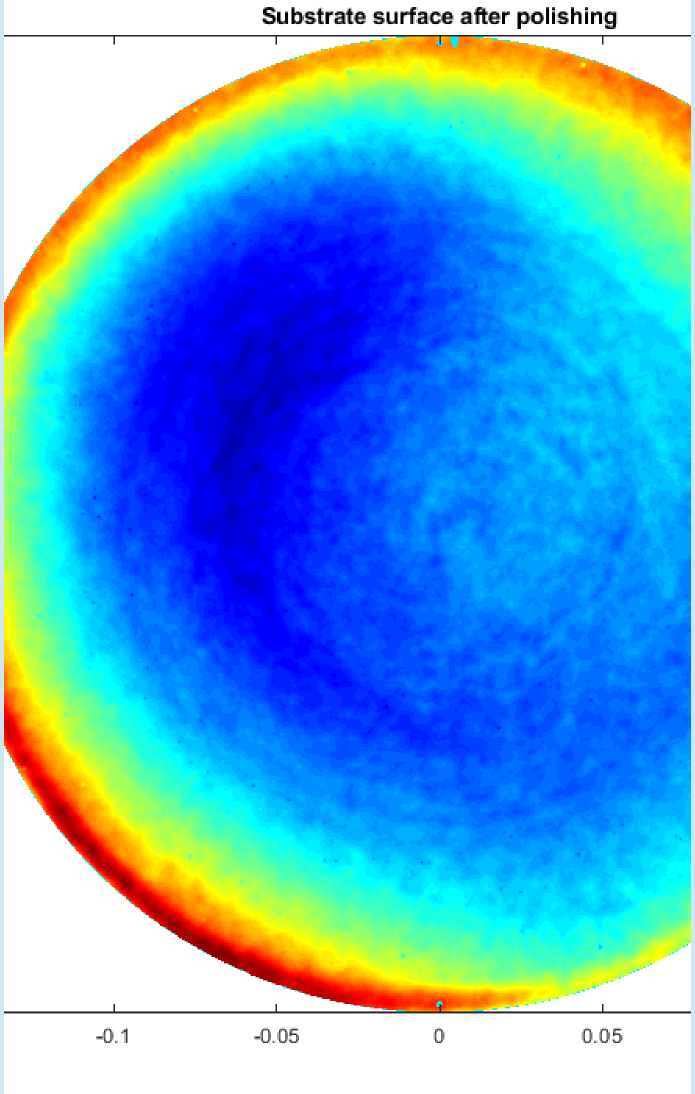
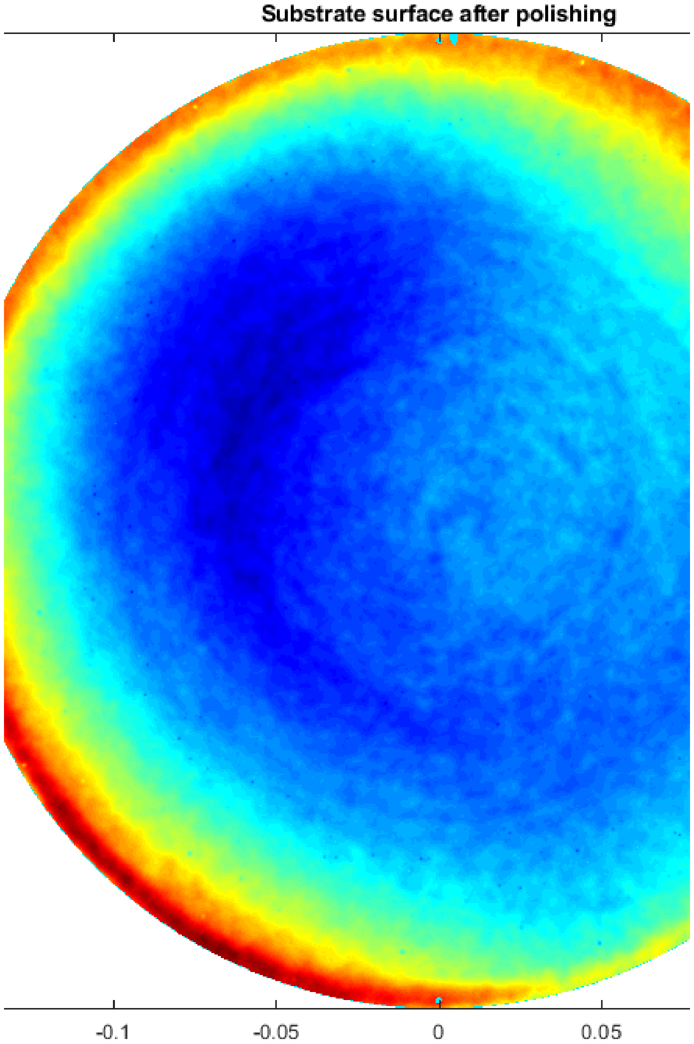


Large optics for next generation gravitational wave detectors

Jerome Degallaix - LMA

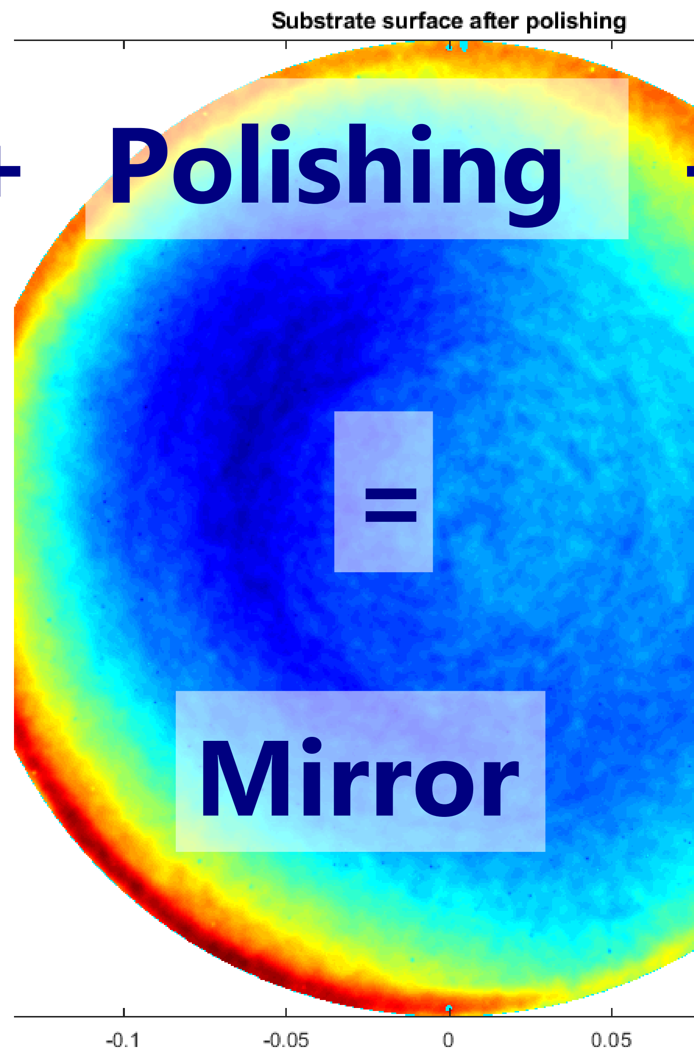
GRAvitational-wave Science & technology Symposium – Padova - 2018

