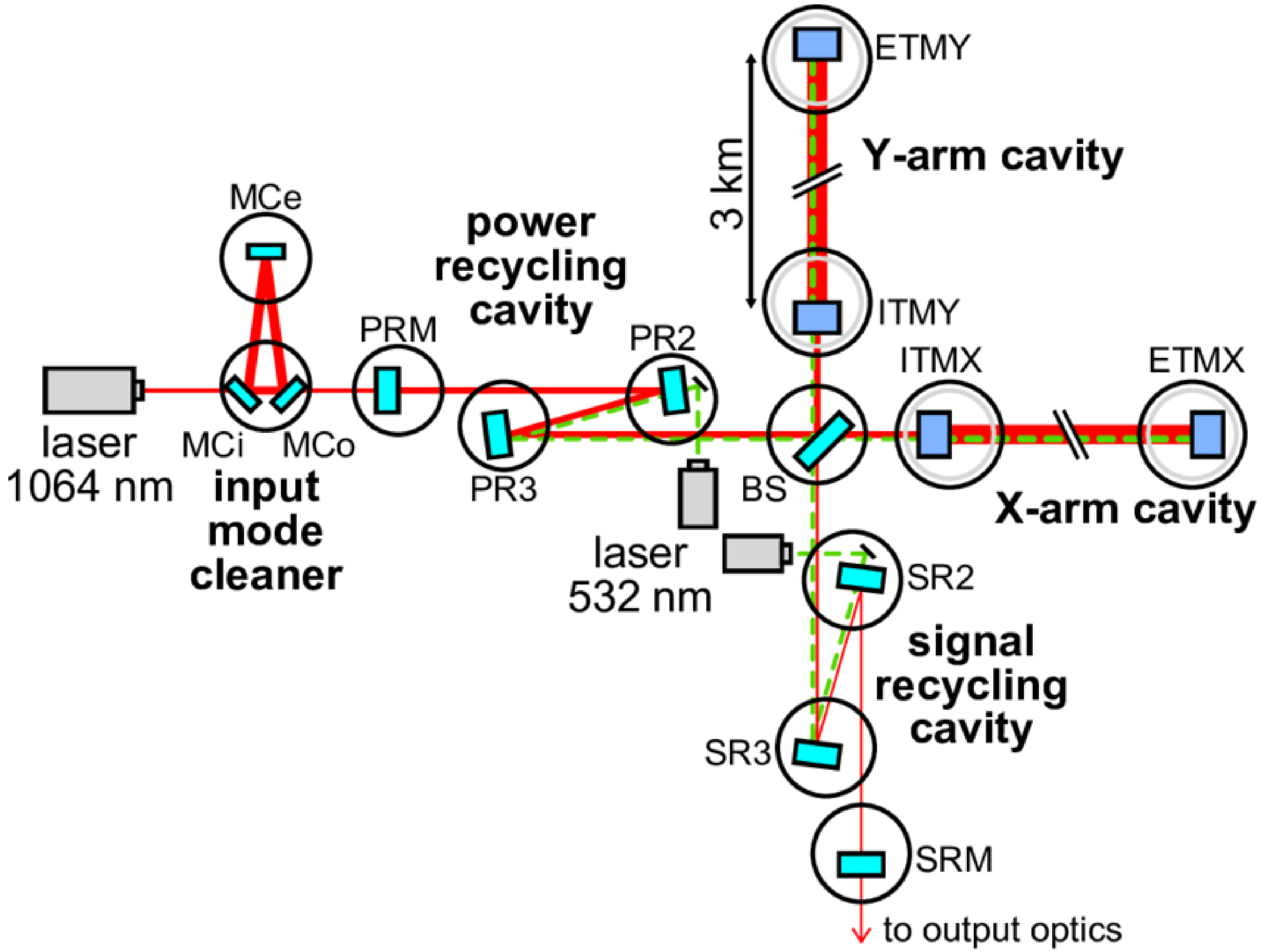
Status of KAGRA mirrors

M. Leonardi on behalf of the KAGRA collaboration

Introduction to KAGRA's mirrors



Sapphire mirrors:

