Core Optics and Coatings ET_Italia + ETIC

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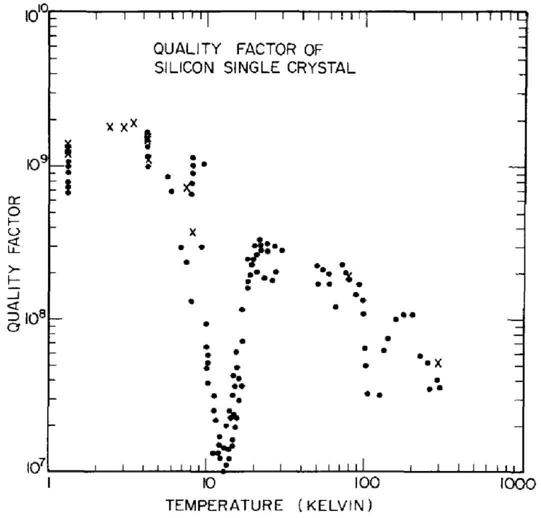
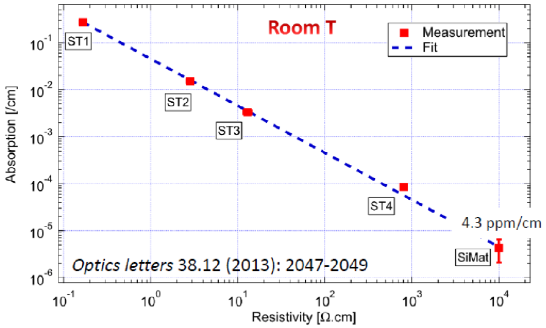
INFN-IFAE Collaboration - Thursday 22 Jun 2023 - EGO

Core Optics

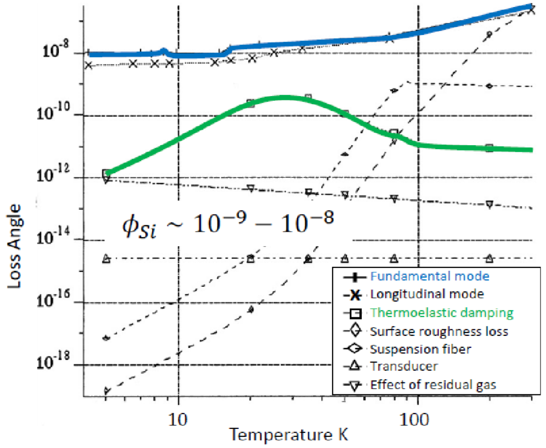
LF-ET:

- Silicon (LF-ET)
  - ✓ Low mechanical loss at cryogenic temperatures
  - ✓ Null thermal expansion coefficient at 123 K and 18 K
  - → Change of the wavelength 1550 nm or 2000 nm (suitable also with aSi as coating material)
  - → Large size and low optical absorption still missing: the maximum diameter and purity depend on the fabrication process (**Float Zone, Magnetic Czochralski, Quasi-mono ingots)**
- **Sapphire (LF-ET)**
  - ✓ Transparent for 1064 nm, low mechanical loss at room and low temperature
  - ✓ Higher Young's modulus
  - → Birefringence, absorption and scattering in dependance of manufacturers (axis orientation). Both absorption and birefringence could be due to structural defects -> technological problem

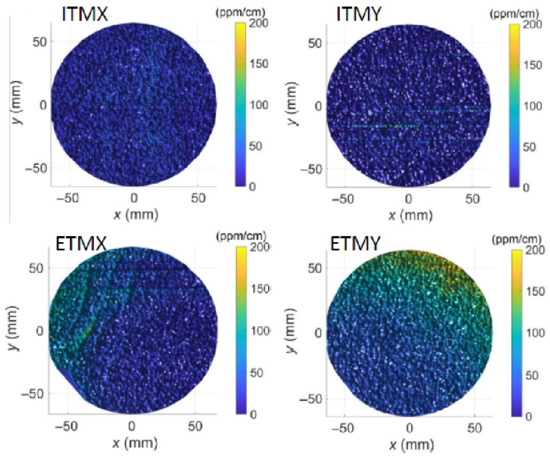




Physics Letters A **261**.1-2 (1999): 5-11



Phys. Rev. Applied **14**,014021 (2020)



Coating Thermal Noise

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

TEMPERATURE on MIRROR

COATING MECHANICAL LOSS (depends on material properties)

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

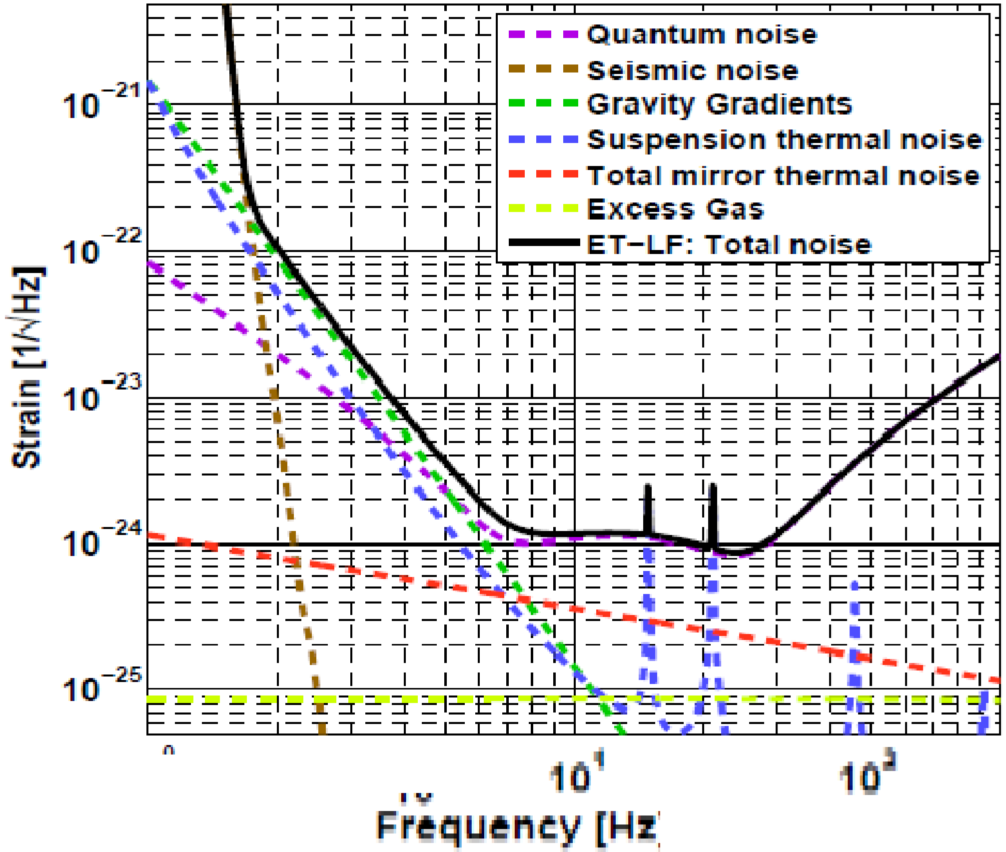
COATING THICKNESS (depends on reflectivity and refractive indices)