The 3 ingredients of a mirror:



The 3 ingredients of a mirror:

Substrate +



Polishing +

Coating

=

Mirror

My perfect mirror:

Substrate

- as big as I want
- no optical loss
- no mechanical loss
- heavy
- easy to polish
- ...

My perfect mirror:

Substrate

- as big as I want
- no optical loss
- no mechanical loss
- heavy
- easy to polish
- ...

Polishing

- perfect curvature
- no roughness
- arbitrary shape
- ...

My perfect mirror:

Substrate

- as big as I want
- no optical loss
- no mechanical loss
- heavy
- easy to polish
- …

Polishing

- perfect curvature
- no roughness
- arbitrary shape
- …

Coating

- as big as I want
- no optical loss
- no mechanical loss
- maintain the polishing quality
- …

My perfect mirror:

Substrate

- as big as I want
- no optical loss
- no mechanical loss
- heavy
- easy to polish
- …

Polishing

- perfect curvature
- no roughness
- arbitrary shape
- …

Coating

- as big as I want
- no optical loss
- no mechanical loss
- maintain the polishing quality
- …

And all of that for a good price and with a quick delivery!

This morning session

I will not talk about coating thermal noise since it has some dedicated talks:

Topic 2: Development Of Enabling Technologies For Gravitational Wave Detectors		11:40-13:10
11:10	Large optics for next generation gravitational wave detectors	DEGALLAIX Jerome
11:40	LISA optical metrology challenges	PENKERT Daniel
12:00	The VIRGO coating collaboration: research lines and preliminary results of a detailed study on thermoelasticity in crystalline materials	CESARINI Elisabetta
12:20	The VIRGO coating collaboration: a new deposition facility and preliminary results on nano-layered coatings	PRINCIPE Maria

More this afternoon also at 2:30

I

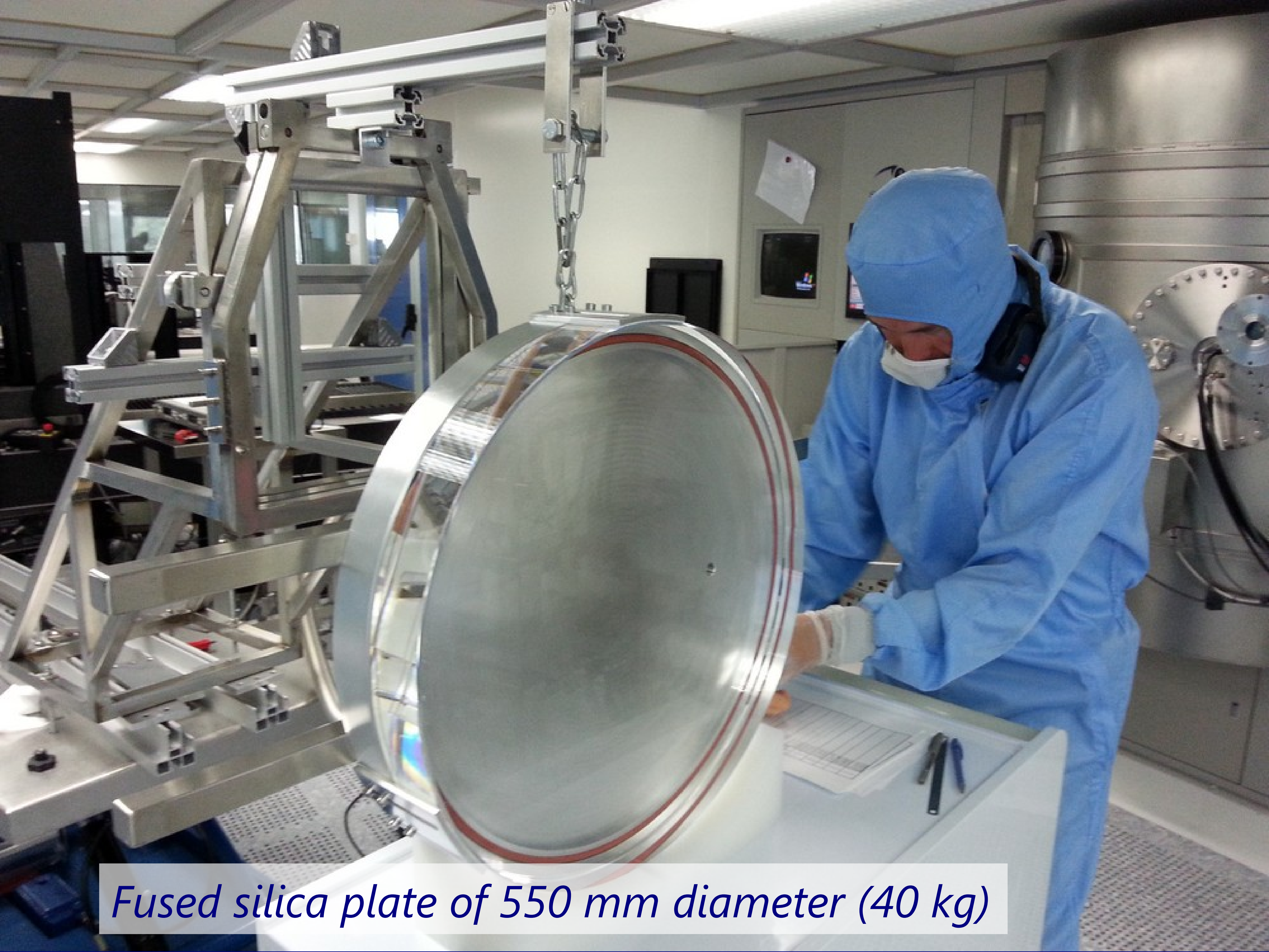
The substrate’s choice

The king: fused silica

THE test mass substrate for the room temperature first and second generations of gravitational wave detectors

