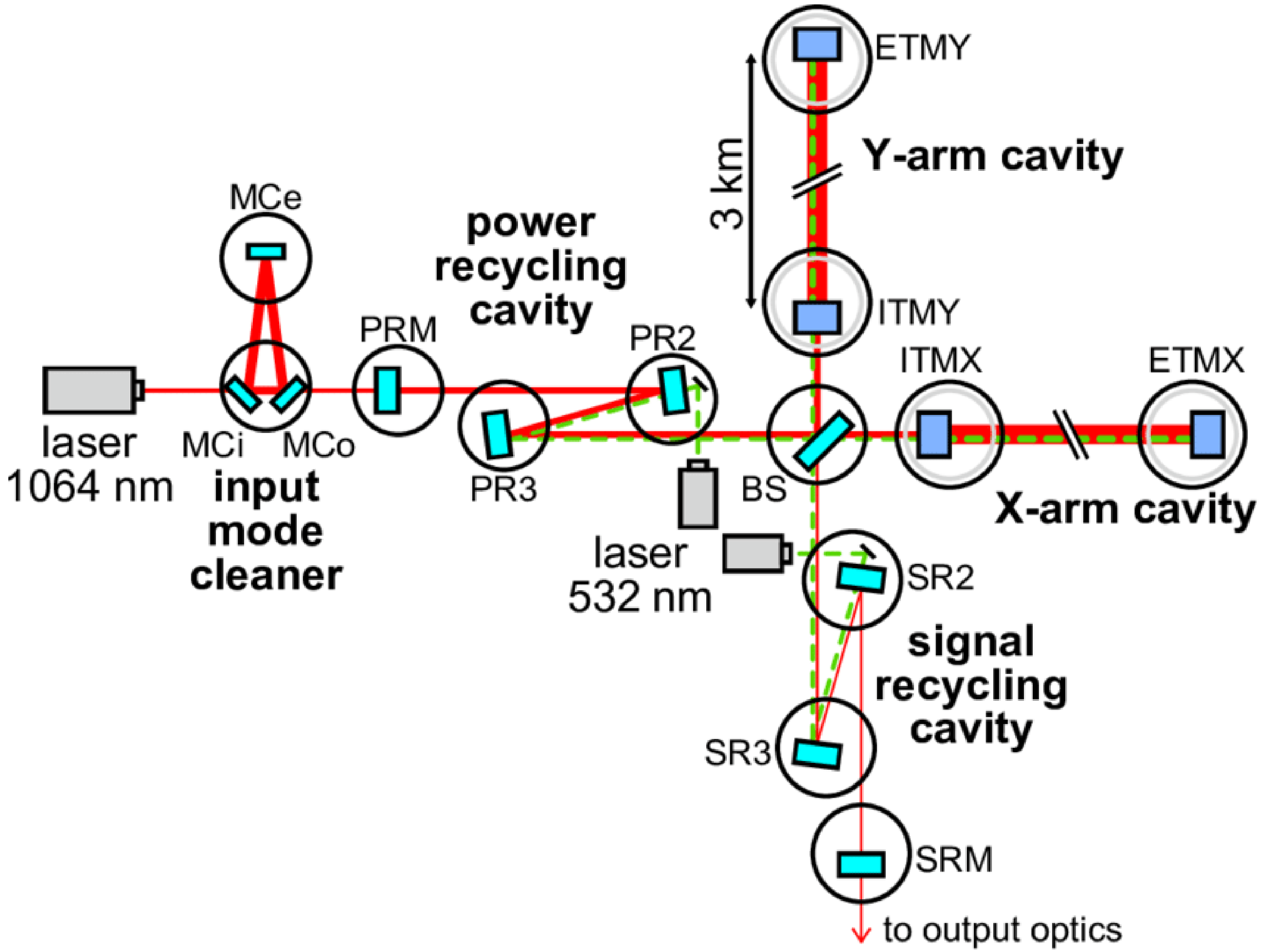
KAGRA mirrors

Matteo Leonardi on behalf of KAGRA MIR subsystem

iLANCE workshop

Introduction to KAGRA’s mirrors



Sapphire mirrors:

- Two input test masses (ITMX and ITMY)
- Two end test masses (ETMX and ETMY)

Fused silica mirrors:

- One beam splitter (BS)
- Three input mode cleaner mirrors (MCi, MCo, MCe)
- Three power recycling cavity mirrors (PRM, PR2, PR3)
- Three signal recycling cavity mirrors (SRM, SR2, SR3)
- Two input mode matching telescope mirrors (IMMT1, IMMT2)
- Two output mode matching telescope mirrors (OMMT1, OMMT2)
- …

Introduction to “sapphire”

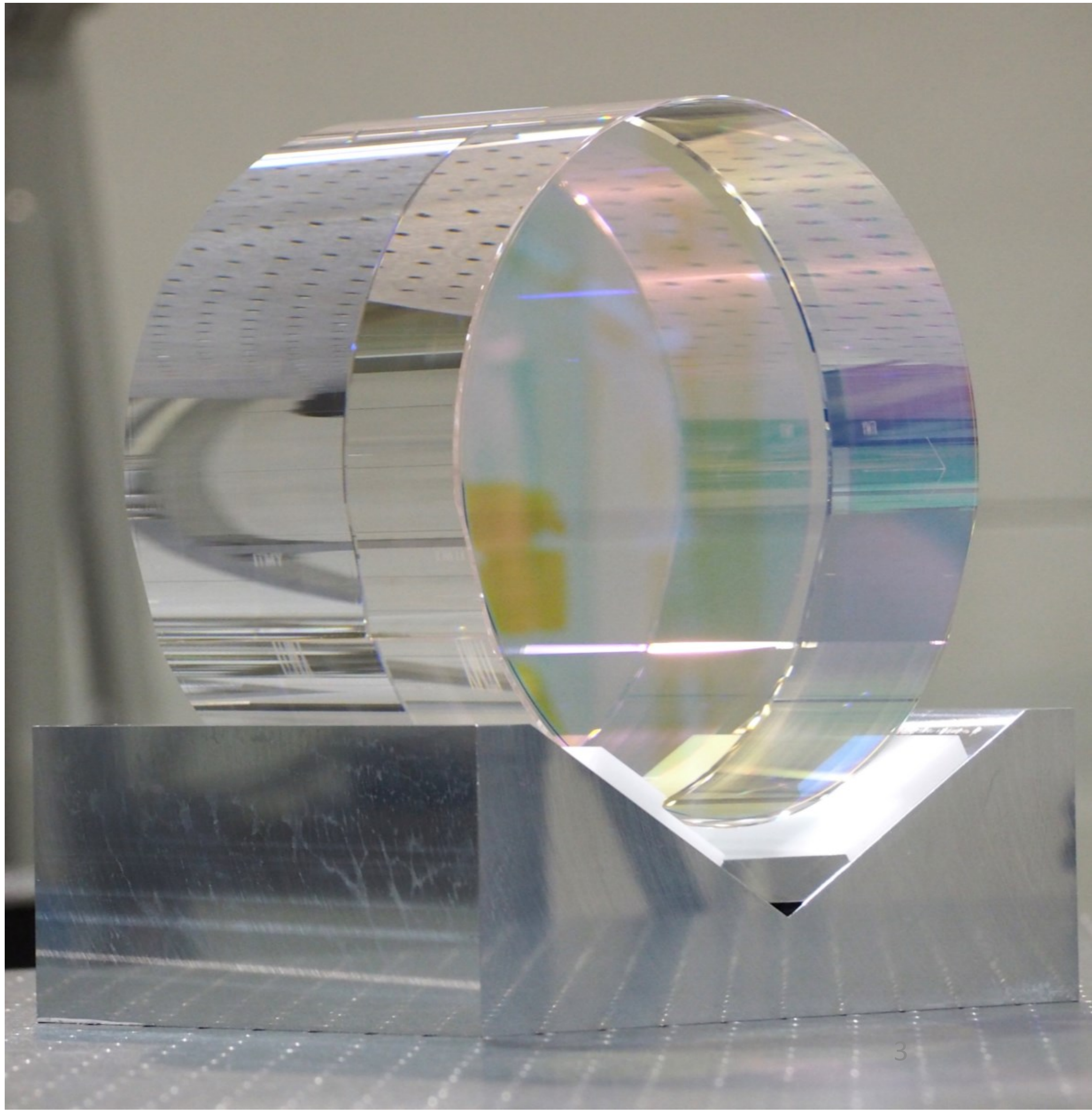
KAGRA mirrors: Aluminum oxide (corundum)

Pro:

- Very high thermal conductivity at cryogenic temperature
- Transparent at 1064nm
- High density
- Good industrial manufacture techniques
- …

Cons:

- Second hardest material in the world
- Birefringent material (in a-axis)
- …



KAGRA's mirror status

- All core optics delivered (and characterized) by mid-2018
  - 2018/11/09: last TM installed in KAGRA site
  - 2018/12/10: SRM installed
- All core optics were characterized at Caltech LIGO lab (thanks to GariLynn Billingsley, Liyuan Zhang, Hiro Yamamoto)
- Several characterization facilities were realized:
  - NAOJ: optical absorption (RoomT), scatterometer (RoomT), Zygo interferometer (RoomT), birefringence (RoomT), coating thermal noise (CryoT)
  - Kashiwa: optical absorption (CryoT)
  - Toyama: coating Q (RoomT and CryoT)

Optical absorption in sapphire mirrors

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

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

Right side depends mainly on fiber diameters

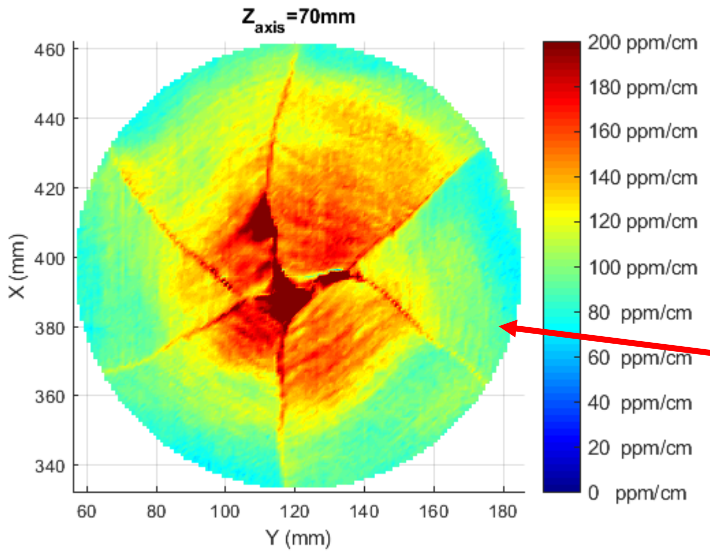
- Suspension thermal noise is determined by fibers geometry

Left side can be minimized optimizing PRG and arm Finesse

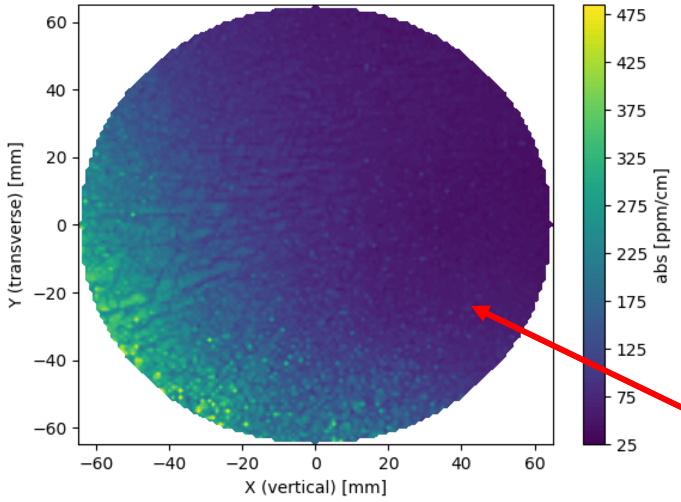
- This choice has impact on ITF quantum noise
- (design): $P_{BS}\alpha_{bulk}L \approx P_{arm}\alpha_{coat}$

Growth orientation impact on opt. absorption spatial distribution

C-axis growth:



A-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)

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)

MIR related issues

During characterization and commissioning some problems were identified:

- ITMs **transmittivity unbalance**
- ITMs **Transmitted Wavefront Error** (TWE) maps not within specs
- ITMs **bulk birefringence**

ITMs transmittivity unbalance

Measurement from T1809173

	Specification	ITMX	ITMY
Transmission	0.4% < T < 0.5%	0.444(2)%	0.479(2)%
Asymmetry $\frac{2\lvert T_1+T_2\rvert}{T_1+T_2}$	< 0.01	0.077(6)	

Cause:

- Non-simultaneous coating process due to polisher delay on ITMY

Consequences:

- Different arm finesse (klog#14258):
  Xarm: 1456 +/- 21
  Yarm: 1312 +/- 26
- Increased laser intensity and frequency noise coupling (T2011662)

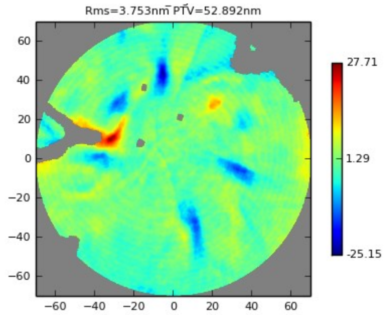
Solution:

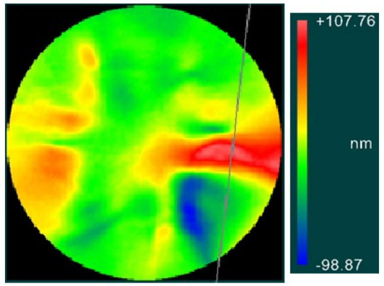
- Re-coat ITMs

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

Consequences:

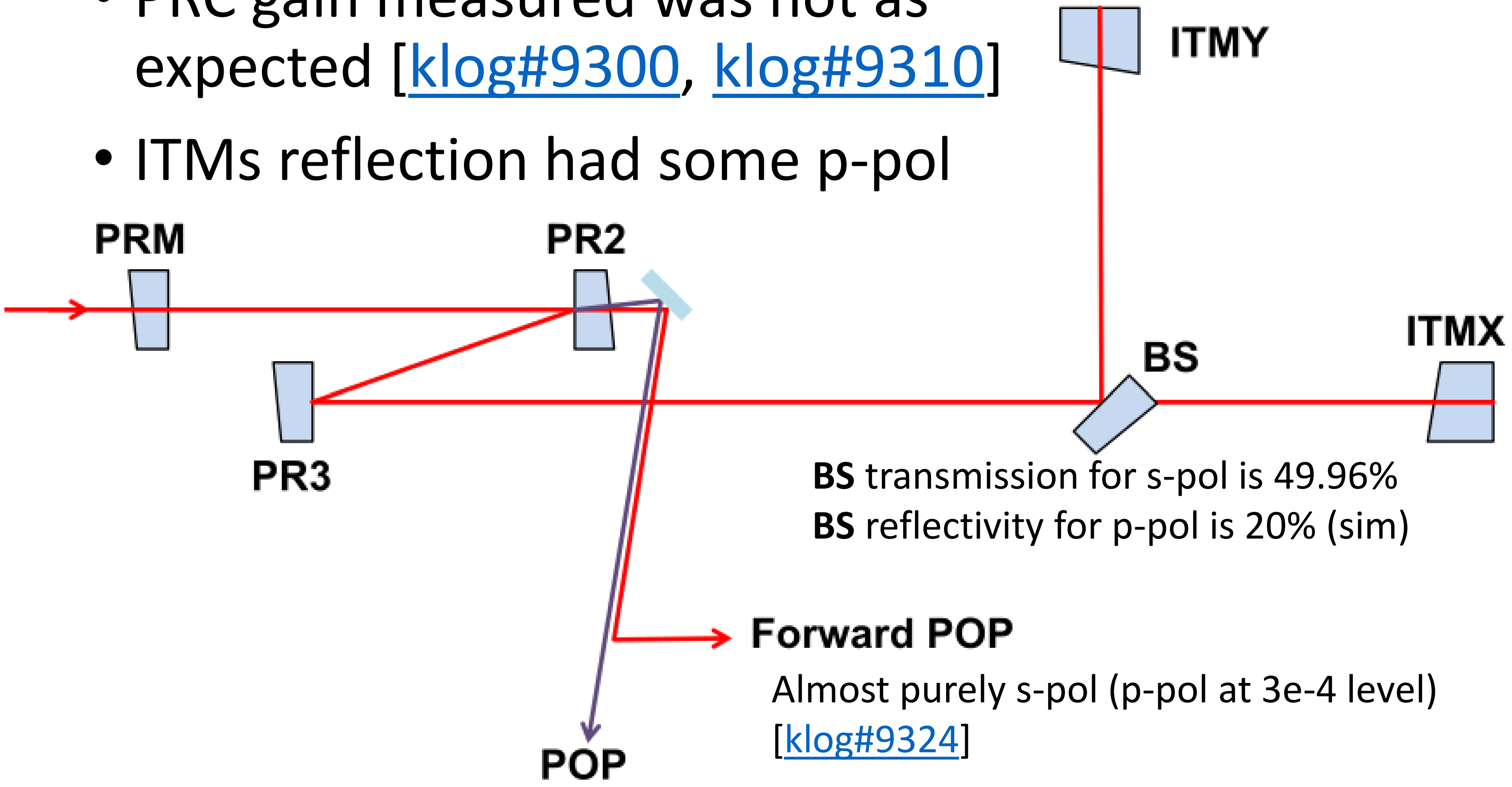
- Increased laser intensity and frequency noise coupling (T2011662) and increased HOMs at the dark port (G1809362, Phys. Rev. D 100, 082005)

