Characterization and direct thermal noise measurement of coatings

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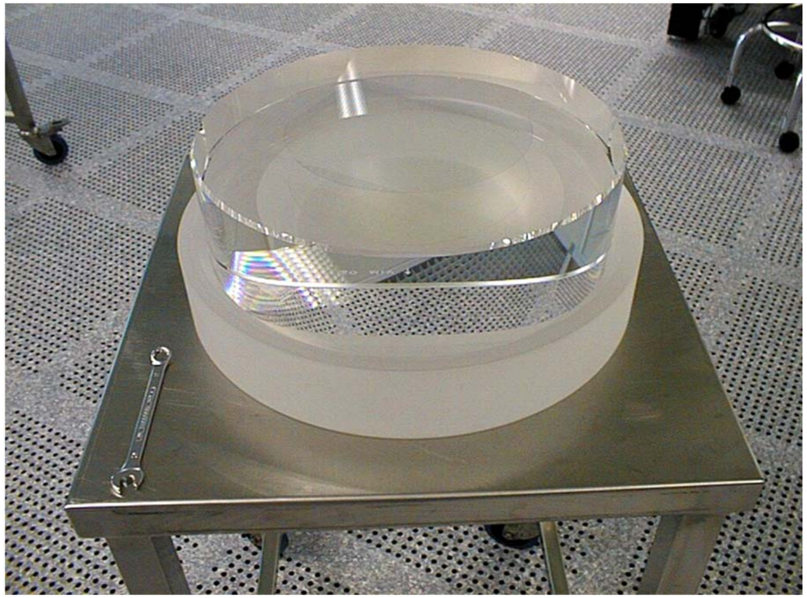
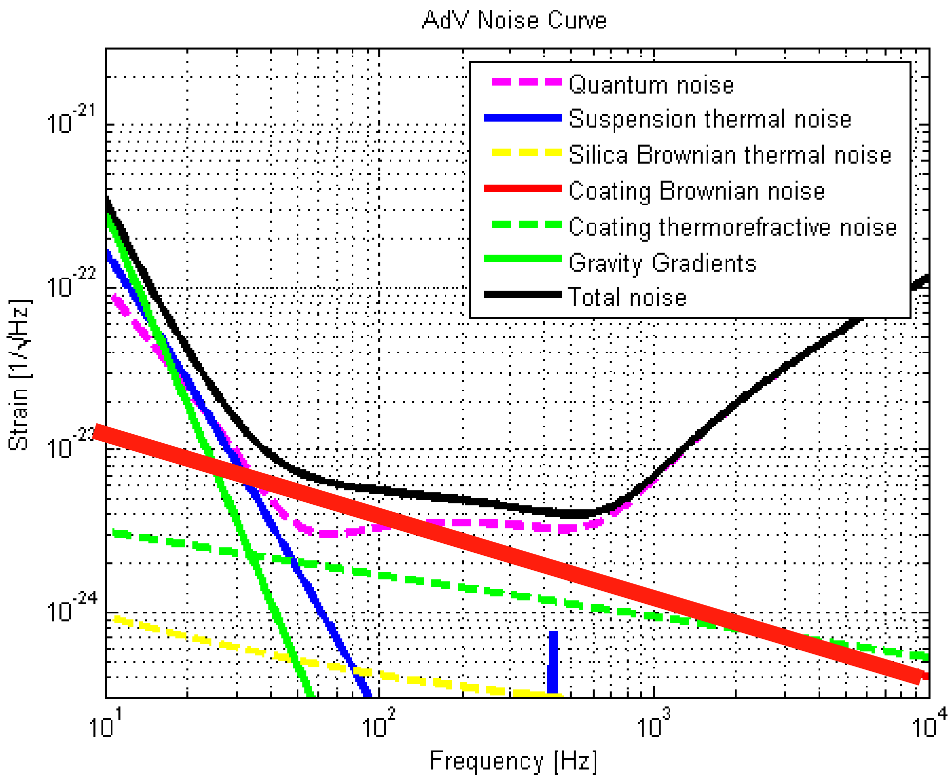
I. Introduction & facilities at LMA
II. Coating Q measurements with cantilevers
III. Coating Q measurements with GENS
IV. Direct coating thermal noise measurement
V. Conclusions and perspectives

I. Introduction and facilities at LMA

Foreword

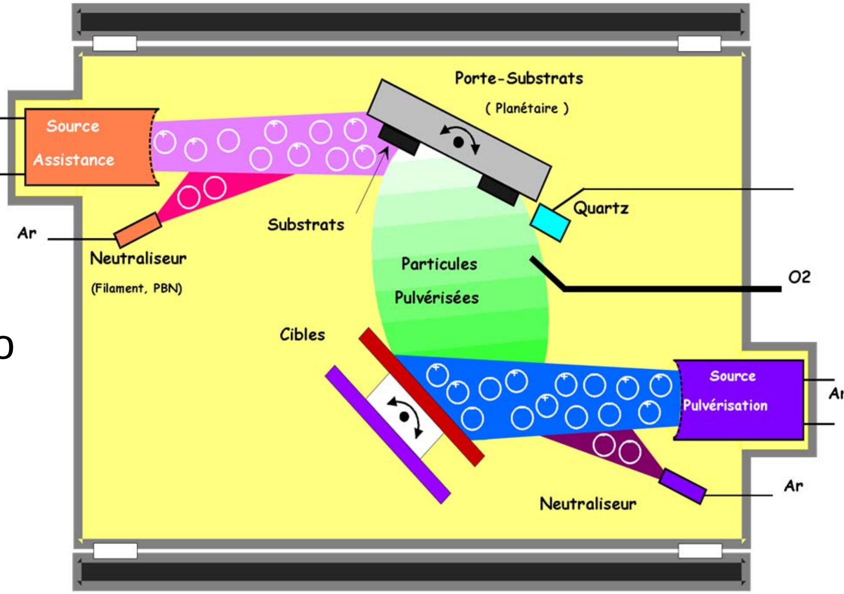
- Mirror thermal noise the main limitation in Advanced GW detectors
- A few microns of coating the main source of mechanical losses in a 40 kg mirror !

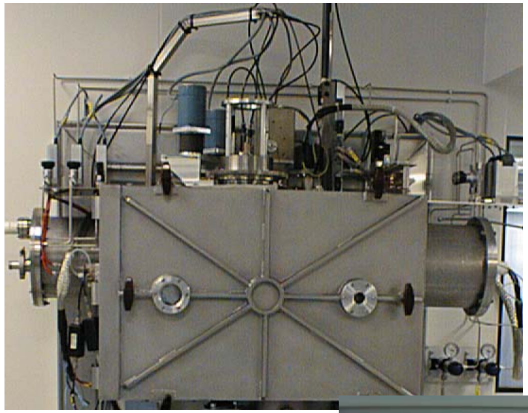




IBS chambers LMA

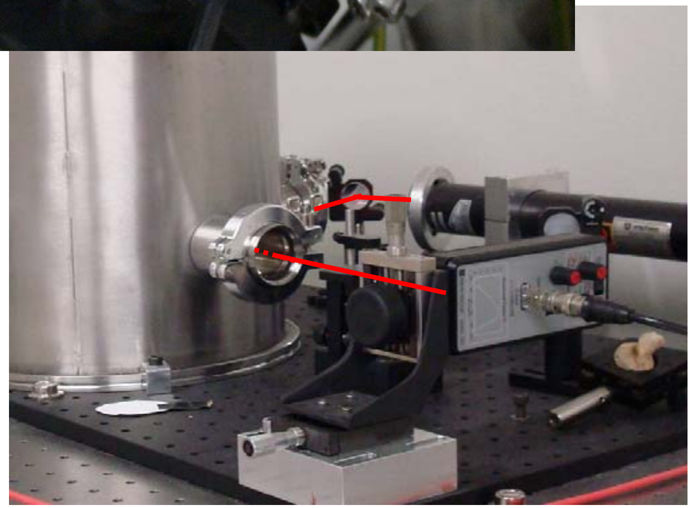
- Ion Beam Sputtering
  - Best technology for low losses coatings so far
- Developed at LMA since the 80s
  - Mirrors for gyrolasers
  - Virgo initial mirrors
  - Mirrors for Advanced LIGO and Advanced Virgo



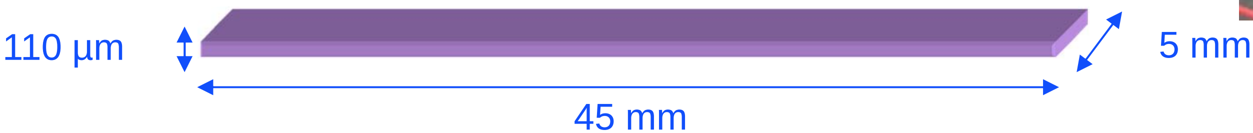


Coating Q measurement bench

- Q measurement bench
  - Collaboration with INFN Perugia
- Principle
  - Measure damping of thin cantilever modes
  - First mode at ~60 Hz
    - » Allows covering the interesting frequency range
  - Compare uncoated cantilevers with coated $\Rightarrow$ deduce coating losses