ARM LENGTH

BEAM-SIZE on MIRROR

Coating Thermal Noise

ET-LF: Cooling at low temperature (10K 20K or 120 K?) means reduce coating thermal noise at its origin



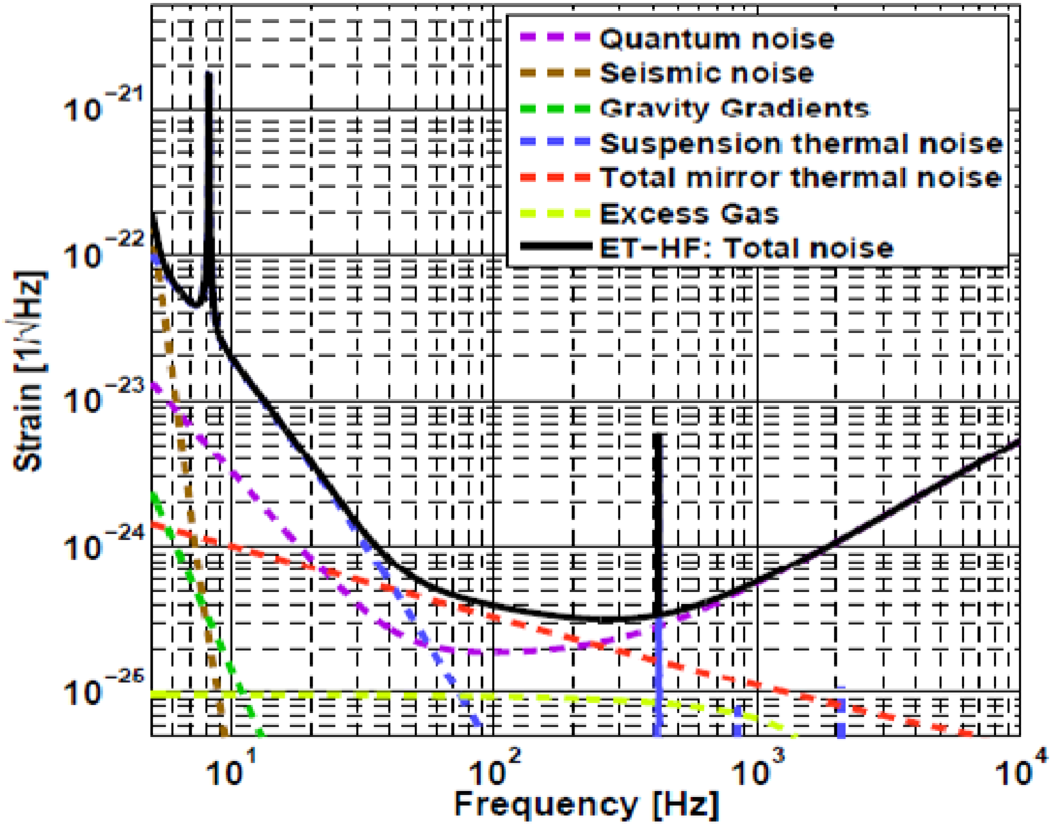
- Operation at **low T** requires a replacement substrate material and a suitable coating for this new substrate material and new temperature condition and possible different wavelength.

- A reduction in temperature should in principle provide a direct reduction in coating thermal noise. Thermal noise will be dominated by the **mirror suspension**, which must be able to extract the thermal load imposed by the optical power absorbed in the mirror; in this case the **optical absorption** plays a key role in the performances and must be held in the range of 1 ppm.

Take absorption under control to prevent cryogenics operation!!!

Coating Thermal Noise

ET-HF: New coating materials to tolerate high power operation



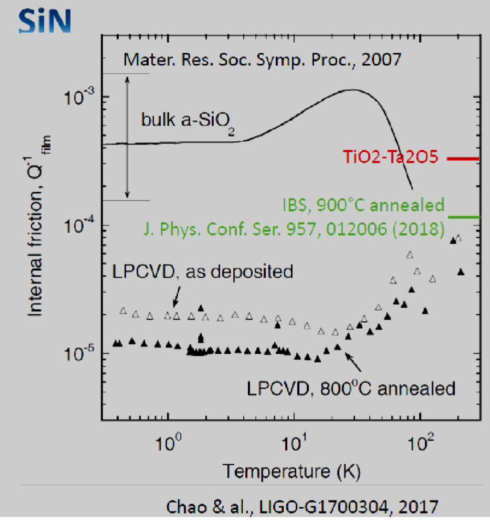
- Same wavelength, substrate material and operation temperature as LIGO/Virgo.
- Due to high input power, the main issue is to keep the total **optical absorption** at a very low level. It must **be less than 0.5 ppm**, although some relaxation of this target is possible if required by low thermal noise coatings at the expense of making thermal management more challenging.

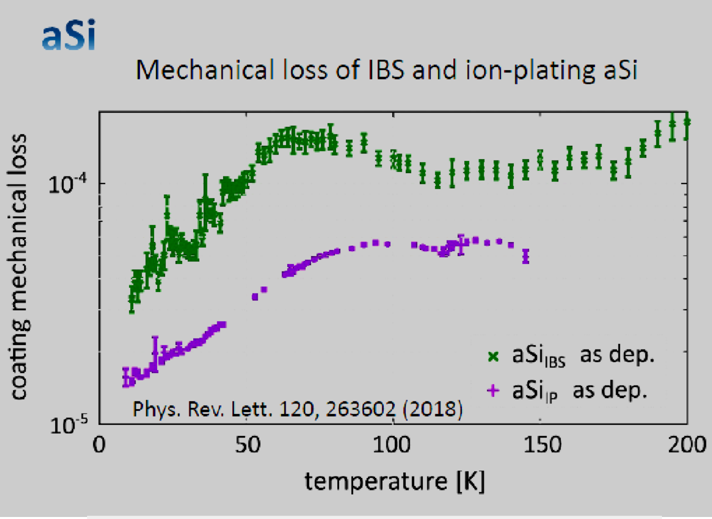
Take absorption under control to face high power operation!!!