A well justified choice:

- extremely good optical properties
    - bulk absorption < 1 ppm/cm @ 1064 nm
    - birefringence < 1 nm / cm
    - excellent homogeneity $\Delta n < 2\times10^{-6}$
    - 3D isotropic
- available in large size
- polishing and coating well mastered



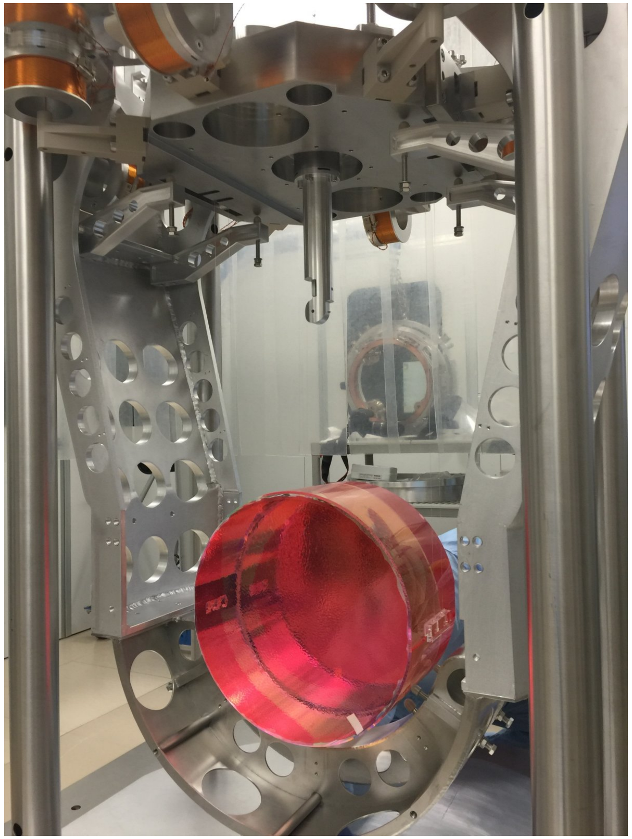
Fused silica plate of 550 mm diameter (40 kg)

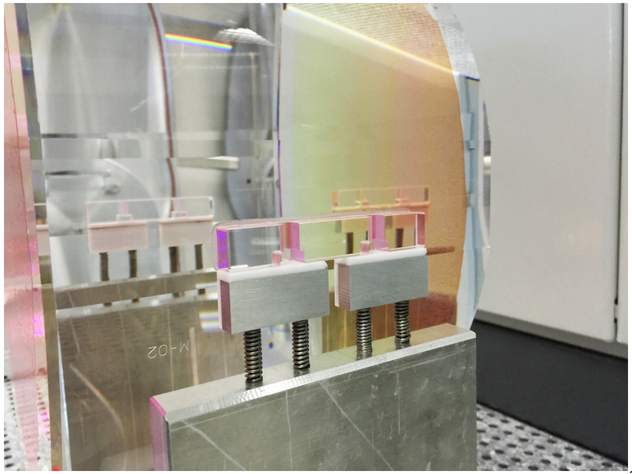
The king: fused silica

Some more properties particularly relevant to GW detectors:

- very low bulk thermal noise
- possibility of monolithic suspension

Reduction of the undesired displacement of the surface mirror due to thermal noise





Fused silica substrate for next generations

2 days ago, visit to Heraeus one of the main providers of very high purity fused silica.

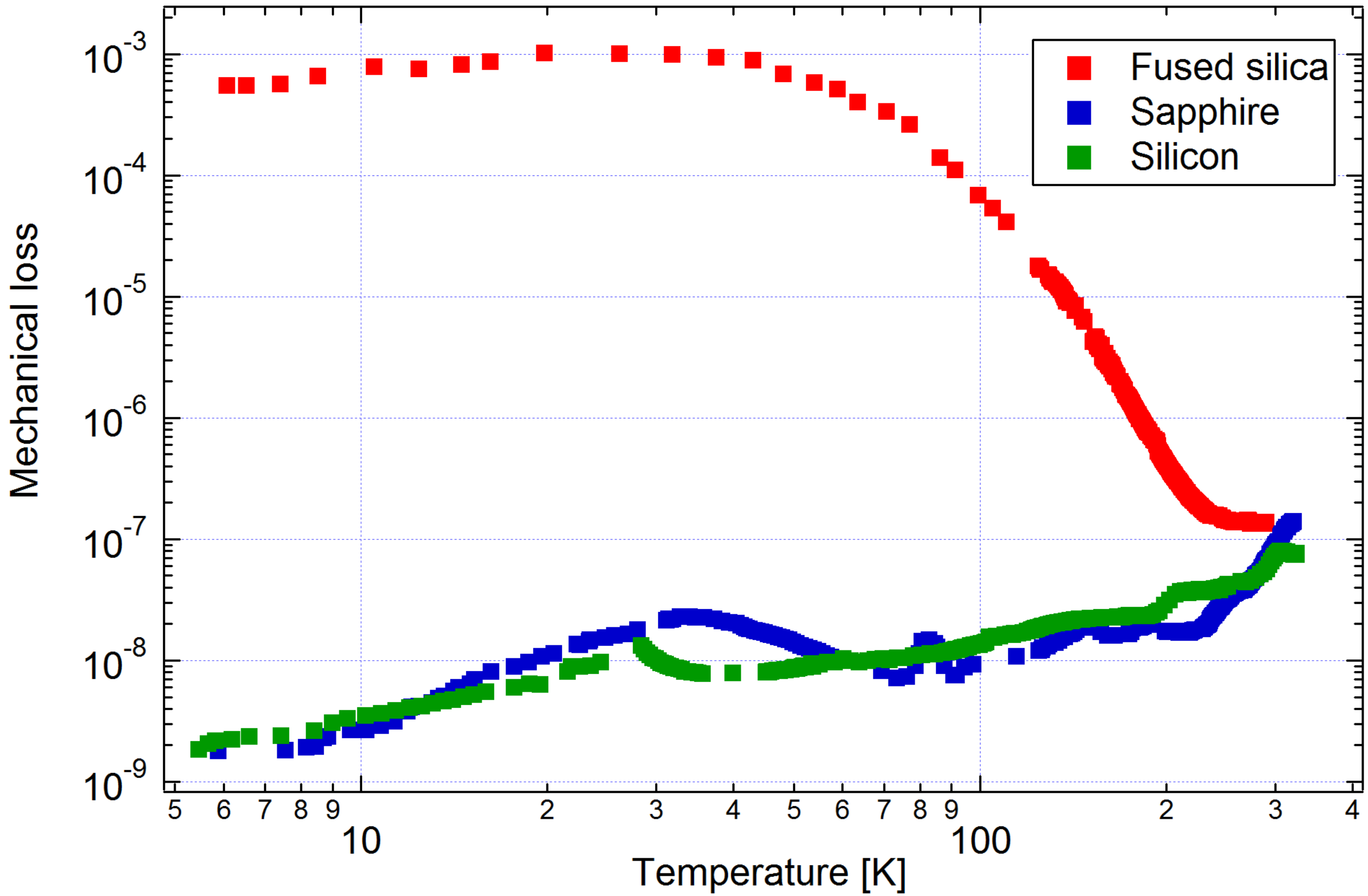
What we learned:

- for 1D functional materials (IM, EM, PR,…):
  100kg or 200 kg, 600 mm diameter : no problem
  limit: handling tool, roof of the factory

- for 3D functional materials (BS):
  limited to 40 kg due to the homogenisation process
  will investigate how to go further, but no promise

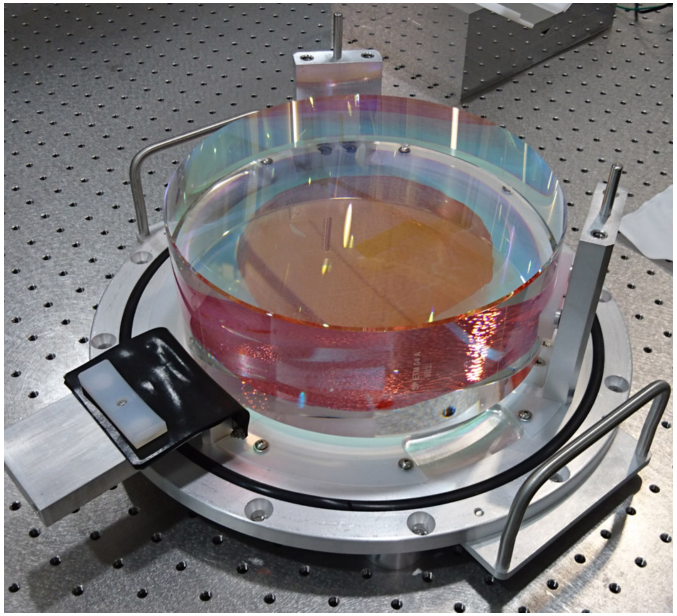
We may need something else for low T

Crystalline materials have Lower substrate mechanical loss at low temperature

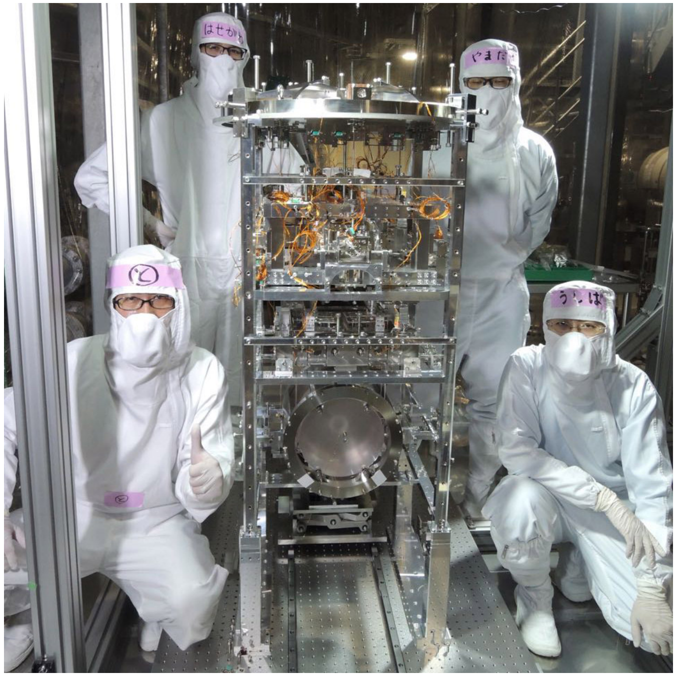


The cool outsider: sapphire

- crystalline material
- not available in large size for high purity (Ø 220 mm for Kagra)
- relatively high absorption (~ 20 ppm/cm at best)
- high thermal conductivity
- implemented in KAGRA with monolithic suspension (talk at 14:50)