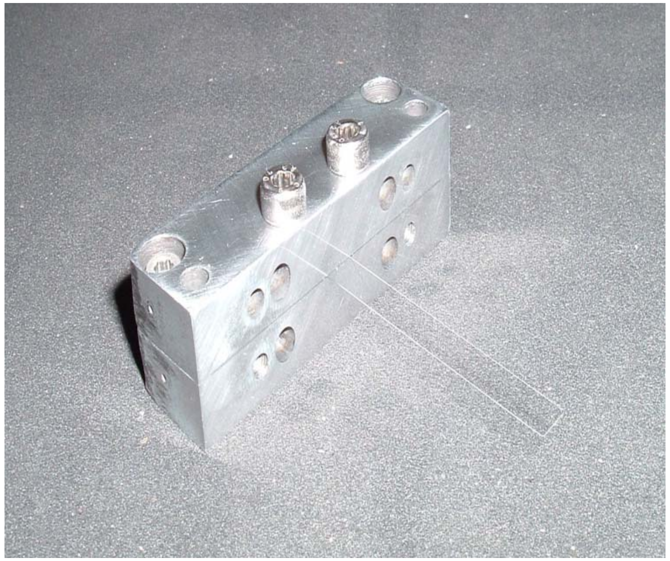


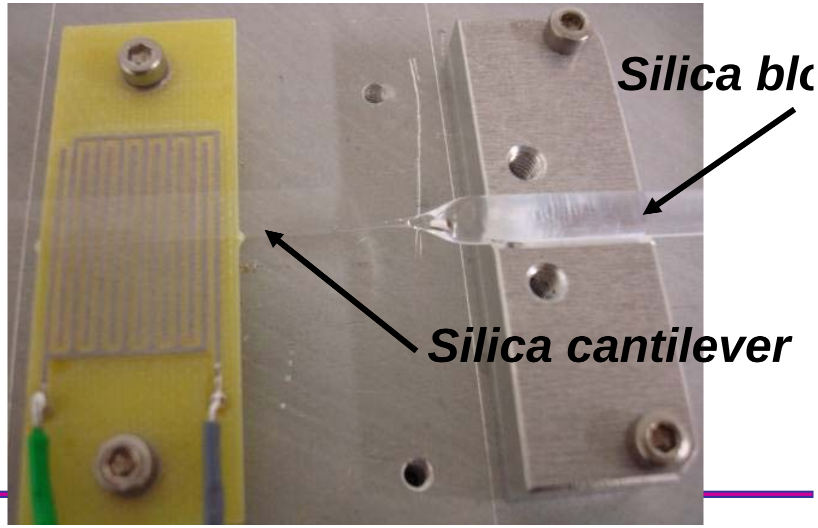
- Cantilever : Silica *SUPRASIL 311* from *HERAEUS*



Coating Q measurement bench

- A few tricks
  - Clamp mechanics and polishing
    - » Minimize clamping losses
  - Cantilever cleaning
    - » Remove polishing impurities
  - Cantilever annealing
    - » Cure cracks due to polishing
- Initial sensitivity
  - @ 60 Hz: Q=250000, $\Phi = 4 \cdot 10^{-6}$
  - Determined by residual clamping losses
- Improvements
  - Cantilevers welded to silica block
  - Improved cleaning (chemical)
- Present sensitivity
  - @ 50 Hz: Q>500000, $\Phi = 2 \cdot 10^{-6}$
  - Q can be larger than 1 million





II. Coatings Q measurement with cantilevers

Q measurement on monolayers

- Q of Ti:Ta_2O_5 measured regularly at LMA since 2006
  - No variation seen with thickness (in the range of few 100's nm)
  - No variation seen along the years
  - Average value of losses 2.4 +/- 0.4 10^{-4}

- Q of SiO_2 monolayers
  - Difficult to measure with clamped cantilevers
  - Measured properly with welded cantilevers
  - Average value of losses: 4.6 +/- 0.1 · 10^{-5}

Losses of multilayer coatings

- Losses of multilayer = linear combination of losses of monolayers
  - $\langle {x_{th}}^2(\omega) \rangle = \frac{4k_B T}{\omega} \frac{(1-\sigma^2)}{\sqrt{\pi} E_0 w} \phi_{eff,coating}(\omega)$
  - $\phi_{eff,coating}(\omega) = \frac{t}{\sqrt{\pi} w} \left(\frac{E_0}{E_\perp} \phi_\perp + \frac{E_\parallel}{E_0} \phi_\parallel \right)$
  - t coating thickness
  - w laser beam radius
  - σ Poisson ratio
  - E_0 substrate Young modulus
  - $E_\parallel$, $E_\perp$ coating Young modulus, linear combination of layers material Young modulus
  - $\phi_\parallel$, $\phi_\perp$ coating loss angles, linear combination of layers material losses

$$E_\perp = \frac{t_1 + t_2}{t_1/E_1 + t_2/E_2}$$

$$E_{||} = \frac{E_1 t_1 + E_2 t_2}{t_1 + t_2}$$

$$\phi_\perp = \frac{E_\perp}{t_1 + t_2} \left(\frac{t_1}{E_1} \phi_1 + \frac{t_2}{E_2} \phi_2 \right)$$

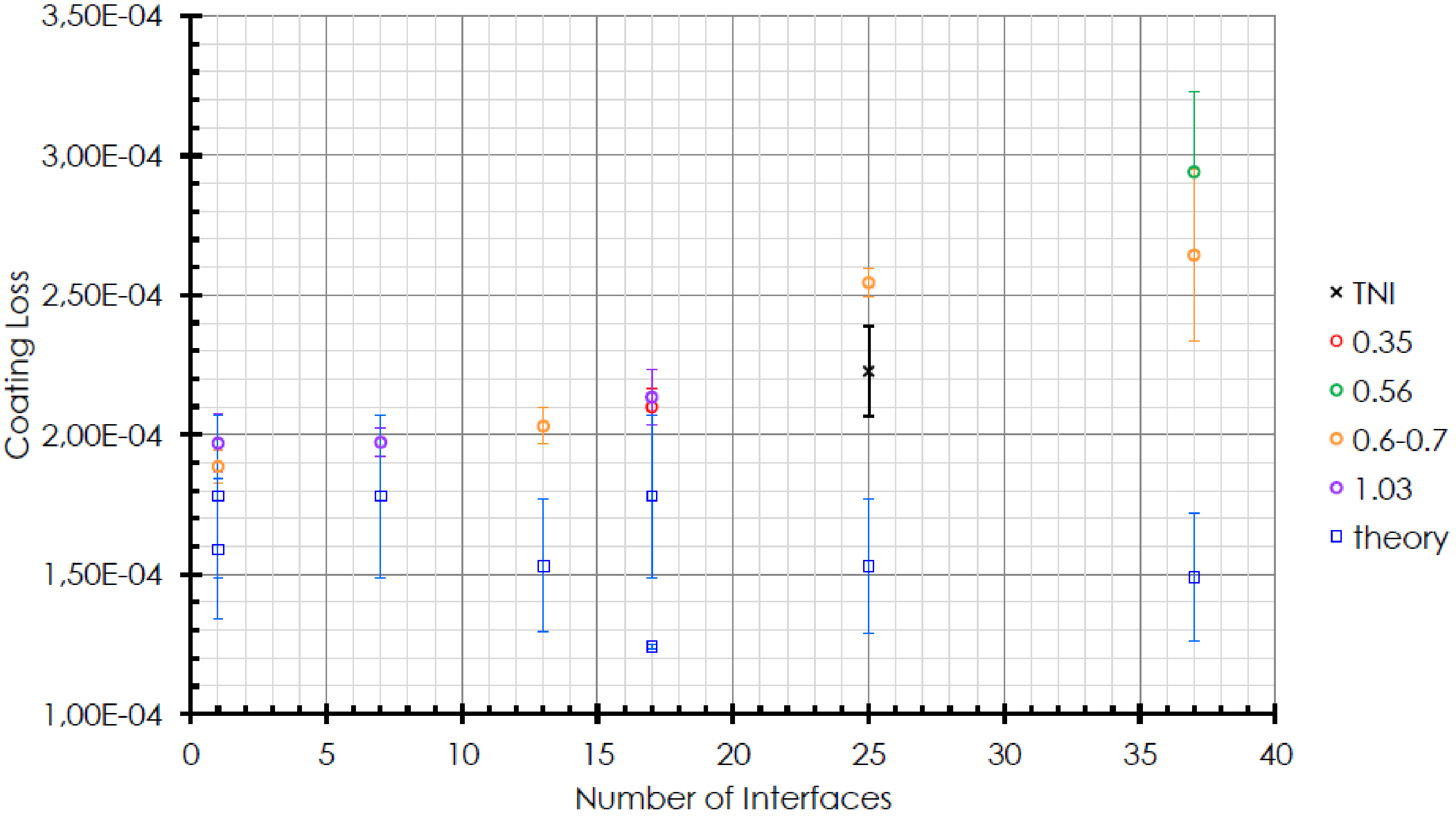
$$\phi_{||} = \frac{E_1 t_1 \phi_1 + E_2 t_2 \phi_2}{E_{||}(t_1 + t_2)}$$

