KAGRA's experience with sapphire mirrors

M. Leonardi on behalf of KAGRA collaboration

Summary

Sapphire substrate:

- Absorption:

  well known problem from design phases

- Birefringence:

  partially unexpected problem

Optical absorption in sapphire mirrors

To achieve a stable temperature for the test masses (ITM case):

$$P_{rad} + P_{BS}\alpha_{bulk}L + P_{arm}\alpha_{coat} < P_{cryo}$$

Left side can be minimized by optimizing PRG and arm Finesse

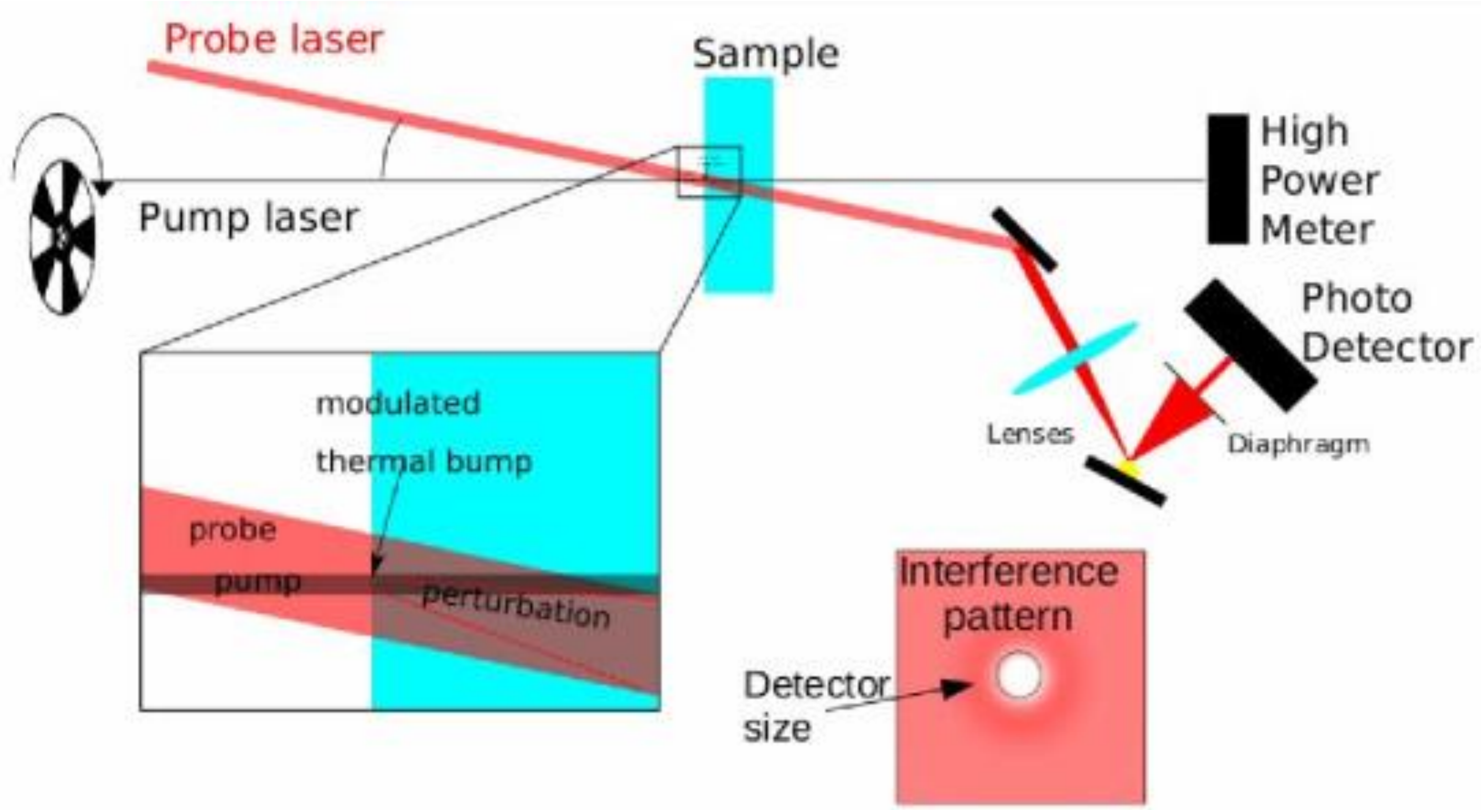
- This choice has impact on ITF quantum noise
- (design): $P_{BS}\alpha_{bulk}L \approx P_{arm}\alpha_{coat}$

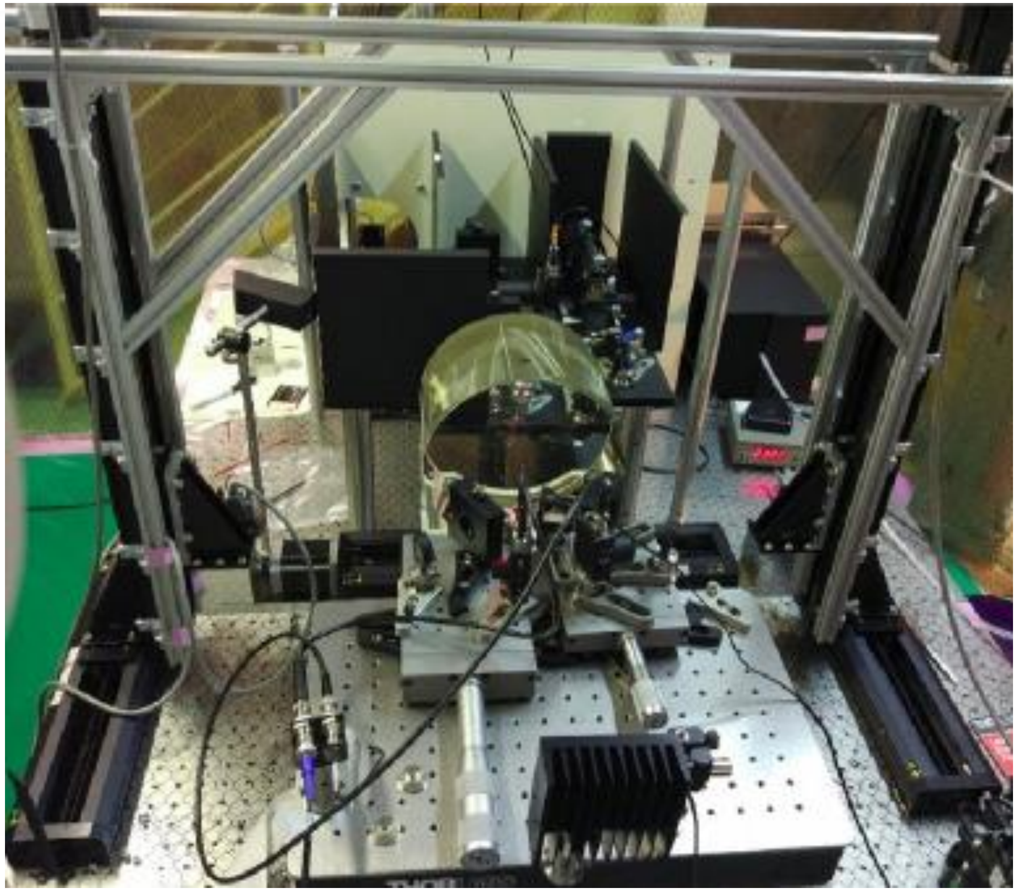
Right side depends mainly on fiber diameters

