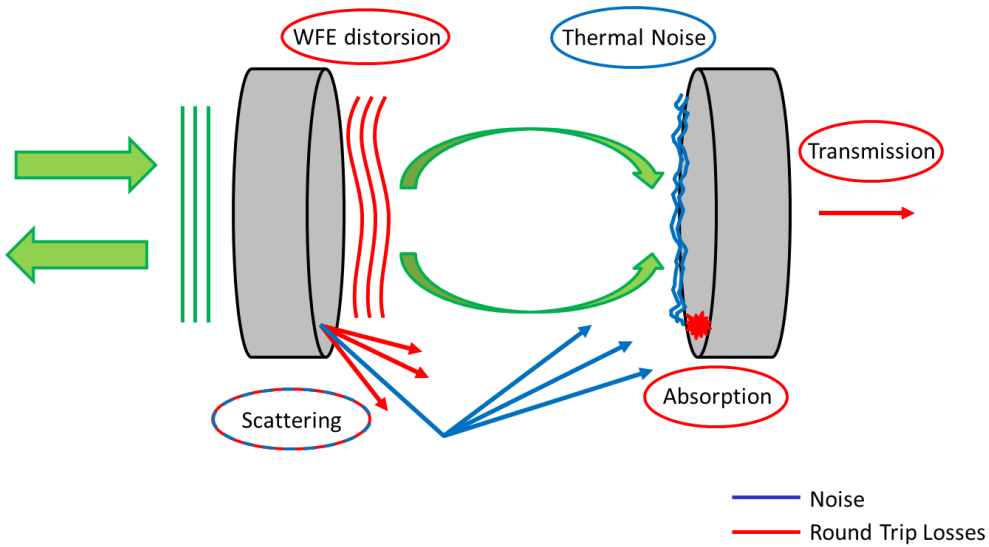
Coatings

ET-France meeting 2025

Benoit Sassolas

Major effects in mirror coating



Parameters	Adv Virgo	ET-HF	ET-LF
Arm power	100 - 150 kW (O4)	3 MW	18 kW
Mirror mass	42 kg	200 kg	211 kg
Temperature	290 K	290 K	10-20 K
Laser Wavelength	1064 nm	1064 nm	1550 nm
Mirror diameter	35 cm	62 cm	45 cm
Beam radius	5 - 6 cm	12 cm	9 cm
Bulk absorption	Suprasil 3002 0.2 ppm/cm	< 0.5 ppm/cm (3002)	20 ppm/cm
Coating absorption	0.3-0.4 ppm	<0.5ppm	<5 ppm
Scattering	<10 ppm	<10 ppm	<10 ppm

Advanced Virgo: DOI 10.1088/0264-9381/32/2/024001
ET Design Report 2020: https://apps.et-gw.eu/tds/ql/?c=15418

