Status of KAGRA calibration toward O4

KAGRA Calibration subgroup

Dan Chen on behalf of the KAGRA collaboration

2020/12/19 KAGRA International Workshop

Outline

- What is “calibration" for a gravitational wave telescope?
  - h(t) reconstruction, calibration systems (Pcal, Gcal)
- What we did in O3GK and plant for O4
- Gcal
- Pcal
  - Pcal in KAGRA
  - Status of Pcal improvement toward O4

How do gravitational wave telescopes provide GW signal?

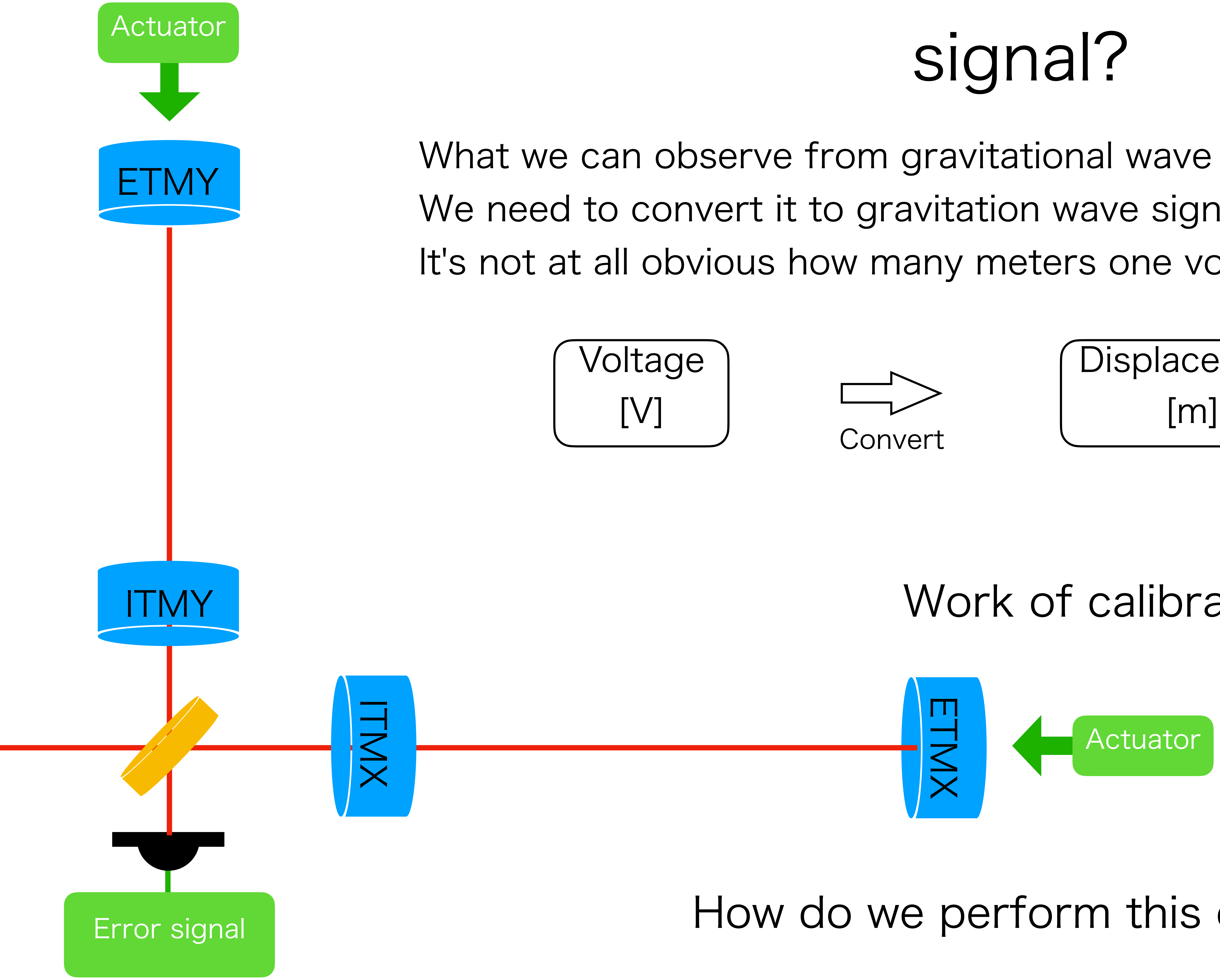
What we can observe from gravitational wave telescope is voltage signals.
We need to convert it to gravitation wave signal h(t).
It's not at all obvious how many meters one volt equals.

Voltage [V] ⇨ Convert ⇨ Displacement [m] ⇨ Convert ⇨ GW signal h(t) [-]

This conversion is easy.
We just use the arm length.

Work of calibration(CAL) team

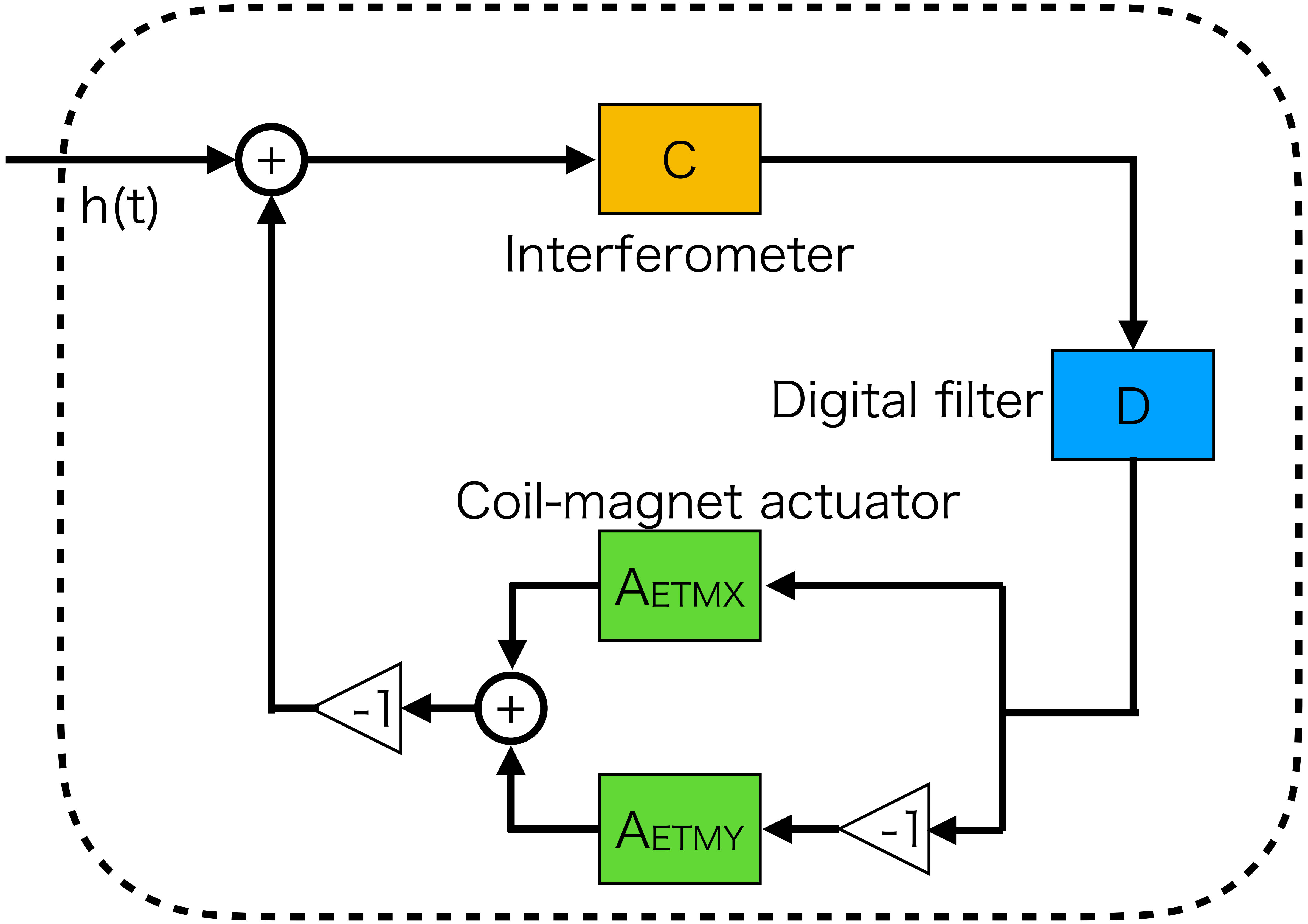
How do we perform this conversion (= h(t) reconstruction)?



Simplified GW telescope

Schematic view of h(t) reconstruction

Control loop in O3GK



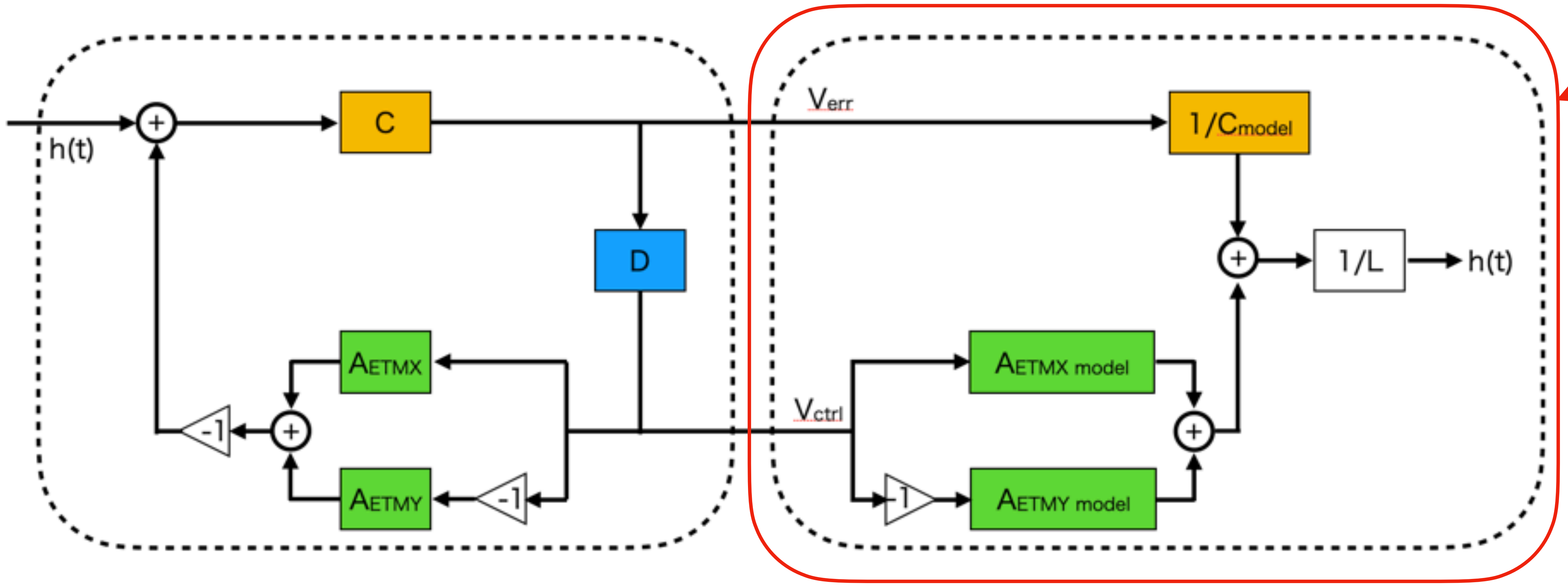
In order to keep the interferometer at operational and sensitive condition, control loops are performed in the system.

Schematic view of h(t) reconstruction

We need to estimate parameters in A and C.

To do this, we need precise actuators to make known input.

