# The french contribution to the coating R&D effort

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# Coating requirements

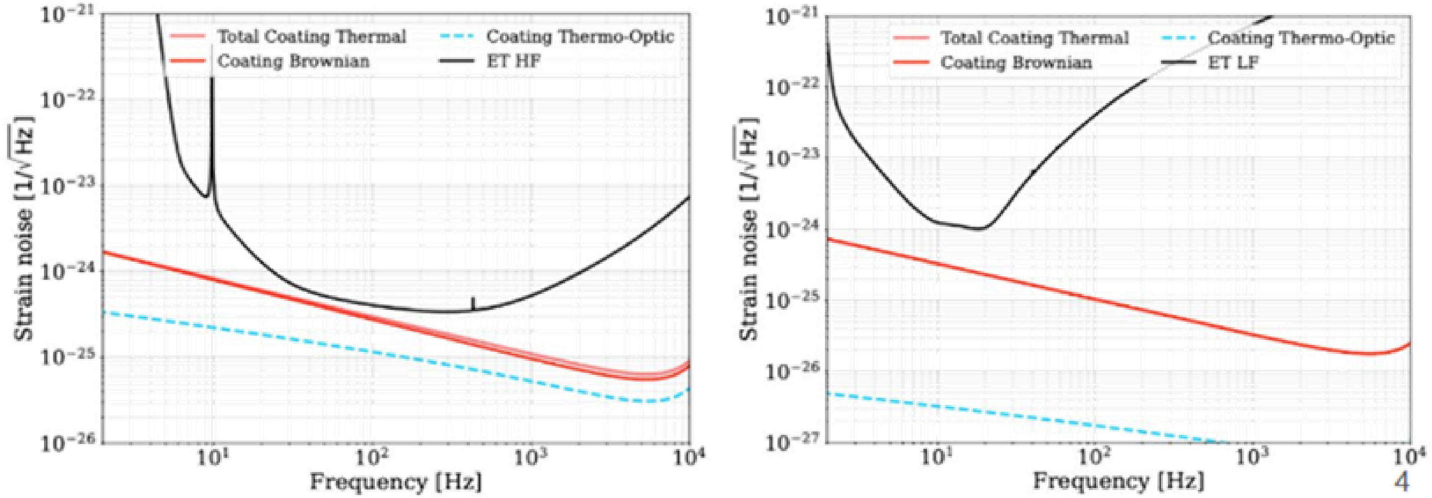
| Parameters | Adv Virgo | ET-HF | ET-LF |
|---|---|---|---|
| Arm power | 100 - 150 kW (O4) | 3 MW | 18 kW |
| Mirror mass | 42 kg | 200 kg | 211 kg |
| Temperature | 290 K | 290 K | 10-20 K |
| Laser Wavelength | 1064 nm | 1064 nm | 1550 nm |
| Mirror diameter | 35 cm | 62 cm | 45 cm |
| Beam radius | 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 |
| Birefringence | | TBD | TBD |

