Core Optics
Materials Properties and Heat Extraction

ISB WORKSHOP OCTOBER 2022

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Topics

Materials Parameters

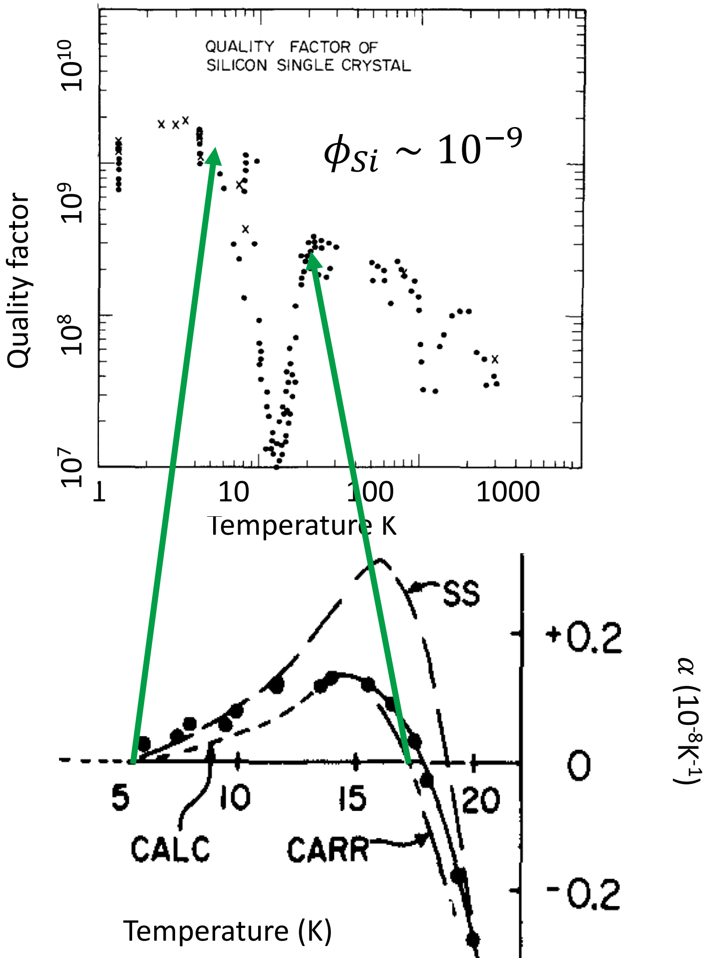
- ☐ Substrate - Silicon
- ☐ Substrate - Sapphire
- ☐ Coatings

Heat Extraction

- ☐ Laser Absorption
- ☐ Ice Layer problem
- ☐ Thermal Radiation → See Fulvio Ricci's talk
- ☐ Fibres → See Graeme Eddolls' talk

Substrate Parameters - Silicon

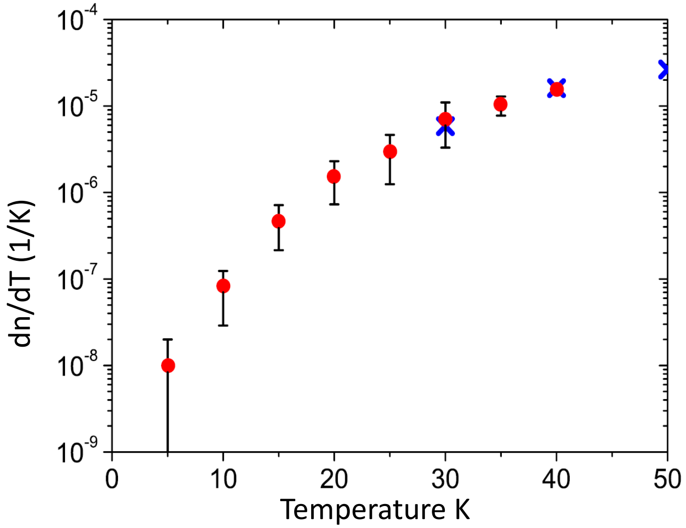
J Low Temp Phys **30** no. 5, (1978) 621–629.



J. Appl. Phys. **48**, 865 (1977) 865–868

Coefficient of thermal expansion is zero at around 18 K (NO thermoelastic loss)

Appl. Phys. Lett. **101**, 041905 (2012)



The thermo-optic coefficient leads to thermal lensing, thermo-refractive noise and birefringence

Class. Quantum Grav. **33** (2016) 015012

Thickness (mm)	Diameter (mm)	Mass (kg)	$\Delta n \times 10^{-7}$
65	100	1.2	0.23–1.07
28	24	0.059	1.08–1.11
30	24	0.063	0.33–0.49
99	24	0.21	0.09–0.17

All the substrates have the shape of cylinders with biconvex faces with the light propagating along the (111) direction.

$$Y_{\text{silicon}} = 130 - 180 \text{ GPa}$$

$$\rho_{\text{silicon}} = 2{,}33 \text{ g/cm}^3$$

(if 55 cm diameter, 210 kg, then t = 38 cm)