- Suspension thermal noise is determined by fibers geometry

Optical absorption characterization

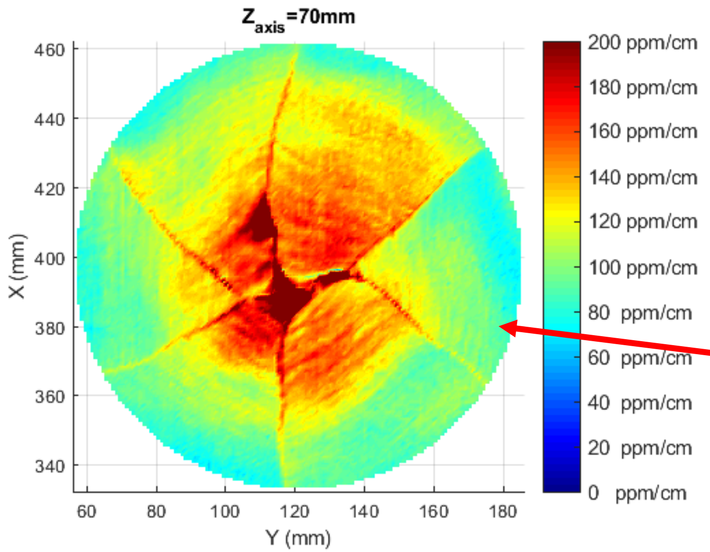
Photothermal Common-path Interferometer:





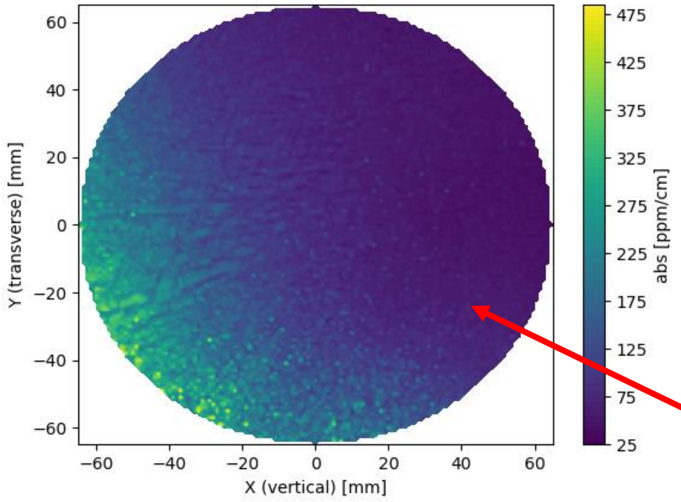
Growth orientation impact on opt. absorption spatial distribution

C-axis growth:



Company B	S1	S2	S3
#0	167.6 (35.5)	126.8 (41.7)	26.6 (17.0)
#1	96.1 (31.2)	93.1 (28.7)	99.3 (38.0)
#2	27.1 (11.0)	31.5 (10.5)	24.8 (10.5)
#3	73.3 (23.2)	137.6 (34.7)	143.1 (39.9)
#4	130.9 (39.1)	99.4 (22.7)	139.5 (35.7)
#5	85.3 (34.7)	56.5 (14.9)	119.6 (39.9)
#6	184.9 (54.5)	140.9 (36.1)	201.6 (54.8)
#7	65.1 (14.9)	62.2 (16.6)	91.2 (28.7)
#8	111.4 (34.1)	66.3 (18.6)	143.2 (30.3)
#10	112.5 (51.7)	38.7 (17.6)	32.9 (13.7)
#11	21.2 (12.3)	22.8 (18.2)	33.4 (23.4)
#12	77.1 (24.2)	83.6 (30.2)	89.7 (31.1)

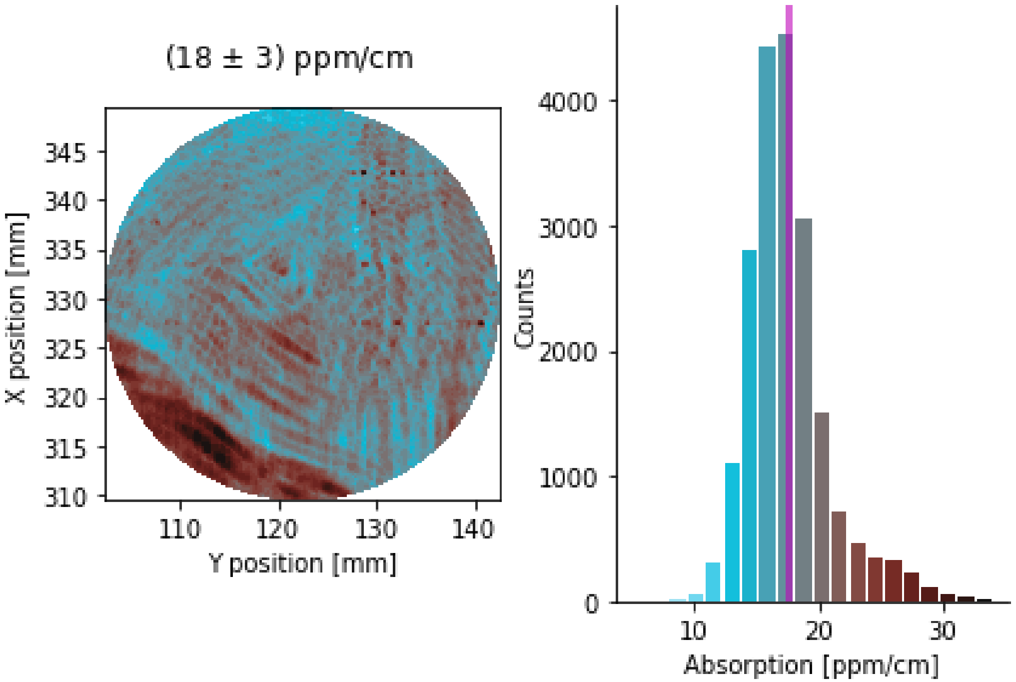
A-axis growth:

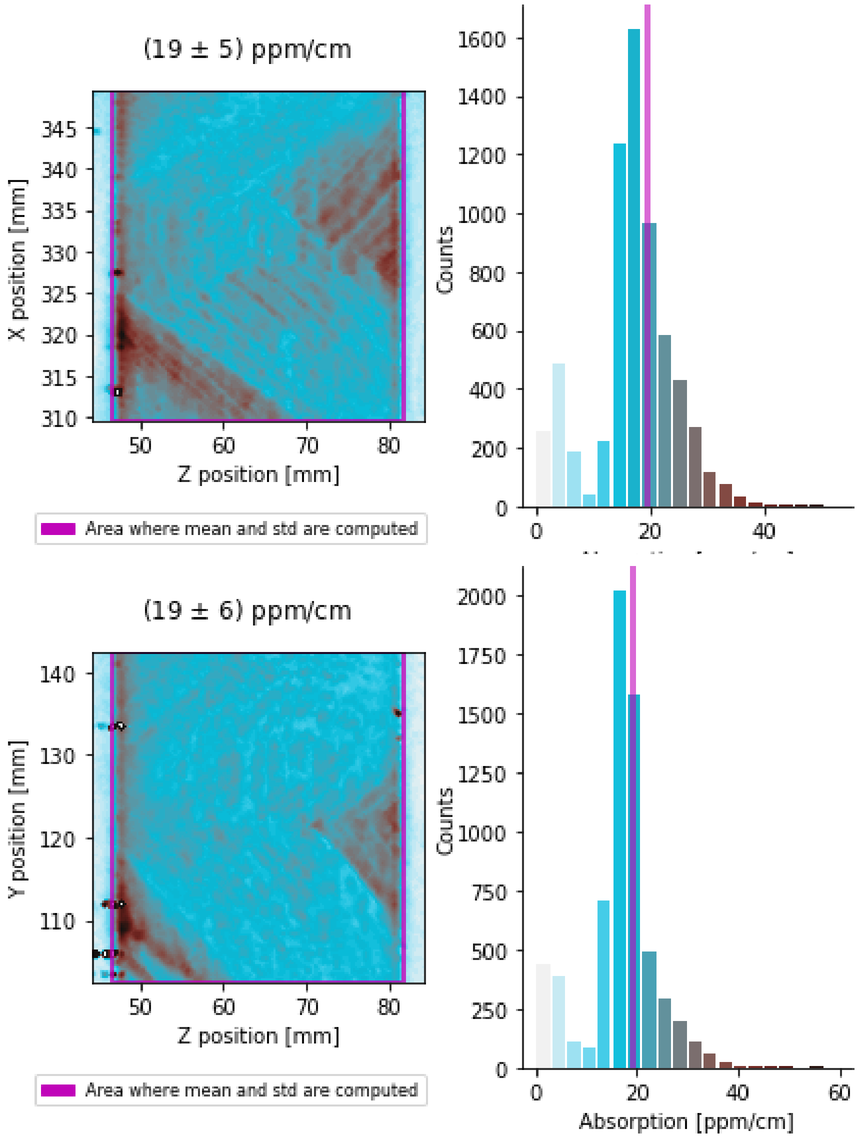


Company A	S1	S2	S3
#1(F62-22)	41.1 (23.1)	64.3 (23.3)	59.9 (19.8)
#2 (F47-21)	72.1 (31.1)	87.3 (38.2)	93.4 (36.5)
#3 (AC-179)	60.6 (76.0)	37.7 (17.3)	47.7 (34.1)
#4 (F39-56)	94.0 (139.6)	305.3 (250.0)	160.2 (171.4)
#5 (MMK-1)	106.98 (45.68)	69.02 (22.91)	76.0 (31.0)
#6 (MMK-2)	216.47 (108.01)	82.82 (30.90)	99.4 (49.5)
#7 (C14-11c)	114.2 (95.5)	79.3 (49.9)	72.4 (42.7)
#8 (OC-1)	86.6 (45.7)	69.5 (35.5)	58.0 (25.2)

Growth orientation impact on opt. absorption spatial distribution

C-axis growth:





Even in low absorption samples the striation are present

Dislocation and optical absorption

- Structural defects as preferential sites for the inclusion of absorbing centers

