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# Film Sottili-
## Optical Thin Films

E. Cesarini, M Bazzan, M. Magnozzi

15-16 Feb 2023 ETIC Industrial Day

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# Coating Thermal Noise

- Coating thermal noise (CTN) limits the detection of GW detectors in the middle frequency bandwidth
- The key parameters are:

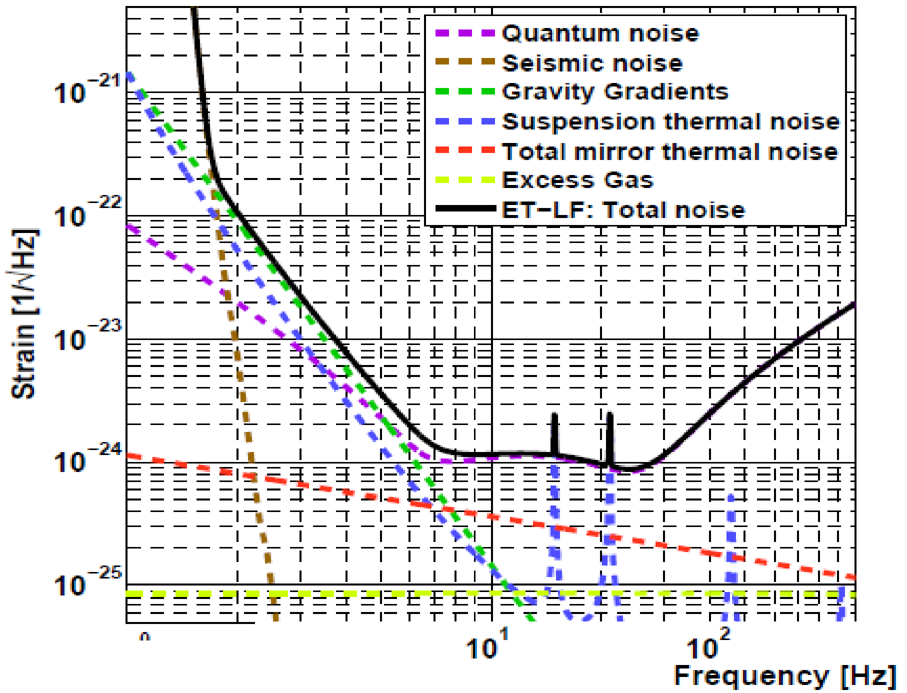
**The thermal noise performance of a coating can be related to its mechanical properties.**

$$\mathrm{CTN}(f) \propto \sqrt{\frac{\frac{T}{f}\,\frac{1}{{w_b}^2}\,\varphi\, t_{coat}}{L}}$$

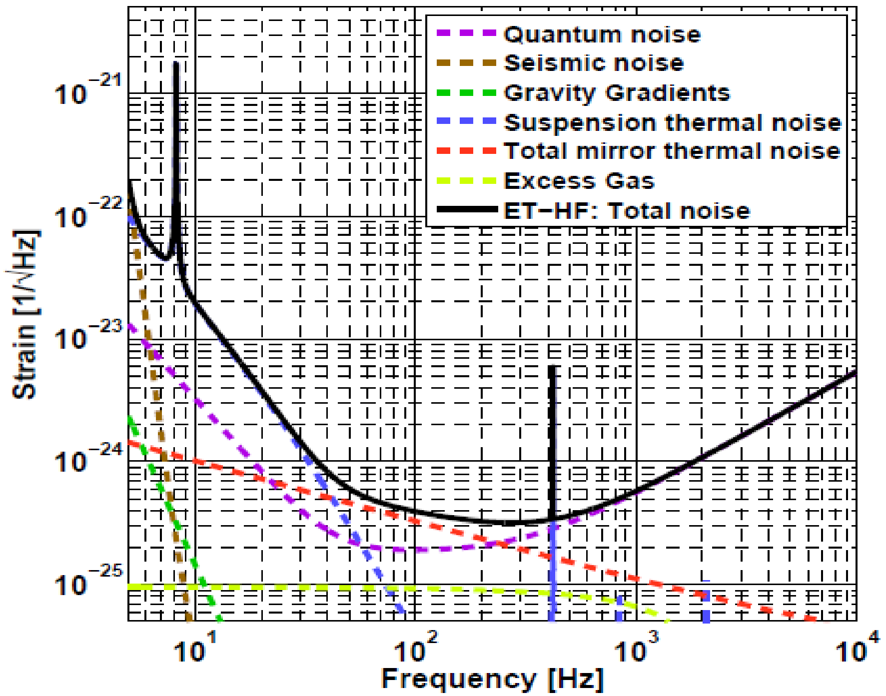
- TEMPERATURE on MIRROR → $T$
- COATING MECHANICAL LOSS (depends on material properties) → $\varphi$
- COATING THICKNESS (depends on reflectivity and refractive indices) → $t_{coat}$
- BEAM-SIZE on MIRROR → $w_b$
- ARM LENGTH → $L$

# Coating Thermal noise in Einstein Telescope

Cooling at low temperature (10K 20K or 120 K?) means reduce thermal noise at its origin.




**Sensitivity curve LF-ET**



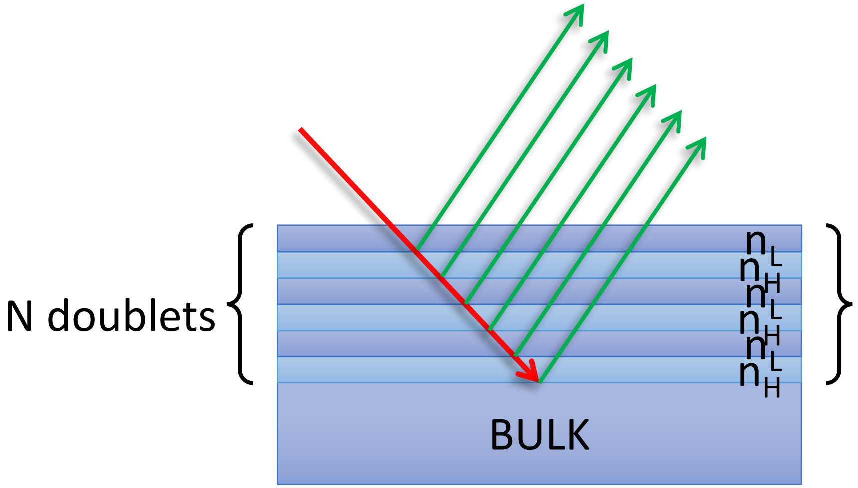

**Sensitivity curve HF-ET**

Different laser wavelength, different materials. take absorption under control and allow **cryogenics operation**