Substrate Parameters - Silicon

Silicon

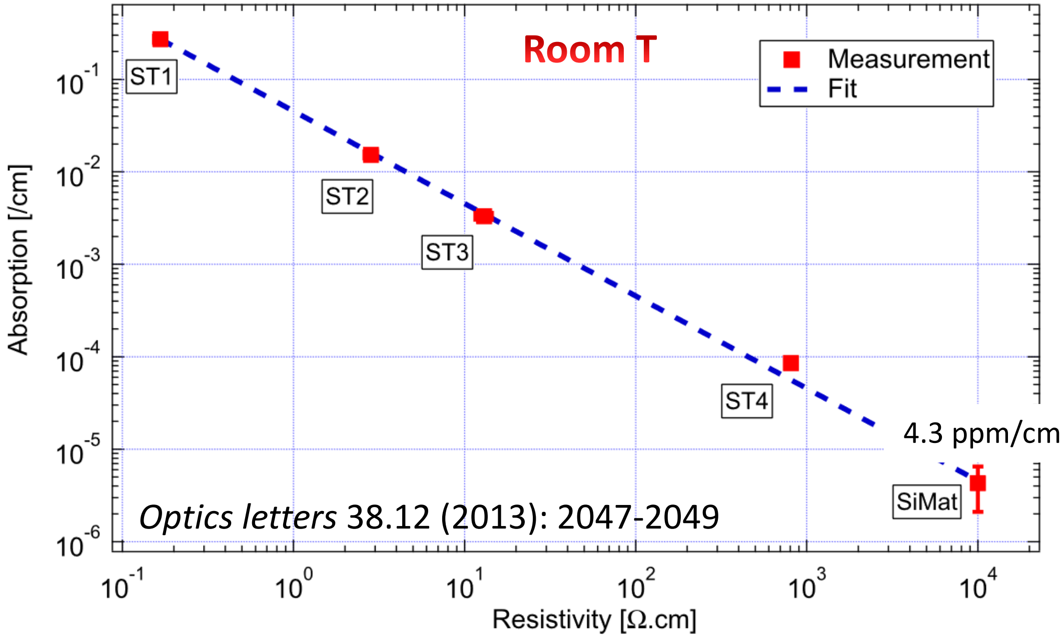
The IR optical absorption in crystalline silicon is normally limited by interband energy states associated with impurities. The maximum diameter and purity depend on the fabrication process.

Float Zone
- Small samples (Ø 20 cm)
- Low absorption: 4 - 50 ppm/cm

(*Optics letters* 38.12 (2013): 2047-2049)

Magnetic Czochralski
- Large samples (Ø 45 cm)
- High (?) absorption (20 ppm/cm)

(ET DR 2020)



Optics letters 38.12 (2013): 2047-2049

Quasi-mono ingots (P. G. Murray – LVK Sept. 2020)
- Large samples (Ø 40 cm)
- High absorption ($3\cdot10^{-3}$ 1/cm -> Potential for 3 – 4 orders of magnitude improvement)

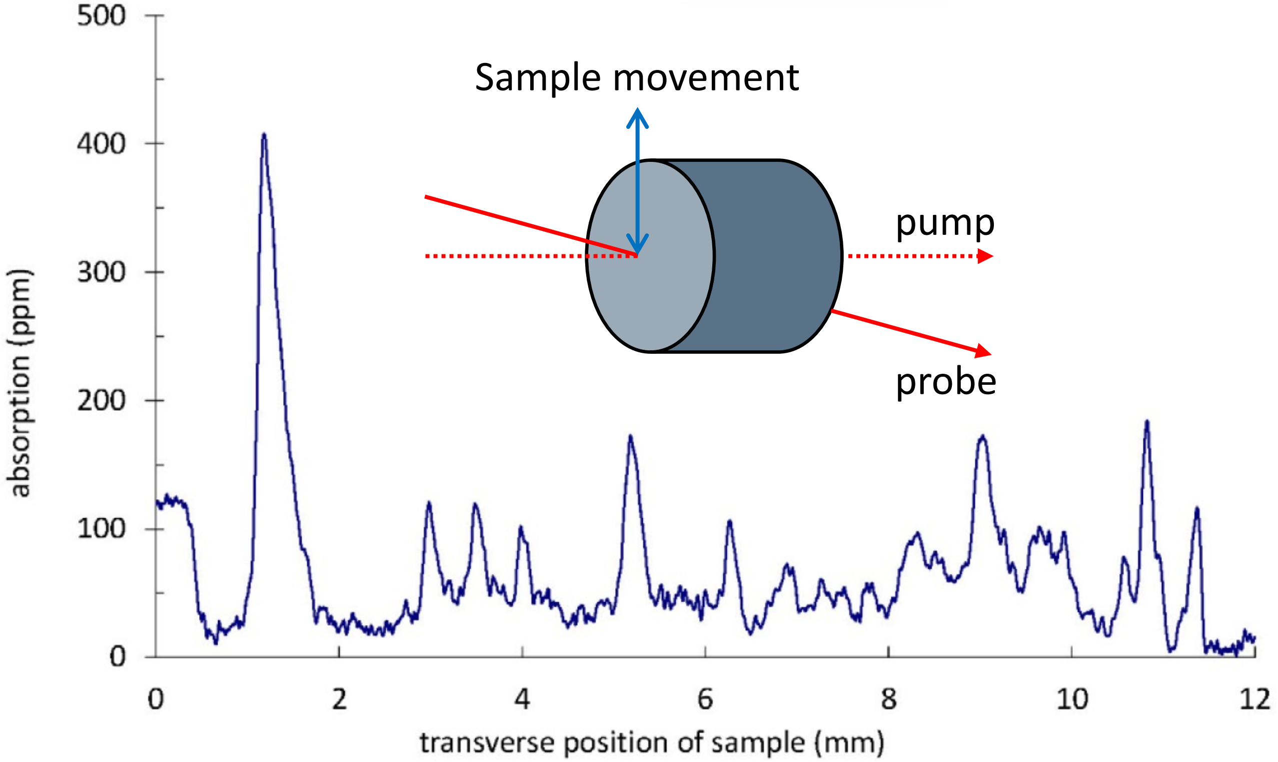
(thank to its size, QM silicon might be suitable for large ETMs where absorption can be greater)

