Radiation pressure noise measurement

K. Agatsuma
(National Astronomical Observatory of Japan)
and T. Mori, D. Friedrich,
S. Sakata, S. Ballmer, O. Miyakawa, K. Numata,
S. Kawamura

Contents

R&D for KAGRA

- Radiation pressure noise measurement
- Quantum efficiency measurement
- Misc.

Radiation pressure noise measurement

Objective and Scope of experiment

Future GW detectors will be limited by radiation pressure noise

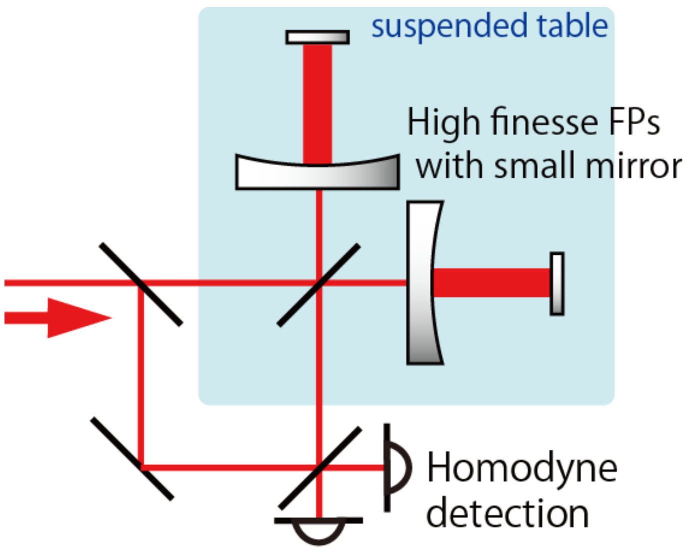
- Objectives
  - Observe radiation pressure noise
    - Use of tiny mirrors
  - Reduce radiation pressure noise
    - measurement of ponderomotively squeezed vacuum fluctuations at the best homodyne angle
    - SQL not possible: thermal noise of a mirror is big in the current setup

=> contribute to large scale GW detectors including KAGRA

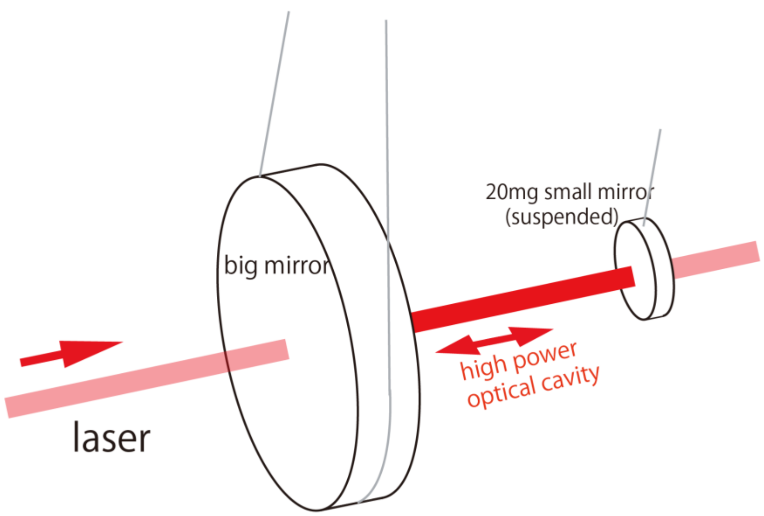
- Scope
  - Fabry-Perot cavities with very small mirrors and high Finesse

Conceptual design

- Main interferometer: Fabry-Perot Michelson interferometer with very small mirrors (20mg) and high Finesse (10000)
- Output light homodyne detected with local oscillator
- Observation and reduction of radiation pressure noise around 300Hz – 1kHz



