VCR&D

ICORE

Centro Studi e Ricerche Enrico Fermi

E. Cesarini

Giornate di Studio: Progetti del Centro Fermi 2019-2021

CENTRO FERMI

MUSEO
STORICO DELLA FISICA
E
CENTRO
STUDI E RICERCHE
ENRICO FERMI

Università di Roma
Tor Vergata

INFN

Work done in this year:

* Loss Angle Measurements (GeNS)
* Coating Detectability
* Knowledge and Stability Of Substrate (From Edge Effect To Ageing, Thermoelastic Damping)
* Silica Monolayer From New Coating Facility in Benevento

Planning new year:

* Future Measurements On Nano-layered Coatings
* Other Research Lines (High Coordination Number Materials)
* Facilities developments

Publications, Conferences And Collaborations

All the work has been done in collaboration with colleagues in Roma Tor Vergata (**Diana Lumaca,** Phd student Università Roma Tor Vergata and **Dr. Matteo Lorenzini** GSSI) that allowed me to follow and continue the work during my maternity leave.

Overview

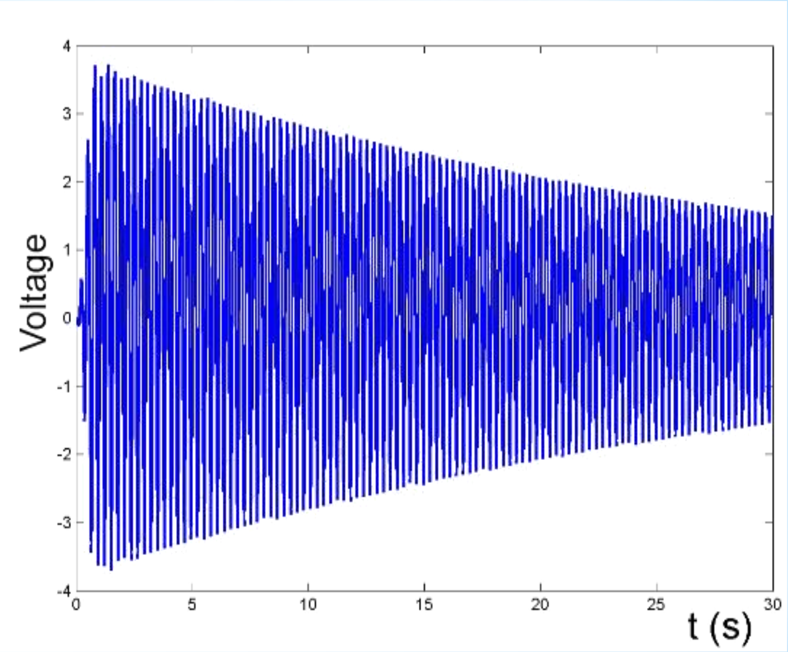
Loss Angle Measurement

- The dissipation of mechanical energy can be modeled by using a **complex elastic constant** in the Hooke's law, with a small phase called **loss angle** ϕ

$$-\omega^2 m\tilde{x} = -k\big(1 + i\varphi(\omega)\big)\tilde{x} + \tilde{F}$$

- The **loss angle** is the ratio between energy lost in a cycle and the total energy and it can be evaluated measuring the free decay time at the resonance

$$Q = \frac{1}{\varphi(\omega_0)} \qquad \varphi = 1/\pi f_0 \tau$$



Possible critical issues:

- ✓ transfert of energy from sample to clamp
- ✓ damaging of the deposited coating
- ✓ Reproducibilty of the measurement

* GeNS

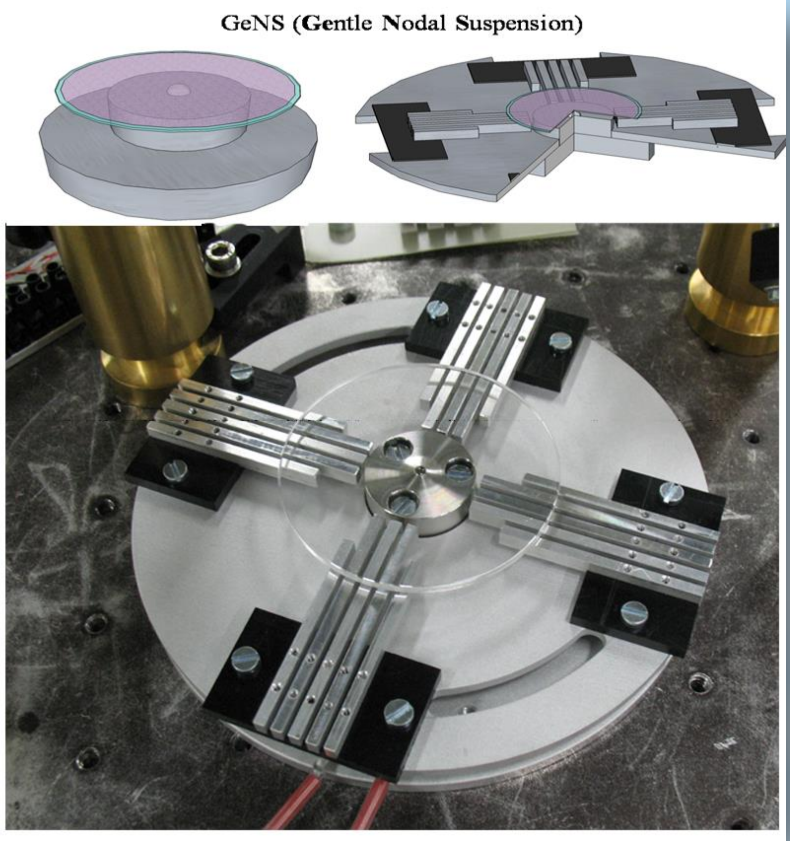
(Gentle Nodal Suspension)