Amplitude Spectral Density of thermal noise

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

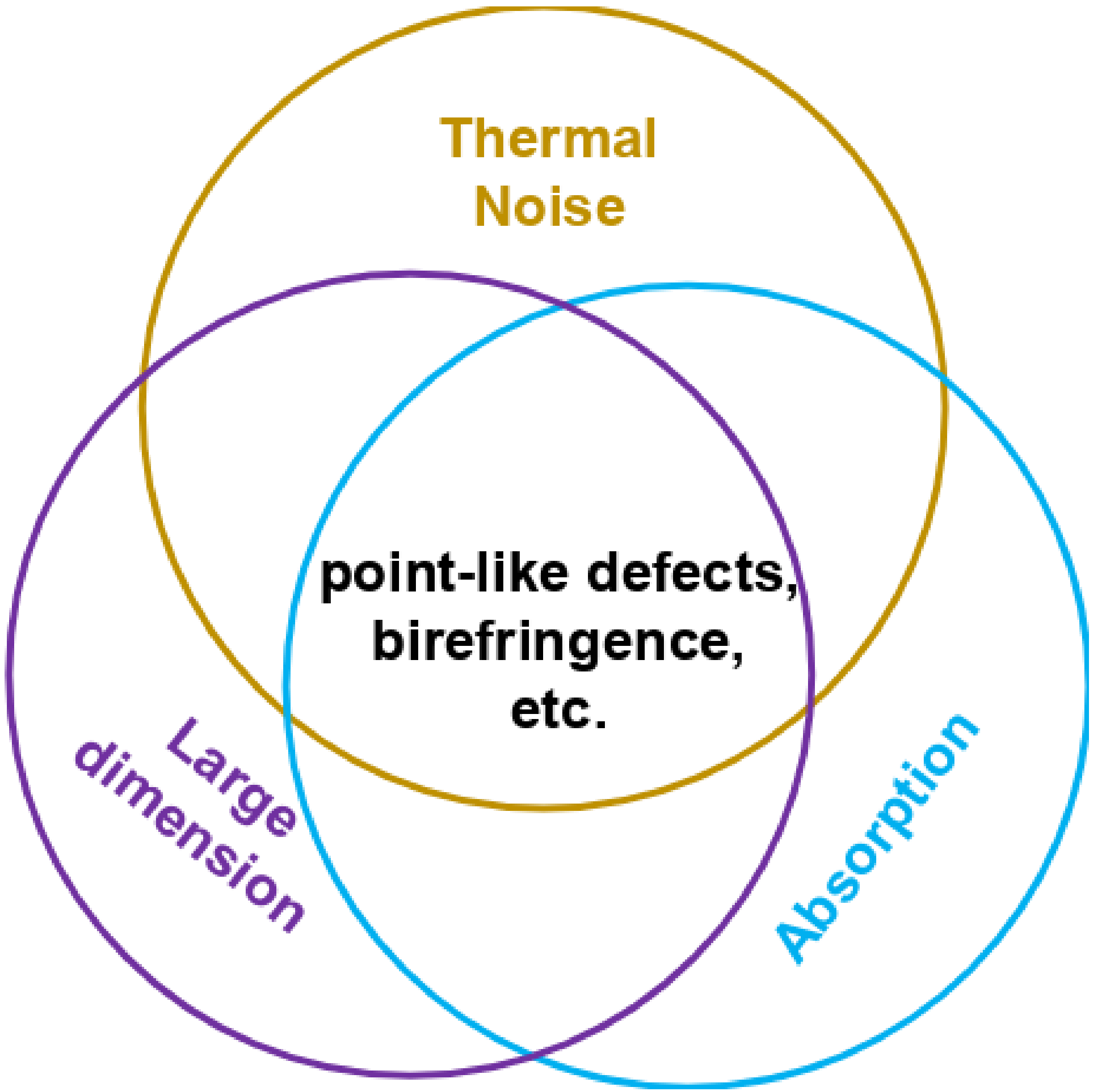
Temperature ($T$), Total thickness ($d$), Beam diameter ($w$), Mechanical loss ($\phi$)

- Factor of 3.8 lower than aLIGO for ET-LF
- Factor of 4 lower than aLIGO for ET-HF




[ET-0007C-23]

# Coating requirements



# Amorphous coatings : extend IBS beyond its frontiers

- Nitrides/Oxinitrides
- Development for room temperature but promising results @ cryogenic temperature
  - Recent low absorbing layer k~7e-7 and φ~3e-4 [*Wallace et al. 2024*]
  - Low loss at room temp. φ=8e-5 rad [*Granata et al. 2020*] and φ=1e-5 rad @ 10K [*Liu et al. 2007*]
  - Ternary coating gave good results A=1.5ppm and CTN~ $10.3\times10^{-18}$ $m\cdot Hz^{-1/2}$ at 100 Hz (25% lower than Advanced LIGO and Advanced Virgo) *[Amato et al. 2025]*
- Strong synergy with A# and VnEXT

Challenges

- Reduce the optical absorption
- Reduce point defect density
- Large deposition chamber

