# Alignment sensing and control using Wave Front Sensing demodulated at the difference frequency between two phase-modulation sidebands in KAGRA

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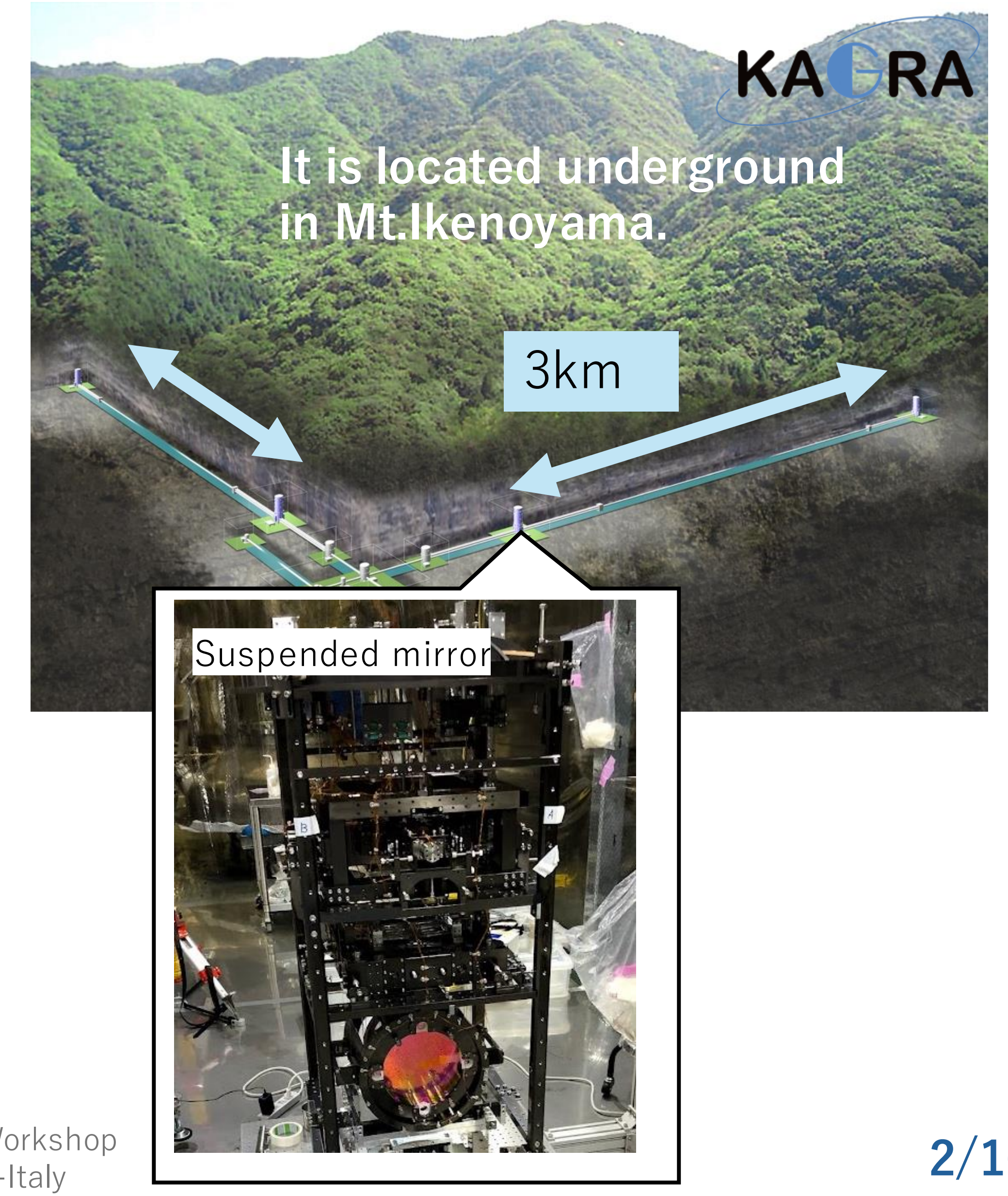
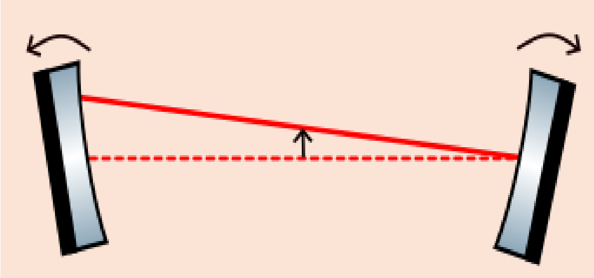
# Background of Alignment Sensing and Control (ASC)

- To determine the direction of gravitational waves, it is necessary to refer the time of detection by simultaneous observation of three or more detectors.
  We need stable operation of each detector.

- KAGRA‘s mirrors are suspended for vibration isolation.
  The angle of the mirror oscillates.
  → The interferometer is unstable.
  → Noise increases.



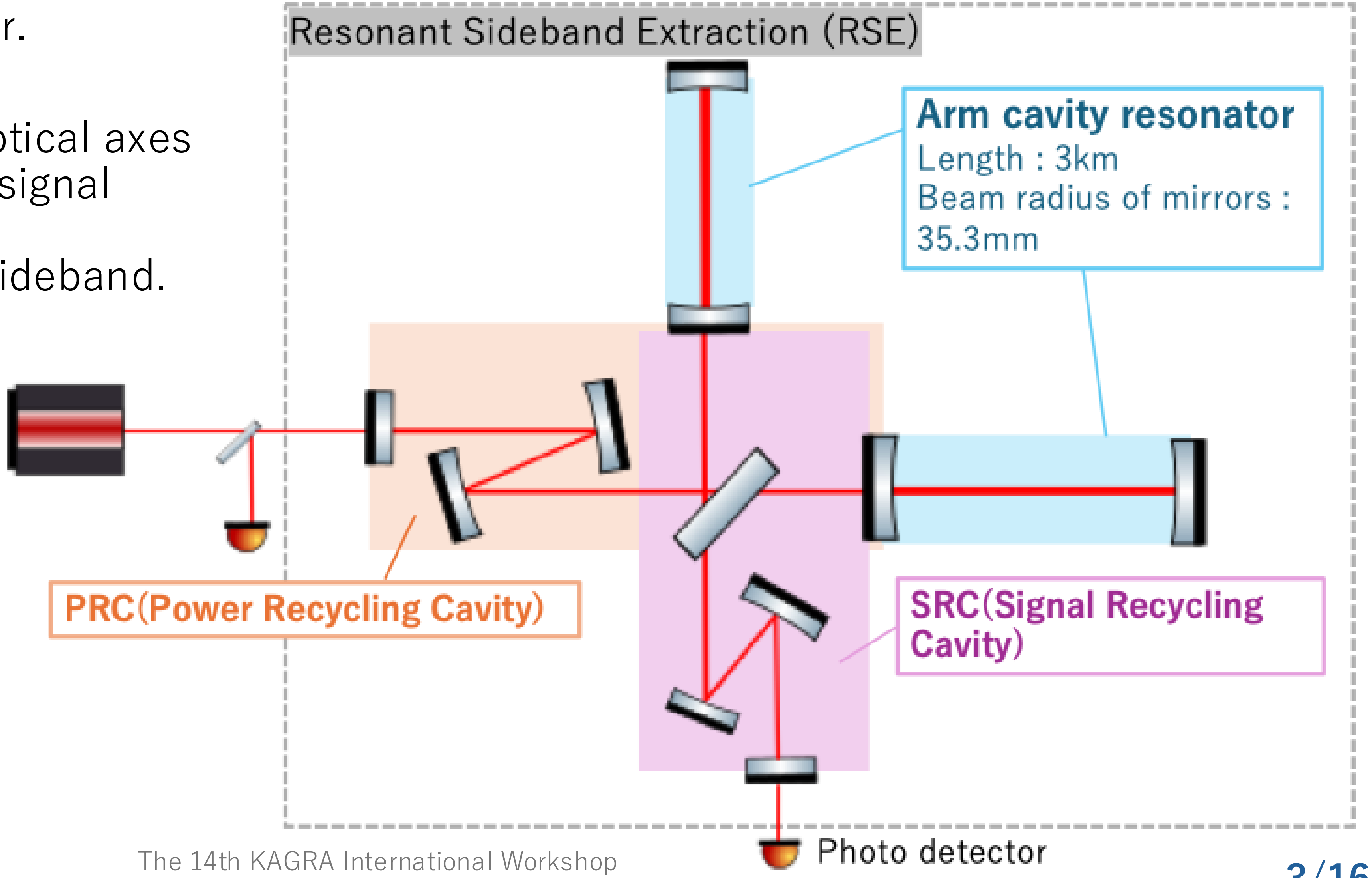

Install Alignment Sensing and Control (ASC) to KAGRA



# Alignment Sensing Control (ASC) in KAGRA

- ASC of KAGRA's optical axes is for stabilizing the interferometer.
- **<u>Wave front sensing(WFS)</u>**: The method for detecting optical axes misalignment with the beat signal between the carrier and the phase modulated(PM) sideband.
- The length and the beam radius of KAGRA's arms are large.

→The alignment signal of the arms is detected to be larger than that of PRC and SRC signal.

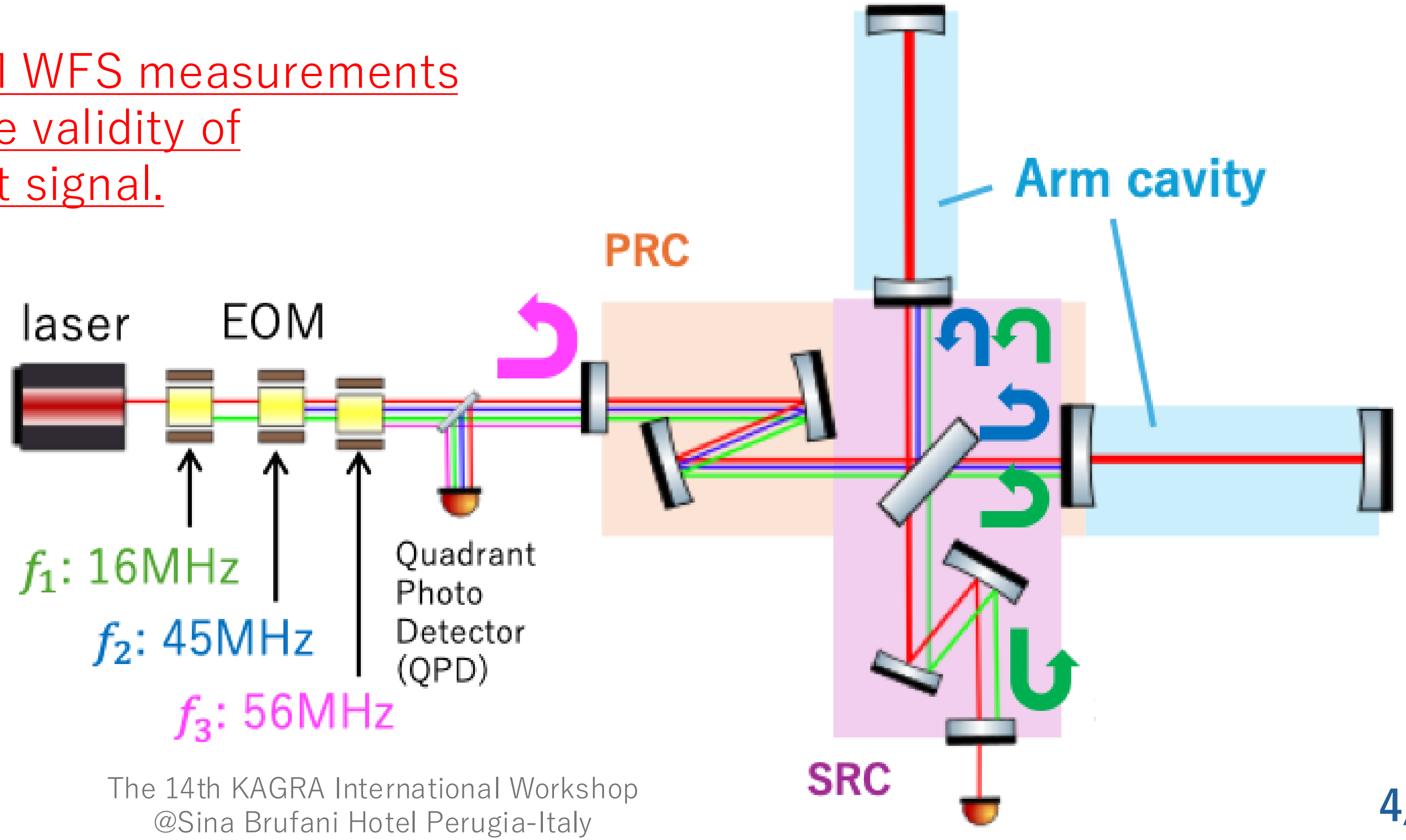


# New WFS

- **PMPMWFS**: WFS using RSE anti-resonance PM sideband $f_3$ (RSE incident optical axis) and ARM anti-resonance PM sideband $f_2$ (PRC cavity axis).