Solution:

- Re-polish ITMs (using correct TWE map)

ITMs bulk birefringence: p-pol detected

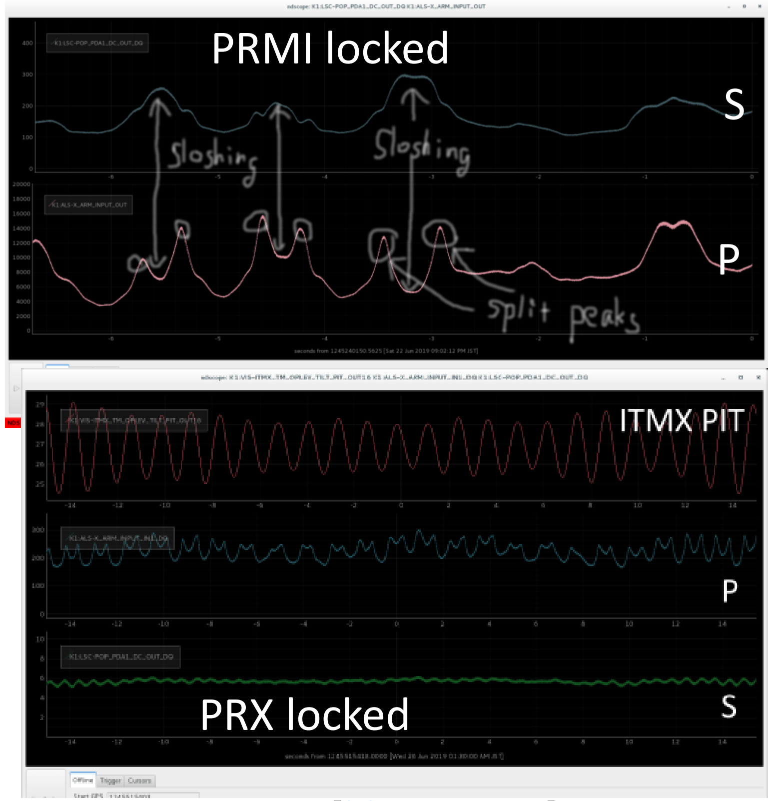
- PRC gain measured was not as expected [klog#9300, klog#9310]
- ITMs reflection had some p-pol



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]

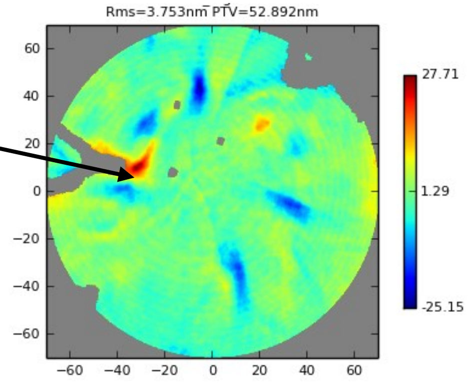


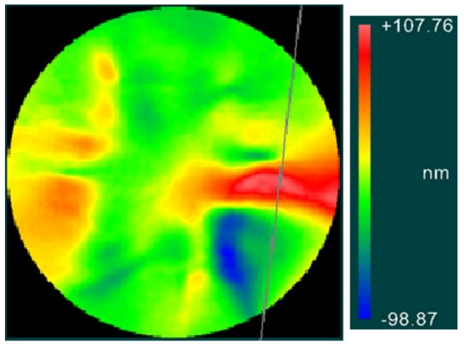
[klog#9325]

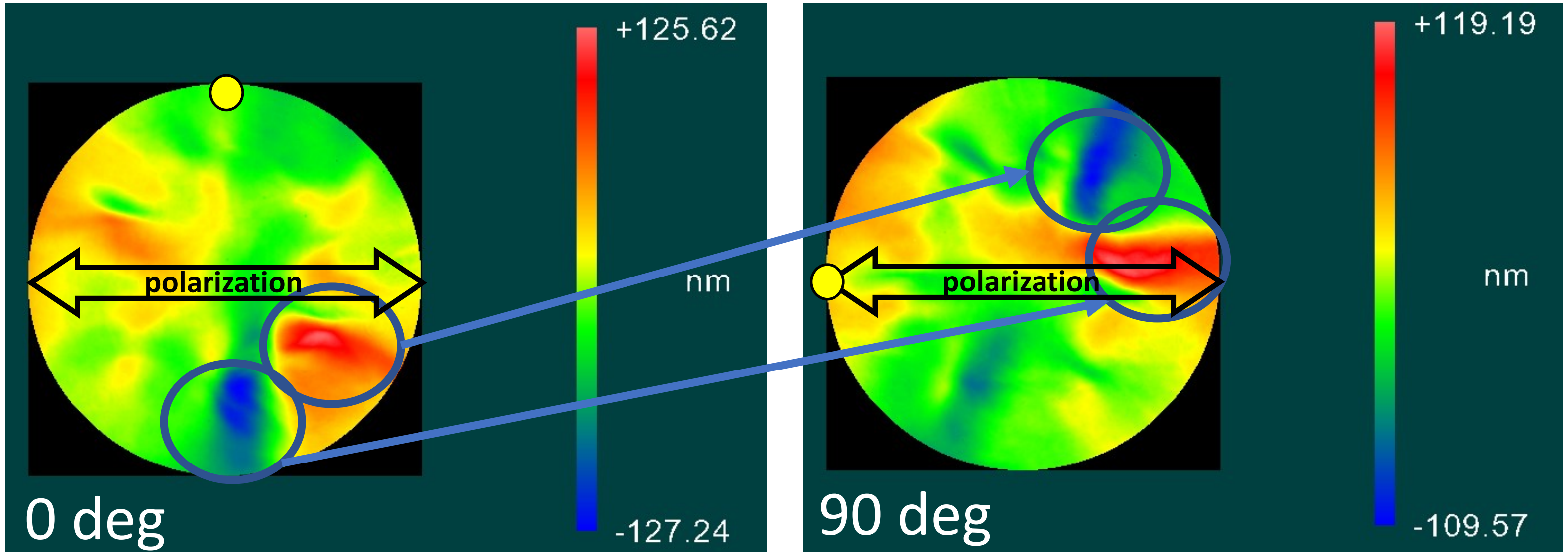
Birefringence information from TWE maps

- TWE maps from Zygo and Caltech were different

- Different maps for different "input polarization"







Constructing birefringence from TWE

$$\theta = -\frac{1}{2}\tan^{-1}\frac{TWE(45) - TWE(135)}{TWE(0) - TWE(90)}$$

$$\alpha_- = \frac{2\pi}{\lambda}\cdot\frac{TWE(0) - TWE(90)}{\cos 2\theta}$$

θ looks very random due to the inhomogeneity of sapphire substrate.

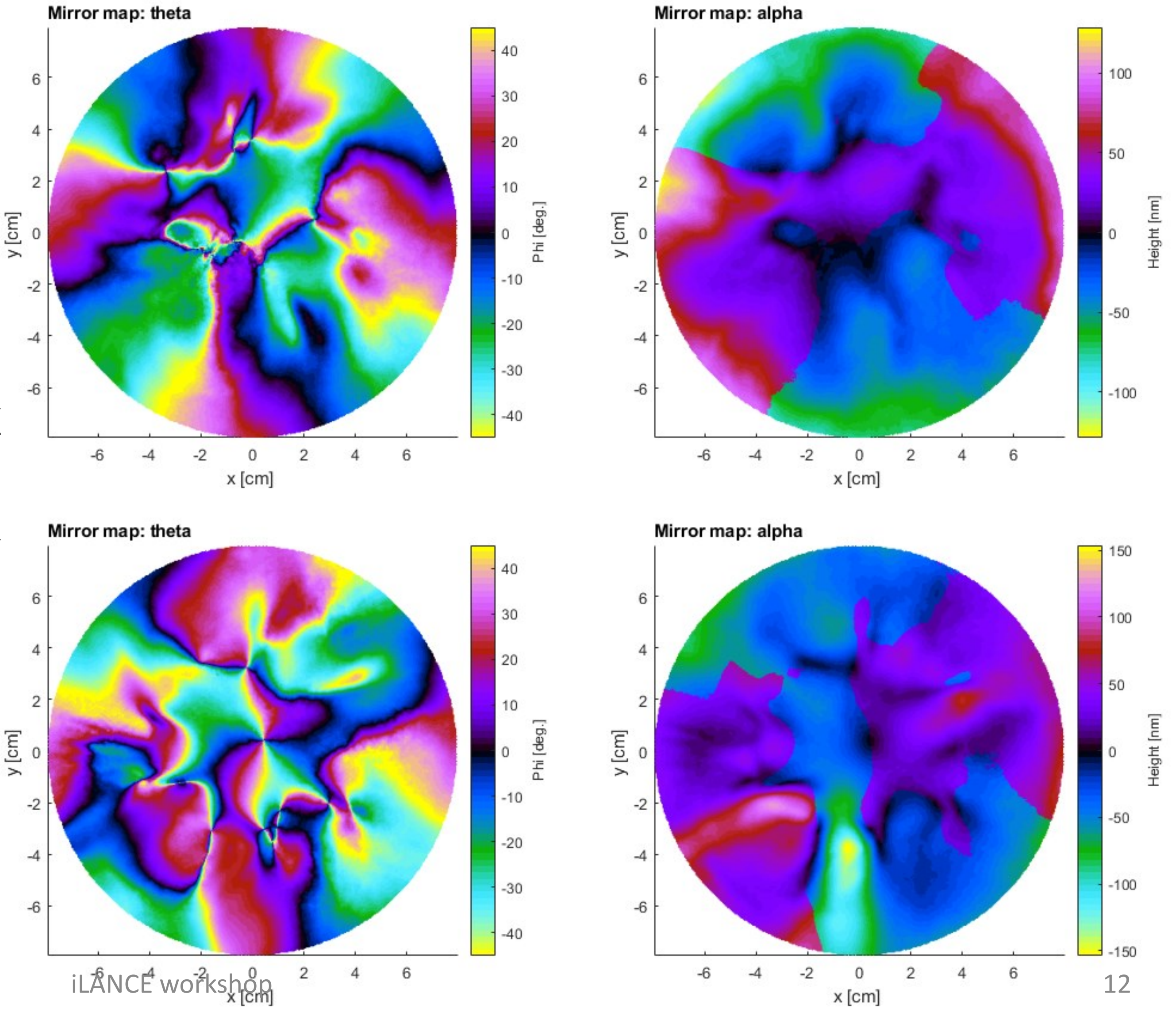
The PV value of α_- is around ±150nm.