Same wavelength, substrate material and temperature as LIGO and Virgo detectors. New coating materials to **tolerate high laser power**

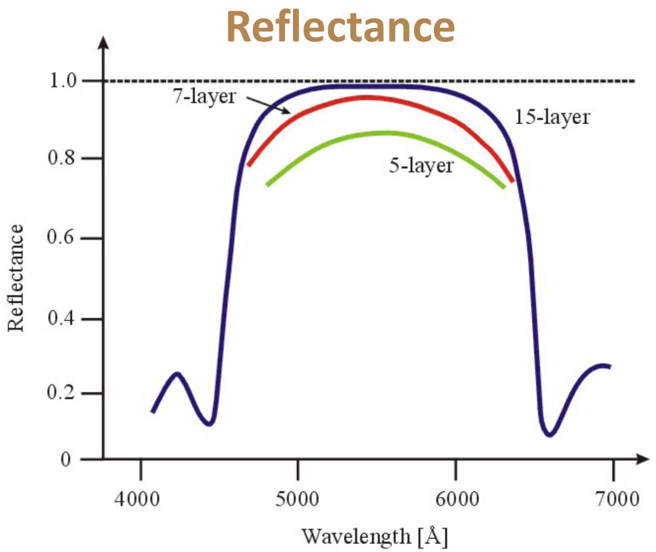
# Mirror Coatings basics

Gravitational wave mirrors are made of :
bulk material + multi-layer reflective coatings




## *Bragg reflectors*

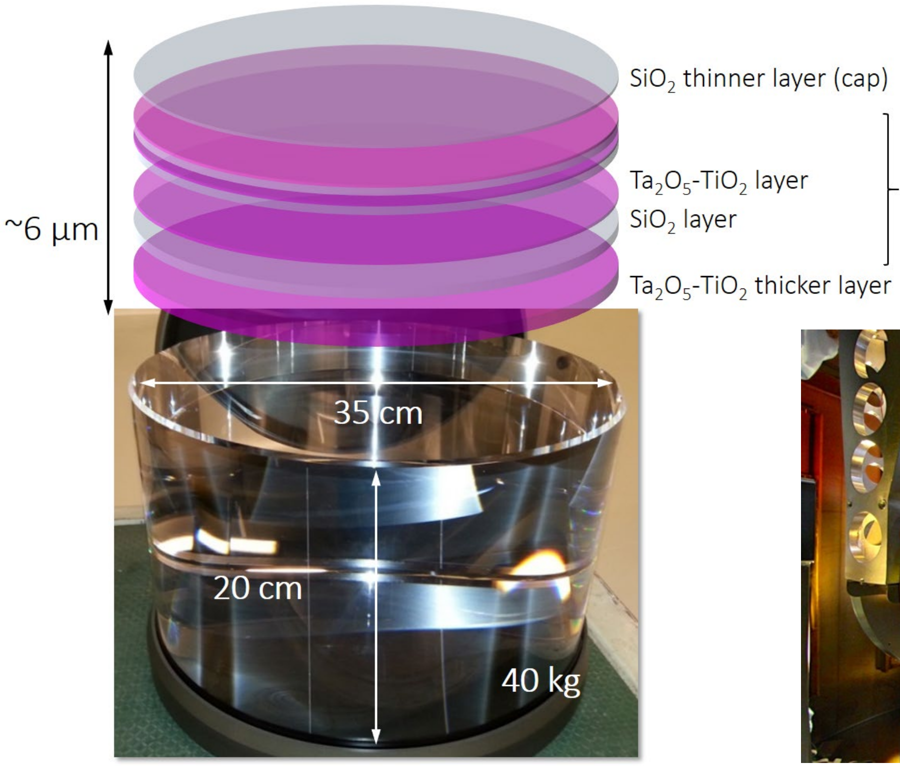
- A stack of alternate layers of high- and low- refractive index materials
- Accurate choice of thickness (order of lambda/4)
  - Constructive interference
  - High-quality reflector

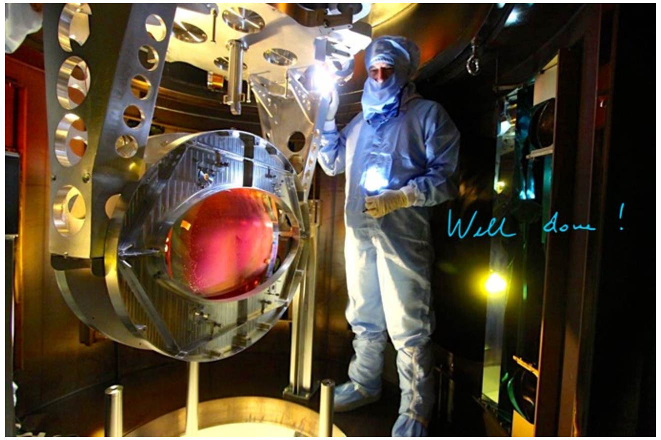



$$R = |r^2| = \frac{1 - n_{sub}\left(\frac{n_L}{n_H}\right)^{2N}}{1 + n_{sub}\left(\frac{n_L}{n_H}\right)^{2N}}$$

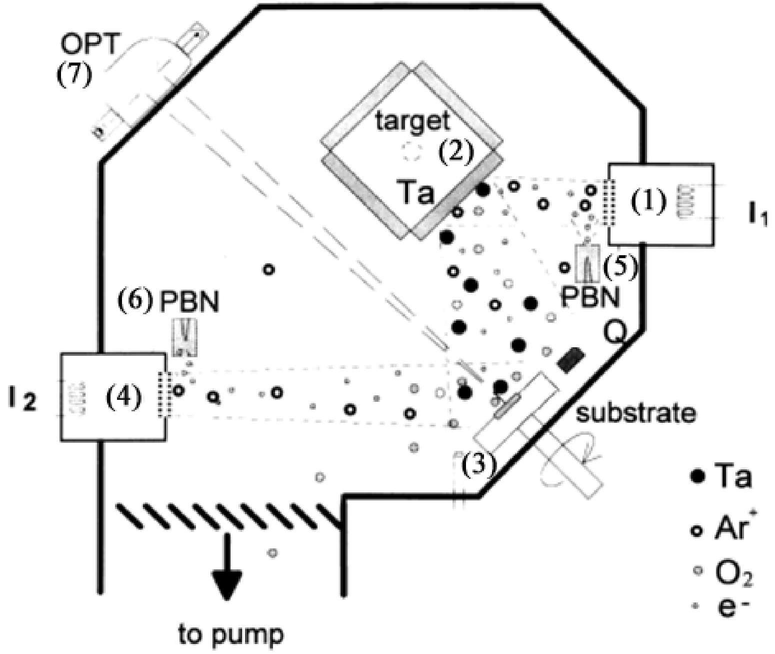
# State of the Art (Virgo/LIGO)

| |
|---|
| Silica SiO2 n=1.45 |
| Tantala TiO2:Ta2O5 n=2.09 |




*Ion Beam Sputtering (IBS) deposition*
*at Laboratoire de Materiaux Avances, in Lyon.*



