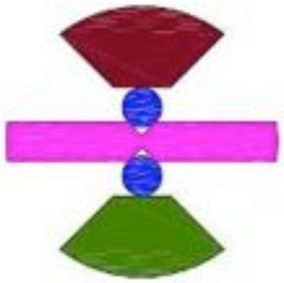
Measuring Si disc mechanical loss – nodal suspension

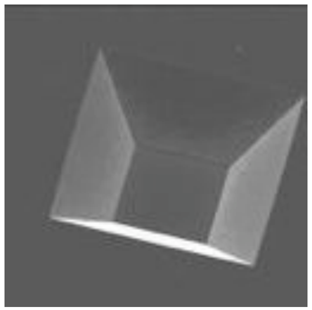
(not to scale)



silicon bulk wet etching

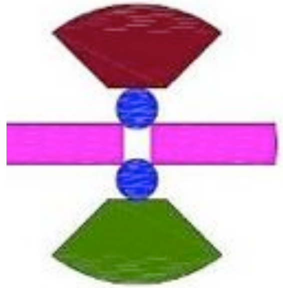
Set up #1

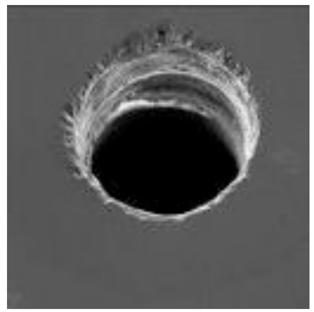




175 mm deep pyramid hole (chemical hatching), with square opening 500 mm side

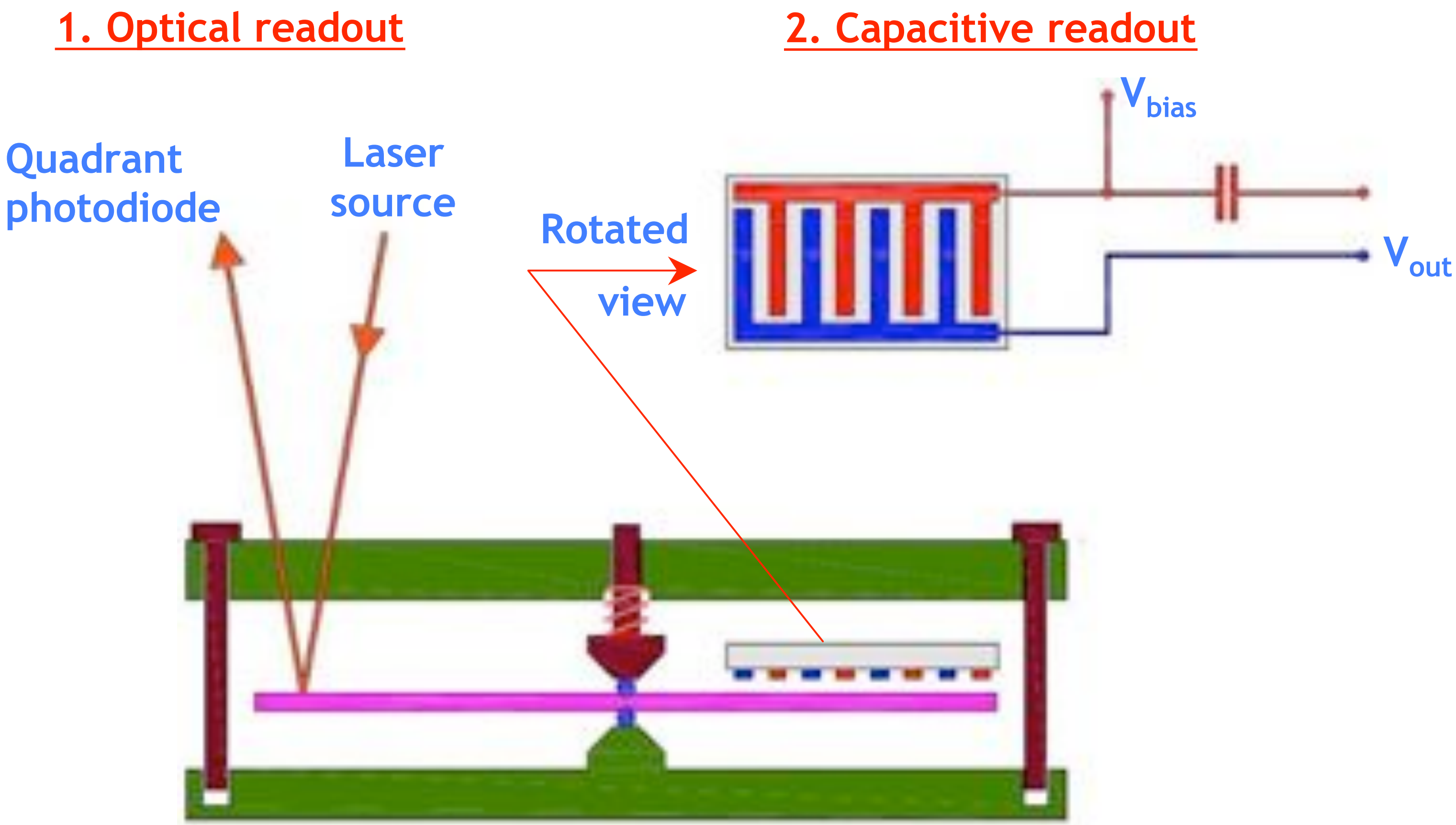
Set up #2





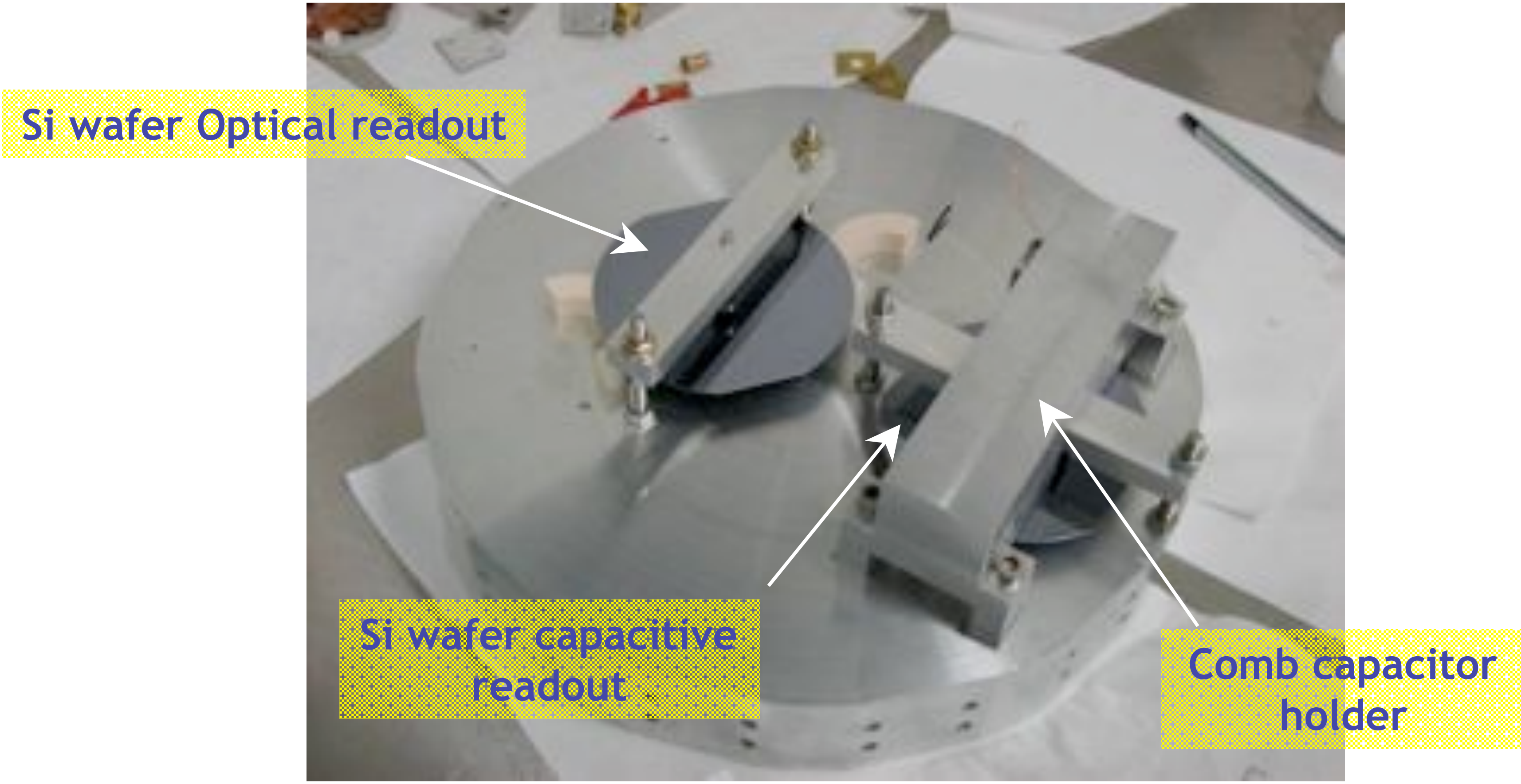
Hole about 300 mm in diameter, Milled using dentist’s tools