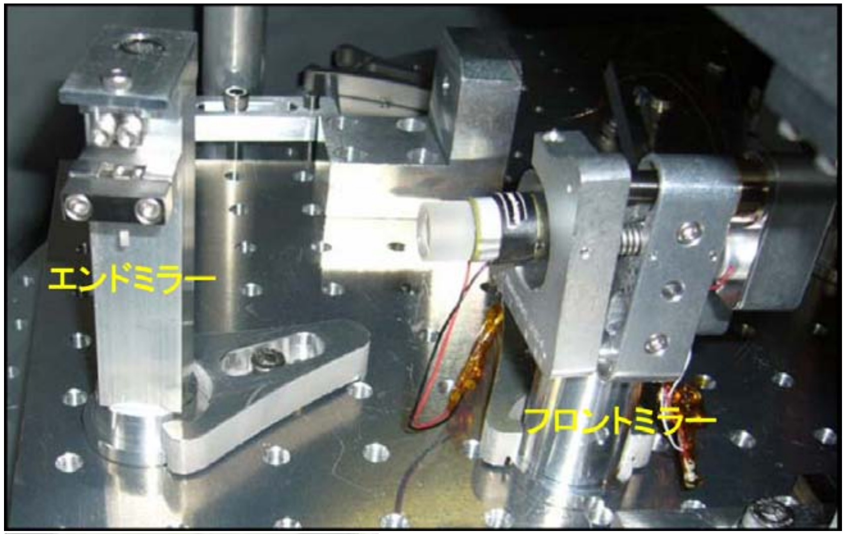
optical configuration

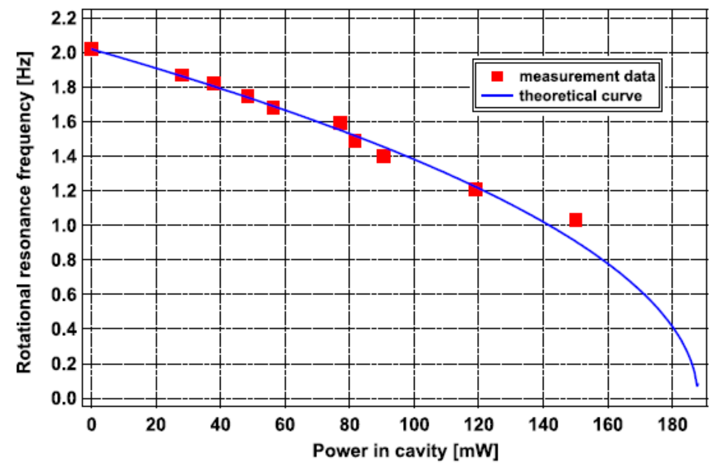


Fabry-Perot (FP) cavity

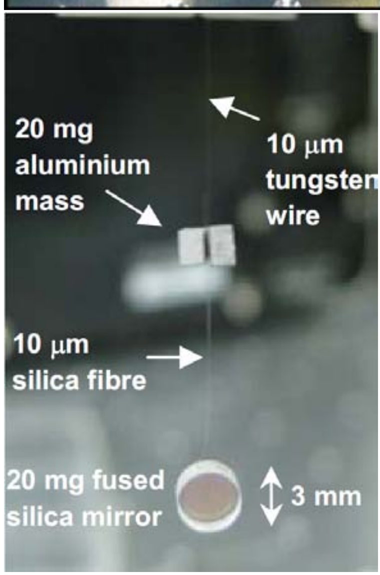
Previous results

One Fabry-Perot cavity experiment





S. Sakata et al., PRD 81, 064023 (2010)



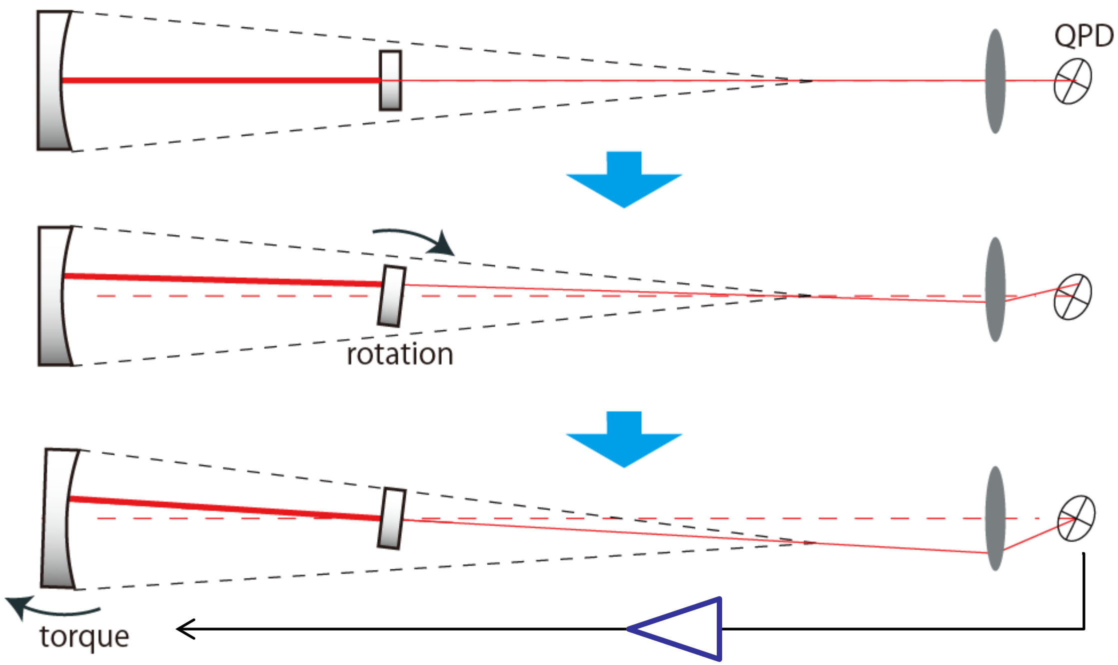
At high power, angular anti-spring effect caused by radiation pressure destroys the stability

- ♦Radiation pressure actuates the torsion mode of small mirror
- ♦Radiation pressure acts as angular anti-spring

=> In order to reach the designed intra-cavity power, an angular control is needed.

Opto-mechanical angular control

How to control a small mirror using radiation pressure



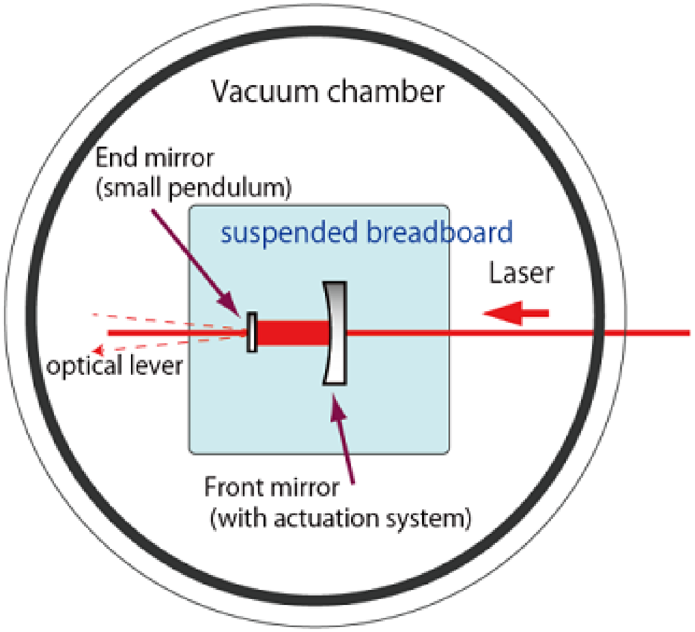
Optical axis is shifted
=> anti-spring instability