# Mirror Coatings basics



## Requirements:

### MECHANICAL PROPERTIES

- ➢ Low coating thermal noise (CTN):
  - linked to mechanical dissipation
  - Material research

### OPTICAL PROPERTIES

- ➢ Low scattering (from e.g. defects or micro-roughness or micro-crystals)
  - To avoid diffused light in the ITF
  - only purely amorphous or single-crystalline materials are suitable
- ➢ Low optical absorption: below 1 ppm ($10^{-6}$)
  - to avoid thermal effects in HPO
  - To avoid heating in cryogenic detectors

| Flatness | Thickness uniformity | Absorption | Scattering |
|---|---|---|---|
| <0.5 nm RMS (within ⌀ 150 mm) | 0.05 % (within ⌀ 150 mm) | <0.4 ppm | <10 ppm |

The optical losses in a cavity are due to:
- diffraction at low spatial frequency (depending on flatness)
- scattering at high spatial frequencies (depending on micro-roughness)
- absorption in the coating/substrate
- punctual defects on the mirror surface, scratches, digs and points defects.

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# Mechanical Properties

Essential quantities to characterize the dissipative behavior of materials:

***Quality factor*** ➡ $$Q \equiv 2\pi \frac{E_{tot}}{E_{diss}}$$

Systems with high dissipations have low and larger off-resonance contribution, and viceversa

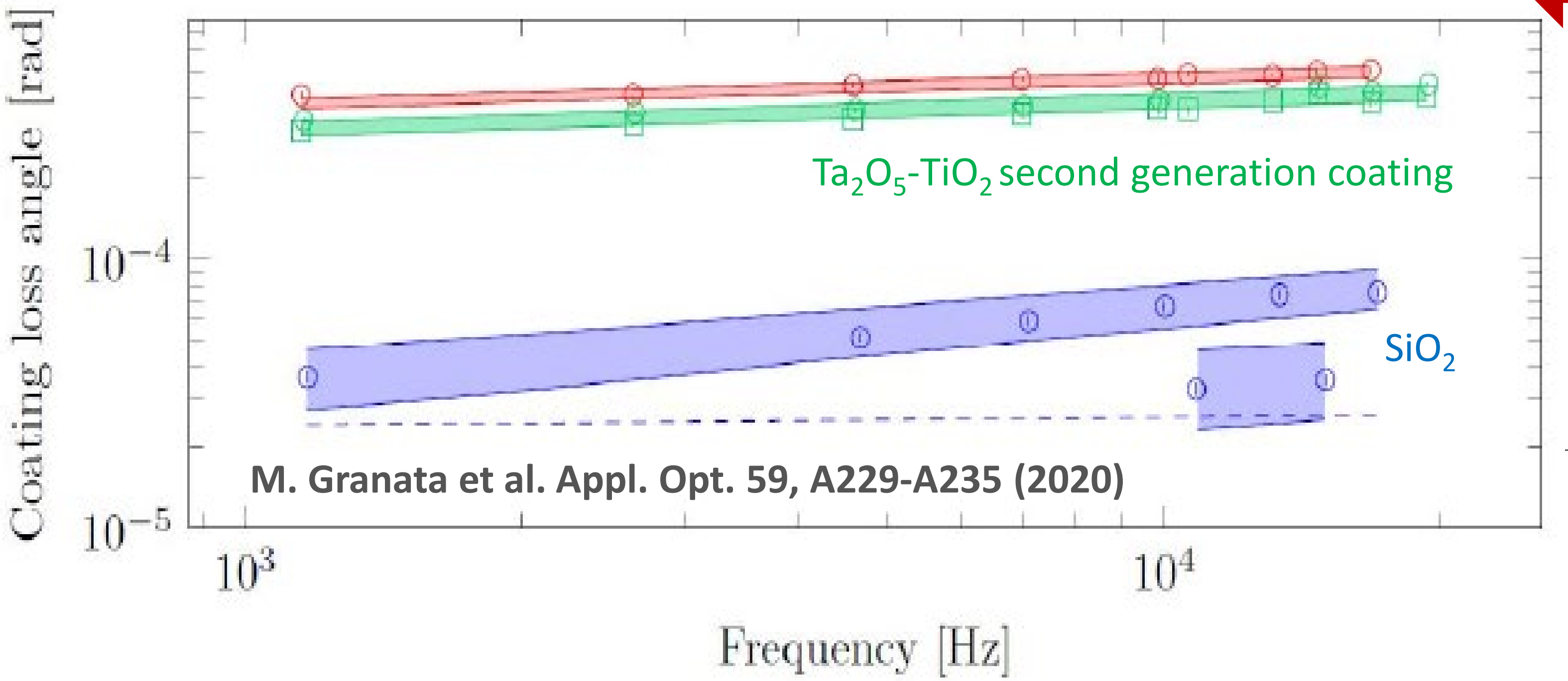
A system is dissipative whenever its response to a step input is characterized by a finite *relaxation time*

- Phase lag between input and response ***Loss angle*** ➡ $$\varphi(\omega) = \frac{1}{2\pi} \frac{E_{diss}}{E_{tot}}$$
- At resonance ➡ $$\varphi(\omega_0) = \frac{1}{Q}$$
- Additive quantity

Any physical system can be composed by many different parts (i), whose stored energies (s) can be dissipated by many different mechanisms:

- Structural losses
- Thermo-elastic losses
- Thermo-optic losses
- Surface losses

# State of the Art (Virgo/LIGO) – mechanical properties




Lossy material

Loss angle dependent from frequency in a simple form in amorphous material: $\varphi = a \cdot f^b$

Elastic parameters

| Coating material | $Ta_2O_5$-$TiO_2$ | $SiO_2$ |
|---|---|---|
| $n$ (at 1064 nm) | 2.09±0.01 | 1.45±0.0 |
| $\rho_c$ [g/cm$^3$] | 6.65±0.07 | 2.20±0.04 |
| $a$ [$10^{-4}$ rad Hz$^{-b}$] | 1.43±0.07 | 0.20±0.04 |
| $b$ | 0.109±0.005 | 0.030±0.024 |
| $\mathcal{Y}_c$ [GPa] | 120±4 | 70±1 |
| $\nu_c$ | 0.29±0.01 | 0.19±0.01 |

**Table 3.2:** Optical and mechanical parameter of present coating materials [79]: the loss angle can be extrapolated from $a$ and $b$ parameters and is based on the frequency dependence $\phi_{coat}(f) = af^b$.