Main works of calibration team



Making pipelines to provide h(t) data

Name	When	Accuracy	Purpose
C00	Real Time	Good	Control room
C10, C11, ... (Low Latency)	< 10 sec	Better	· Shared by LVK · Detection pipelines
C20, C21, ... (High Latency, Offline)	~ several months	Much Better	· Scientific Analysis · Paper Publications

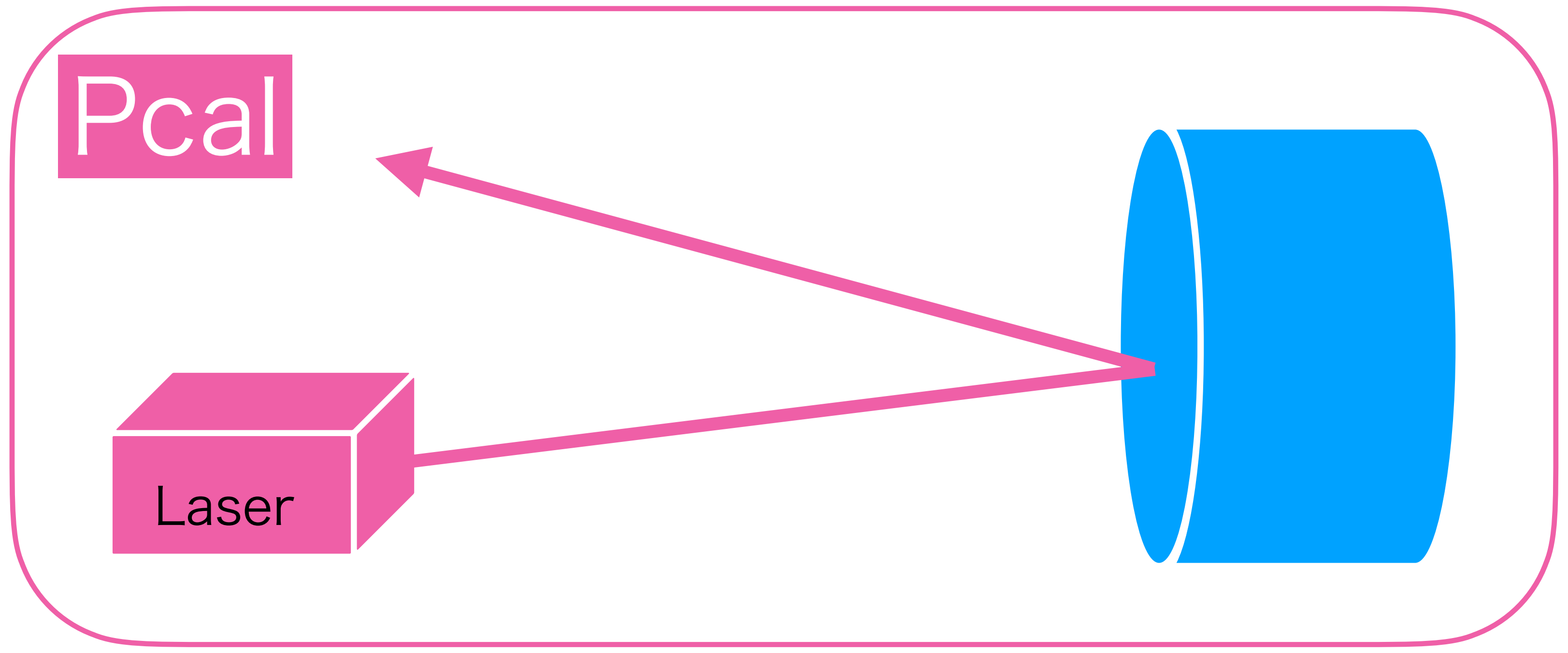
https://gwdoc.icrr.u-tokyo.ac.jp/DocDB/0120/G2012094/001/c20.pdf

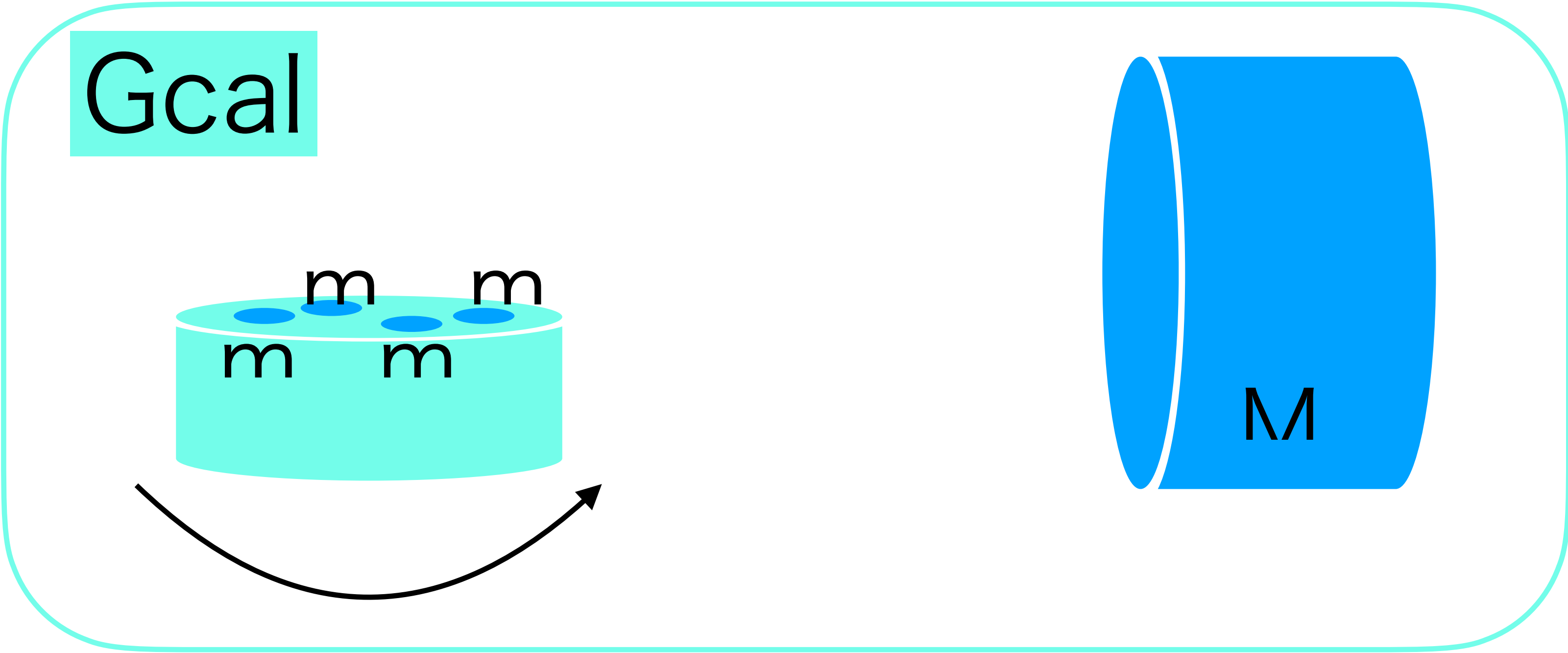
Related talk:

Honglin Lin (11:25-, today)

"Study of frequency domain analysis method to estimate calibration errors"

Making precise calibration systems

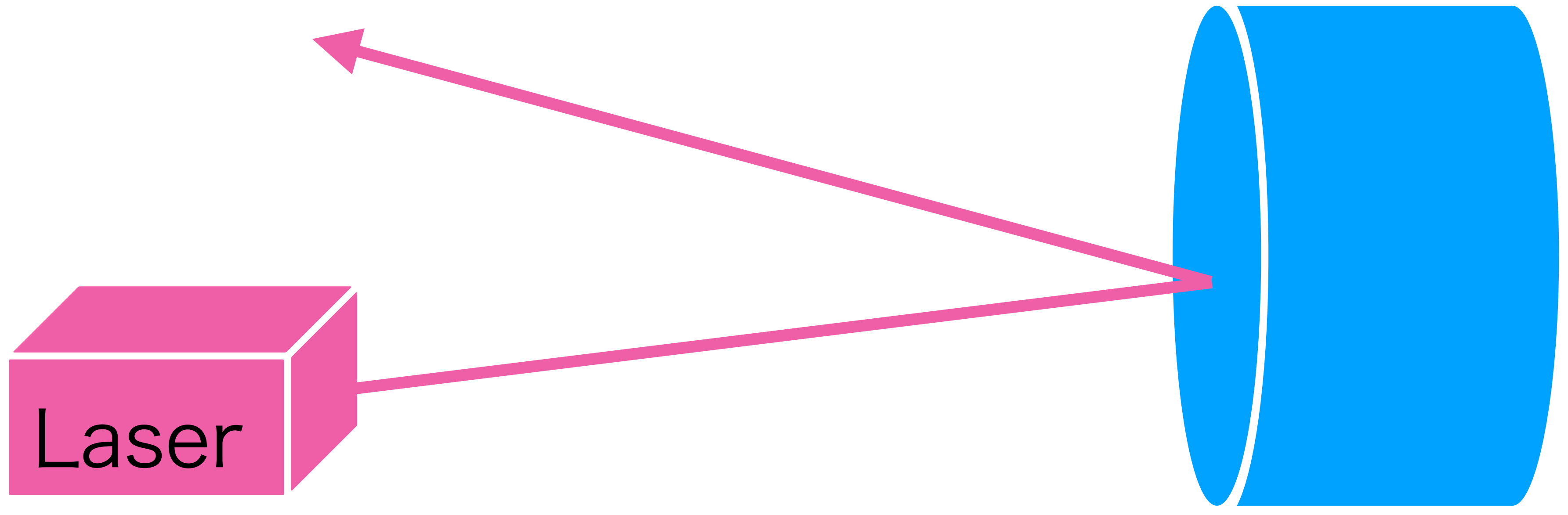




Precise actuators as calibration system

- Laser wave length -> not enough accuracy
- Coil magnet actuator -> not enough accuracy
- Photon calibration system (Pcal) based on radiation pressure -> most accurate calibration system we can use now
- Gravity field calibration system (Gcal)

Pcal



= Pcal laser ≠ IF laser

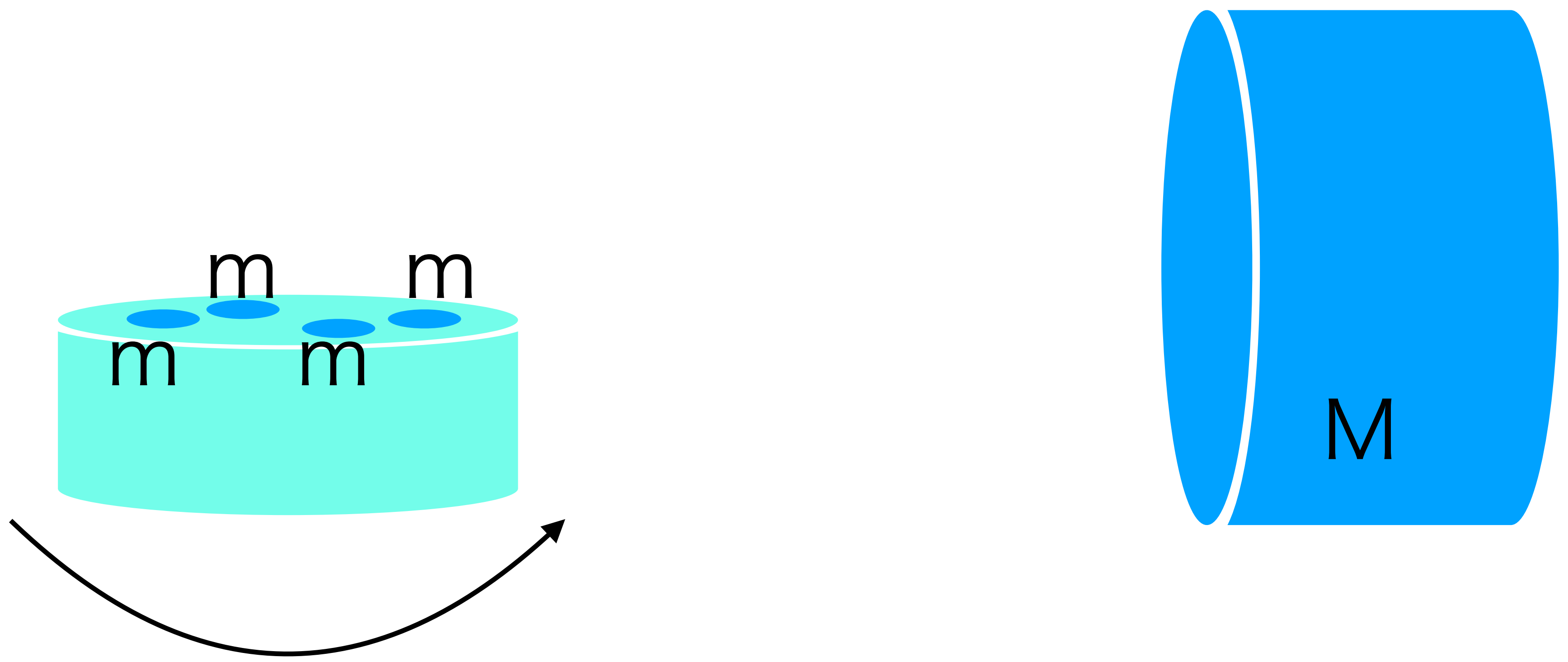
We can use radiation pressure of laser to push the TM of KAGRA

$$F = \frac{2P}{c}$$

Power of the laser on TM

Speed of light

Gcal



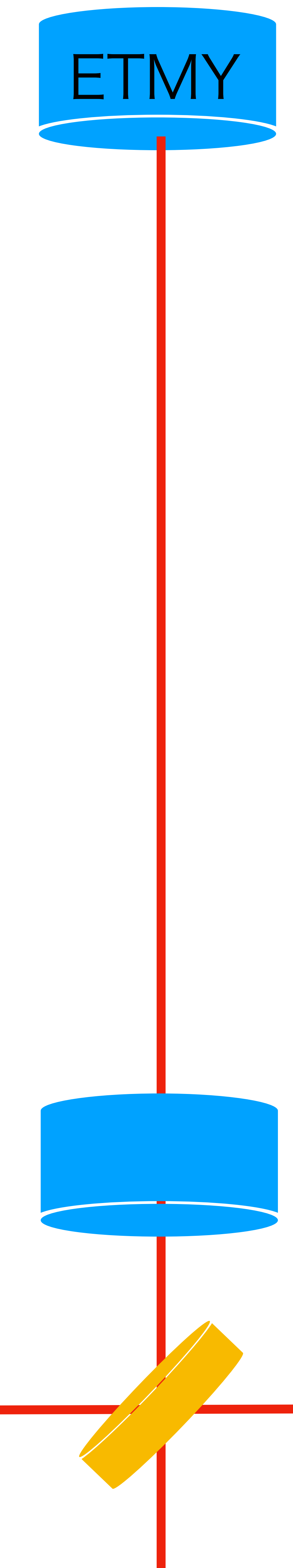
$$V = -GMm \sum_{i=0}^{N} \frac{1}{L_i}$$