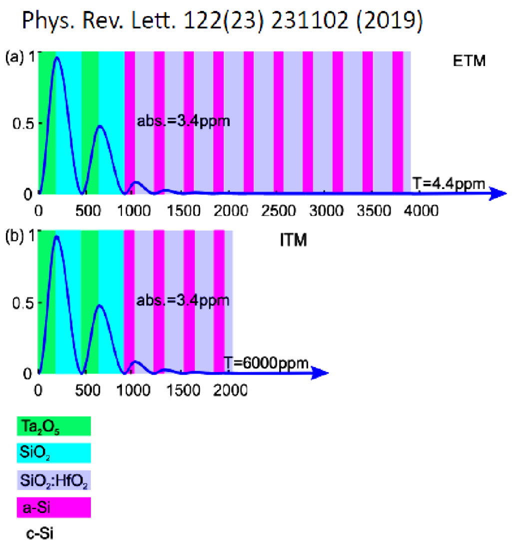
Materials for GW detectors under investigation

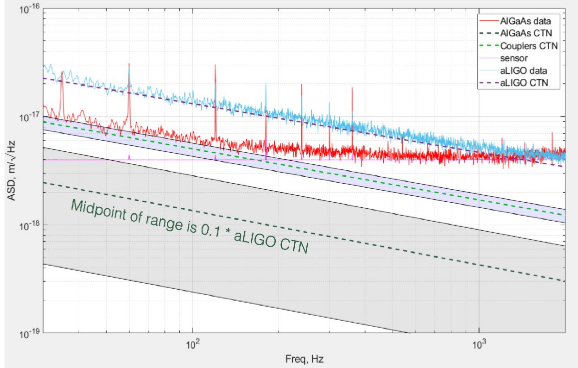
Perfect synergy with PO5 – R&D Plan of V_nEXT

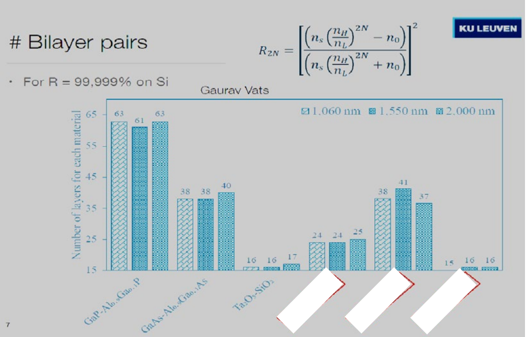
- Oxides – mixture of oxides - nanolayer
- HCNG – Nitrides (SiN, GaN), Semiconductors (a-Si, GaP, GaAs, InP): high coordination number makes atom structure more rigid decreasing TLS density → low loss dissipation
- Multimaterial Coating or Ternary Coatings (based on Oxides or Nitrides or a-Si): multi-material 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
- Crystalline Coating – (Semiconductor or Oxides): epitaxially grown coatings consisting of alternating layers of high and low index layers of crystalline materials











Material Characterization

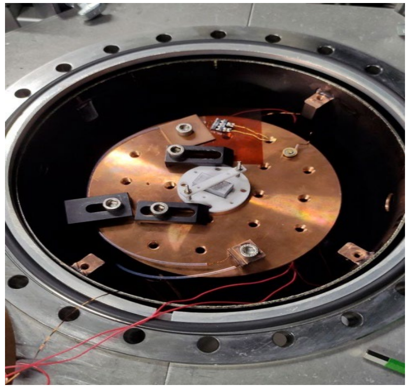
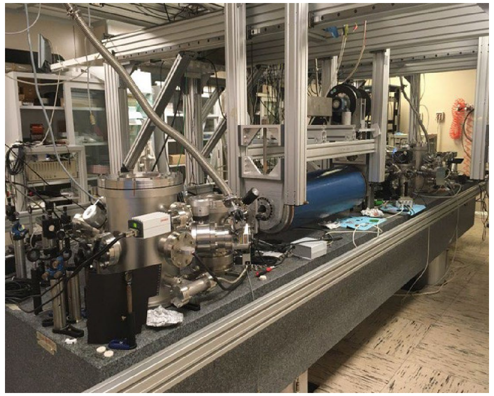
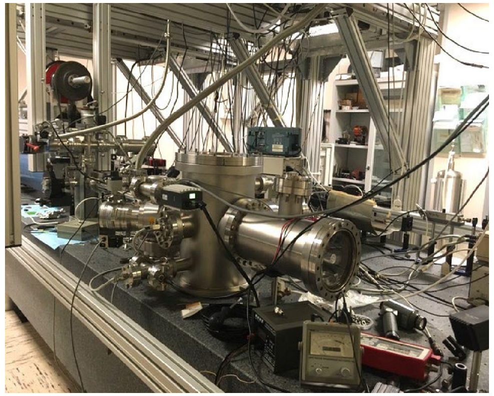
Main ET R&D activity @Italy on thin films is characterization of optical, mechanical and structural properties:

- Many set-up already in operation
- Cryogenic upgrades under development
- Multi-technical investigation flow already broken-in inside Virgo Coating R&D
- **General optical elements and coatings can be characterized (availability of many facilities)**

Characterization of prototype samples for baffles/optics

Core Optics Characterization

LF-ET: Both materials need to be studied from optical point of view, measuring scattering, optical absorption and uniformity of optical absorption depending on production method, polishing, orientation, presence of impurities

- WP1 Optical absorption measurements in bulk materials (PADOVA):
  - Cryogenic measurement campaign of the optical absorption of monocrystalline silicon at 1550 nm.
- WP2 Birefringence characterization in bulk materials (GENOVA, FERRARA):
  - Characterization and modeling of birefringence effects, measurement of mirror birefringence noise in different producing crystals.

Optical Properties - Coating

Optical properties: Solid knowledge of the optical properties is mandatory. These properties must be investigated at the proper wavelength, that in principle can be different from the one used in nowadays detector. Furthermore, these properties can guide the operating temperature choice.