www.nature.com/scientificreports

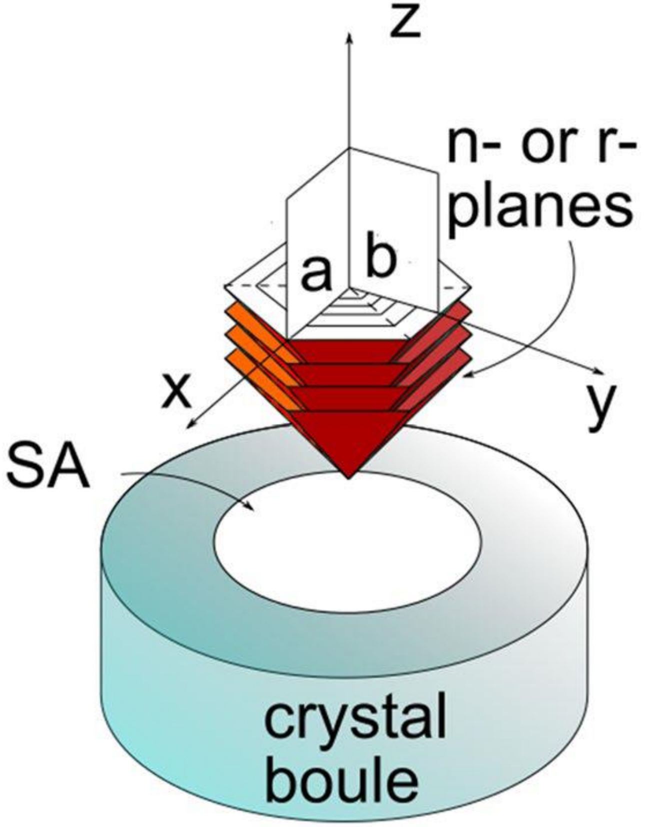
scientific reports

Check for updates

OPEN **3D characterization of low optical absorption structures in large crystalline sapphire substrates for gravitational wave detectors**

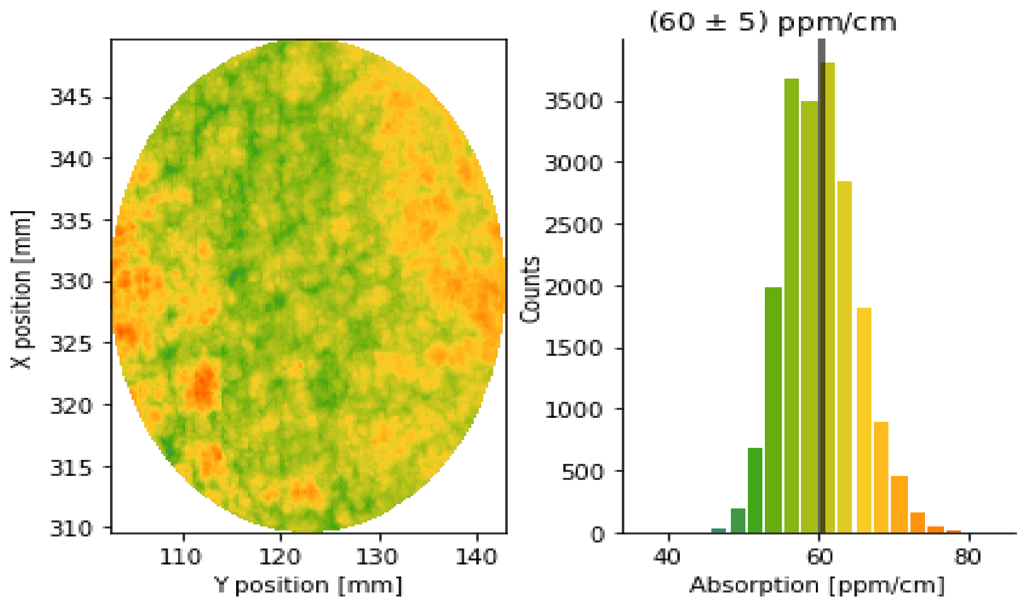
Manuel Marchiò[1,2]✉, Matteo Leonardi[2], Marco Bazzan[3] & Raffaele Flaminio[2,4]

https://doi.org/10.1038/s41598-020-80313-1



New and better sapphire substrates

Several samples are being / have been analyzed…



Companies:

- Many additional samples from old and new companies are being constantly characterized

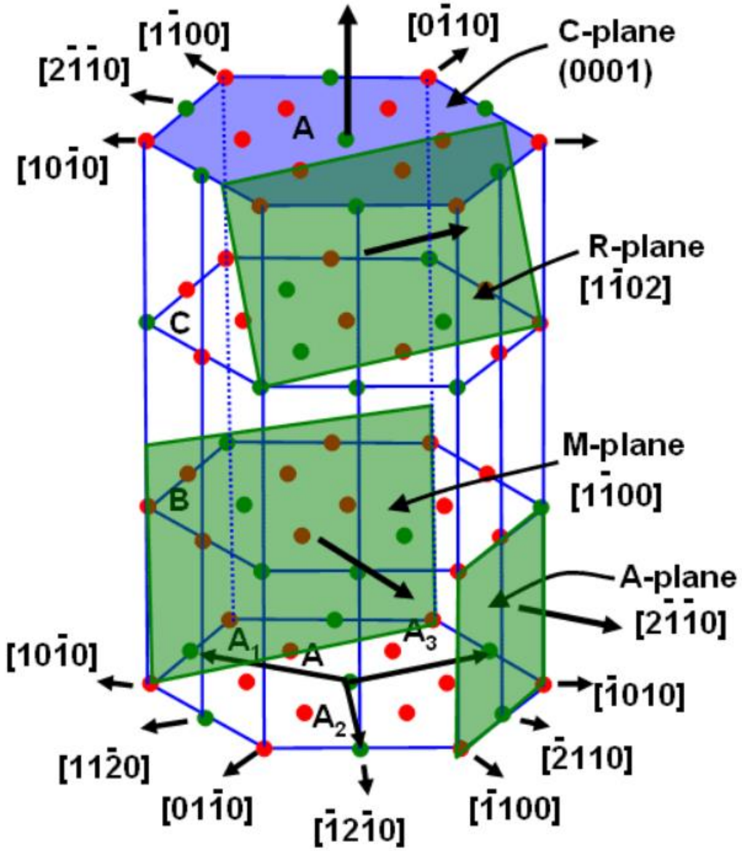
iLM:

- KAGRA is collaborating and supporting the realization and study of new sapphire substrates

Sapphire: a birefringent material

Substrate original requirements:

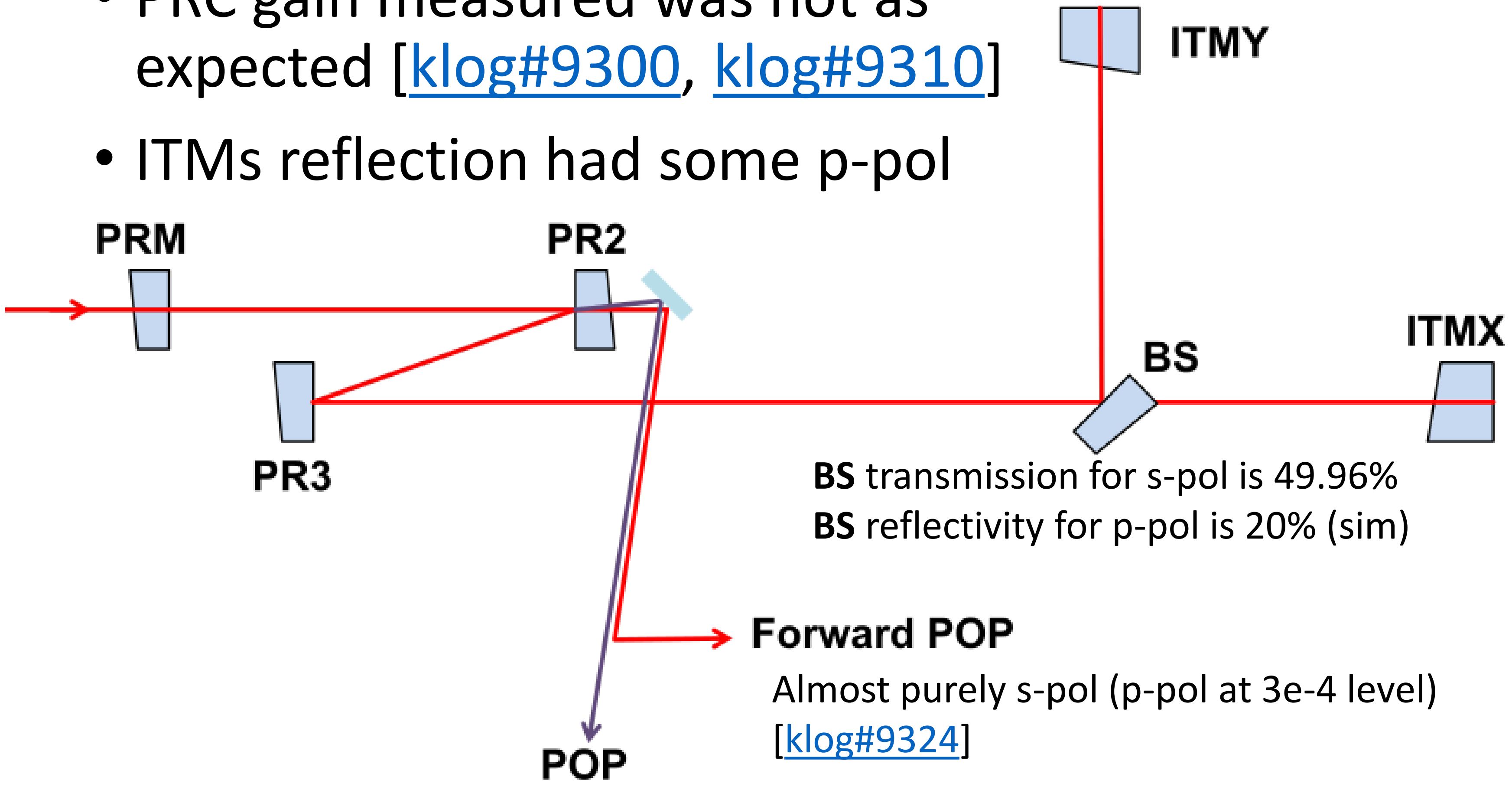
- Crystal orientation: c-plane +/- 0.2deg
- dn< 5e-7 (RMS) @633nm
  - No requirements on $dn_b \propto n_o - n_e$



Global c-axis orientation is not an issue, but local anisotropies are!

ITMs bulk birefringence: p-pol detected

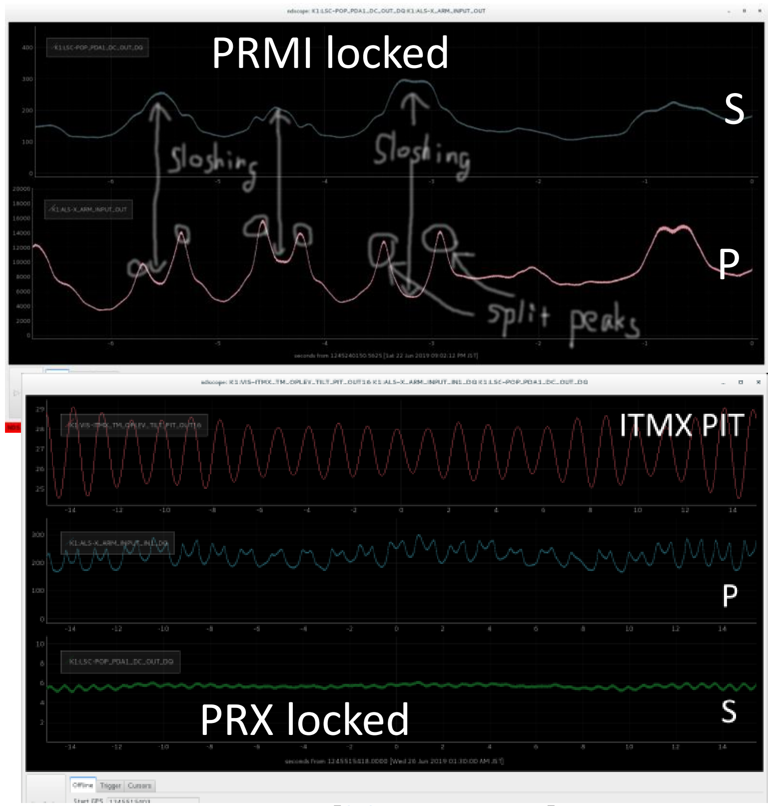
- PRC gain measured was not as expected [klog#9300, klog#9310]
- ITMs reflection had some p-pol



BS transmission for s-pol is 49.96%
BS reflectivity for p-pol is 20% (sim)

Almost purely s-pol (p-pol at 3e-4 level) [klog#9324]

9.4 % p-pol from ITMX single bounce
4.6 % p-pol from ITMY single bounce [klog#9314]