# Origin of Absorption

## Material Choice

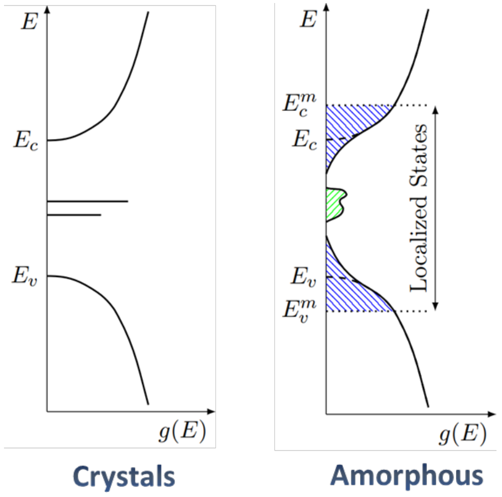
- **Energy bandgap** need to be high enough to be transparent at the used wavelength
- **Refractive index** need to be high enough to guarantee a high optical contrast and small thickness of layers

## Optical Absorption origin

- There is not yet a well-established model
- Target values for each material are given by the cristalline form
- Amorphous structure produces localized states in the band gap
- the bandgap needs to be clean of electronic states

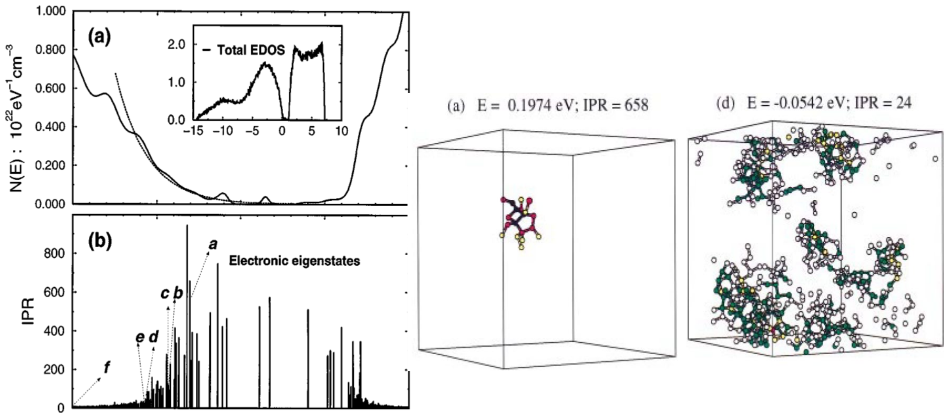
## Possibles causes

- Wrong **stoichiometry**
- Presence of **contaminants**
- Presence of **structural defects**




Atomistic Structure of Band-Tail States in Amorphous Silicon

Jianjun Dong and D. A. Drabold



# Dedicated Coating Chambers

The coaters must be able to:

- Produce samples of diameter 2" or 3"
- Limiting contamination (by residual water vapor and other gases, or by the noble gases used for ion beams).
- Controlling the final stoichiometry
- Involve deposition techniques with:
  - high vacuum,
  - high temperature
  - exploration of ternary systems
- Involve a  full set of in-situ characterization facilities:
  - ellipsometer,
  - stress monitor,
  - residual gas analyzer and/or mass spectrometer,
  - optical plasma monitoring systems.

# Multi-technique investigation

- The absorption in thin films is determined by an interplay of several factors (stoichiometry; contaminants; films homogeneity; …)
- The investigation of the origin of absorption involves (at least) three domains

**Optical properties**

| Quantity | Technique |
|---|---|
| n | Spectrophotom.<br>Ellipsometry |
| k | Spectrophotom.<br>Phototherm. defl.<br>Ellipsometry |
| gradient | Spectrophotom.<br>Ellipsometry |

**Chemical/compositional properties**

| Quantity | Technique |
|---|---|
| Stoichiometry,<br>H content,<br>O content,<br>Contaminants | EDX<br>XPS<br>"<br>Raman<br>FTIR<br>RBS<br>SIMS<br>ERDA<br>**XRD** |

**Morphological/structural properties**

| Quantity | Technique |
|---|---|
| Thickness | Spectroph.<br>Ellipsom. |
| Surface analysis | SEM<br>AFM |

# Possible new coating materials under investigation

- Oxides
- HCNG: Nitrides (SiN, GaN), Semiconductors (a-Si, GaP, AlP, InP, GaAs, CdTe, AlSb ) high coordination number makes atom structure more rigid decreasing TLS density low loss dissipation
- Multimaterial Coating or ternary coatings: multi-material coatings with mixed-oxydes (Ti-Si, Ti-Ge, Ti-Ta, Zr-Ta,…) or ternary coatings in which the top layers, where the optical intensity is highest, consist of materials with low optical absorption but too large mechanical loss, while the lower layers consist of materials with low mechanical loss but too large optical absorption (based on nitrides, oxides or a-Si)
- Crystalline Coating – Semiconductor or Oxides –: epitaxially grown coatings consisting of alternating layers of high and low index layers of crystalline materials present an alternative method. Those materials have much better mechnaical performances than amorphous ones, but are difficult to be fabricated over a large – area substrate

# GALILEO – Genova (ref Dott. Michele Magnozzi Michele.Magnozzi@edu.unige.it)

**Mission: fabricate and characterize high-quality, small-scale (2'' to 3'') sample coatings, with the aim to identify critical fabrication parameters and explore new candidate materials for GWD mirrors.**

Deposition machine:

- Ion Beam Sputtering
- Custom made
- Small, UHV custom chamber
- 2 sources+assist
- In-situ diagnostics (ellipsometry, QCM...)