Sapphire substrate



Cryogenic suspension

For third generation detectors…

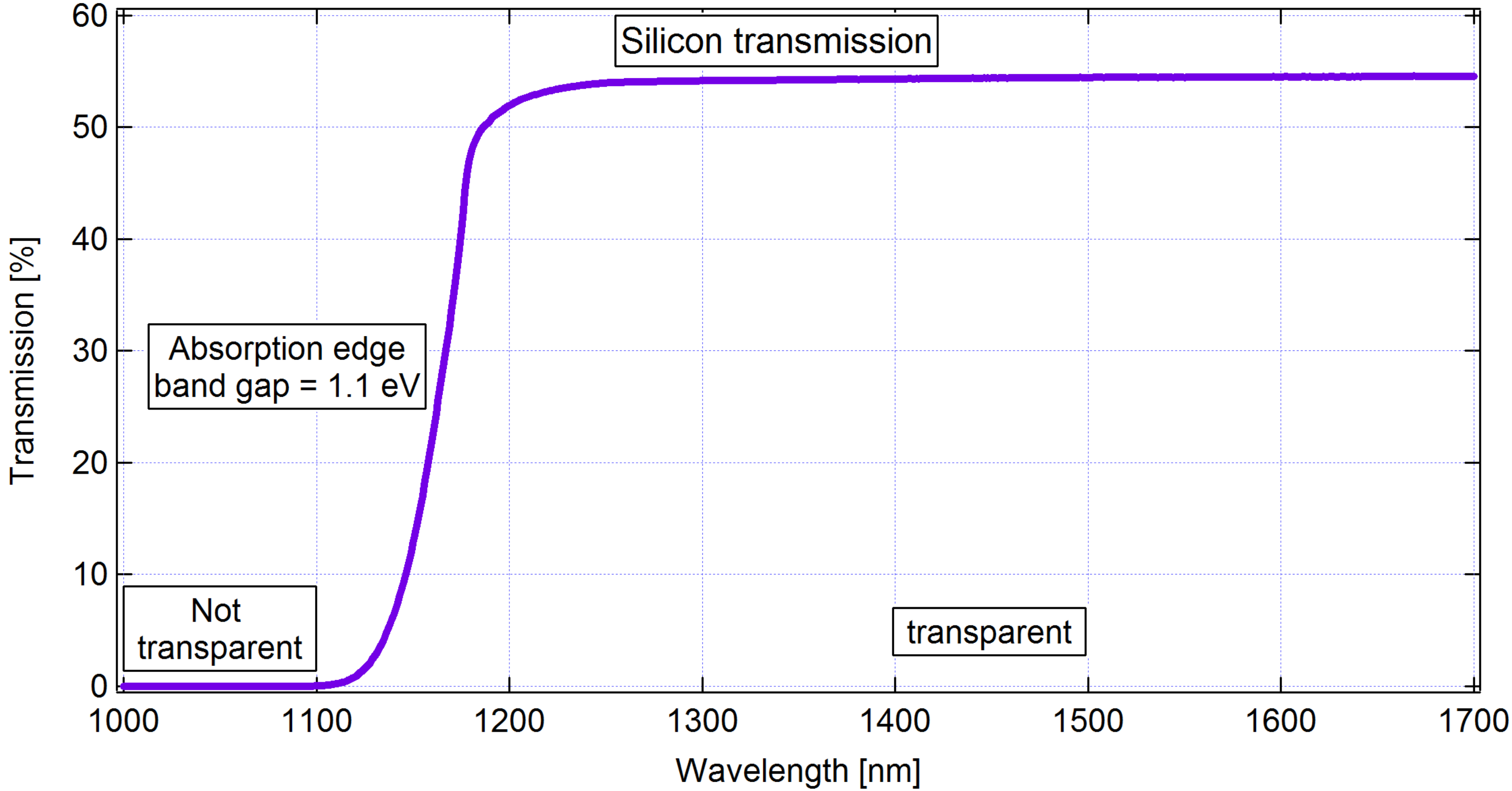
Longer arm length → larger beam size

→ looking for larger substrates

- For room temperature: keep the fused silica
- For low temperature, we would like:
  - the size and optical properties of fused silica
  - the mechanical / thermal properties of sapphire

Is silicon the answer ?

Transmission spectra

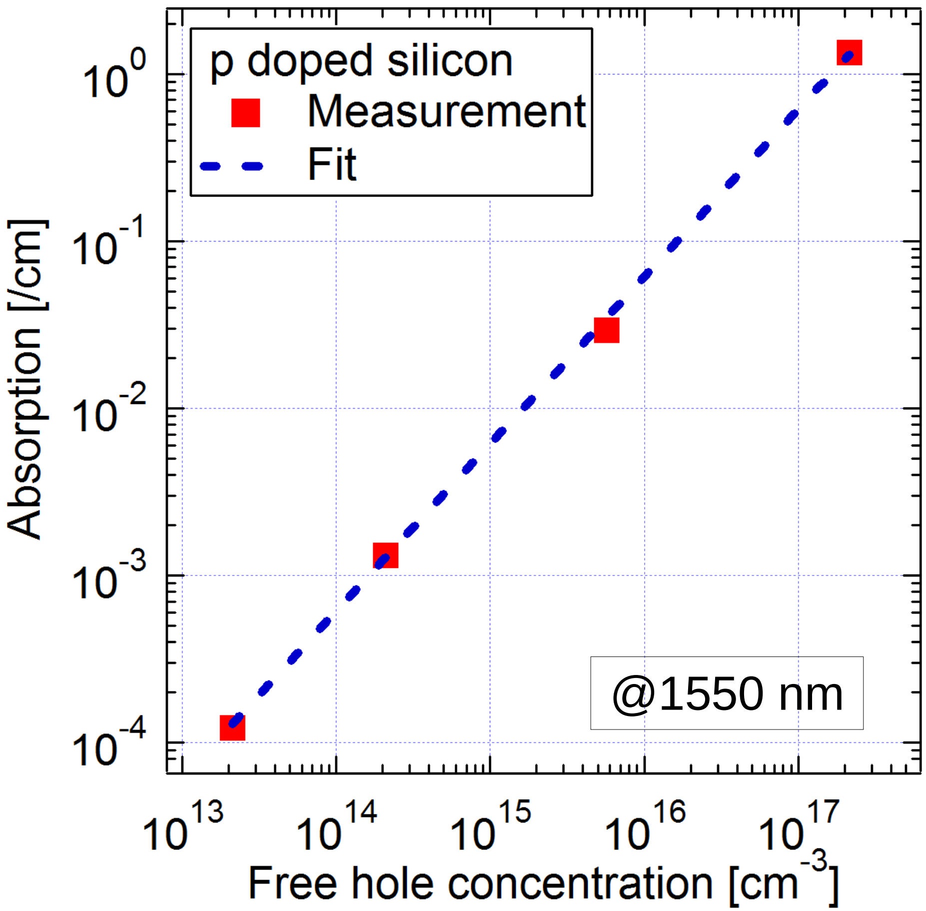


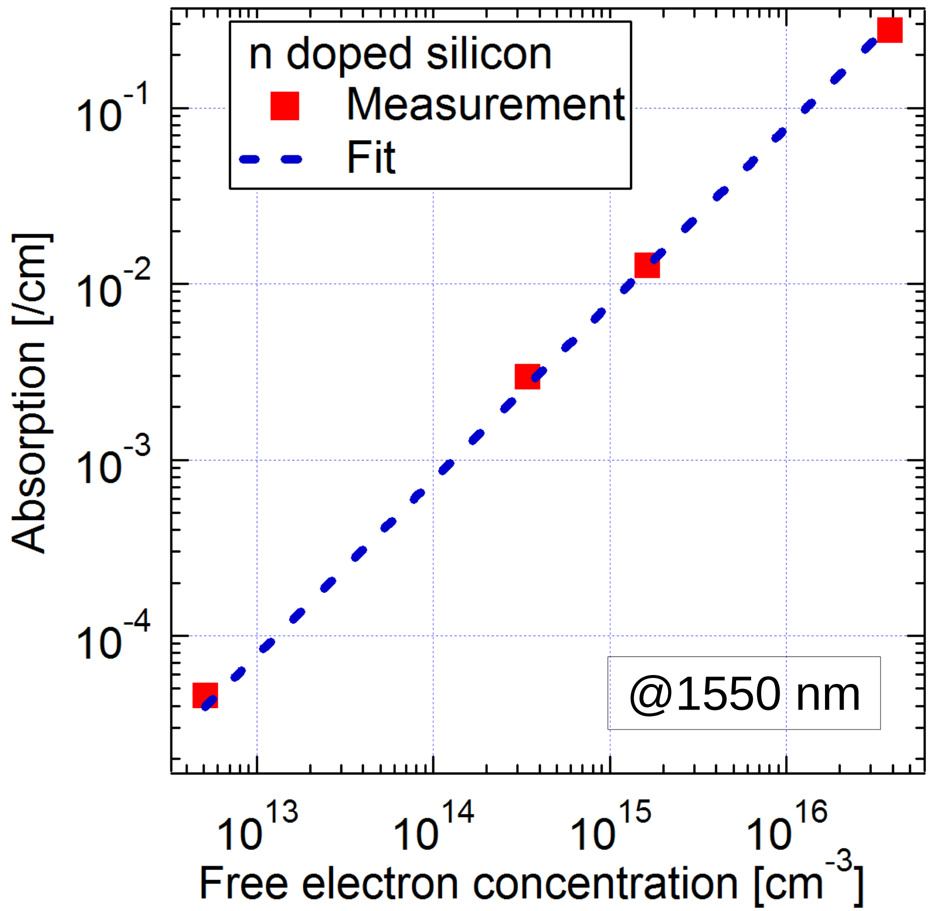
Not transparent at 1064 nm → new laser, likely 1550 nm