- Origin of optical absorption (GENOVA, CAMERINO/PERUGIA, CAGLIARI, FERRARA): analyses of optical properties (extinction coefficient, refractive index, homogeneity of the refractive index, thickness, birefringence)
- Direct measurements of optical absorption (GENOVA, PADOVA, ROMA TV) to test the coating optical absorption by a common path interferometer or by the response of a FP cavity with a freestanding membrane inside
- Measurement of birefringence noise (FERRARA)

Spectroscopic ellipsometers

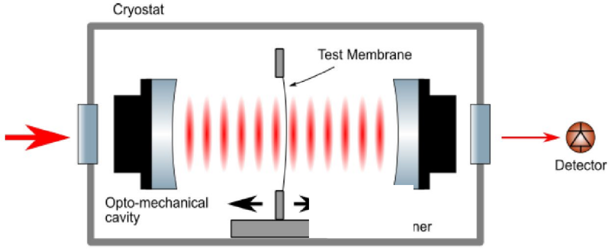
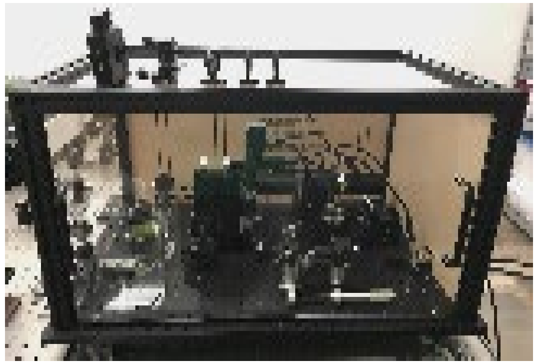
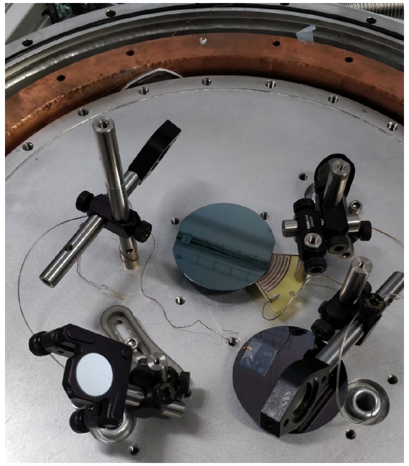


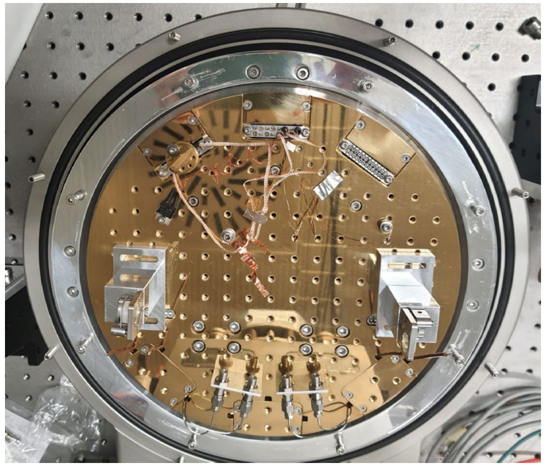
Figure 4.1: Simplified scheme of the opto-mechanical cavity. The membrane to be tested is mounted in the middle of a Fabry-Perot cavity, on the top of a linear piezo-translation stage. All the apparatus is mounted inside a low-vibration cryostat.

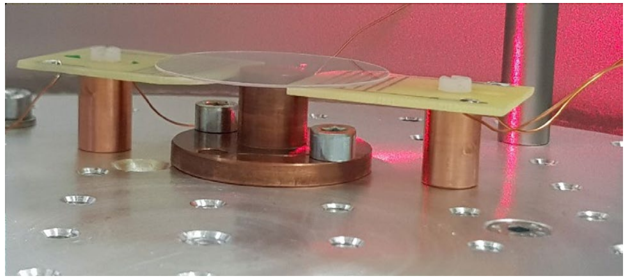


Mechanical Properties - Coating

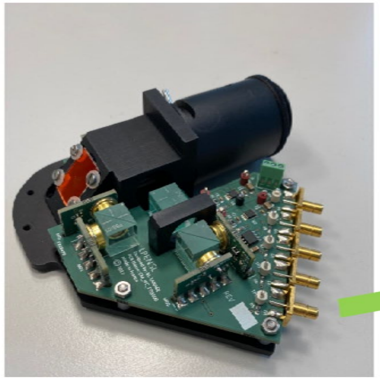
Mechanical properties and thermal noise measurements: TN can be measured directly or calculated indirectly starting from mechanical properties. In some cases, the two methods gave different results for reasons still not well understood. It is mandatory to develop both direct and indirect techniques to investigate TN at room and cryogenic temperatures. Furthermore, the possibility to mechanically characterize the samples at different temperatures would allow the modelling of any thermally activated dissipative processes for a better understanding of their nature

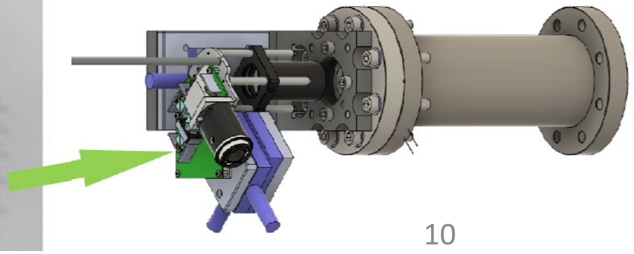






- Mechanical characterization at low temperature with Cryo GeNS (URBINO, CAMERINO/PERUGIA, ROMA TV)
- Mechanical characterization through the intensity output of an optical cavity with a freestanding membrane at cryogenic T (PADOVA)
- Direct measurement of coating Thermal noise through QPDI and cryo-QPDI (ROMA TV, SANNIO/SALERNO)

