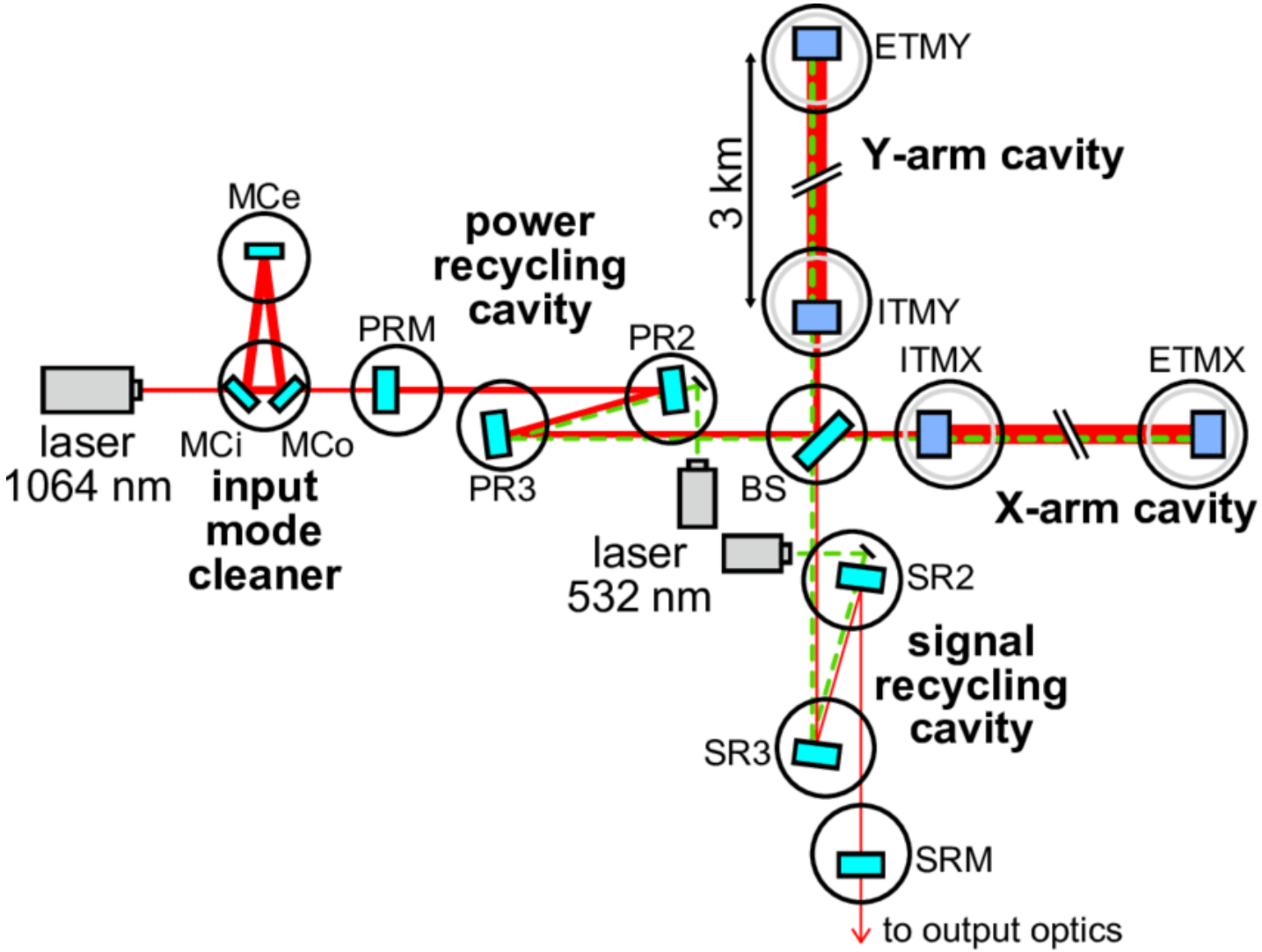
KAGRA sapphire mirror issues and current status

M. Leonardi (National Astronomical Observatory of Japan)

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”