Si disk displacement readout

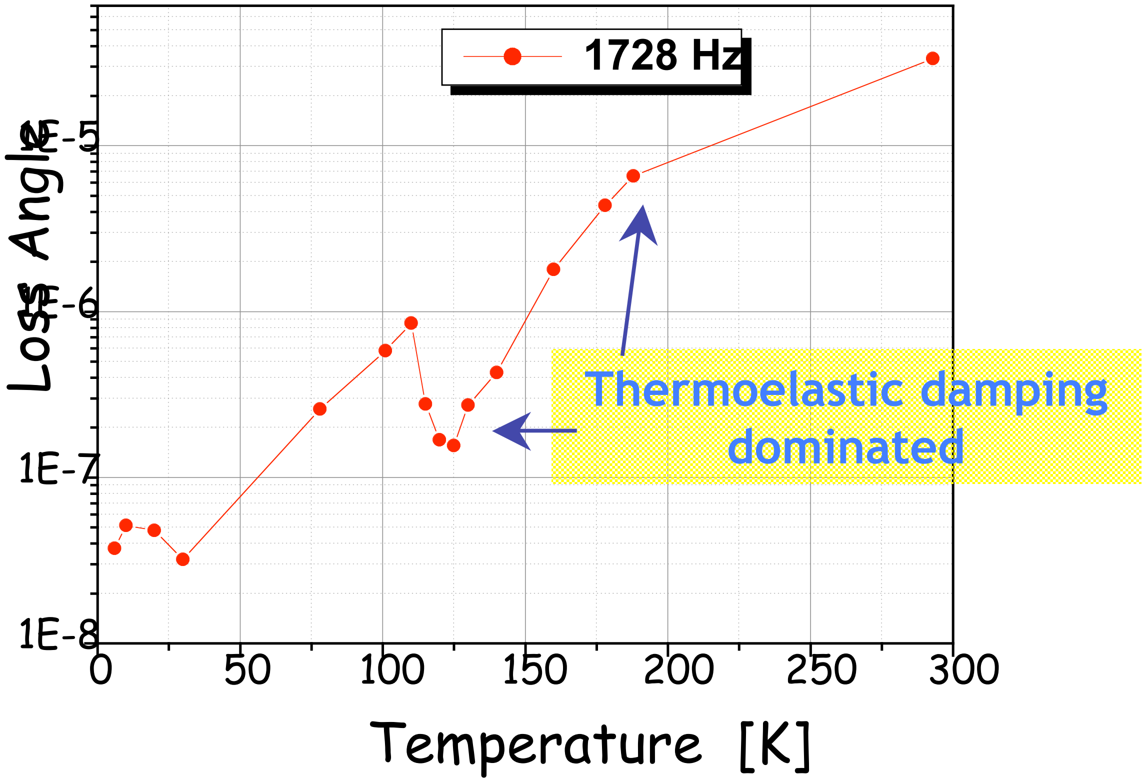


Sensitivity for both the readout about 1 nm

Experimental setup



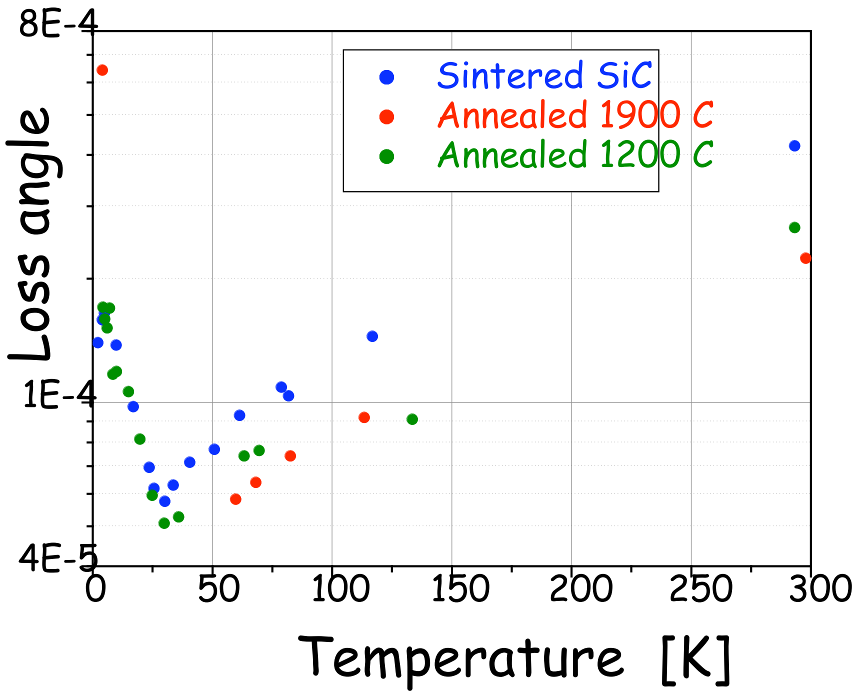
Si disk of thickness 0.5mm - results

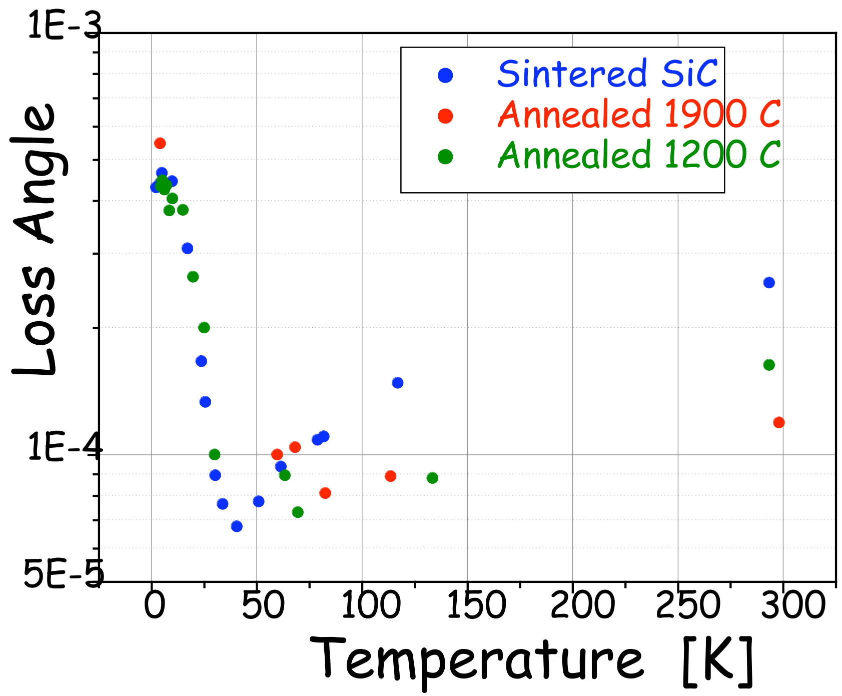


For almost all the measured modes the quality factor of the sample with the pyramidal hole (best achieved value 4_10^7) have a quality factor about (10-30)% higher than the sample with drilled hole.

Sintered silicon carbide - results

- Cantilevers of different thicknesses (0.3-0.5 mm) and length (5-10 cm)
- Both optical lever and capacitive readout



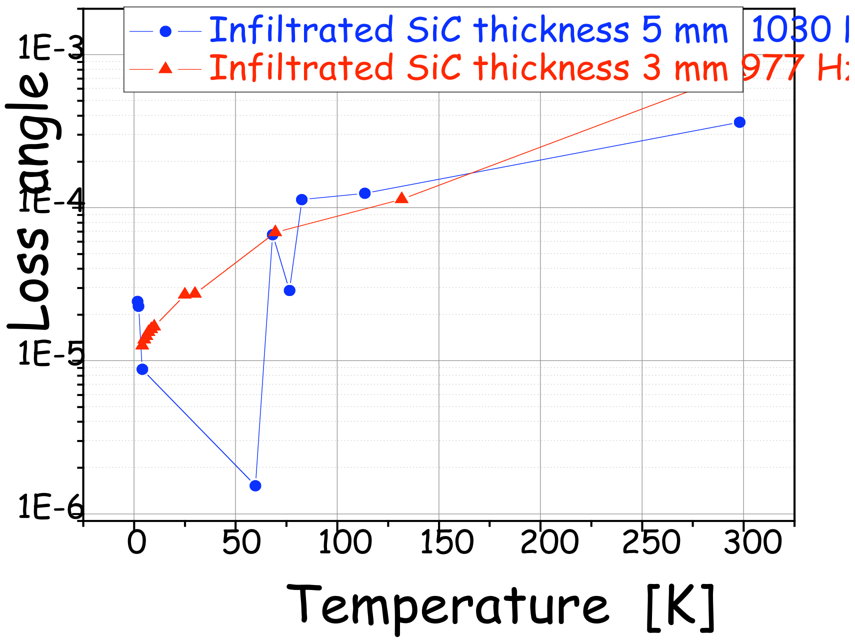


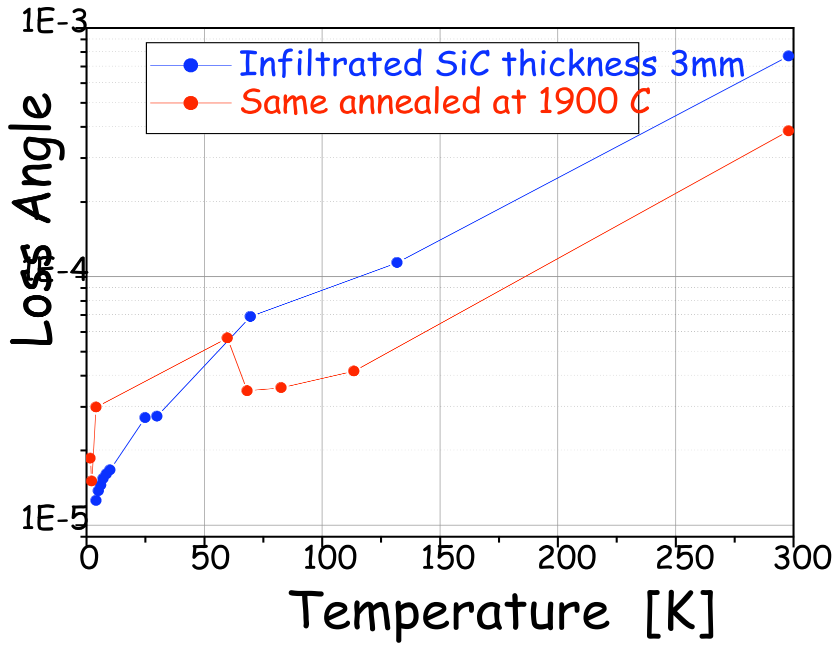
Infiltrated silicon carbide C/SiC - results

- Measured samples: two cantilever of different thickness and length from Cesic (Germany)
- Different Carbon matrices - capacitive readout

Not annealed

Annealed

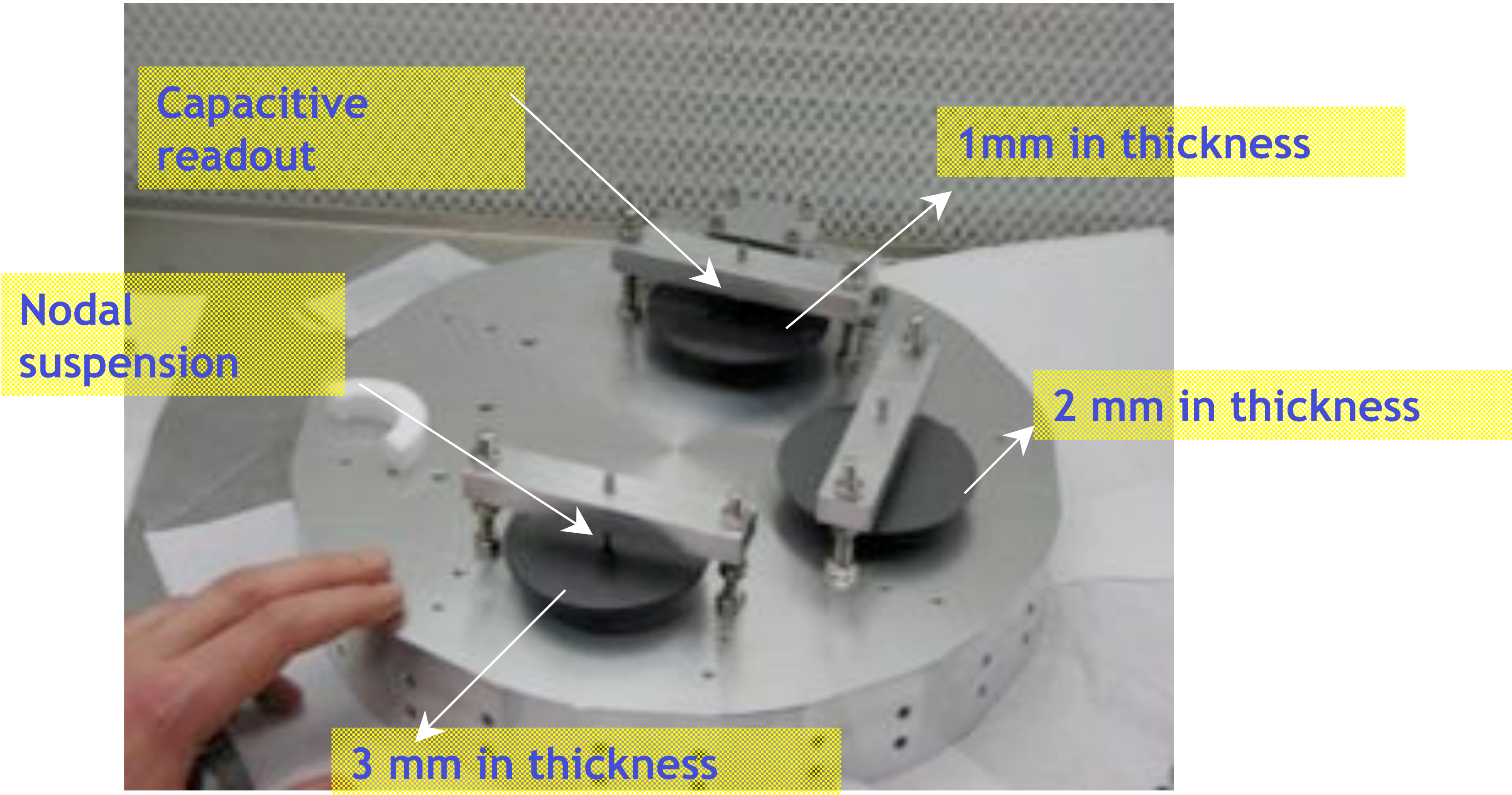




Expected clamping losses order of 10^{-5} dominating mechanism?