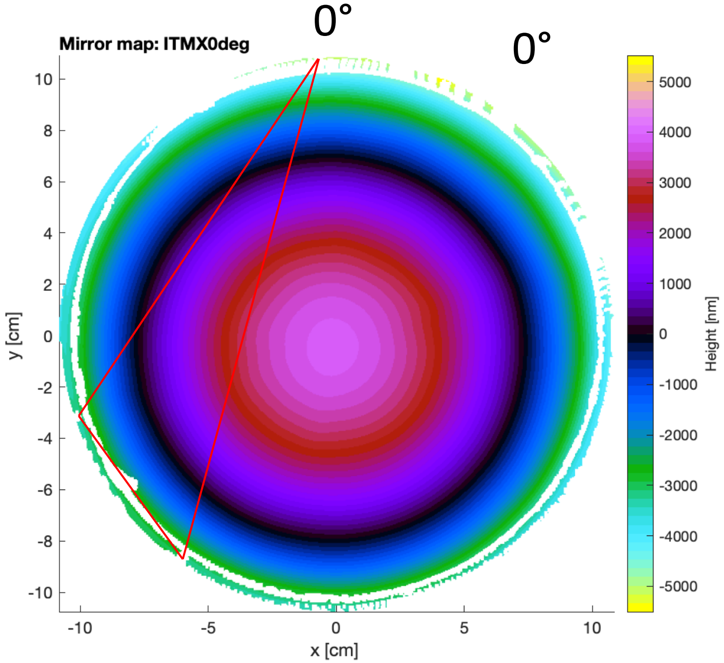
There are many sharp features, which is bad.

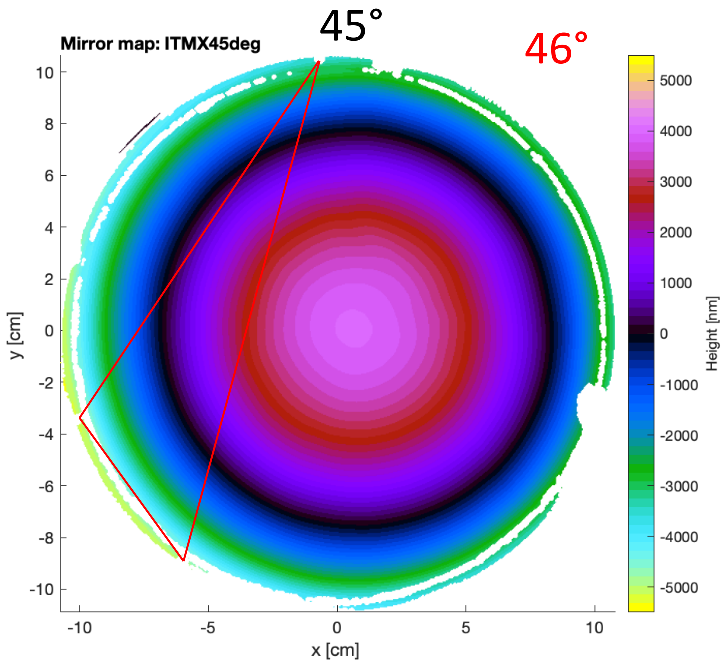
θ α_-

ITMX

ITMY

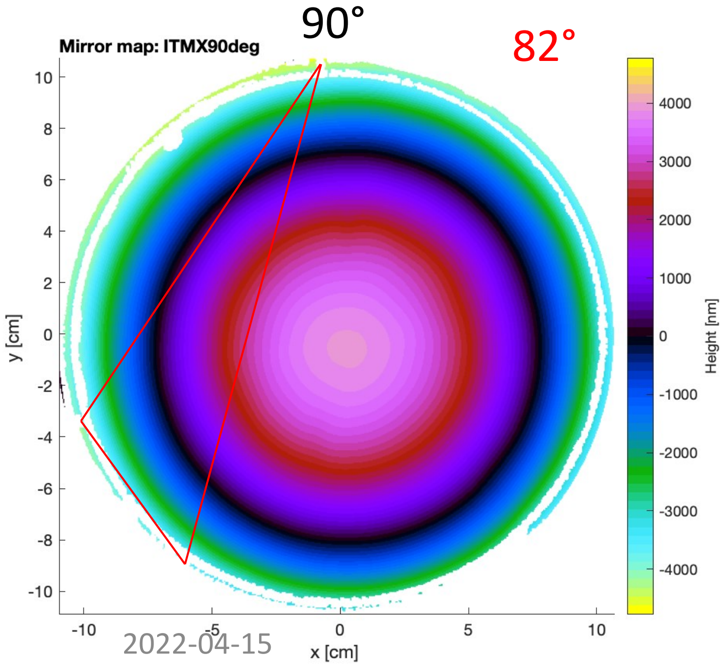


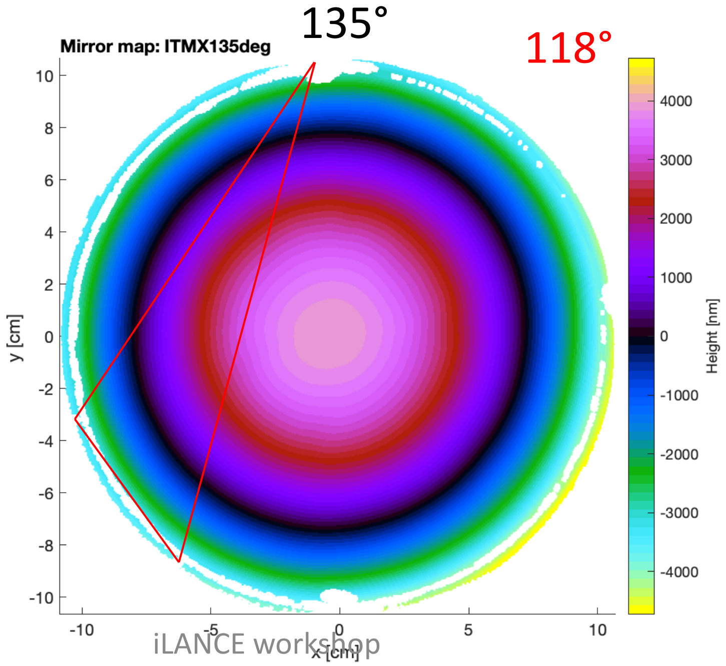




TWE maps

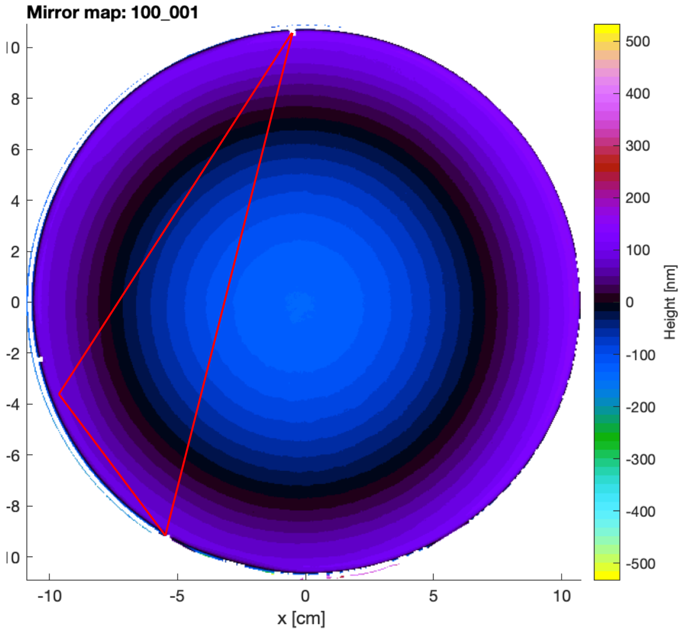
HRthAR





We calibrated rotation errors according to the markers in the TWE measurements.