Multilayer coatings on cantilevers

- No multilayers coating done on cantilevers until 2009
  - Defects in the coatings due to defects on the cantilever surface
  - Problem solved with new cleaning technique
- First “good” multilayer coating deposited on cantilevers at LMA was the TNI optimized coating
- Losses found to be larger than expected
  - Expected Losses: $1.5\ 10^{-4}$
  - Measured losses: $2.55\ 10^{-4}$
- Same trend found from TNI measurement
  - Measured losses: $2.2\ 10^{-4}$ (Villar A. et al., LIGO-G1101096)
- Several multilayer coatings deposited on cantilevers since 2009
  - Some excess of losses observed (J. Franc et al. GWADW2010, E. Saracco et al. GWADW2012, M. Granata et al. GWADW2013)

Losses of multilayer coatings

- Measured losses on multi-layers coatings deposited on cantilevers



Losses of multilayer coatings

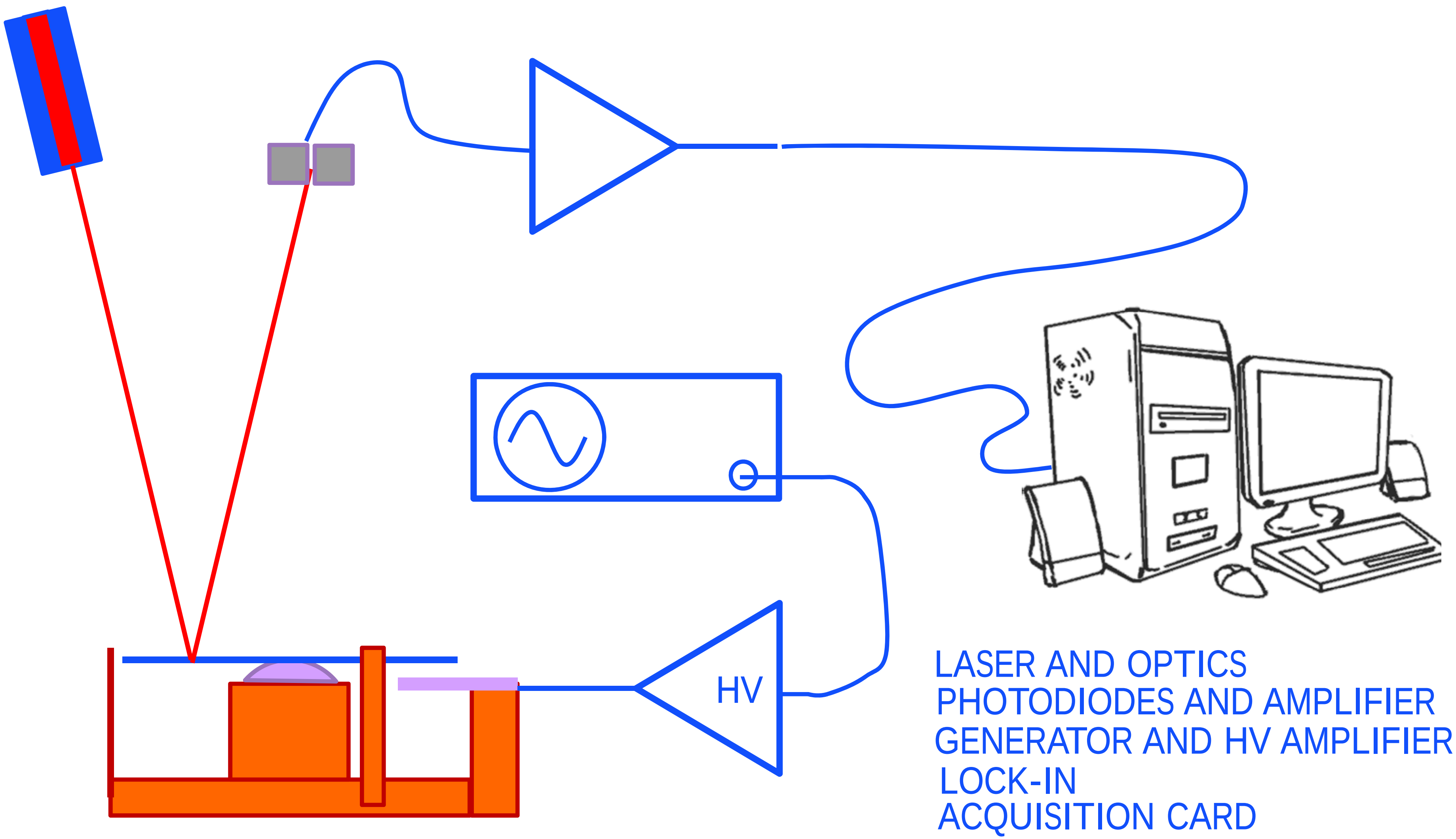
- Effect of interfaces?
  - Model developed assuming interfaces layers with bad mechanical losses
  - Results DO NOT explain excess of losses (M. Granata et al, GWADW 2012)

- Ti:Ta_2O_5/SiO_2 multilayer coatings made at LMA in the large coating chamber back in 2005
  - G.M. Harry et al, Class. Quantum Grav. **24** (2007) 405–415
  - Excess of losses did not observed at that time
  - Substrates were 3” silica discs (2.5 cm and 2.5 mm thick)

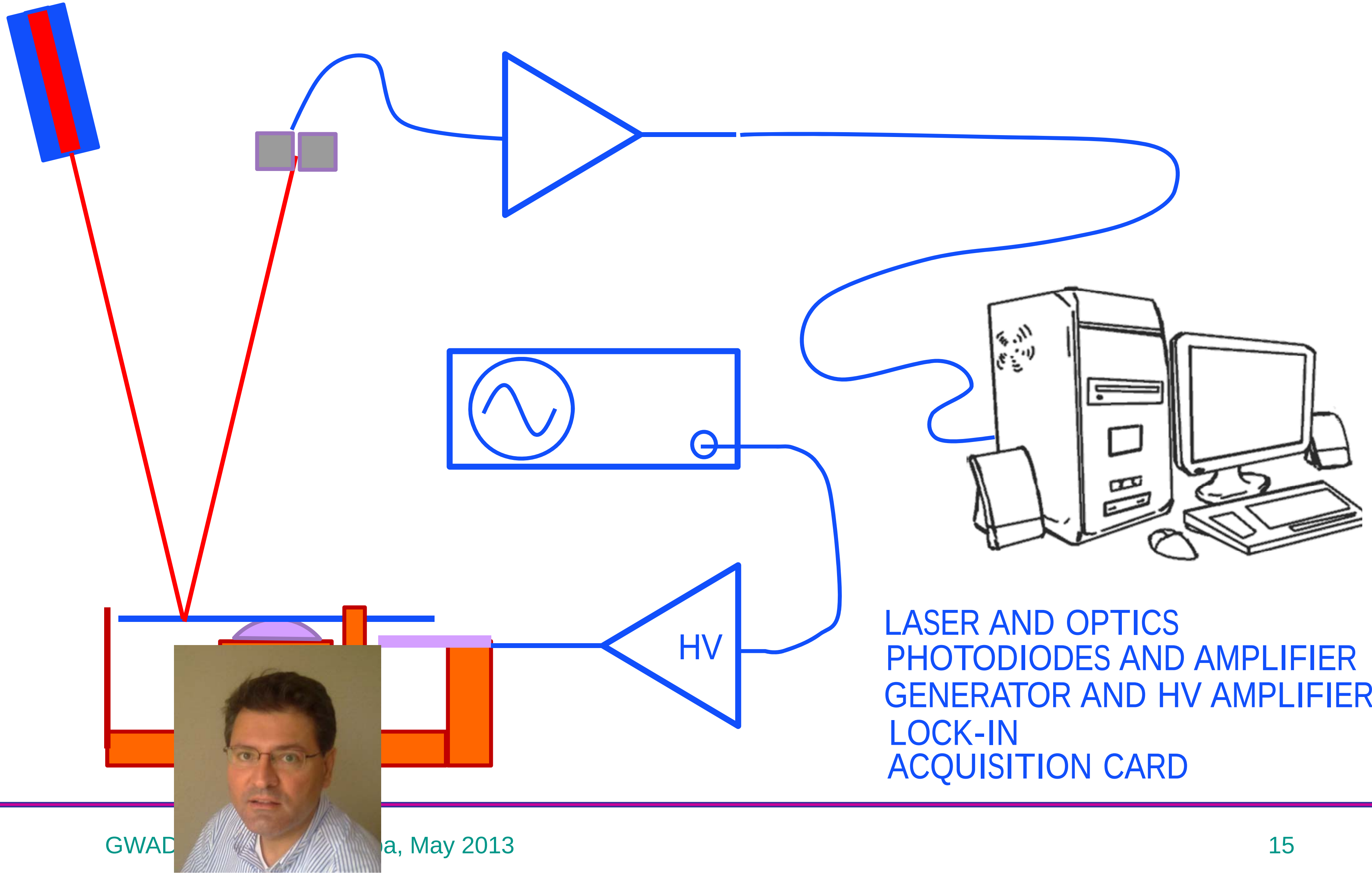
- Is there some spurious effect due to the apparatus and/or the type of substrate?