C/SiC new experimental set-up

In order to **reduce the clamping losses** effect the samples, new samples are now thin discs (3 inch in diameter) suspended with **nodal suspension**.



Perugia – slides from Flavio Travasso

Cryogenic activity in Perugia

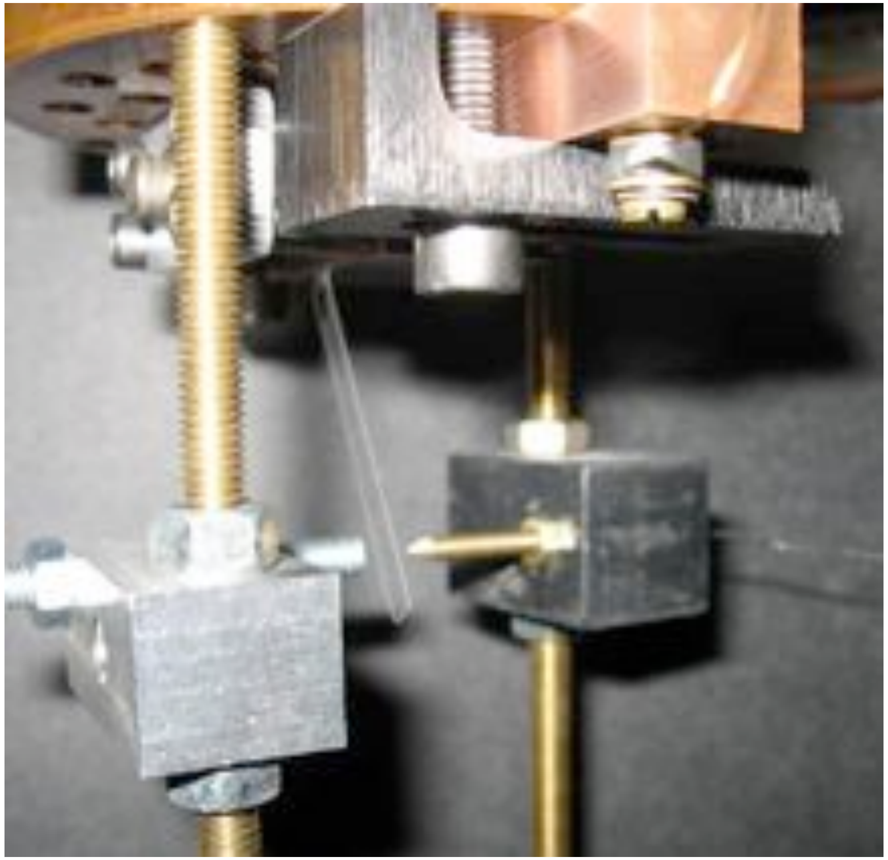
1. Cryogenic Coating Measurements:

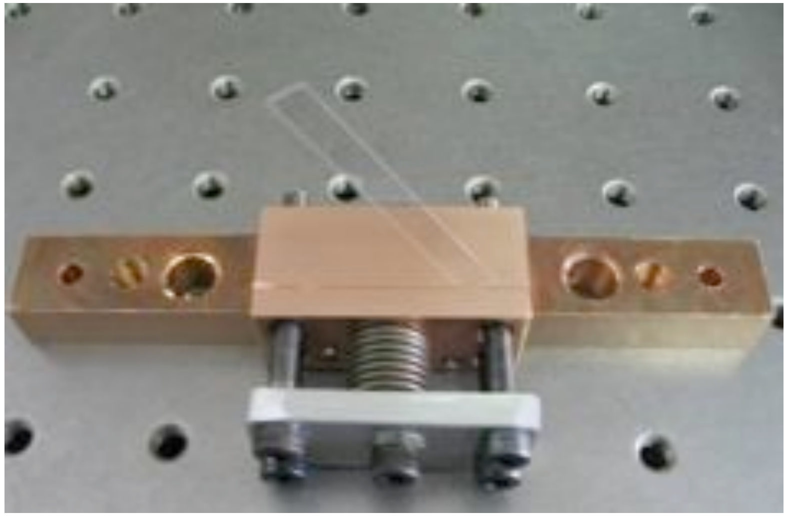
- Changes in the coating _$_{coat}$(T): to find a change in the coating changing the temperature Measured fused SiO_2 Slabs (3 samples – provided and coated by LMA-Virgo Lyon):
  - Uncoated Slab
  - Titania doped tantala coated slab (single layer 520 nm TiO_2 doped Ta_2O_5).
  - Cobalt doped tantala coated slab (single layer 500 nm Co doped Ta_2O_5).

2. Fused silica Substrate cryogenic behavior
   - Experimental activity - about 20 modes studied for 3 uncoated slabs
   - Theoretical activity - for the amorphous material the classical laws used for the crystalline materials are not so easy to use or to support.