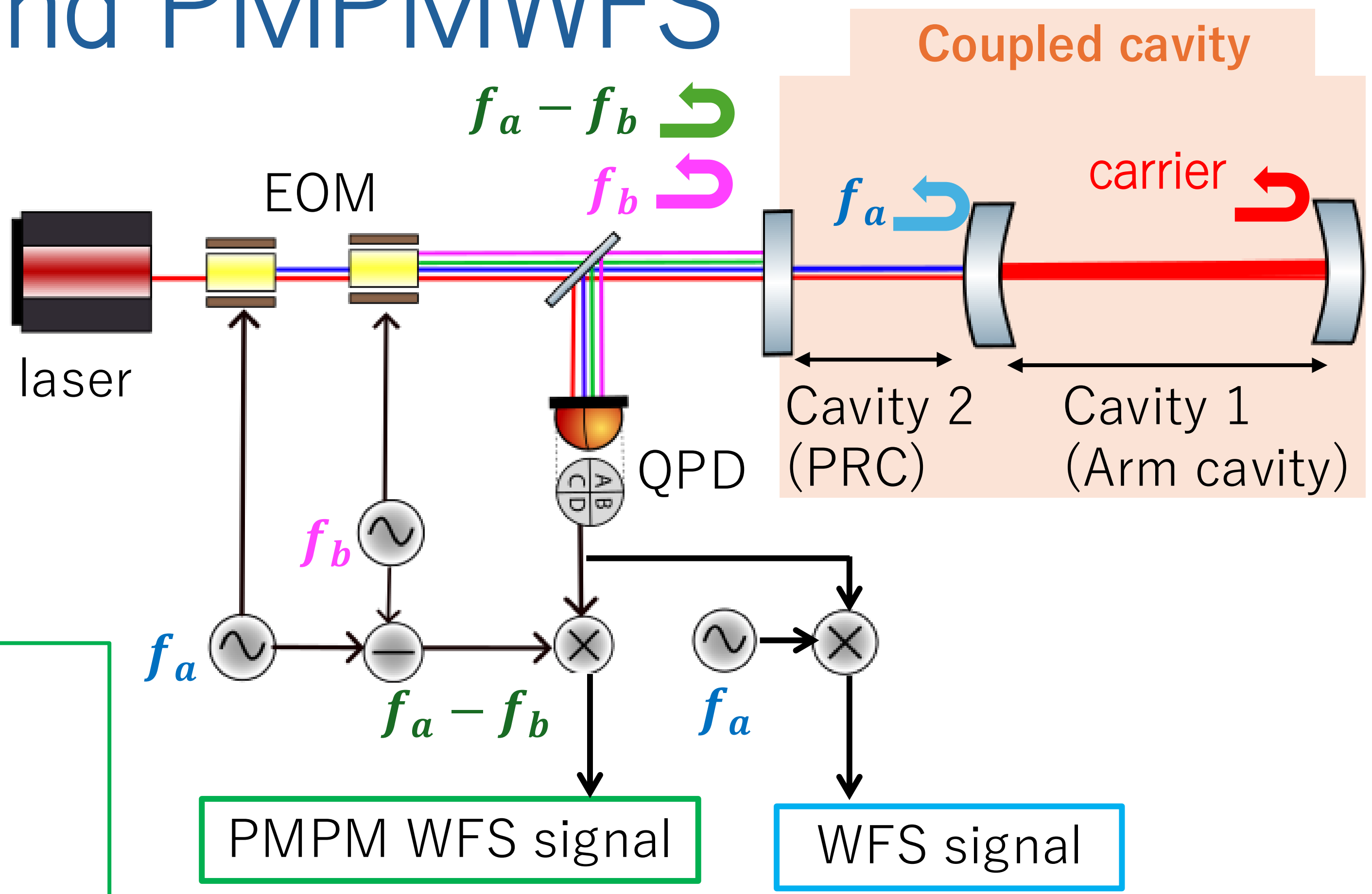
→ Assumed that the RSE would not couple to the arm optical axis because the two side bands do not pass through the arms.

➡ Actually performed PMPM WFS measurements with KAGRA to confirm the validity of the PMPM WFS alignment signal.



# The Theory of WFS and PMPMWFS

- [PMPMWFS Hypothesis 1]
  Can it detect the difference between the two sidebands?
  → **Yes, it can.**
- [PMPMWFS Hypothesis 2]
  Does it depend on the carrier component?
  → **Yes, it does.**



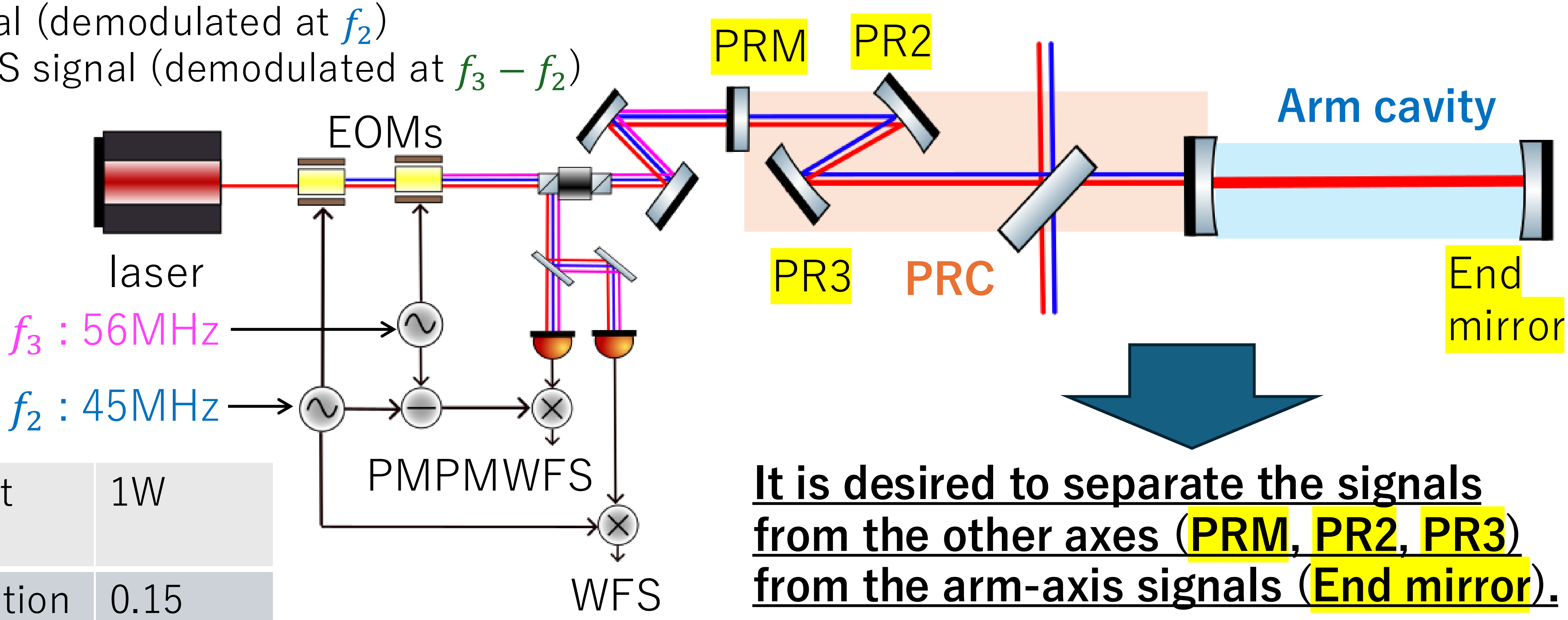

PMPM WFS signal
∝ (The beat part of $f_a$ and $f_b$)
+ (The beat part of carrier and the diffirence frequency $f_a - f_b$)
= **(The relative misalignment between $f_a$ and $f_b$)**
**+ (The relative misalignment between the carrier and $f_a - f_b$)**

WFS signal
∝ (The beat part of the carrier and $f_a$)
= **(The relative misalignment between the carrier and $f_a$)**

# Theoretical calculation model

Interferometer configuration: KAGRA's PRXARM configuration (PRC + X-axis arm resonator)
Mirror degrees of freedom: PRM, PR2, PR3, End mirror
Signal acquisition:

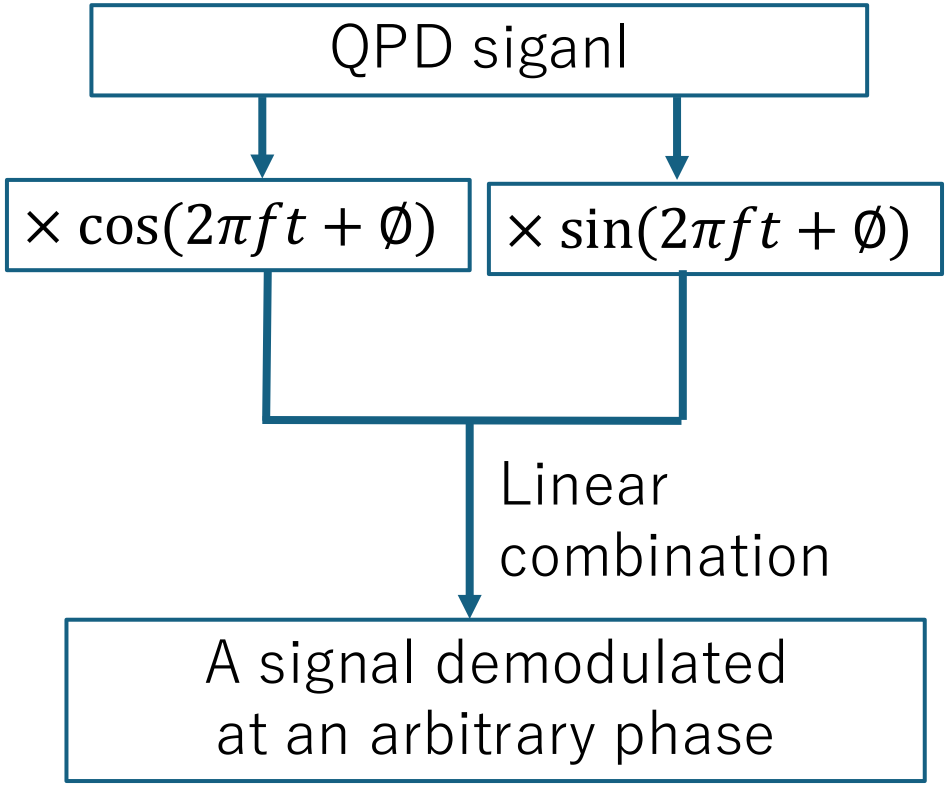
- WFS signal (demodulated at $f_2$)
- PMPMWFS signal (demodulated at $f_3 - f_2$)