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

Fused silica mirrors:

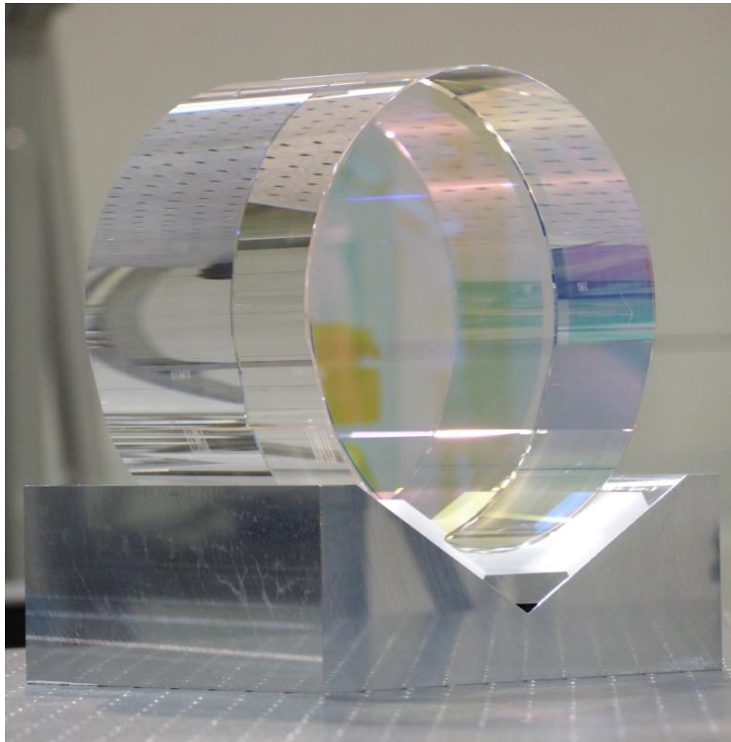
- One beam splitter (BS)
- Three input mode cleaner mirrors (MCi, MCo, MCe)
- Three power recycling cavity mirrors (PRM, PR2, PR3)
- Three signal recycling cavity mirrors (SRM, SR2, SR3)
- Two input mode matching telescope mirrors (IMMT1, IMMT2)
- Two output mode matching telescope mirrors (OMMT1, OMMT2)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

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)

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)

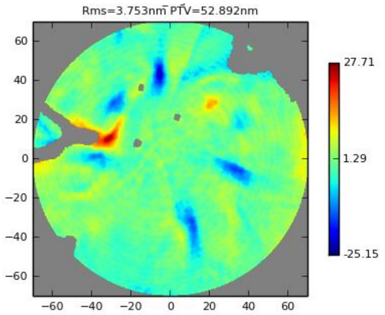
Solution:

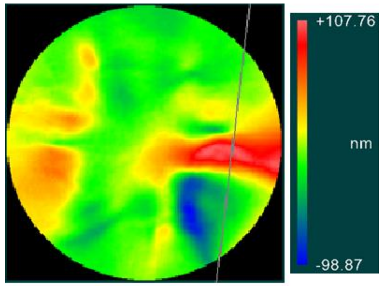
- Re-coat ITMs

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:

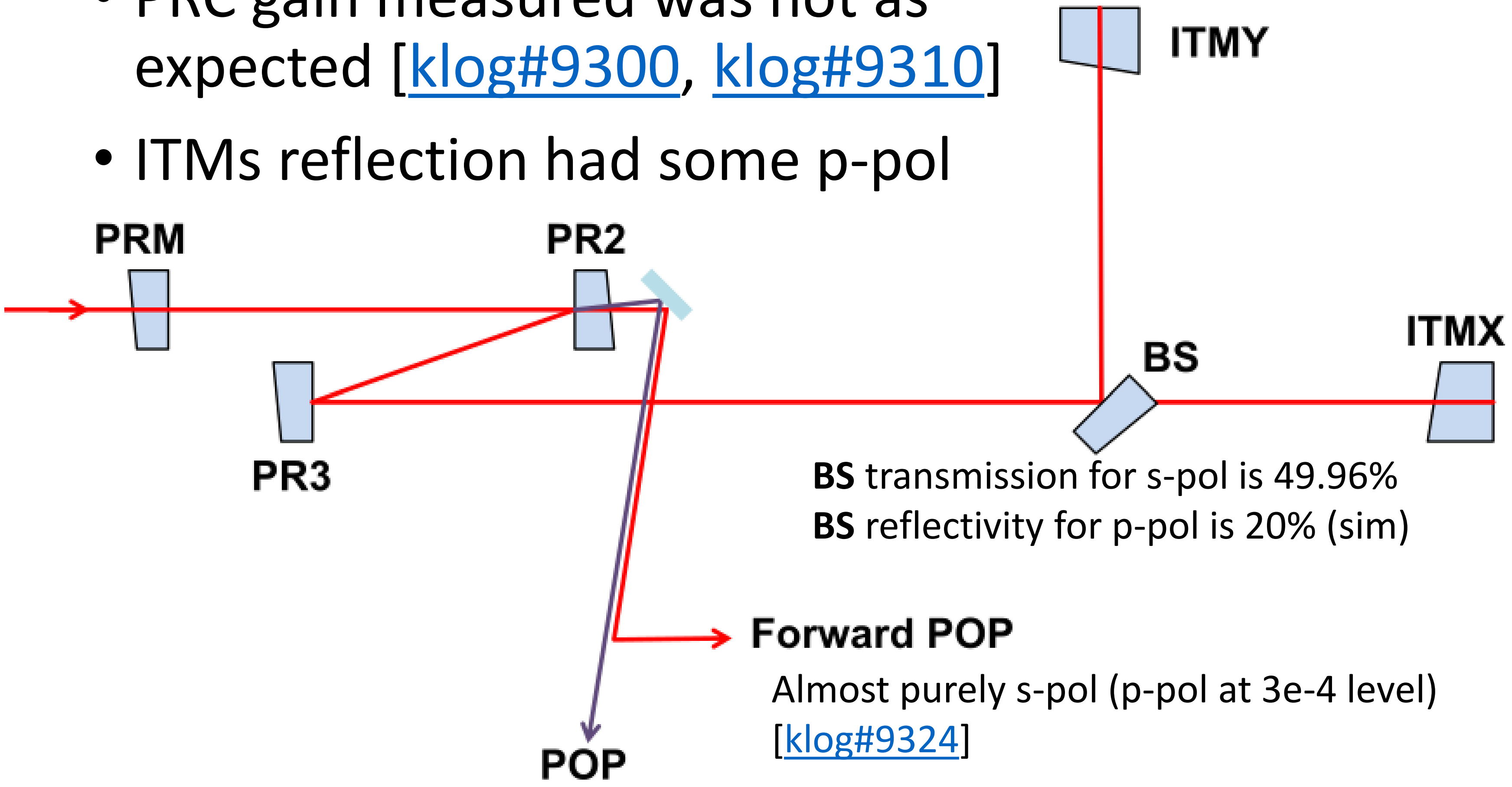
- Increased laser intensity and frequency noise coupling (T2011662) and increased HOMs at the dark port (G1809362, Phys. Rev. D 100, 082005)

Solution:

- Re-polish ITMs (using correct TWE map)