Cryogenic activity in Perugia

- Samples



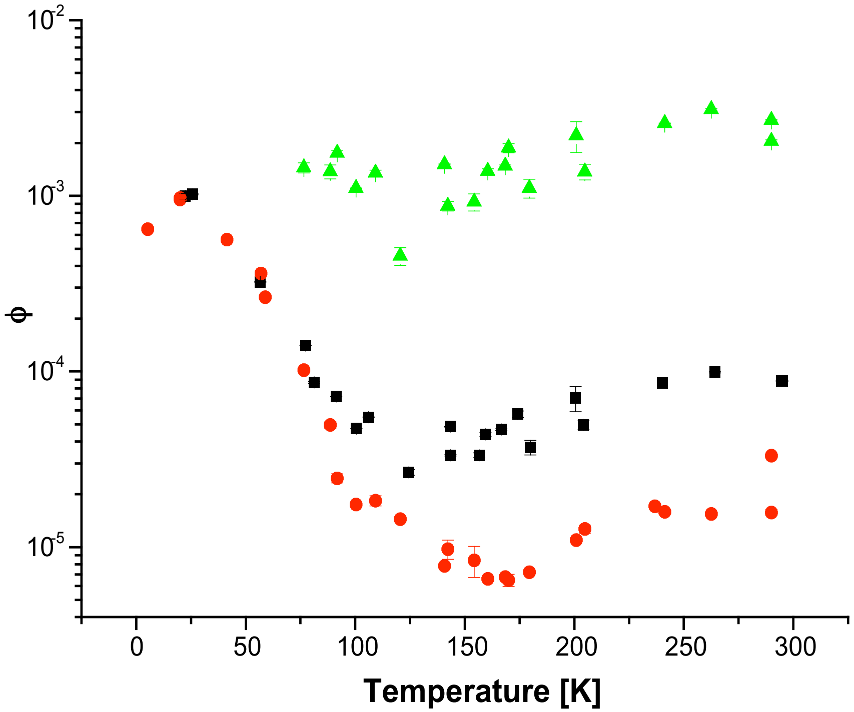


Coated silica slabs - results

TiO_2 doped Ta_2O_5 coated SiO_2 slab

$_{\text{Coat-mean}}$ = (3.4 ± 1.0) _ 10^{-3}

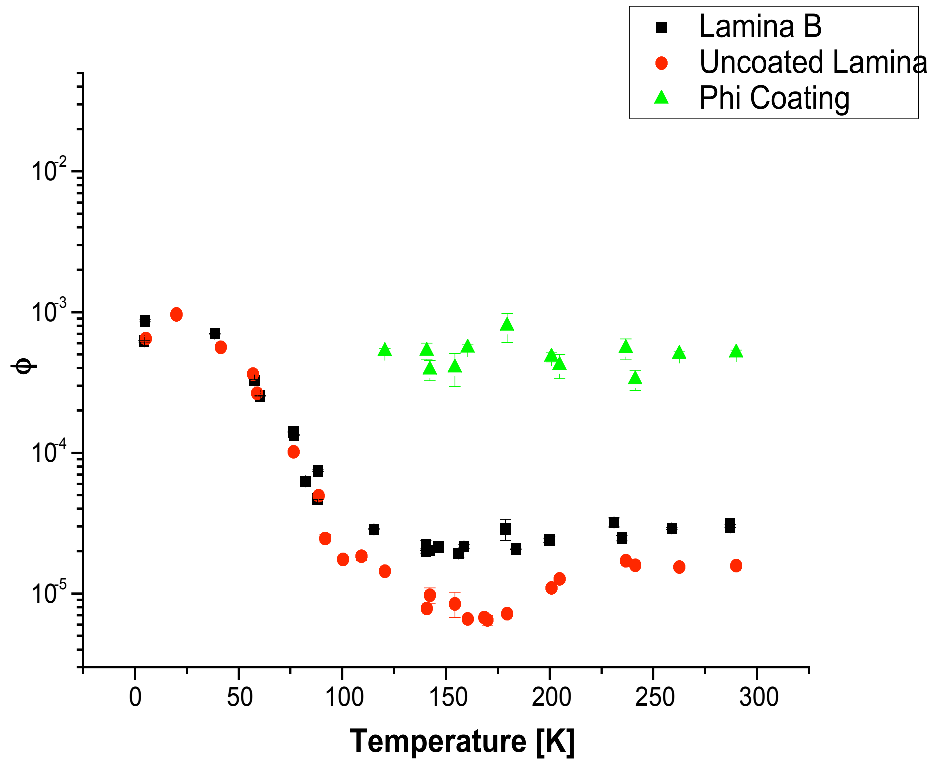
520 nm



Co doped Ta_2O_5 coated SiO_2 slab

$_{\text{Coat-mean}}$ = (7 ± 2) _ 10^{-4}

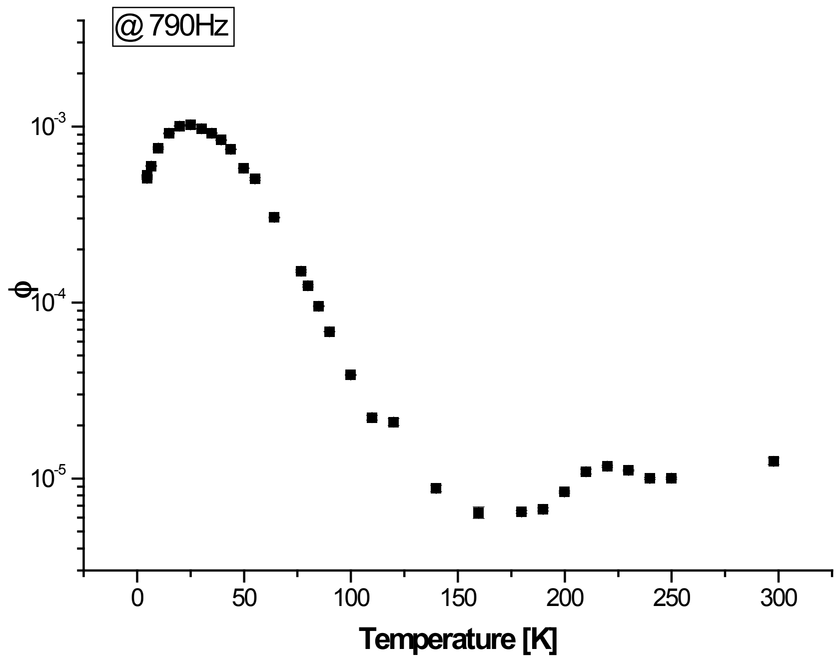
500 nm



Investigating dissipation processes in fused silica

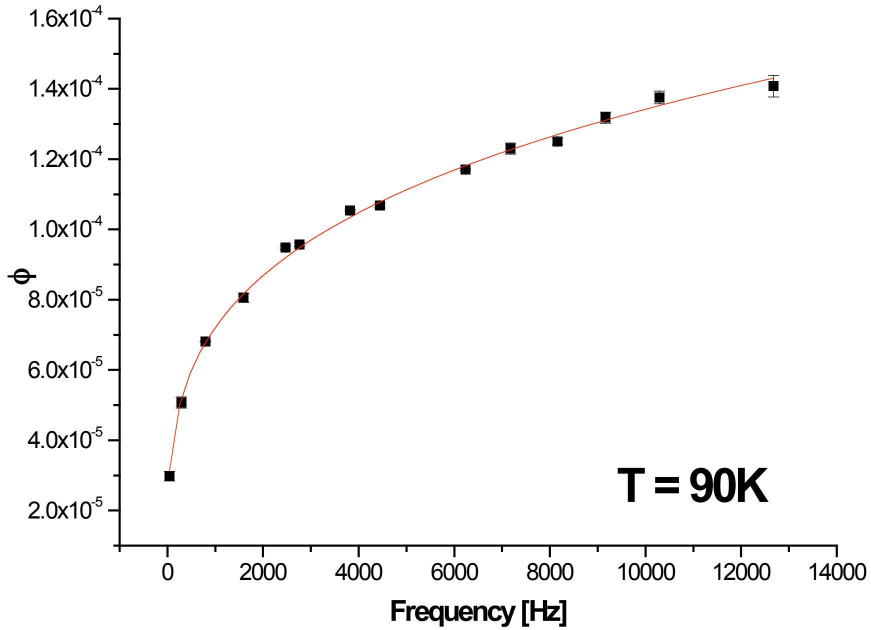
1. _ vs temp:

- 2 possible dissipation peaks observed



2. _ vs freq:

- 3 different scenarious observed in 3 temperature ranges
  - 3 possible dissipative processes



Conclusions - Perugia

SiO_2 Results:

The measurements show a clear behaviour with temperature:

- an almost constant loss angle above 140K
- between 140K and 30K the loss angle has a significant increase that can be interpreted by calling for thermally activated relaxation dynamics (in multi-stable potentials)
- below 30K the loss angle starts to decrease: the thermally activated dissipation is less effective and a different dissipative mechanism starts to drive the dynamics (quantum tunnelling effects become active at very low temperature… that is quantum tunnelling assisted by thermal fluctuations)

Work in progress:

A new refined dynamical model for the interpretation of the losses in the low frequency region is required.

Florence/Urbino – slides provided by Matteo Lorenzini

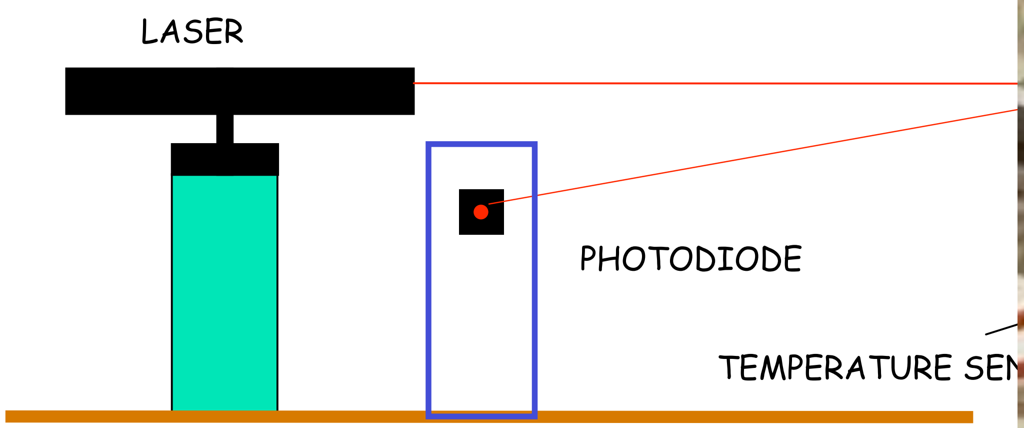
Gentle Nodal Suspenion (GeNS) - 1

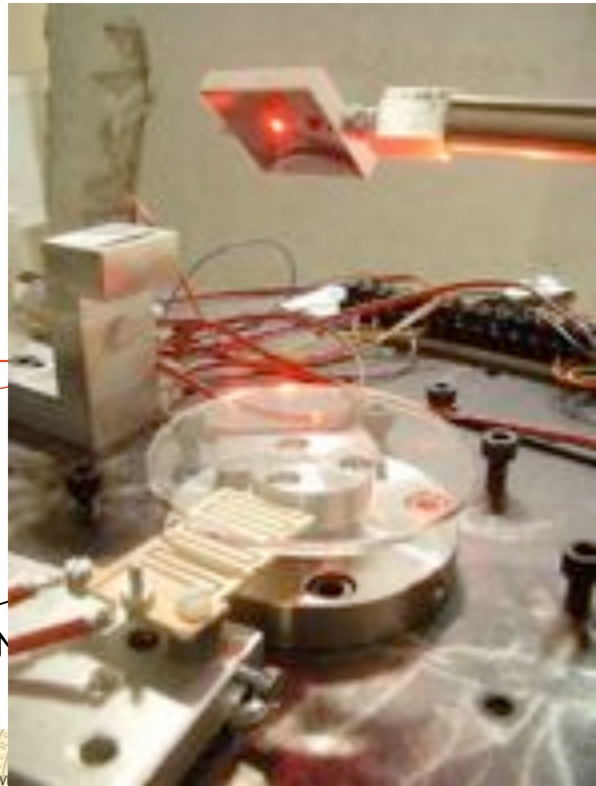
- Simple but innovative idea
  - Thickness < diameter ⇒ stable equilibrium
- Advantages w.r.t. other methods
  - No clamp
    - Coated samples tested
    - Contact surface is minimised
  - All relevant parameters are measured
    - Disk-sphere friction measured with rolling mode
    - Surface roughness measured directly
    - Q-dependence on contact point position

SAMPLES:

-Herasil (HOQ300) disk 75x1 mm
75x3 mm

- Sapphire sphere D= 3.18, **4.75 mm**
- Steel sphere D= 4.75, 5.5 mm

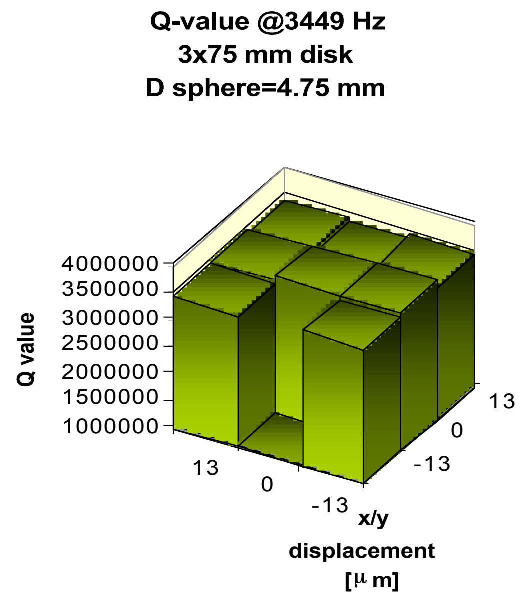


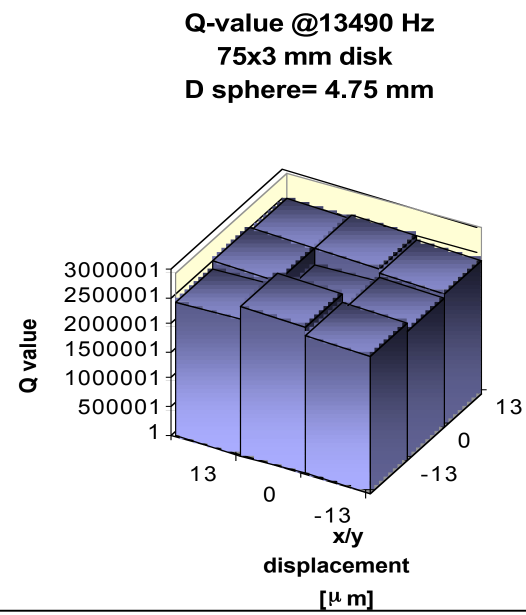


Gentle Nodal Suspenion (GeNS) - 2

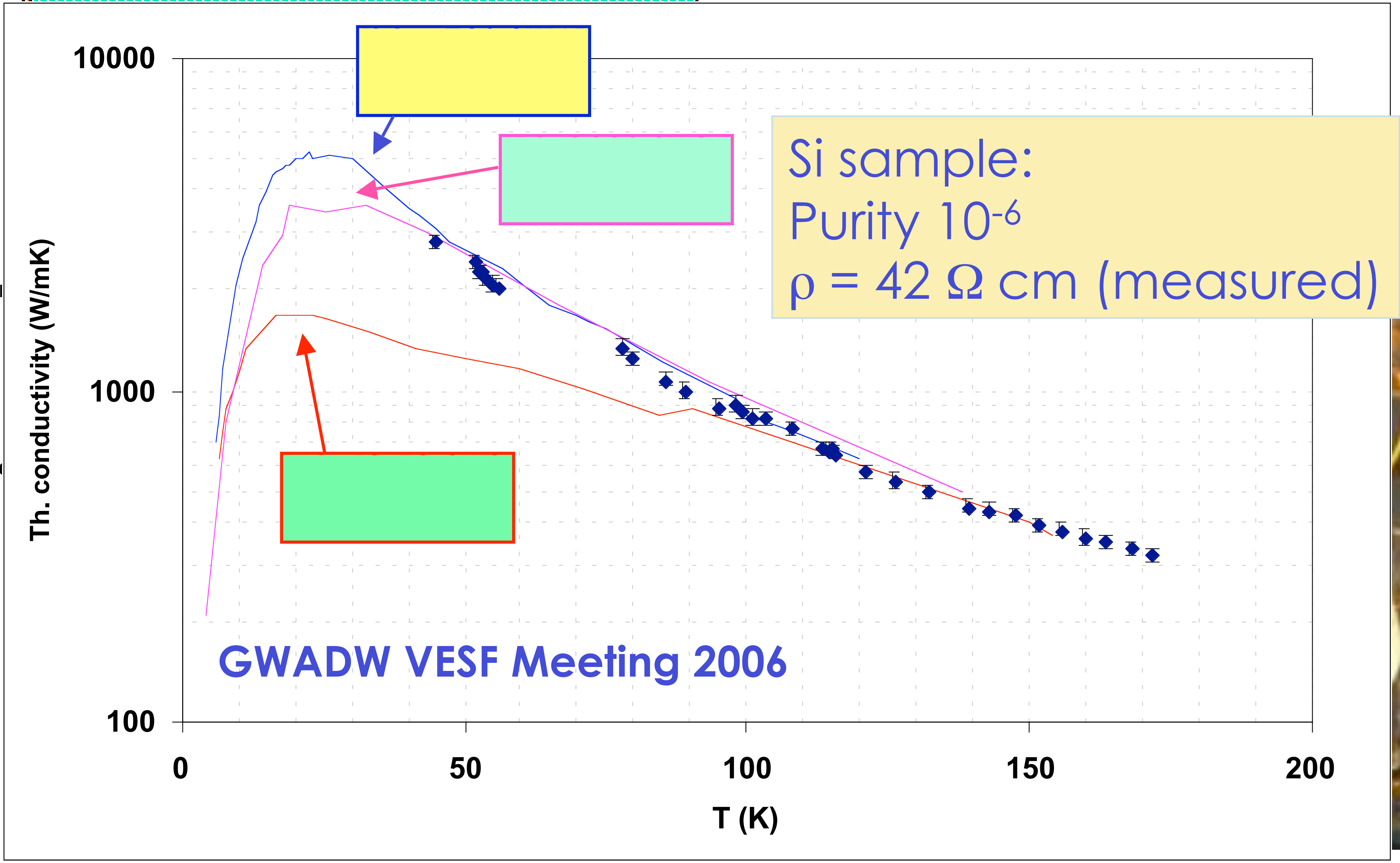
Suspension characterisation:

- Q dependence on disk position
- Stability in time (hours, days, weeks)
- Modal frequencies dependence on temperature
- Roll mode Q measurement
- Q dependence on radius of suspension sphere





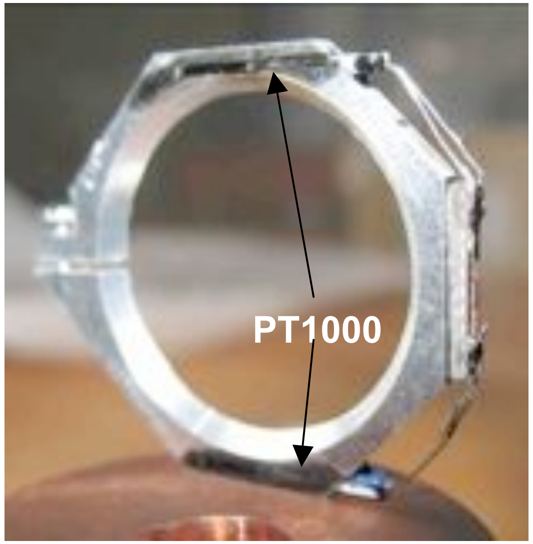
Thermal Conductivity Measurements

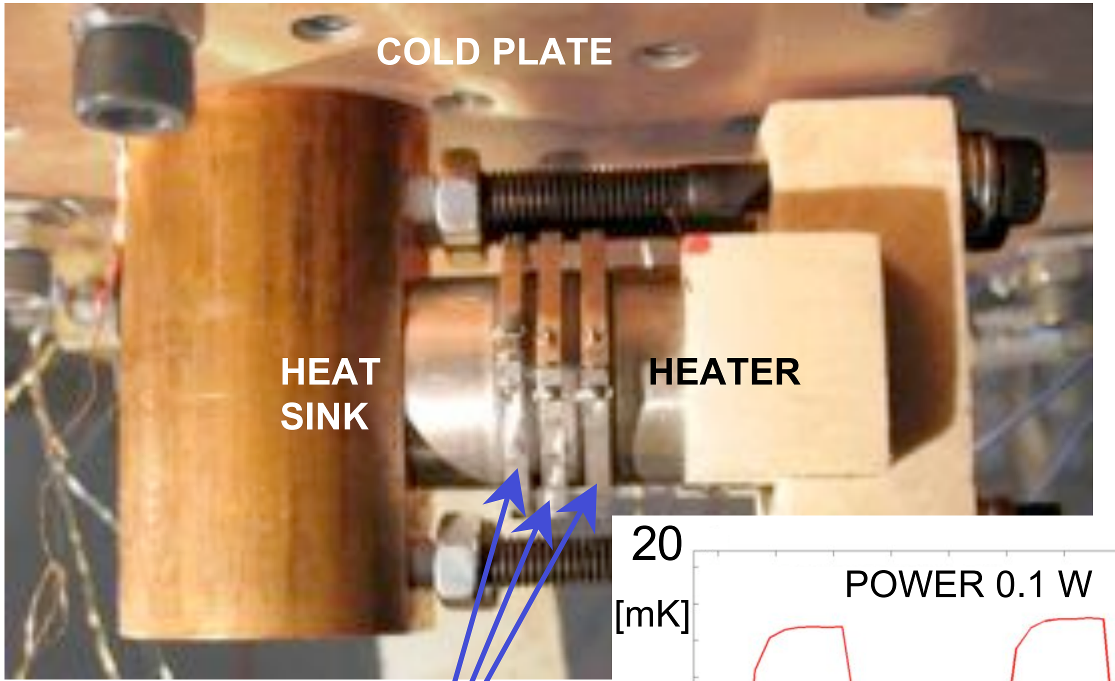


From Y.S. Touloukian, E.H. Buyco, "Thermo-physical properties of matter", Plenum, NY, 1970

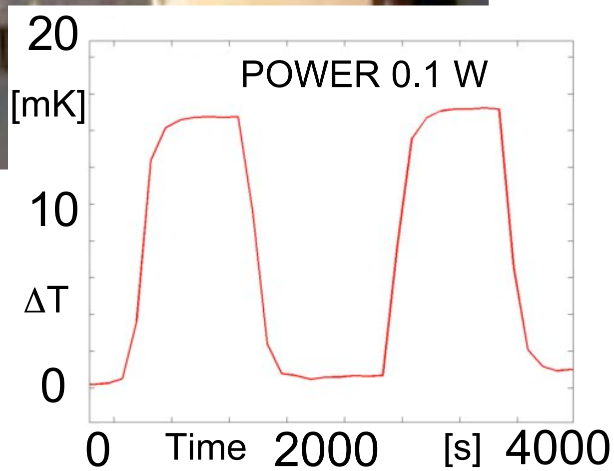
Thermal conductivity of silicate bonds

Bonded samples: nº 3 couples of disks with 1/2'' radius and 6 mm thick, produced by the Glasgow IGR group