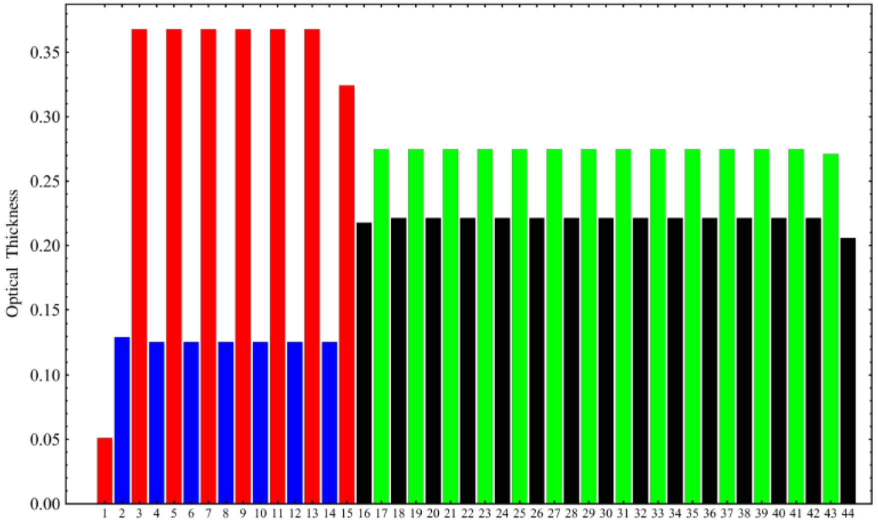
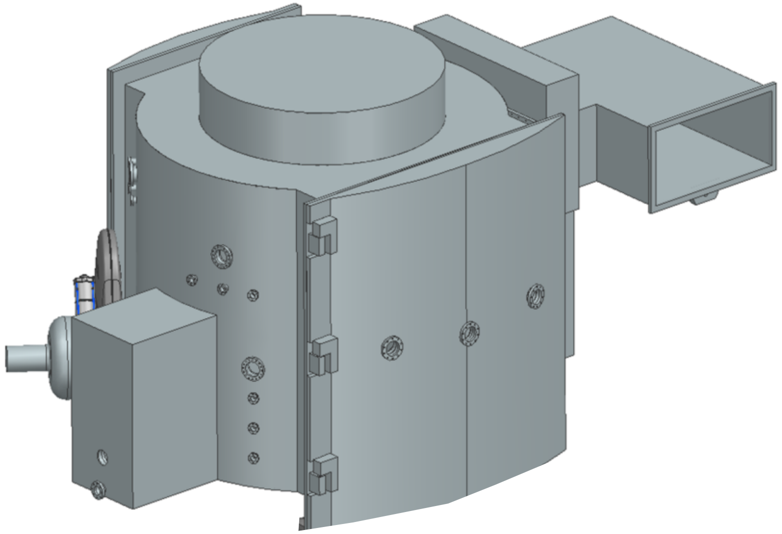
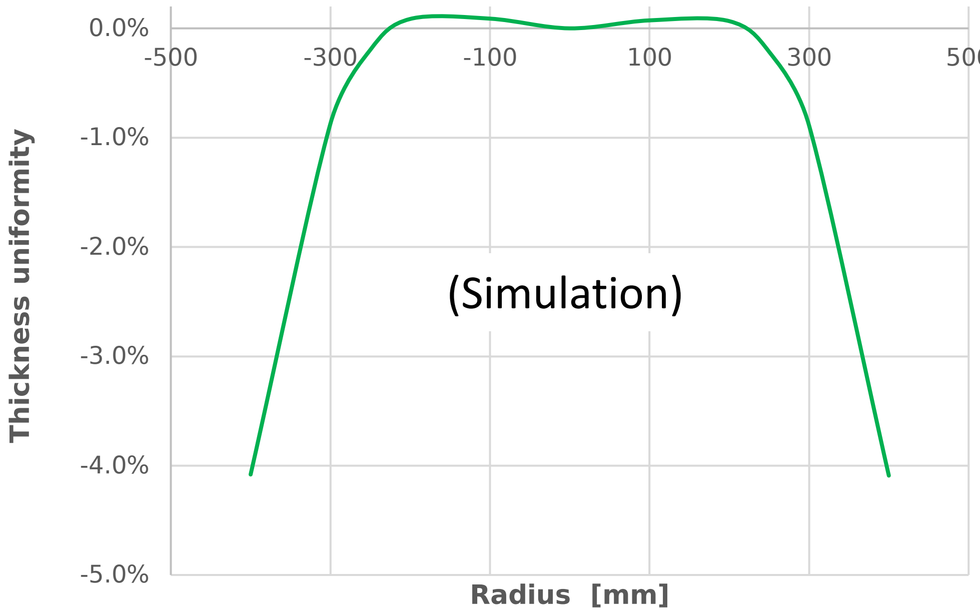



FIG. 14. Layout of a thickness-optimized ternary Bragg reflector for operation at $\lambda_0 = 1064$ nm, composed of IBS $SiN_x$ (black), tantala-titania (blue) and silica (green and red) thin layers. The optical thickness of each layer, normalized to $\lambda_0$, is shown as a function of the layer number (the substrate is set to be on the right, by convention).