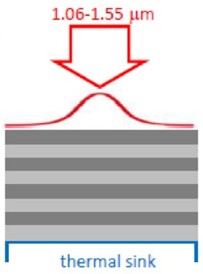


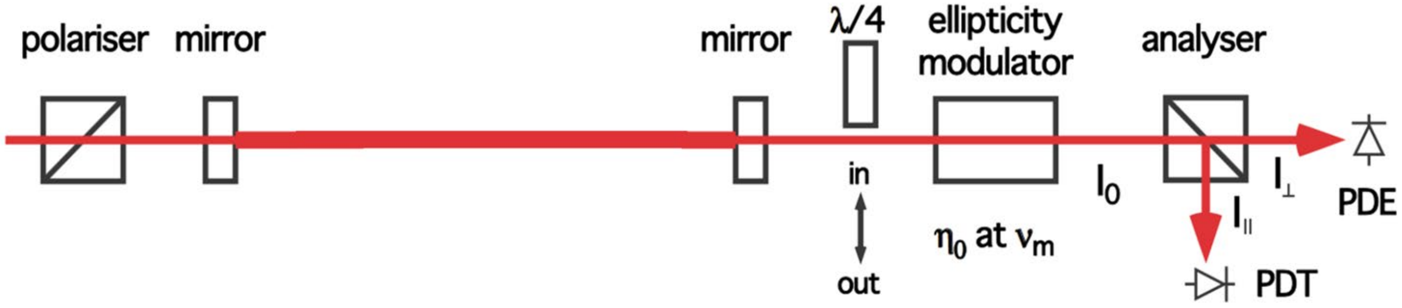


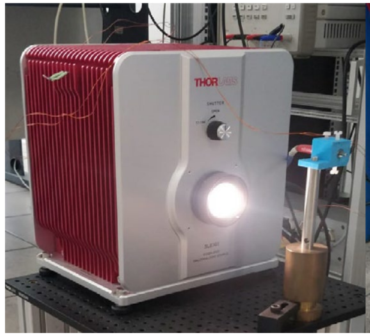
Thermo-Optic properties - Coating

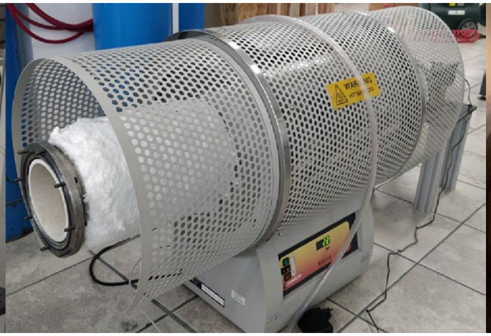
Thermo-optic measurement: Thermal dissipation causes thermal fluctuations in the coating which produce noise via the thermo-elastic and thermo-refractive mechanisms the so called thermo-optic noise, that need to be investigated both at room and cryogenic temperature.

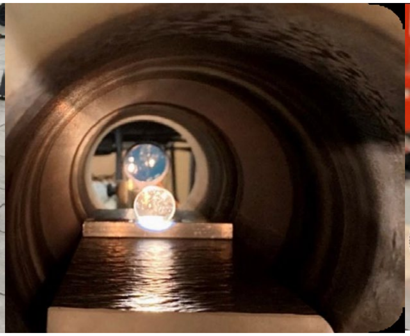
- Thermo-refractive noise characterization @room T by using a spectroscopic method both in transmission and in reflection, decoupling thermal expansion effect (FIRENZE/URBINO, CAGLIARI)
- Thermo-optic noise characterization @cryo T (CAGLIARI)
- Birefringence noise by using polarimetry (FERRARA)



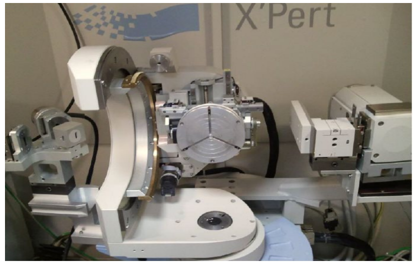


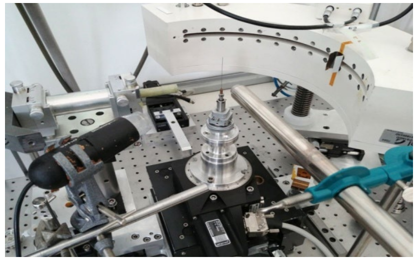


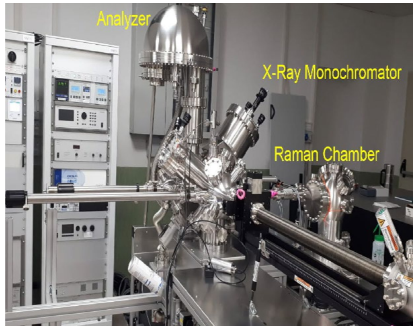


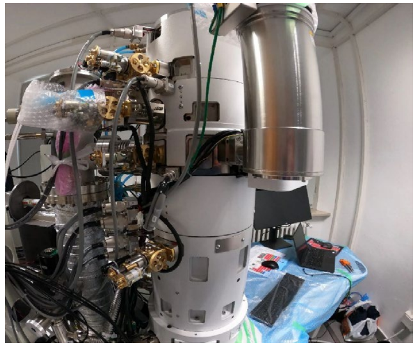


Structural properties - Coating









Structural measurements: materials limitation mainly comes from its chemical quality. Stoichiometry imperfection and water contamination are the main limiting factors for absorption. Correlate losses and absorption to the chemical status of the material is fundamental

- Morphological and compositional characterization (4.3): morphological, chemical characterization at room temperature of multilayer coatings through AFM, SEM-EDX, FEM, EDX, FTIR spectroscopy, X-Ray diffraction, X-Ray Absorption spectroscopy, X-Ray Photoelectron Spectroscopy, Raman Spectroscopy, Outgassing (BOLOGNA, CAGLIARI, CAMERINO/PERUGIA, GENOVA, PADOVA, PISA, ROMA, ROMA TOV, SANNIO/SALERNO)

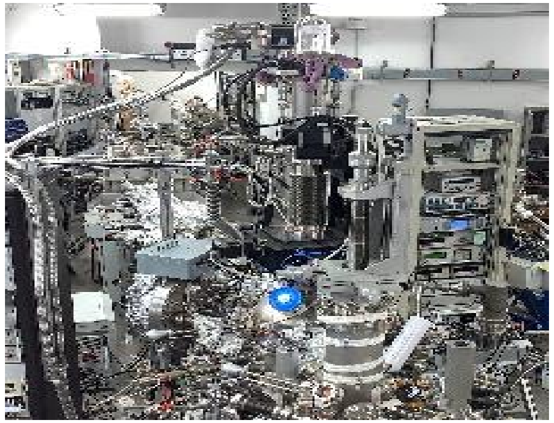
Structural measurements: a particular class of materials is suitable for cryogenic operations, crystalline oxides, and crystalline semiconductor growth directly on sapphire or silicon or bonded on crystalline test masses, can be considered an innovative solution that need to speed up. Structural analysis on lattice mismatch, level of strain, presence of defects, chemical composition is needed.