III. Coatings Q measurement with GENS

GENS – GEntle Nodal Suspension



GENS – GEppo Nodal Suspension



GENS – Gentle Nodal Suspension

- Originally developed in Florence for Q measurements on thin disks and wafers
  - Cesarini E. et al., A "gentle" nodal suspension for measurements of the acoustic attenuation in materials, Review of Scientific Instruments, 80 5 053904 (2009)

- Pro:
  - Easy procurement of samples
  - Higher mode density than 1D cantilevers
  - High repeatability of Q and frequency measurement
  - Suspension point can be displaced easily

- Cons
  - Drum modes cannot be excited
  - Excess loss for modes that roll over the sphere

GENS – Gentle Nodal Suspension

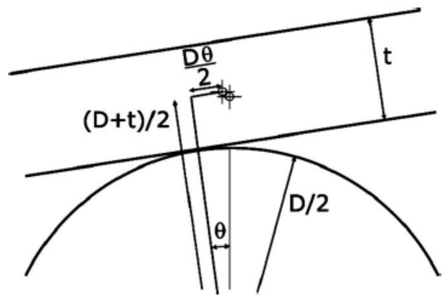
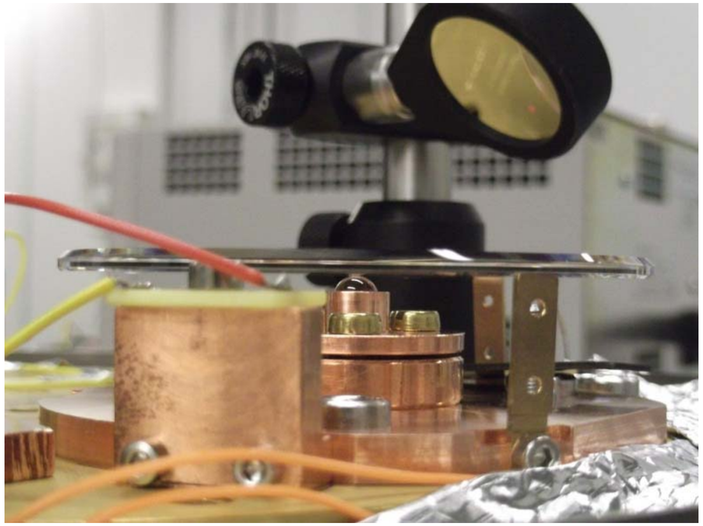
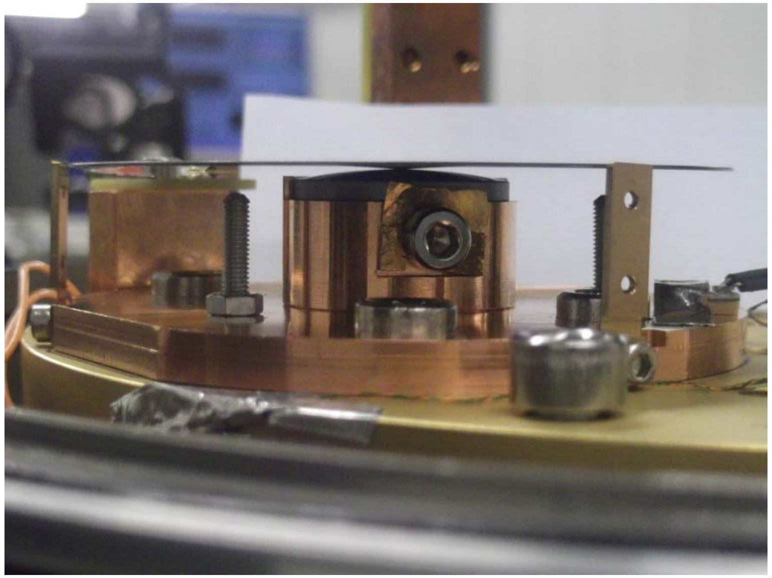


FIG. 1. Geometrical parameters useful to calculate the equilibrium condition. Only when $D > t$, at each small oscillation around the (horizontal) equilibrium position corresponds an increase in the vertical coordinate of the c.m.