ITMs bulk birefringence: p-pol detected

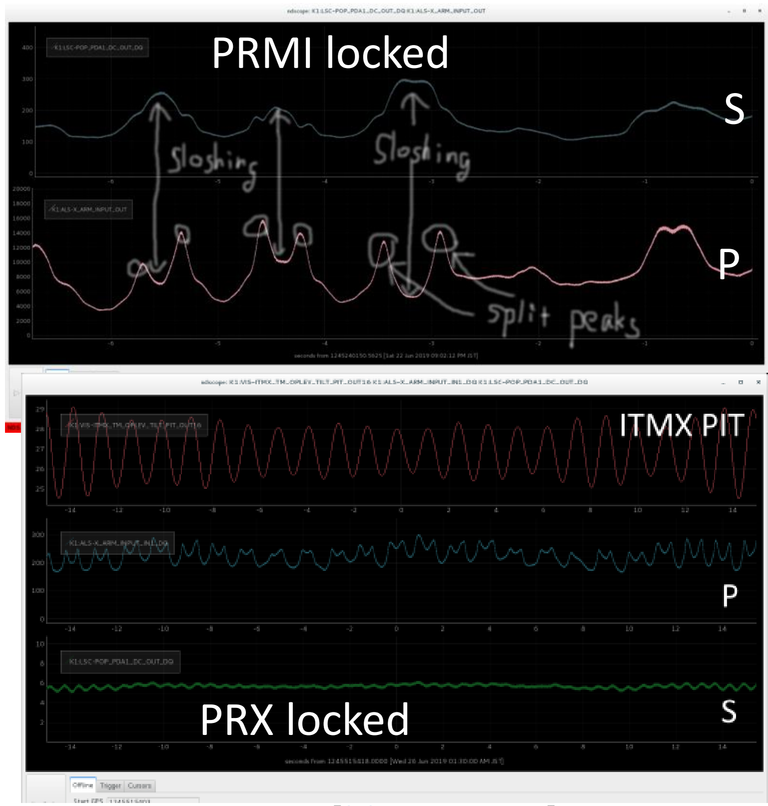
- PRC gain measured was not as expected [klog#9300, klog#9310]
- ITMs reflection had some p-pol



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]

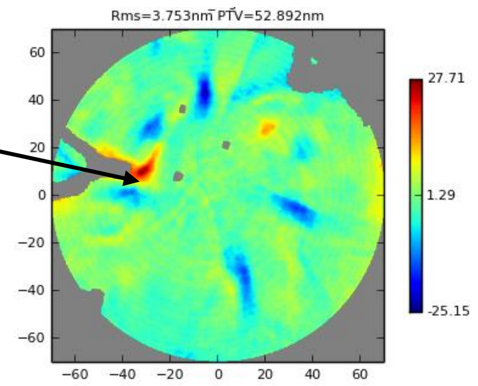
9.4 % p-pol from ITMX single bounce
4.6 % p-pol from ITMY single bounce [klog#9314]

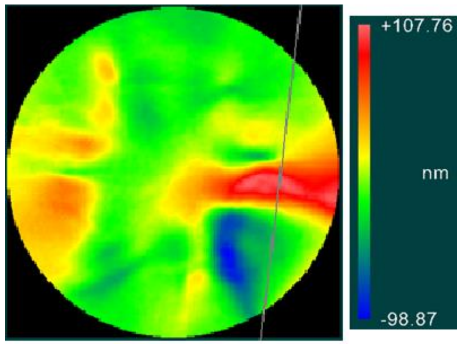


[klog#9325]