| | |
|---|---|
| Incident power | 1W |
| Modulation index | 0.15 |

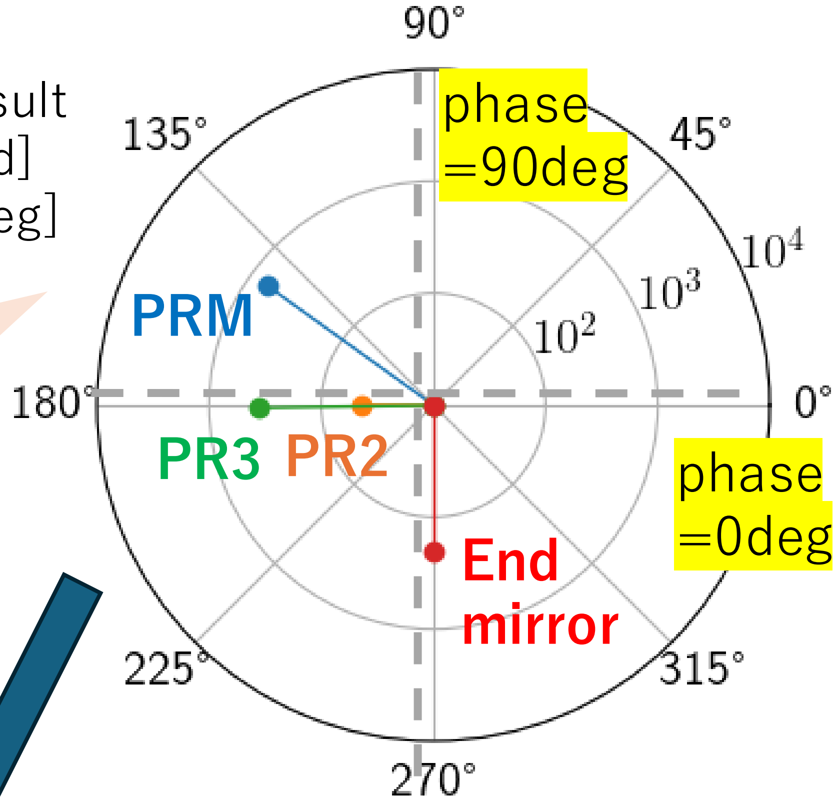
**It is desired to separate the signals from the other axes (PRM, PR2, PR3) from the arm-axis signals (End mirror).**

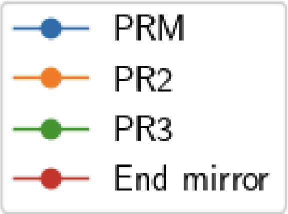
# Plot of calculation results




Example) PMPMWFS signal result
Abs: Signal/mirror angle [W/rad]
Phase: Demodulation phase [deg]

※ Adjusted the phase so that End mirror signal is minimized at a 0-degree phase




| Phase | PRM | PR2 | PR3 | End mirror |
|---|---|---|---|---|
| 0deg | **-556** | **-43** | **-358** | 0 |
| 90deg | **396** | 0.68 | 0.22 | **-201** |

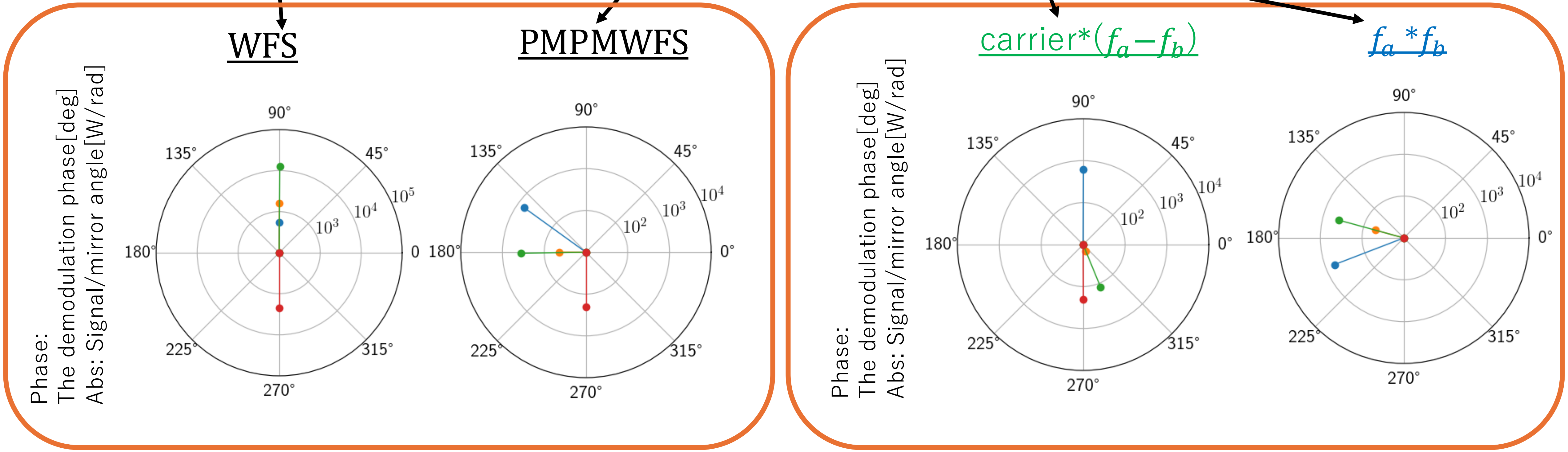
**By selecting the demodulation phase, it is possible to separate the signals for each degree of freedom**

# [Calculation] Plot in PRXARM configuration

WFS signal $\propto$ (carrier$*f_a$ )

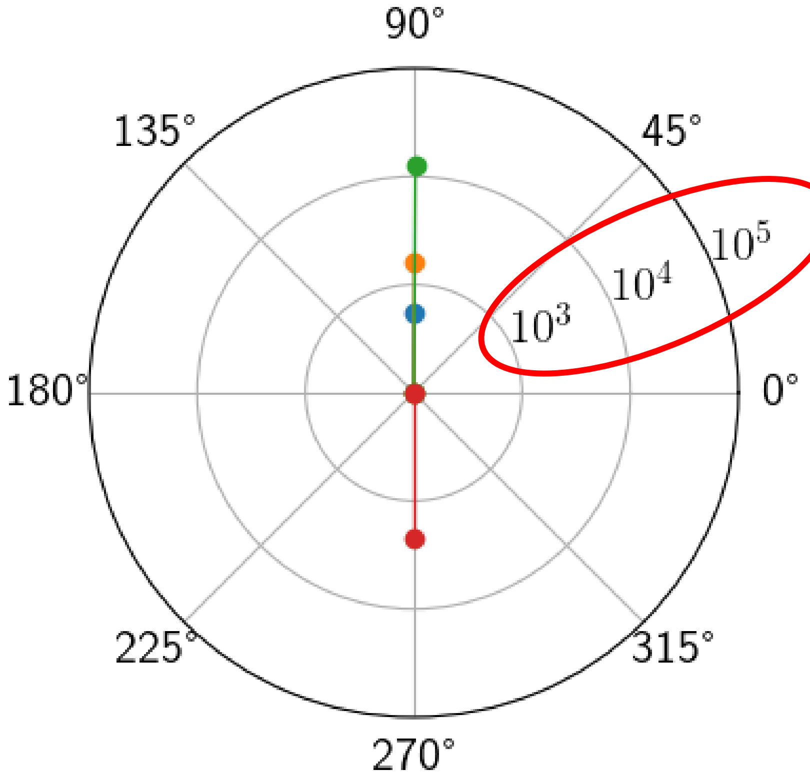
PMPM WFS signal

$\propto f_a * f_b + \text{carrier}*(f_a - f_b)$

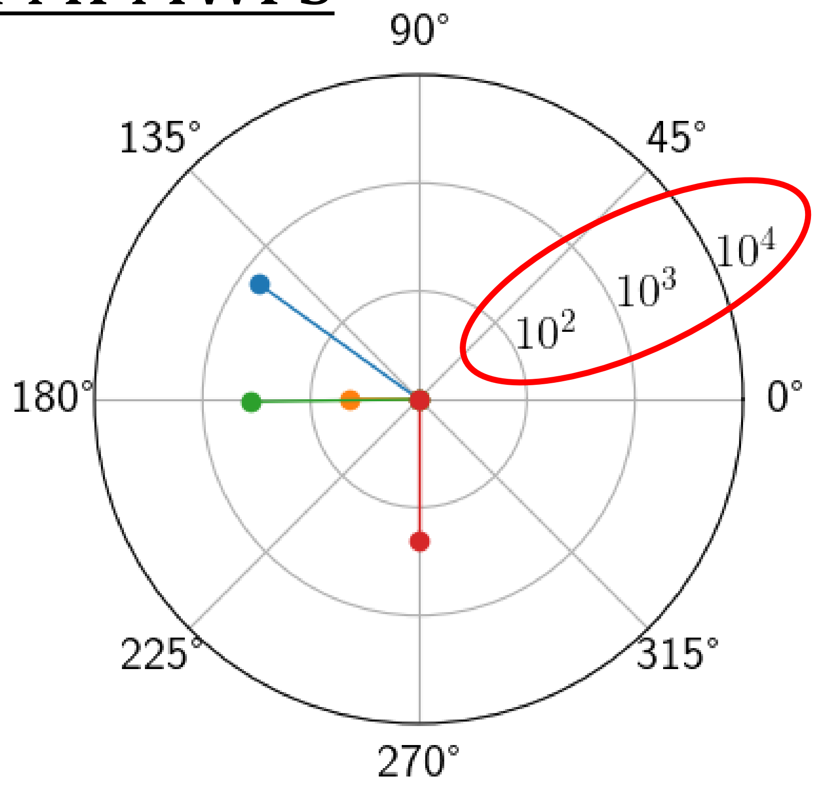


# [Calculation] WFS vs. PMPMWFS

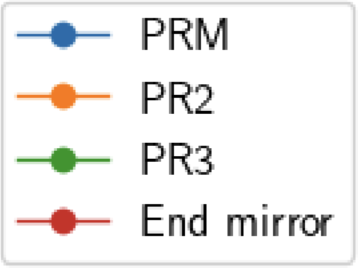
**WFS**




**PMPMWFS**




Phase:
The demodulation phase[deg]
Abs: Signal/mirror angle[W/rad]



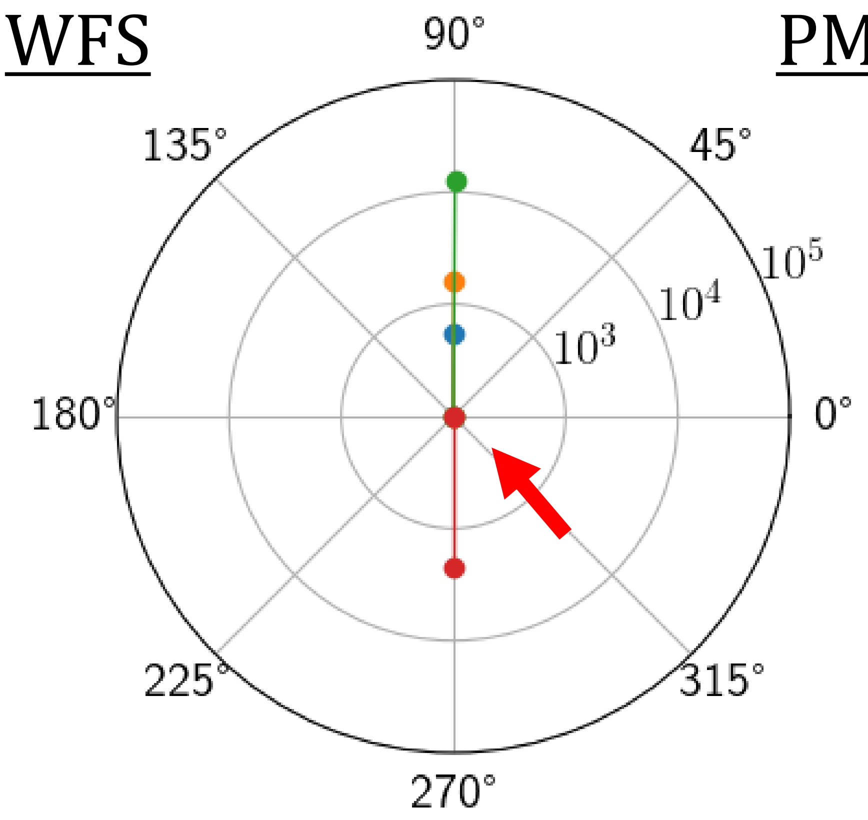

[Amplitude]