# NOVA : the extremely large IBS coating machine at LMA



Planetary motion enables the coating of two Ø800 mm mirrors in the same batch.

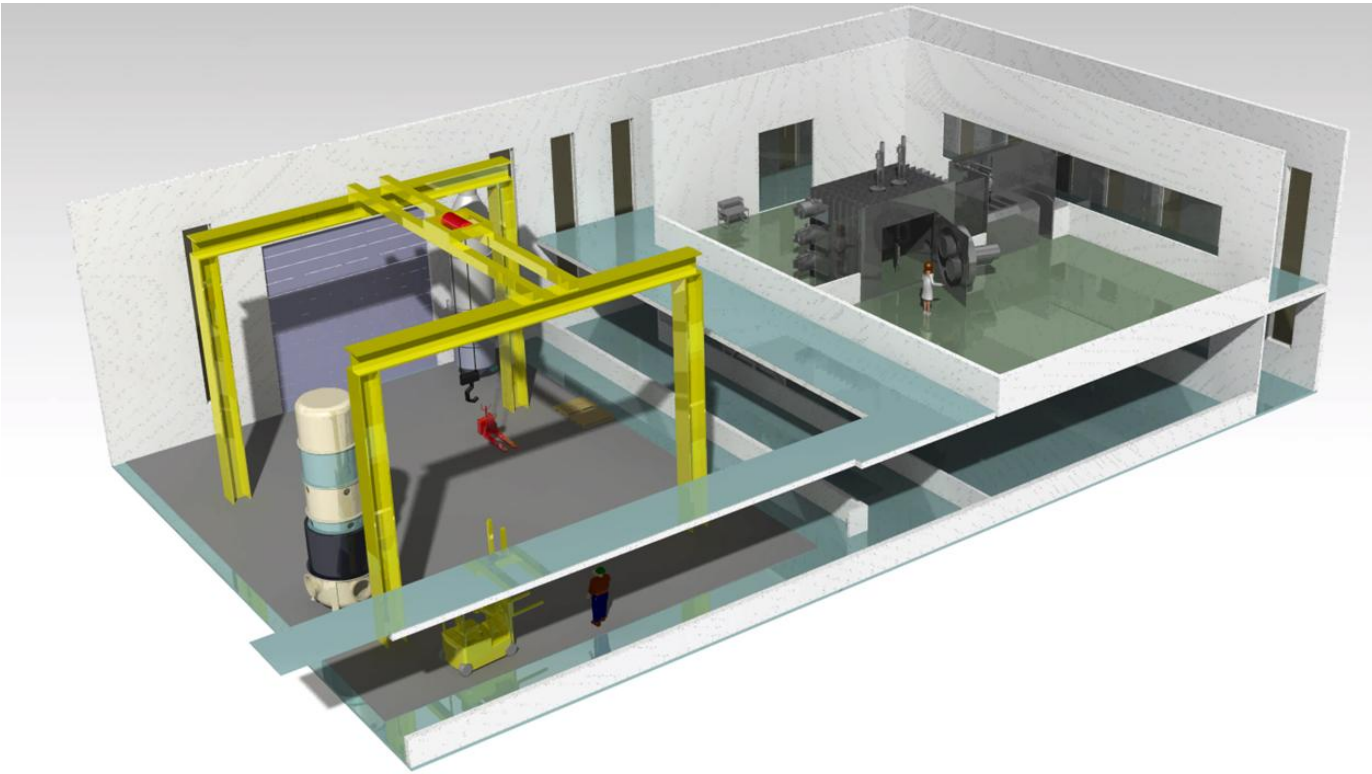



25-30%

Total budget invested (4.8 M€)

Call for tenders for the chamber manufacturing – coming soon.
Chamber delivery – Summer 2028
Chamber on-site validation – November 2028

# VIRGO+ building : unique facility to host NOVA



- 150 m² ISO 3 cleanroom + 100 m² technical rooms + 250 m² “clean” air in the basement
- Similar concept to the VIRGO cleanroom

La Région Auvergne-Rhône-Alpes · Union Européenne · cnrs

15-20%

Total budget invested (6.5M€)