* **Angular stability** range:

  equilibrium with D>t

$$\vartheta = \sqrt{3(D-t)/t}$$

* Read-out system: electrostatic actuator to excite the resonance vibrating mode, optical lever to read the free oscillations
* **Reproducibility: within 10%**



E. Cesarini et al. Rev. Sci. Instr. 80, 053904 (2009)

Recognized worlwide as the **best tool** for loss angle measurement in coating research and lately adopted by national and international lab involved in this research

*Results Achieved

Coating detectability

- Coating losses are evaluated looking at their effect on the substrate loss

$$\phi_{COAT} \cong \frac{E_{SUB}}{E_{COAT}}(\phi_{SUB+COAT} - \phi_{SUB}) =$$

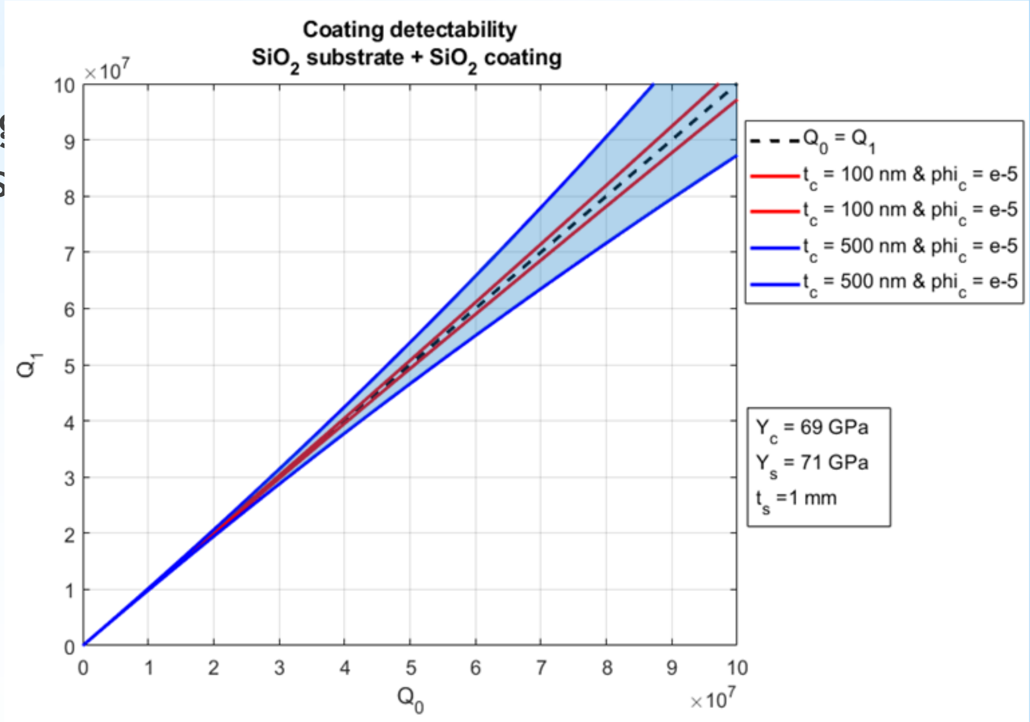
$$= \frac{1}{D_C}(\varphi_{SUB+COAT} - \varphi_B)$$

- To detect φ_{coat}, one should be able to distinguish :

$$\varphi_{sub}^{meas} = \varphi_0$$

$$\varphi_{sub+coat}^{meas} = (\varphi_0 + \Delta\varphi_0) + D_C\varphi_c$$

$$\Delta\varphi_c \cong {}^{\Delta\varphi_0}/_{D_C}$$



$$\varphi_{coating} \cong 10^{-5}$$

Meas. Repr.: 10%
T_{coat} = 100 nm
T_{coat} = 500 nm

Stability of the substrate

Amorphous materials (SiO_2)

- By measuring different SiO_2 substrates we obtained unexpected results:

loss is **mode-dependent → edge losses**

loss is **time-dependent → ageing effect**

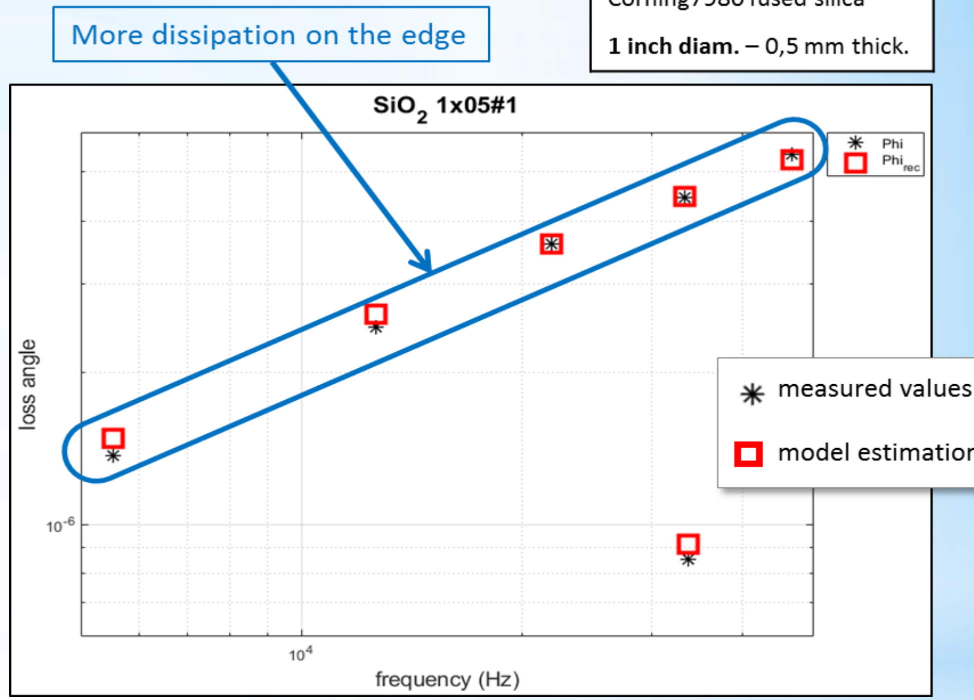
G. Cagnoli et al., *Mode-dependent mechanical losses in disc resonators*, Phys. Lett. A (2018), **Vol 382**, **Issue 33**, 2165-2173

- **Annealing** at high temperature of the SiO_2 substrate restores the initial condition, but (alone) it was **not a definitive solution**
- Absorption of contaminants trough the rough edge? **Spurious dissipation in the rough lateral surface** of the samples (not polished)

Samples:

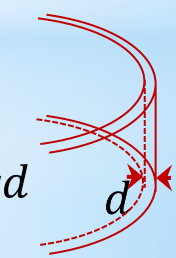
Corning7980 fused silica

1 inch diam. – 0,5 mm thick.



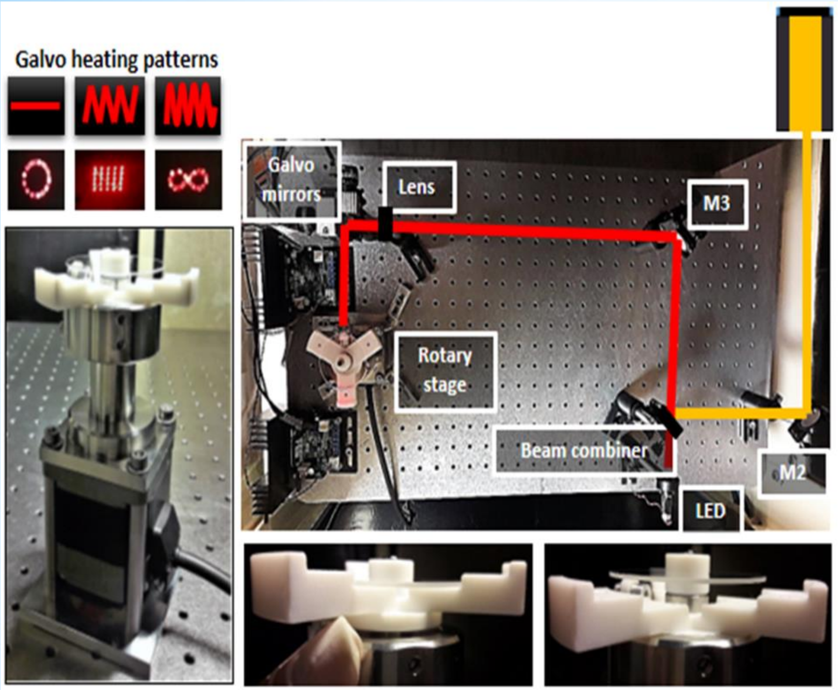
$$\varphi_{TOT} = D_{disc}\varphi_{disc} + D_{edge}\,\varphi_{edge}$$
$$= Af^{B} + d\varepsilon\varphi_{edge}$$

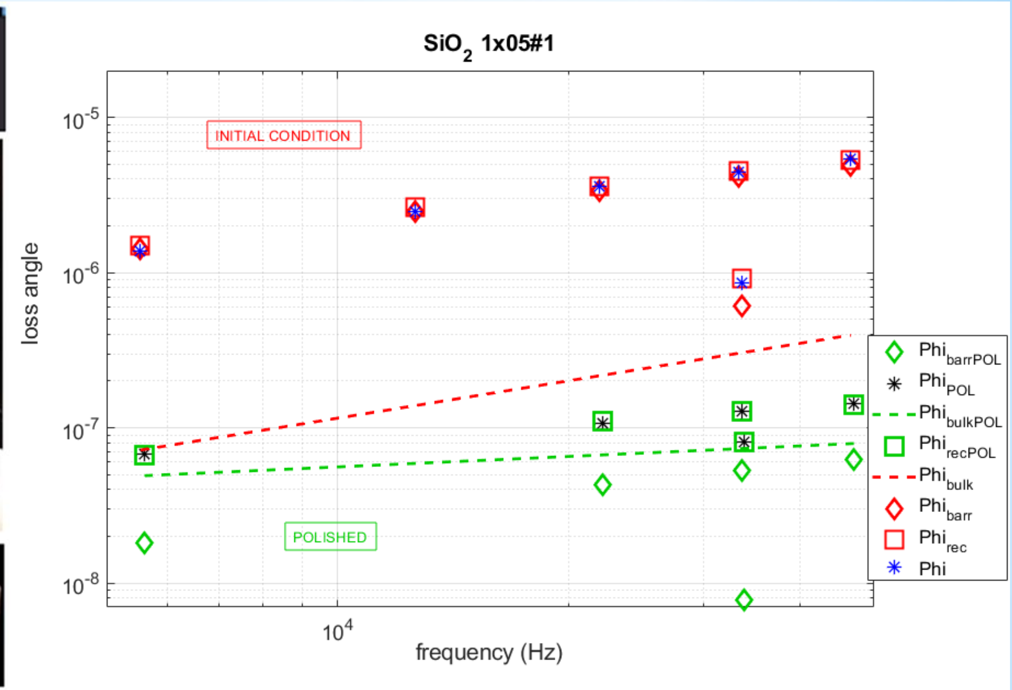
$$D_{edge} = \frac{E_{edge}}{E_{Tot}} = \varepsilon d$$