Thermal Noise : the most critical issue …

Amplitude Spectral Density of thermal noise

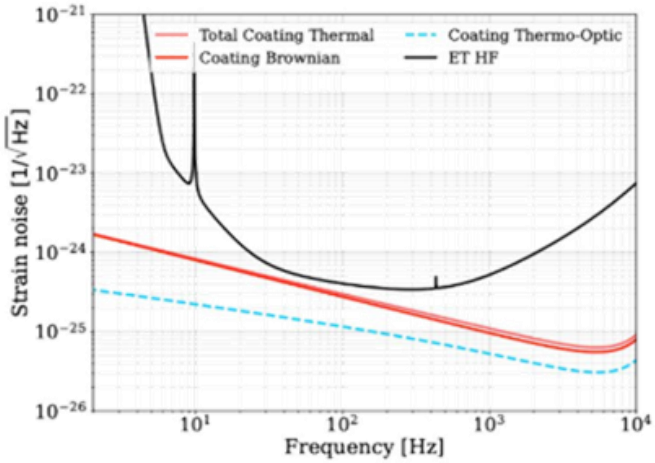
Temperature

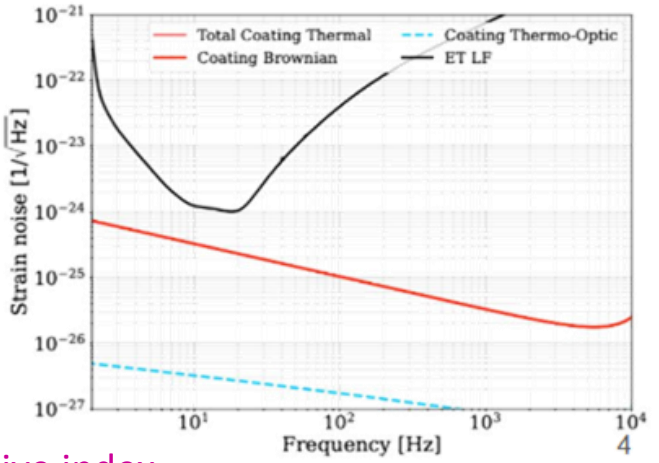
Total thickness

$$x(f) = \sqrt{\frac{2k_B T}{\pi^2 f} \frac{d}{w^2} \phi \left(\frac{Y_{coat}}{Y_{sub}^2} + \frac{1}{Y_{coat}} \right)}$$

Beam diameter

Mechanical loss





[ET-0294A-25]

Several approaches to decrease the thermal noise :

- Reducing the temperature (ET-LF) => cryogenic
- Reducing the total thickness => increase the contrast in refractive index
- Increasing the beam diameter (ET-LF & ET-HF) => larger mirrors
- Reducing the loss of the coating materials
  - Factor of 3.8 for ET-LF
  - Factor of 2.6 for ET-HF

Challenging requirements !!!

A coating compliant with the A+ specs would be suitable for ET-HF !!!

… but do not forget that other parameters matter !

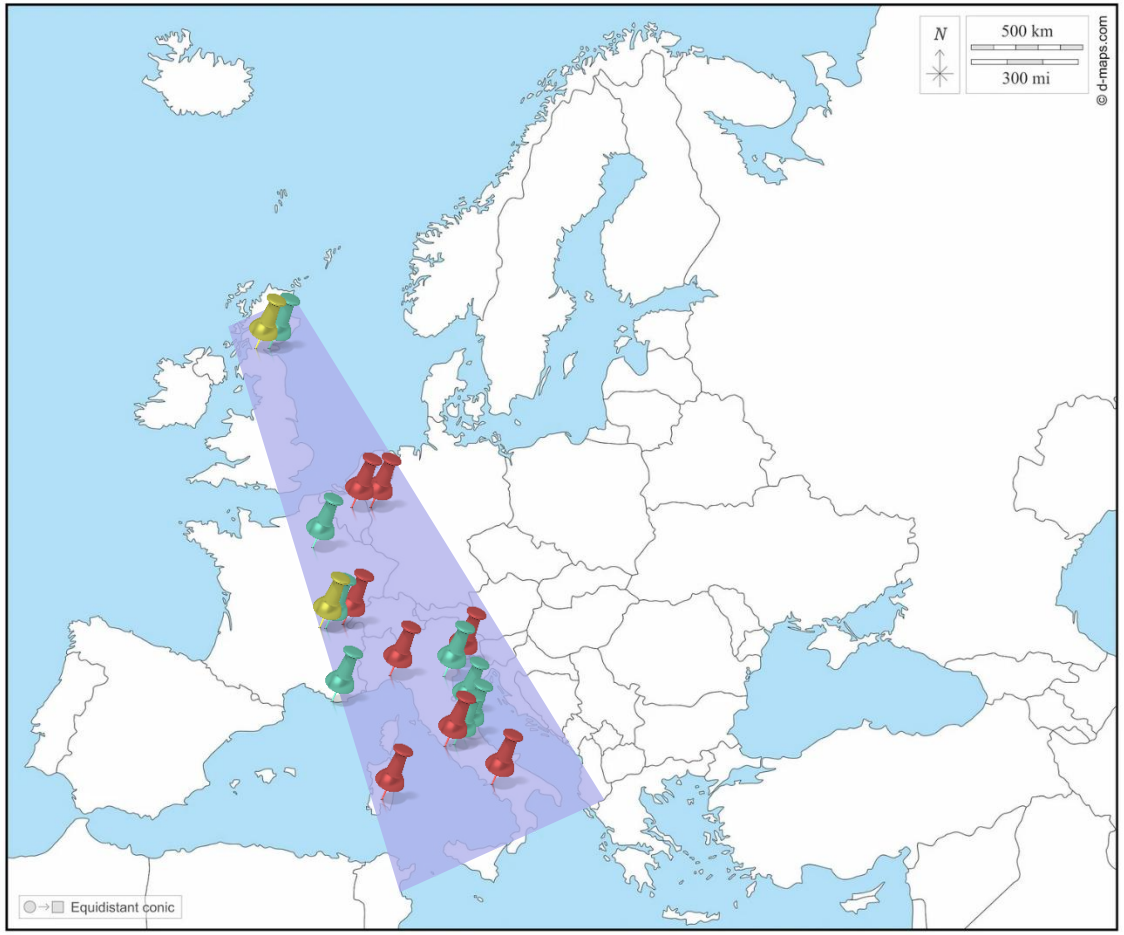
The coating MUST be :