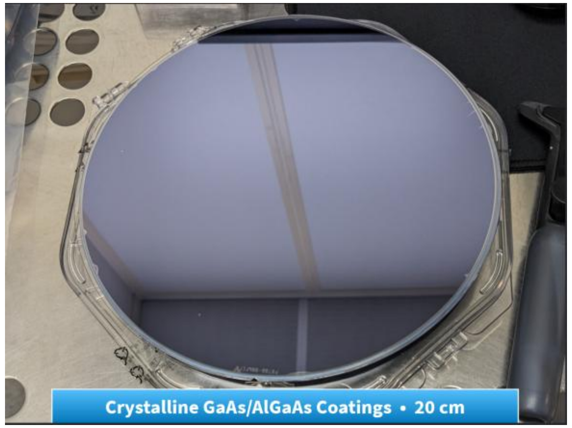
Call for tenders for construction on-going.
Delivery – Summer 2028

**This facility to start ET with amorphous layers will be available in 2029**

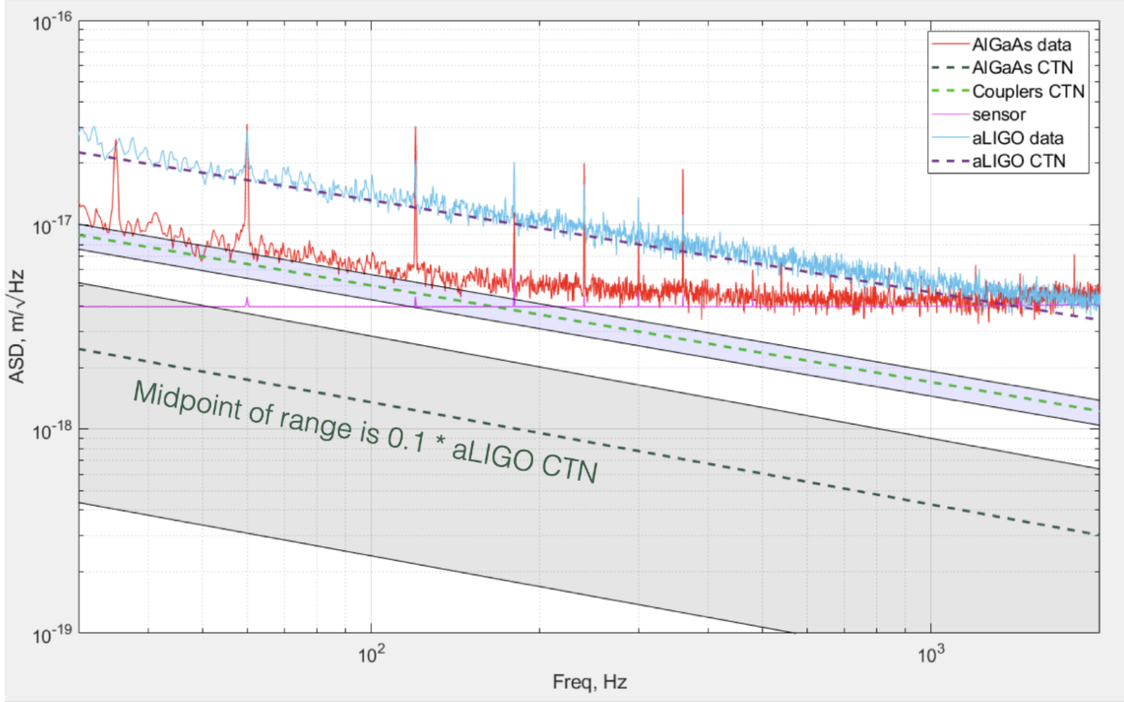
# Crystalline coatings : a disruptive technology for gravitational waves detectors

AlGaAs DBR

- Epitaxy of $GaAs/Al_xGa_{1-x}As$ stack
- Coating transfer from GaAs (Ge) substrate towards a large substrate (silica or silicon)
- Oustanding performance already demonstrated on small sample (Ø1’’-3’’)
  - Scattering < 10ppm [*Marchio et al. 2018*]
  - Absorption < 1ppm [*Marchio et al. 2018*]
  - Mechanical loss $\varphi$=2.5e-5 rad @ room temperature [*Penn et al. 2019*]




- Suitable for room and/or cryogenic temperature




Challenges:

- Scaling-up
- Large GaAs or Ge wafer
- 300 mm epitaxy production system
- Big bonder

[LIGO-G2501475]

# The MICRONG project (1/2)

MICRONG : French effort in the development of crystalline coating coordinated by LAPP (1/2)

ANR funding.