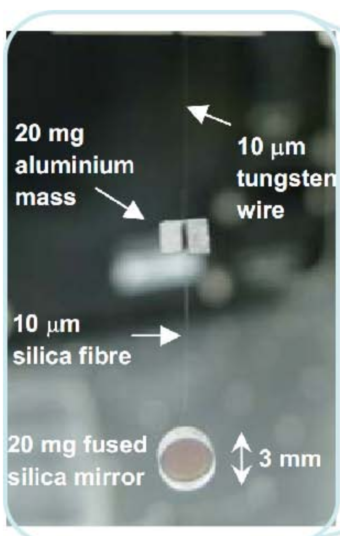
Control using front mirror

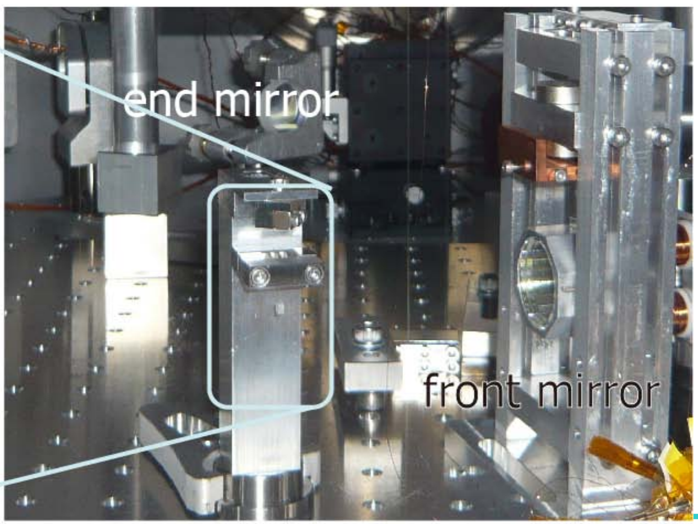
- Beam position on the end mirror is kept center of the mirror, by controlling the front mirror in angular direction.
- Motion of the end mirror is coupled with that of the front mirror through radiation pressure

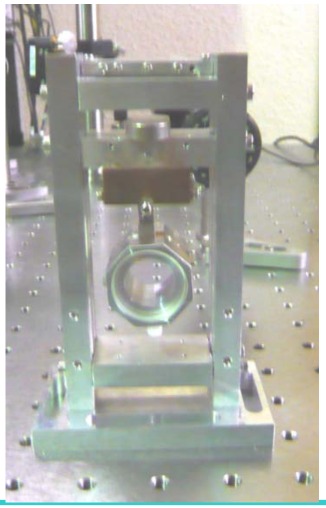
Experimental setup

- Vacuum, Suspended table
- End mirror: Tiny mirror
- Front mirror: 1-inch mirror suspended by double pendulum
- Length of cavity: 80mm
- Monitoring motion of tiny mirror: Optical lever
- Angular control: Yaw direction

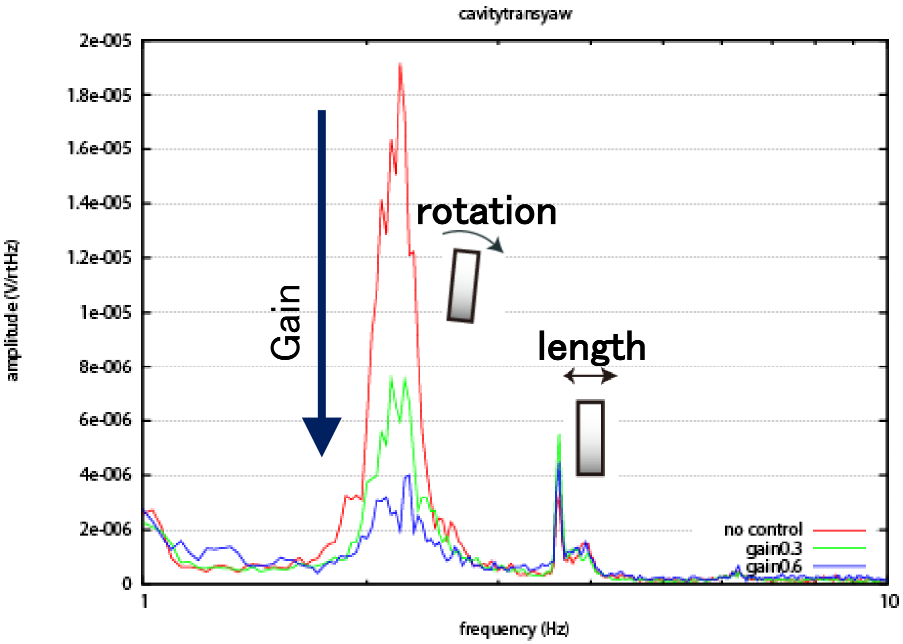






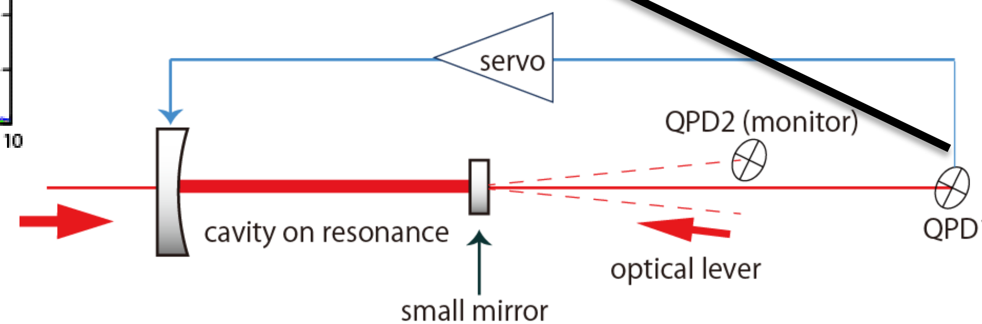


Angler control demonstration



Transmitted-light position:

Error signal

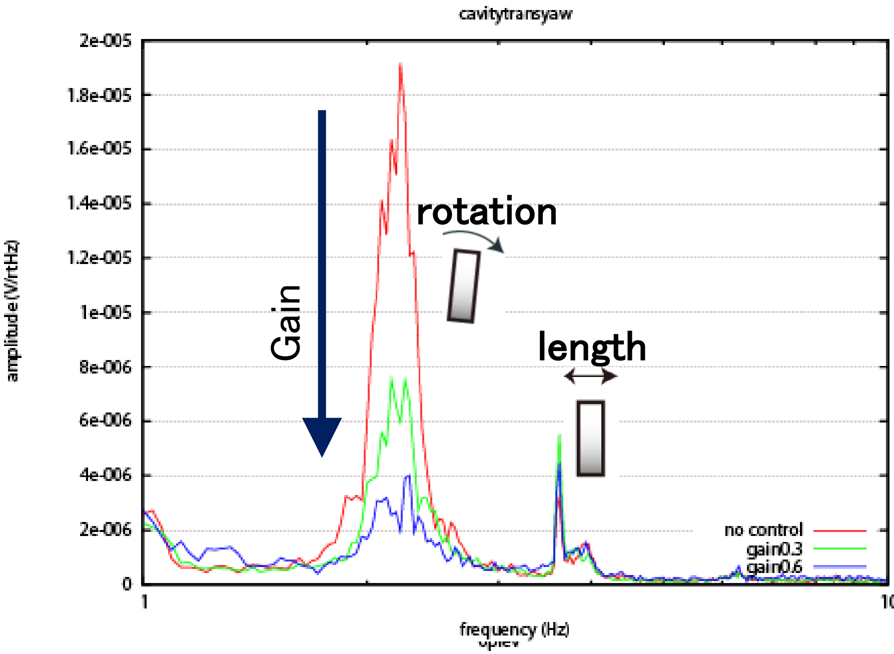


QPD: quadrant photo diode

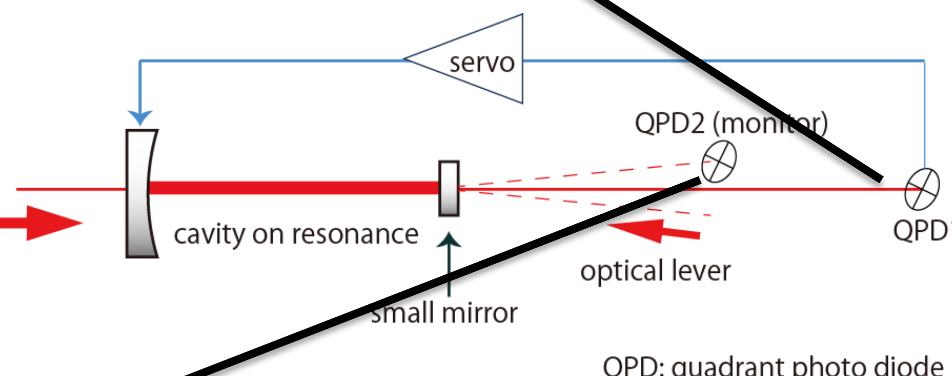
- Control is achieved
- As control gain is increased, angular motion is suppressed
- Shift of resonance frequency is not confirmed yet.

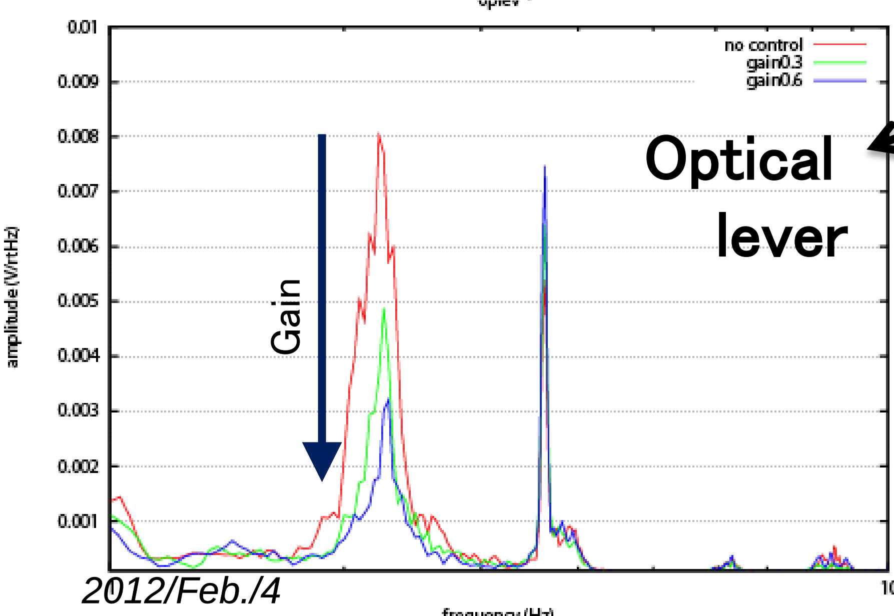
(T. Mori, doctor thesis)

Angler control demonstration



Error signal





Optical lever

Out-of-loop confirmation

- Local sensor (optical lever) signal also indicates suppression of angular motion

(T. Mori, doctor thesis)

summary

Recent product

- Opto-mechanical angular control is achieved in Yaw direction.

Next step

- Confirmation of increase of intra-cavity power by angular control.
- Alignment control noise measurement.
  (estimation is already done by Dr. Sakata)
- Pitch motion control
- Frequency stabilization

Quantum efficiency measurement

Quantum efficiency measurement

Background

♦Squeezing level will be limited by the quantum efficiency(QE) of a photodiode(PD).

♦The accuracy of QE measurement is limited by the accuracy of the incident laser power.