- Uniform over a large area (~ ∅ 200mm)
- Defect-free (neither point scatterers nor point absorber)
- Low scattering
- Non-birefringent

All the parameters are interconnected and have a strong impact on the optimization of deposition process.

The final decision can be made only on a real HR stack that complies with all the specs.
A scale 1:1 pathfinder ?

The european « coating corridor »



R&D coating facilies

Characterization facilies (mechanical loss, absorption, birefringence, ellipsometry, structural)

Large coating chambers

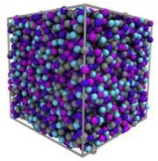
No real coordinated R&D activities at the project level.

R&D roadmap in preparation
Pros : identify lack of research on certain aspects.
Cons : only consultative right now

Several solutions under investigation

Amorphous coatings

- SiN_x
- $Ti:GeO_2$
- a-Si
- Fluorides
- $SiO_2:HfO_2$
- $TiO_2:SiO_2$
- Al_2O_3
- Multimaterial structure
- Nanolayering
- Implantation



ET-HF

ET-LF

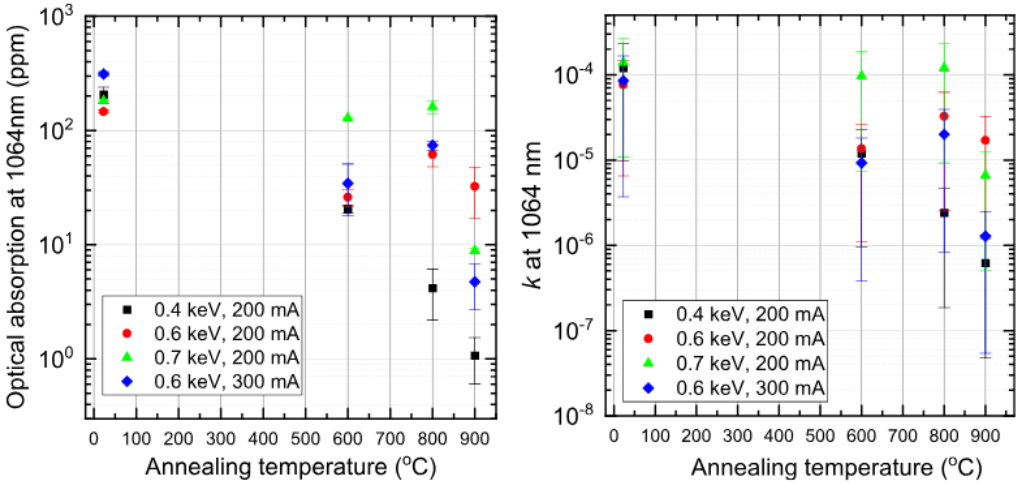
Crystalline coatings

- GaAs/AlGaAs
- Cr_2O_3/Fe_2O_3