Substrate Parameters - Silicon

Silicon

NB: Surface quality is also important for the absorption

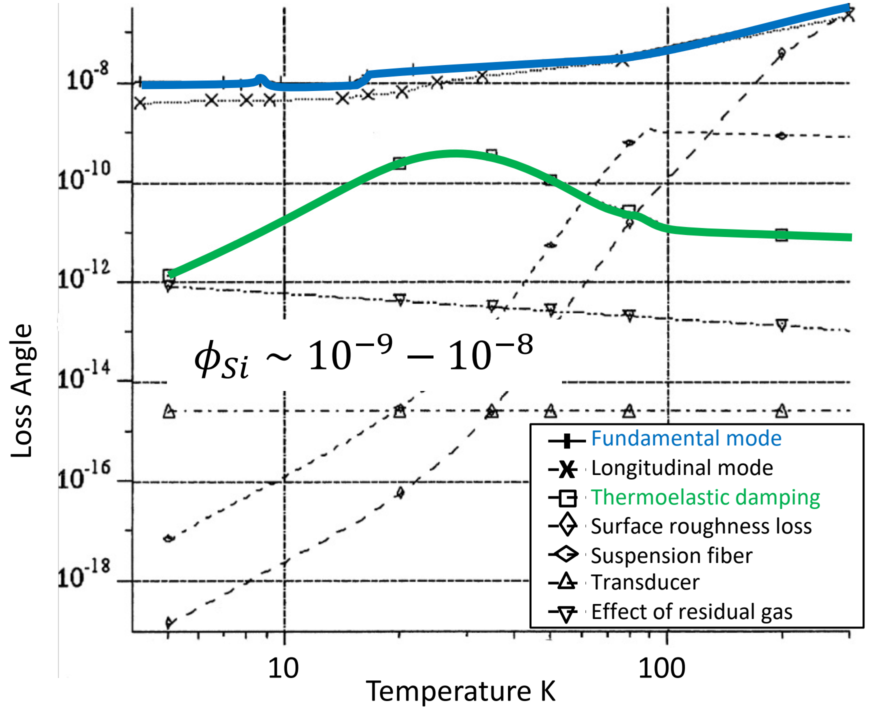
Class. Quantum Grav. **34** (2017) 205013



Substrate Parameters - Sapphire

Sapphire

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

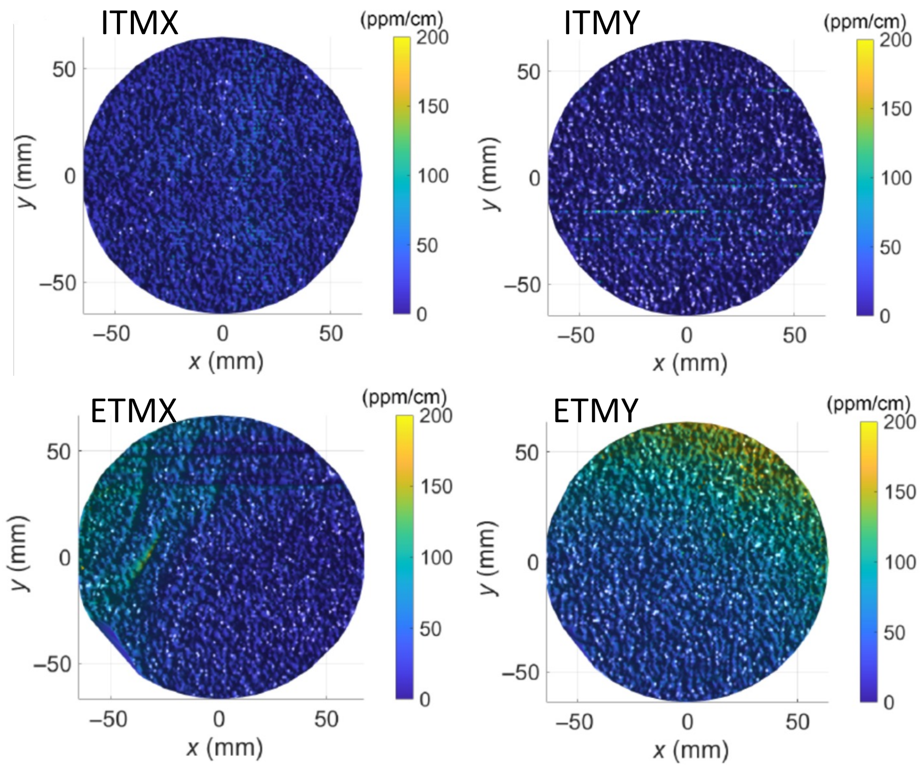


$Y_{sapphire}$ = 450 – 490 GPa

ρ_{sapphire} = 3,97 – 3,99 g/cm^3
(if 55 cm diameter, 210 kg, then t = 22 cm)

Sapphire is transparent @ 1064 nm

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

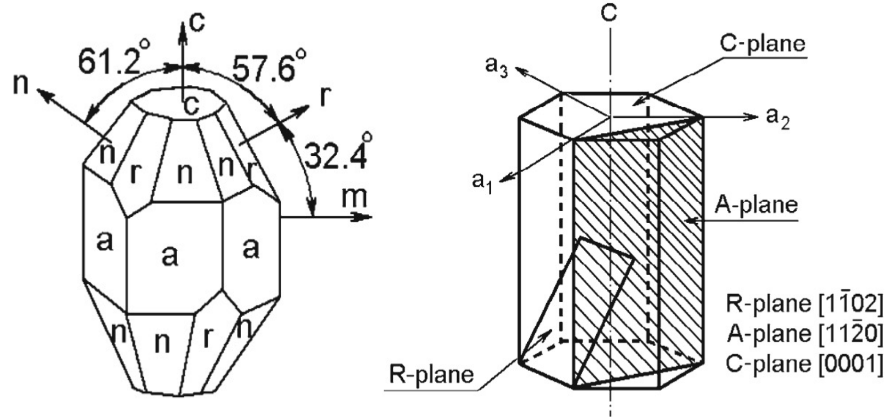


Absorption @ 1064 nm of KAGRA TMs
Values @1064 nm → @1550 nm better ?