HR maps



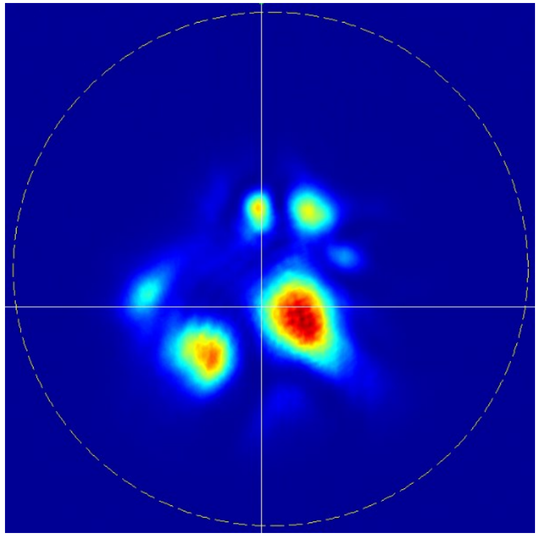
Rotation angles and markers in HR map masurements are different from TWE (HRthAR) measurements.

ITMX single bounce

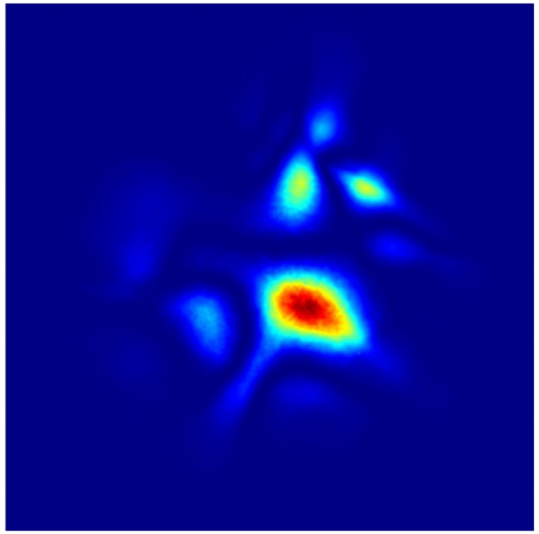
After careful calibrations for the TWE maps

P-pol shape

Measurement



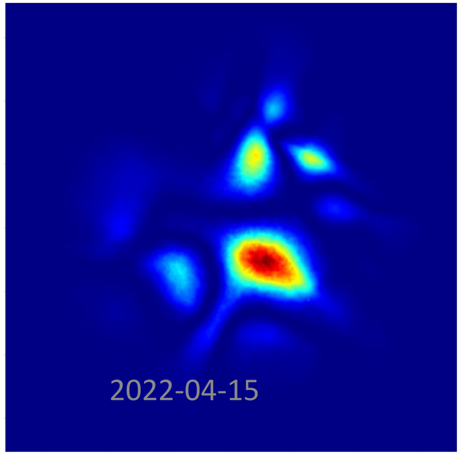
Simulation



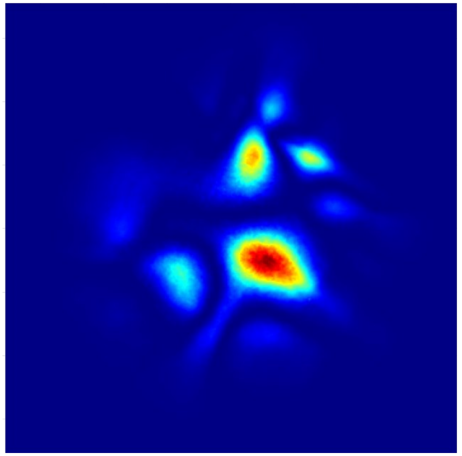
Calibration from rotation error of the 0° TWE map

One last thing, the 0° TWE map may be not measured at 0°.
If there are rotation errors (HR maps indicate the error is around 3°):

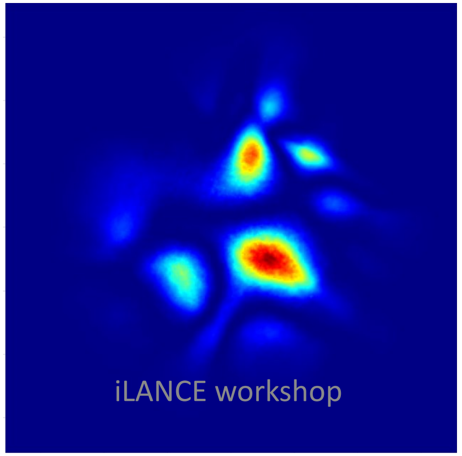
1°



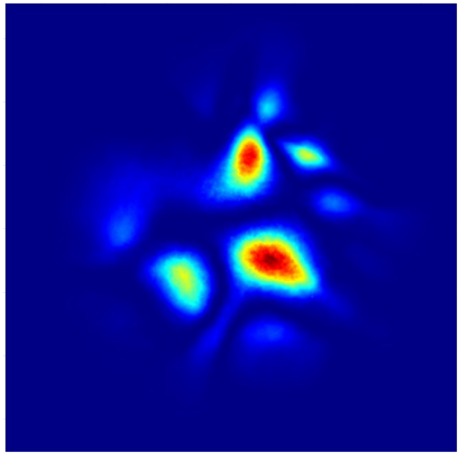
2°



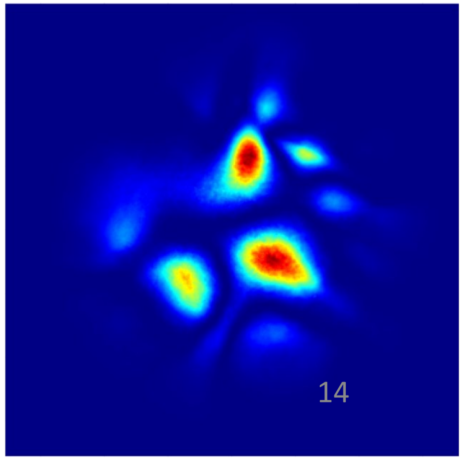
3°



4°

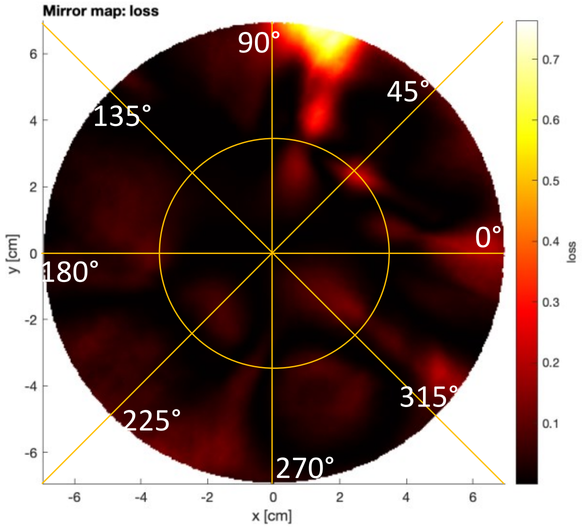


5°



S-pol loss estimation

ITMX

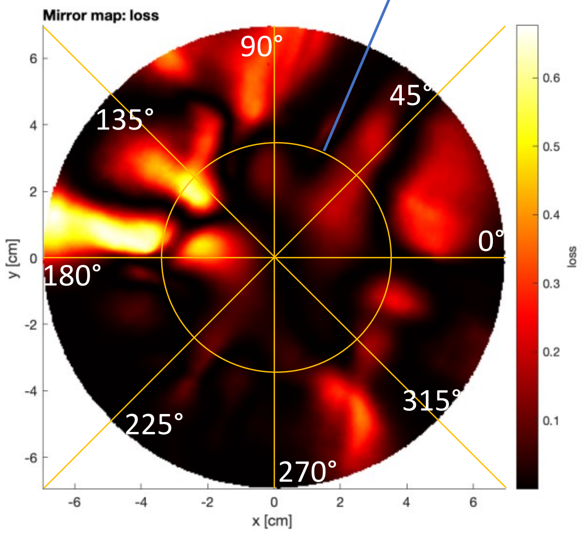


Loss estimation 2.5%
(2.3%~2.7% with 0.5cm decenter)
Measurement 6.1%

Birefringence loss can be slightly reduced by introducing beam decenter: about 1% (by 0.5cm) and 1.5% (by 1cm).