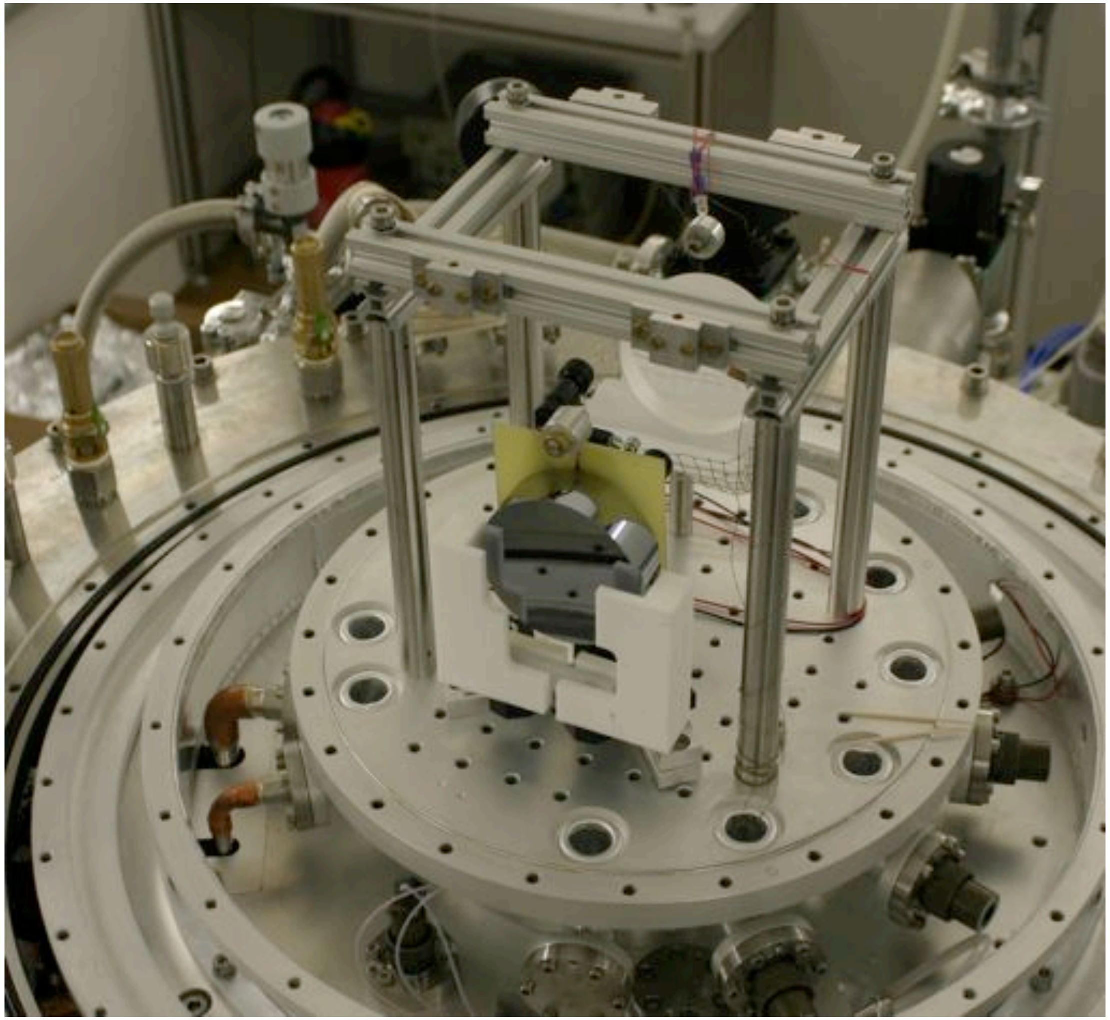
TEMPERATURE SENSORS



WORK IN PROGRESS…

Jena – slides provided by Ronny Nawrodt & Anja Zimmer

Experimental setup - 1

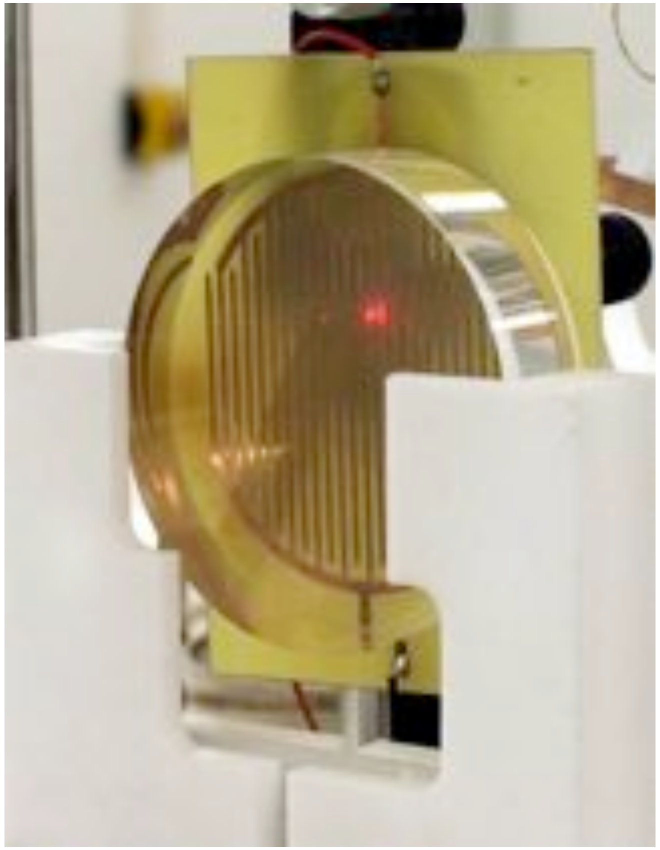


5 … 300 K
probe temperature

< 10^{-5} mbar
residual gas pressure

∅ 300 mm, height 500 mm

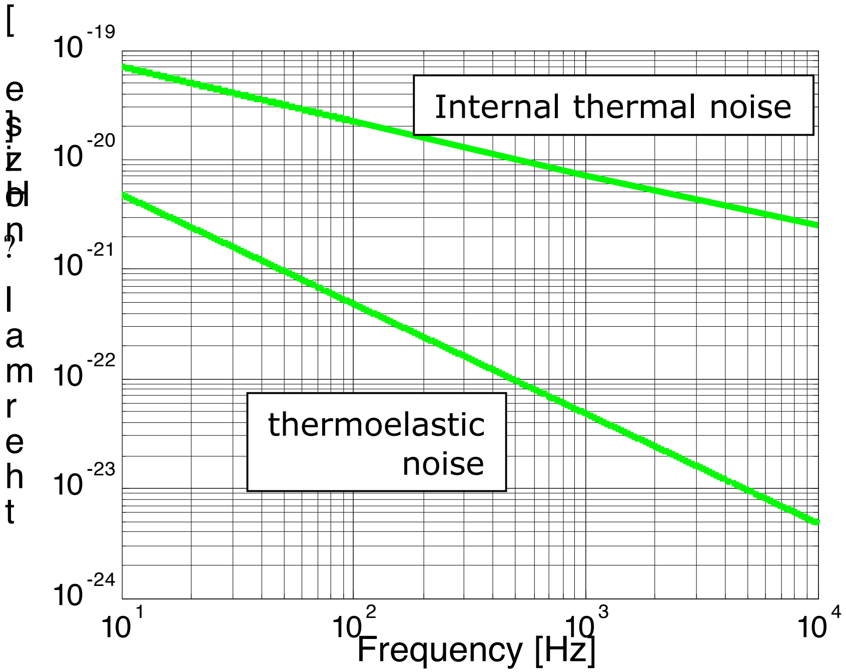
Samples

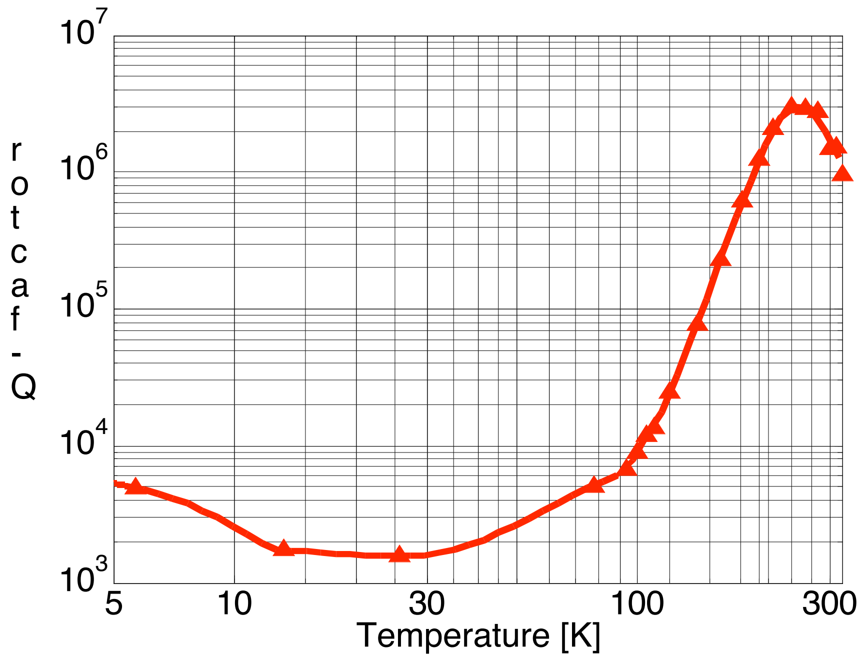


samples: silicon, cryst. quartz

Fused Silica

- Current material of choice for interferometers
- high purity, low absorption
- excellent thermal properties – low thermoelastic noise

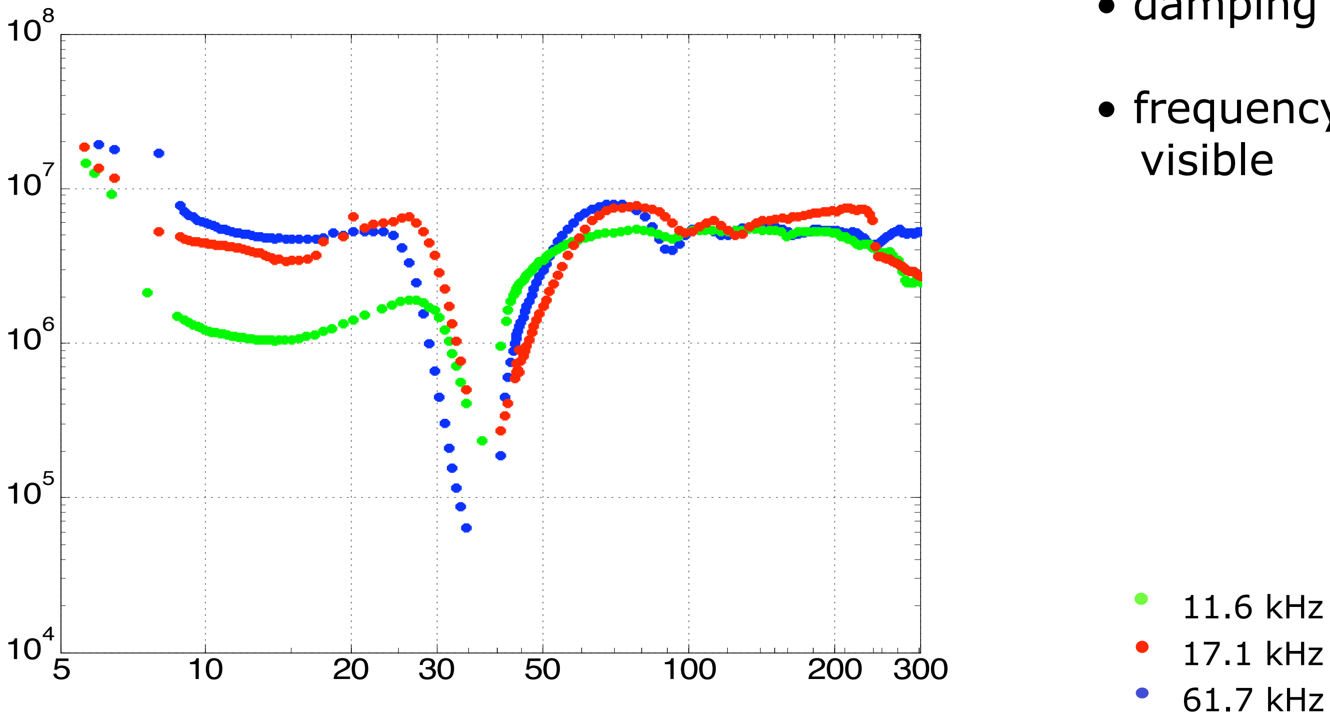




Crystalline Quartz (1)

Chemistry: SiO_2

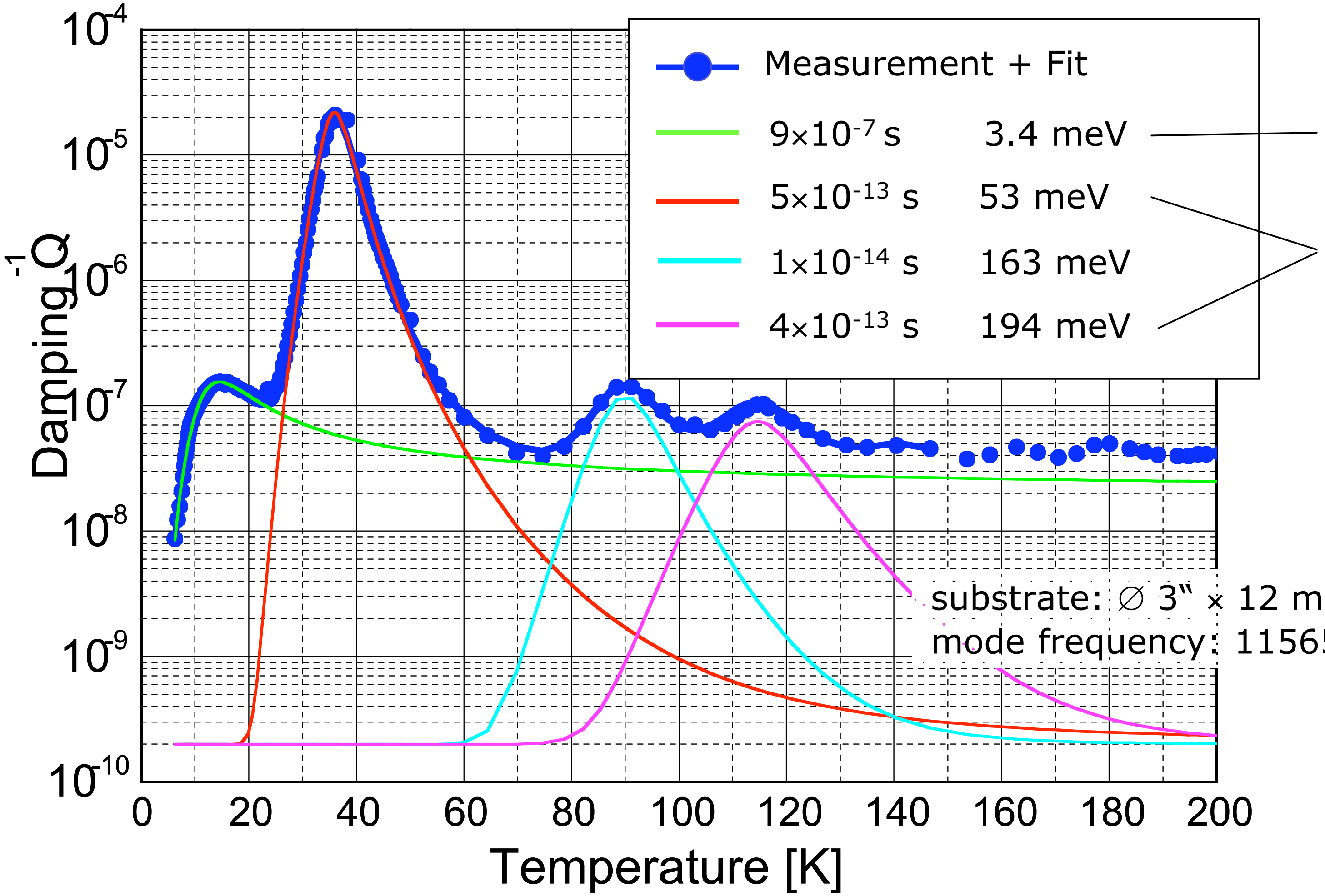
Solid-state-physics: crystalline structure



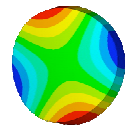
- damping peaks
- frequency dependence visible