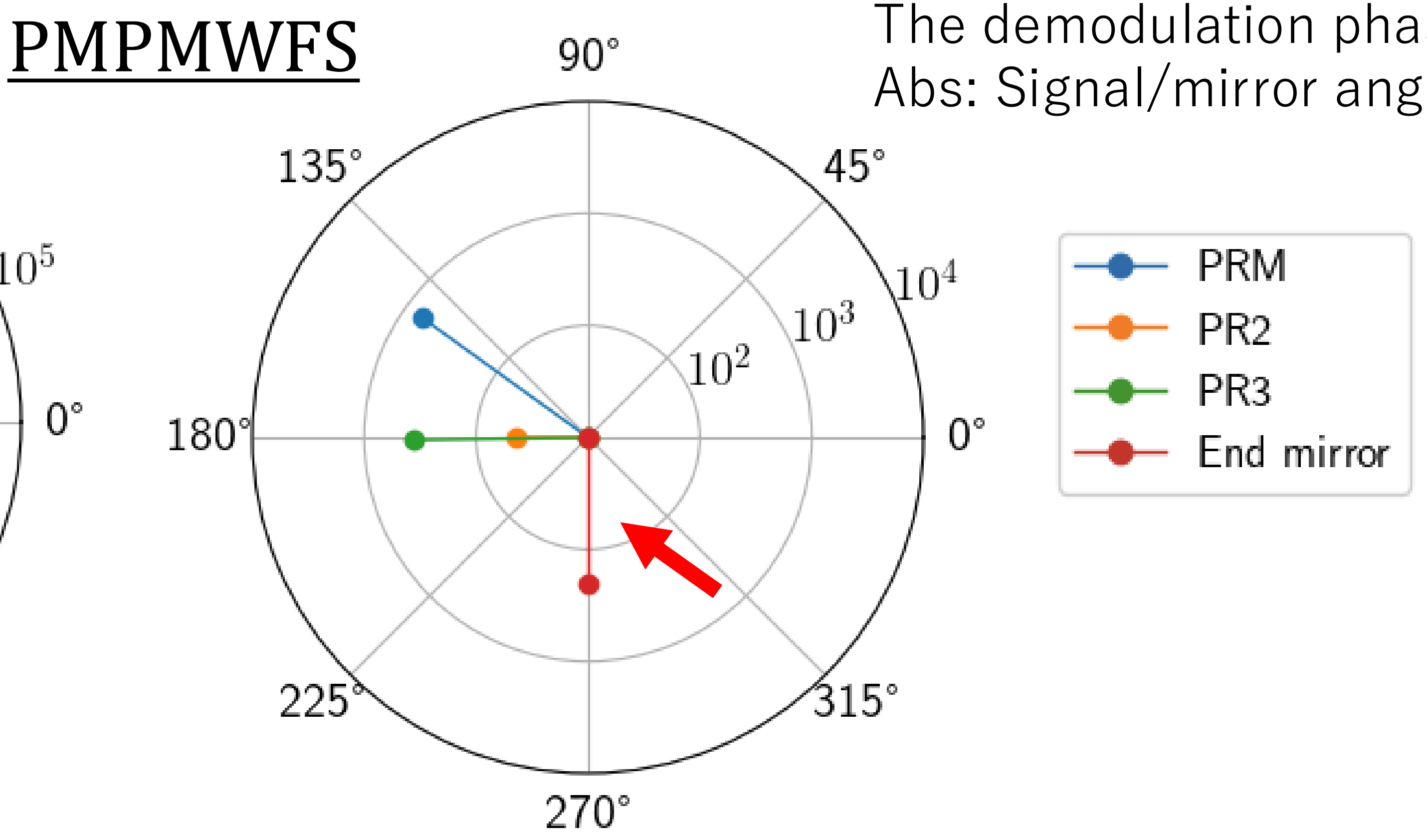
- PMPMWFS is about one-tenth of WFS.

| Detection limit [prad] | PRM | PR2 | PR3 | End mirror |
|---|---|---|---|---|
| PMPMWFS | 4.30 | 6.22 | 0.756 | 1.85 |

# [Calculation] WFS vs. PMPMWFS

Phase:
The demodulation phase[deg]
Abs: Signal/mirror angle[W/rad]



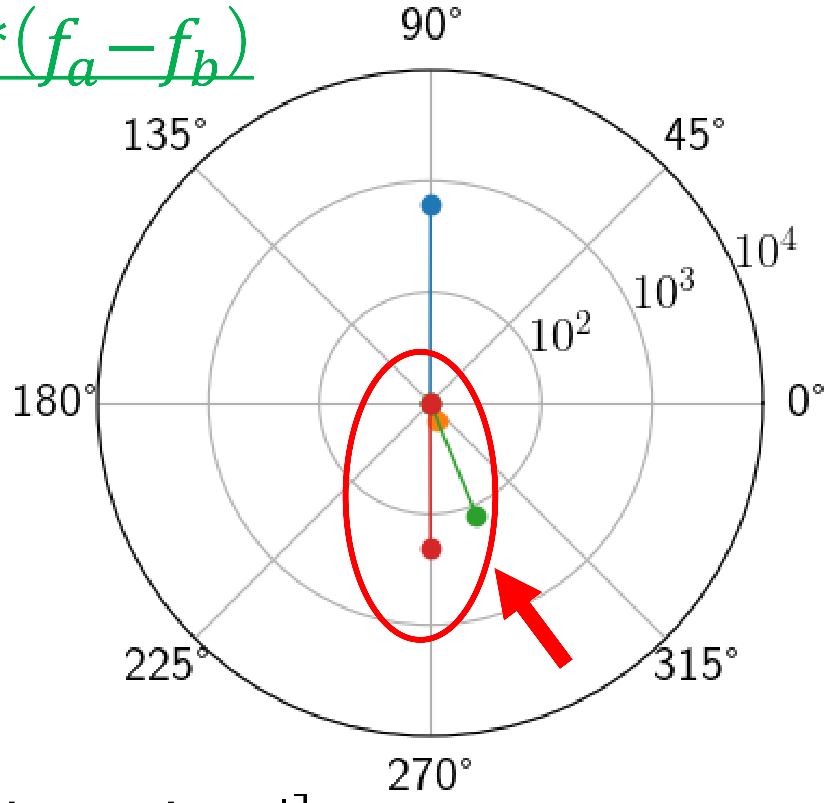



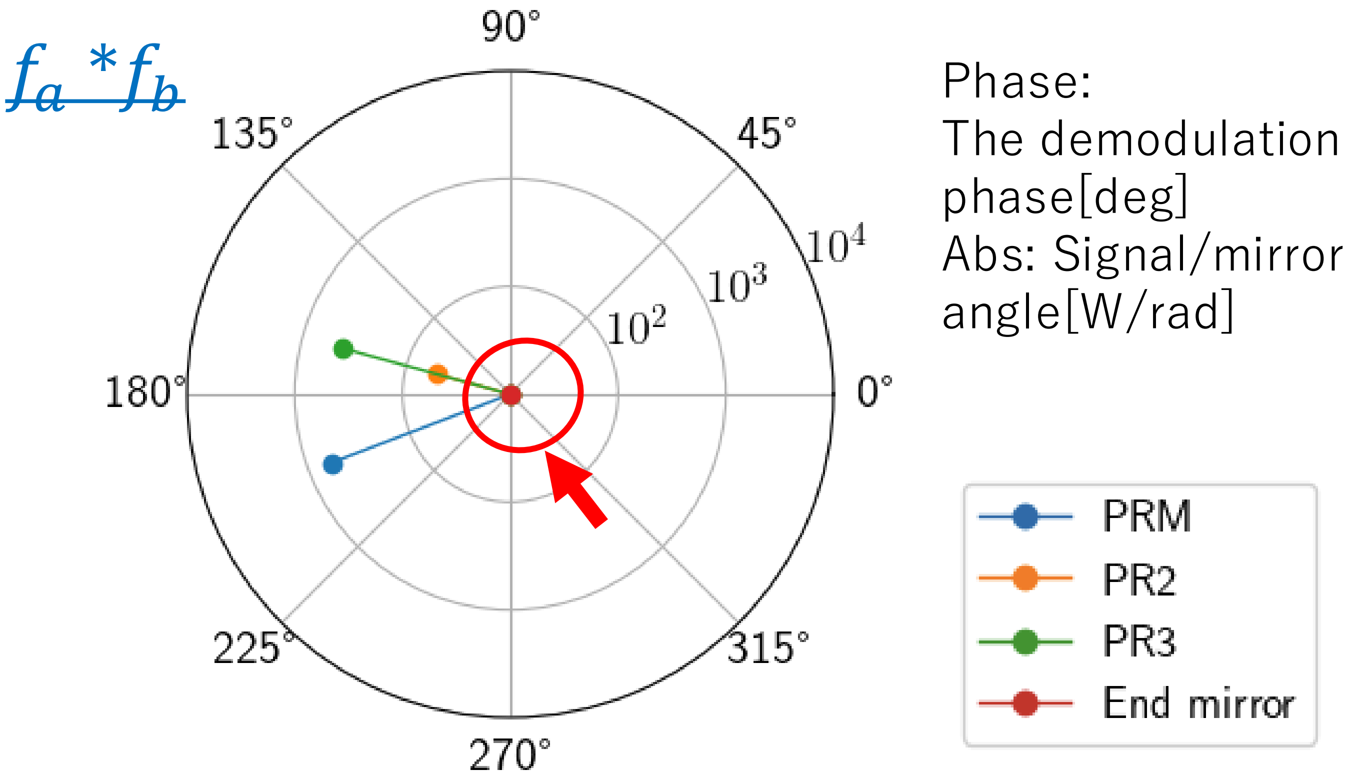

[Relationship between End mirror and the demodulation phase of PR2/3]

- In PMPMWFS, orthogonal (up to 89 degrees).
- In WFS, in phase.

→ **In PMPMWFS, it is possible to separate signals from other axes by selecting the demodulation phase.**

# [Calculation] The beat components of PMPMWFS




Phase: The demodulation phase[deg]
Abs: Signal/mirror angle[W/rad]

[End mirror signal]

- carrier*($f_a - f_b$) beat part → visible
- $f_a * f_b$ beat part → not visible.