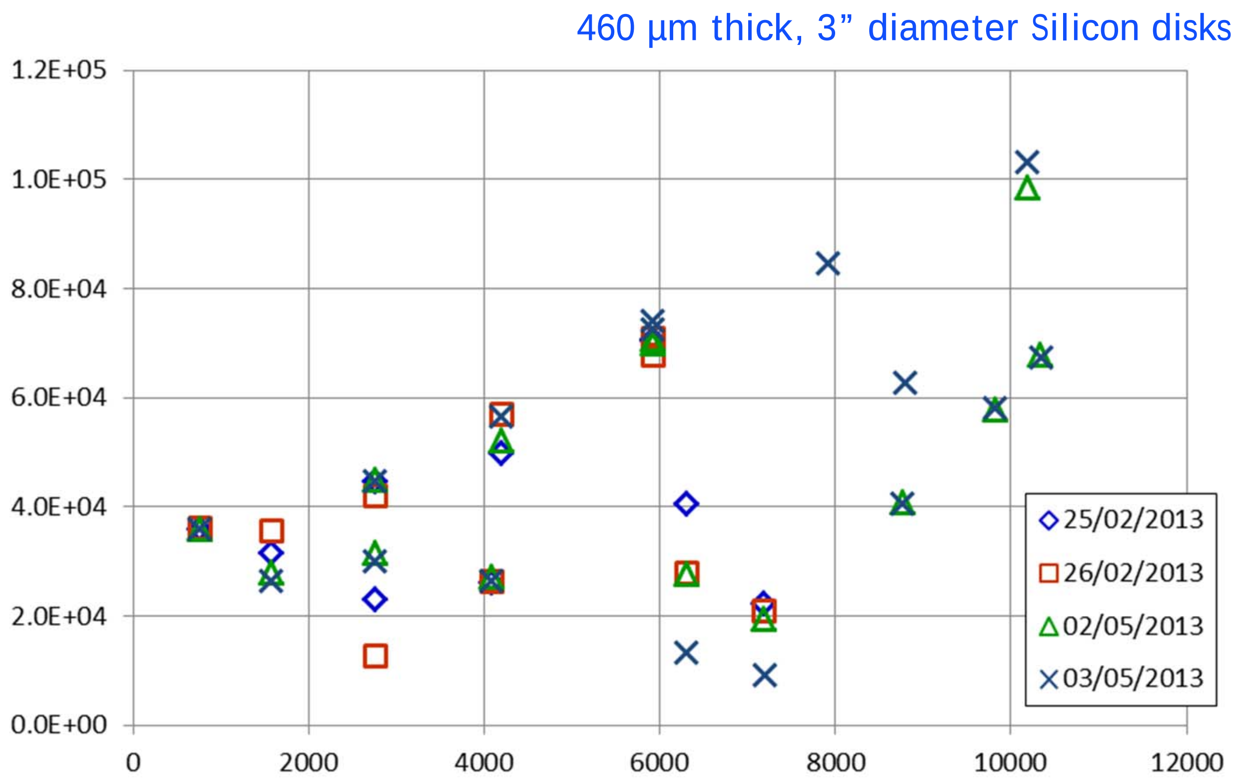




Mounted in a cryostat to make tests at low T
See M. Granata talk on Friday

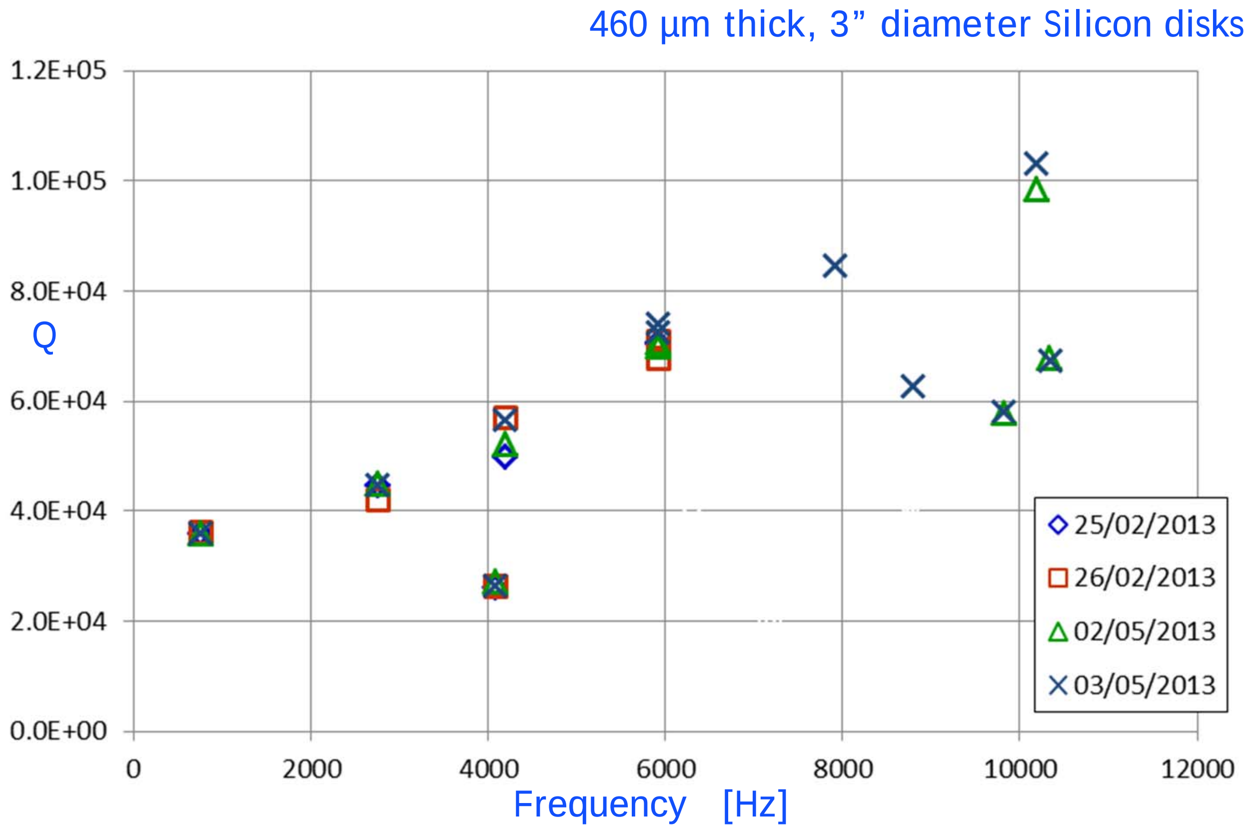
GENS – Performances

- Reproducibility:
  - Same sample measured several times
  - All modes



GENS – Performances

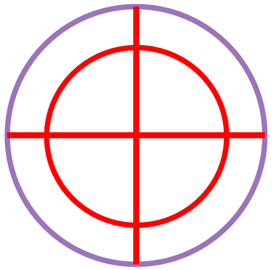
- Reproducibility:
  - Same sample measured several times
  - Only “good” modes



GENS – Performances

- Reproducibility:
  - ◆ Same sample measured several times

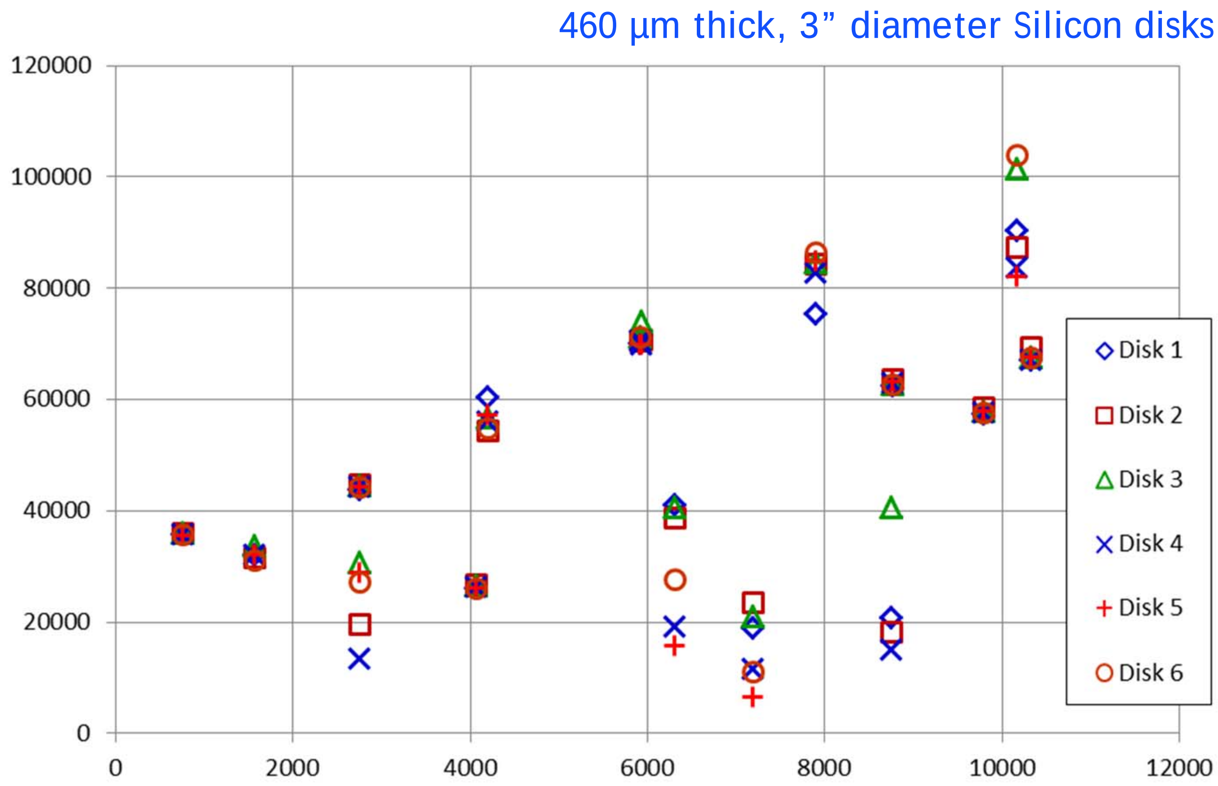
Mode numbering example: 1,2 correspond to the following mode



Mode		25-Feb	26-Feb	02-May	03-May
0,2	f [Hz]	752.03	752.03	752.02	752.03
	Q	36000	36200	35927	35893
0,4b	f [Hz]	2755.4	2755.5		2755.35
	Q	44700	42200	44923	44713
1,2	f [Hz]	4072.8	4072.8	4072.73	4072.7
	Q	26300	26450	27180	26360
0,5	f [Hz]	4196.2	4196.42	4196.23	4196.35
	Q	49750	57000	52135	56467
0,6a	f [Hz]	5915.9	5915.9	5915.84	5915.71
	Q	70550	67850	70060	72447
0,6b	f [Hz]	5919.8	5919.83	5919.65	5919.62
	Q	70750	71050	70680	74090
0,7	f [Hz]				7912.41
	Q				84619
1,4b	f [Hz]				8787.42
	Q				62730
2,2	f [Hz]			9810.74	9811.01
	Q			57805	58027
0,8a	f [Hz]			10183.88	10183.90
	Q			98625	103270
0,8b	f [Hz]			10335.33	10342.56
	Q			67840	67383