Distance between mirror and rotating mass

What we did in O3 (observation run 3 with GEO = O3GK)
What we will do toward O4

	Pipeline	Pcal	Gcal
O3GK	h(t) data made by C20 pipeline was successfully released to collaborators.	Both of Xpcal and Ypcal was installed. Xpcal worked during O3GK.	Design and preparation.
O4	Basically, we will use the same pipelines as what we used in O3GK. C10 was not enough accurate in O3GK. We will improve it toward O4.	Make Xpcal and Ypcal work to meet the O4 requirements.	Experiments and developments in labs. We will install one at Xend if we can.

Status of gravity filed calibration system = Gcal in KAGRA



Rotating mass distribution makes periodic gravity field change on the test mass.

This can be an independent calibration system from any other systems.

Status:

Most of the hardware components are in KAGRA tunnel now.

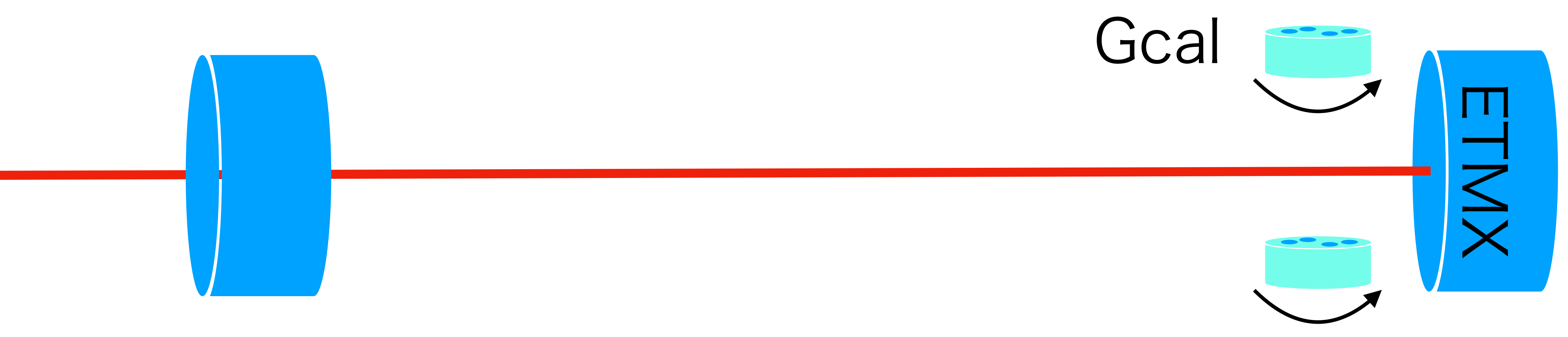
Anchor holes for this Gcal have already made.

Tungsten mass

Related talk:

Hsiang-Yu (12:05-, today)

“Improvement of calibration error method with higher order harmonics”



Y.Inoue, et al. PRD 98 022005, 2018

Photon calibration system = Pcal

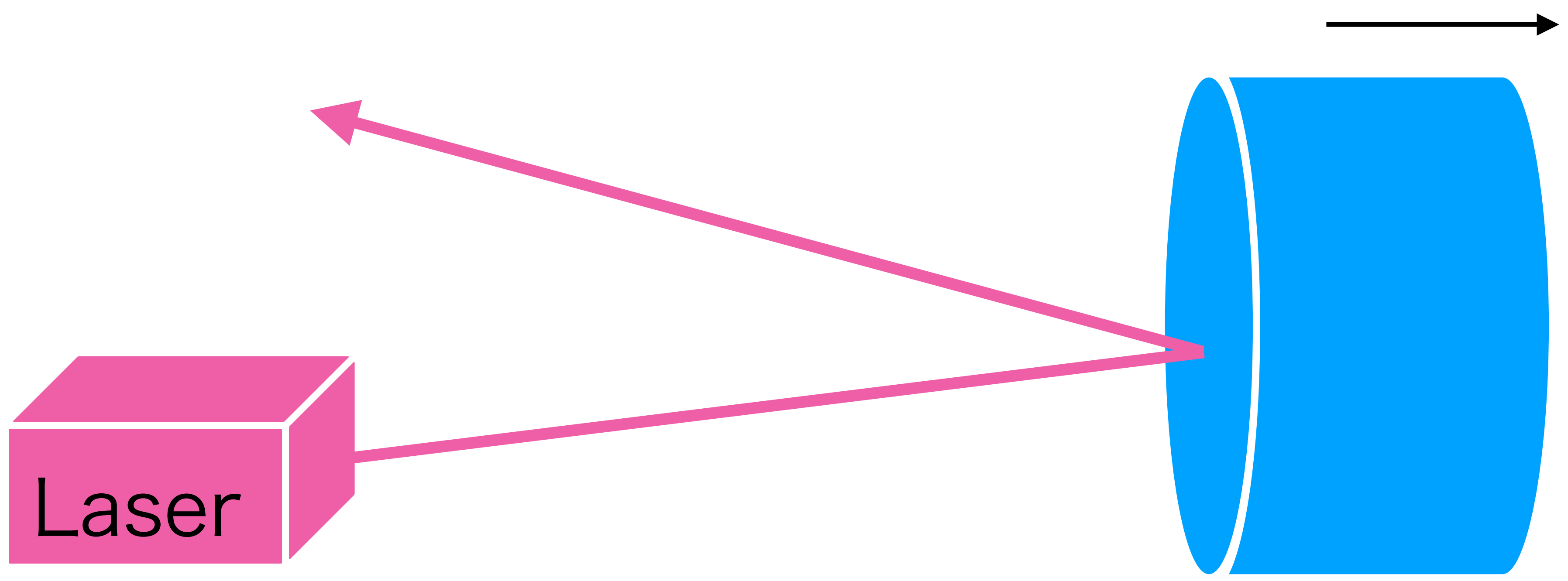
Principle:

Applying force on a test mass by using radiation pressure.

$$F = \frac{2P}{c}$$

Power of the laser on TM

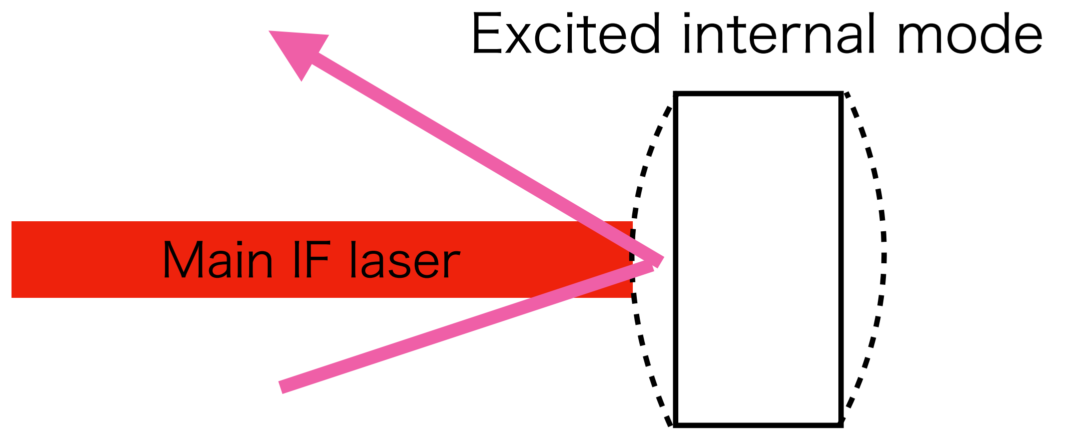
Speed of light



= Pcal laser ≠ IF laser

Points to be considered:

- We need to know the P value precisely
- We need to monitor IF during observation run. The radiation pressure noise caused by Pcal laser should be lower than KAGRA sensitivity.
- We don't want to inject the laser beam on the center to avoid internal mode excitation by Pcal laser and local deformation.
- We don't want to rotate TM by the Pcal laser



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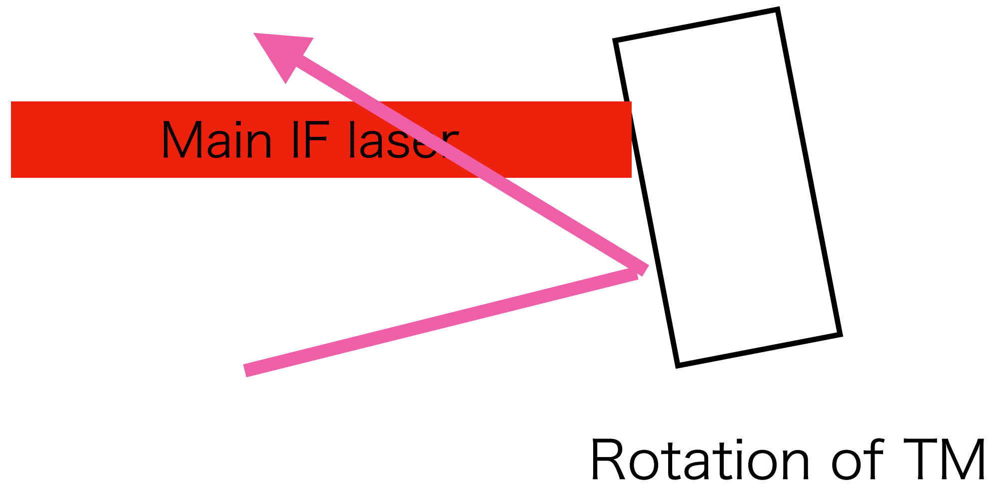

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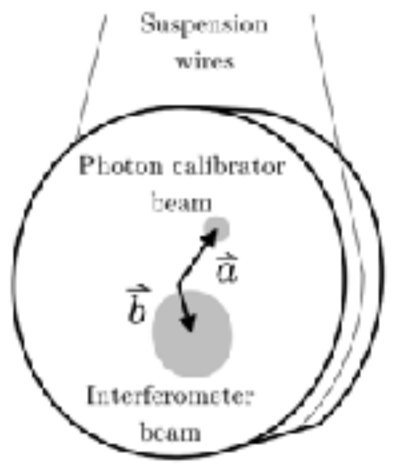
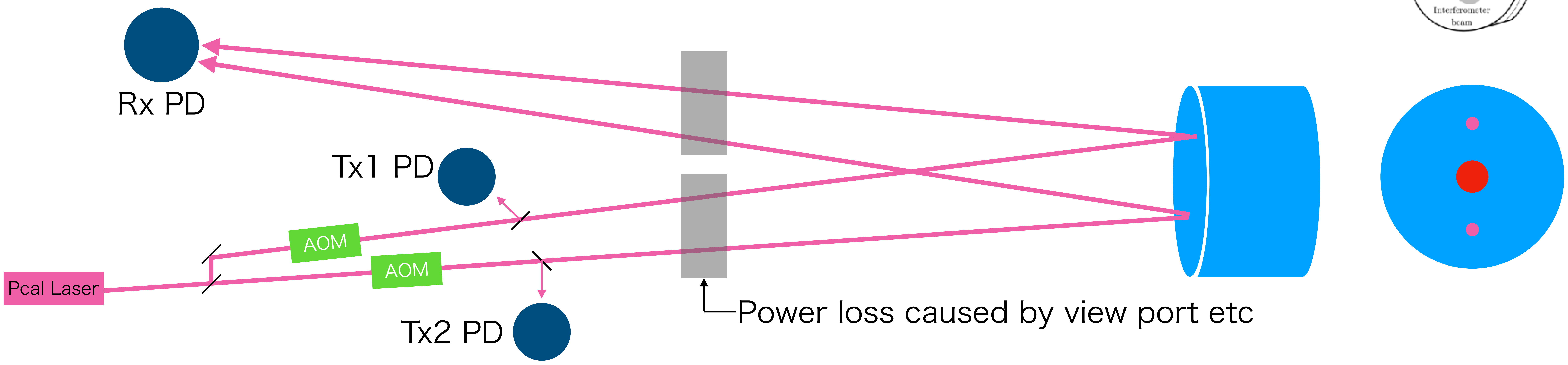
Concept map of Pcal in KAGRA