Characterization tools:

- Ellipsometer in the IR
- Photothermal common-path interferometer

**700 k€ in TOT**

# GALILEO - Genova (ref Dott. Michele Magnozzi Michele.Magnozzi@edu.unige.it)

Items to be acquired for the Genova unit:

- Custom-made UHV chamber
- Ion guns
- High power pump laser, 1064 nm, CW (either 1W or 2W)
- Optical table
- Ellipsometer(s)
- Vacuum systems for IBS

New instrumentation will be hosted in existing labs, with minimal investment on infrastructures.

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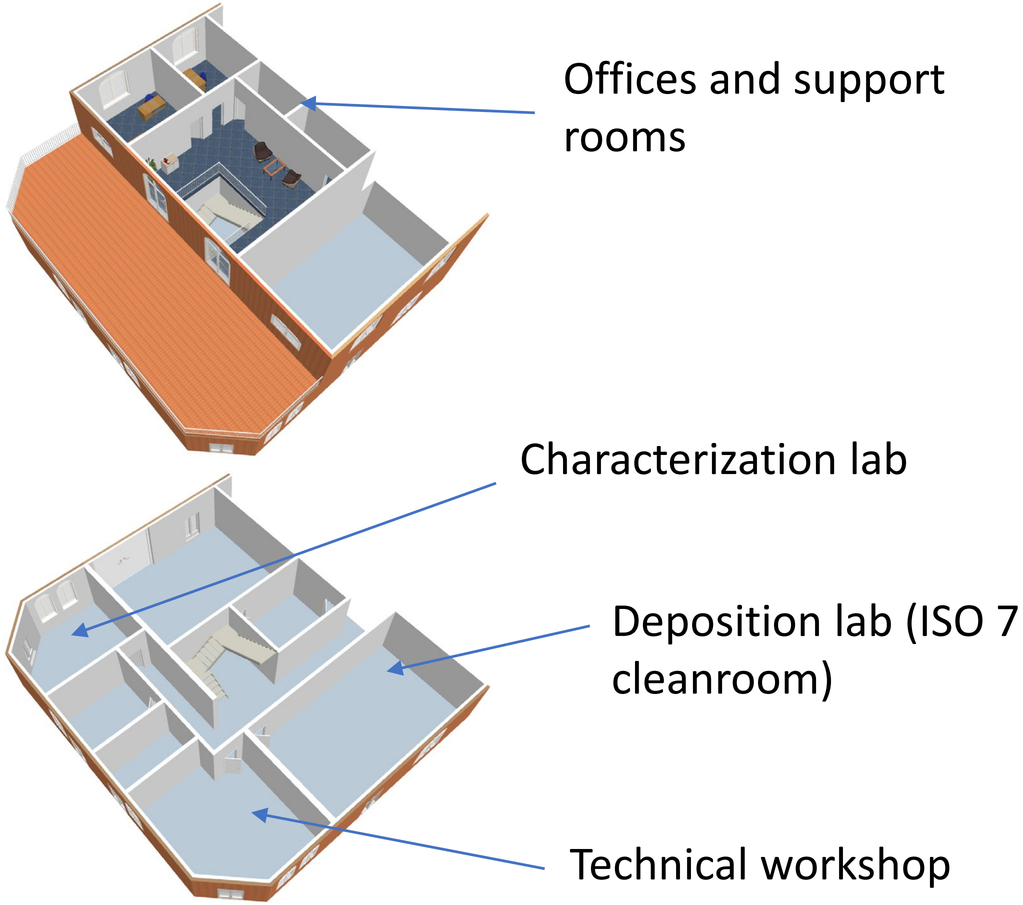
# CoMET – Padova (ref. Prof. Marco Bazzan marco.bazzan@unipd.it)




**MISSION: fabrication of small-scale (up to 3''), high quality coatings for research and exploration of new materials.**

- 250 m$^2$ total surface
- Two different production technologies (Magnetron Sputtering and Ion Beam Sputtering),
  - multi-element oxides, nitrides, semiconductors with controlled stoichiometry.
  - Possibility to increase the number of techniques.
- In-situ characterization techniques to monitor the deposition process.
- Equipped with characterization capabilities to guarantee the quality of the produced samples.
- Interactions with other local laboratories to further enhance the range of analytical techniques available.

# CoMET – Padova (ref. Prof. Marco Bazzan marco.bazzan@unipd.it)

The following equipment will be purchased to set up the CoMET laboratory

## Deposition technologies:

- **Clean room ISO 7 (50 m$^2$) 450 k€**
- **Magnetron sputtering** (high flexibility, up to 4 elements + reactive sputtering) **350-400 k€**
- **Ion Beam Sputtering** (high quality, up to 3 elements simultaneously+ reactive sputtering) **800-900 k€**

Both machines will be designed to enable in-situ characterization of the sputtering process (**500 k€**).

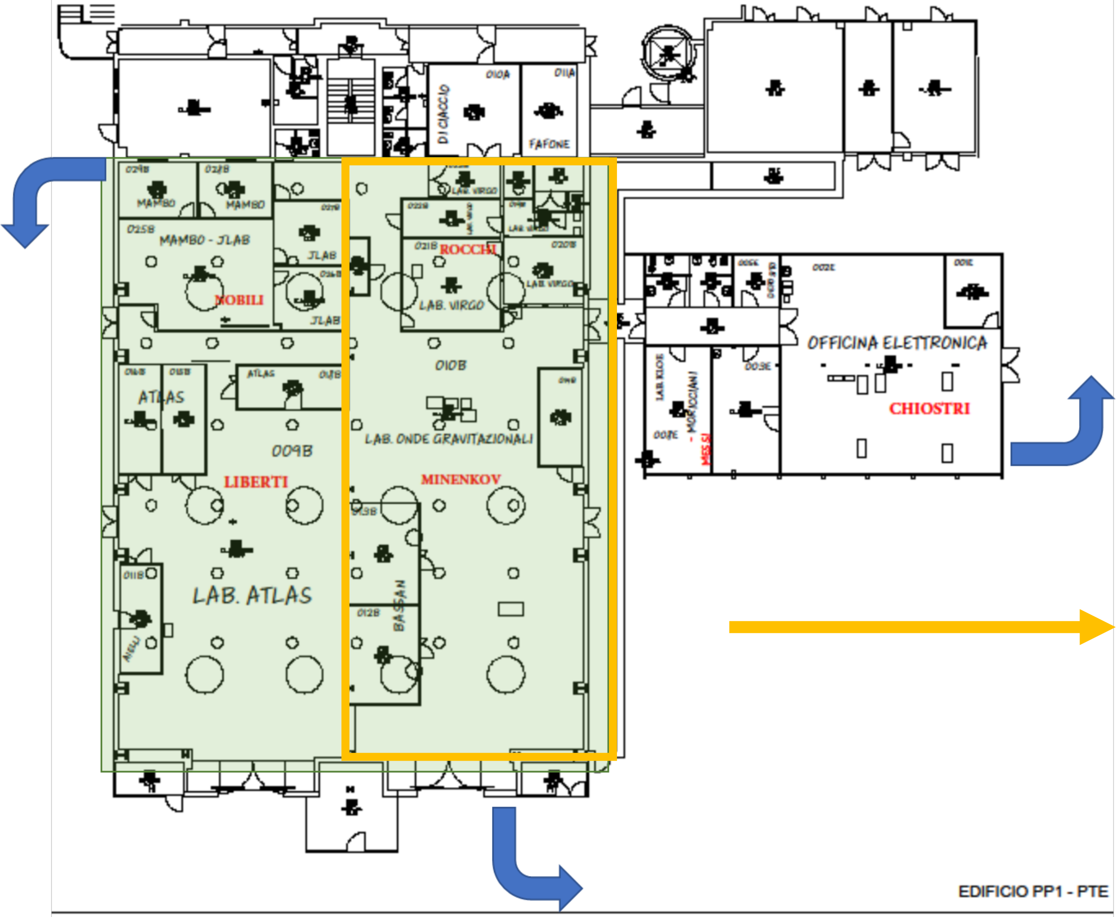
## Characterization technologies:

- Ellipsometer
- Atomic Force Microscope
- Cross section preparation + SEM
- Residual stress analysis
- X-Ray Diffraction and Reflectivity
- Light Scattering Analysis

**1 M€**

Available at the lab, will provide each sample with an ID card.

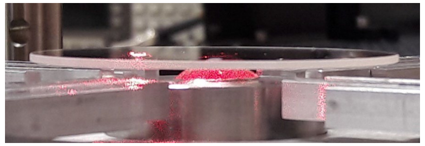
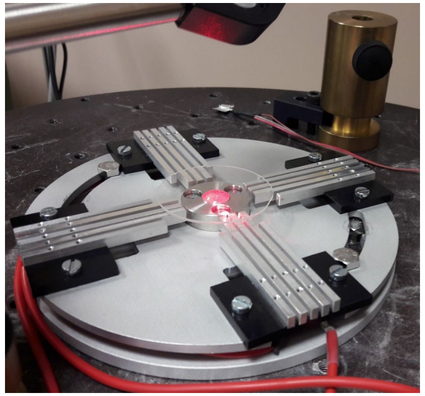
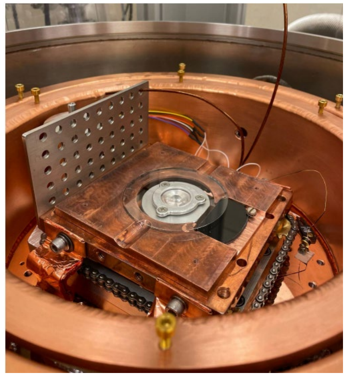
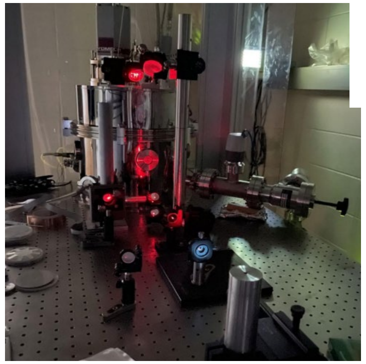
# AiLOV_ET – Roma Tor Vergata (ref. Elisabetta Cesarini elisabetta.cesarini@roma2.infn.it)




**COATING LAB:**
**r**esearch of innovative materials for the realization of the reflective coatings of the ET mirrors
**camera pulita ISO7**

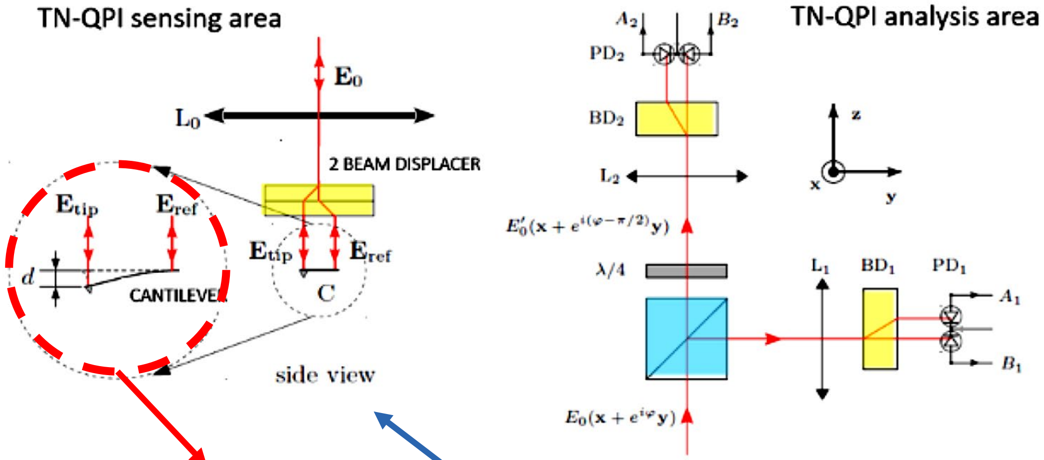
# AiLOV_ET Coating Lab (ref. Elisabetta Cesarini elisabetta.cesarini@roma2.infn.it)