High refractive index, n=3.45 → uncoated: reflectivity of 30%

Absorption as a function of the doping (Troom)

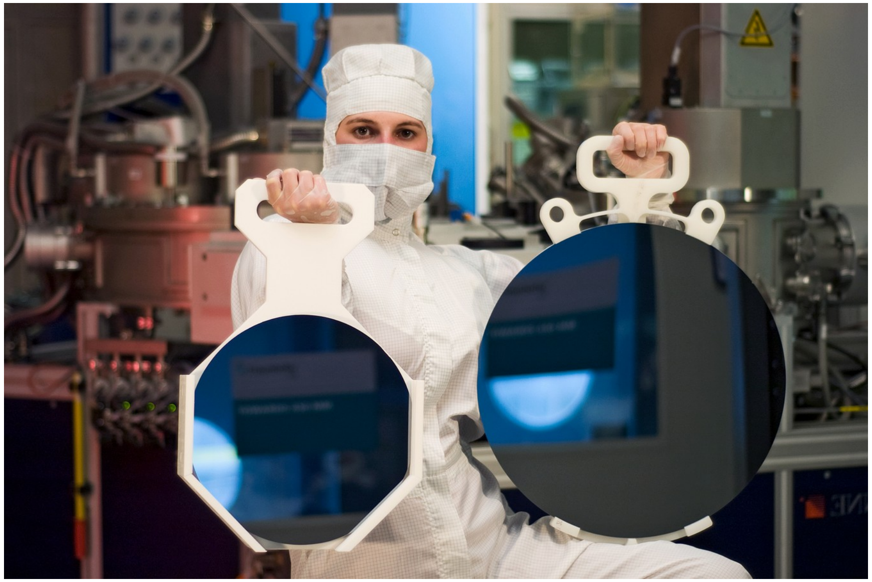
- Absorption is due to the free carrier
- Free carrier concentration is equal to dopant concentration
- Absorption as low as 5 ppm/cm has been measured



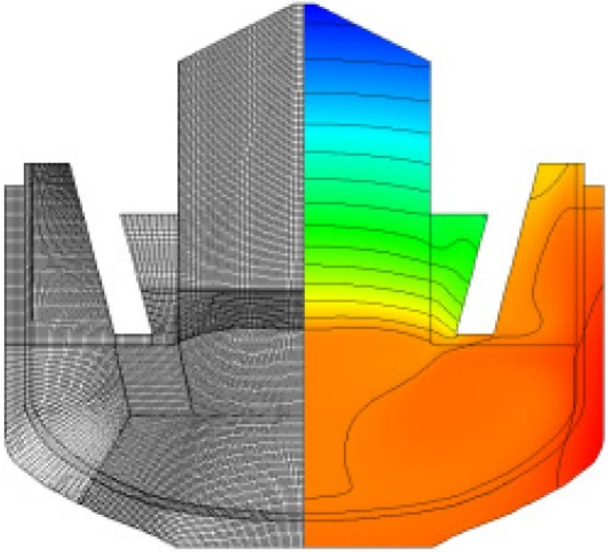


Size and absorption

- Size and absorption are linked (due to the fabrication process)
- High purity Si achieved on smaller samples (Float Zone)
- Magnetic Czochralski crystal growth (MCz) may provide 450 mm diameter substrate with absorption as low as 5 ppm/cm