- Hybrid crystalline/amorphous

Amorphous

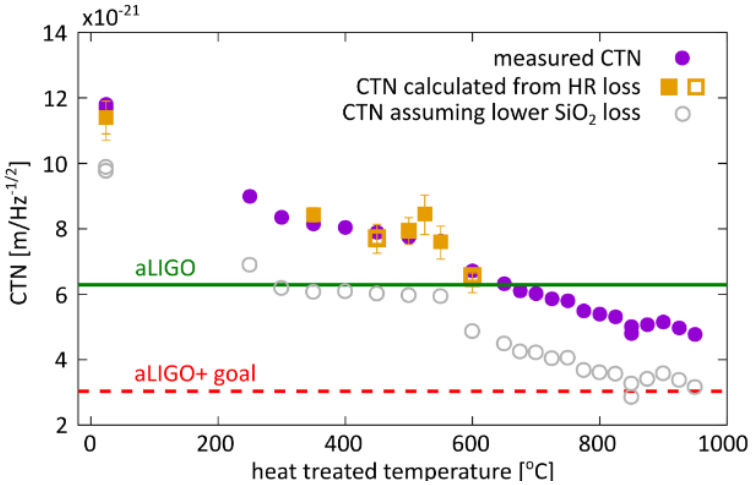
Si_3N_4 [Wallace et al. Class. Quantum Grav. 41 (2024) 095005]

- k~7e-7 – ultra low absorbing nitride
- φ~3e-4



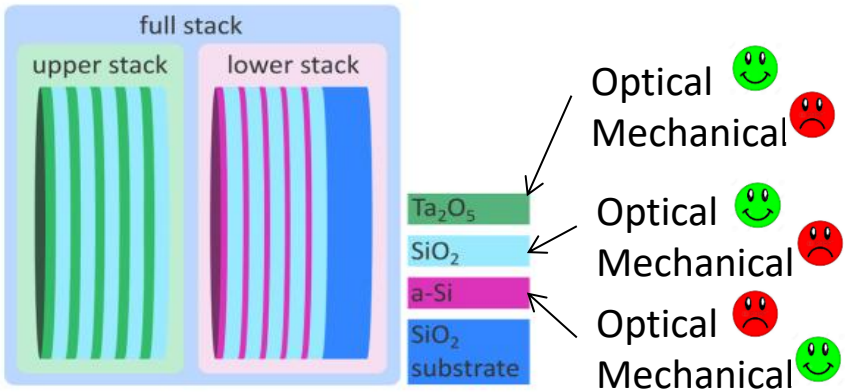
$Ti:SiO_2$ [McGhee PRL 131, 171401 (2023)]

- HR CTN ~75% aLIGO
- A~1 ppm



Multimaterial

Material	CTN (wrt aLIGO)	Absorption (ppm)	Ref.	Comment
$SiO_2/SiO_x/Ta_2O_5$	0.97	1	Demos et al. Class. Quantum Grav. 42 115012 2025	T<<5ppm
$SiO_2/Ti:Ta_2O_5/SiN_x$	0.82	1.5	VIR-0888A-25	
$SiO_2/Ti:Ta_2O_5/TiGeO_2$	0.81	0.7	VIR-0888A-25	



Implantation

Implanting O and N Ions into crystalline Silicon might enable creating Bragg mirror layers with good mechanical loss and absorption

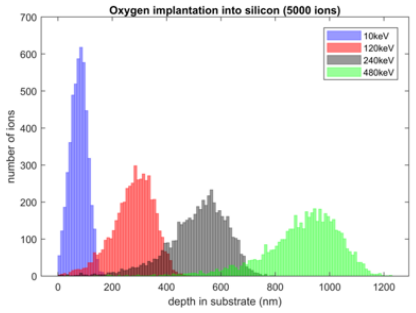
Crystalline Silicon substrates will be used in the Einstein Telescope at cryogenic temperatures

Just bought an ion implanter (located in California)

Implanted Layer Structure

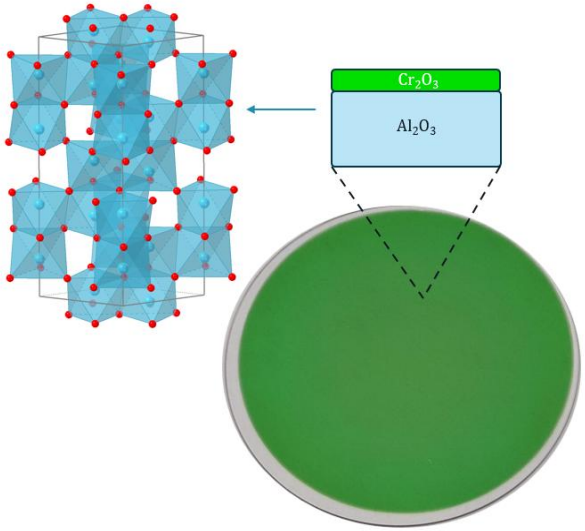
Aim to create Bragg-mirror with implanted Silica layers in crystalline Silicon substrate