$$\varepsilon = \lim_{d\to 0}\frac{1}{d}\frac{E_{edge}}{E_{Tot}}$$

* CO_2 laser polishing and annealing in ToV





CO_2 laser polishing reduces **ageing effect** and the stability of the sample is guaranteed. Stability of the substrate loss checked after 1 year.

D.Lumaca et al., *Stability of samples in coating research: from edge effect to ageing*, to be submitted in Classical Quantum Gravity

A. Amato et al., *Edge effects in coating materials*, to be submitted in Classical Quantum Gravity

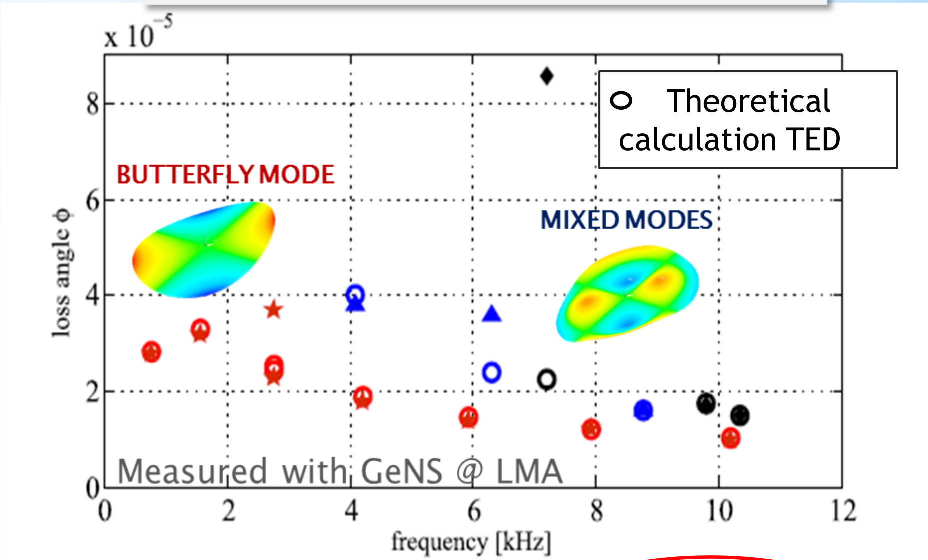
Knowledge of the substrate

Crystalline materials (Silicon and Sapphire)

* Potential bulk materials that will be used in cryogenic detectors are **silicon** and **sapphire**.
* In **thin silicon/sapphire discs**, at acoustic frequencies, the main contribution to the substrate loss is expected to be due to **thermoelastic loss** (Zener 1937)
* The **ratio between the dilation and total energy** (**D_{dil}**) is influenced by the mode shape: the thermoelastic loss must show **a branching behaviour**, depending on mode families and must be obtained using FEM.