- We use accurate PDs (calibrated integration spheres) to measure laser power
- Modulation by AOM makes calibration works in frequency domain.
- AOMs enable laser power stabilization.
- We inject 2 laser beams on TM.
  => We can reduce the influence of internal mode excitation
  => We can avoid to rotate TM by Pcal laser beams

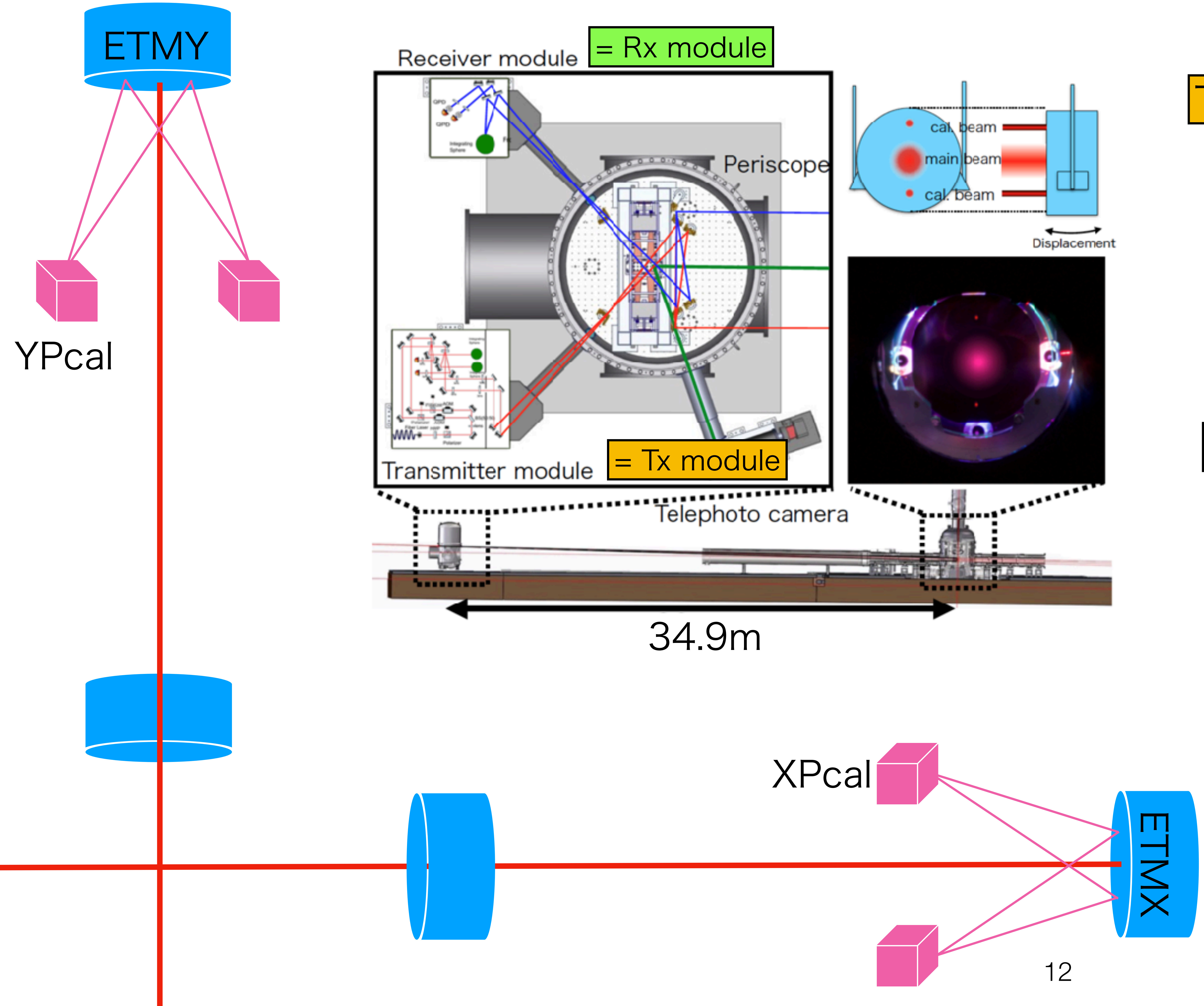
Rotation effect caused by Pcal laser

$$x(\omega) = -\frac{2P\cos\theta}{cM\omega^2}\left(1+\frac{\vec{a}\cdot\vec{b}M}{I}\right)$$

Transfer function of suspension

Error of P is most significant on calibration error.

Photon calibration systems = Pcal in KAGRA



Tx module

- Generate 2 beams
- Power stabilization
- Make periodic excitation of power
- Precise measurement of input laser power

Rx module

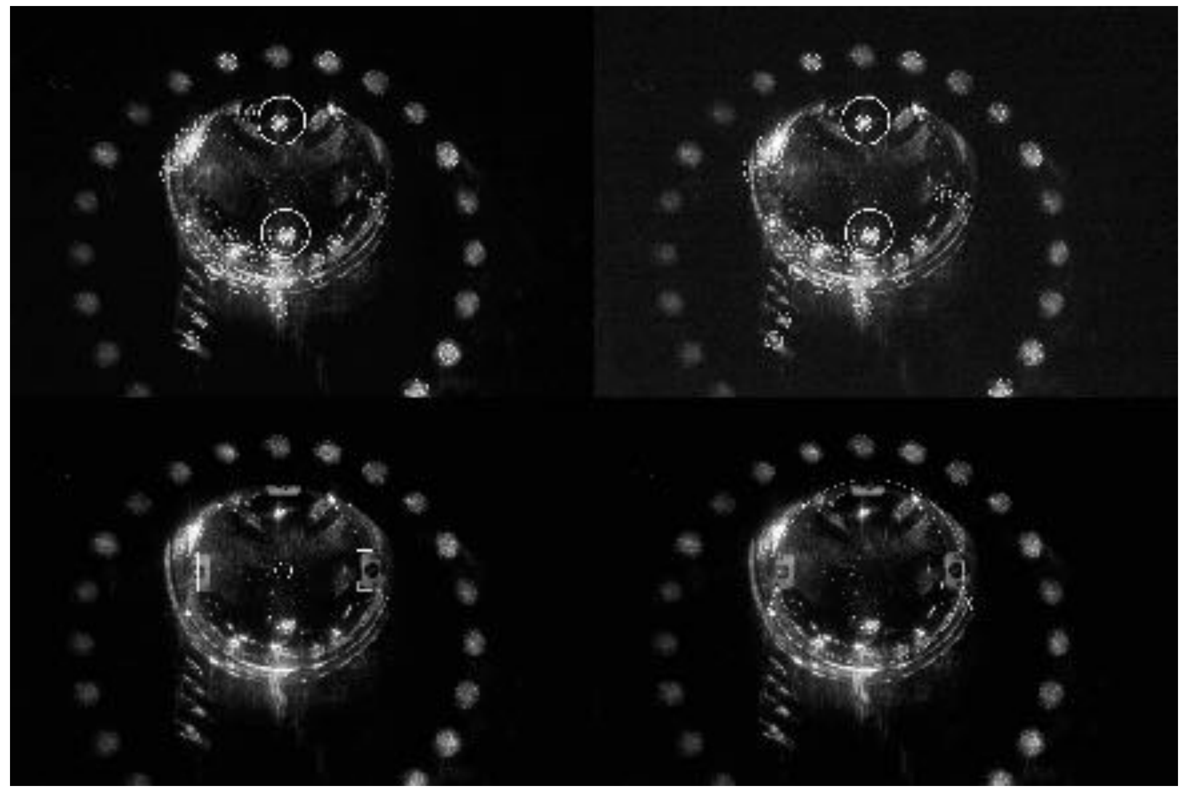
- Precise measurement of output laser power

We can use measured power in both modules to estimate power on the test mass.

Succeeded items in O3GK

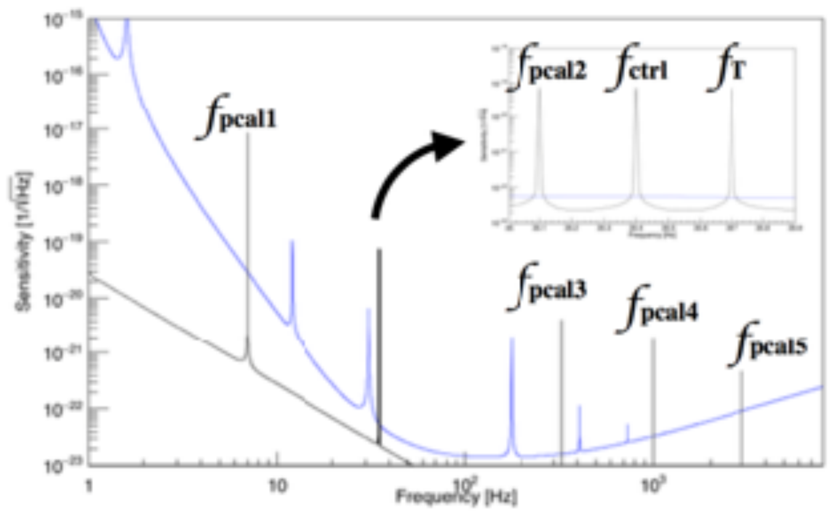
XPcal and YPcal were installed

Laser position monitor system(Tcam) worked continuously.



XPcal worked

- DARM transfer function measurements before/after O3GK were performed.
- Calibration lines were injected continuously during the observation run.
- The noise level was lower than the sensitivity of KAGRA in O3GK.