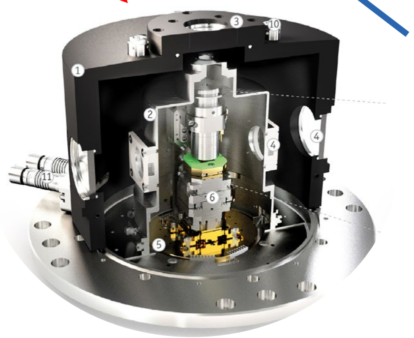
## Loss angle measurements

Gentle Nodal Suspension at low temperature

## Direct Thermal Noise measurement

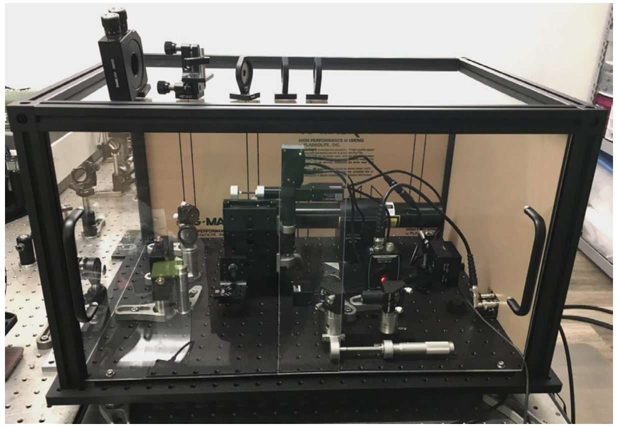


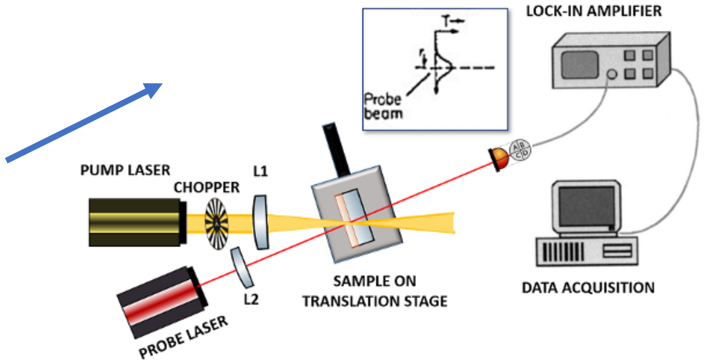



Quadrature phase interferometer

Collinear Photothermal deflection spectroscopy

## Optical Absorption Measurement





# Lista AiLOV_ET (ref. Elisabetta Cesarini elisabetta.cesarini@roma2.infn.it)

- Camera pulita ISO 7 + anticamera e spogliatoio (gara unica con la parte di correzione aberrazioni ottiche che prevede pure una camera grigia 300-400 k€ )
- Laser di pompa 2W (1064 nm, 1550 nm, 2 um) per sistema misura assorbimento
- Sistema per misura assorbimento tramite tecnica fototermica (ca. 70 k€)
- Banchi ottici con sistema di smorzamento alle vibrazioni e coperture
- Criostato ottico da banco per QPDI (4K, 6"-8" area piatto sperimentale freddo) (ca 60 k€)
- Camera criogenica (50-100 l) + tubo pulsato (doppio stadio fino a 4 K) + chiller (ca 150 k€)
- Cappa a flusso laminare verticale per pulizia e stoccaggio ottiche (almeno 2 m di lunghezza)
- Forno per trattamenti termici fino a 1200°C con possibilità di operare in atmosfera controllata

# GRAZIE PER L'ATTENZIONE

Alcuni punti critici che inizio a riscontrare:

- Offerte informali (che servono a stabilire la base d'asta) hanno validità limitata a 2-4 settimane, la tempistica non accorda con i tempi amministrativi per le gare
- Poiché tutti gli ordini devono essere avviati da ora al 31/12/23, la strumentazione potrebbe arrivare in sede quando ancora ci sono lavori di ristrutturazione e non sempre le strutture hanno adeguati magazzini

Quali le possibili soluzioni? Preventivi più alti che tengano conto delle fluttuazioni del mercato?
Mettere data di consegna posticipata già al momento dell'ordine?
Non tutte le ditte lo possono garantire!!!

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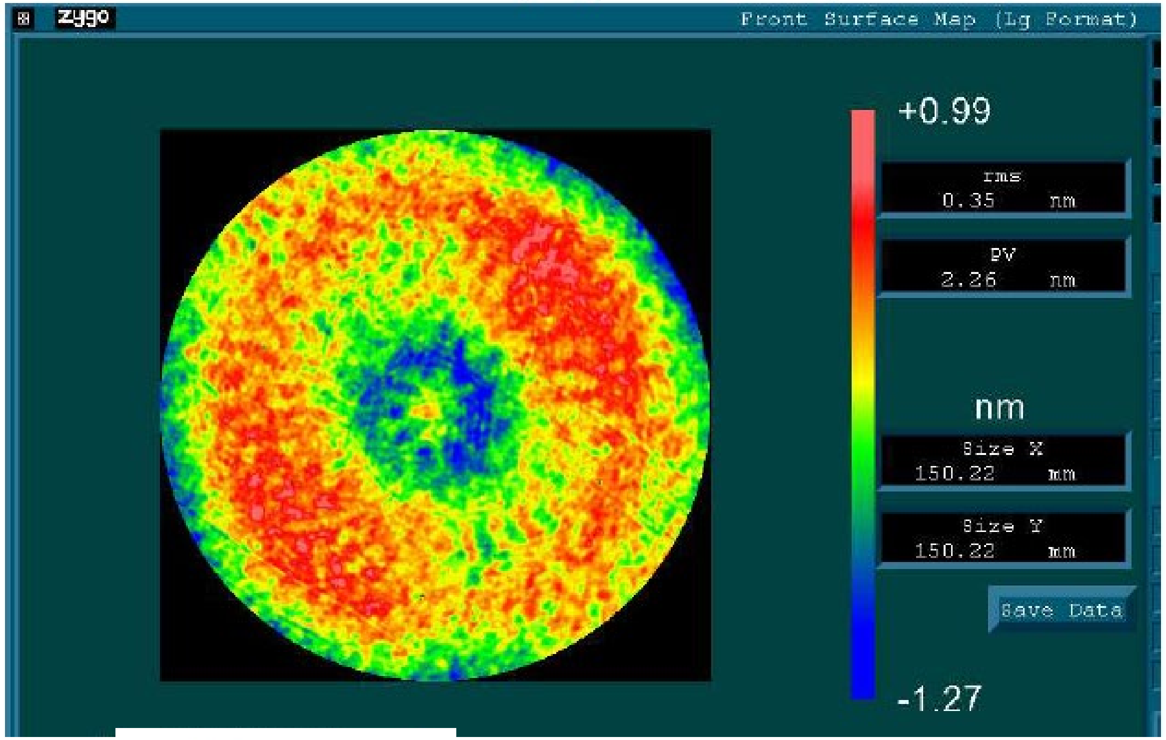
Logo

