R&D on Sapphire Mirrors for the Einstein Telescope Low-Frequency Detector

Einstein Telescope France Workshop

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Laboratoire des Matériaux Avancées de Lyon

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Overview

Updates on substrates for ET

ET-HF: Fused silica

Fused silica is the baseline for ET-HF

- Mechanical and optical properties ✔

Mirror limitation: Coating Thermal Noise (CTN)

- ET HF target: $\sim 4\times$ lower than in aLIGO

CTN mitigation: post-deposition annealing

T $\leq$ 600°C – for aVirgo/aLigo [1] ✔

- Works well in reducing the CTN

T $>$ 600°C – for aLigo O5 ✘

- Surface figure degradation
- Sustrate absorption/birefringence $\nearrow$

Updates on substrates for ET

ET-LF

Requirements

- Low optical absorption
  - Critical for ITMs to avoid heating cryogenic mirrors
  - Absorption target below $<10\,\text{ppm/cm}$
- Large size: $>45\,\text{cm}$, $\sim200\,\text{kg}$
  - To reduce coating thermal noise
  - To reduce radiation pressure noise

Main issue: High purity material of this size is currently not available

More details: MAD 2025 - Introduction on Substrate Research

ET-LF: Silicon

Current state

Method	Absorption	Key Characteristics
Float-Zone (FZ)	< 10 ppm/cm	High purity, Limited ∅ (currently 200 mm) *Projection: 300 mm expected by 2028, 400 mm over 5 years* MAD 2025 - Contribution ID: 63
Czochralski (Cz)	Medium	High impurities, Large ∅ achievable (300–500 mm)
DS/QM [2]	High	Even higher impurities, Larger ∅ achievable (≥500 mm)

**DS = Directional Solidification, QM = Quasi-Monocrystalline*

More details: MAD 2025 - Contribution ID: 63, ET-0456A-25

Summary

- No single method currently meets all ET-LF requirements
- Hybrid approaches: composite test mass (see MAD 2025 - Contribution ID: 56)

Motivation

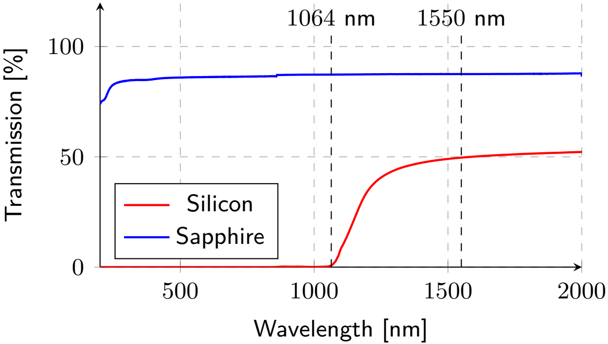


Figure 1: Sapphire[3] and Silicon[4] transmission plots

Better optical transmission from visible to near-infrared

- Well established $\lambda = 1064$ nm technology, a significant advantage

Is it possible to grow sapphire crystals with low or controlled absorption and birefringence?

More details can be found in ET-0469A-25

Sapphire mirrors for ET LF

Sapphire crystal growth in Lyon

Controlled absorption on ⌀30 mm samples (from T. Aventin PhD thesis)

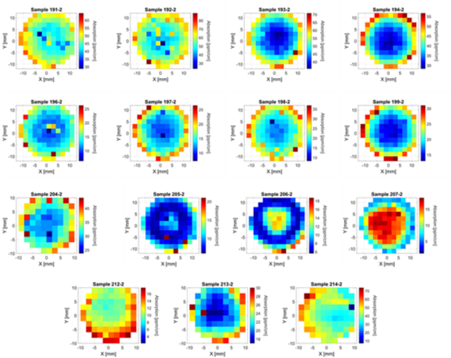
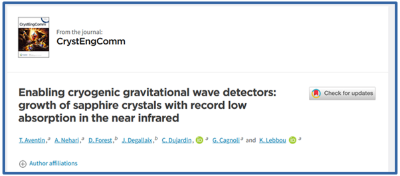


Figure 2: Absorption maps of sapphire crystals for different growth parameters [5]

- Absorption below 15 ppm·cm^{-1}
- Birefringence reduction/uniformity being studied


From the journal:
CrystEngComm

Enabling cryogenic gravitational wave detectors: growth of sapphire crystals with record low absorption in the near infrared

Check for updates

T. Aventin,[a] A. Nehari,[a] D. Forest,[b] J. Degallaix,[b] C. Dujardin,[a] G. Cagnoli[a] and K. Lebbou[a]

Author affiliations

News from KAGRA [LIGO-G2502021]: Sapphire crystals with 10×better birefringence homogeneity were found

Sapphire mirrors for ET LF

Sapphire crystal growth in Lyon

Growing large ingots

Figure 3: Growth furnace for large sapphire crystals

Sapphire bulk of ∅360 mm already produced with Cz method!