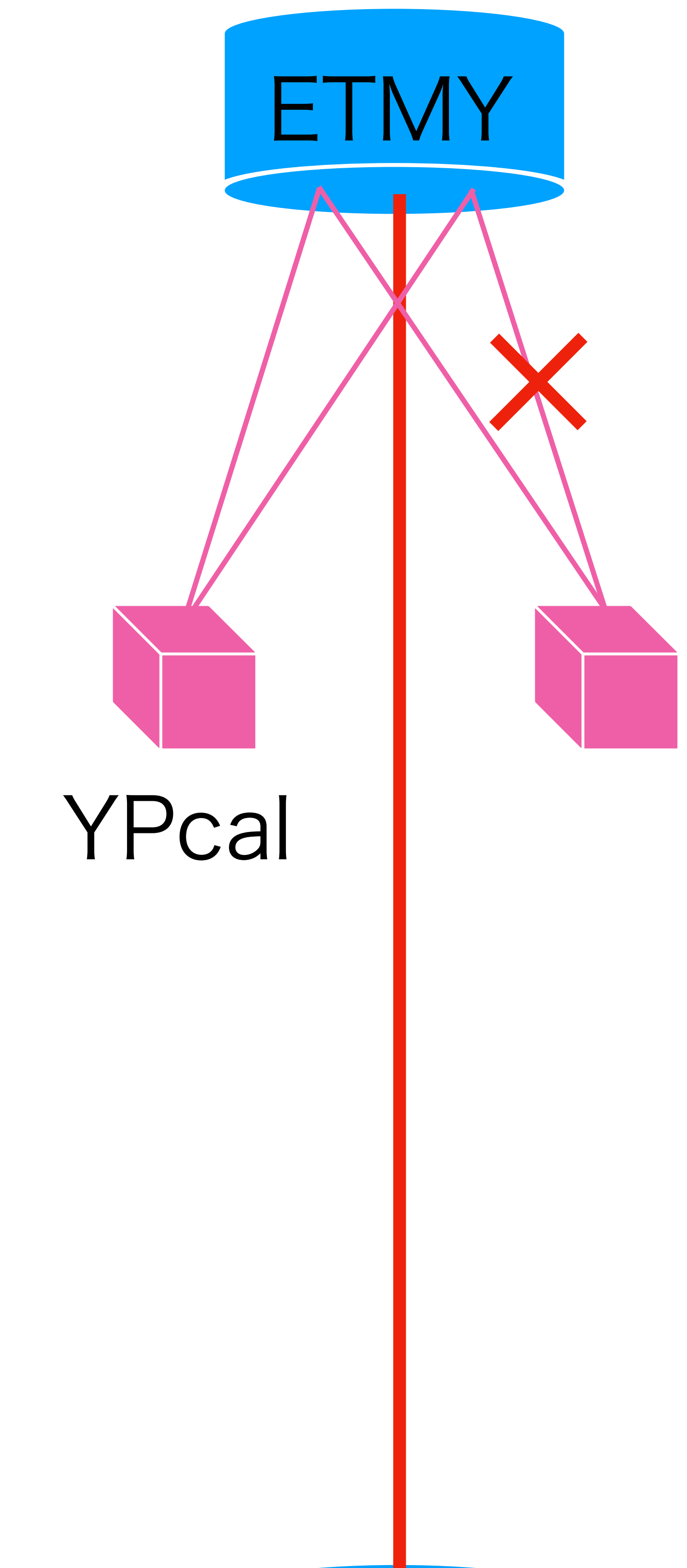


Calibration lines

Pcal improvement toward O4
~What we found in/after O3GK~

- YPcal did not work because an AOM was broken. — Repair YPcal
- Pcal noise can be bigger than KAGRA O4 sensitivity. — Noise improvement
- Pcal had a 3% error. (Error of h(t) will be larger than it) — Error improvement
    - Variation of measured optical efficiency (~1.7%)
    - Variation of integration sphere calibration factors (~2.5%)
    - Fluctuation of laser beam positions on the ETM (~1%)
- We need improvement of alignment tools — Alignment tools improvement

Repair YPcal

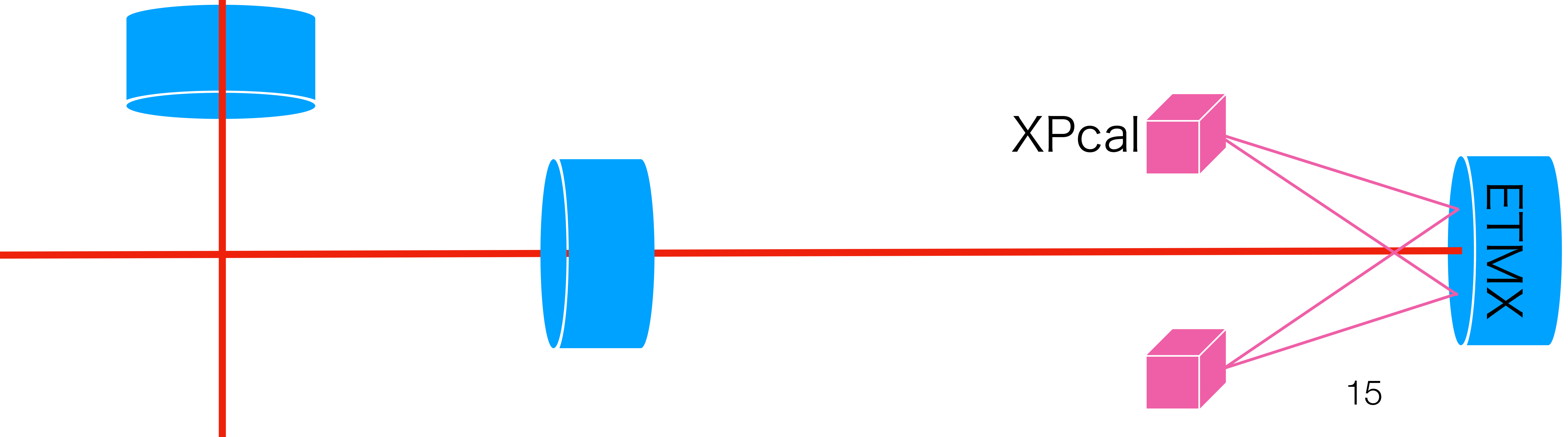


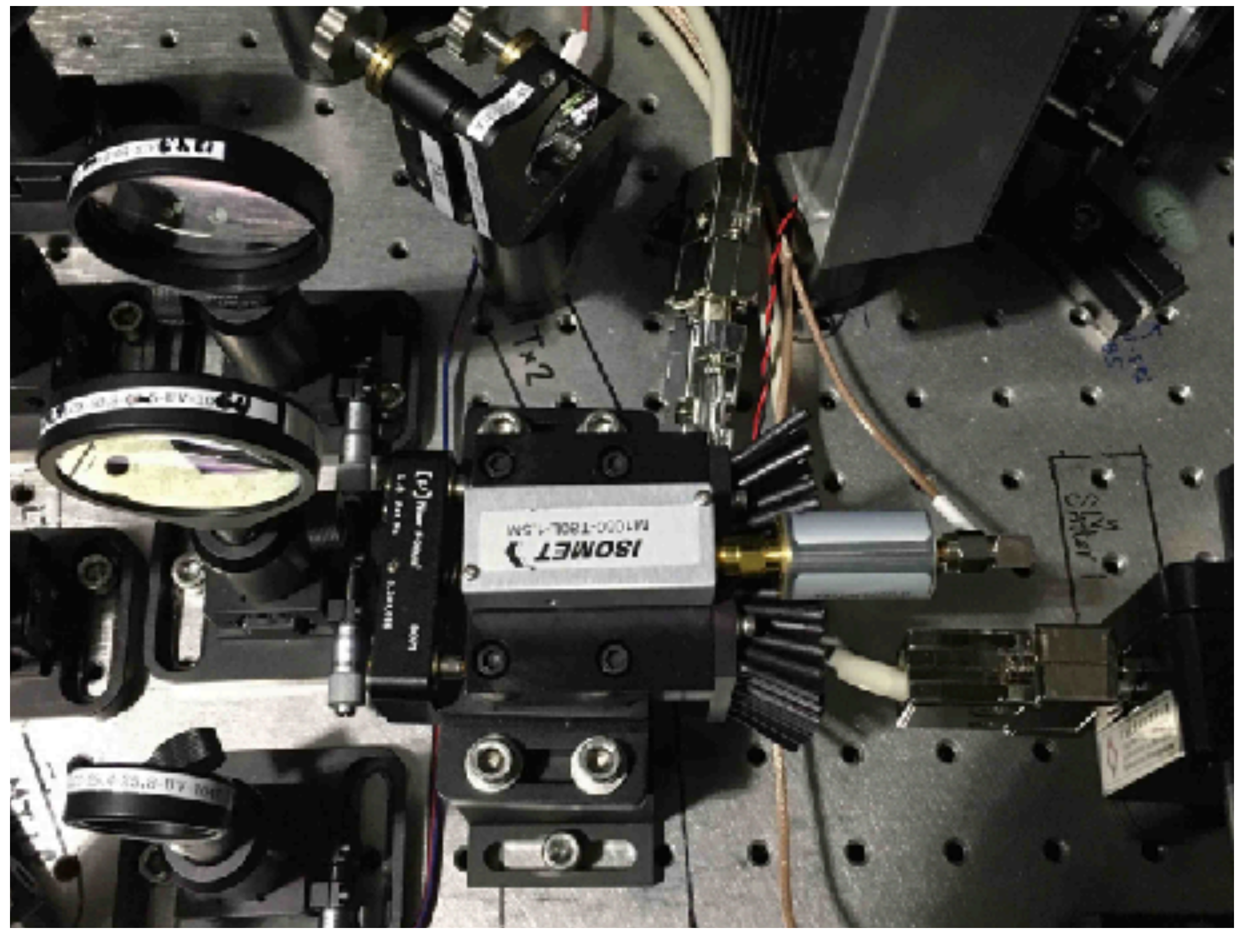
One of AOMs in YPcal was broken before O3GK.

We could not use YPcal in O3GK.

⇩

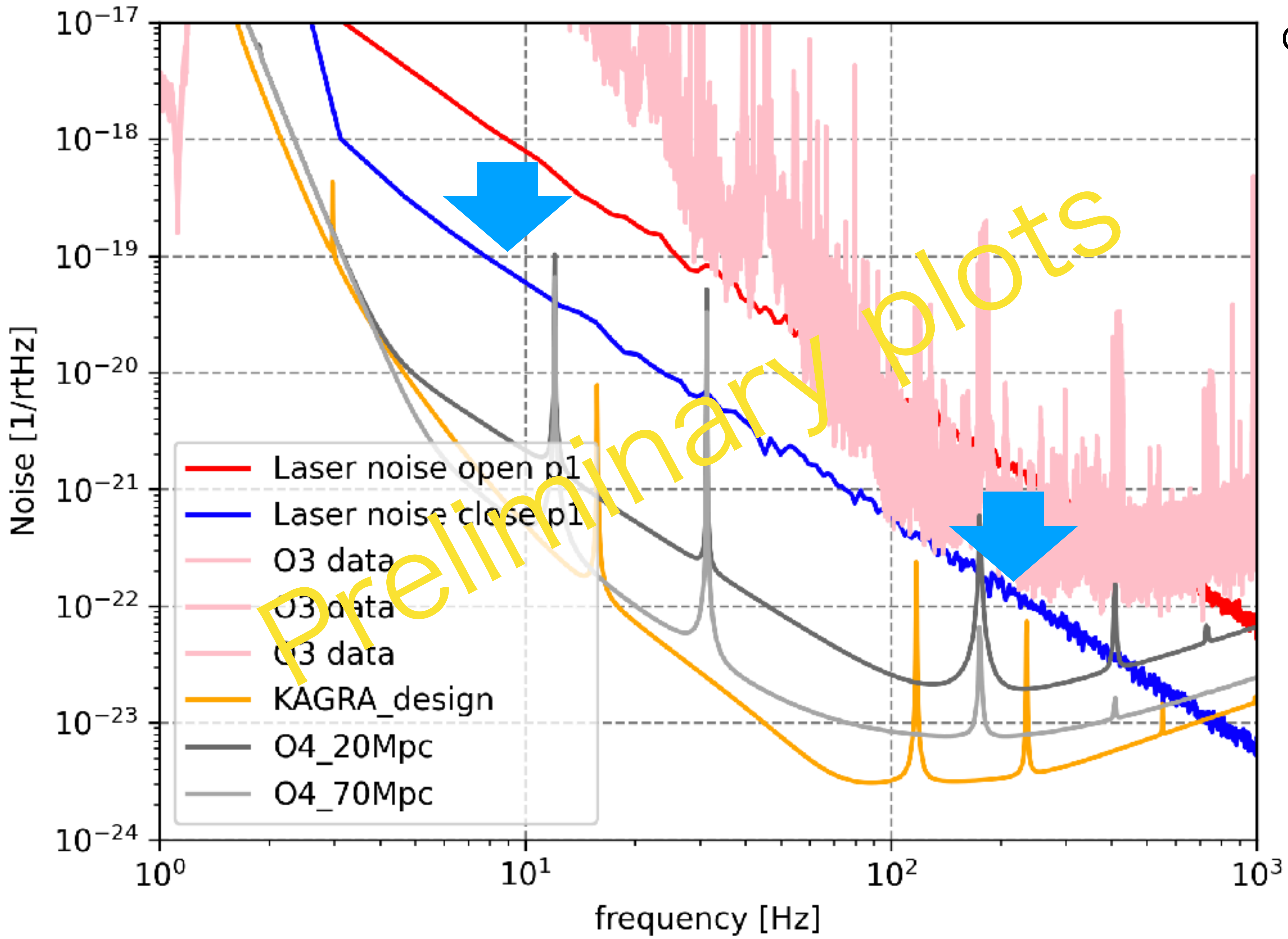
We replaced the broken AOM after O3GK.
After beam alignment, YPcal will be ready for use.





Replaced AOM

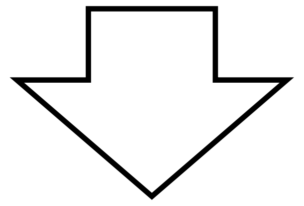
Noise improvement



We use AOM not only for making periodic excitation of laser power, but also for laser power stabilization.

In O3GK:

- We could not raise control gain because of unknown reason(s)
- Noise without control was very high.