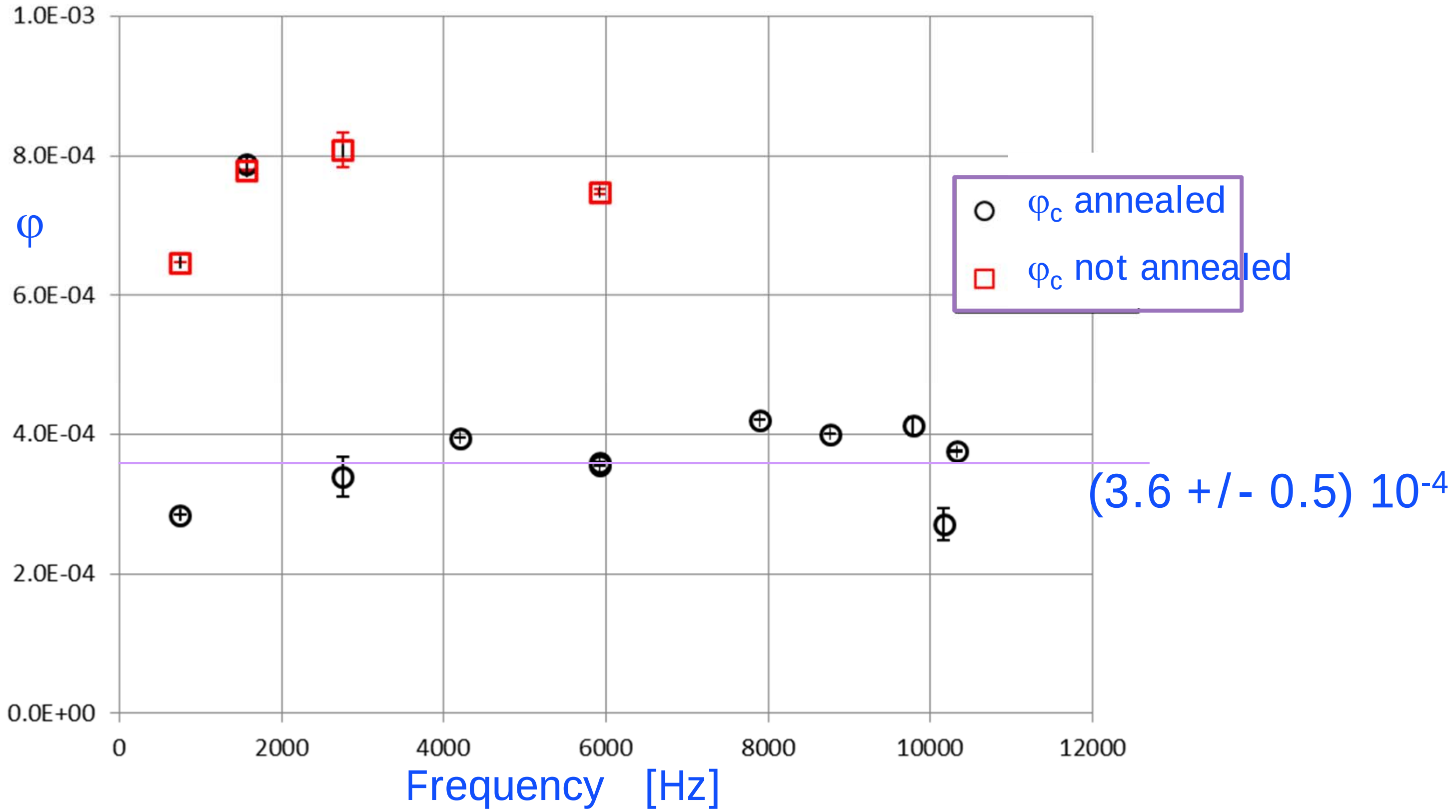
GENS – Performances

- Reproducibility: different disks



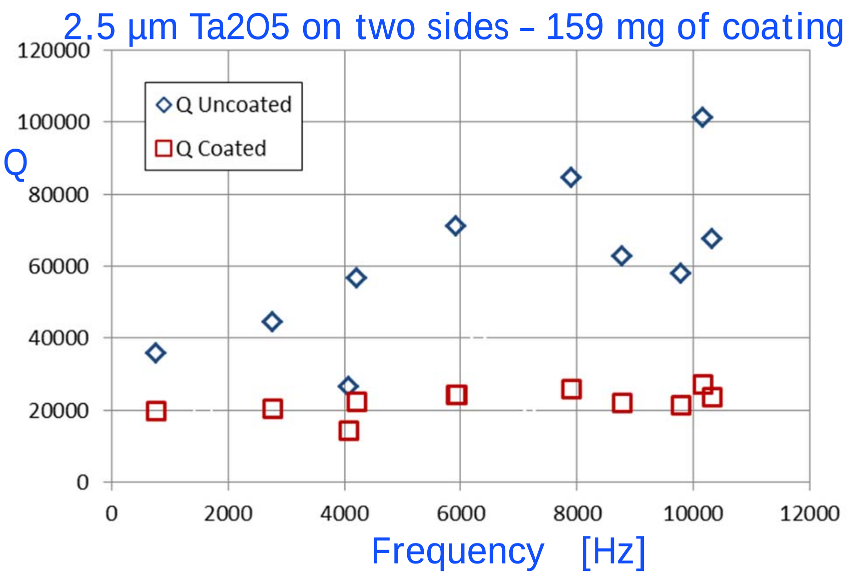
GENS - Results on Ta_2O_5

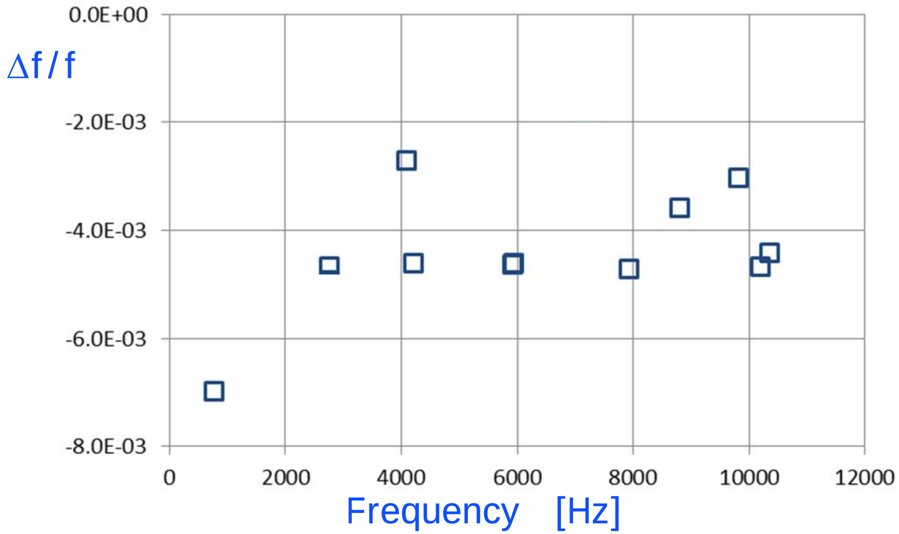
- Measurement of losses of plain Ta_2O_5
  - 2 μm thick monolayer of Ta_2O_5 deposited on a silicon wafer
  - Coating loss deduced from theoretical dilution factor

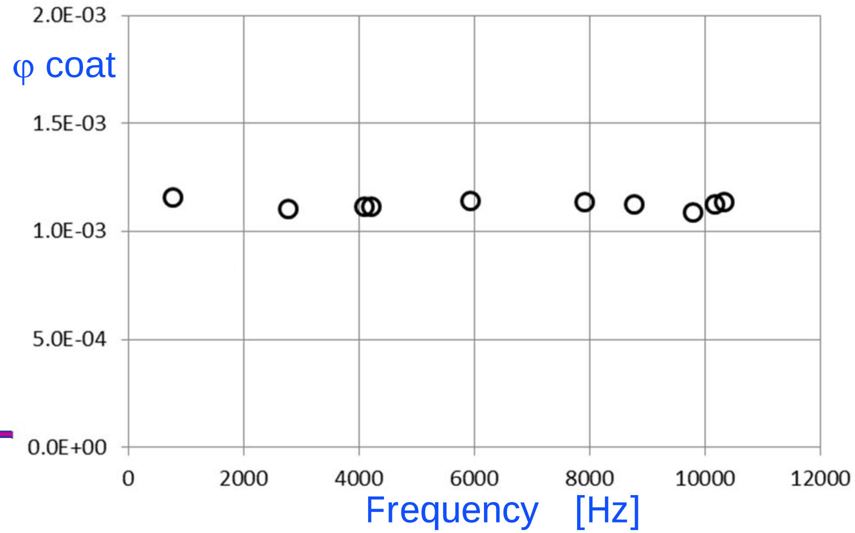


GENS - Results on Ta_2O_5

- Can we measure the dilution factor?
  - Measure coating mass
  - Measure change in frequency
  - Deduce dilution factor