G. Cagnoli et al., *Mode-dependent mechanical losses in disc resonators*, Phys. Lett A, 2017

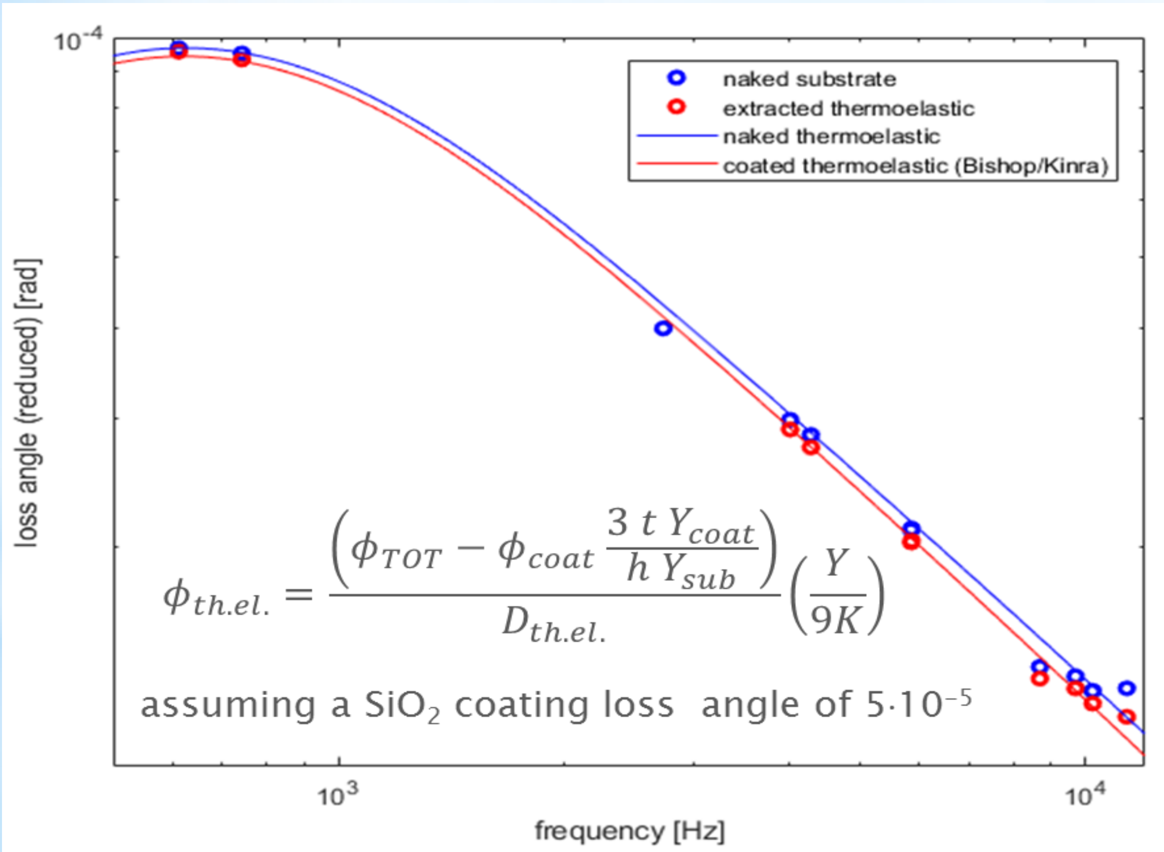
Si <100> wafer #7 (75,9 mm x 458 µm)



$$\phi_{D,\text{th.el.}} = \mathbf{D}_{\text{dil}} \cdot \phi_{\text{th.el.}} = \mathbf{D}_{\text{dil}} \cdot \frac{(3\alpha)^2 K T_0}{c_V} \, \frac{\omega \omega_{peak}}{\omega^2 + \omega_{peak}^2}$$

$$\mathbf{D}_{\text{dil}} = \frac{(1+\nu)(1-2\nu)}{3(1-\nu)} \times \frac{\iint (W_{xx}+W_{yy})^2 \, dx\, dy}{\iint \{(W_{xx}+W_{yy})^2 - 2(1-\nu)[W_{xx}W_{yy} - W_{xy}^2]\} \, dx\, dy}$$

* Thermoelastic damping of the substrate is affected by **coating deposition** (*Bishop J E and Kinra V K Mech. Comp. Mater. Struct. 3 83-95,1996)*



OBSERVATION: looking at coated samples the Quality factor decreases instead of increasing determining a negative coating loss angle

W13014 silicon disc 0.468 mm thick, 2.22 micron SiO2 coating on both surfaces measured at LMA

* Knowledge of the substrate
Crystalline materials (Silicon and Sapphire)

Tests on first monolayer prototype

Silica monolayer from Sannio Coater

Substrate:

Silicon <100> #1

- ✓ 1'' diameter
- ✓ 0.5 mm thickness
- ✓ No treatments

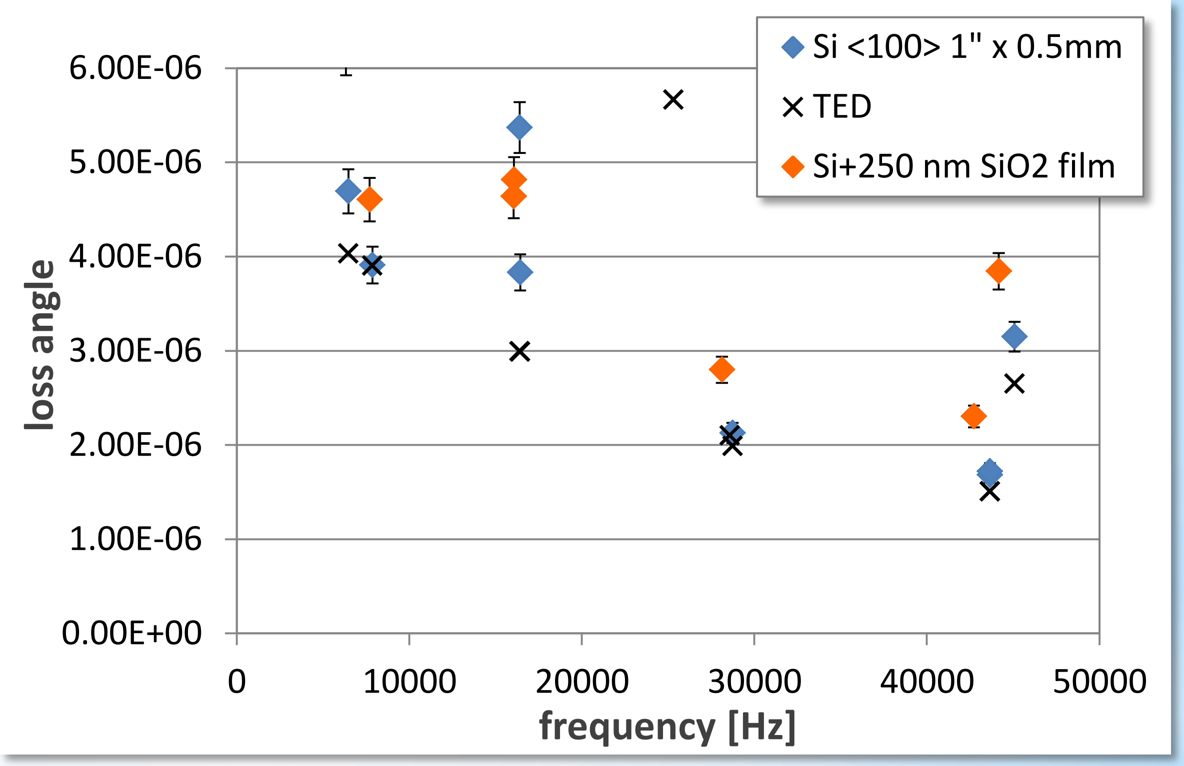
Coating:

SiO_2

Monolayer 250nm

With plasma (800W)

Loss angle measurements



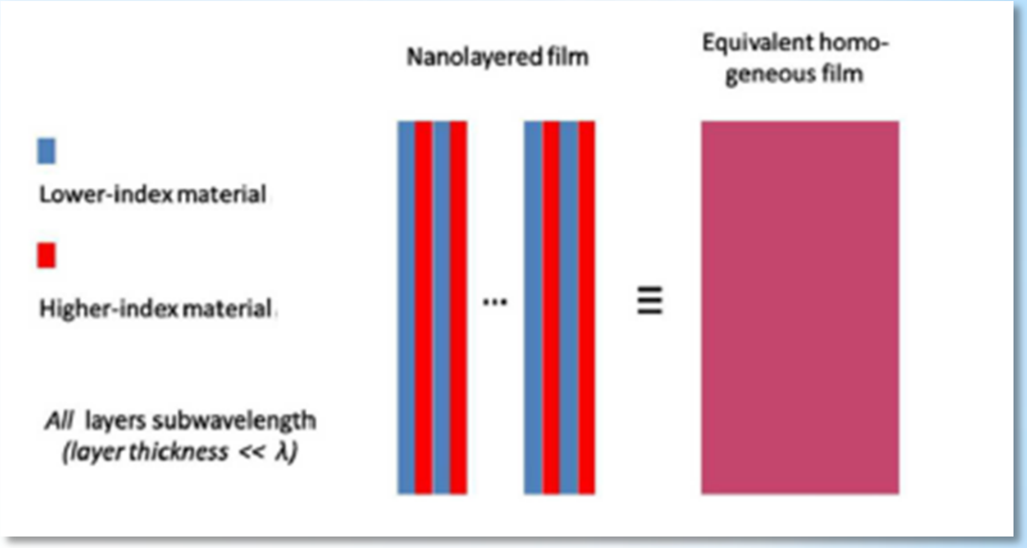
$\phi_{film} = (1.02 \pm 0.10) \cdot 10^{-4}$

As deposited

Same value in literature

*Planned activities for new year

Prototype equivalent (same refractive index and ¼ wavelength) **nanolayered films**, differing in number/thickness layer, and measure to hinder crystallization upon annealing:



- Maximum temperature before crystallization
- Quality factor
- Optical quality
- Surface quality

* List of material binary nanolayered deposition:
  high refractive index (Silica/Titania, Silica/Zirconia, Silica/Hafnia, Silica/Niobia, Silica/ Tantala);
  low refractive index (Silica/Alumina);

* New nanolayered coating

* The **anelastic behaviour** of amorphous materials is explained by the presence of a number of metastable states. Any two of these states that are separated by an energy barrier is called a **Two Level System (TLS)**.
* In order to reduce the loss angle of amorphous materials two basic ideas can be pursued:

1) a reduction of the **total number density** of TLS;

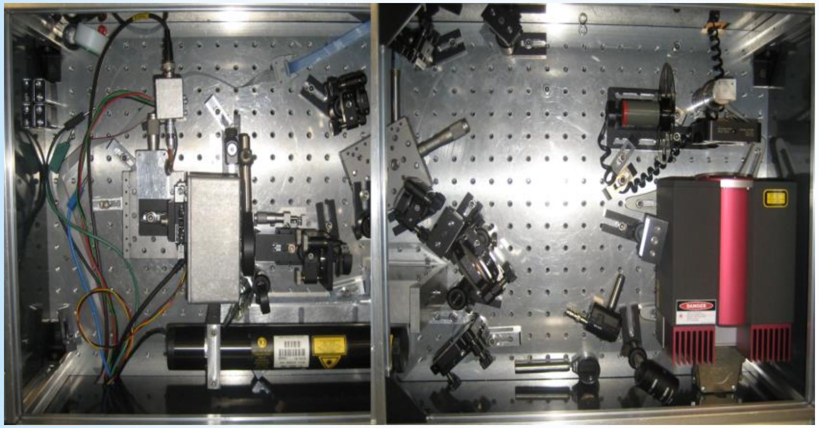
2) an **optimal distribution** of TLS.