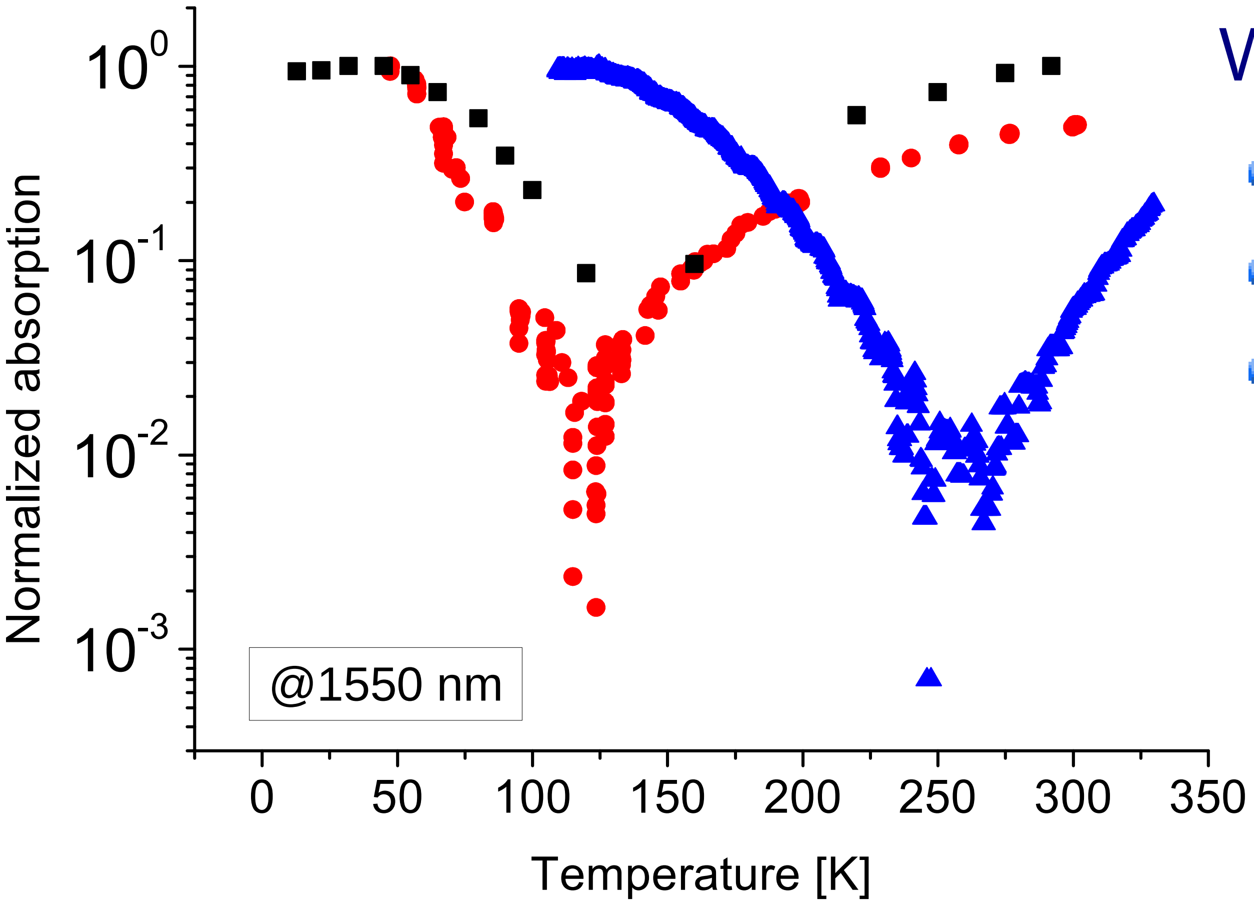


300 mm and 450 mm diameter wafer



Temperature simulation during Si growth

Absorption vs temperature



With different dopant:

- Phosphorus
- Boron
- Gallium

Same magnitude of the optical absorption at cryogenic temperature! could be an issue if not pure material

II

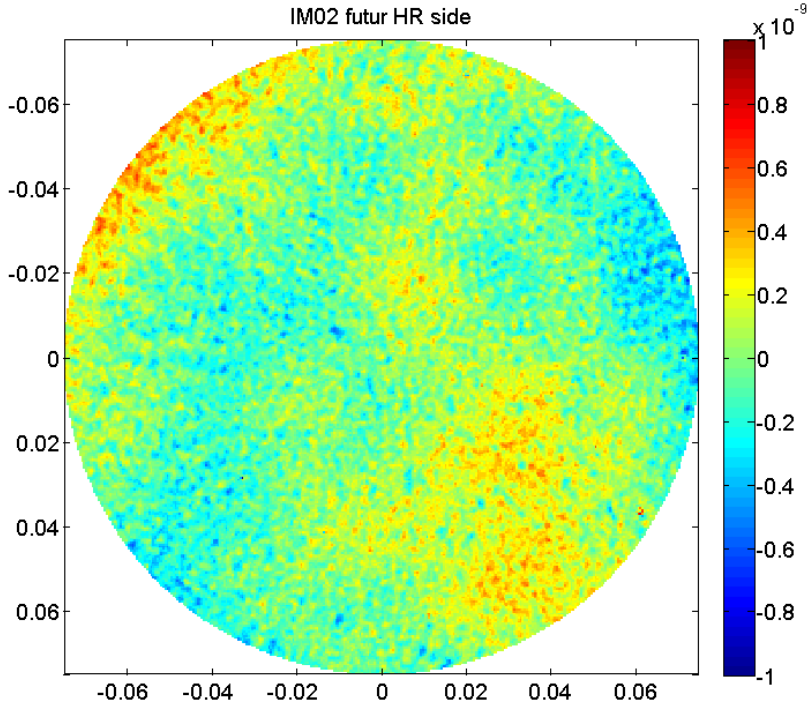
The polishing

Second generation achievement

Outstanding polishing capabilities for fused silica!

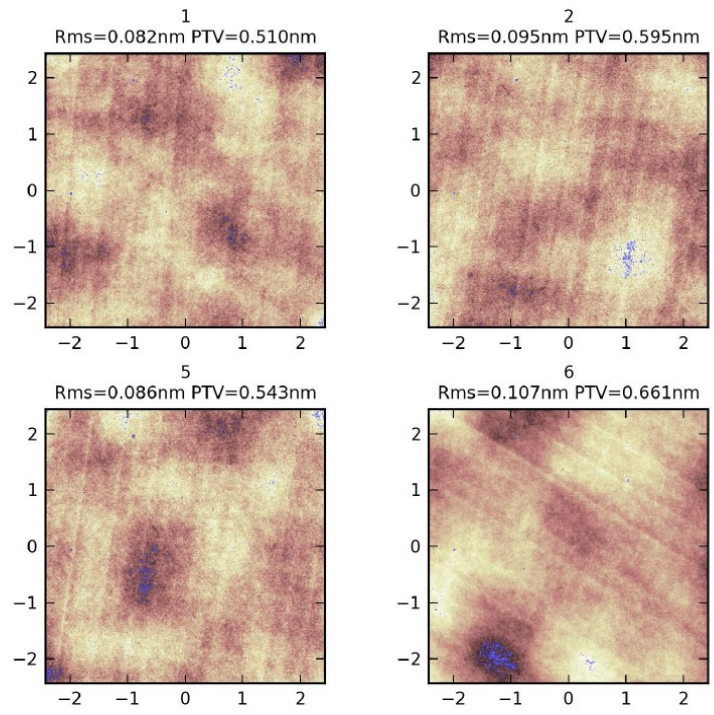
Radius of curvature within 2 meters accuracy (over 1.5 km)

Low spatial frequency surface figure:



RMS < 0.2 nm
over 150 mm diameter

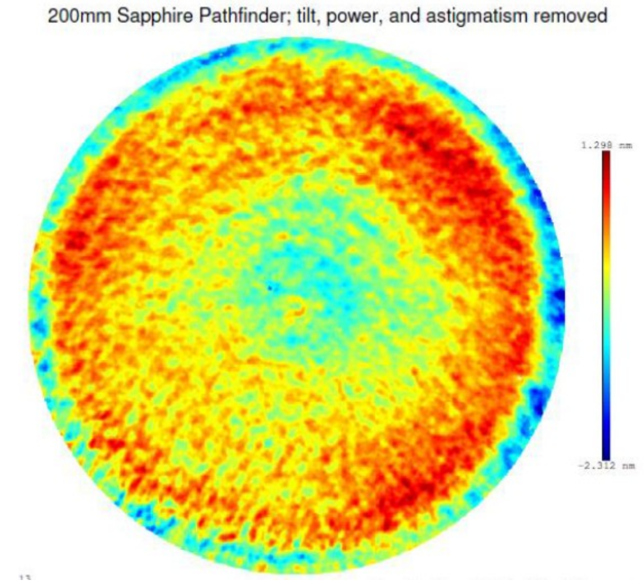
High spatial frequency figure:



RMS < 0.1 nm

Sapphire and silicon polishing

- Sapphire:
  - Used to be difficult
  - Possibility to achieve same performances as fused silica (more expensive)



~ 0.5 RMS over Ø 180 mm

- Silicon:
  - No major issue, large experience in the industry
  - RMS micro-roughness slightly higher than for FS
  - Silicon more brittle, easier to damage during cleaning / handling

Final words on polishing

- Personal thoughts:
  - Currently outstanding
  - Do not expect much better performances for third generation (we are already at the atomic scale)
  - Metrology is also critical at this level
  - The larger the mirrors, the larger the cost of polishing

III

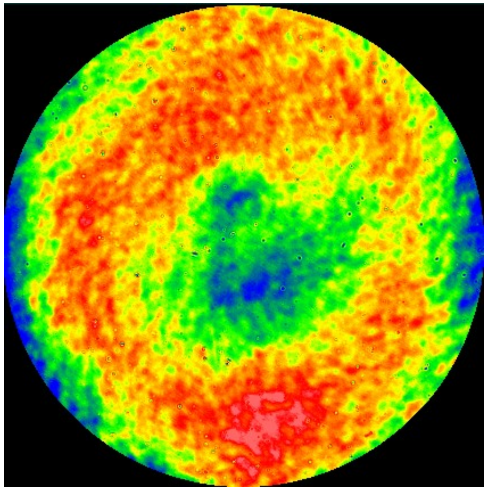
The last step: the coating

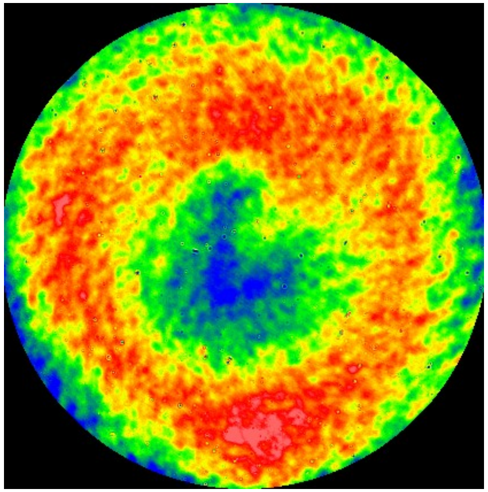

All test masses of LIGO, Virgo and Kagra have been coated at LMA

What has been achieved: the coating

State of the art Ion Beam Sputtering (IBS) coating:

- possibility to coat large substrates (up to Ø 55 cm)
- low mechanical loss (HR coating $\varphi \sim 2\text{-}3\times10^{-4}$)
- very low absorption (< 0.3 ppm @ 1064 nm)
- Low scattering, 4 ppm (on average over 20 mirrors)
- RMS of ~ 0.5 nm for HR ETM (coating thickness: 6 μm)





Surface over 160 mm of the 6 μm HR coating (T = 3 ppm)

Challenges ahead!

- Worldwide research focuses on reducing the coating thermal noise:
  - different coating technologies / parameters
  - new amorphous materials (Nb, SiN, aSi)
  - new coating design (3 material stack)
  - crystalline coating
  - … (not an exhaustive list)

- But we should also keep an eye on the optical performances (absorption, scattering) and the technology scaling for large mirrors

Research on the coating process at LMA

- Research on large coating size (Ø >350 mm):
  - coating one piece at a time
  - simple rotation
  - goal: coating uniformity 0.1% up to 550 mm
  - post deposition corrective coating

- Transmission matching will be crucial
  - in-situ optical monitoring improvement
  - post deposition corrective coating

<u>Legend</u> : work in progress

Research on the coating process at LMA

- Ultra-low antireflective coating
  - state of the art R<100 ppm @ 1064nm AOI 0°
  - goal : R< 50 ppm @ 1064 nm AOI 0°
  - and same performances for other wavelength and AOI
  - in-situ optical monitoring improvement

- Reduce the optical scattering
  - nature and origin of the defect ?
  - 5 months internship has started

Conclusion

- Extremely satisfying optics for second generation have been achieved

- For next generation, substrates* and polishing will be suitable, everyone is looking at progresses on the coating front

- Heavier constraint on the metrology

* a large substrate for cryogenic detector has still to be demonstrated

Sources and credit

Title slide photos and pages 2-3

- left: https://upload.wikimedia.org/wikipedia/ru/7/72/Chohralsky_Silicon_Crystal_Growth.jpg
- middle: surface flatness EM01 AdV
- right: ©Cyril FRESILLON/LMA/CNRS Photothèque

Slide 11

- Picture taken at LMA during the cleaning of the Advanced Virgo beamsplitter

Slide 12

- Pic from the Virgo Collaboration
- From the Virgo logbook post 31956

Slide 14

- “Silicon and Sapphire - mechanical, thermal and optical properties” by R. Nawrodt, P8 (ET-0002A-15)

Slide 15

- From Kagra logbook post 3613
- From Kagra logbook post 3073

Slide 17-18

- /measurement done at LMA

Sources and credit

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- https://wccftech.com/foundries-tsmc-companies-shift-300mm-wafers/
- Simulations of silicon cz growth in a cusp magnetic field - C.-H. Lin et al.

Slide 20
- “Optical measurements at cryogenic temperatures” - J. Komma – GWADW 2013

Slide 22
- Data taken from the polishing reports for the Advanced Virgo arm cavity end mirrors

Slide 23
- “Development of a cryogenic mirror system for the KAGRA GW detector” E. Hirose 2014

Slide 26
- Le Grand Coated ©Cyril FRESILLON/LMA/CNRS Photothèque

Slide 27
- L. Pinard et al, Mirrors used in the LIGO interferometers for first detection of gravitational waves Applied Optics Vol. 56, No. 4
- M. Granata et al, Mechanical loss in state-of-the-art amorphous optical coatings, Phys. Rev. D 93, 2016, p.012007