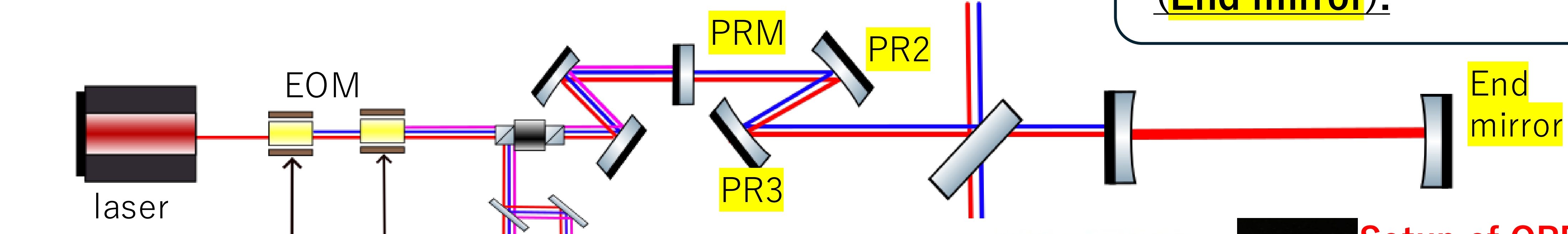
→ the two sidebands $f_a$ and $f_b$ do not enter the arm resonator

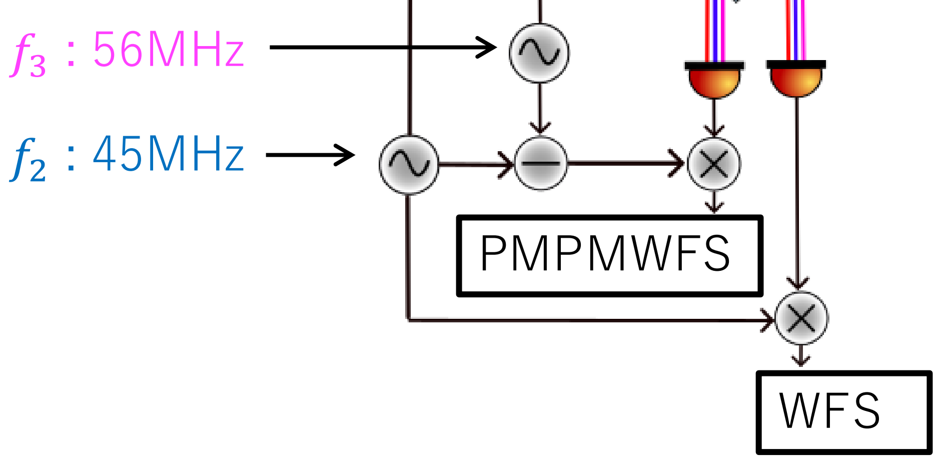
# [Experiment] PMPMWFS Measurement

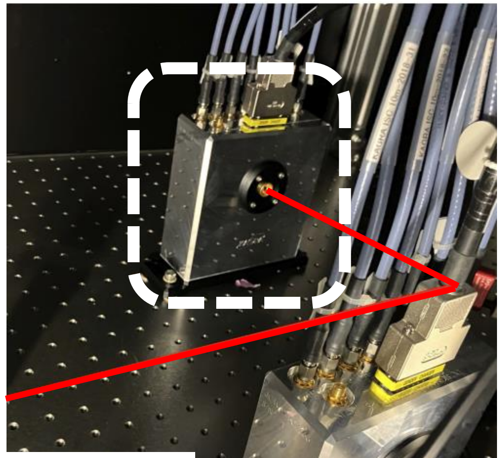
Interferometer configuration: KAGRA's PRXARM configuration
Mirror degrees of freedom: PRM, PR2, PR3, End mirror
Signal detection:

- WFS signal (demodulated at $f_2$)
- PMPMWFS signal (demodulated at $f_3 - f_2$)

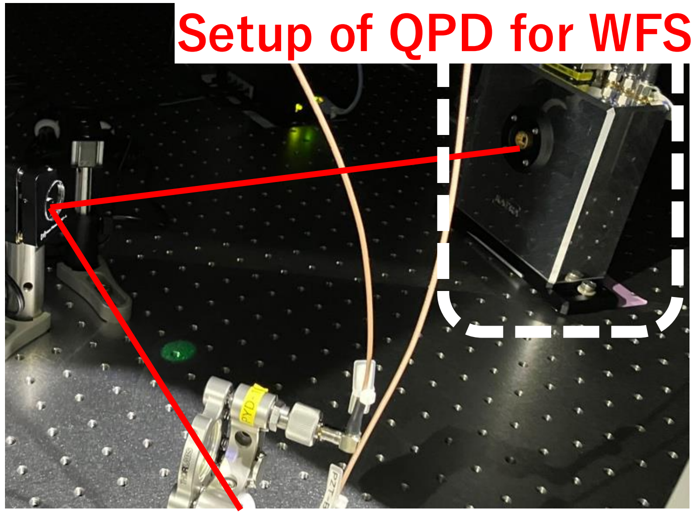
**It is desired to separate the signals from the other axes (PRM, PR2, PR3) from the arm-axis signals (End mirror).**



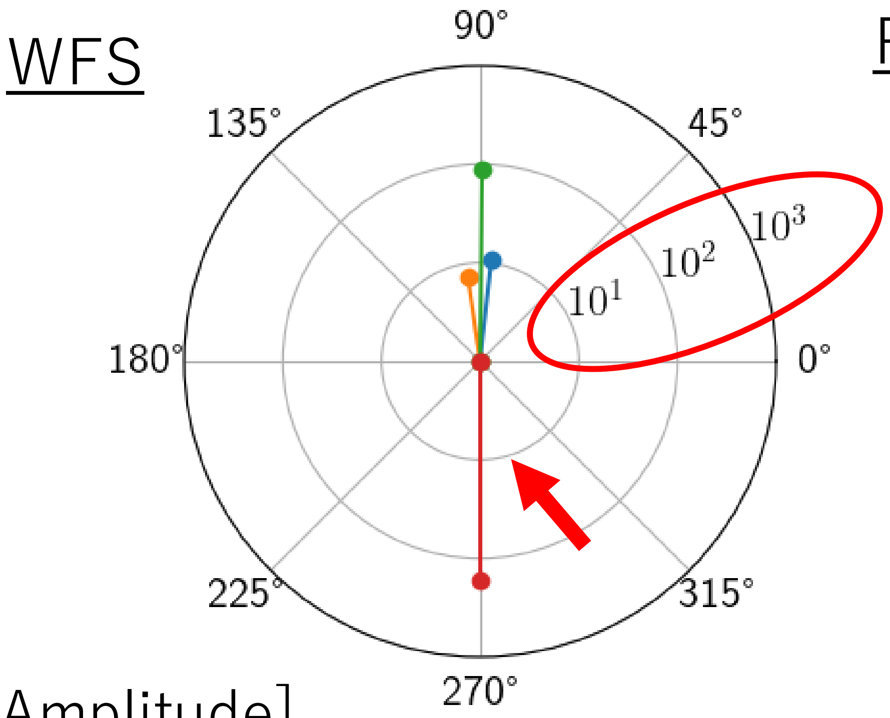



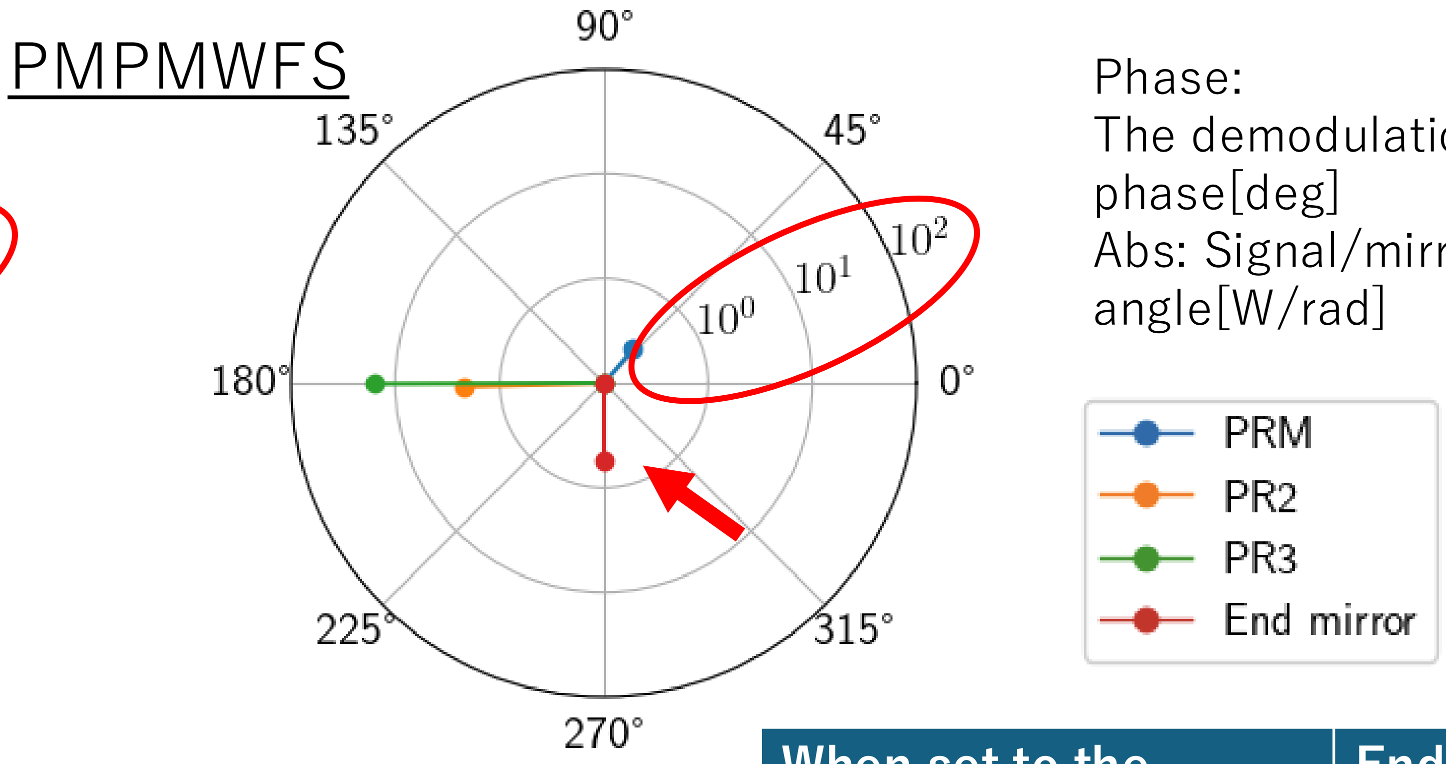
Setup of QPD for PMPMWFS



Setup of QPD for WFS

# [Experiment Measurement] WFS vs. PMPMWFS




Phase:
The demodulation phase[deg]
Abs: Signal/mirror angle[W/rad]

[Amplitude]

- PMPMWFS is about one-tenth of WFS

[Relationship between End mirror and the demodulation phase of PR2/3]

- In PMPMWFS, orthogonal (up to 89 degrees)
- In WFS, in phase

| When set to the demodulation phase to maximized PR3 | End mirror /PR3 |
|---|---|
| PMPMWFS | 0.009 |
| WFS | -1.9 |