- Lattice parameters strain state characterization (4.1) by high resolution X-ray diffraction, X-ray fluorescence, IR and Brillouin Spectroscopy, X-Ray Photoelectron Spectroscopy, Raman Spectroscopy (BOLOGNA, CAMERINO/PERUGIA, GENOVA, PADOVA, ROMA, ROMA TOV, SANNIO/SALERNO)

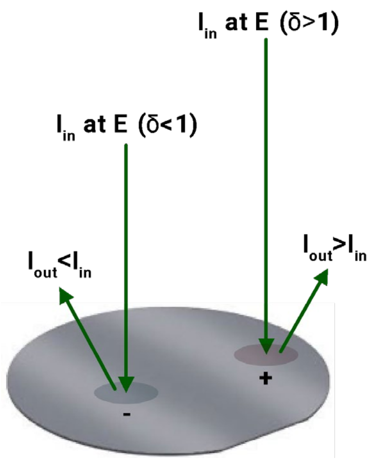
Frost mitigation and electrostatic charging neutralization

Both VIRGO and LIGO optics undergo to **inhomogeneous electrostatic charging** that may induce unwanted noise. The existing mitigation method cannot be applicable at cryogenic temperature since microns of N_2 will cryosorb on the surface. Mirror temperature will define tower operating pressure since, at cryogenic temperature, **residual gas will cryosorb** on the mirror surface inducing detrimental effects on the optical properties

- Passive mitigation: the reduction of the contaminants at cryogenic temperature on the optic surfaces. It is carried out within the research on Vacuum.
- Active mitigation: low energy electrons irradiation method can remove electrostatic charging and the unavoidable frost formation on the optics

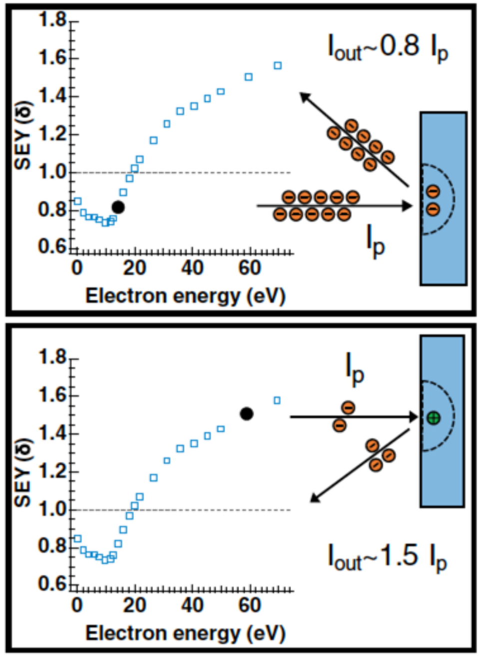


Proof of concept



Secondary Electron Yield (SEY or δ)

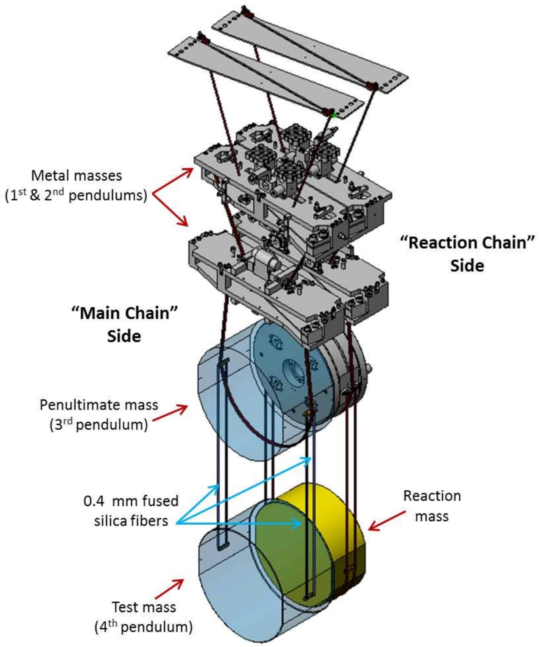
$SEY = I_{out}/I_p$



L. Spallino, et al., Phys. Rev. D, 105, 042003 (2022)

Electrostatic charge mitigation

Limiting noise source

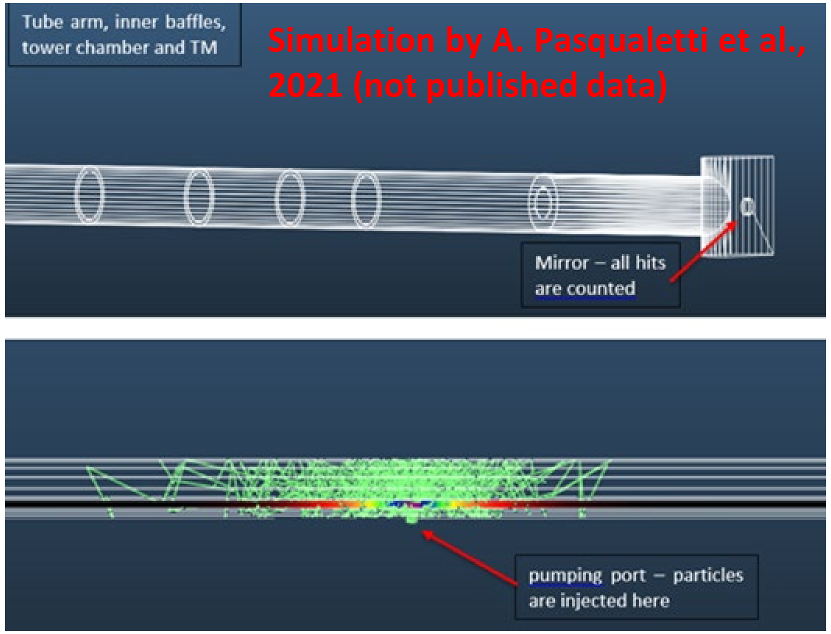


Electric field noise coupling to test mass motion

- Unclear in origin, quantity and even sign
- Effects of charging:
  - Interferers with optical position control
  - Accumulation and motion of charges can generate fluctuating electric fields that could move the test mass at frequencies in the interferometer sensitive band
  - Attracts dust, reducing reflectance, increasing scattering and absorption