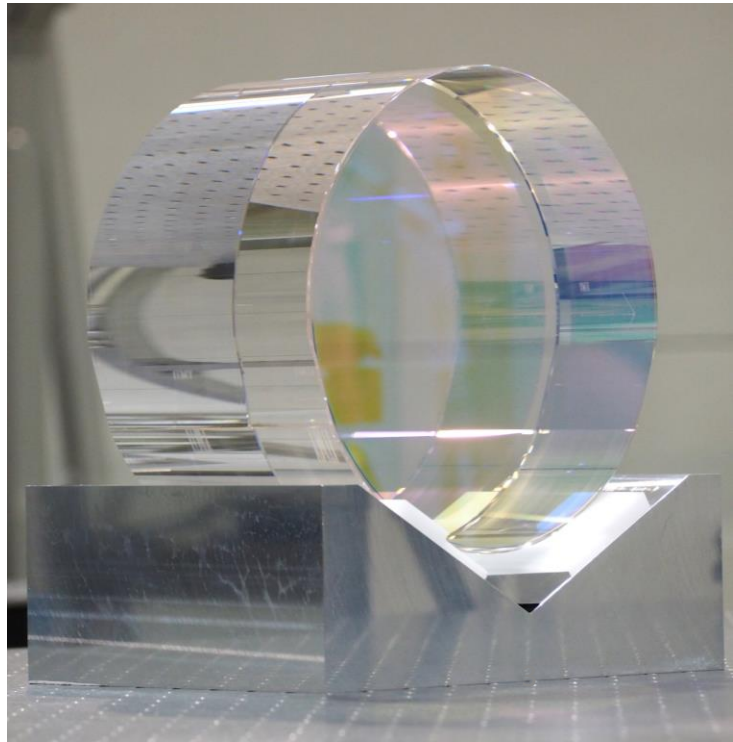
KAGRA mirrors: Aluminum oxide (corundum)

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)
- …



How to build a mirror…

Bulk/substrate:

- Size, optical absorption, crystal orientation, refractive index variation, purity, birefringence, …

Polishing:

- Radius of Curvature, roughness, flatness, surface defects, …

Coating:

- Reflectivity/transmittivity, homogeneity, scattering, absorption, loss angle, …

MIR related issues

- 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)

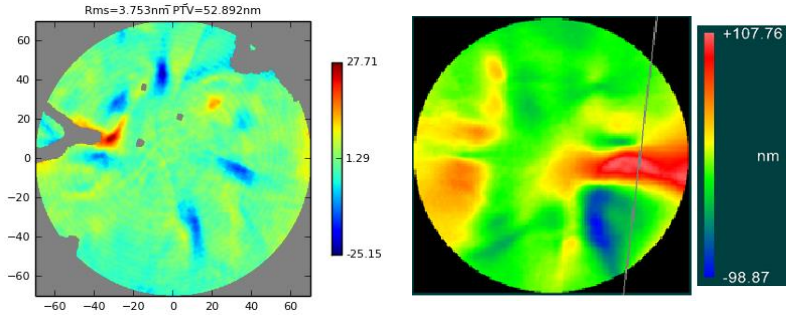
Solution:

- 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:

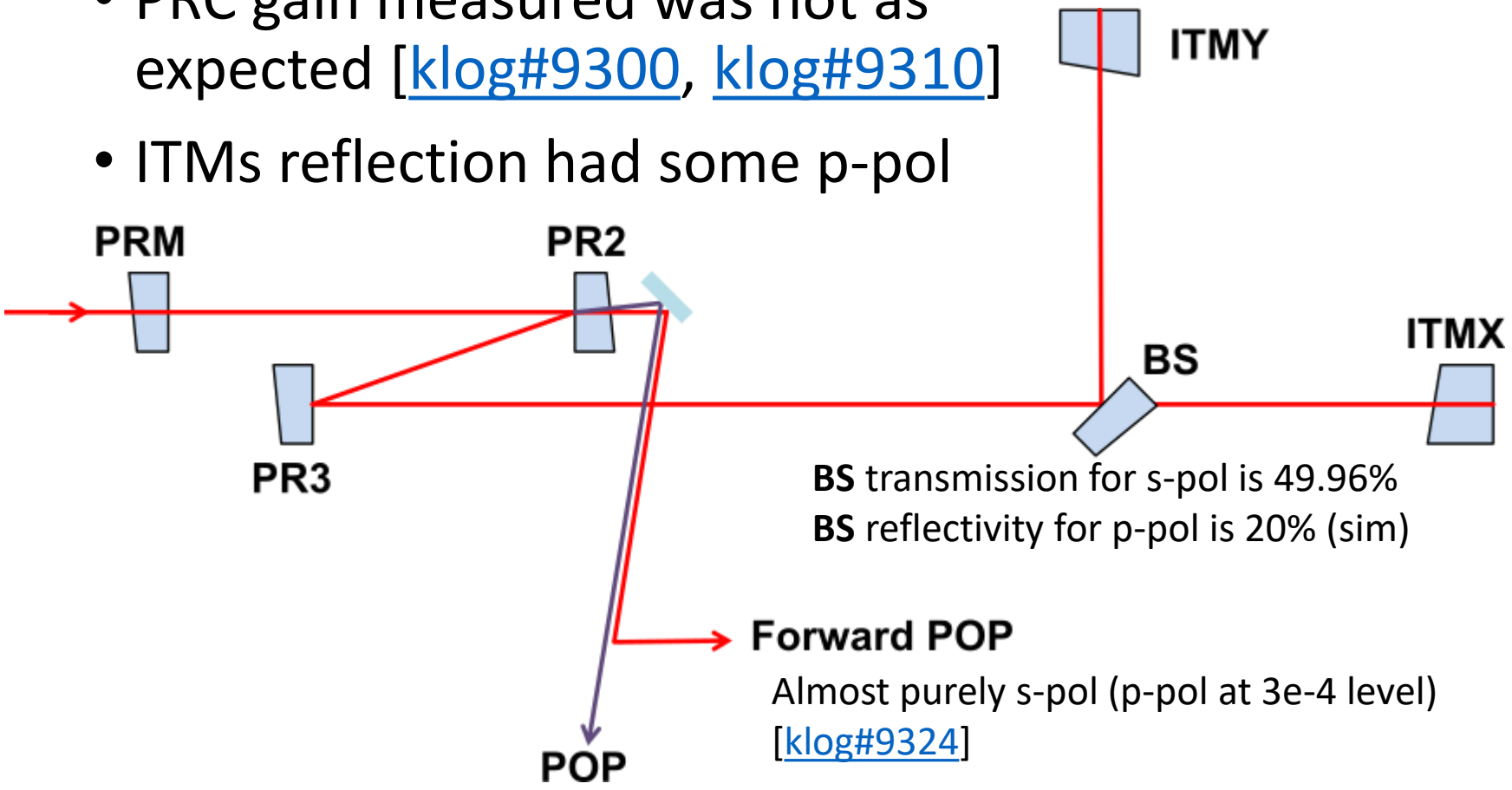
- Increased laser intensity and frequency noise coupling (T2011662) and increased HOMs at the dark port (G1809362, Phys. Rev. D 100, 082005)