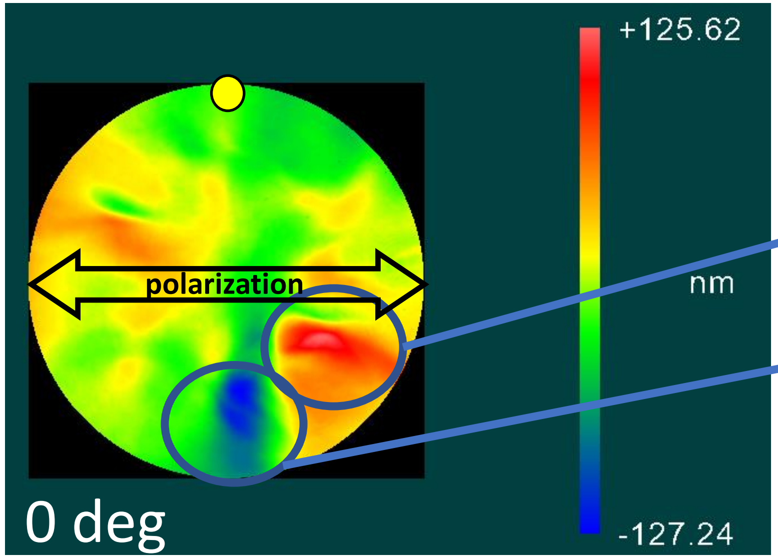
Birefringence information from TWE maps

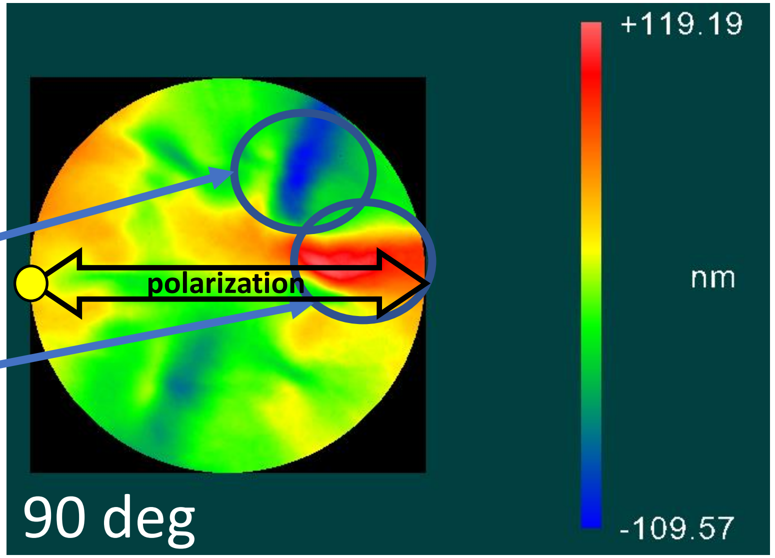
- TWE maps from Zygo and Caltech were different





- Different maps for different “input polarization”





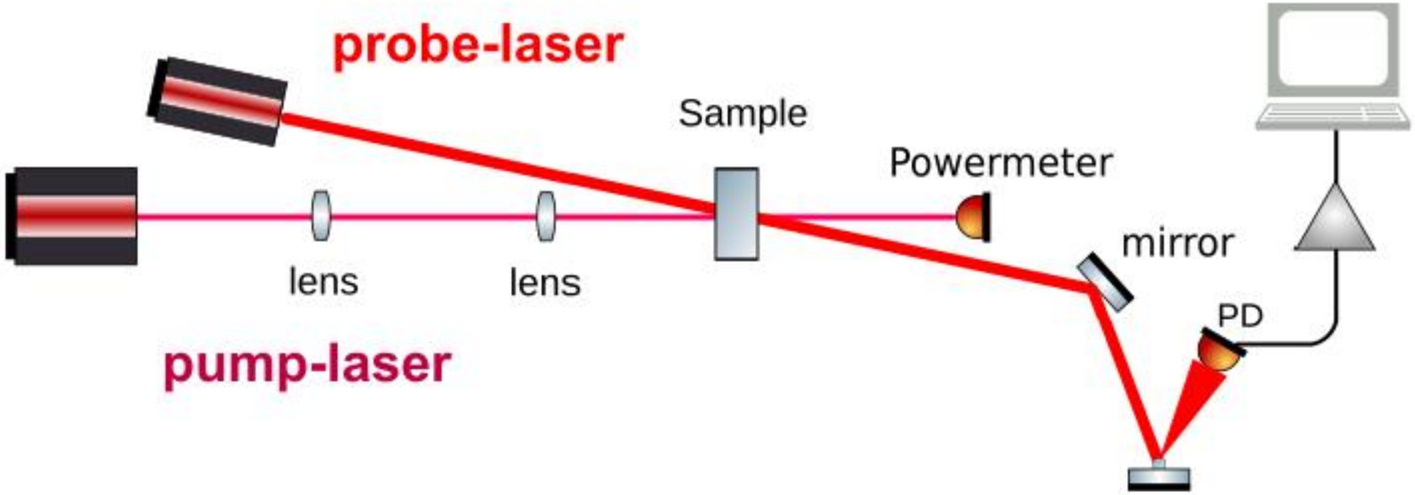
From TWE maps we estimated the expected p-pol at POP:

$$\begin{matrix}10.8\% \\ 4.0\%\end{matrix} \; @POP \; \begin{pmatrix}9.4\% \\ 4.6\%\end{pmatrix}$$