# [Calculation vs. Experiment Measurement]

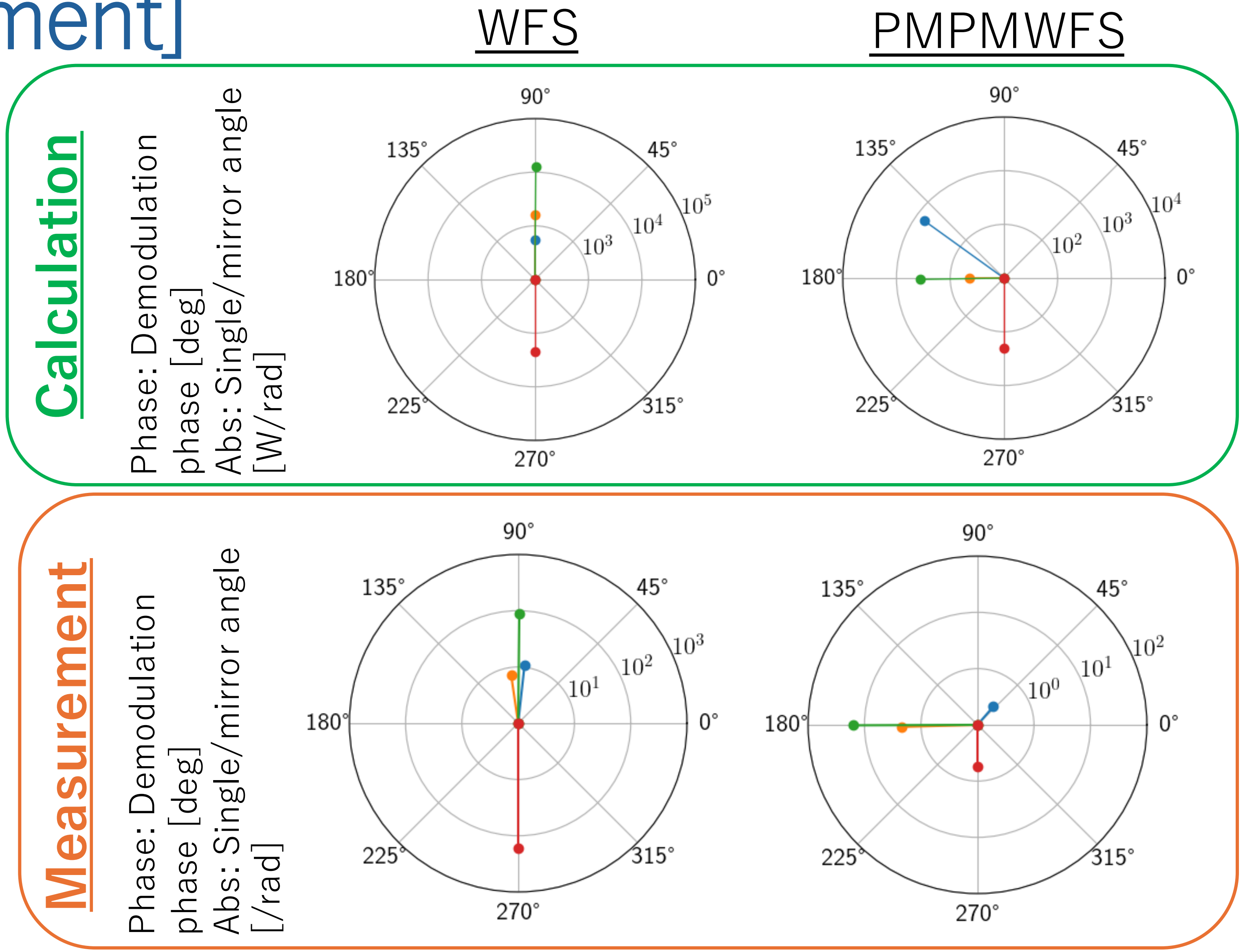
[Amplitude]

- PMPMWFS is about one-tenth of WFS

[Relationship between End mirror and the demodulation phase of PR2/3]

- In PMPMWFS, orthogonal (up to 89 degrees)
- In WFS, in phase

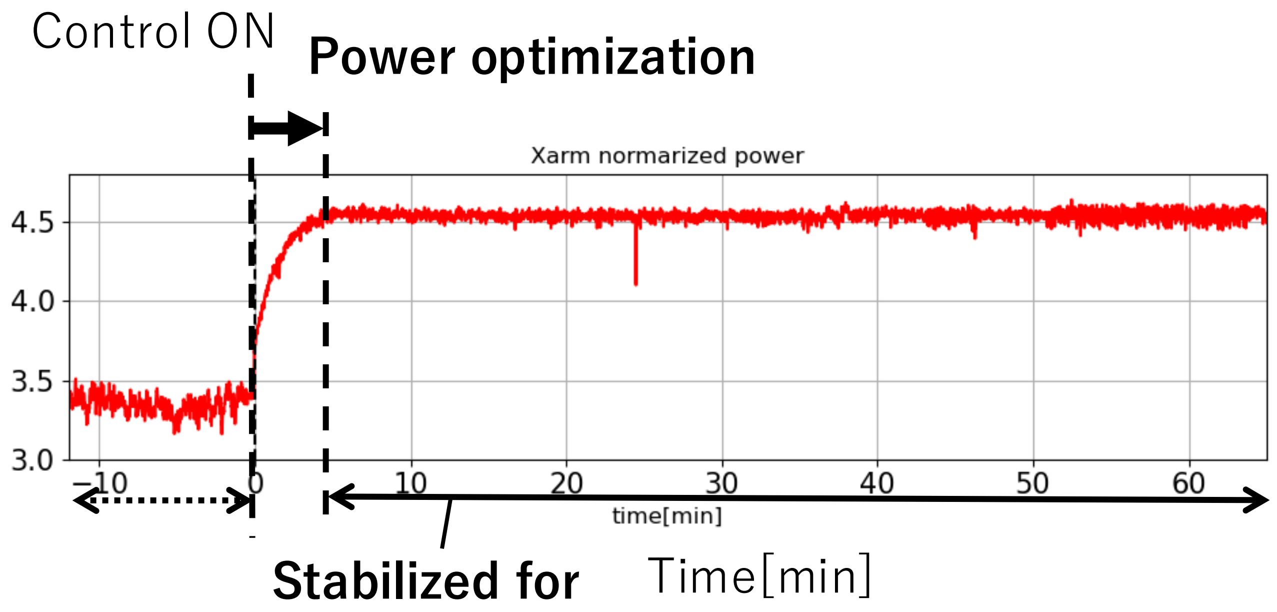
The relationship between PMPMWFS and WFS was confirmed by the agreement between calculation and experimental results.



# Demonstration of control implementation time scale

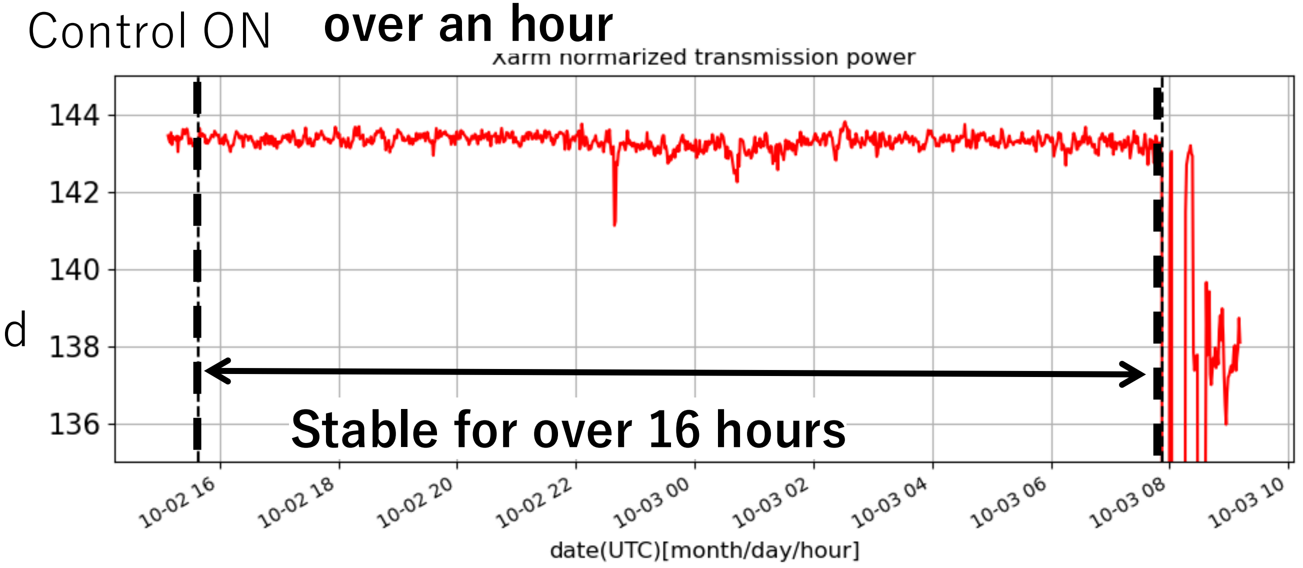
PRXARM

The arm cavity normalized power [a.u.]




PRFPMI

The arm cavity normalized power [a.u.]




**Achieved stabilization in the interferometer configuration for GW observation**

# Summary

- Alignment Sensing and Control (ASC) is required for gravitational-wave detectors
- Conventional Wave Front Sensing(WFS) has difficulty separating arm-axis and other-axis signals → Proposal for PMPMWFS
- PMPMWFS: beat components between two sidebands + beat components between the carrier and the difference frequency
- In the KAGRA PRXARM configuration:
  - ➢ PMPMWFS detects the arm-axis signal and the other-axis signals with orthogonal phases (WFS: in phase)
    → **Successful signal separation using a single signal**
  - ➢ The beat component between the two sidebands does not detect the arm-axis signal
- The relationship between PMPMWFS and WFS in the experiment agreed with the theoretical calculation
  → **Consistency of the theoretical analysis was confirmed**
- **Successful implementation of control in the interferometer configuration for gravitational-wave observation**

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# Outlook

[ASC in GW observation mode]

- Apply PMPMWFS to optical axes other than the arm cavity axis (PRC, incident axis.. etc.)

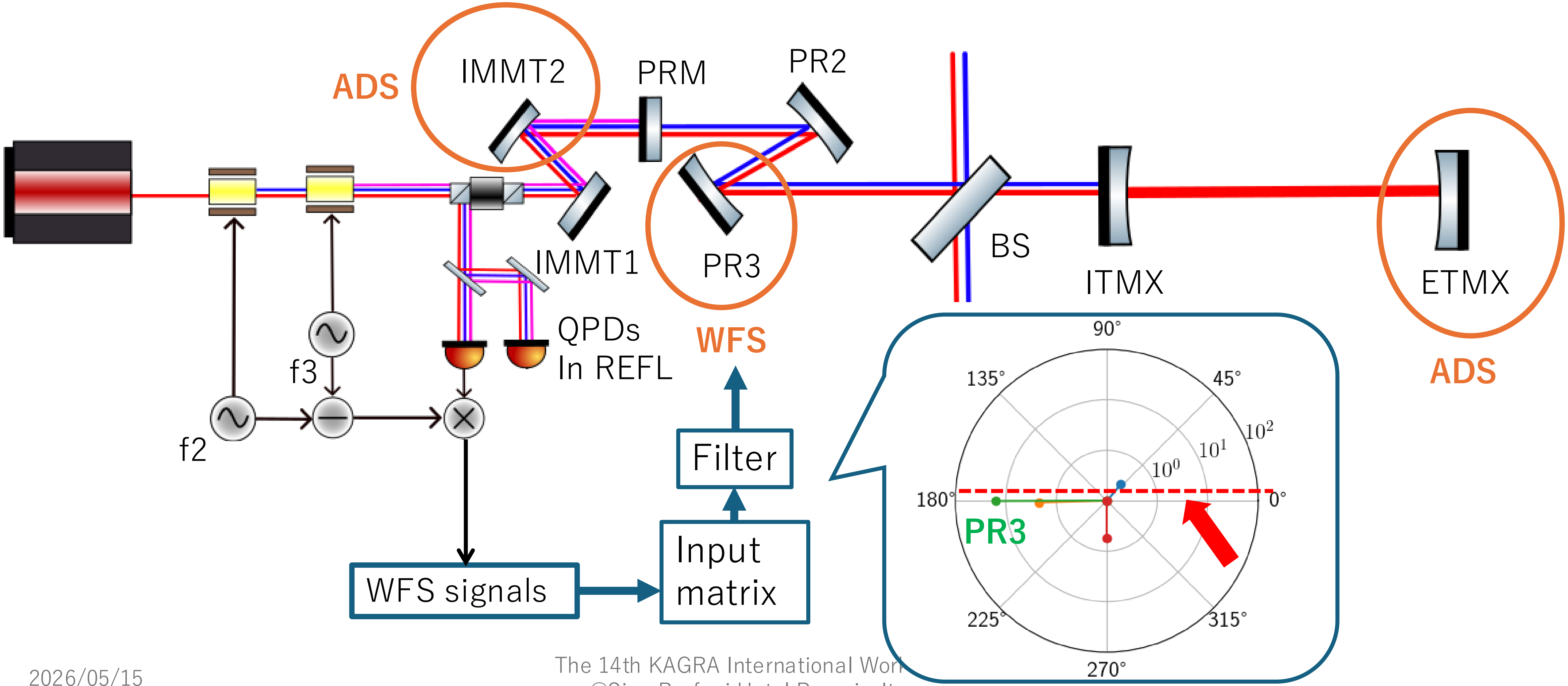
[ASC during GW observation mode preparation]