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

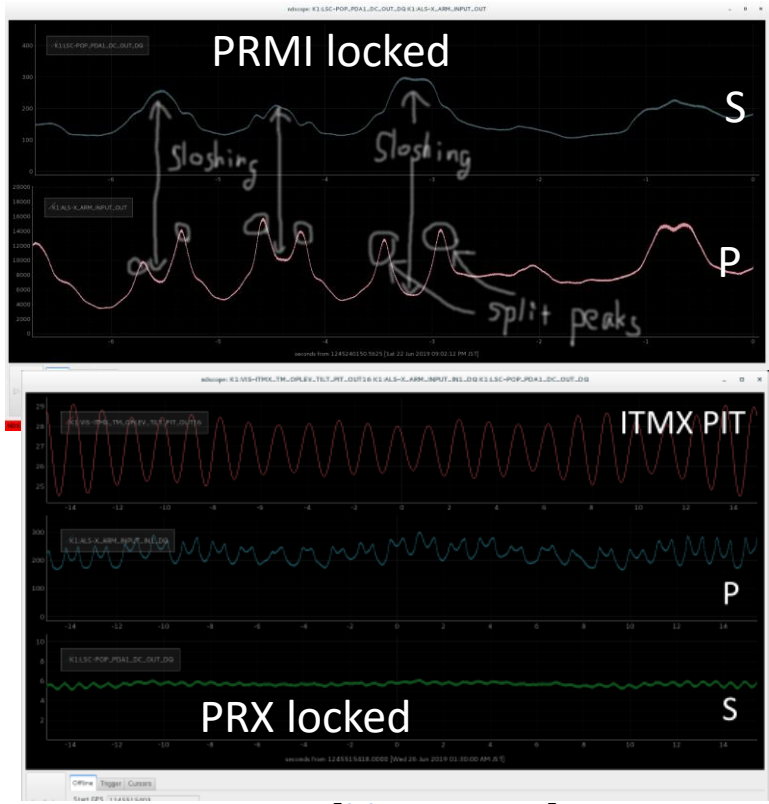


BS transmission for s-pol is 49.96%
BS reflectivity for p-pol is 20% (sim)

Forward POP

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

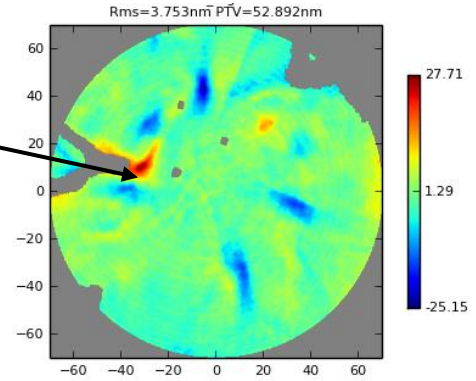
9.4 % p-pol from ITMX single bounce
4.6 % p-pol from ITMY single bounce [klog#9314]

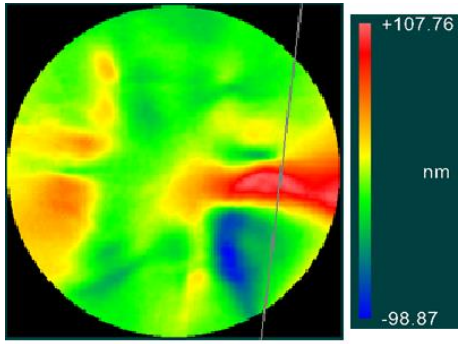


[klog#9325]