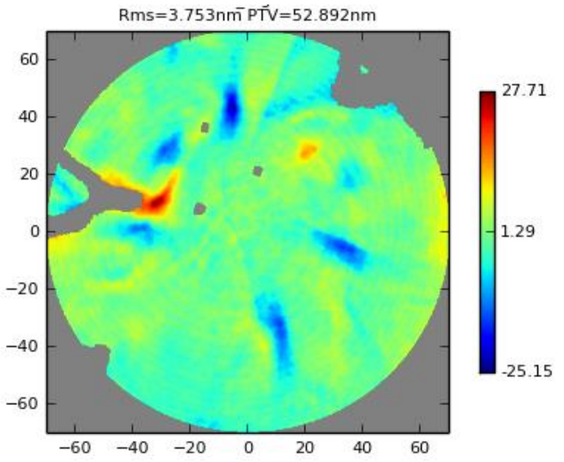


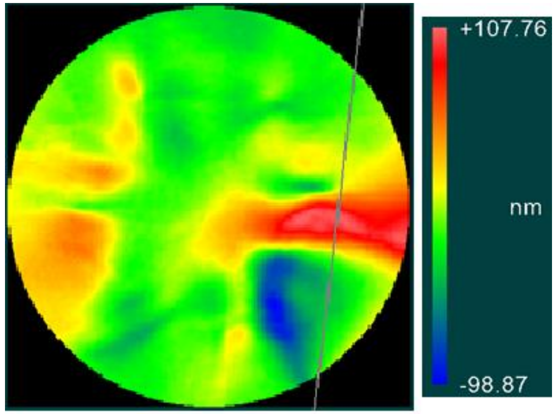
[klog#9325]

ITMs TWE maps not within specs

Measurement from T1809173 (T1808715, T1910386, Phys. Rev. Appl. 14, 014021)

	specification	vendor report	measured
ITMX	< 6nm	3.47	25.9nm
ITMY		4.07	30.1nm



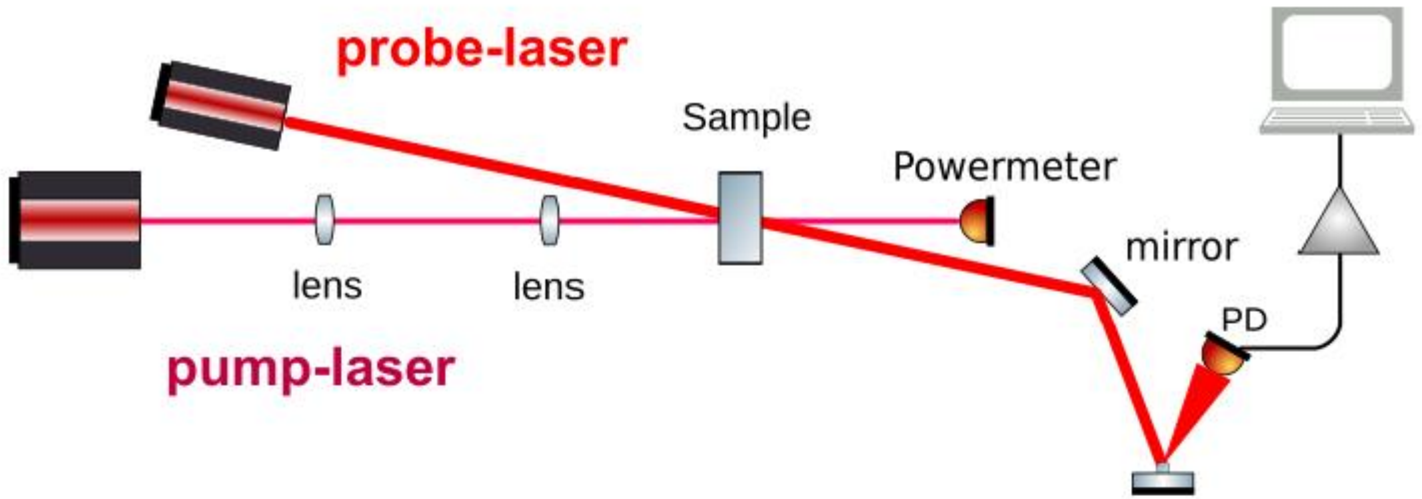


Cause:

- polisher's Fizeau interferometer uses circularly polarized laser while the KAGRA detector uses linearly polarized light

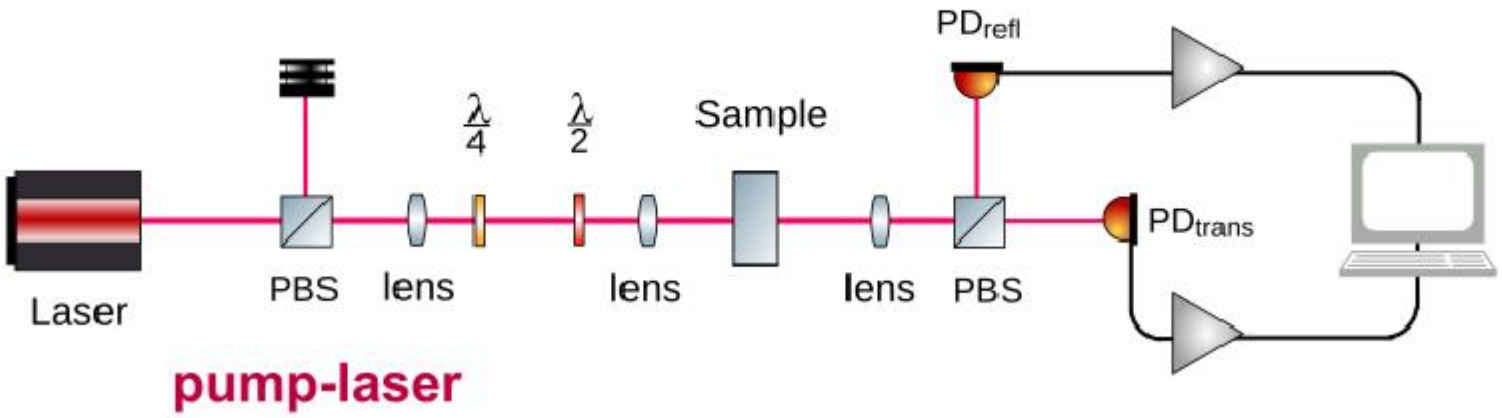
Characterization setup at NAOJ

Absorption:
photothermal common-path interferometer



Birefringence:

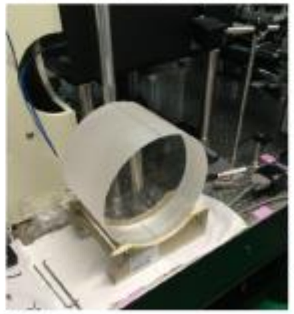
Single-pass polarization rotation

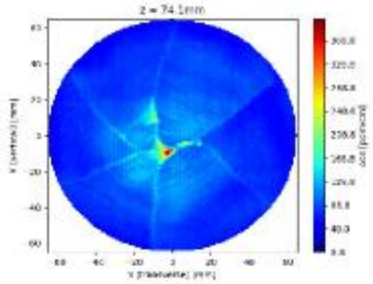


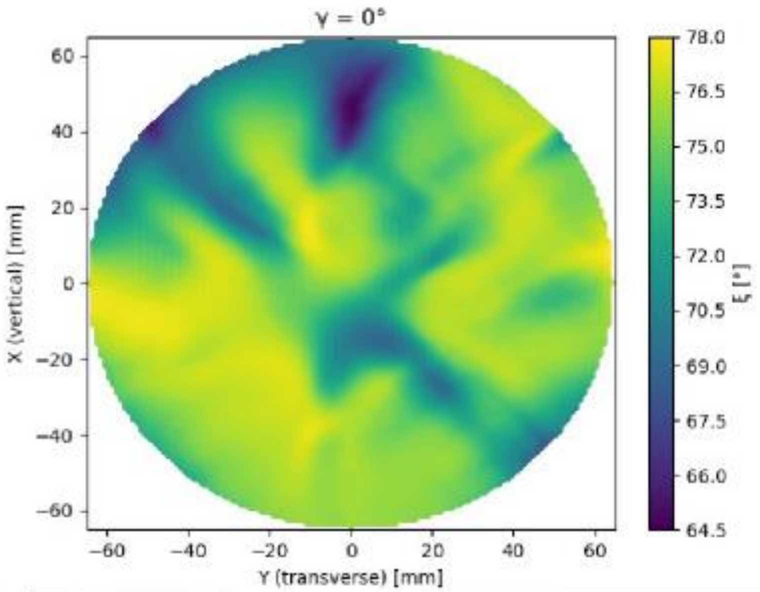
Birefringence measurements

Birefringence measured as cumulative effect: $\xi = \tan^{-1}\sqrt{\frac{P_s}{P_p}}$