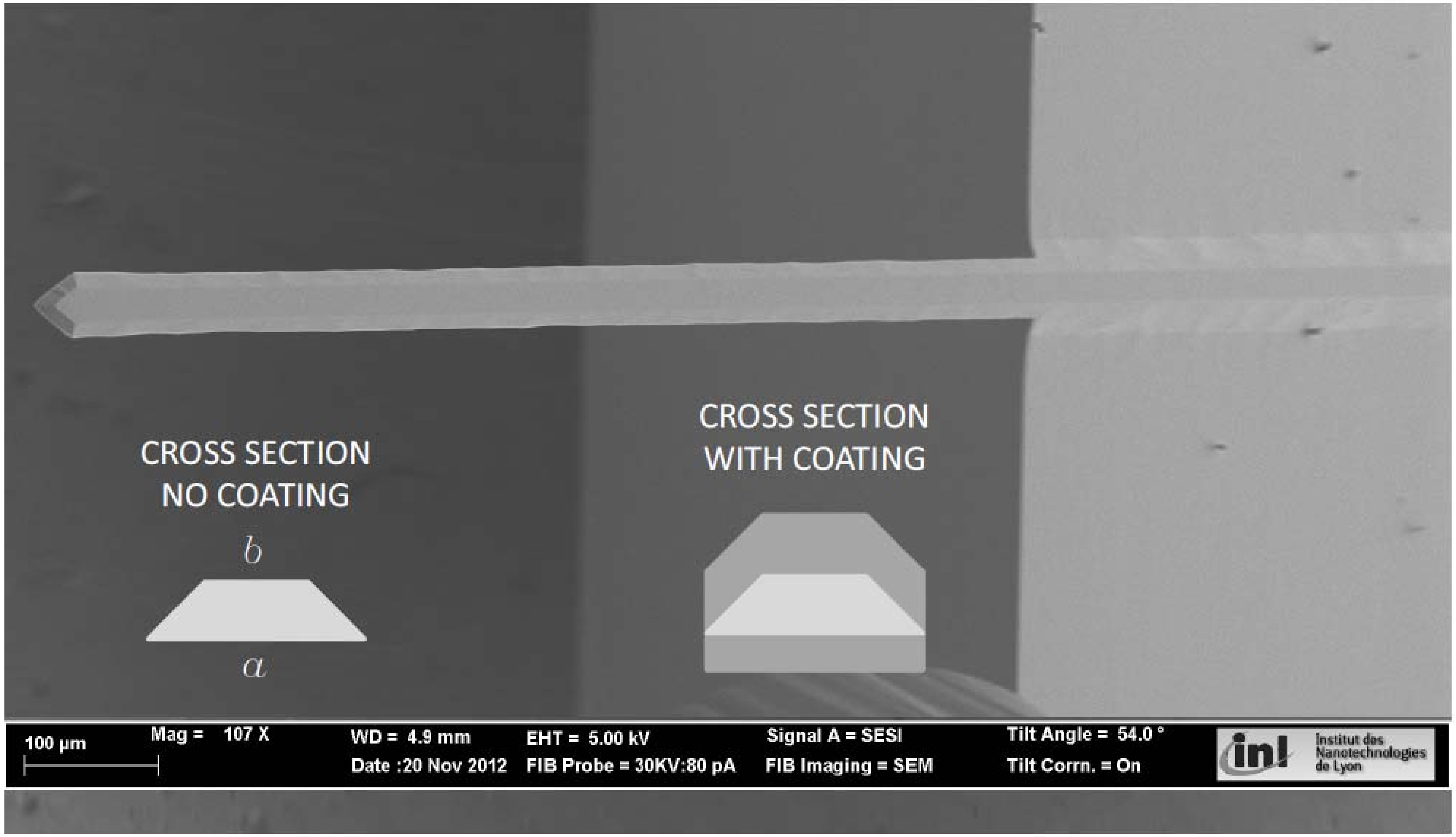


IV. Direct coating thermal noise measurements

In collaboration with:
F. Aguilar, T. Li, M. Geitner and L. Bellon
Ecole Normale Superieure de Lyon, CNRS

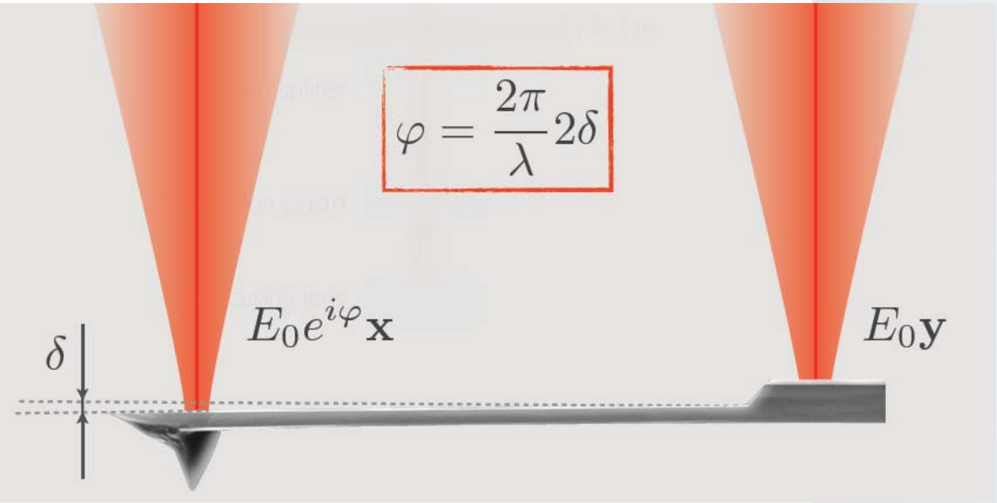
Direct thermal noise measurement

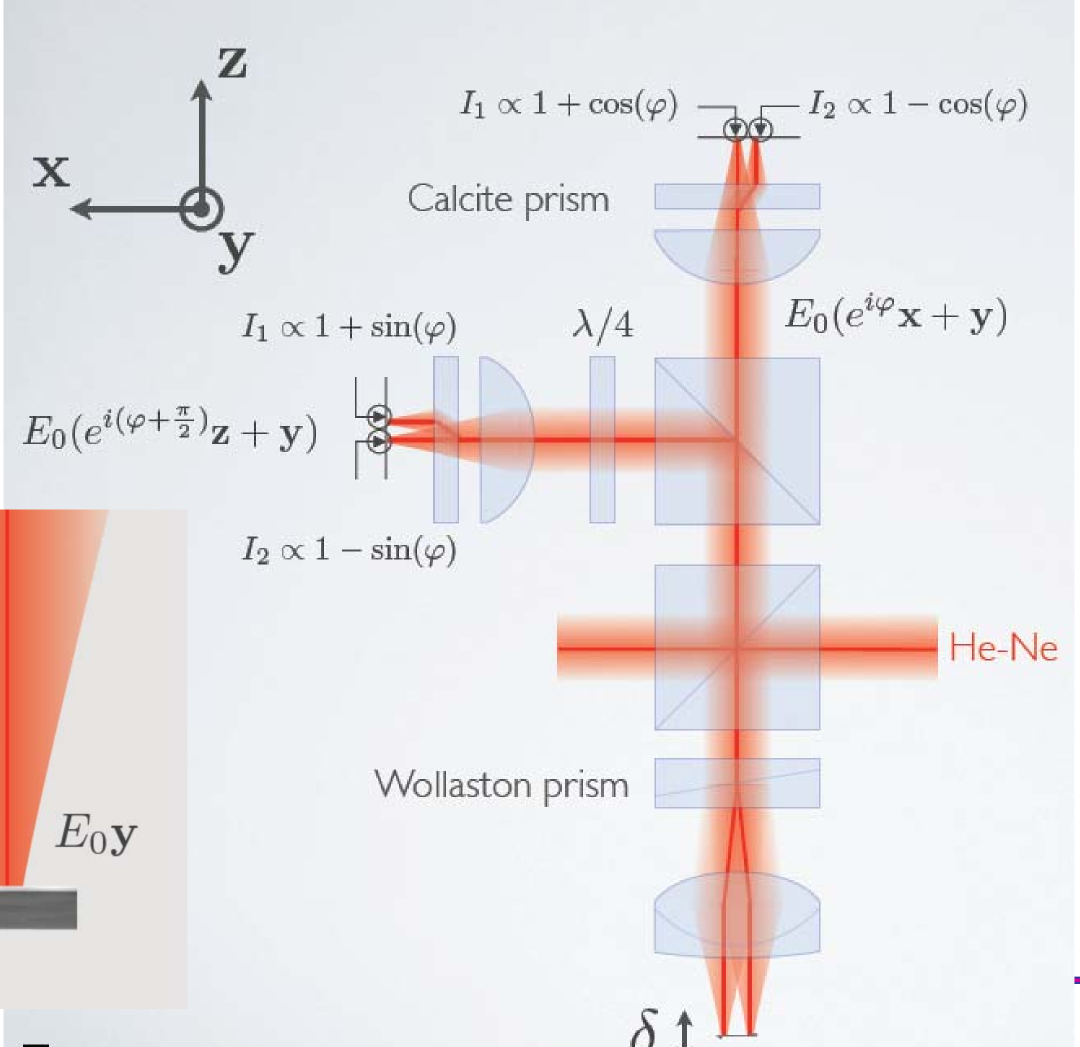
- Use AFM cantilevers as substrate
  - Made of silicon
  - 500 microns long, 3 microns thick, 15-30 microns wide
- Deposit coating on cantilevers



Direct thermal noise measurement

- Measure thermal vibration with a quadrature phase differential interferometer
- Developed at ENS Lyon
- L. Bellon et al.