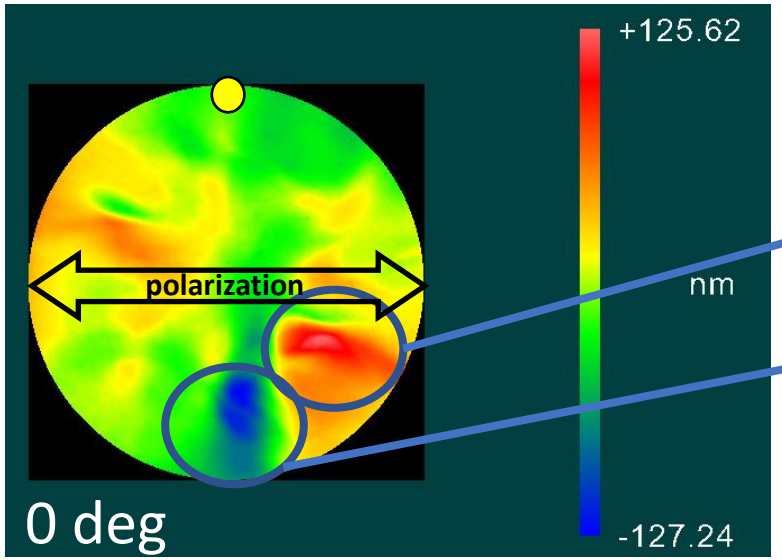
Birefringence information from TWE maps

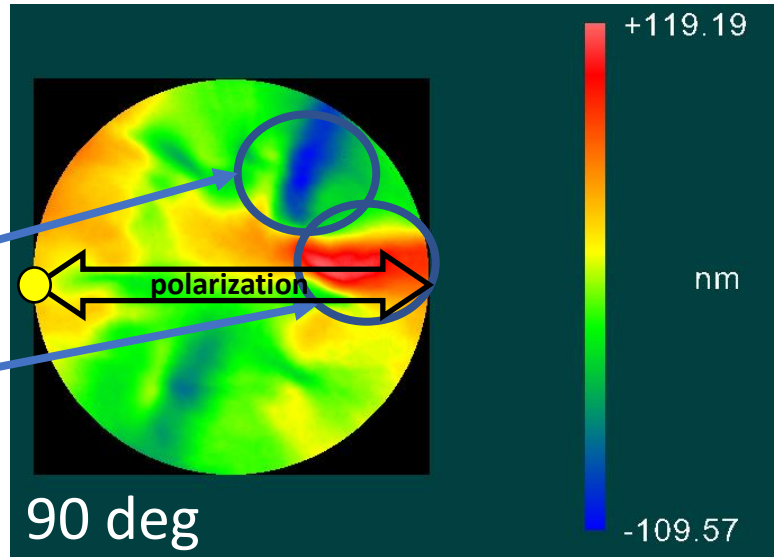
- TWE maps from Zygo and Caltech were different





- Different maps for different “input polarization”





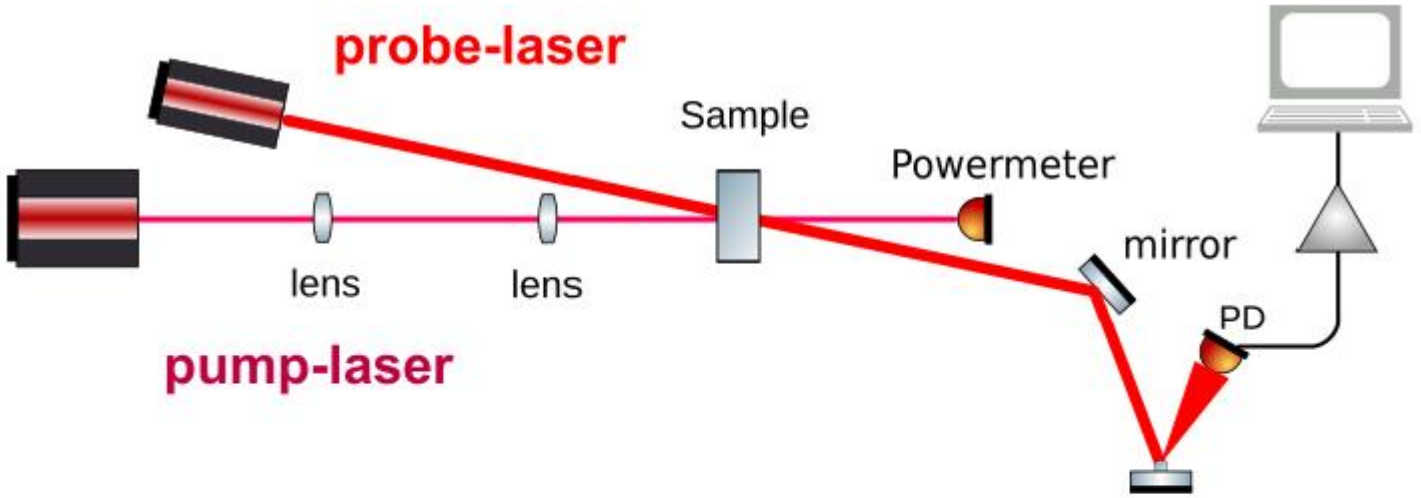
From TWE maps we estimated the expected p-pol at POP:

$$\begin{matrix}10.8\%\\4.0\%\end{matrix} @POP \begin{pmatrix}9.4\%\\4.8\%\end{pmatrix}$$