- Commissioning of the growth furnace
- Scaled to grow ∅450 mm ingots

Sapphire mirrors for ET LF

Sapphire polishing in Lyon

Seven axis CNC optical polishing machine installed in fall 2024

Figure 4: Zeeko polishing machine at the LMA

- Chemical-mechanical polishing machine
- Up to ∅400 mm, m=50 kg
- Compatible with other materials
- Site acceptance tests done
- Commissioning on going...

More details can be found in ET-0469A-25

Sapphire polishing in Lyon: $\varnothing$100 mm

Flatness correction – Preliminary results

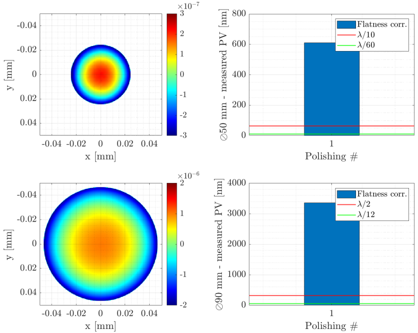


Figure 5: Measured PV after successive polishing iterations

- Results surpassed expectations
  - PV $\simeq \lambda/60$, for $\varnothing$50 mm
  - PV $\simeq \lambda/12$, for $\varnothing$90 mm
- Many iterations, but reducible
- Did we reach the limits of the machine?
- Next step, ion beam figuring!

Very good workflow polishing $\Longleftrightarrow$ metrology at the LMA

Sapphire mirrors for ET LF

Sapphire polishing in Lyon: ∅100 mm

Roughness correction – Preliminary results

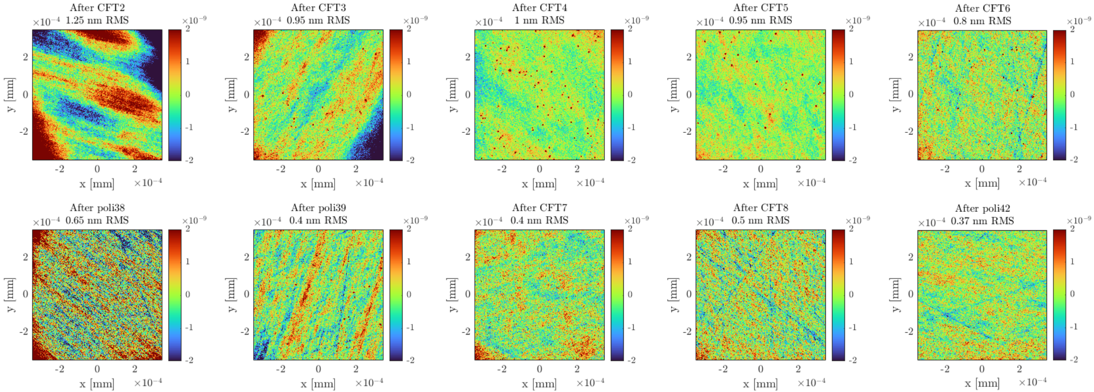


Figure 6: Roughness maps after the specified polishing iterations

Propagation of polarised light in birefringent media

The OSCAR upgrade will account for:

- Arbitrary incident polarization – s and/or p
- Arbitrary angle of incidence – (θ, ϕ)
- Arbitrary c-axis orientation – $\phi_c(x, y)$
- Birefringence magnitude maps – $\Delta n(x, y)$
- Fast axis orientation maps – $\rho(x, y)$

> Accurate computation of $t_{s,p}(x, y)$ and $r_{s,p}(x, y)$ for any birefringent plate

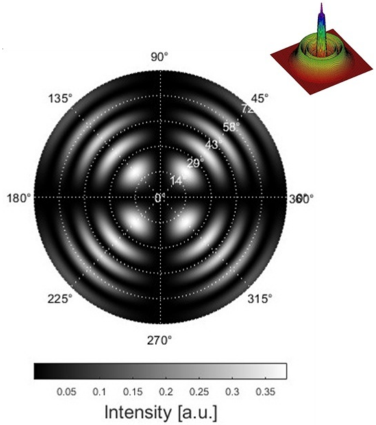
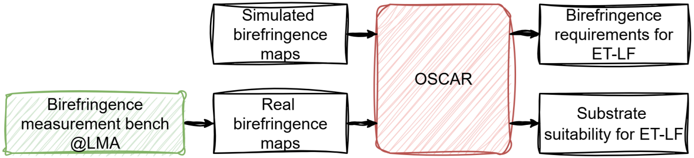


Figure 7: Computed conoscopic pattern of a c-plate between crossed polarisers

Development updates

Towards defining the birefringence requirements of ET LF

- New MATLAB birefringence functions developed
  - Transmission, Reflection, and Propagation
  - Being adjusted for OSCAR scripting
- OSCAR being updated to support s and p pol.