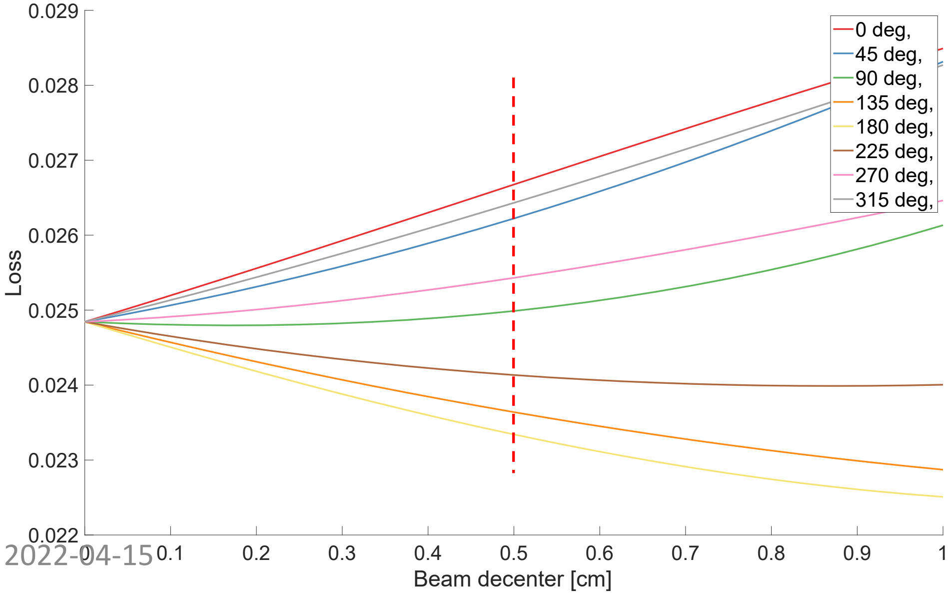
ITMY

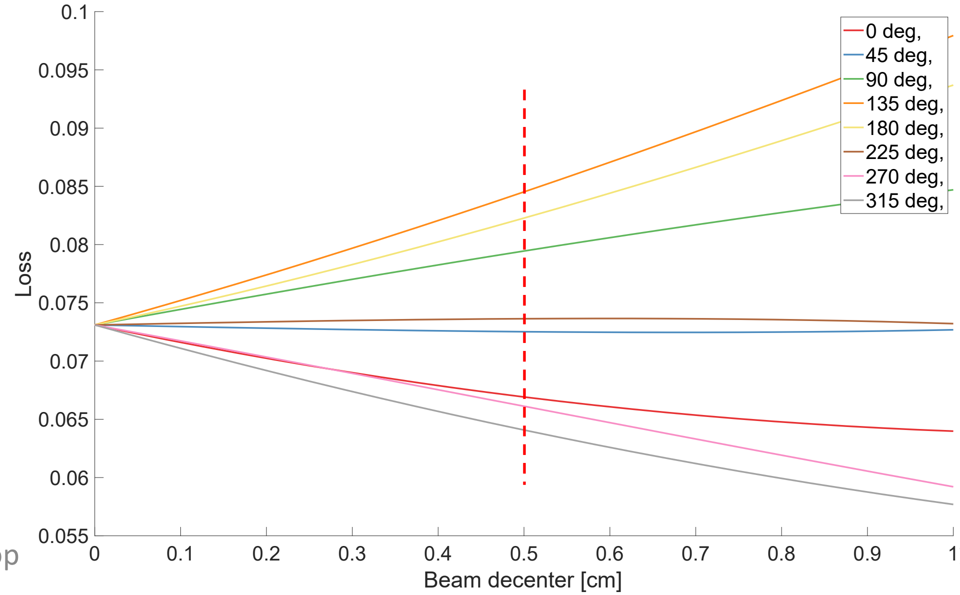
3.5cm beam radius



Loss estimation 7.3%
(6.5%~8.5% with 0.5cm decenter)
Measurement 10.8%

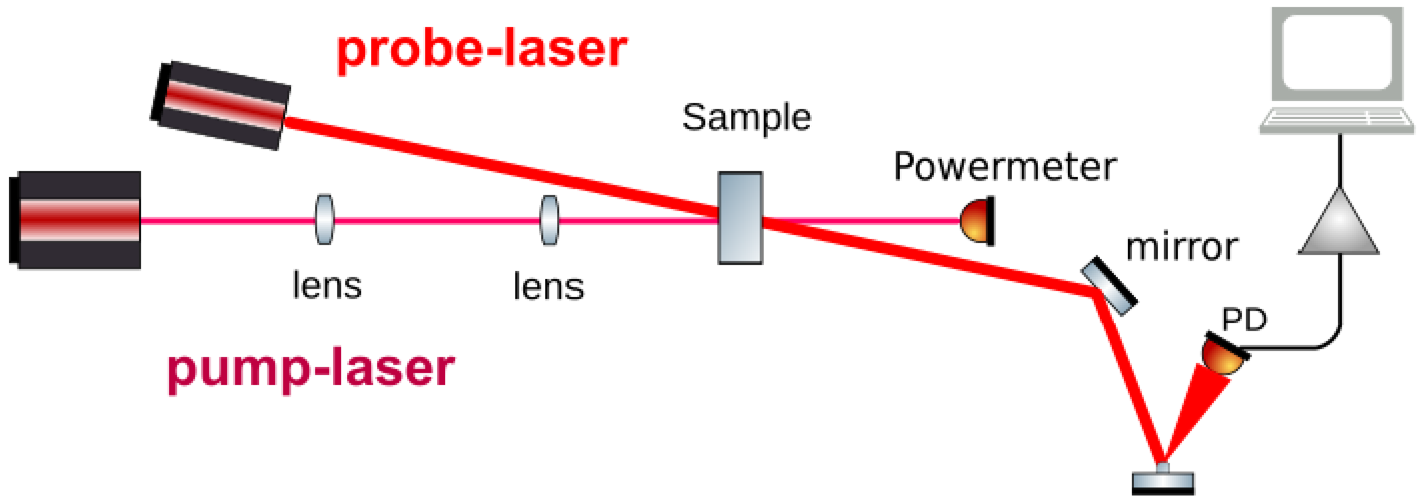
We have installed some polarization optics in KAGRA and are going to take more precise measurements for birefringence loss.





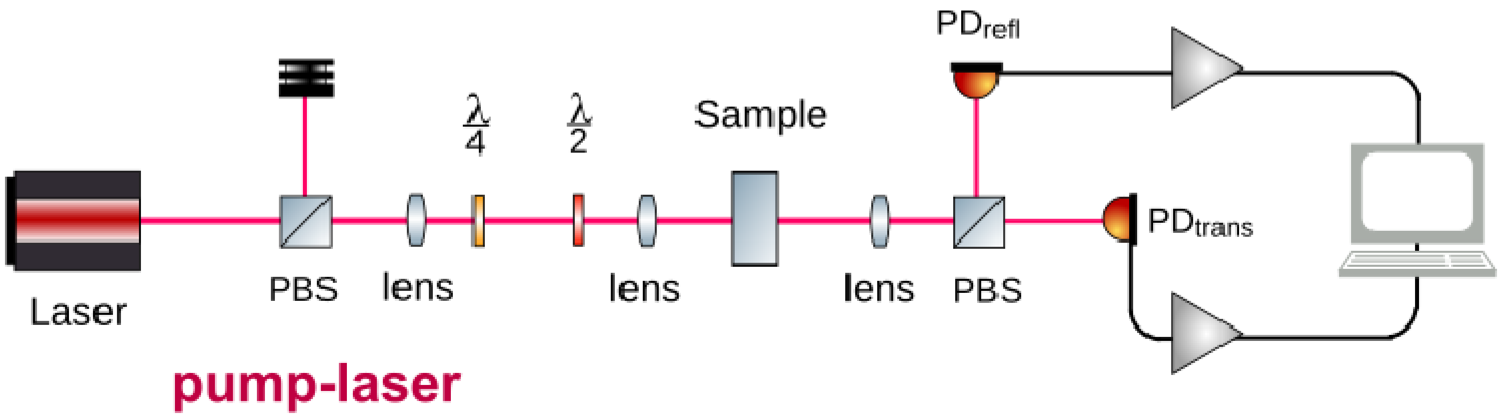
Characterization setup at NAOJ

Absorption:
photothermal common-path interferometer



Birefringence:

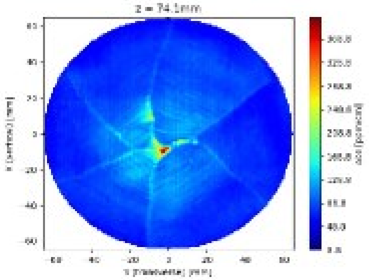
Single-pass polarization rotation

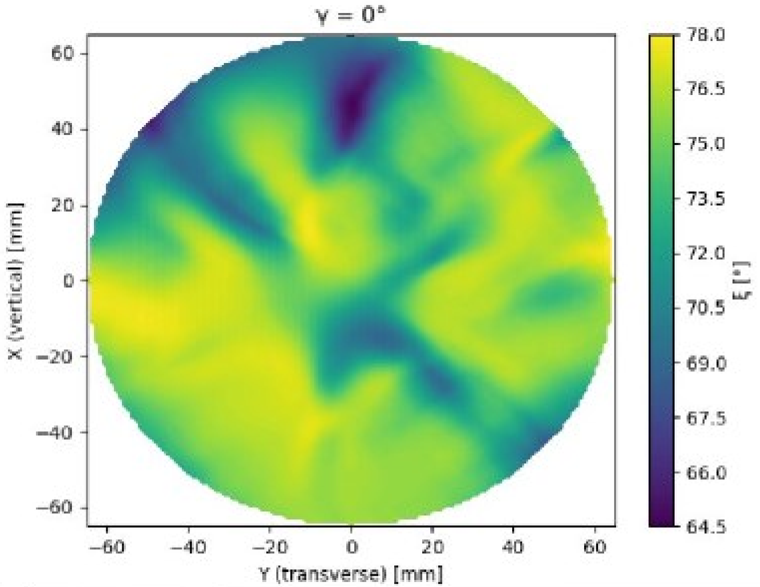


Birefringence measurements

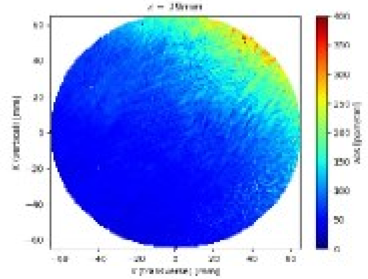
Birefringence measured as cumulative effect: $\xi = \tan^{-1}\sqrt{\frac{P_s}{P_p}}$