- Investigate extraction of pure sideband–sideband beat signals using the difference between PMPMWFS and WFS signals

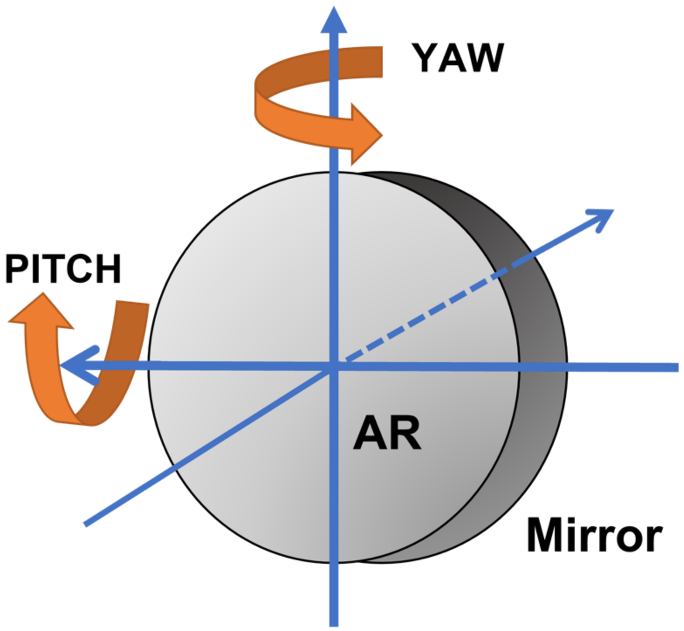
# Appendix

# PMPMWFS control to PRXARM

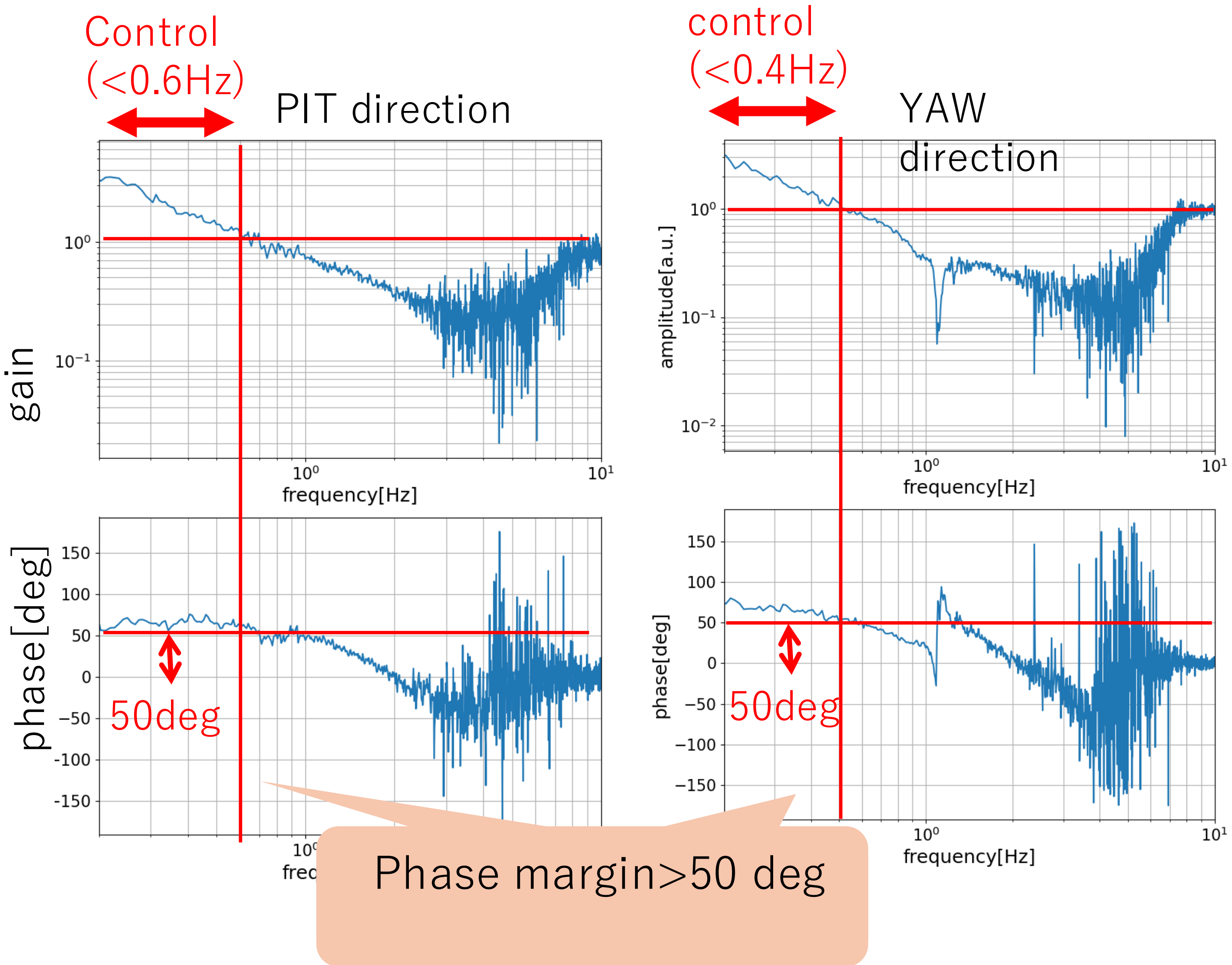
- WFS control using PMPMWFS signal in PRXARM.
- Added ADS (Alignment dither system) to IMMT2 and ETMX as PRXARM ASC.



# OLTF

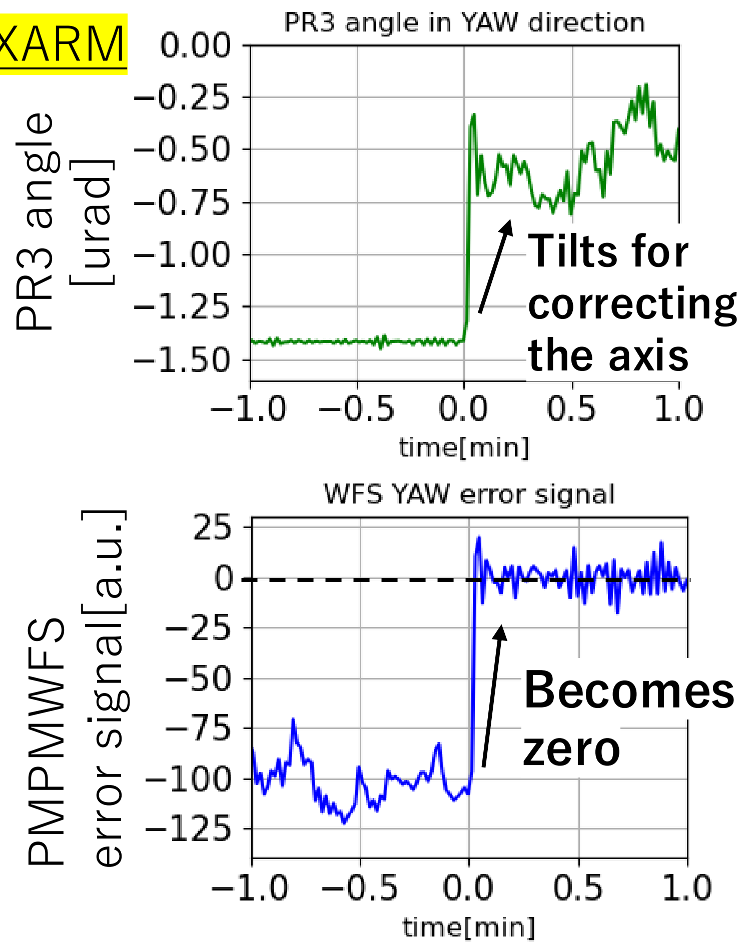


YAW
PITCH
AR
Mirror

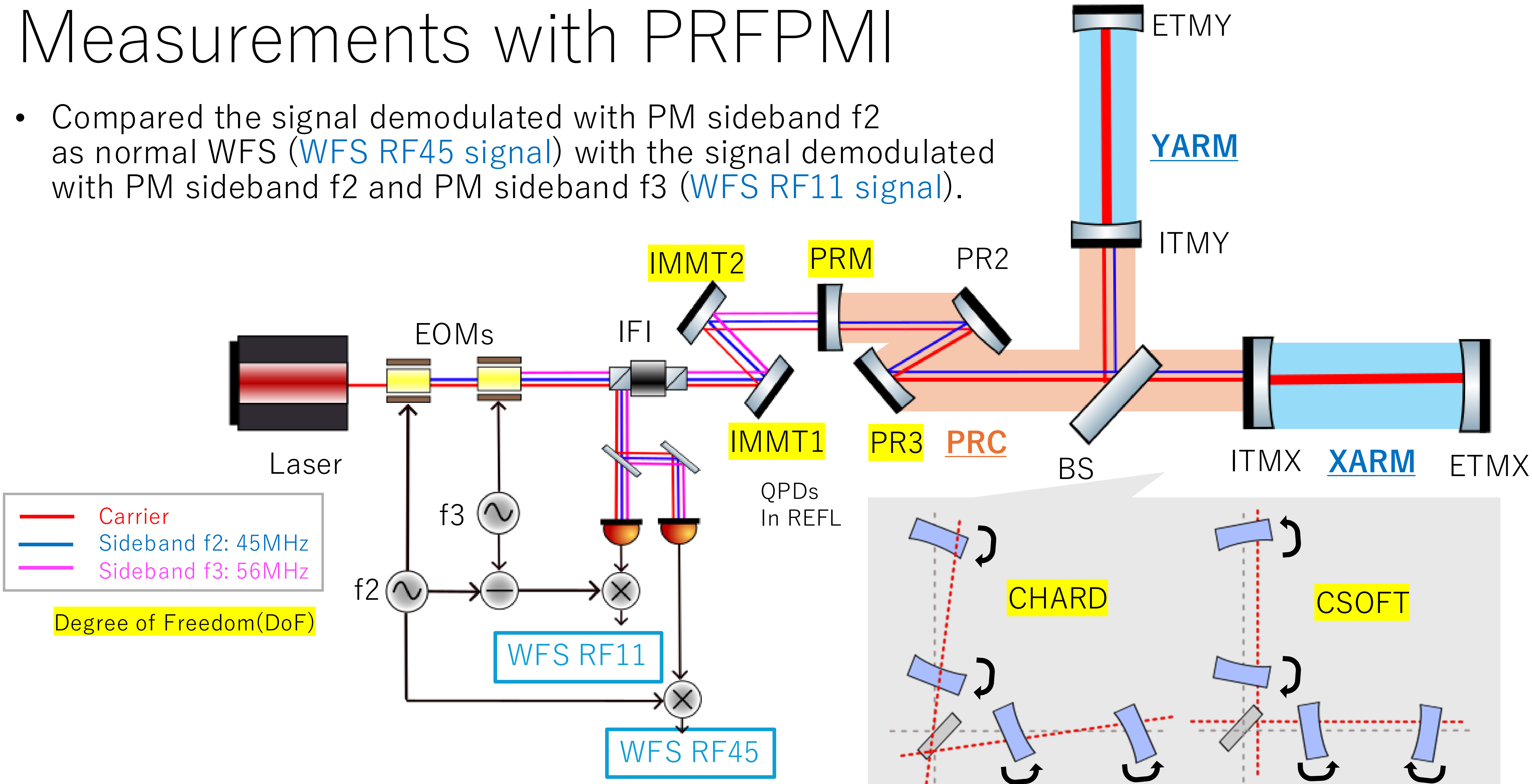
Control (<0.6Hz)
PIT direction
control (<0.4Hz)
YAW direction
gain
phase[deg]
amplitude[a.u.]
frequency[Hz]
50deg
50deg
Phase margin>50 deg