Substrate Parameters - Sapphire

Sapphire

Sapphire is a birefringent crystal, but the index of refraction on the plane (c plane) perpendicular to the C-axis would be uniform if the crystal were perfect

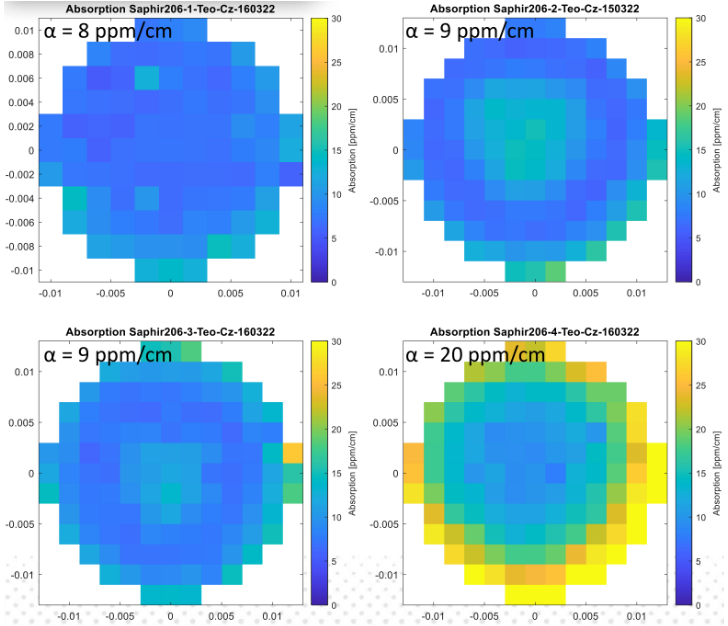


Both absorption and birefringence could be due to structural defects -> technological problem (LIGO-G2201668, LVK2022)

KAGRA is working with the companies providing the substrates in order to understand how to reliably lower the absorption and how to control the birefringence.

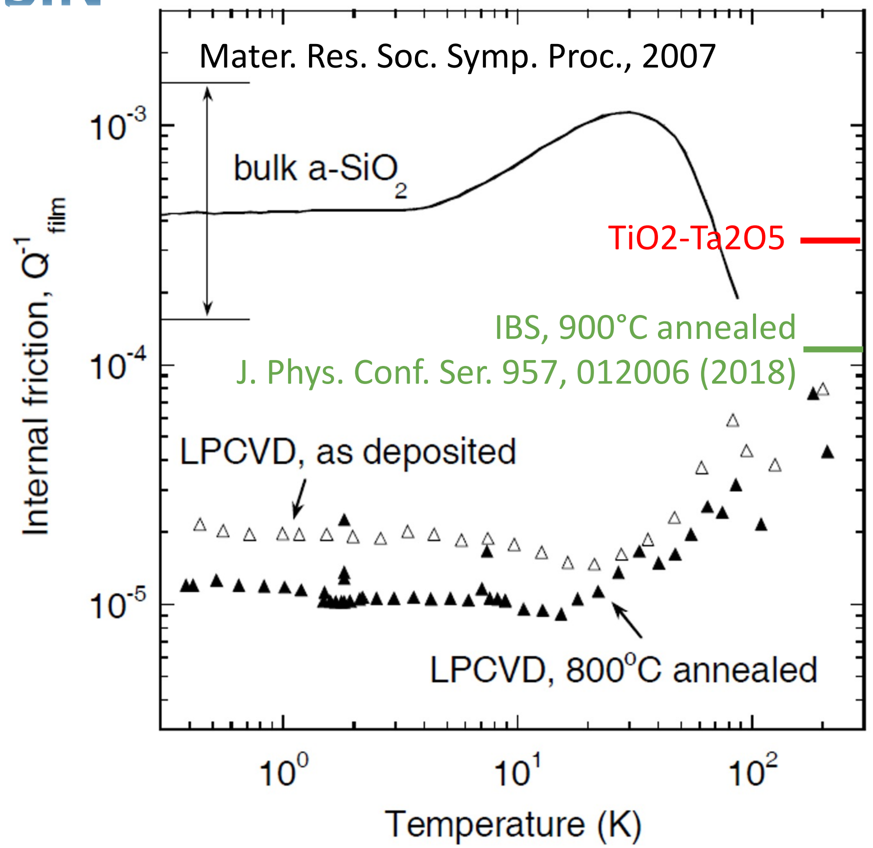
OSAG project in France:

- The oven has produced the first ingot of 200mm diameter. Characterizations will be done soon
- The absorption on 40mm diameter ingots is regularly around 10ppm/cm
- Quality factor measured on 2” diameter, 0.5mm thickness commercial grade sapphire wafer at 40K is around 2.5e8



Coating Parameters

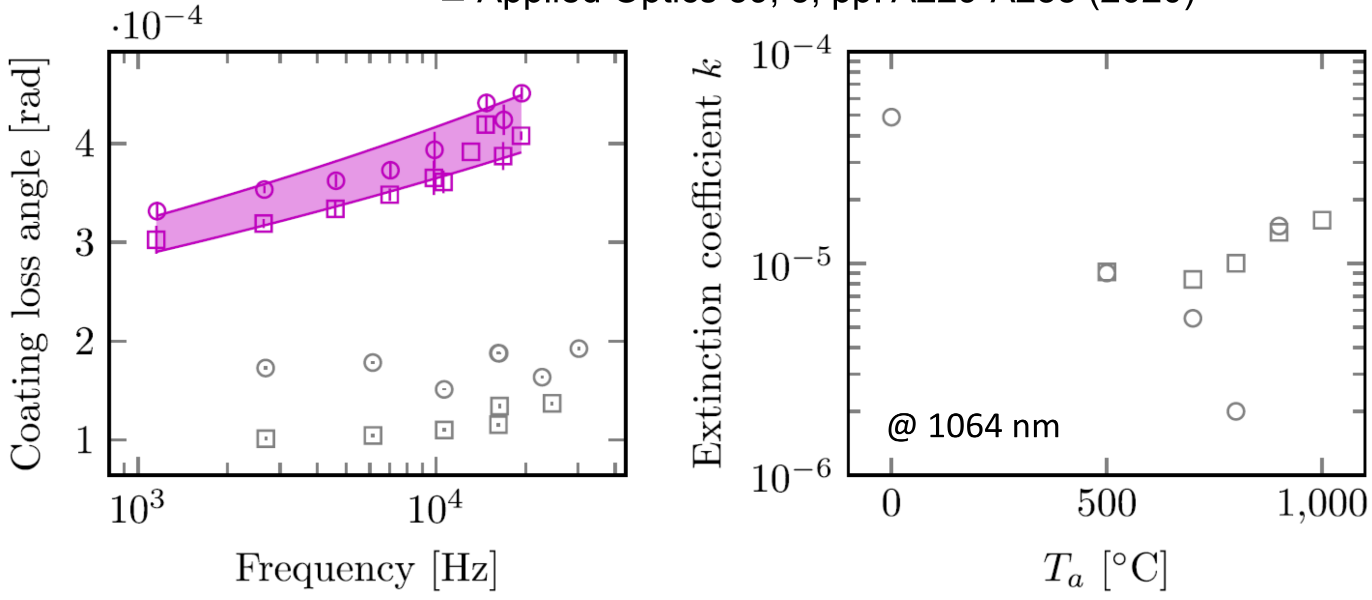
SiN



Chao & al., LIGO-G1700304, 2017

- $SiN_{0.40}$ (n = 2.30@1064, n=2.28@1550)
- $SiN_{0.65}$ (n = 1.93@1064, n=1.92@1550)
- $SiN_{0.87}$ (n = 1.78@1064, n=1.78@1550)