JGW- G1910369

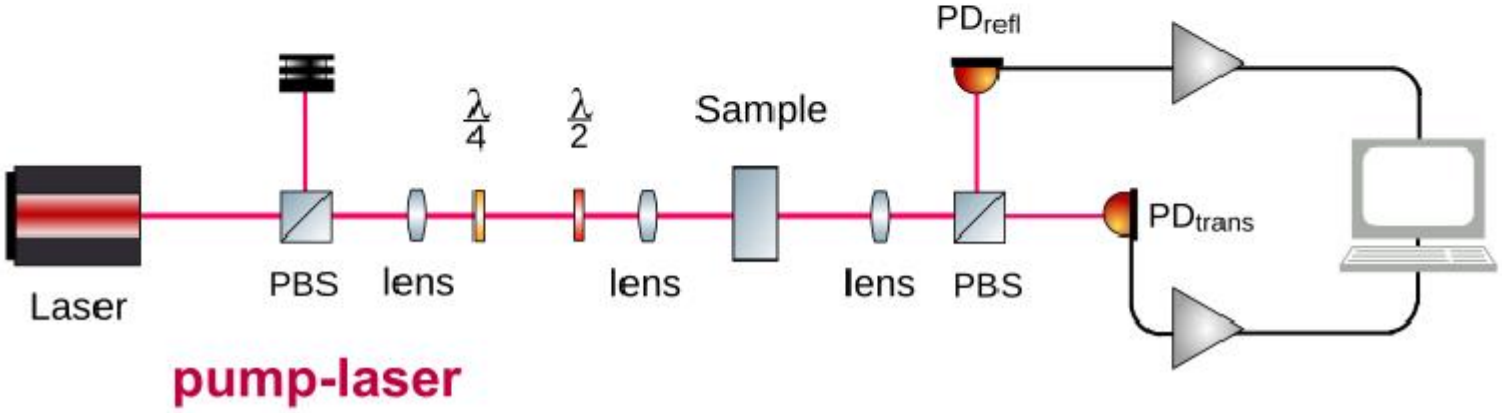
Characterization setup at NAOJ

Absorption:
photothermal common-path interferometer



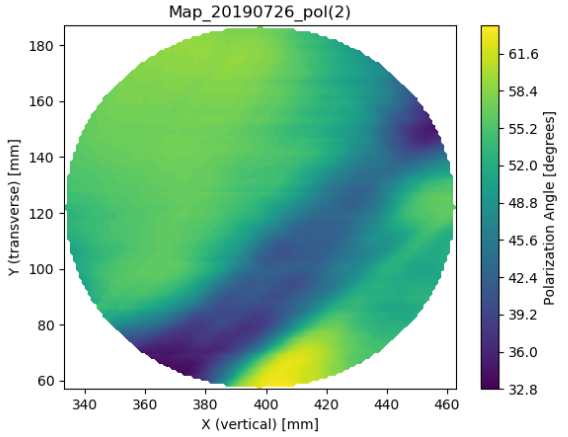
Birefringence:

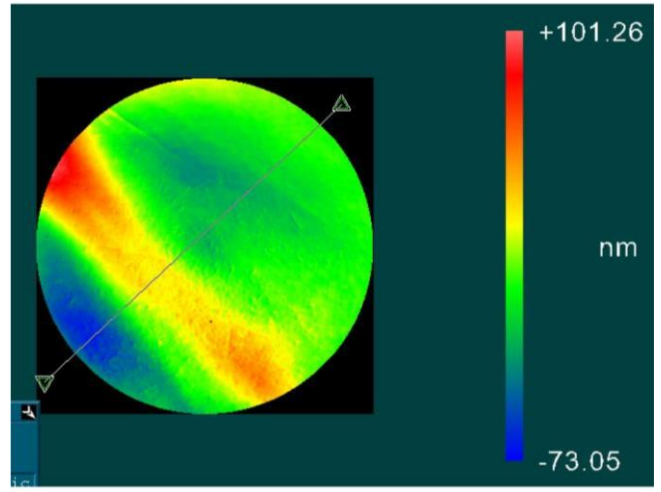
Single-pass polarization rotation



Birefringence measurement setup

Spare ETMs:
characterized at Caltech
(TWE maps available)





STD @130mm = 6.38deg

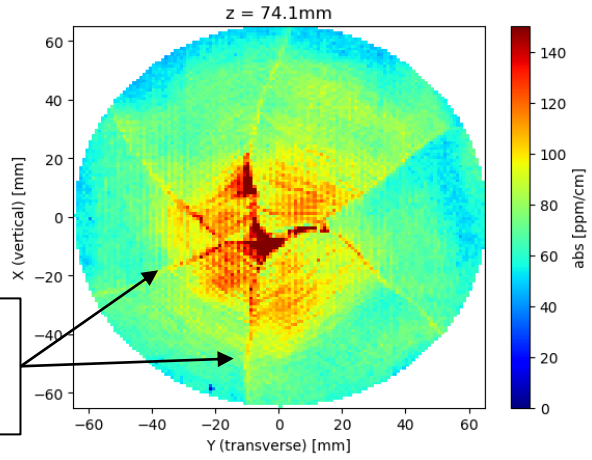
$$\theta = \frac{2\pi\Delta l_b}{\lambda} \rightarrow 18.8\text{nm}$$