PRXARM

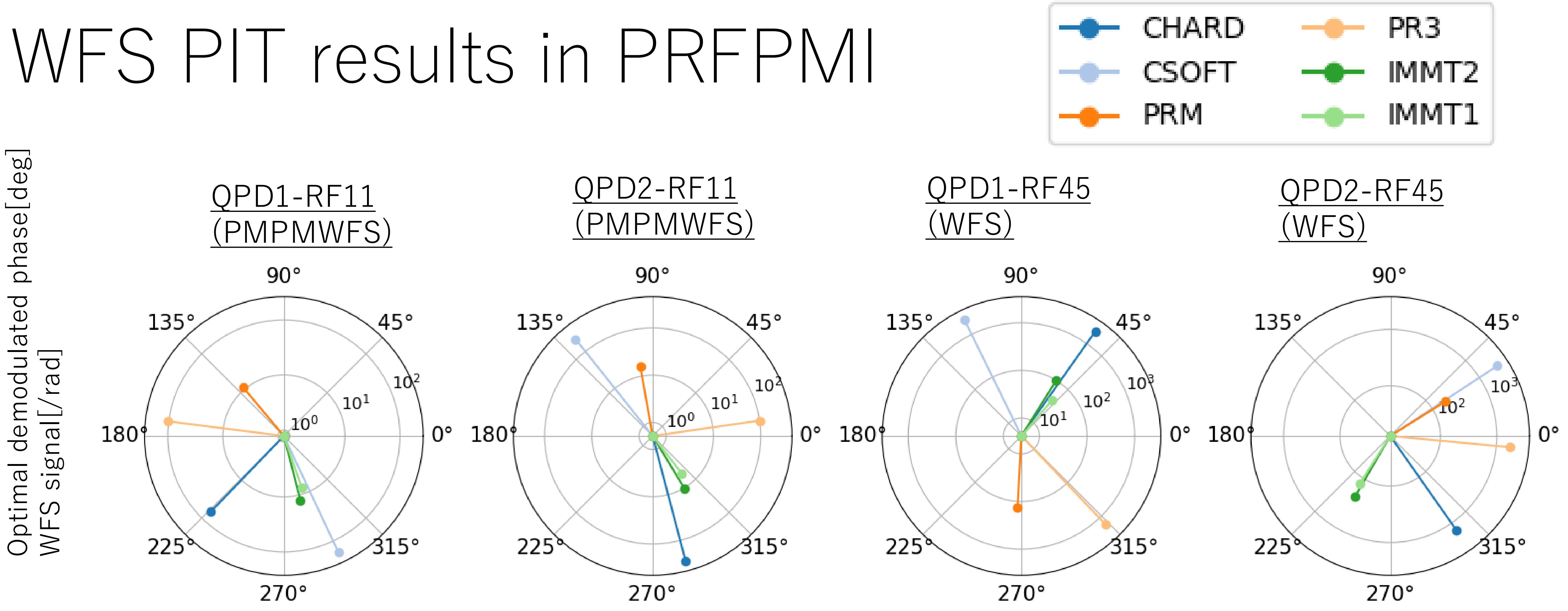

PR3 angle in YAW direction
PR3 angle [urad]
0.00
−0.25
−0.50
−0.75
−1.00
−1.25
−1.50
−1.0
−0.5
0.0
0.5
1.0
time[min]
Tilts for correcting the axis
WFS YAW error signal
PMPMWFS error signal[a.u.]
25
0
−25
−50
−75
−100
−125
−1.0
−0.5
0.0
0.5
1.0
time[min]
Becomes zero

# Measurements with PRFPMI

- Compared the signal demodulated with PM sideband f2 as normal WFS (WFS RF45 signal) with the signal demodulated with PM sideband f2 and PM sideband f3 (WFS RF11 signal).



# WFS PIT results in PRFPMI




- The RF11 signal was detected with large PR3, CHARD, and CSOFT signals.
- The amplitude of the RF11 signal was one-tenth that of the RF45 signal.

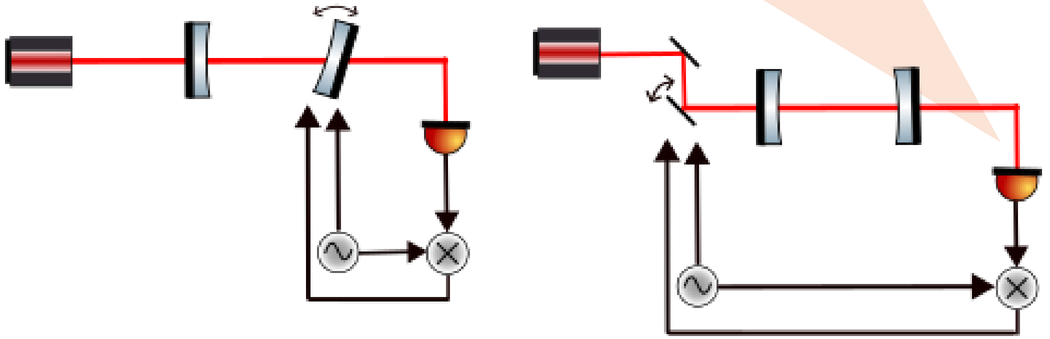
# How to ASC (3ways)

## ASC to align two optical axes relatively

- **Alignment Dither System(ADS)**

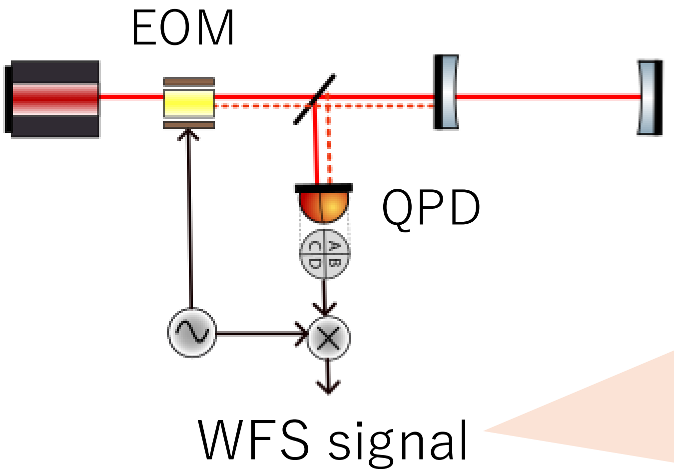
Oscillate the mirror angle and detect cavity power oscillation.

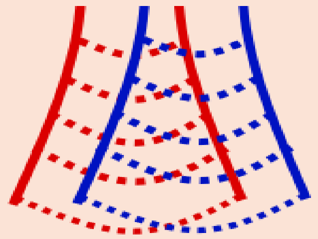
If a mirror oscillates, the incident axis and cavity axes are misaligned.
→Transmission power decreases.



- **Wave front sensing(WFS)**

Detect misalignment of the optical axes by wavefront detection.



Wavefront misalignment between cavity axis and incident axis.

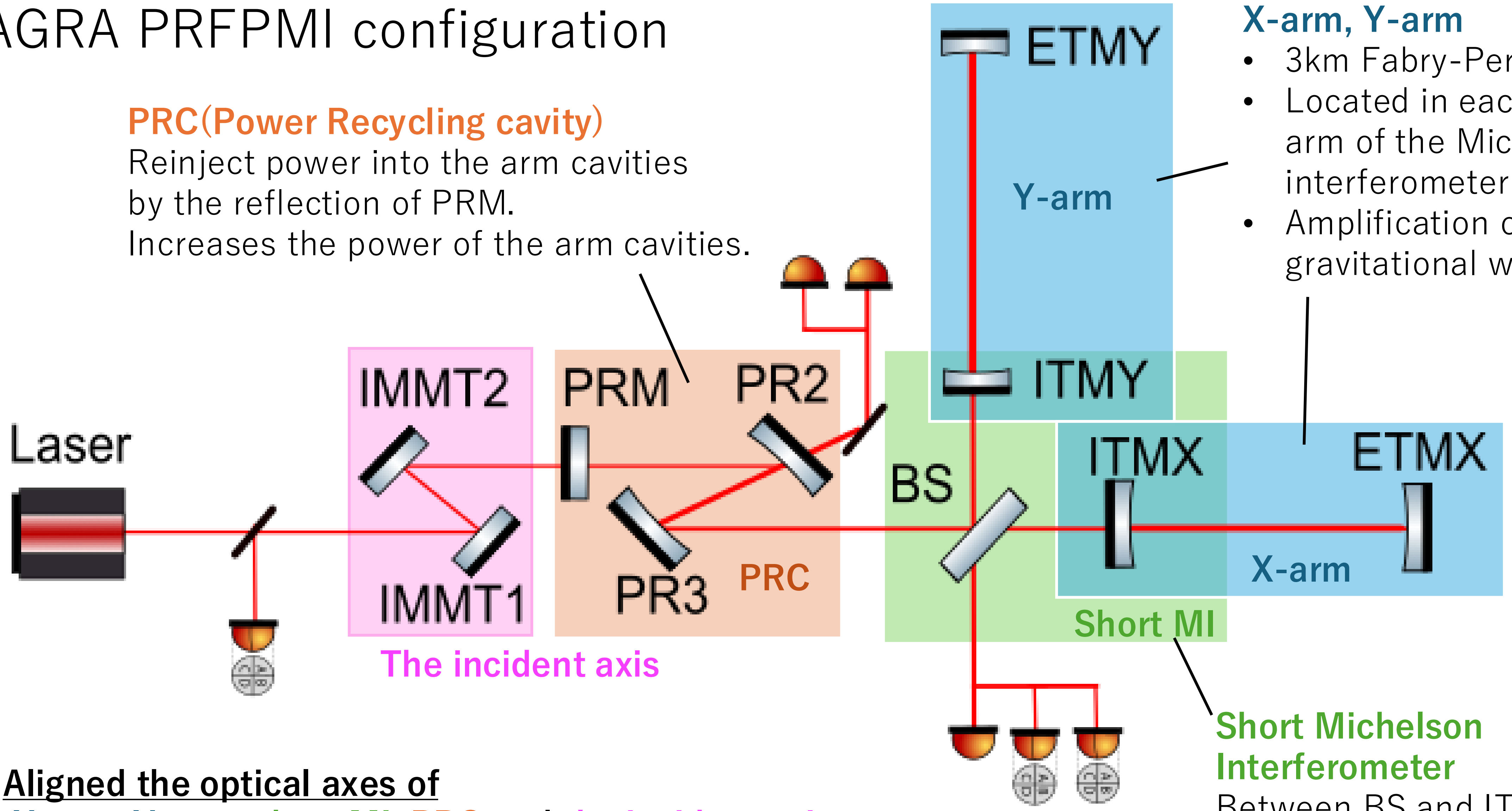
## ASC to fix the beam position on the mirror

- **Beam Position Control(BPC)**

# KAGRA PRFPMI configuration

**PRC(Power Recycling cavity)**
Reinject power into the arm cavities by the reflection of PRM.
Increases the power of the arm cavities.

**X-arm, Y-arm**
- 3km Fabry-Perot cavities.
- Located in each of the arm of the Michelson interferometer.
- Amplification of the gravitational wave signal.




**Short Michelson Interferometer**
Between BS and ITMs

**Aligned the optical axes of X-arm, Y-arm, short MI, PRC and the incident axis.**