Consortium including academic labs and a world leading company in MBE

- III-V Lab, Paris
- CNRS-LAPP, Annecy
- CEA-LETI, Grenoble
- CNRS-LMA, Lyon
- RIBER, Paris

Goals :

1. Develop AlGaAs coatings on Ø200 mm deposited onto GaAs.
2. Developp the same technology for Ge wafers.
3. Draw up a plan for the scaling up to Ø300 mm.

# The MICRONG project (2/2)

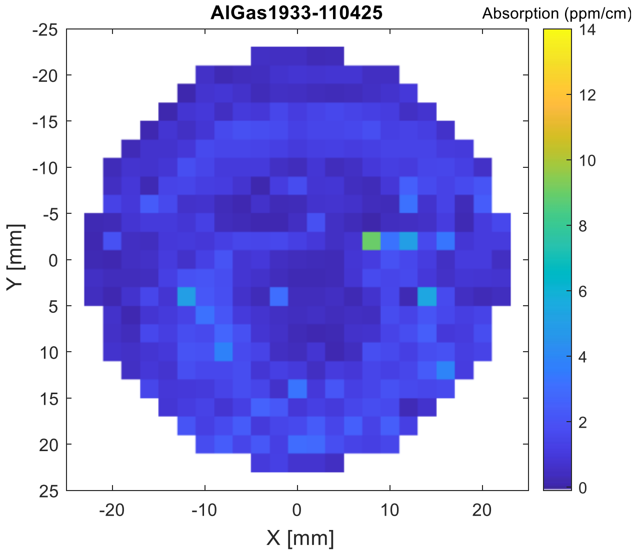
Production of several $\lambda/4$ multilayer reflectors according to

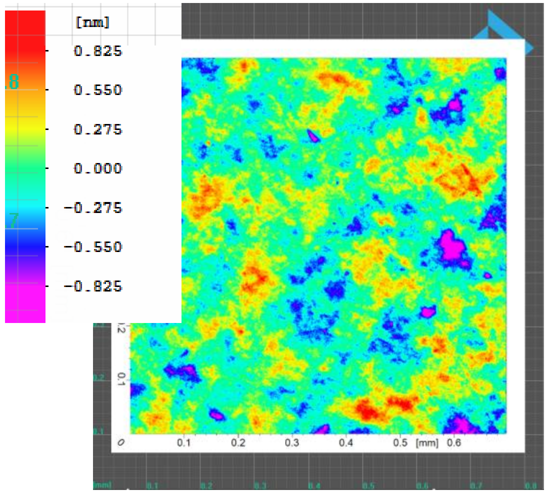
- Different number of layers
- Different diameter/material for the substrate
- Different process condition

Results

- <<1% of thickness uniformity over Ø100mm
- 1% of thickness uniformity over Ø200mm
- ~500 surface defects over Ø100mm (10% larger than 35µm)
- Scattering ~10 ppm @ 1064nm
- Absorption < 1ppm @ 1064 nm
- Roughness ~0.3-0.4 nm RMS

RIBER - MBE System 49




[VIR-0020A-26]

# The Gravitational Wave Astrophysics Infrastructure Network (GRAIN)

The bonding technique : key point for the crystalline mirrors.
Synergy between A# and ET.

Université de Montréal
The University of Arizona
Plasmionique
LMA Laboratoire Matériaux Avancés
LIGO
Syracuse University
Maastricht University
The University of British Columbia
UdS Université de Sherbrooke
McGill

Development of a bonder for 100kg TM and Ø550 mm.

Installation and operation in the ISO3 cleanroom @ LMA.

Target : 1st bonding in 2029

Important step for ET :

- Scaling-up
- Develop skills within the collaboration

[LIGO-G2600609-x0]

# What else ?

Metrology will be necessary to definitely validate the final components.

- Wavefront
- Absorption
- Point scatterers/absorbers
- Birefringence
- Optical scattering
- Roughness
- Transmittance/reflectance
- CTN ?

Technologies are already available at the required level of sensitivity (also for ET-LF ?)

Upgrade or construction of new benches able to handle 200 kg optics.

Not really covered yet.

# Thank you for your attention