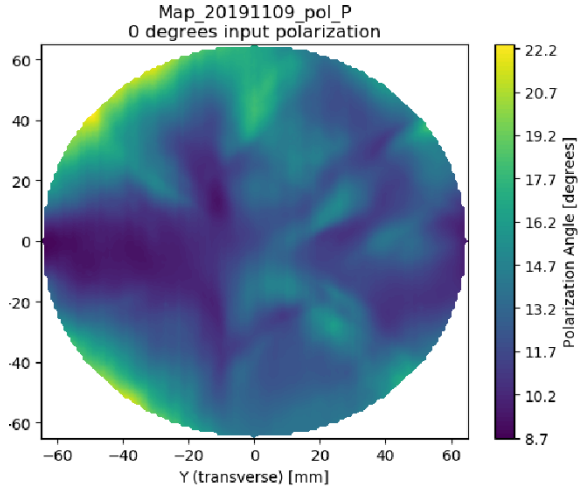
RMS @140mm = 25.9nm

JGW-T1909948

Discarded ITM:
same growth method of
installed ITMs

M- and R-planes intersections



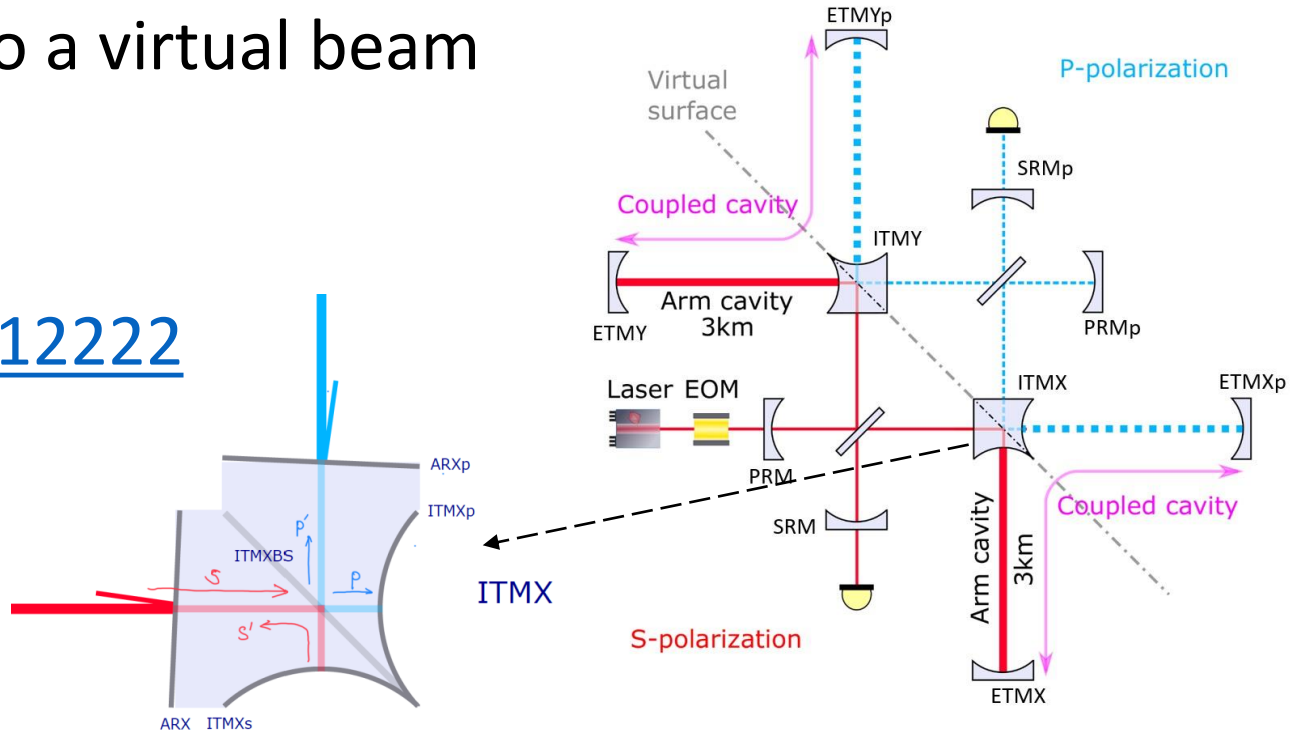


Simulating birefringence in KAGRA

Started ad-hoc simulation using Finesse (led by **Haoyu Wang** and **Kokeyama-san**):