JGW- G1910369

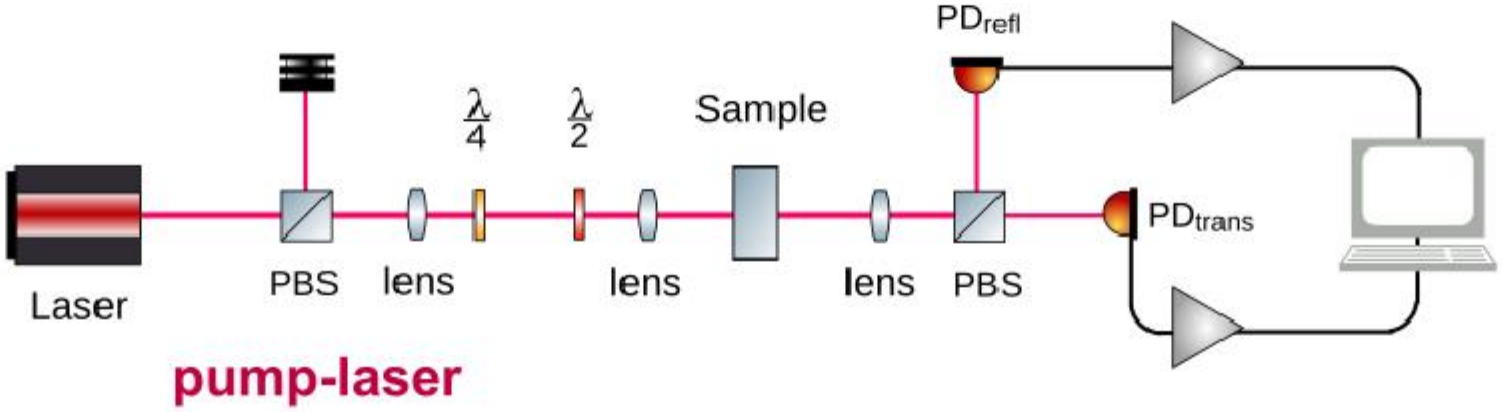
Characterization setup at NAOJ

Absorption:
photothermal common-path interferometer



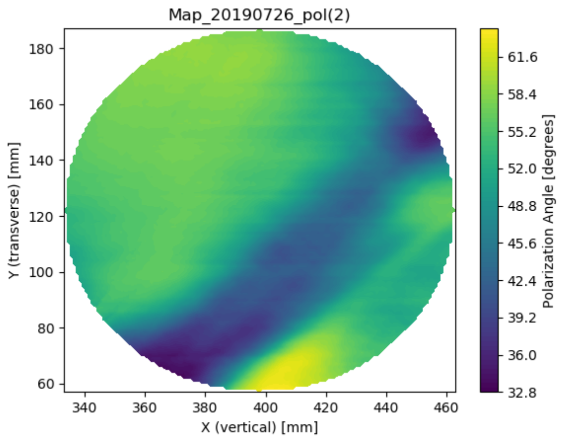
Birefringence:

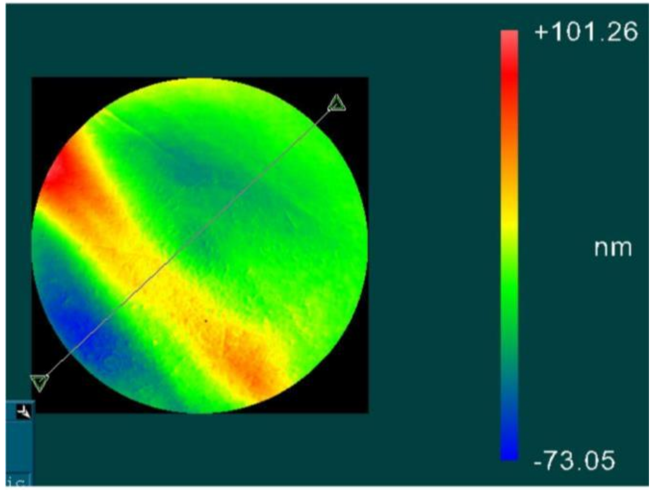
Single-pass polarization rotation



Birefringence measurement setup

Spare ETMs:
characterized at Caltech
(TWE maps available)