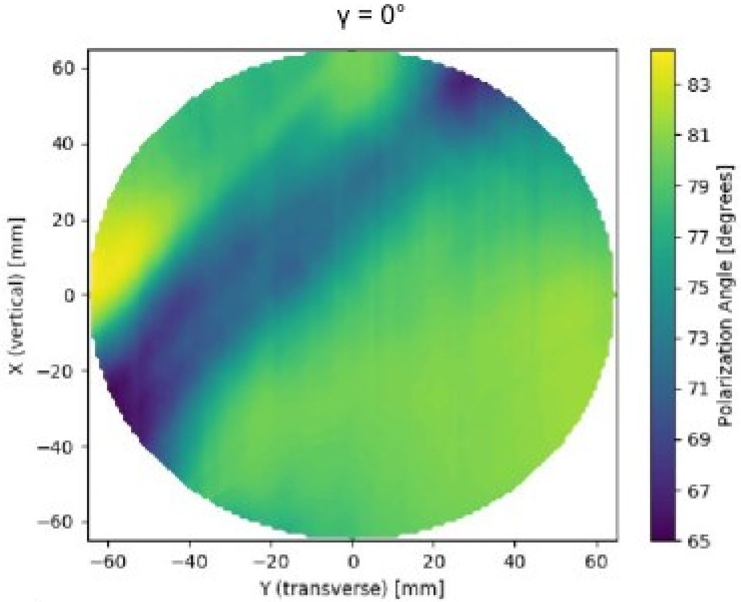
C-axis





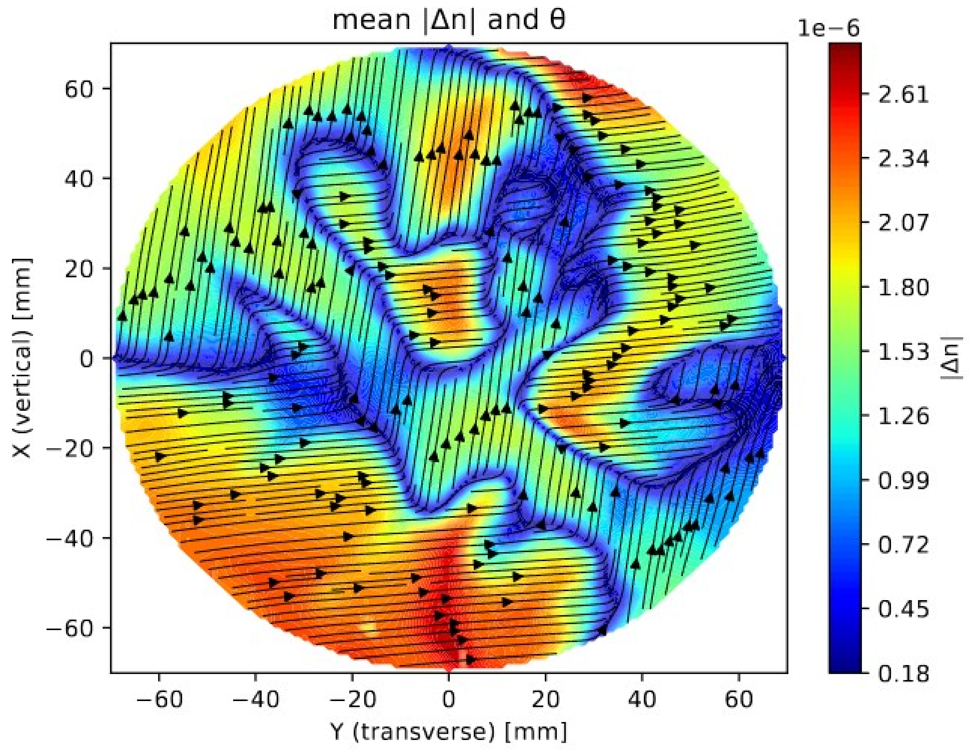
A-axis



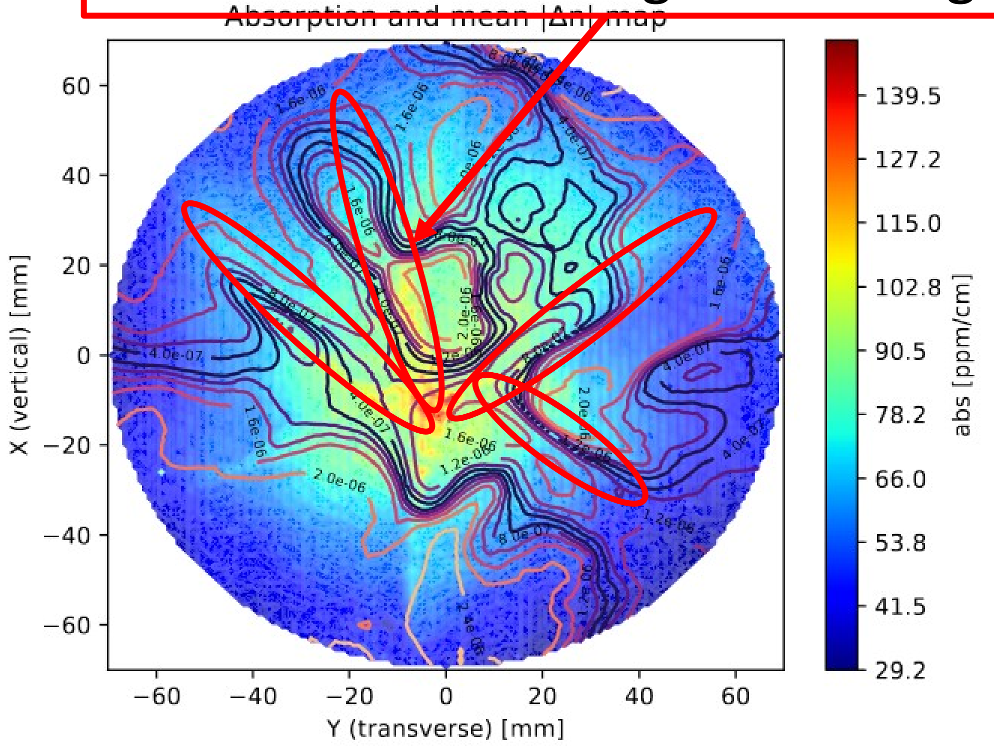


From birefringence to Δn

Δn_{RMS} is within original specs



Correlation between absorption and internal stress leading to birefringence

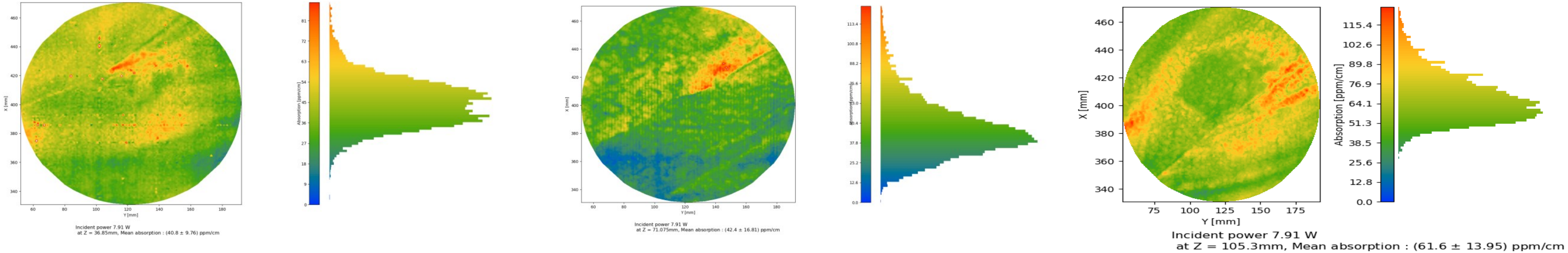


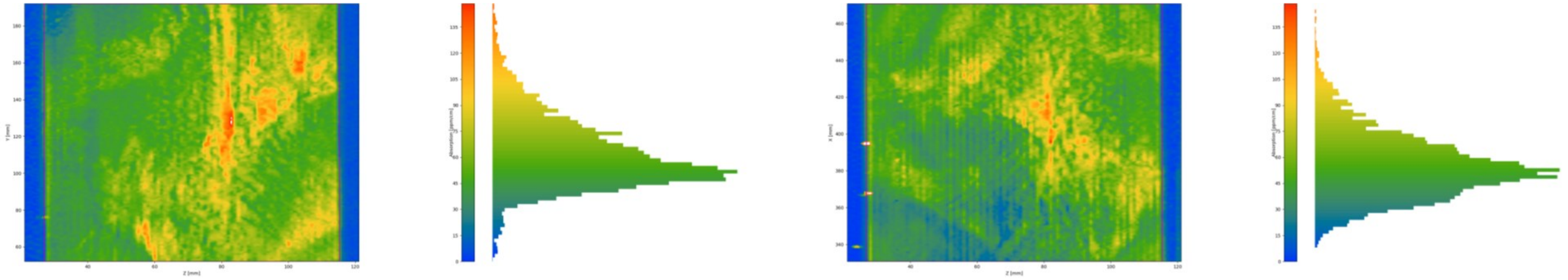
Structural defects can be the cause of both absorption and birefringence*

*Paper in preparation: [JGW-P2214004-v2]

New sapphire substrates

We are measuring performances of crystals from new makers and interacting with old makers to improve their quality.

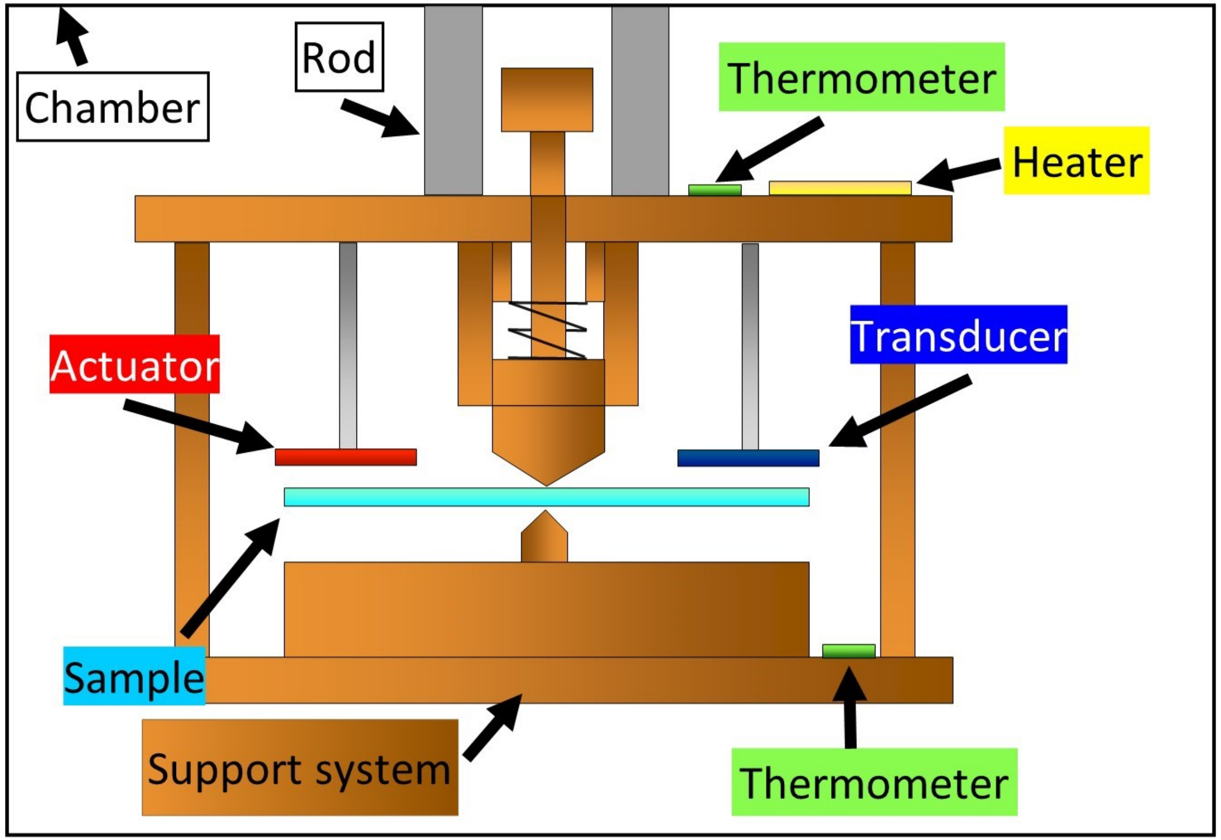


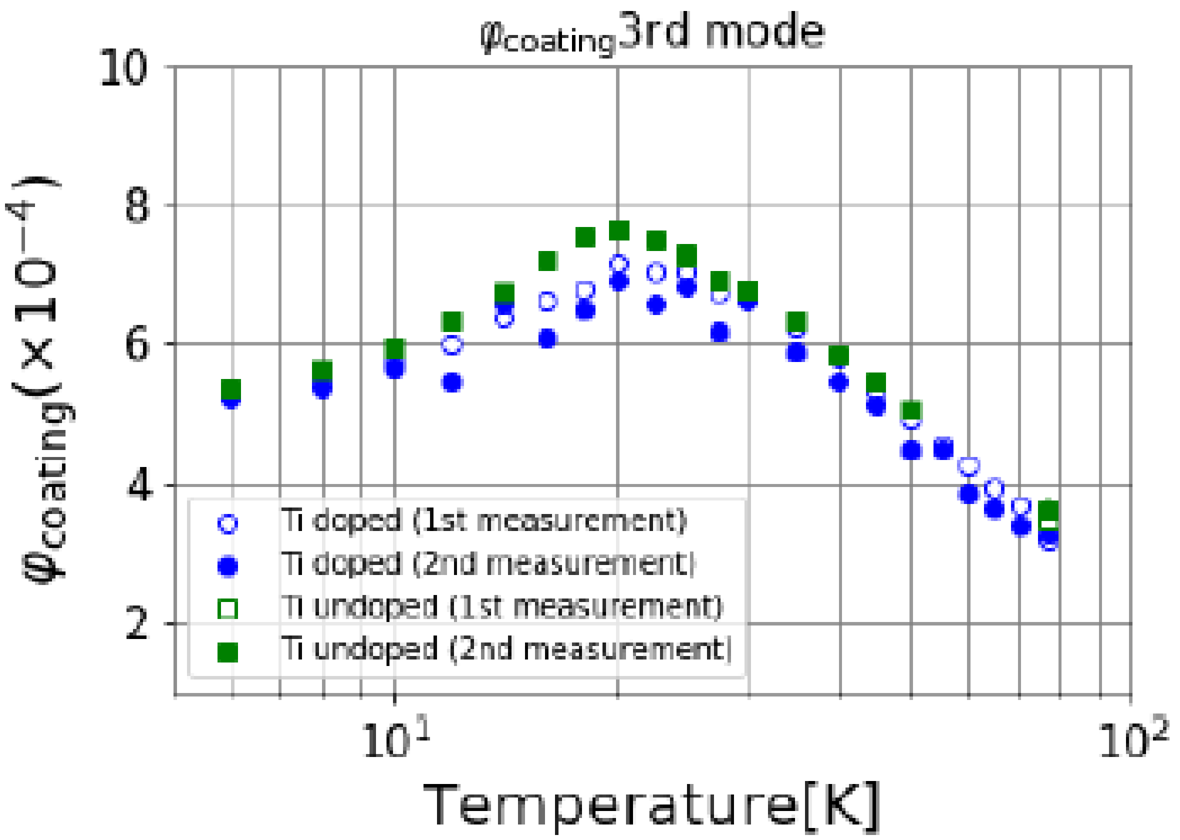


Absorption of about 50ppm/cm and quite homogeneous

Coating characterization at cryogenic temperature

Measurement system: nodal support





End