Objectives

♦Measure the quantum efficiency of PD within 1% accuracy

♦It correspond to make power meter with high accuracy

=> contribute to estimate an accurate squeezing level

Method

♦Michelson interferometer with a tiny mirror

=> Tiny mirror is sensitive for changing input power
(Application of the tiny mirror in RPN measurement)

=> Accurate measurement of the laser power (i.e. number of photon)

=> We can get an accurate quantum efficiency of a PD

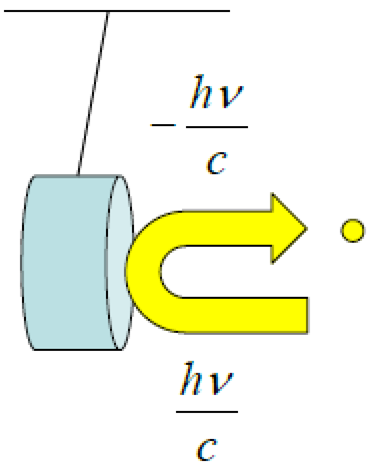
Theory

$$QE = \frac{N_e}{N_p}$$

Fine measurement of N_p lead to a high accuracy of QE.

<< Notation >>
h: Planck constant
N_P: Number of photons in input light
m: Mass of small mirror
c: Speed of light
ν: Laser frequency
ω: Frequency of the intensity modulation
ϕ: Angle of the incident laser to mirror
QE = Quantum Efficiency
(Efficiency to convert light power to current)
N_e: Number of electrons in output current of PD

One photon



Equation of motion

(Mechanical response)

$$m\ddot{x} = \frac{2h\nu}{c}$$

$$\rightarrow d\tilde{X} = -\frac{2h\nu N_P}{m\omega^2 c} \cdots (1)$$

$$N_p = \frac{P}{h * \nu}$$

Response of Michelson IFO (Optical response)

$$d\tilde{X} = \frac{\lambda}{2\pi V_0} dV_{PD} \cdots (2)$$

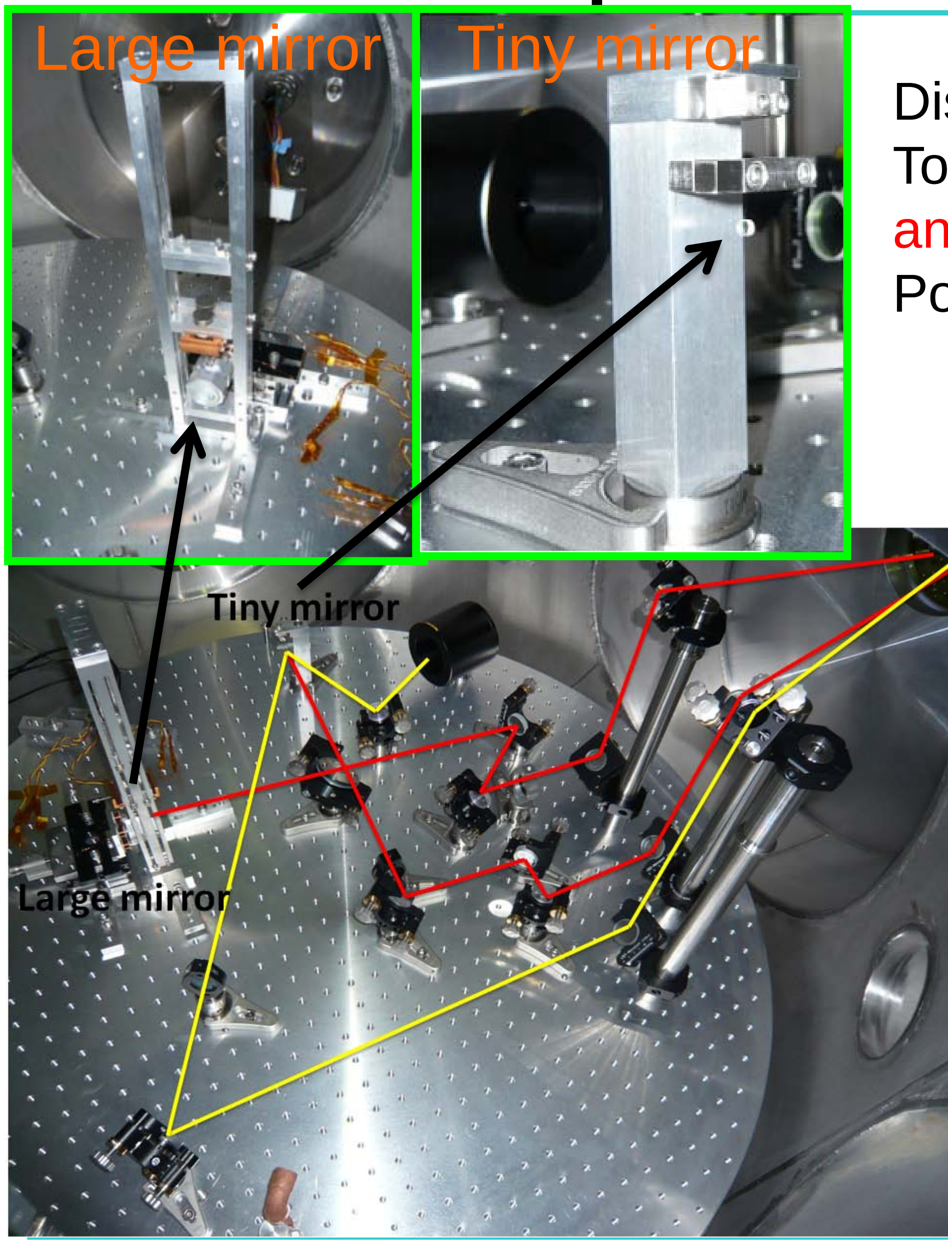
(1) + (2) = opto-mechanical response through radiation pressure