STD @130mm = 6.38deg

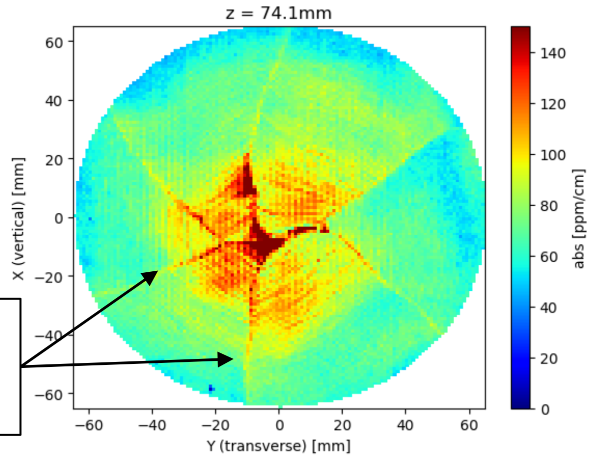
$$\theta = \frac{2\pi\Delta l_b}{\lambda} \rightarrow 18.8\text{nm}$$

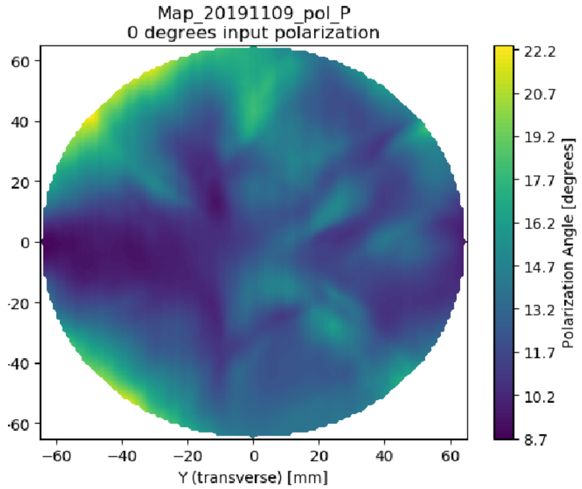
RMS @140mm = 25.9nm

[JGW-T1909948](JGW-T1909948)