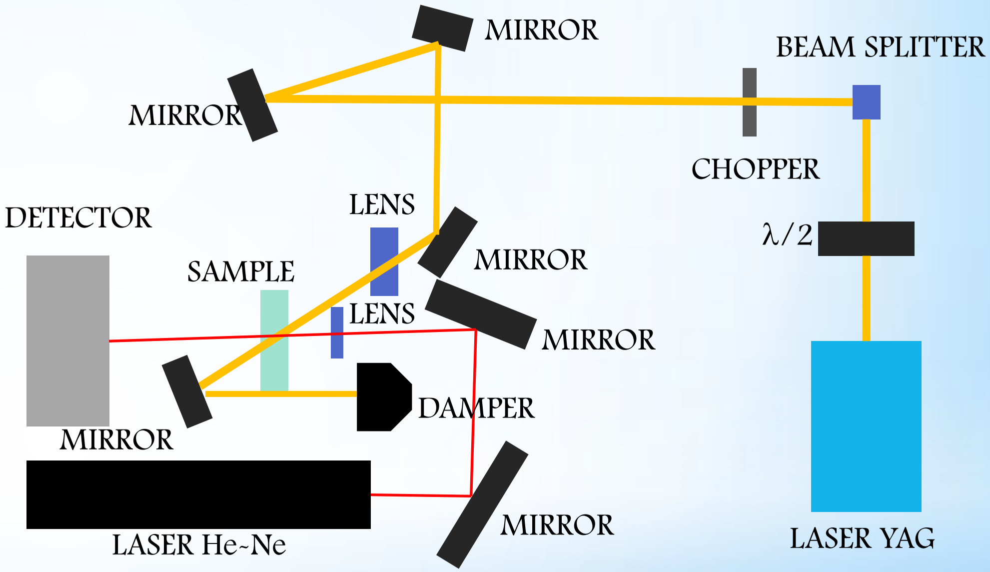
* Depositing amorphous films whose molecular **coordination number** is superior than 3 should lead to a low number of TLS. Indeed, if an atom is linked on 2 other atoms, local structural rearrangements can occur. Whereas, if this atom is linked to at least 3 atoms, the structure is more rigid and TLS are unlikely. This idea is known as the **Phillips' conjecture**.
* **Monolayer of ZnS** (500+/-0.2 nm) has been purchased and will be characterized soon (loss angle measurements and XRD analyses to look at crystallization)

* High coordination number materials

*Facility developments

* Absorption measurements :low optical absorption measurement (until 1 ppm) of thin film layer @1064 nm through **thermal deflection spectroscopy system (PDS)**, with a custom made remotely controlled set up developed by me is now @EGO. Need to be upgraded.



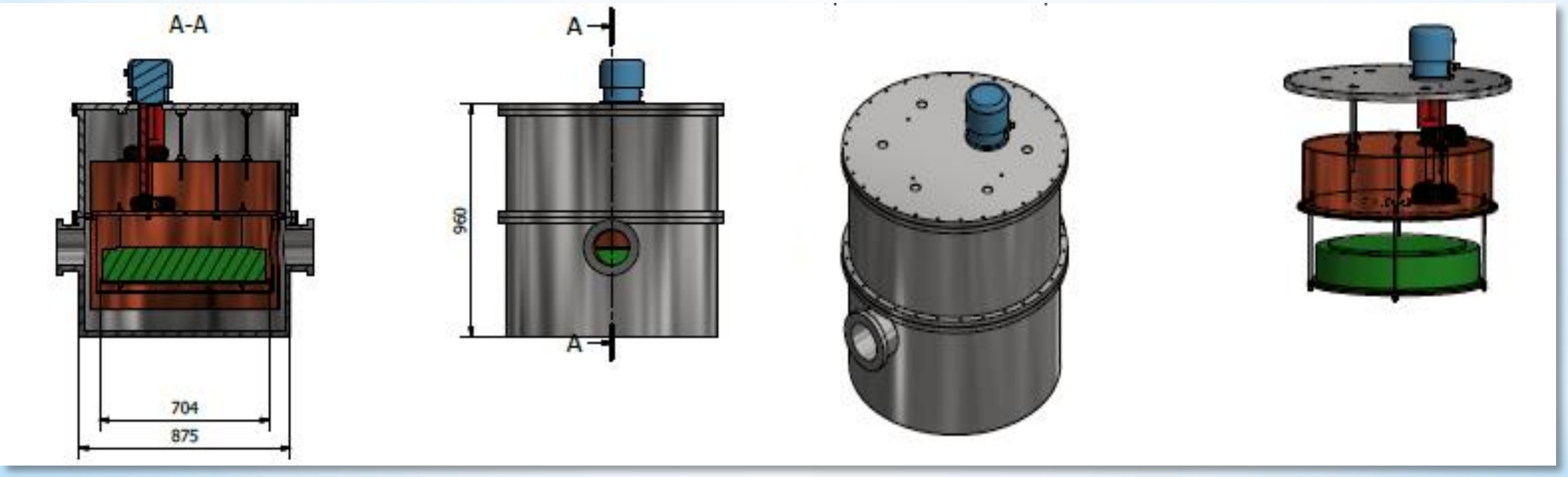


PROTOTYPE:

- Low power pump laser 0.5W @1064nm
- No isolation system

* Future development

* Loss Angle measurements at cryogenic temperature with a GeNS set up working at low temperature (cryostat and pulse tube *Sumitomo SHI Cryocooler* already purchased)
* Capacitive read out system could be implemented



* Future development

* **Direct measurement of thermal noise**: a project has been submitted to CSN5 (not funded, but the plan and budget are ready), called **DAMeN** (direct Analysis of Mechanical Noises)
* A table top facility for the direct measurement of TN using an innovative **quadrature phase differential interferometer**. The working principle of this facility is based on the measurement of the phase lag of two beams reflected by a micro-cantilever. This scheme relies on the measurement of the optical path difference between a sensing and a reference beam reflected by points, respectively, at the free end and close to the clamping base of a micro-cantilever. Being the **interferometer** nearly a **common path** one, the sensitivity to external vibrations or drifts is strongly reduced.
* This setup is versatile allowing characterization of many materials and can be suitable to measure not only TN in substrates and coatings, but also generic mechanical noises.