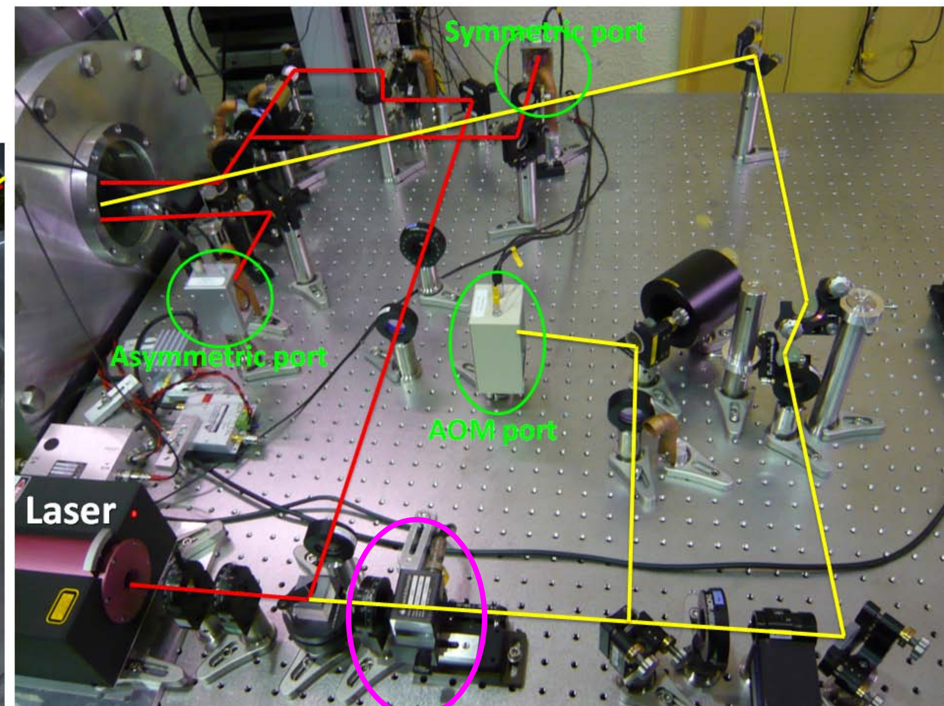
$$dP = \frac{m * c * \omega^2 * \lambda}{4 * \pi * V_o} * dV_{PD}$$

An opto-mechanical response makes a new kind of power meter

Experimental setup

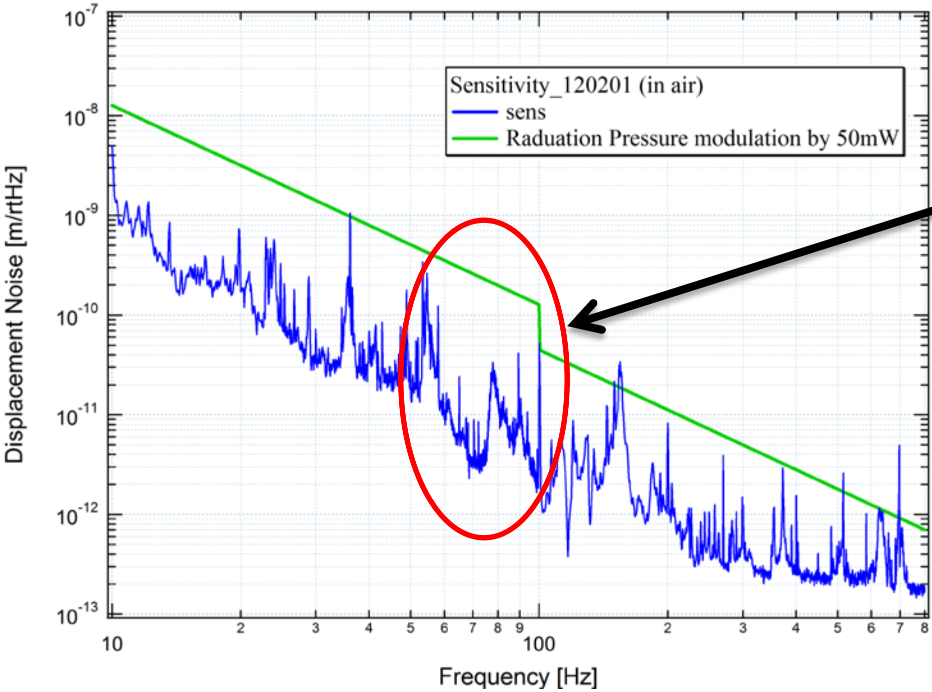
Displacement sensor: Michelson IFO
Tow path: for shaking mirror (Yellow line) and for MI (Red line)
Power modulation: AOM





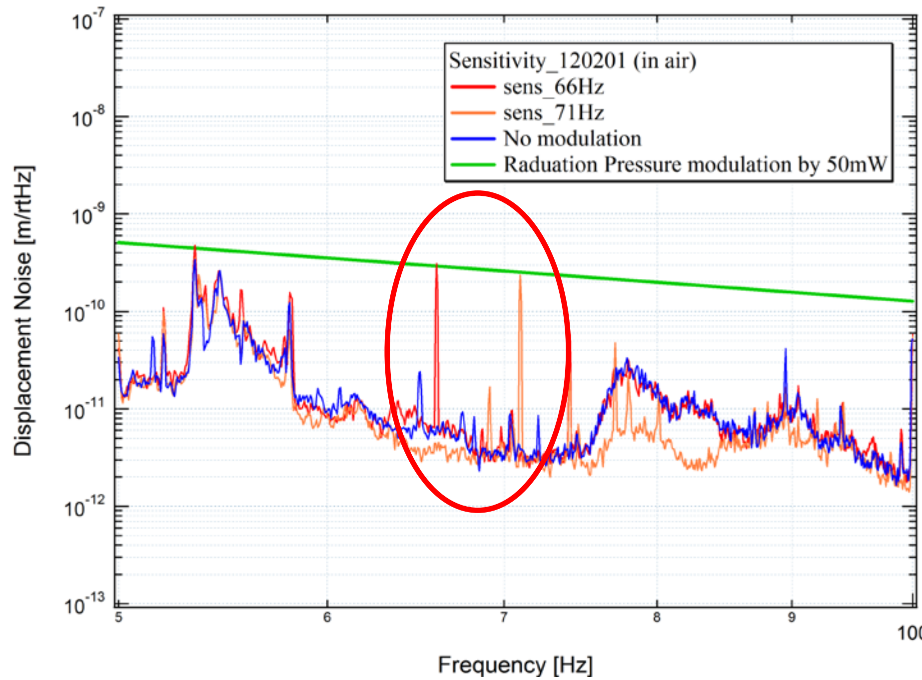
AOM

Displacement by shaken radiation pressure



Suitable region for measurement

When I shake the laser power using AOM at 66Hz and 71Hz



Large amplitude of displacement comparing with floor noise is observed

=> It corresponds to 50mW shaking

Error contribution

Detailed formula of the laser power is

$$P = \frac{c\lambda}{4\pi H_m V_{pp} \alpha_\mathrm{m} \cos\phi} G_\mathrm{CL} \cdot T_{AH} \cdot V_f. \tag{4}$$