Discarded ITM:
same growth method of
installed ITMs

M- and R-planes intersections



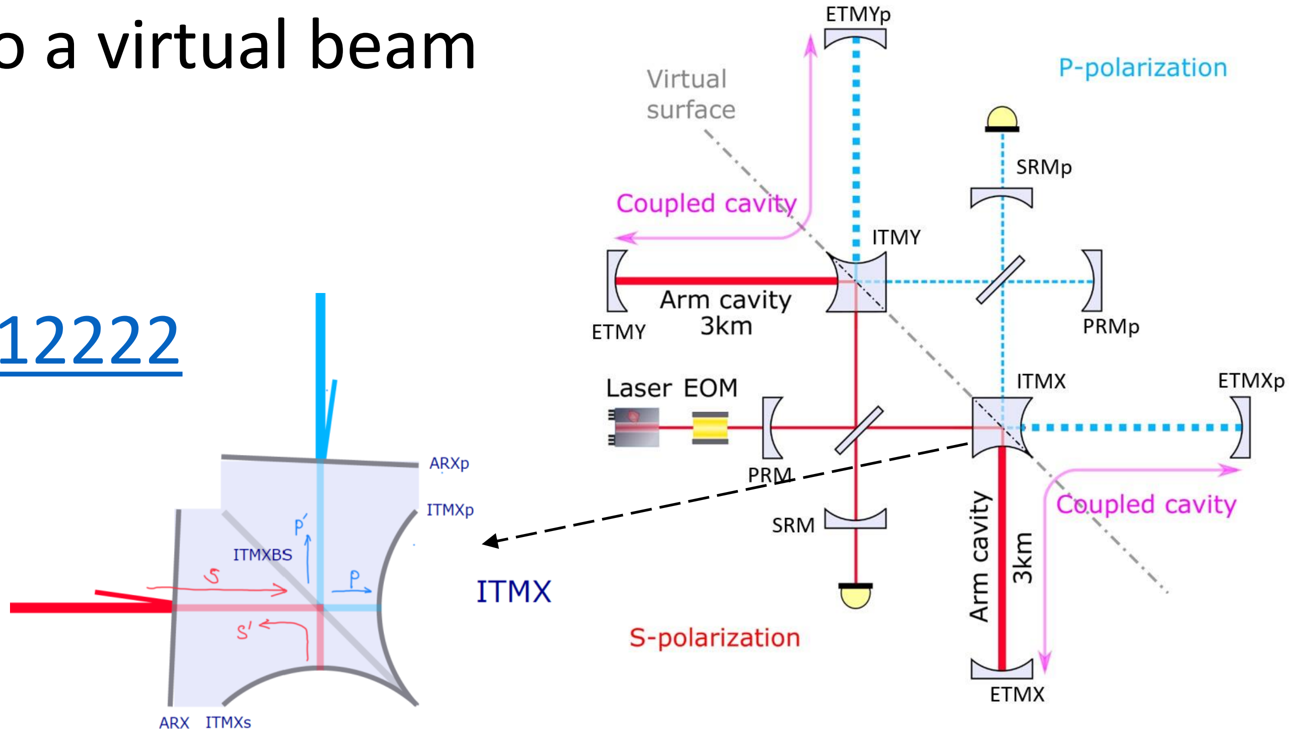


Simulating birefringence in KAGRA

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

- 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:

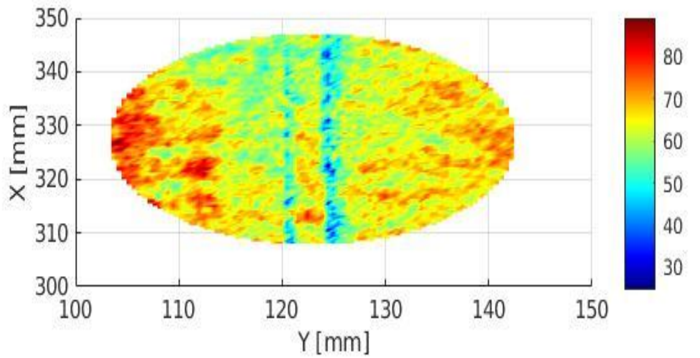
- Obtain more homogeneous bulks for new ITMs
- Develop post-growth processes to reduce inhomogeneities (?)

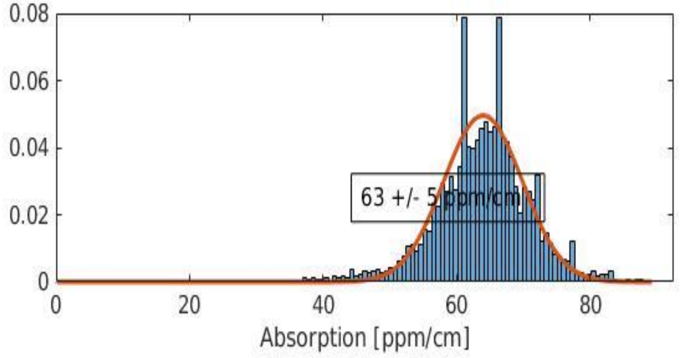
*(?) = investigation still ongoing

Collaborations to improve sapphire

Industries:

- Collaborations with several sapphire growth companies (Japan, Korea, US, Europe, …)
  - Very promising results from initial tests on Aztec sample
  - Continuing the collaboration with Shinkosha





Research institutes:

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

Summary

1. KAGRA core optics installation terminated in 2018, but some issues were discovered
2. Birefringence effect was underestimated and lead to issues with polishing and PRC/SRC losses
3. Ad-hoc setup were created to investigate birefringence anisotropy and characterize new substrates
4. New collaboration were established to achieve better sapphire quality for new mirrors
   - We plan to install new ITMs before O5