Quartz (cryst.), c-cut, ∅ 3" × 12 mm

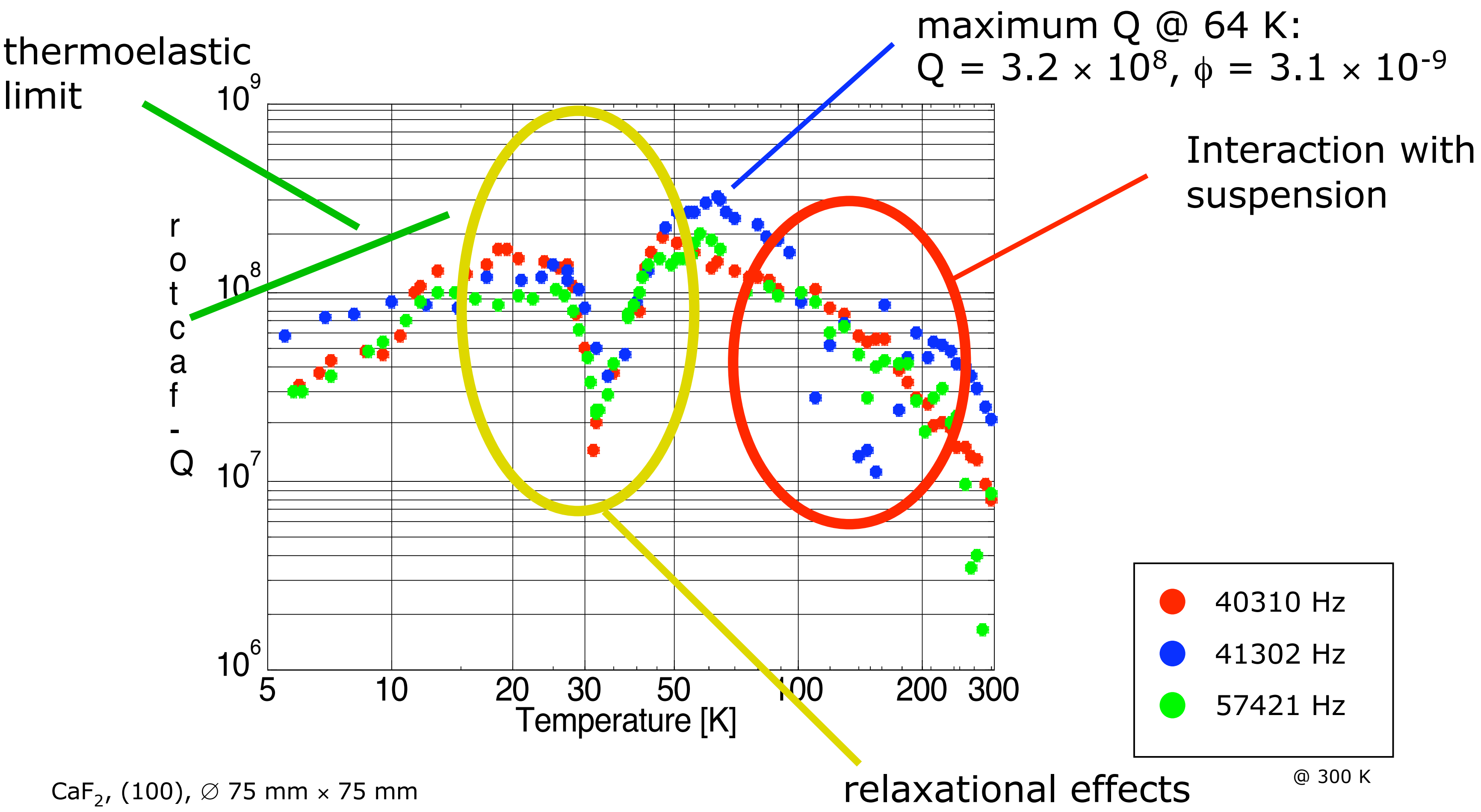
Crystalline Quartz (2)



mode shape:

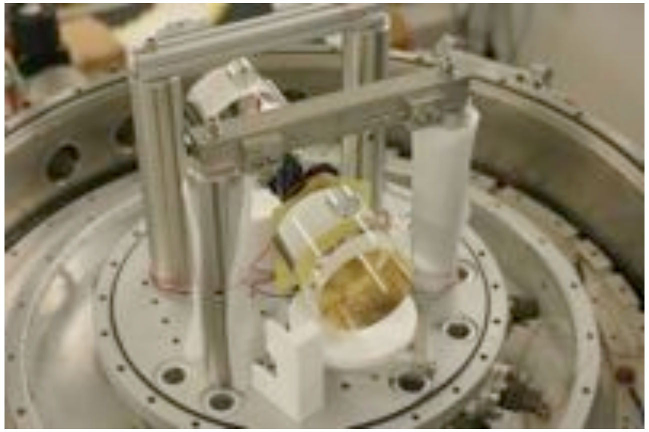


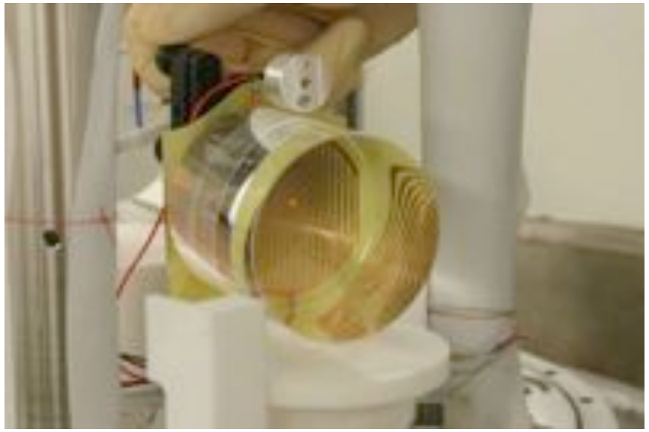
Calcium fluoride (1)

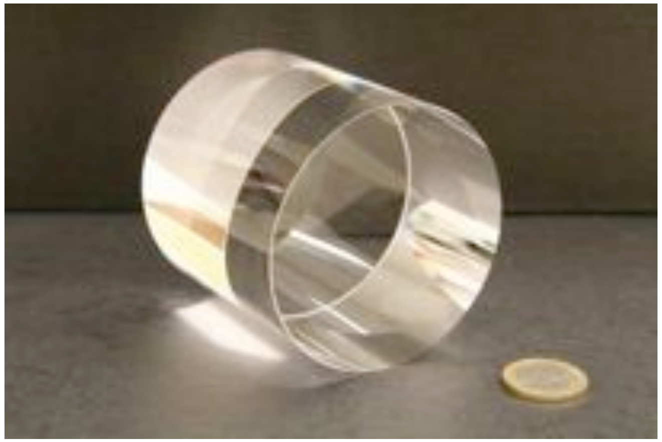


CaF_2, (100), ∅ 75 mm × 75 mm

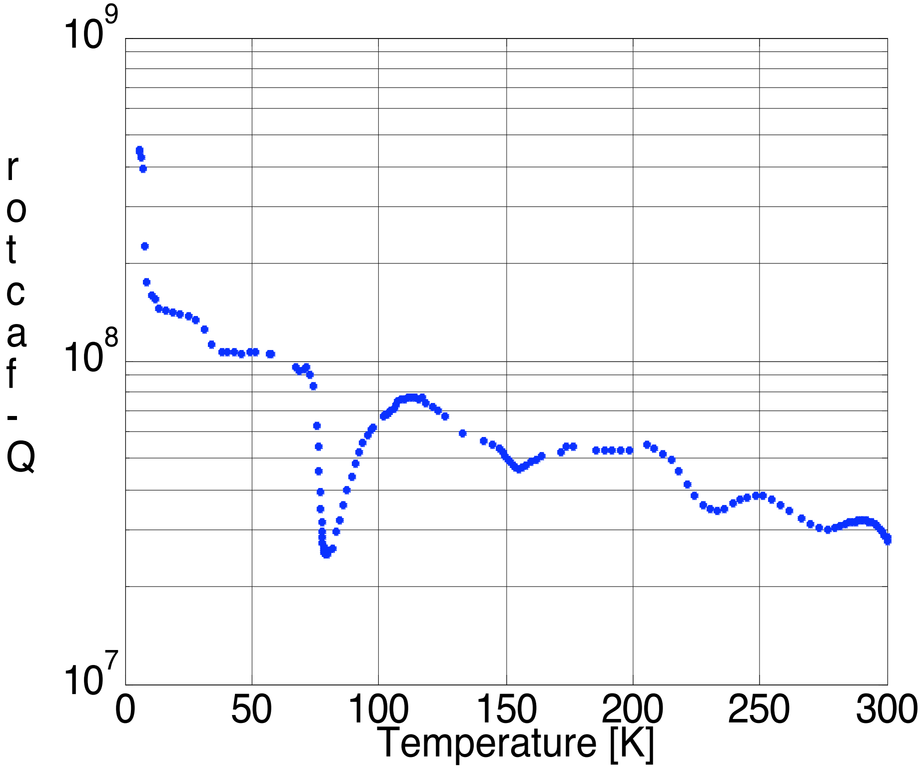
Calcium fluoride (2)







Silicon (2)



silicon (100), ∅ 3" × 12 mm, boron-doped, 14886 Hz mode

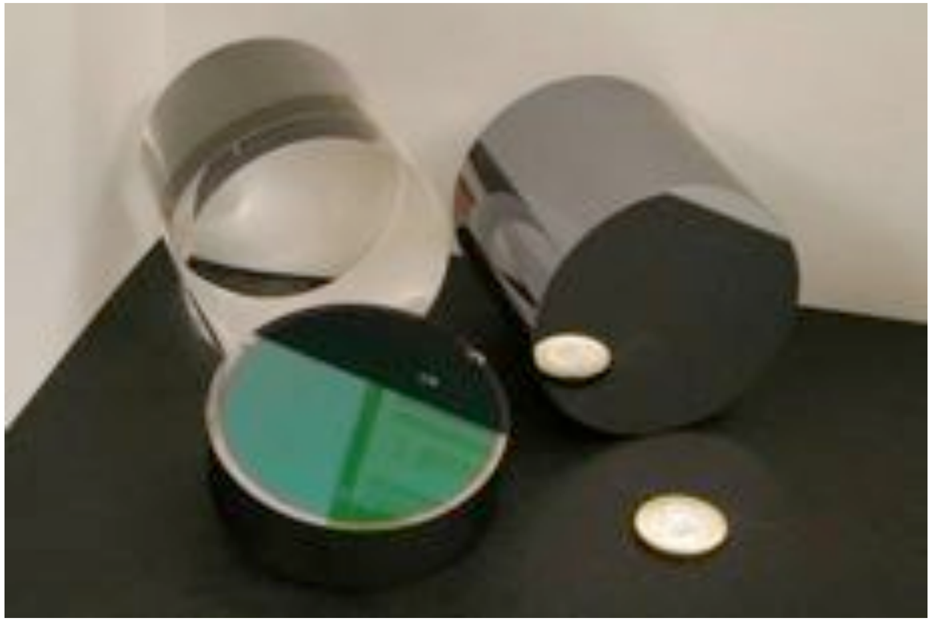
- relaxation processes
- similar to those in crystalline quartz
- investigation of the solid state physics of impurities and phonon-phonon-interaction

Planned continuation

- Effect of doping concentration on mechanical loss (several samples currently polished, measurements start in april)
- phosphorus- and boron-doping (n- and p-doping), all (100)
- comparison between different orientations (100) and (111)
- all measurements between 300K and 5K
- understanding solid-state processes that cause mechanical loss
- Compare to float-zone silicon.
- crystalline quartz: investigation of the anisotropy of the mechanical damping to understand relaxation processes

Coating research on tantala

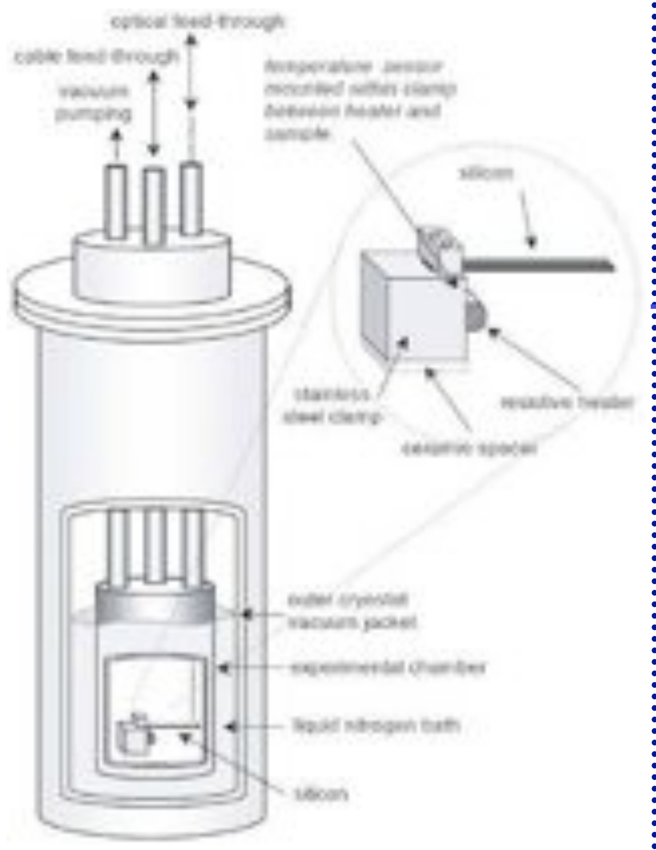
- Systematic investigation of the low temperature mechanical losses for doped tantala coatings