- Laser source itself is clean. Electronics make the noise.
- It seems the original noise can be suppressed by 10dB if we connect circuit GND well.
- Cutting high frequency noise into stabilization loop can improve the noise by 15dB?

These are still under investigation and discussion.

Three “O3 data”s are typical noise in O3GK.

Error improvement

O3GK

Error source	Effect on x(w) [%]
Laser power measurement	2.5
Optical efficiency measurement	1.7
Laser position fluctuation	0.99
Other	0.48

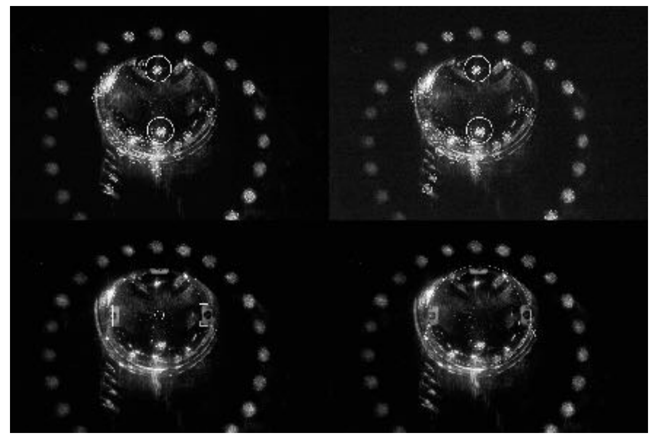
→ 3% error in total
(Pcal hardware error)

Related talk:
Koki Ito (12:05-, today)
"Calibration of PCal Laser Power with O3GK"

Displacement caused by Pcal:

$$x_{tot}(\omega) \simeq -\frac{2P_m \cos\theta}{Mc\omega^2}\left(1+\frac{\vec{a}\cdot\vec{b}M}{I}\right)$$

Estimated power on TM
$P_m = f(P_{TX1}, P_{TX2}, P_{RX}, e_{T1}, e_{R1}, e_{T2}, e_{R2})$

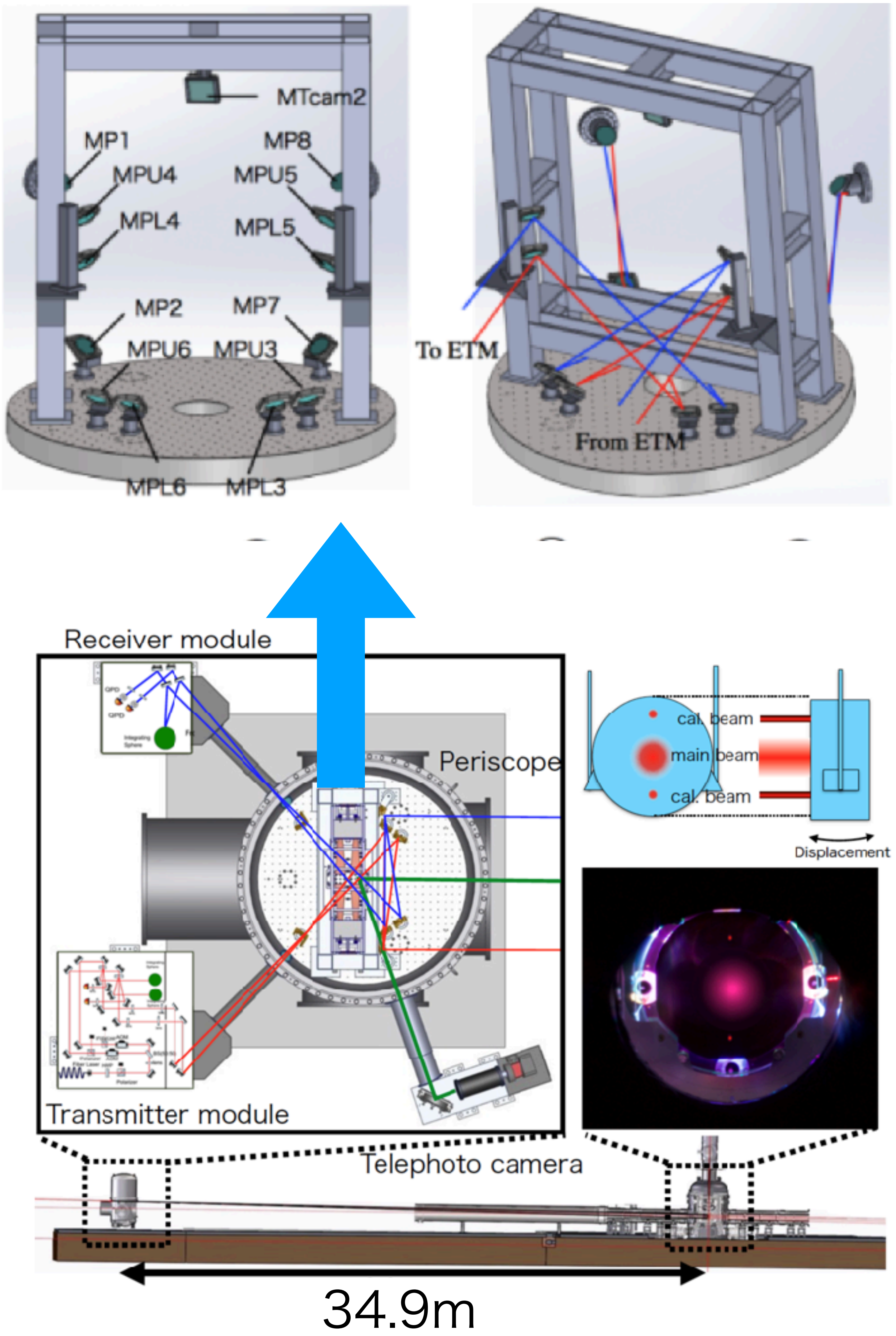


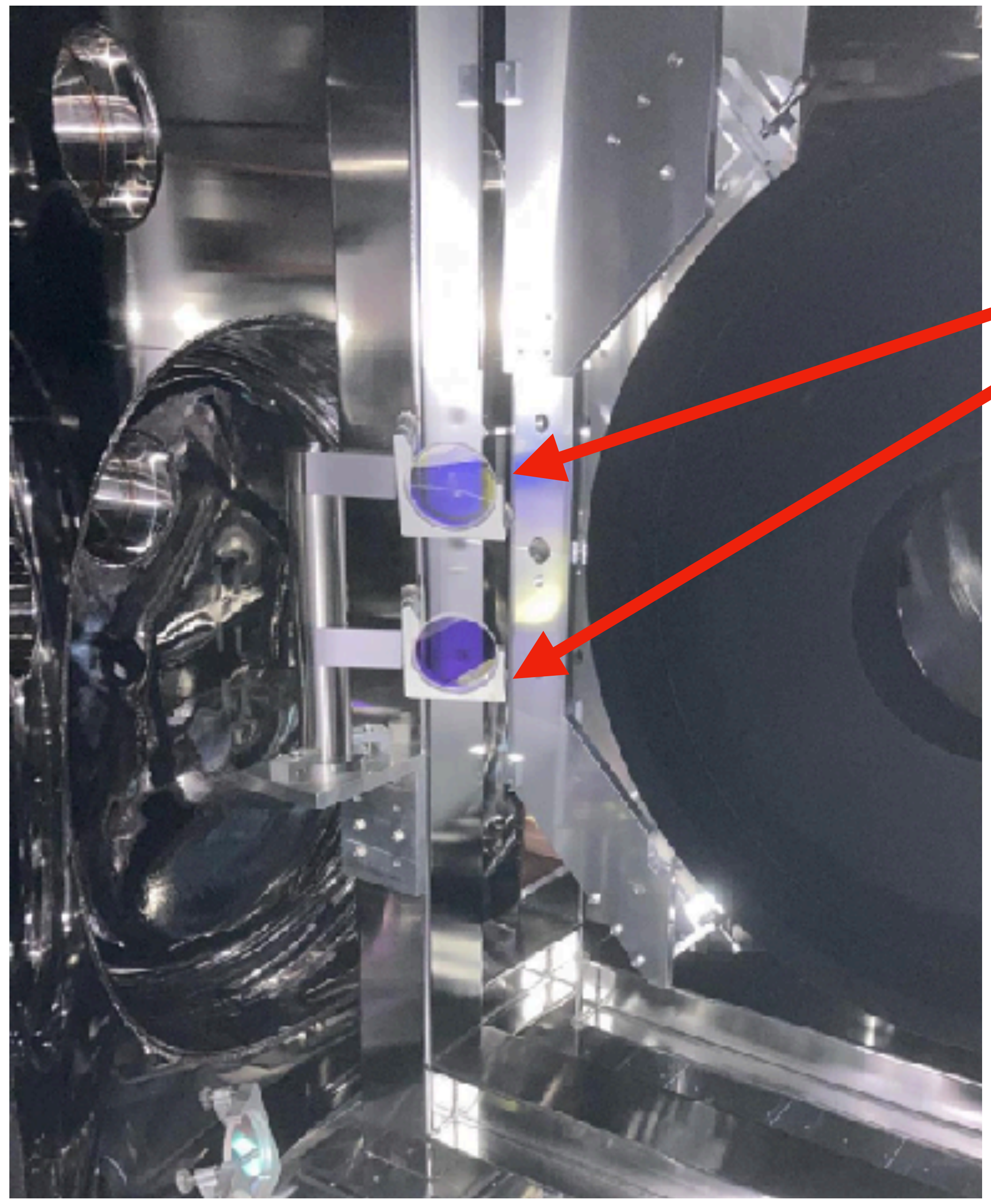
Laser position on TM observed by camera

Measurements by integration spheres are the main error source

Possible cause 1: Measurement process has some problem. (Warming time before measurement was too short or others.)
Possible cause 2: Scattered light in Tx module

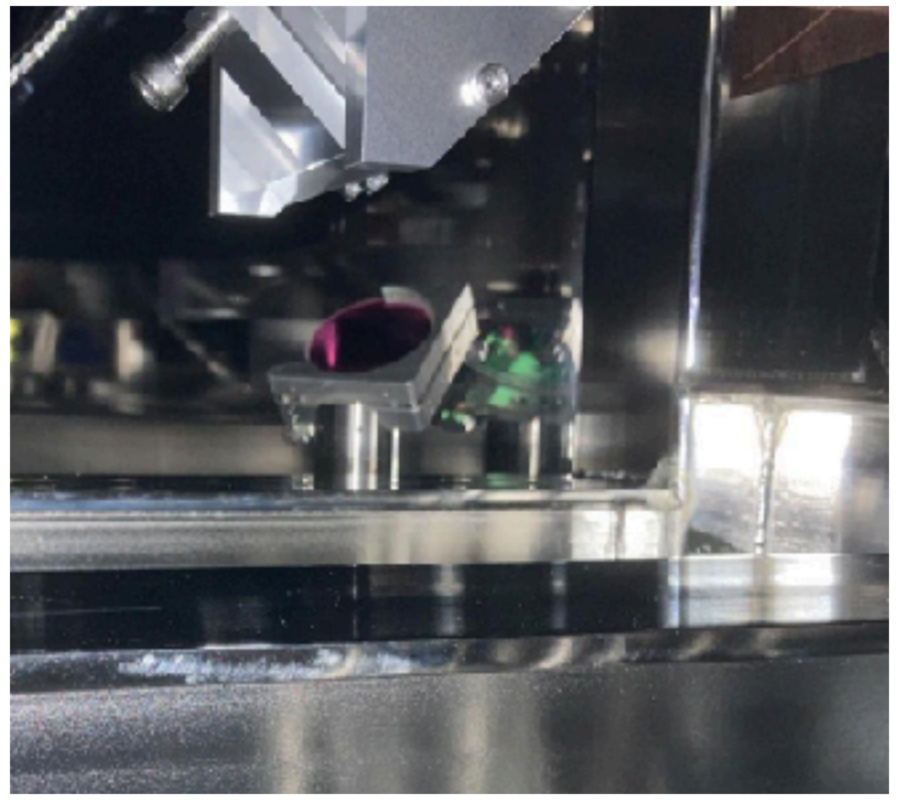
Alignment tools improvement

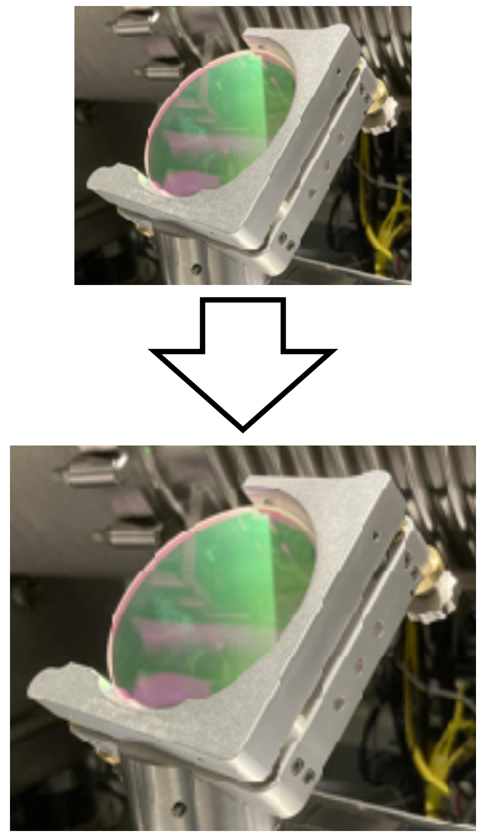




Newport 8823-UHV

Install picomotors on mirrors before long path





Replace the mirror receives 2 beams with a bigger mirror. This also improves reliability.