Mitigation strategies are needed

From Virgo experience



Electrons coming from ion pumps propagates along the beampipes

↓

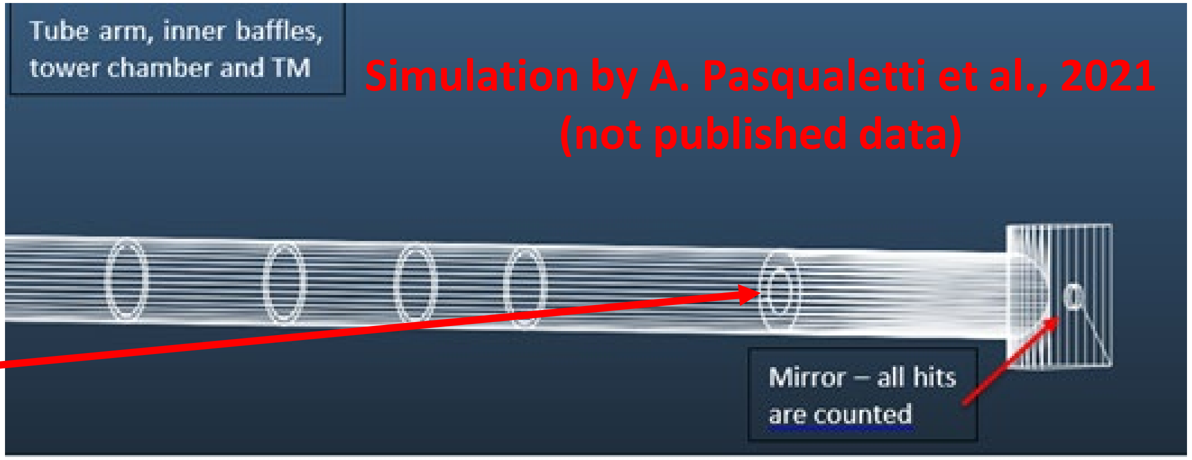
Electrostatic charges are generated by low energy electrons impinging on the test masses

Passive mitigation strategy

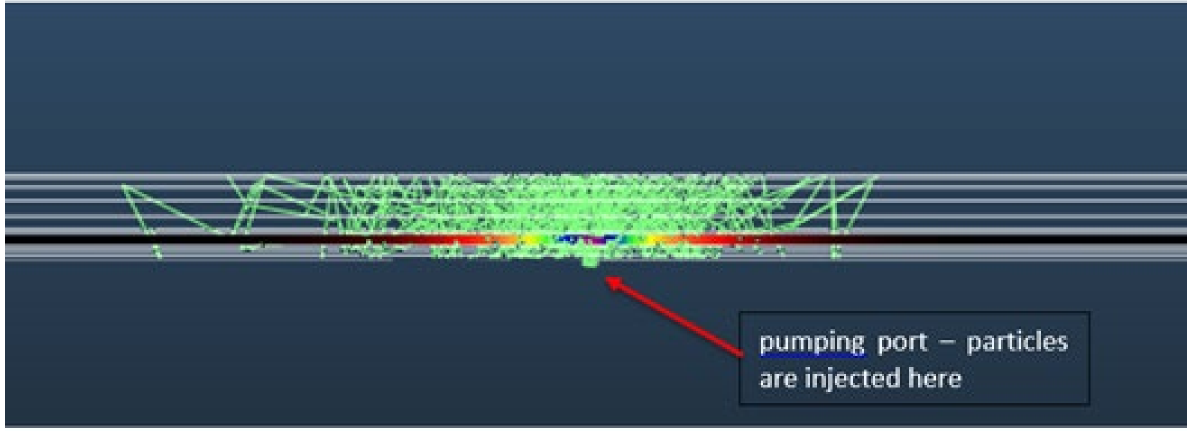
Electrostatic charges are generated by low energy electrons impinging on the test masses

Careful evaluation of the distance of the ion pumps from the test mass

Electrostatic ring on baffle



Simulation by A. Pasqualetti et al., 2021 (not published data)



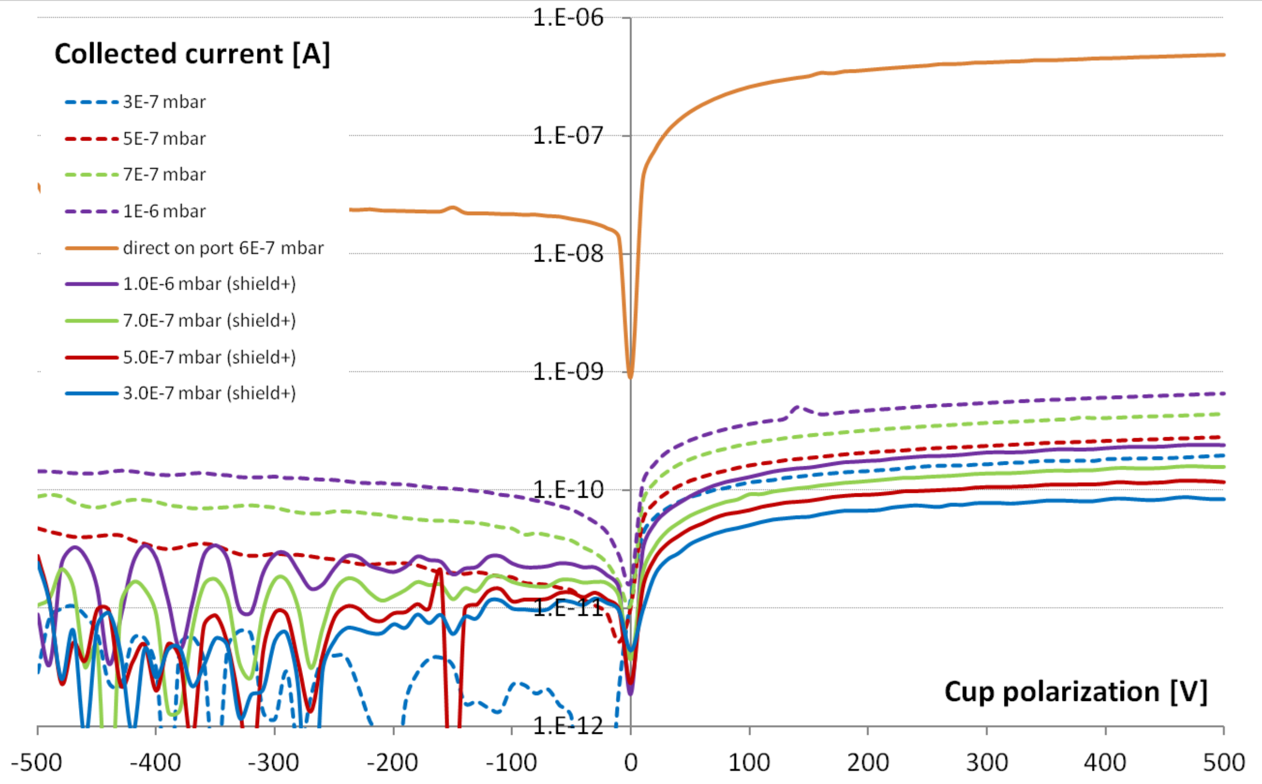
R&D activity LNF-EGO/Virgo to test the possibility of integrating an electrostatic ring on selected baffles to mitigate the charges' flow from the beampipes to the mirrors' chamber.