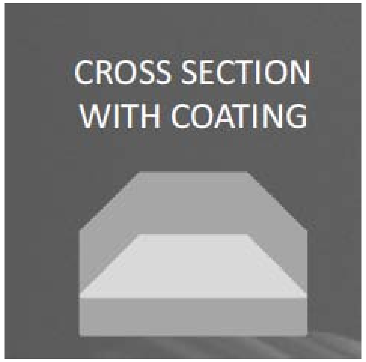
L. Bellon, S. Ciliberto, H. Boubaker, and L. Guyon, *Optics Communications* **207**, 49–56, 2002.

Direct thermal noise measurement

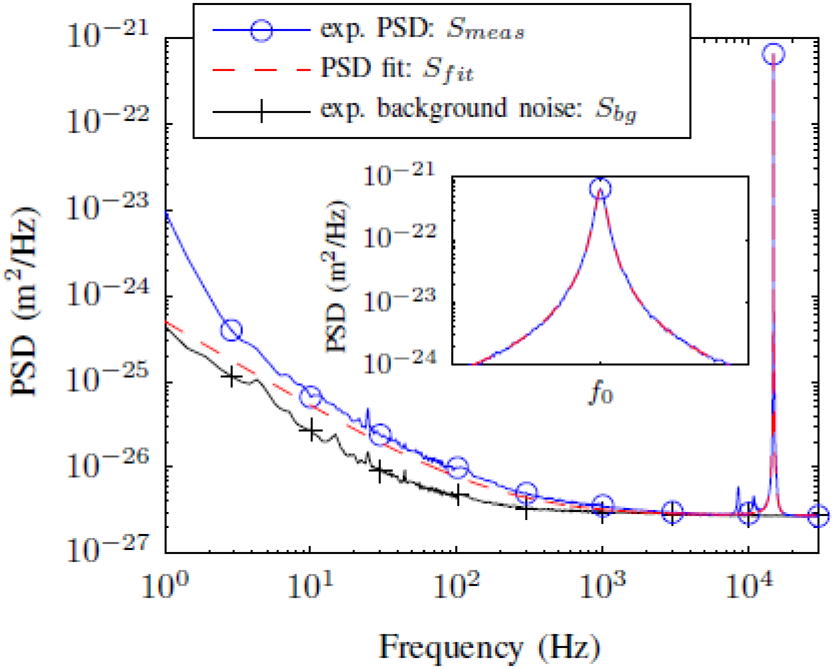
- First test with monolayers of Ta2O5 and SiO2

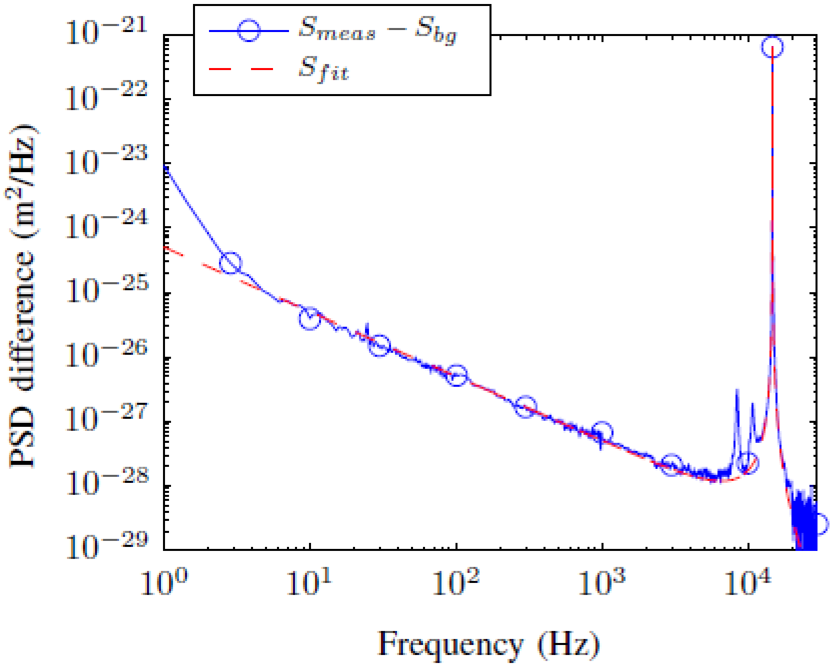
TABLE I. COATING PARAMETERS FOR THE TWO MEASURED SAMPLES.

	Coating material	Thickness on a [nm]	Thickness on b [nm]	ρ [g/cm^3]	E [GPa]
Coating T	Ta_2O_5	373	476	7.2 ± 0.1	140
Coating S	SiO_2	424	541	2.4 ± 0.1	70



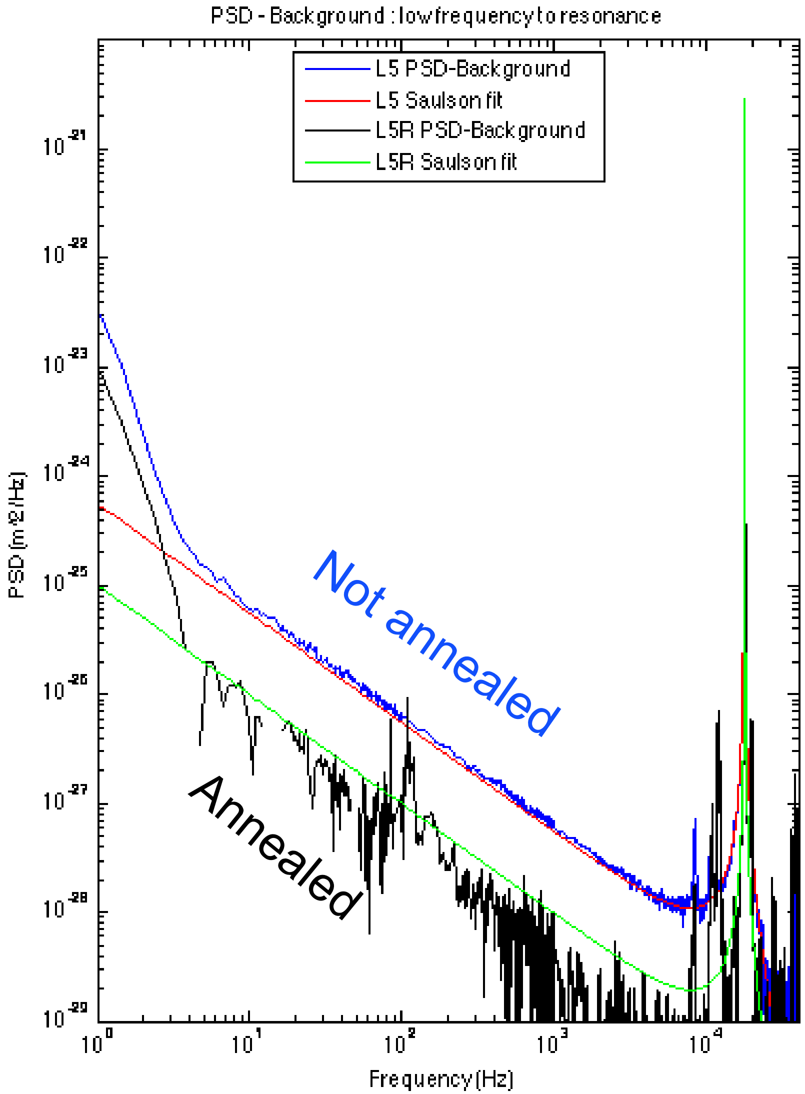
- Results with Ta2O5





Direct thermal noise measurement

- Results with SiO2
  - Measured before and after annealing



Direct thermal noise measurement

- Coating losses of monolayers

TABLE III. LOSS ANGLE OF THE COATINGS

Coating	Cantilever $\phi \cdot 10^4$	$\phi_{sub} \cdot 10^4$	D	$\phi_{coa} \cdot 10^4$
Tantala	2.30 ± 0.25	< 0.3	0.56 ± 0.01	3.9 ± 0.4
Silica	2.60 ± 0.50	< 0.3	0.42 ± 0.01	5.8 ± 1.0

Agrees with GENS measurements

Not annealed

Silica $4 \pm 2 \cdot 10^{-5}$ (TBC) ← Annealed

Conclusions

- Coating Q measured at LMA for several years using thin silica and silicon cantilevers
  - Both on monolayers and multilayers coatings
  - Some excess of losses observed in multilayers compared to monolayers
- Attempt to have independent measurements with different apparatus and substrates
- GENS: GEntle Nodal Suspensions
  - Very nice reproducibility
  - First direct measurement of dilution factor
  - Measurement started with monolayers
- Direct coating thermal noise measurement
  - AFM cantilevers as substrates
  - Compact (and simple) interferometric sensor
  - First measurements on monolayers agrees with GENS first results