The propagation low of error (the standard deviation) is expressed as

$$\sigma_F = \sqrt{\sum_{j=1}^{s} \left(\frac{\partial F}{\partial X_j} \sigma_j \right)^2} \tag{5}$$

Using this equation and Eq.(4), the error of power is written as

$$\frac{\sigma_P}{P} = \sqrt{\left(\frac{\sigma_G}{G_\mathrm{CL}}\right)^2 + \left(\frac{\sigma_T}{T_{AH}}\right)^2 + \left(\frac{\sigma_{V_f}}{V_f}\right)^2 + \left(\frac{\sigma_H}{H_m}\right)^2 + \left(\frac{\sigma_{V_{pp}}}{V_{pp}}\right)^2 + \left(\frac{\sigma_\alpha}{\alpha_\mathrm{m}}\right)^2 + (\sigma_\phi \cdot \tan\phi)^2} \tag{6}$$

1%

~0.3%
(inside round bracket)

Error estimations are in progress.
The details will be talked in JPS on Mar. and GWADW on May.

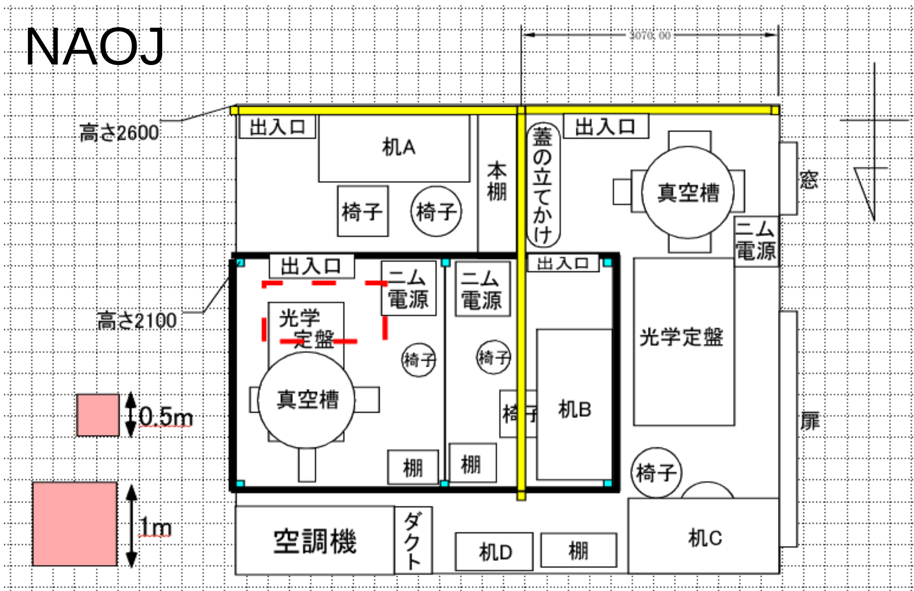
Misc.

Member

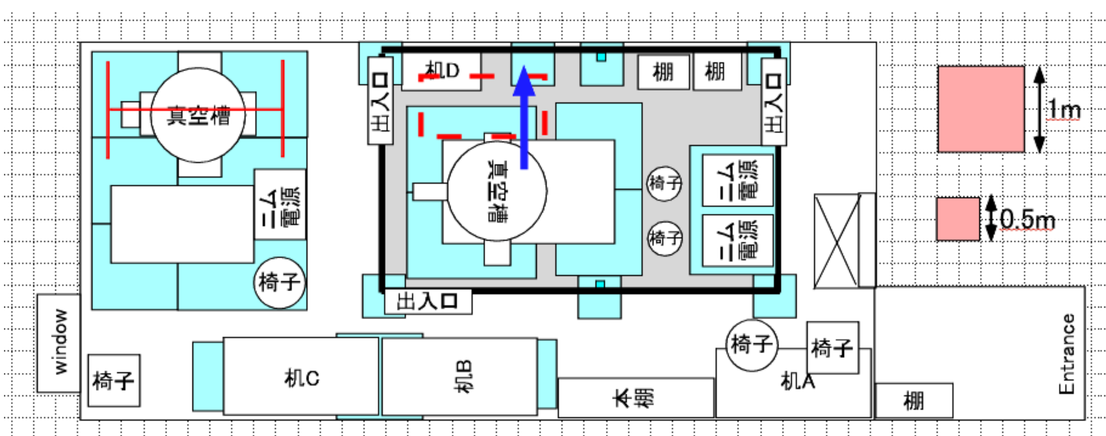
- Prof. Kawamura transferred from NAOJ to ICRR
- Dr. T.Mori will transfer to a company by the next Apr.
- Dr. Daniel Friedrich has joined us.

(from Dec. in the last year)

Move lab. from NAOJ to ICRR



- Moving date
  27/Feb.--1/Mar.



The next building of ICRR

We continue to study RPN measurement in Kashiwa campus.