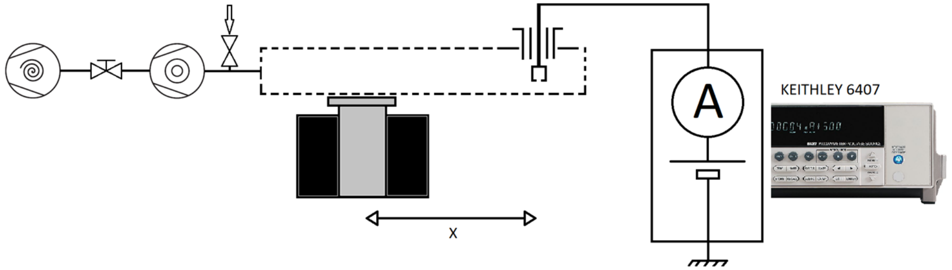
- **numerical simulation**
- **electrostatic measurements**
- **mock-up system design/realization for validation**

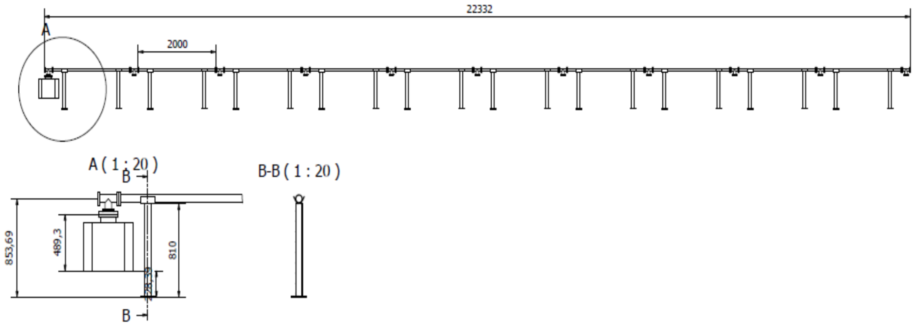
Strong interaction with the baffles' community is needed

Preliminary data from Virgo

Collected charges from an ion pump: X-axis reports the polarization voltage of the electrode, Y-axis reports the absolute value of the measured current. Negative charges are measured for + polarization values, and vice versa. The background current is of the order of E-12 A (= same measurement repeated with ion pump set OFF). Orange curve = charges measured directly at pumping port (pump model ND 300) at 6E-7 mbar. Other curves are for the shielded configurations of a typical Virgo setup.







Deposition system

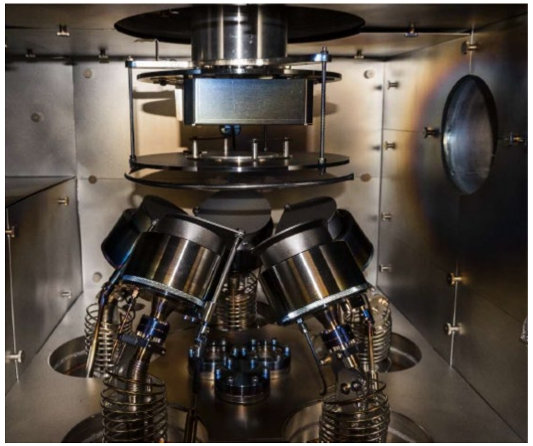
Dedicated Coating Chambers (@CAGLIARI,GENOVA, PADOVA)

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.

Custom Ion Beam Sputtering

- Multimaterial deposition with compositional control <u>up to 3 different metals</u>
- Substrate Rotation/Heat/Bias
- In-situ diagnostics
    - ✓ Plasma mass spectrometer
    - ✓ Ellipsometer
    - ✓ Stress monitor
    - ✓ Gas analyzer
- Assistance ion source
- High vacuum ($< 1 \times 10^{-7}$ mbar)
- multiple assistance and reactive, high purity gas lines



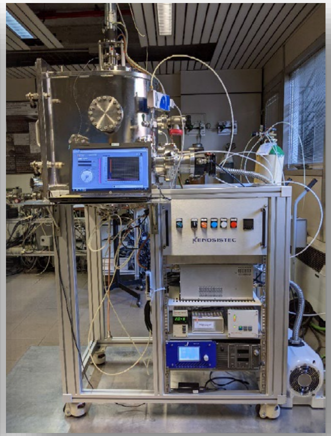
Magnetron Sputtering

- 2 DC and 2 RF torches for co-deposition
- Substrate Rotation/Heat/Bias
- Optical In-situ diagnostics (both plasma and sample)
- Assistance ion source
- High vacuum ($< 1 \times 10^{-7}$ mbar)
- multiple assistance and reactive, high purity gas lines

Deposition system

Other coating production system:

- Coating deposition machine not dedicated, but available for small prototype samples
  - SANNIO/SALERNO e-beam IAD (Virgo dedicated machine)
  - PISA Dip. Fisica e-beam IAD (not dedicated machine)
  - ROMA TV: Magnetron sputtering (not dedicated machine)
  - PADOVA: Magnetron sputtering
  - BOLOGNA: Magnetron Sputtering
- System for post deposition treatment
  - Thermal annealing (FIRENZE/URBINO, CAMERINO/PERUGIA, ROMA TOV)
  - Rapid Thermal Annealing (PADOVA)
  - Outgassing (ROMA)



Design/Optimization/Production of prototype samples for baffles

Thank you

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Electrostatic charge mitigation: roberto.cimino@lnf.infn.it

ET ITALY Einstein Telescope

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