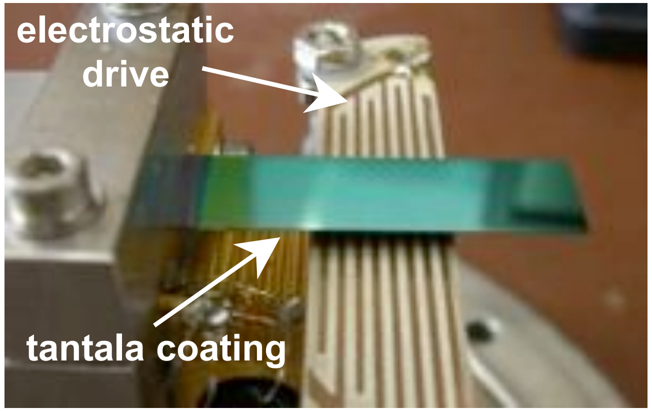
Glasgow

Coated silicon flexures - experimental setup.

schematic of cryostat



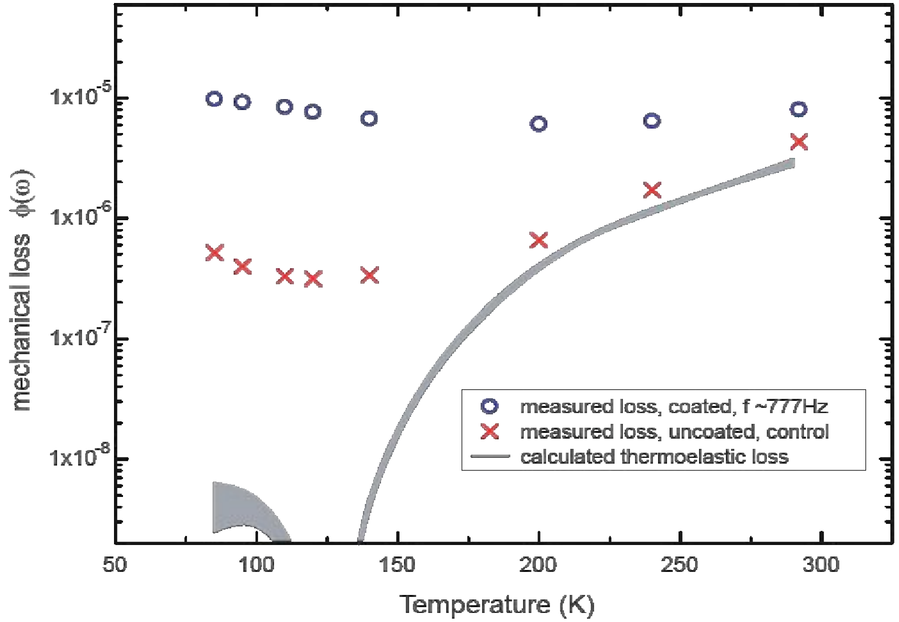
samples



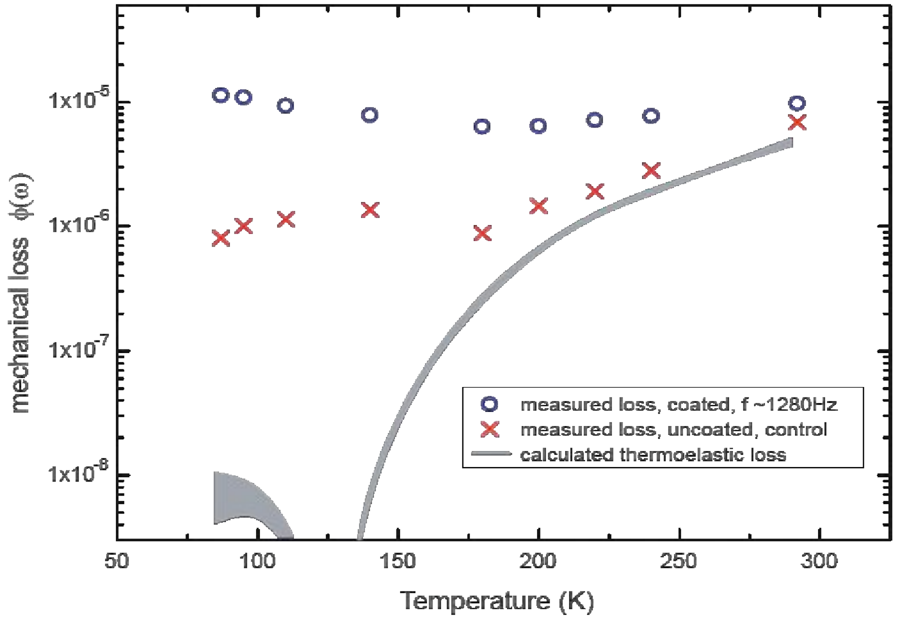
coated (LMA) cantilever in situ

Coated silicon flexures – results 1

- Silicon properties: n-type Ph doped (resistivity 5-10 Ωcm)
- Coating properties: 0.5 μm Ta_2O_5 doped with (14.5 ± 1) % TiO_2



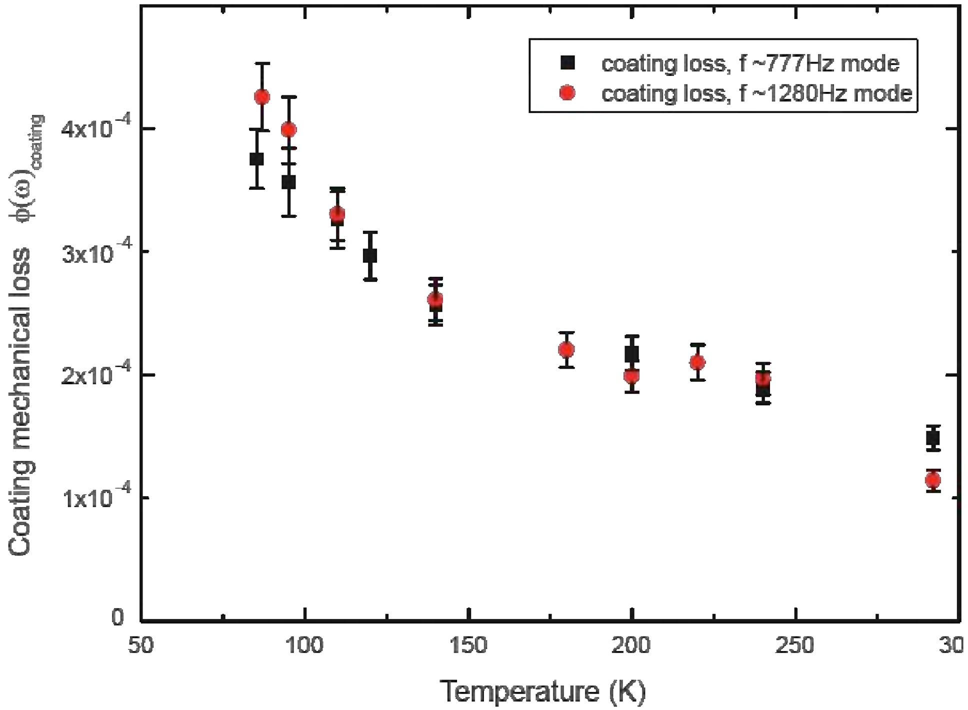
Measured mechanical losses of the coated and uncoated cantilevers (4th bending mode, f ~777 Hz).



Measured mechanical losses of the coated and uncoated cantilevers (5th bending mode, f ~1280 Hz).

Coated silicon flexures – results 2

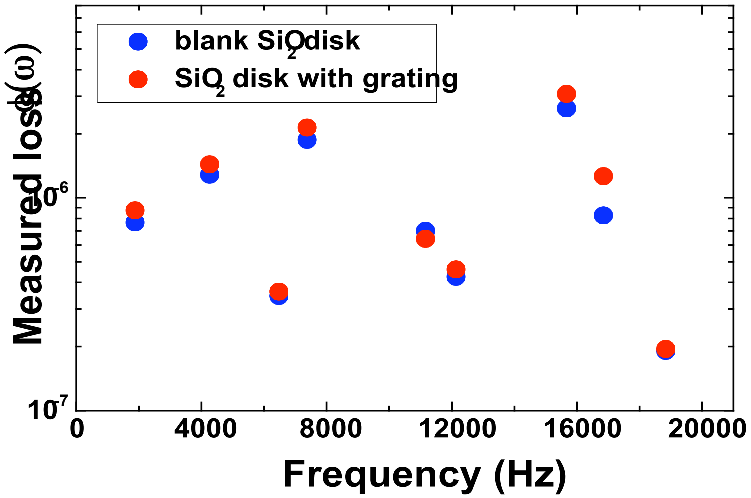
- Calculated coating loss for the 4th and 5th bending modes.



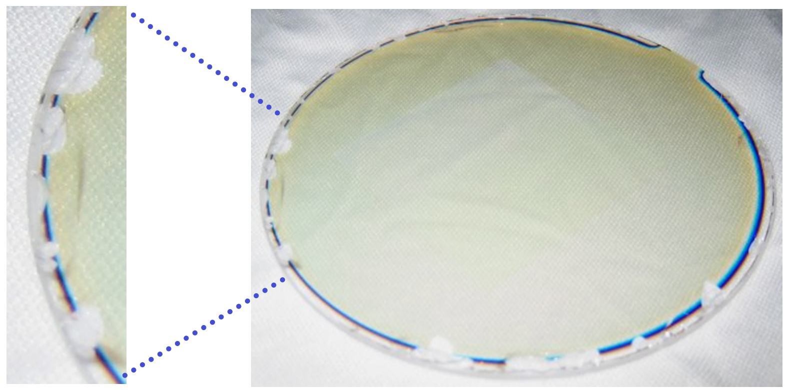
- Measurements of Si cantilevers down to He temperature are now underway (Iain Martin).

Ongoing research

- Investigating the mechanical loss associated with diffraction gratings and their coatings. Results suggest a negligible increase in loss associated with etching diffraction gratings on fused silica disks.



Comparison of measured loss of blank and diffraction grating silica disks



First coating run was not successful – the disks came loose from the clamp during coating and were significantly chipped – new disks are now being sent for coating from Glasgow.

- Bulk silicon measurements to 77K continue, in addition to commissioning a new nodal support.

STREGA – Conclusions for M1,2,4,5

- Currently 3 years into the ILIAS and FP6 timeline
- Results for advanced materials and coatings at cryogenic temperature coming from every group.
- Collaborative efforts underway, examples:
  - Coordination across all the labs is working well.
  - Visits/discussions between Jena & Glasgow scientists in 2005 and 2006.
  - Iain Martin (Glasgow) to travel to Jena with various coated Si cantilevers for comparative measurements and exchange techniques (3 weeks in March 2007).
  - Visits/discussions between Jena and Florence-Urbino groups in 2006.
  - Silicate bonded silicon samples fabricated in Glasgow are under study in Florence (thermal conductivity).
- Results indicate that the thermal noise associated with the dielectric coatings will set the limit to future detector sensitivity. This has caused some changes in focus within the STREGA plan.