○ Class. Quantum Grav. 37, 095004 (2020)
○ J. Phys. Conf. Ser. 957, 012006 (2018).
□ Applied Optics 59, 5, pp. A229-A235 (2020)

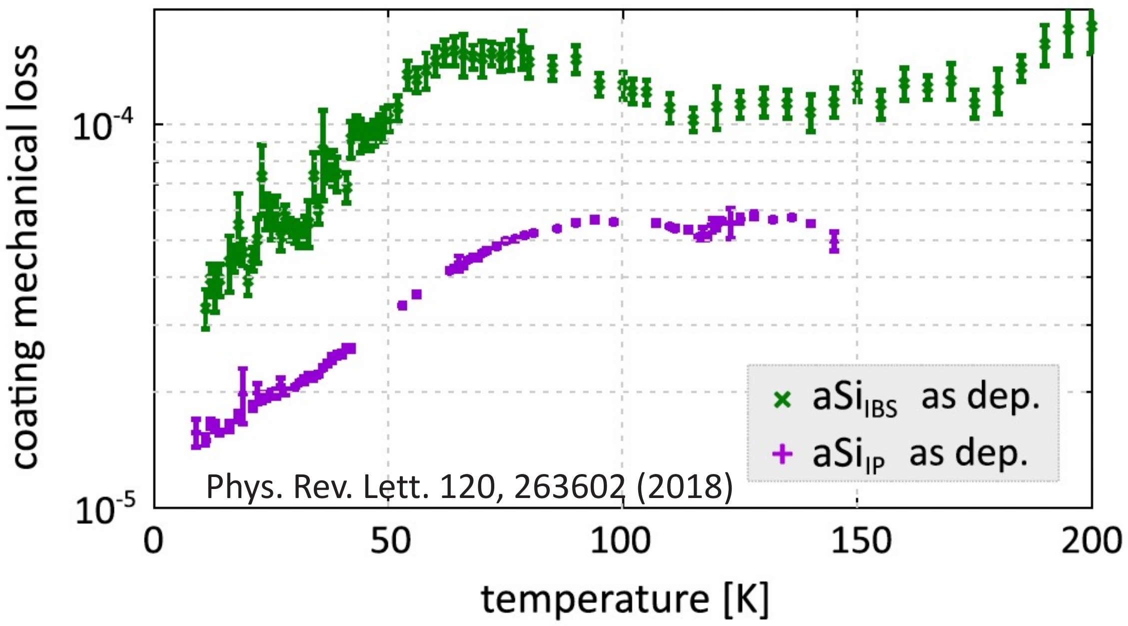


- Could meet thermal noise requirements
- Absorption is high but there is potential for improvement
  HR SiN/SiO2 (Optimize as Vigo ETM): 44 ppm
  k of 4.3E-6 observed at 2um for LPCVD
  (further study of IBS coatings of interest)
- Refractive index related to stoichiometry
  (Could be used as high- or low-index layer)

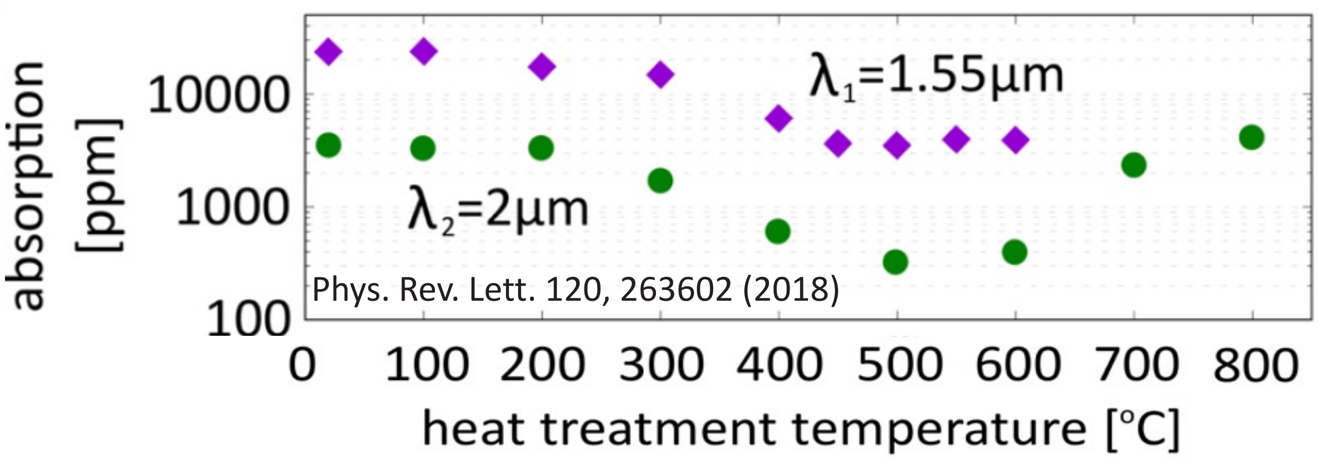
Coating Parameters

aSi

Mechanical loss of IBS and ion-plating aSi



1 µm thick aSi layer (ion plating aSi, room temperature)



Significant potential for meeting thermal noise requirements

- loss more than 10x lower than Ta2O5 at 10/20 K.