Choosing different implantation energies creates layers at different depths



LIGO-G2400579-x0

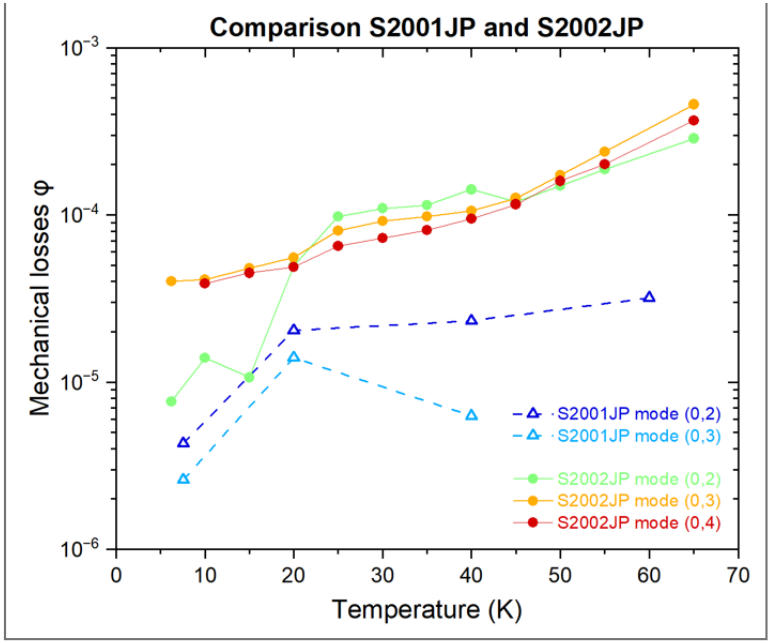
Oxide crystaline coatings



Cr_2O_3 can be directly grown onto sapphire.
Demonstation of a 500 nm thick on a ∅2’’ substrate.

Strong impact of the growth quality on the mechanical loss.

Good epitaxy quality allows to achieve φ=3e-6 at cryogenic temperature.



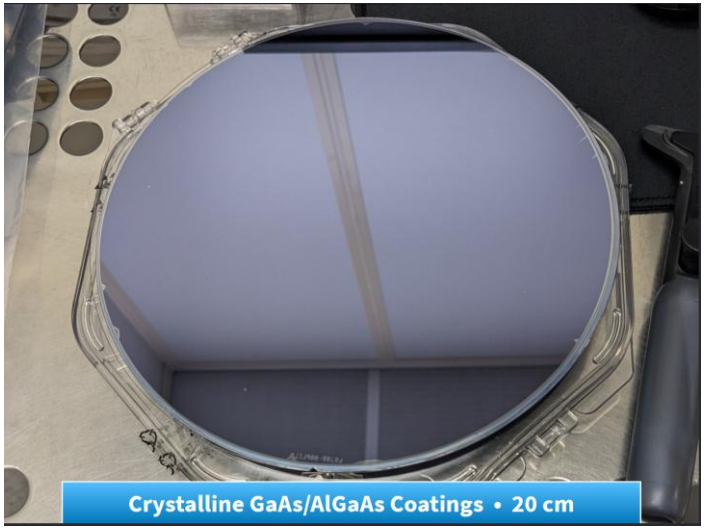
Comparison film with **good epitaxy (S2001JP)** and film with **mixed** polycrystalline/epitaxial **structure (S2002JP)**

[Binetti et al. GRASS 2024]

GaAs/AlGaAs

Several project aim to develop compliant coating over Ø200mm

- MICRONG – R. Flaminio
- MIRI - S. Penn



GaAs/InGaAs coating on ∅20 cm (max GaAs wafer available).

Birefringence variation of 5% over ∅ 100 mm.

New plan growth on ∅30cm Ge wafer.

[LIGO-G2501475]
[OIC FA.6]

Conclusion

A lot of activities are ongoing regarding the fabrication of the ET coating.

Quality and performance have been improved.

Still a lot of work that all the requirements can be met.

Scaling up to be checked/developped.

To be continued …