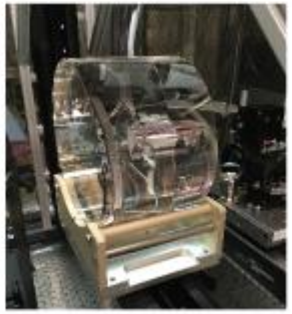
C-axis

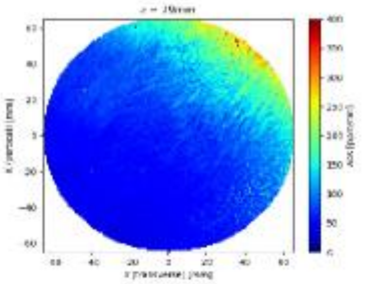


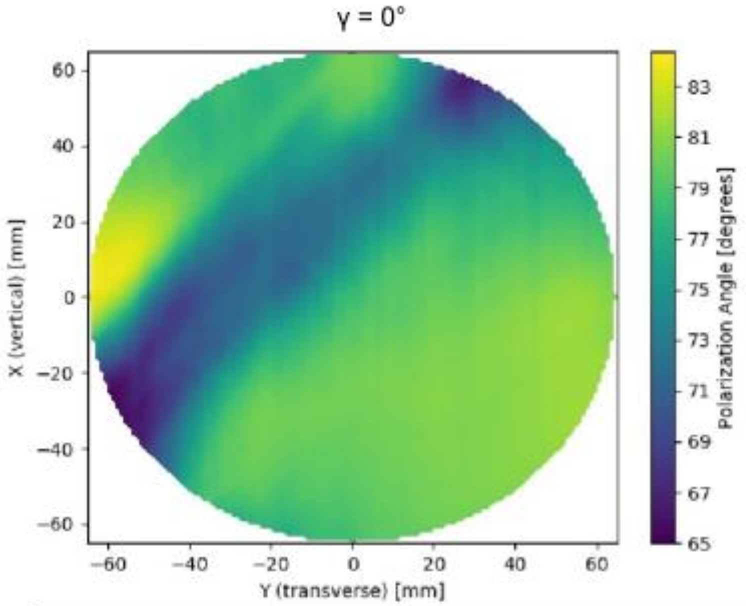




A-axis

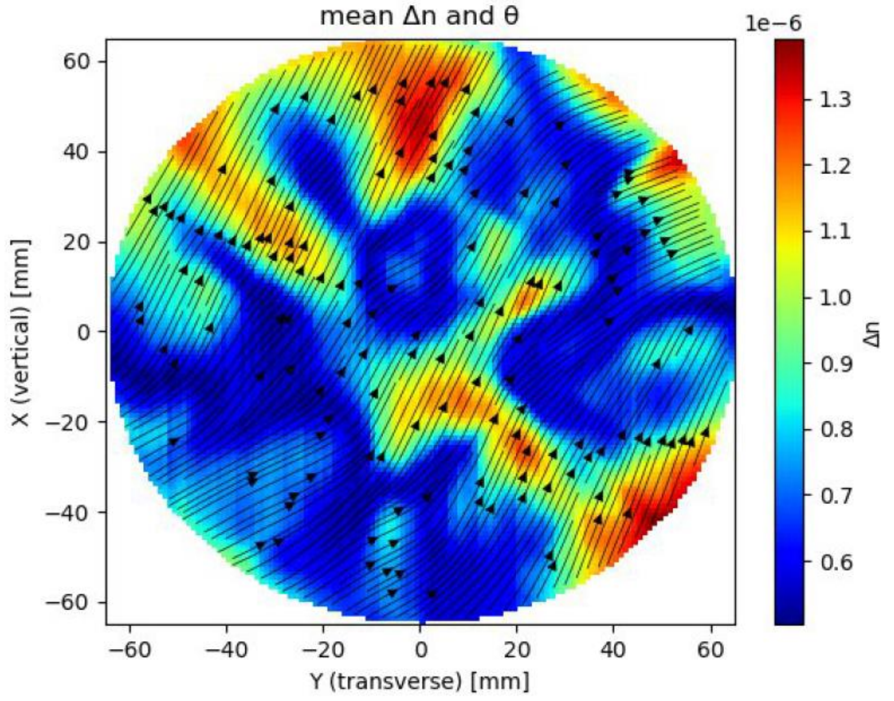




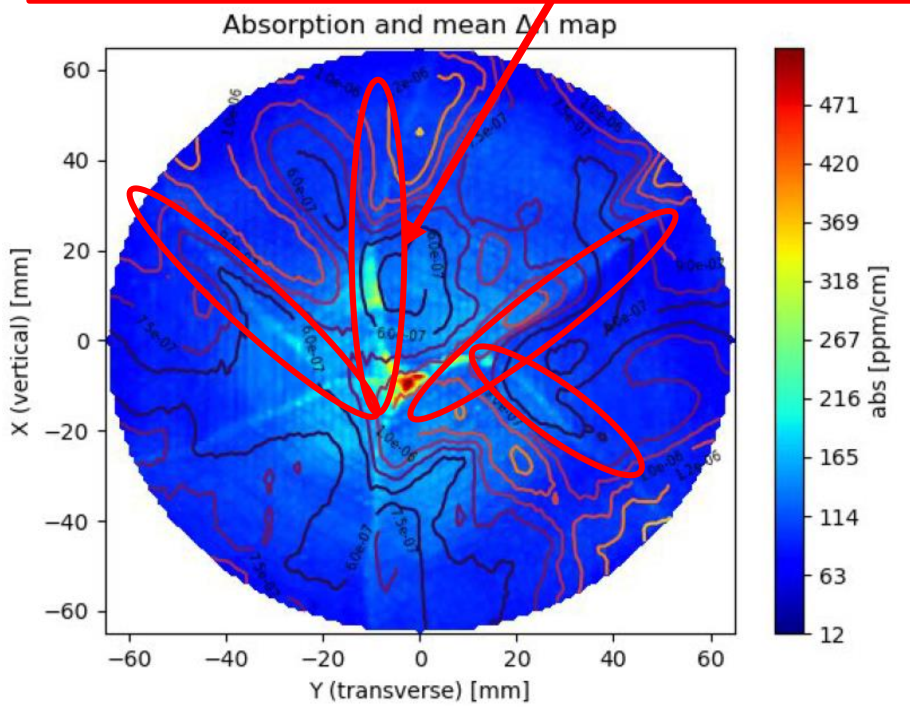


From birefringence to Δn

Δn_{RMS} is within original specs



Correlation between absorption and internal stress leading to birefringence



Structural defects can be the cause of both absorption and birefringence*

*Paper in preparation.

Summary and future

Sapphire main problems:

- Optical absorption
- Birefringence

} ***Growth process has large impact***

Sapphire (optical) advantages:

- Works with 1064nm technology
- Do not exhibit stress induced behaviors

Future steps (for KAGRA):

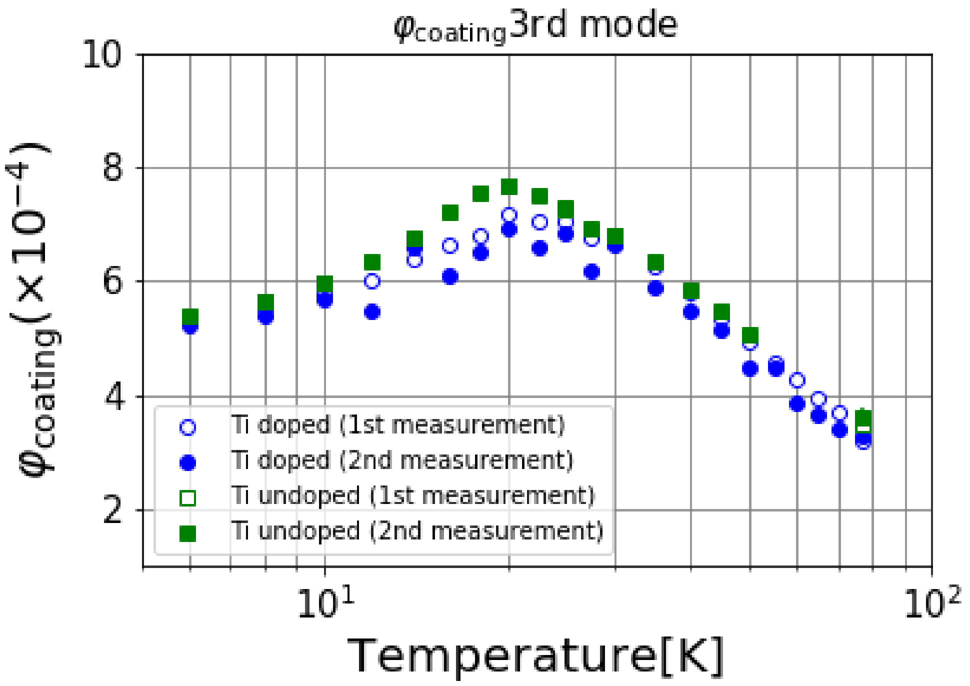
- Interface with crystal makers (companies and iLM) to tune the growth process parameters
- Post-growth heat treatments

Coating thermal noise measurements

Measurement of the mechanical loss of reflective coatings for KAGRA

Yota Nakayama, Y.Mori, K.Yamamoto, T.Ushiba[A]
University of Toyama, ICRR[A]

KAGRA F2F meeting @online
(August 27-29 ,2021)
Email :m2041105@ems.u-toyama.ac.jp



KAGRA coating thermal noise: $2.9 \times 10^{-24} [1/\sqrt{\text{Hz}}]$ at 100Hz (Ti undoped, 3rd mode at 20K)

Discussion with Virgo Coating R&D ongoing to characterize new coating type at cryogenic temperature @Toyama facility