Summary of Pcal improvement toward O4

	Repair YPcal	Noise improvement	Error improvement	Alignment tools improvement
Issue	An AOM was broken before O3GK run.	Pcal laser noise is close to O3GK sensitivity, which is higher than O4 target sensitivity.	Pcal has a 3% error, which can be improved.	Difficulty of beam alignment.
Goal	Make the YPcal work.	Noise lower than O4 target sensitivity.	Lesser than 3% error. (Target error value is under discussion)	Reduce alignment work time.
Current Status	Repaired AOM. Performed beam alignment roughly in Tx module.	We found some candidates for improvement (25dB?)	We are preparing for updating calibration procedure and scattered light management.	80% of the stuff we need have already been prepared.
Remaining tasks	Beam alignment of total system.	Try the candidates with real Pcal system. (Maybe more noise hunting)	Check the improvement.	After the remained stuff arrived, we will install picomotors and big size mirrors.

Summary and related talks

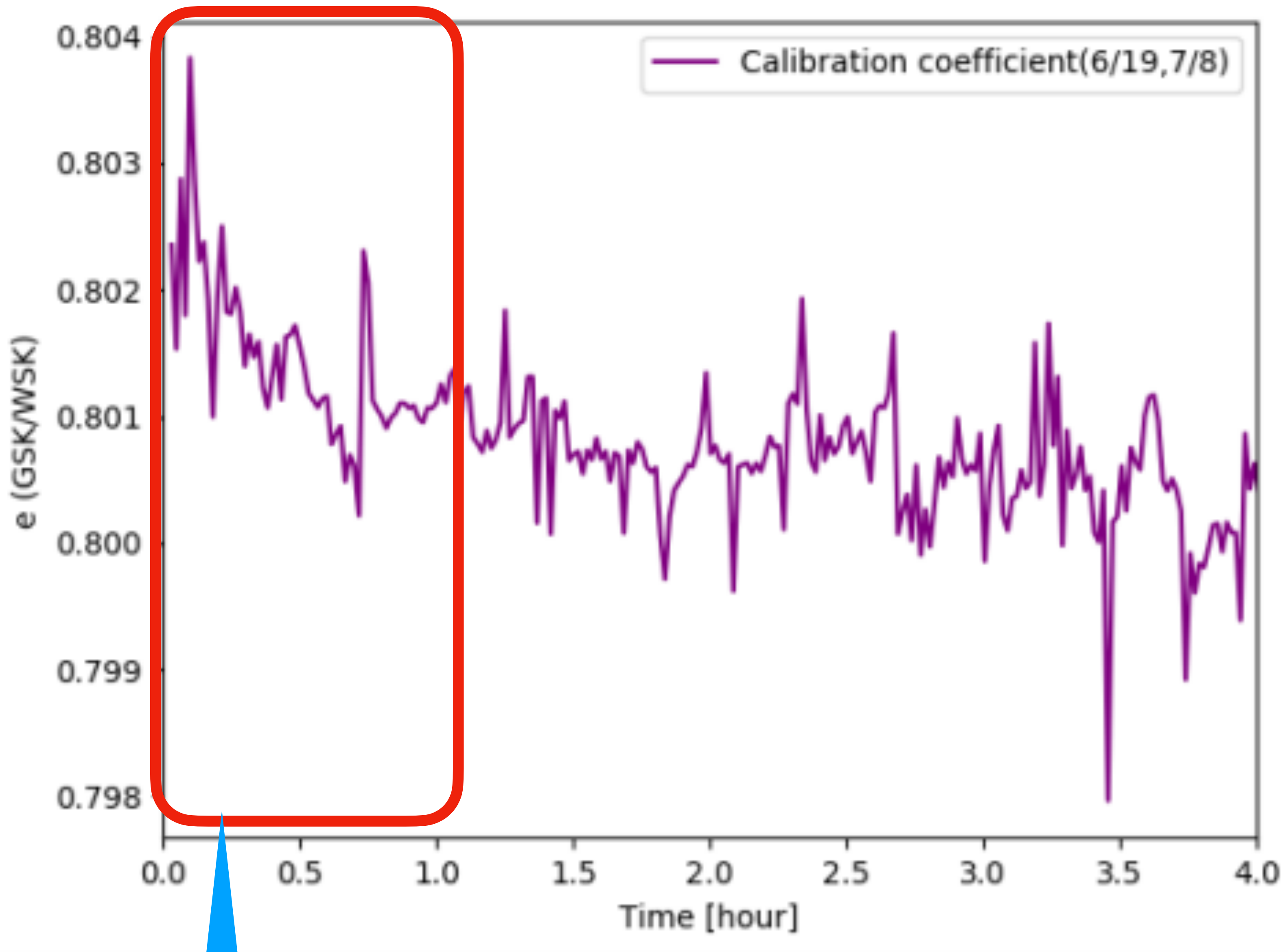
- In order to make h(t):
  - We need make pipeline, which contains IF models and estimated/measured parameters
  - We need calibration system(s), which provide precise reference signals. We use these signals to calibrate IF signal.
- In KAGRA, we (will) have Pcal and Gcal as the calibration system.
- In O3GK, XPcal worked. Toward O4 we need improvements:
  - Repair YPcal, noise improvement, error improvement, and alignment tools improvement
  - No major delays at this time. Basically, we will finish preparation works by March, and start install from April.
- Related talks:
  - Honglin Lin (11:25-, today) “Study of frequency domain analysis method to estimate calibration errors”
  - Hsiang-Yu (12:05-, today) “Improvement of calibration error method with higher order harmonics”
  - Koki Ito (12:05-, today) “Calibration of PCal Laser Power with O3GK”

End

Error improvement

Possible cause 1: Measurement process has some problem.
(Warming time before measurement was too short or other.)

Time dependance of IS calibration output (GSK/WSK)
@Toyama Univ

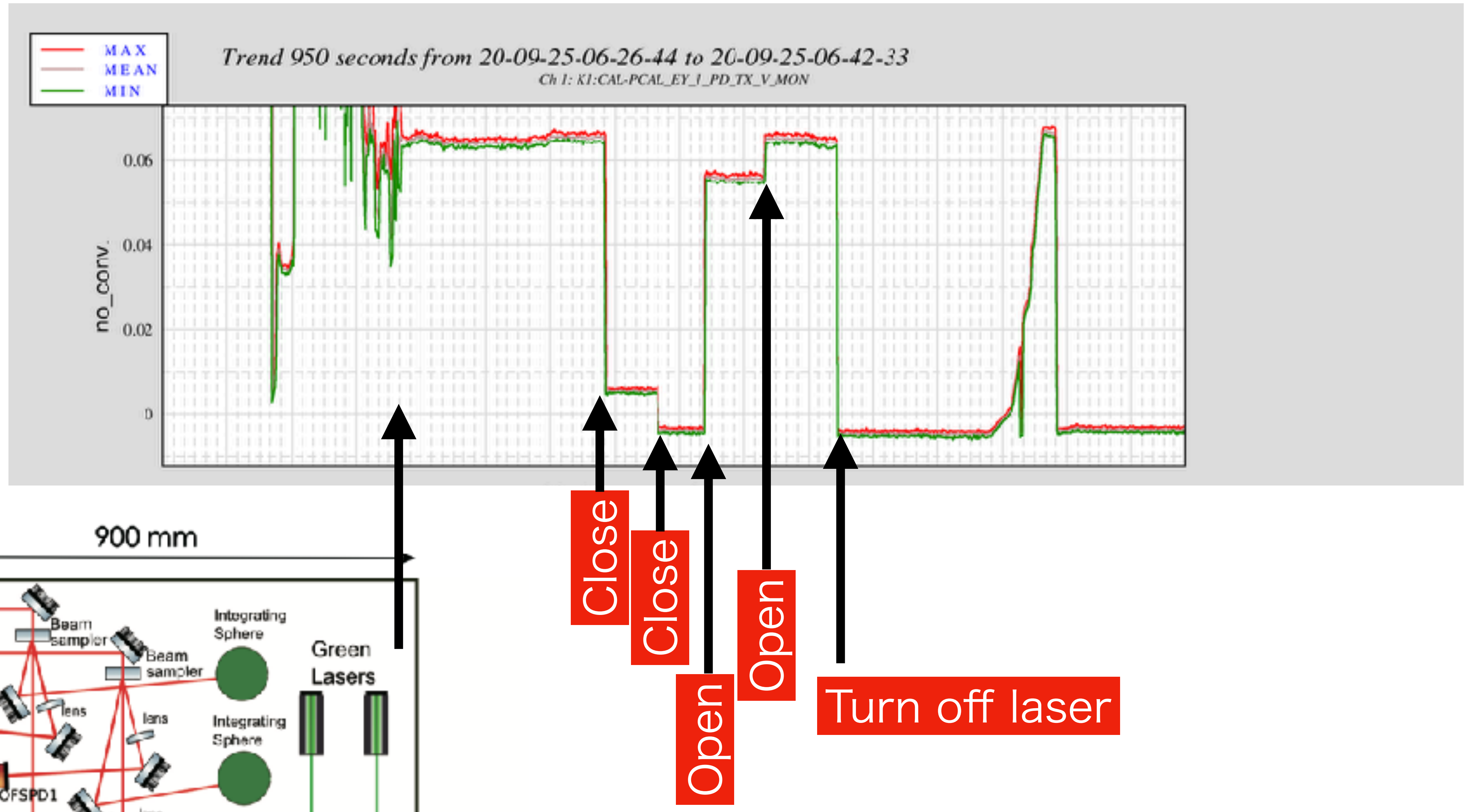


We have to wait at least one hour in order to have a stable measurement.

We also will compare our calibration procedure with LIGO.