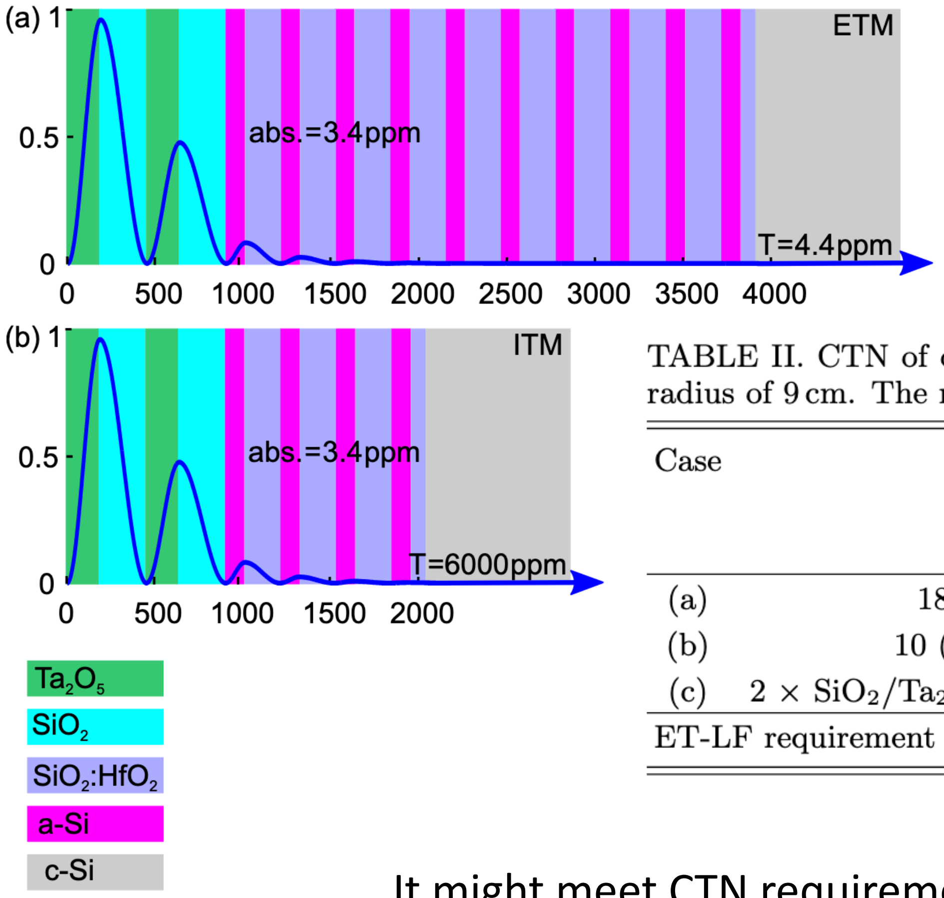
Absorption is significantly higher than aLIGO / Advanced Virgo coatings

- Absorption can be 7-10x lower at 2 µ m compared to 1.55 µ m
- High refractive index -> few layers and thinner stack!

Coating Parameters

Current HR stack

Phys. Rev. Lett. 122(23) 231102 (2019)



It is in the first layers of the stack where laser reflection mainly occurs and the absorption of materials is crucial.

A theoretical stack, based on single layer measurements, is used as the current design for CTN curve:

Sub/(SiO_2:HfO_2/aSi)$_n$/(SiO_2/Ta_2O_5)$_2$

TABLE II. CTN of different coatings on cSi substrates at a reference frequency of 10 Hz, a temperature of 10 K and a beam radius of 9 cm. The material parameters used are shown in Tab. I.

Case	bilayers ETM (ITM)	Transmission ETM (ITM) [ppm]	Heat treatment [°C]	CTN ETM (ITM) $[\times 10^{-21} \mathrm{m}/\sqrt{\mathrm{Hz}}]$	$\mathrm{CTN_D}$	α_{HR} [ppm]
(a)	18 (7) $\times$ SiO_2/Ta_2O_5	4 (8500)	600	4.0 (2.4)	6.6	0.6
(b)	10 (4) $\times$ SiO_2:HfO_2/a-Si	2 (9000)	400	1.4 (0.9)	2.4	11.9
(c)	2 $\times$ SiO_2/Ta_2O_5 + 10 (4) $\times$ SiO_2:HfO_2/a-Si	4.4 (6000)	400	1.9 (1.6)	3.5	3.4
ET-LF requirement [13]		5 (7000)			≈ 3.6	≤ 5

It might meet CTN requirements but needs verification and possible some more absorption reduction

Coating Parameters

AlGaAs - Crystalline

Development: LIGO-G2201621 (LVK Sep. 2022)

- Single-crystal AlGaAs HR coatings have 5× lower thermal noise than the best A+ IBS coatings.
- Low absorption (< 1 ppm)
- Low scattering (TIS) < 10 ppm

It is usually grown on GaAs wafer and then transferred to the substrate:

- Development needed for large optics:
  - Bonding not confirmed for 20 cm

What if we use 20 cm ITM (Room T) and 70 cm ISB ETM (Cryo)?

- We can gain a factor of $\sqrt{2}$ for the CTN
- The costs need to be considered (AlGaAs development + Cryo + 70 cm optics)
- **What about suspensions, payload etc.. ??**

Costs: LIGO-G2201305

Estimated costs and time for different options:

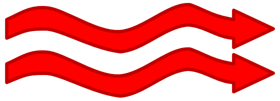
- 20 cm on aLIGO test mass (smaller beams)
  - 8 M$
  - 1-2 years
- 30 cm on a LIGO test mass
  - 20 M$
  - 3-4 years
- 30-45 cm on 100 kg test mass
  - >> 20 M$
  - > 5 years