Summary

R&D for KAGRA

●Radiation pressure noise measurement

- Opto-mechanical angular control is achieved in Yaw direction

●Quantum efficiency measurement

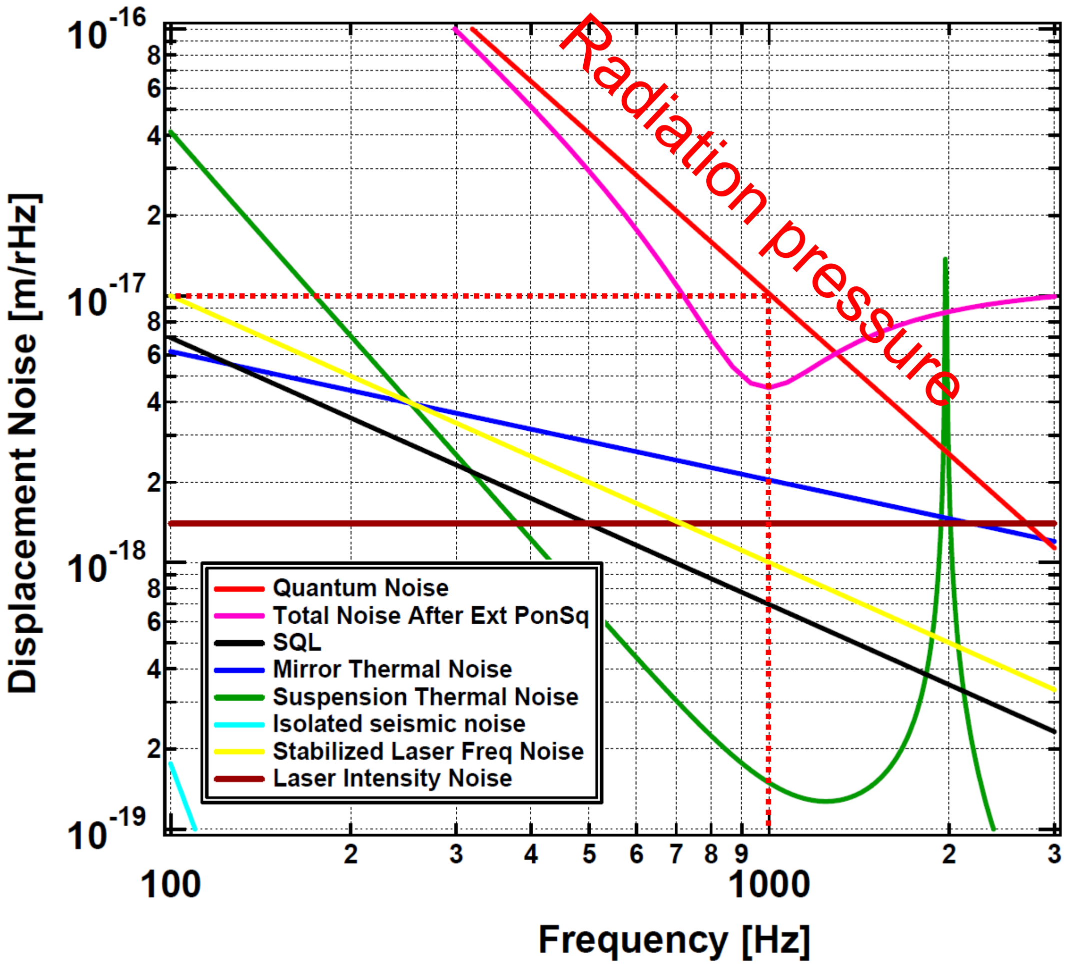
- Power measurement using radiation pressure is in progress.

●Misc

- Daniel has joined us.
- Move lab. from NAOJ to ICRR between 27/Feb. and 1/Mar.

Supplement slide

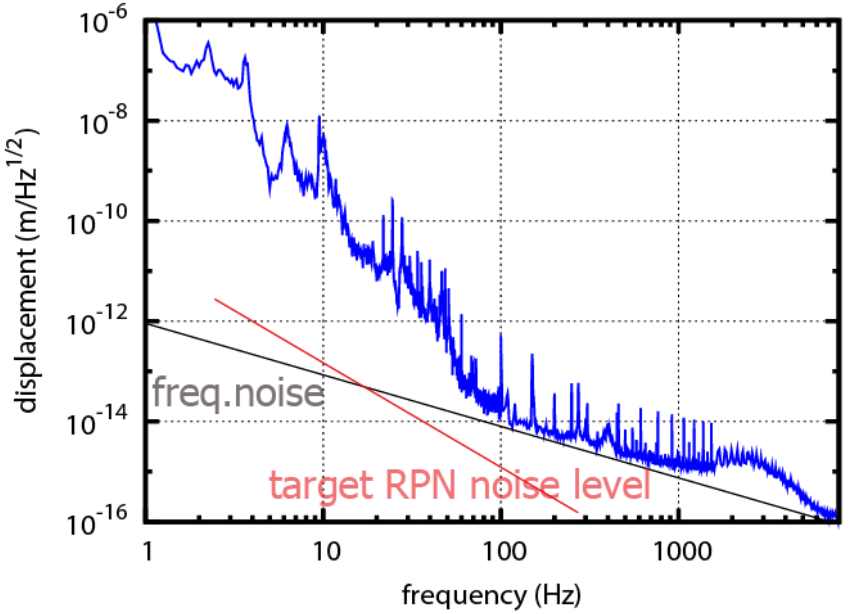
Design sensitivity



Laser power	200 mW
Injected laser power	120 mW
Finesse	10000
End mirror mass	20 mg
Diameter of end mirror	3 mm
Thickness of end mirror	1.5 mm
Front mirror mass	14 g
Reflectivity of end mirror	99.999 %
Reflectivity of front mirror	99.94 %
Optical loss	50 ppm
Beam waist of end mirror	340 μm
Mechanical loss of substrate	10^{-5}
Mechanical loss of coating	4×10^{-4}
Length of silica fiber	1 cm
Diameter of silica fiber	10 μm

Current sensitivity

- Sensitivity of interferometer obtained from voltage applied to coil to control the interferometer
- toward target RPN noise level,
  - ~10 times worse @ 100Hz
  - ~100 times worse @ 1kHz



- (classical) frequency noise of laser was dominating
  - Frequency stabilization needed
- Low laser power