# State of the Art (Virgo/LIGO) – optical properties

**FLATNESS: Surface Roughness 0.35 nm RMS ⦰ 150 mm**

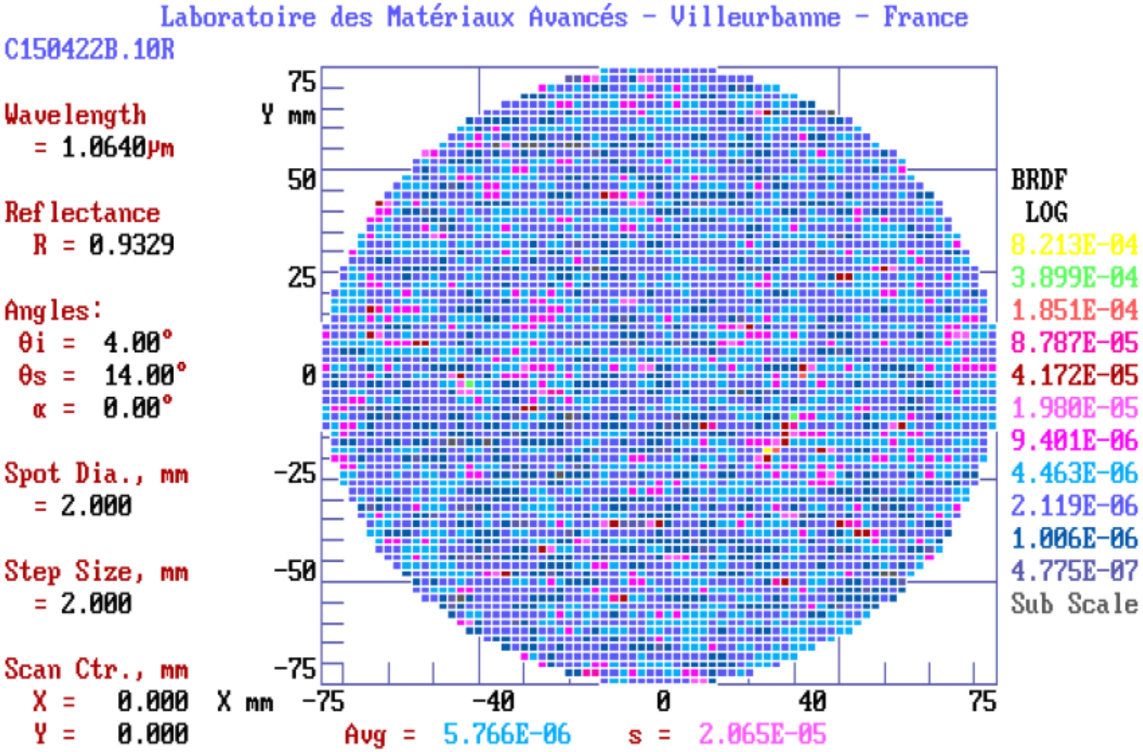
Wavefront Surface 1 (HR), incidence 0° (∅150 mm)




VIRGO

**SCATTERING: Scattering Surface 4° AOI ⦰ 150 mm Avg= 6 ppm**

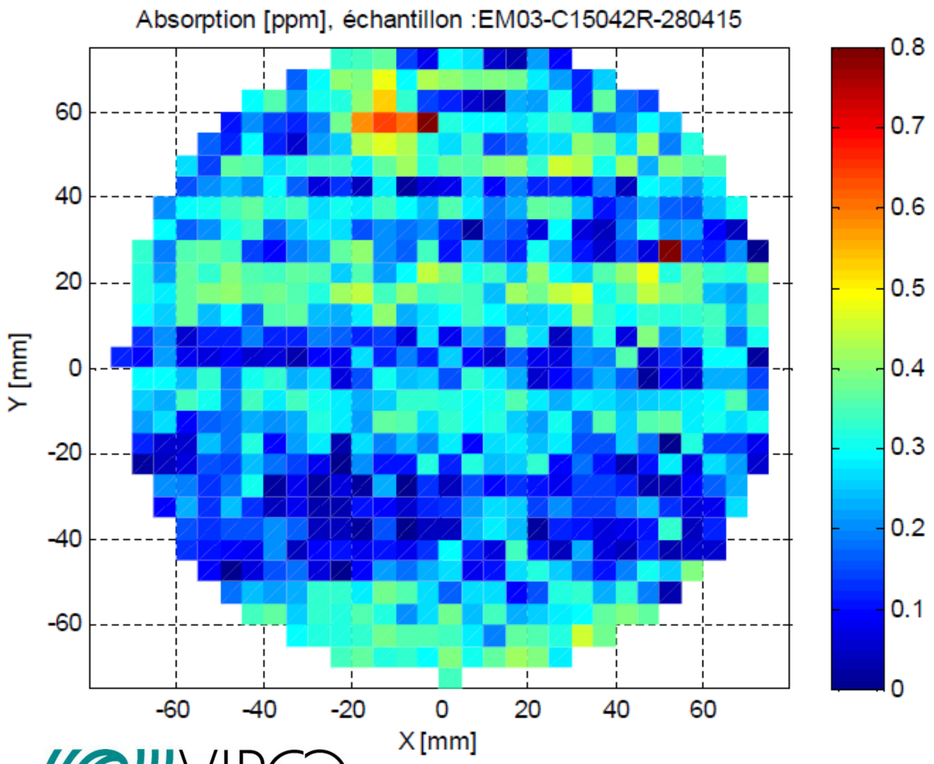
Average Scattering Surface 1 (HR), incidence 4° (∅150 mm)



# State of the Art (Virgo/LIGO) – optical properties

**Optical Absorption 0.24 ppm ⦰150 mm**

Average Absorption Surface 1 (HR)° (∅150 mm)

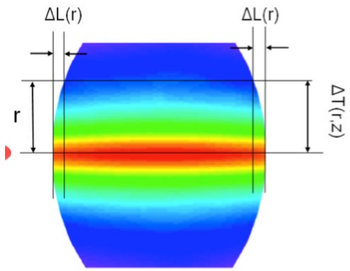



Absorption of optical power in the coating and substrate of the optics is a **dynamical thermal effect**

It needs to be under 1 ppm to avoid **thermal effects**

- Thermal lensing

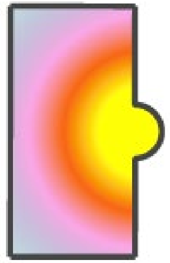
$$\Delta OPL_T = \frac{dn}{dT}\int_S \Delta T ds$$




OPL distorsions due to dependence of refractive index from temperature variation

- Thermo-elastic effect

$$\Delta u \approx \alpha \int_S \Delta T ds$$



Change of RoC of mirrors due to the absorption of laser power