AlGaAs > 45 cm ⇨ No cryo needed
AlGaAs < 45 cm ⇨ only with cryo and larger ETM

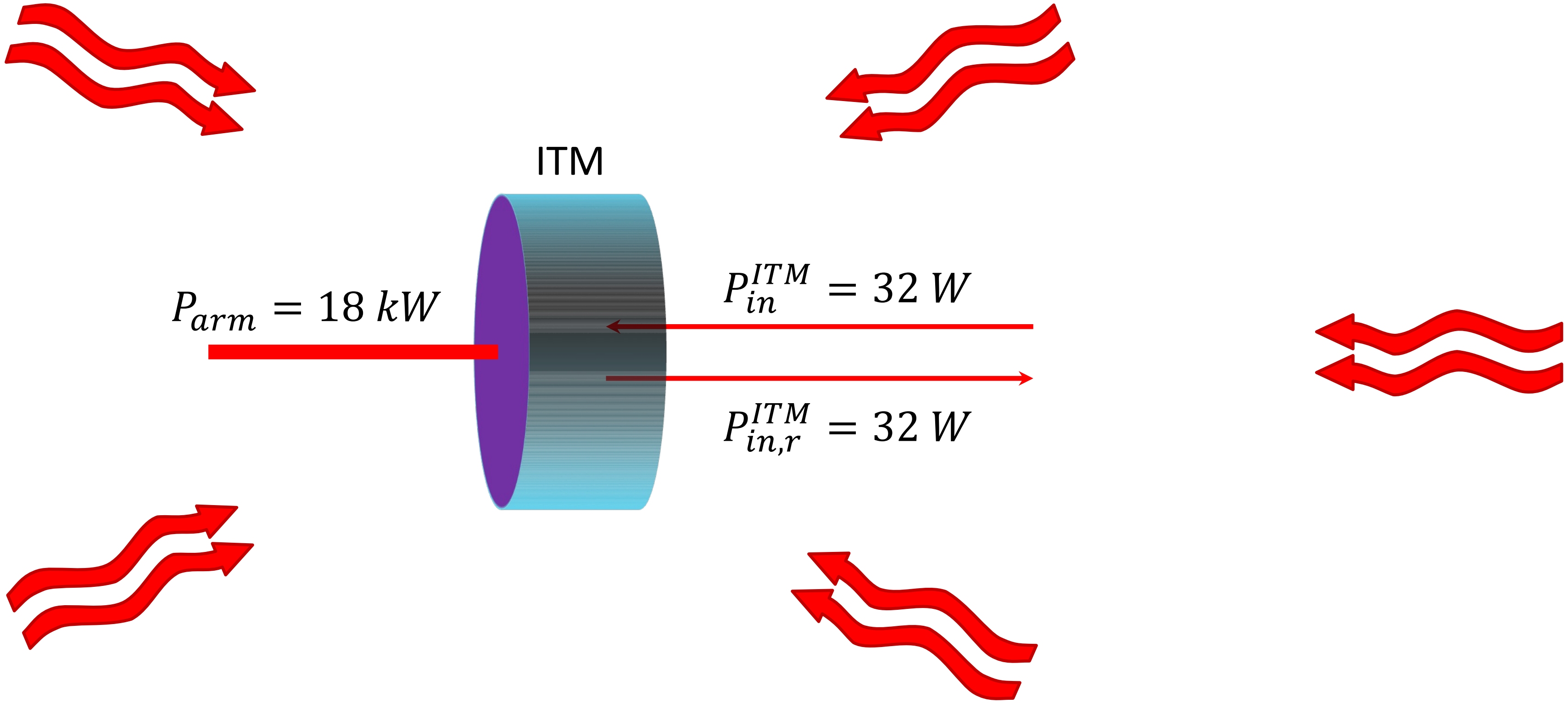
Heat in Test Mass

There are two main factors that generate heat in the core optics:
Optical absorption and thermal radiation

From two temperatures:
$P_{80\ K}$ and $P_{300\ K}$

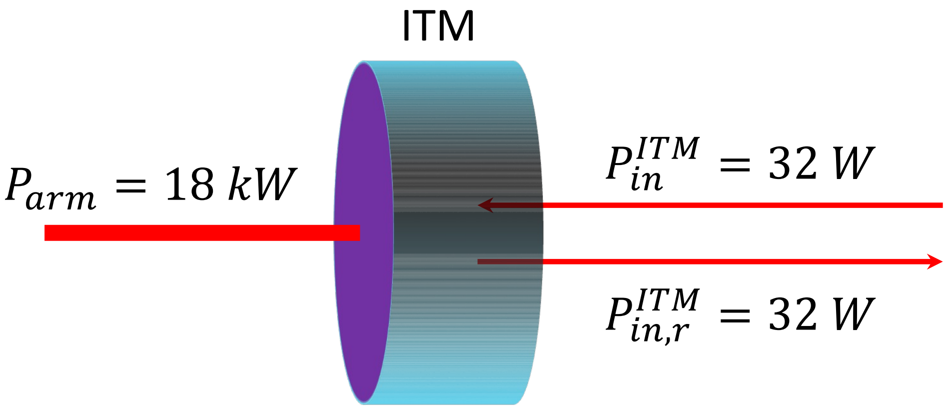


See F. Ricci's talk for thermal radiation.



Heat Absorbed by Test Mass

The absorption has to be small enough so the heat can be extracted through the suspension fibres
NB: the amount of heat directly impacts the thickness of the fibres which impacts the suspension thermal noise.



Finesse, $\mathcal{F} = 880$ (old design report)

Recycling gain, $G_R = 21.6$

Build up factor, $\beta = 2\mathcal{F}/\pi$

Input power, $P_{in}^{ITM} = P_{arm}/\beta = G_R P_{in}/2 = 32\ W$

__Power on Test Mass__

From Coating ($\alpha_{coat} = 5\ ppm$)