Future development

*Thanks for your attention

* Pubblication, conferences and collaborations

* **List of conferences with oral contribution:**

1. Ligo-Virgo collaboration meeting, CERN Geneve
2. Virgo collaboration Meeting, EGO Cascina(PI)
3. GRASS conference, Padova

* **Papers: 12 for LVC and 3 more:**

1. Cagnoli, G., Lorenzini, M., Cesarini et al. *Mode-dependent mechanical losses in disc resonators* (2018) Physics Letters A, 382 (33), pp. 2165-2173. DOI: 10.1016/j.physleta.2017.05.065
2. Lumaca D., Cesarini E., Lorenzini M. et al. *Stability of samples in coating research: from edge effect to ageing* to be submitted in Classical Quantum Gravity
3. Amato A., Lumaca D., Cagnoli G., Cesarini E. et al. *Edge effects in coating materials* to be submitted in Classical Quantum Gravity

* **Collaborations:**

1. Virgo Coating R&D (VCRED)
2. LIGO-Virgo Optics Working Group

* Pubblication, conferences and collaborations

1. KAGRA, LIGO Scientific Collaboration e Virgo Collaboration (Abbott B. et al.) Prospects for observing and localizing gravitational-wave transients with Advanced LIGO, Advanced Virgo and KAGRA (2018) Living Reviews in Relativity, 21 (1) DOI: 10.1007/s41114-018-0012-9
2. Cagnoli, G., Lorenzini, M., Cesarini, E., Piergiovanni, F., Granata, M., Heinert, D., Martelli, F., Nawrodt, R., Amato, A., Cassar, Q., Dickmann, J., Kroker, S., Lumaca, D., Malhaire, C., Rojas Hurtado, C.B. Mode-dependent mechanical losses in disc resonators (2018) Physics Letters, Section A: General, Atomic and Solid State Physics, 382 (33), pp. 2165-2173. DOI: 10.1016/j.physleta.2017.05.065
3. LIGO Scientific Collaboration e Virgo Collaboration (Abbott B. et al.) Search for Tensor, Vector, and Scalar Polarizations in the Stochastic Gravitational-Wave Background (2018) Physical Review Letters, 120 (20), art. no. 201102, . DOI: 10.1103/PhysRevLett.120.201102
4. LIGO Scientific Collaboration e Virgo Collaboration (Abbott B. et al.) Full band all-sky search for periodic gravitational waves in the O1 LIGO data (2018) Physical Review D, 97 (10), art. no. 102003, . DOI:10.1103/PhysRevD.97.102003
5. LIGO Scientific Collaboration e Virgo Collaboration (Abbott B. et al.) Constraints on cosmic strings using data from the first Advanced LIGO observing run (2018) Physical Review D, 97 (10), art. no. 102002, . DOI:10.1103/PhysRevD.97.102002
6. LIGO Scientific Collaboration e Virgo Collaboration (Abbott B. et al.) GW170817: Implications for the Stochastic Gravitational-Wave Background from Compact Binary Coalescences (2018) Physical Review Letters, 120 (9), art. no. 091101, . DOI: 10.1103/PhysRevLett.120.091101
7. LIGO Scientific Collaboration e Virgo Collaboration (Abbott B. et al.) Effects of data quality vetoes on a search for compact binary coalescences in Advanced LIGO's first observing run (2018) Classical and Quantum Gravity, 35 (6), art. no. 065010, . DOI: 10.1088/1361-6382/aaaafa
8. LIGO Scientific Collaboration e Virgo Collaboration (Abbott B. et al.) All-sky search for long-duration gravitational wave transients in the first Advanced LIGO observing run (2018) Classical and Quantum Gravity, 35 (6), art. no. 065009, . DOI: 10.1088/1361-6382/aaab76
9. LIGO Scientific Collaboration e Virgo Collaboration (Abbott B. et al.) First Search for Nontensorial Gravitational Waves from Known Pulsars (2018) Physical Review Letters, 120 (3), art. no. 031104, . DOI:10.1103/PhysRevLett.120.031104
10. LIGO Scientific Collaboration e Virgo Collaboration (Abbott B. et al.) Prospects for observing and localizing gravitational-wave transients with Advanced LIGO, Advanced Virgo and KAGRA (2018) Living Reviews in Relativity, 21 (1), art. no. 3 DOI: 10.1007/s41114-018-0012-9
11. LIGO Scientific Collaboration e Virgo Collaboration (Abbott B. et al.) GW170817: Measurements of Neutron Star Radii and Equation of State (2018) Physical Review Letters, 121 (16), art. no. 161101, DOI: 10.1103/PhysRevLett.121.161101
12.Virgo Collaboration (Acernese F. et al.) Calibration of advanced Virgo and reconstruction of the gravitational wave signal h(t) during the observing run O2 (2018) Classical and Quantum Gravity, 35 (20), art. no. 205004, .
DOI: 10.1088/1361-6382/aadf1a
13. Virgo Collaboration (Acernese F. et al.) Status of advanced virgo (2018) EPJ Web of Conferences, 182, art. no. 02003, DOI: 10.1051/epjconf/201818202003