Possible cause 2: Scattered light in Tx module

Output from an integration sphere



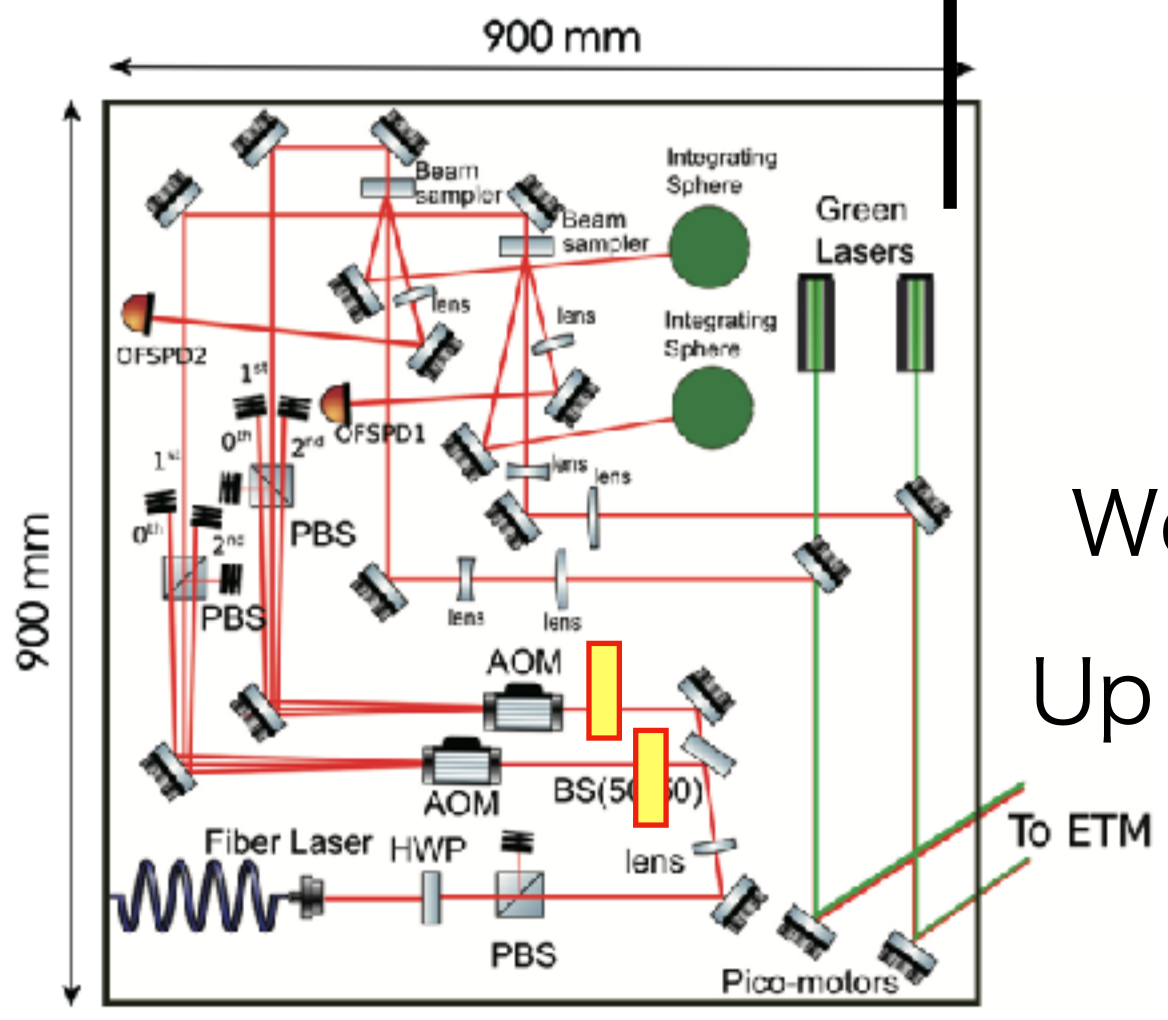


FIGURE 4.9: Optical layout of Tx module

We have 2 shutters in Tx module.

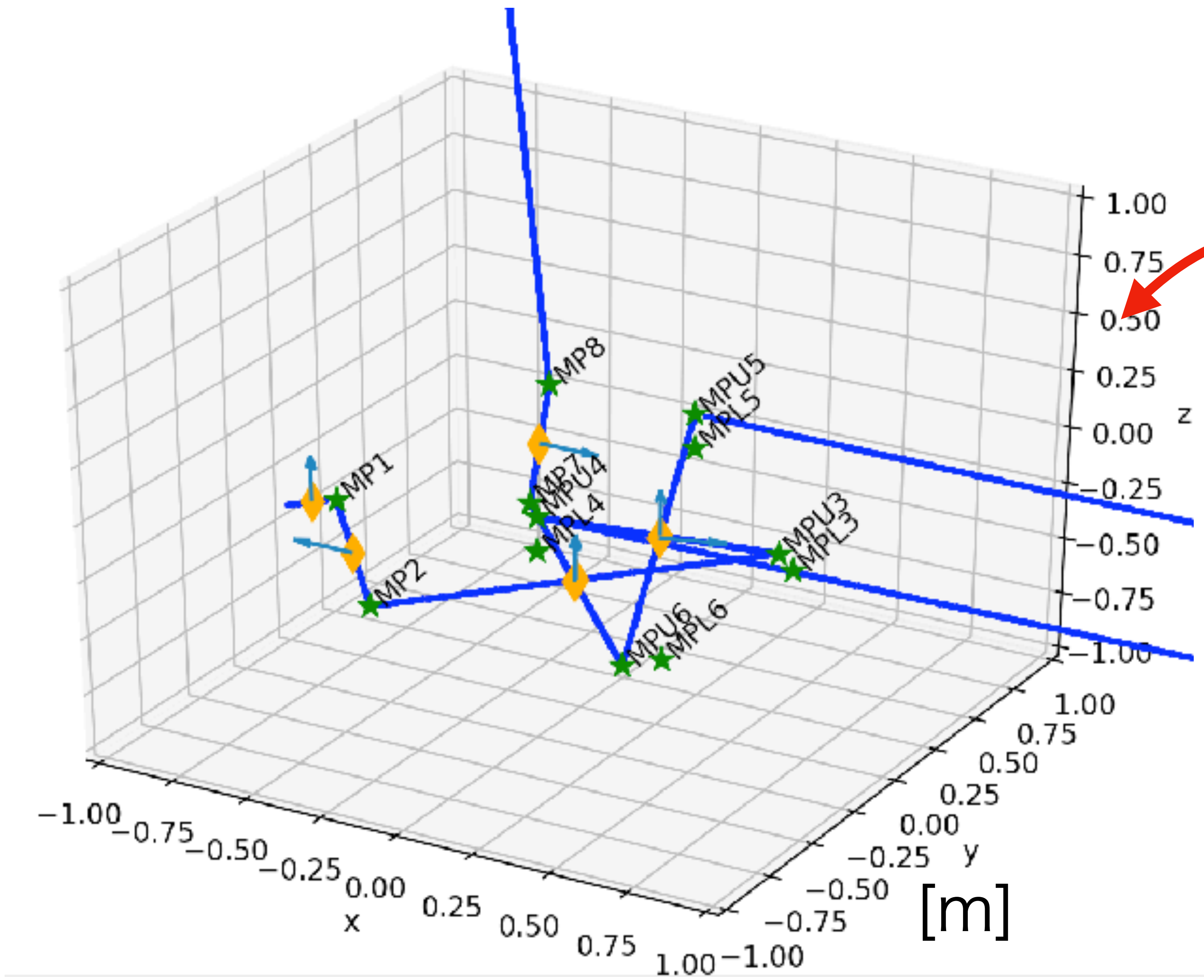
Up to 5% effect from scattered light

We will use dumpers and make walls to cut the scattered light.

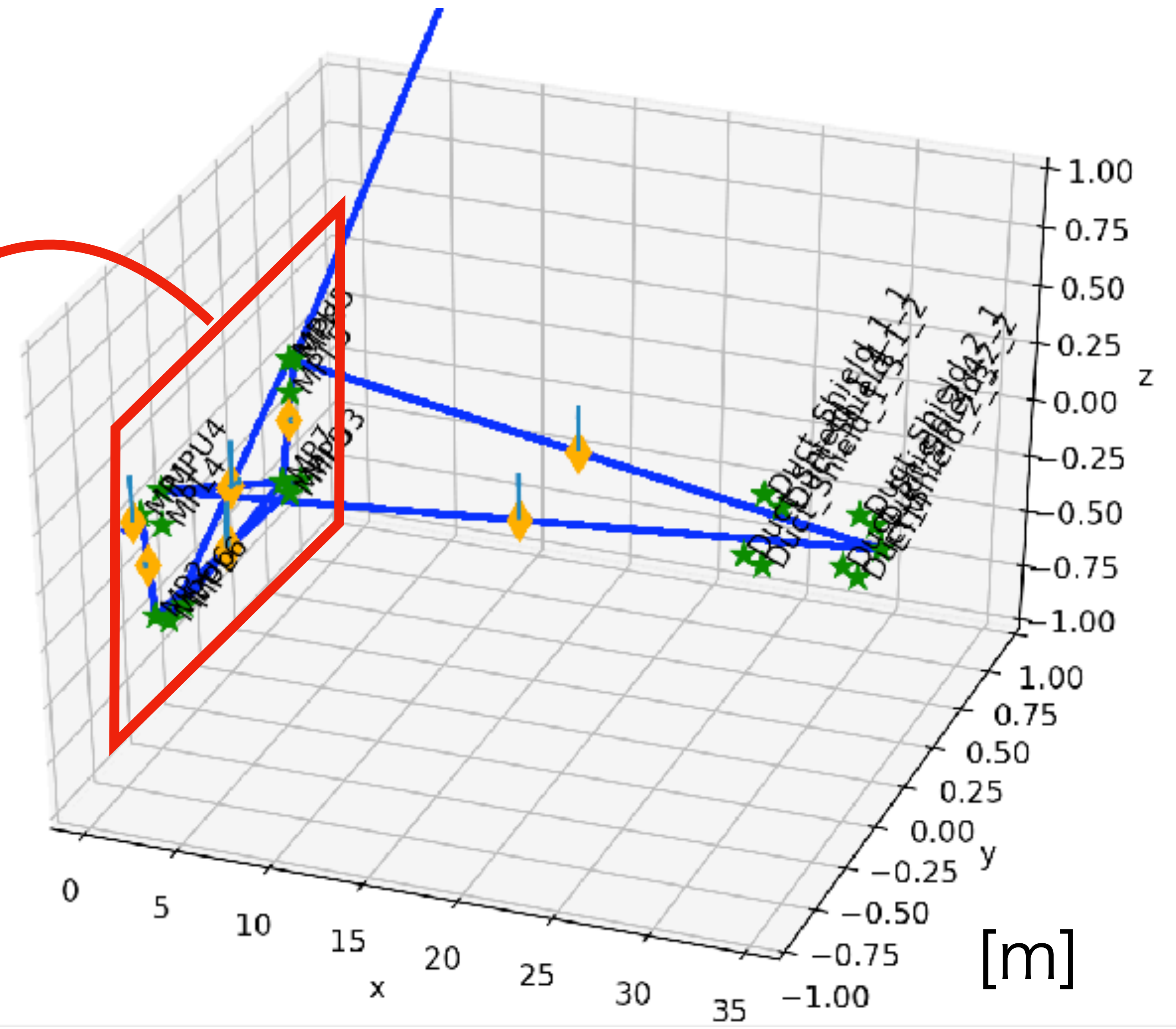
Alignment tools improvement

Ray tracing for redesigning mirror positions.

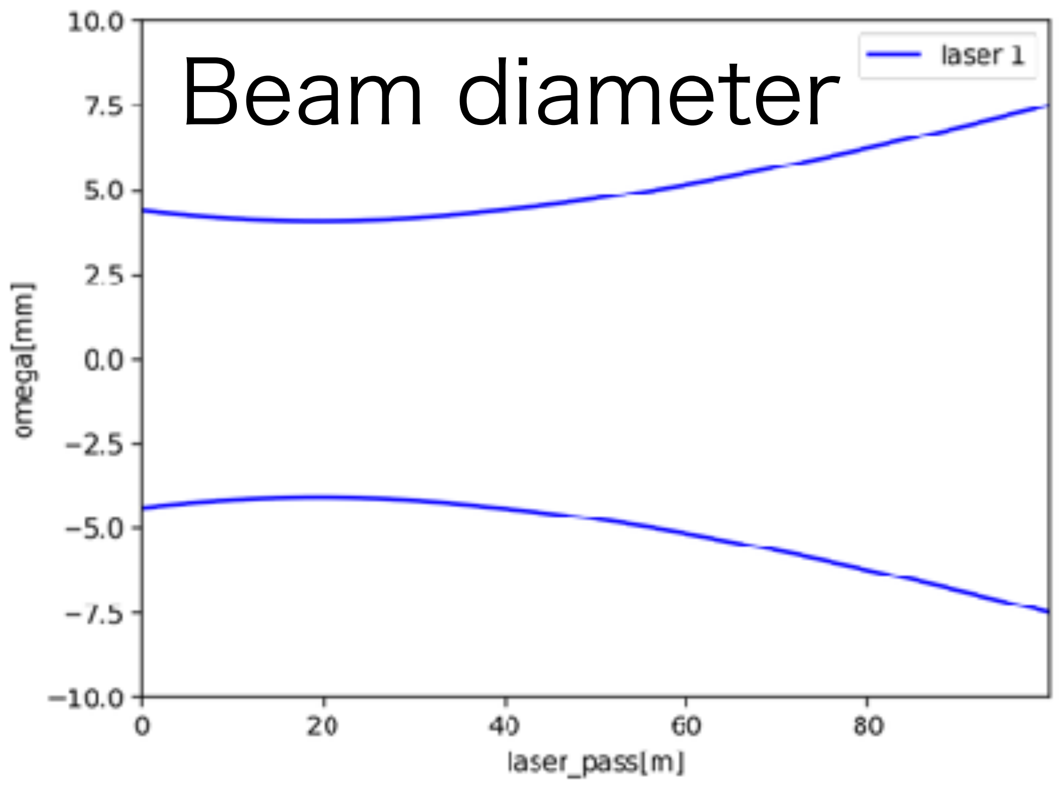
Because the space is limited in chamber, we need to move mirrors a little to make space for picomotor.



Laser path in chamber



Laser path in tube



Checked whether the laser hit tube structure

Checked the mirrors are enough size.