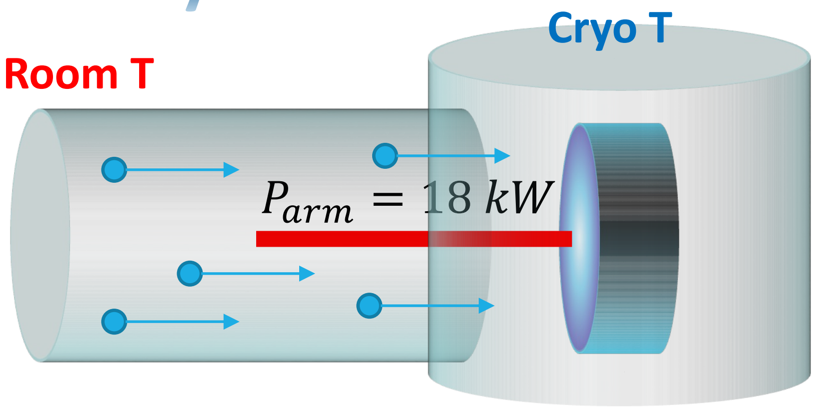
$P_{\text{coat}} = \alpha_{coat} P_{arm} = 90\ mW$

From Substrate ($\alpha_{sub} = 10\ ppm/cm$, incident + reflected, t = 40 cm)

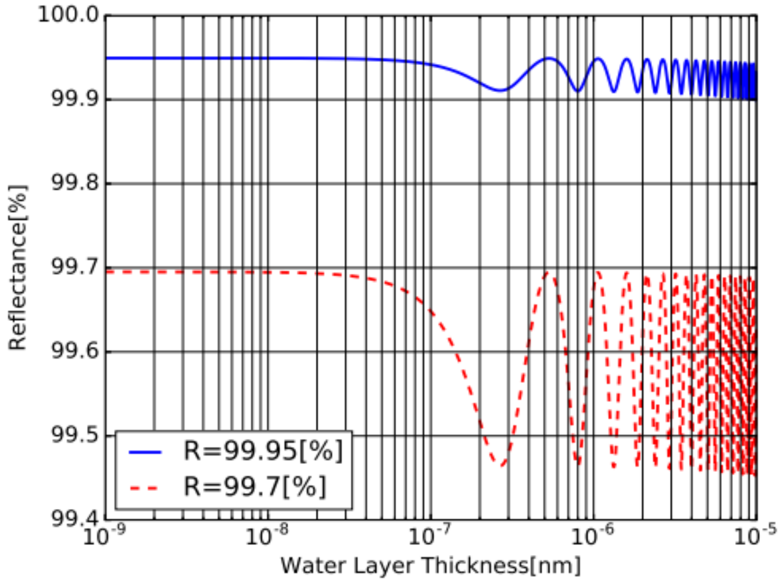
$P_{\text{sub}} = \alpha_{sub}\ 2\ P_{in}^{ITM}\ t_{sub} = 25.7\ mW$

Heat Absorbed by Test Mass

Ice Layer

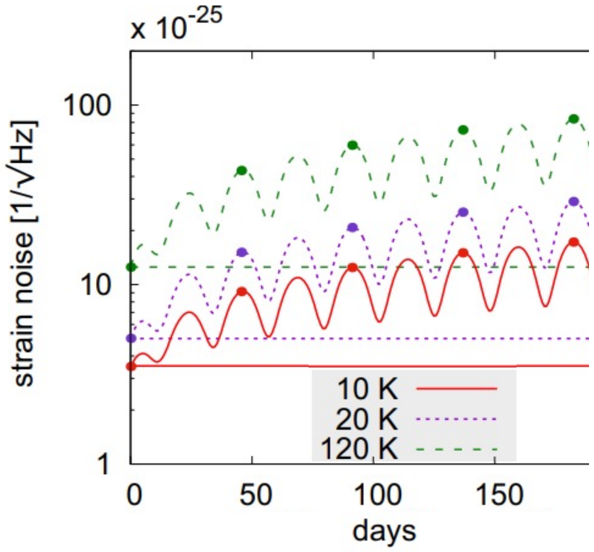


Phys. Rev. D 99, 022003 (2019)



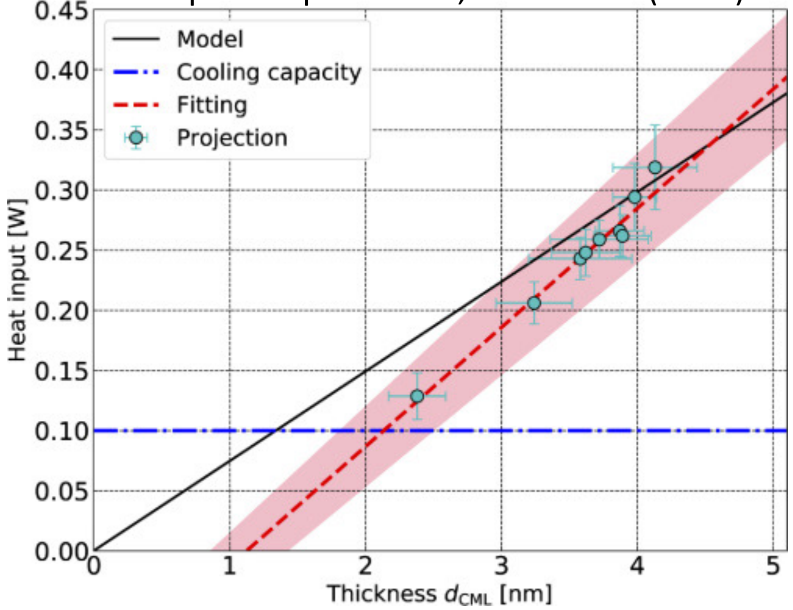
Through measurements on the finesse of a FB cavity, they estimated fluctuations in reflectance

Phys. Rev. Research 1, 013008 (2019)



Significant increase in CTN which is also superimposed by an oscillation.

Optics Express 29:5, 6780-6793 (2021)



Heat input to the test mass for the case of the ET.

$\alpha = 2.7 \pm 0.2\ ppm/nm$

27 ± 2 nm/day for a mirror at 47 K

Difference between 10 K and 20 K ?

Core Optics – Tasks for Workshop

Parameters

- ☐ Define better estimate about substrate production (diameter, absorption, …)
- ☐ Define the missing data for R&D (both substrate and coatings)
- ☐ AlGaAs: time and costs – Is it a real option?

Heat Extraction

- ☐ Define an upper limit of heat that can be extracted by the fibres
- ☐ Accordingly to the upper limit, define maximum absorption allowed
- ☐ Accordingly to the upper limit, define size of fibres