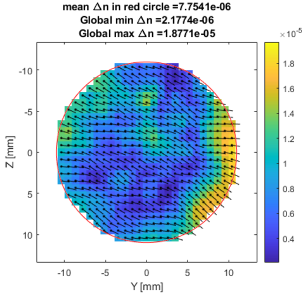


Figure 8: Example of birefringence map.

Summary and outlook

Substrates for ET

- ET-HF: Silica substrates can't handle high-temp annealing for CTN reduction
- ET-LF: High purity silicon/sapphire ET-scale substrates are not yet available

Sapphire polishing (LMA and IP2I)

- Polishing larger sapphire substrates: $\varnothing$200 mm and $\varnothing$300 mm
- Polishing of the barrel and flats

Birefringence characterisation and modelling (LMA)

- Measuring the birefringence on upto $\varnothing$450 mm sapphire substrates
- Using OSCAR to set birefringence requirements and verify substrate suitability for ET

MAD26 in Lyon! Save the date :)

Next Materials for Advanced Detectors workshop in Lyon, 12-14 october 2026

- LMA Lab tour: the famous ”Grand coater”, the polishing machine, the sapphire growth furnace, etc.

References

M. Granata, A. Amato, G. Cagnoli, M. Coulon, J. Degallaix, D. Forest, L. Mereni, C. Michel, L. Pinard, B. Sassolas, *et al.*, “Progress in the measurement and reduction of thermal noise in optical coatings for gravitational-wave detectors,” *Applied optics*, vol. 59, no. 5, pp. A229–A235, 2020.

F. M. Kiessling, P. G. Murray, M. Kinley-Hanlon, I. Buchovska, T. K. Ervik, V. Graham, J. Hough, R. Johnston, M. Pietsch, S. Rowan, *et al.*, “Quasi-monocrystalline silicon for low-noise end mirrors in cryogenic gravitational-wave detectors,” *Physical review research*, vol. 4, no. 4, p. 043043, 2022.

Thorlabs, “Transmission of uncoated sapphire. measurement at normal incidence of the total transmission of our 5 mm thick uncoated sapphire window.”

Thorlabs, “Transmission of uncoated silicon. measurement at normal incidence of the total transmission of our 5 mm thick uncoated sapphire window.”

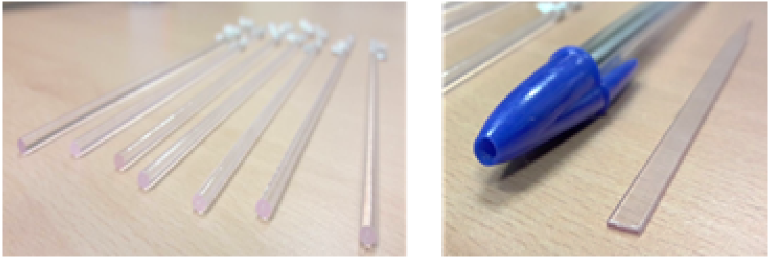
T. Aventin, *Development of very low optical absorption sapphire substrates for the cryogenic gravitational wave detector mirrors.*
PhD thesis, Université Claude Bernard-Lyon I, 2024.

Thank you for your attention!

Questions?

Sapphire crystal growth in Lyon

Monocrystalline fibres and ribbons (micro-pulling down method)



- Different geometries with good surface quality
- Up to 1 m long fibres, with ∅3 mm
- Better cooling, higher tensile strength for suspensions

Implementation of birefringent effects in OSCAR

Example: sapphire (a-plate) half wave plate

$$
\begin{cases}
n_o = 1.7680 \\
\Delta n_{x,y} = -0.008 \pm 10^{-5} \\
\phi_{c_{x,y}} = \dfrac{\pi}{4} \pm 10^{\circ} \\
\lambda = 1064 \text{ nm} \\
d = \dfrac{\lambda}{2\overline{\Delta n}}
\end{cases}
$$