- s-pol/p-pol ITFs
- Birefringence maps are applied to a virtual beam splitter (AOI=0deg)

More in JGW-T2011792, JGW-G2012222



ITMs bulk birefringence recap

Causes:

- Local anisotropies of crystalline axis orientation (?)
- Local-stress (static) induced birefringence (?)

Consequences:

- Low PRG for sidebands
- A2L couplings (?)
- Increased scattered light (?)
- …

Solution:

- Obtain more homogeneous bulks for new ITMs
- Develop post-growth processes to reduce inhomogeneities (?)

*(?) = investigation still ongoing

Collaborations to improve sapphire mirrors

Industries:

- Collaborations with several sapphire growth companies (Japan, Korea, US, Europe, …)
- Difficult interaction since our requirements are extremely demanding and we want very few samples!

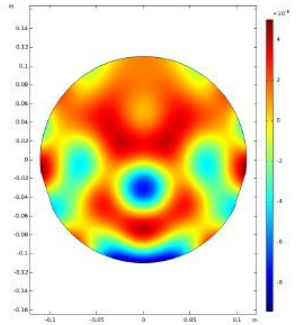
Research institutes:

- Collaboration with iLM (Lyon – FR) and with “ET” groups

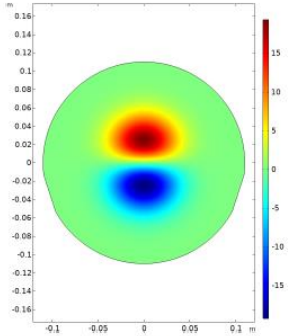
Follow the talks from Geppo, Kheirreddine and Jerome for more…

Other MIR related activities

- Study of Parametric Instabilities
  (see Kaihotsu-san's talk)



Elastic mode
84.746 kHz

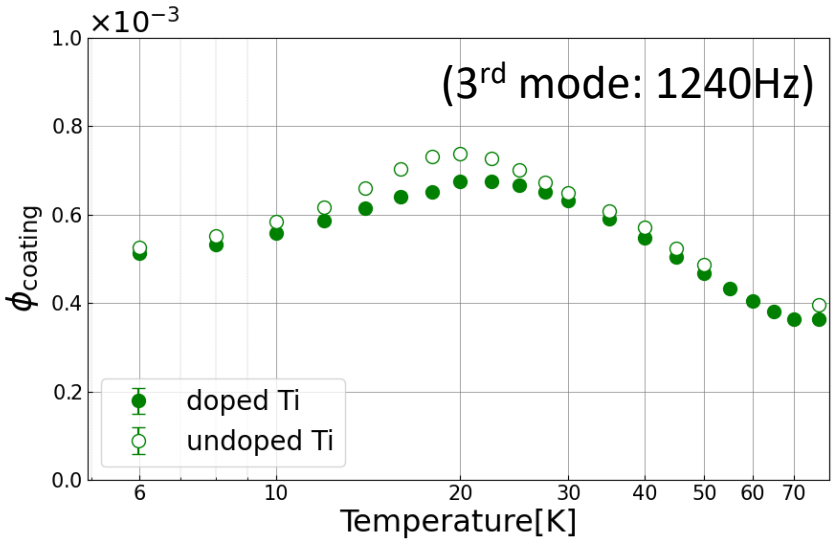


Higher-order mode
TEM_{01}
at 84.75 kHz in X-arm
at 84.78 kHz in Y-arm

X-arm
$\Lambda = 0.4$
$\mathscr{R} = 66.19$

Y-arm
$\Lambda = 0.4$
$\mathscr{R} = 13.49$

- Measurement of coating loss angle at cryogenic temperature
  (see Mori-san's talk)



Questions?