Development and application of cryogenic displacement sensors towards the damping control of KAGRA cryogenic payload

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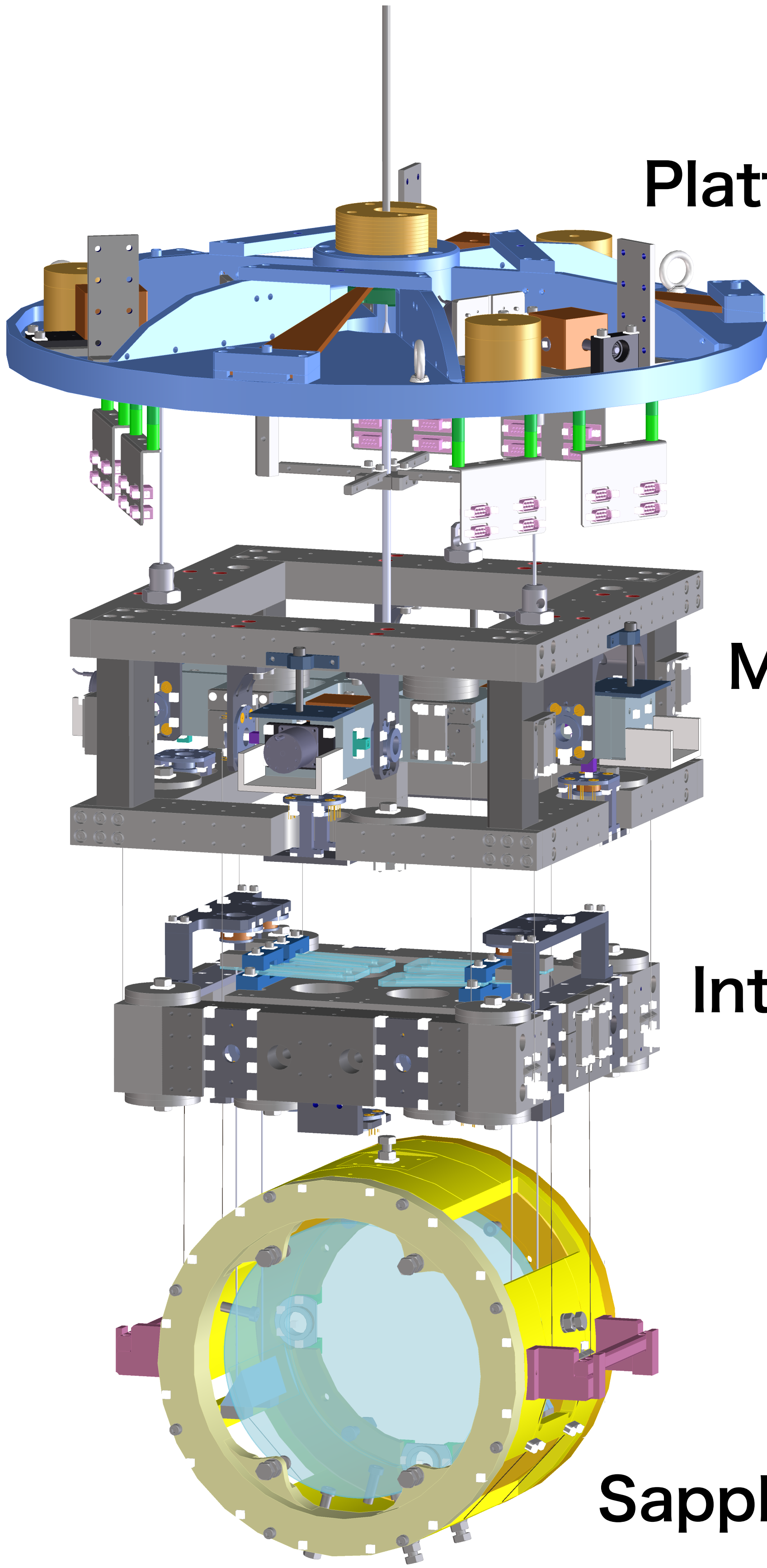
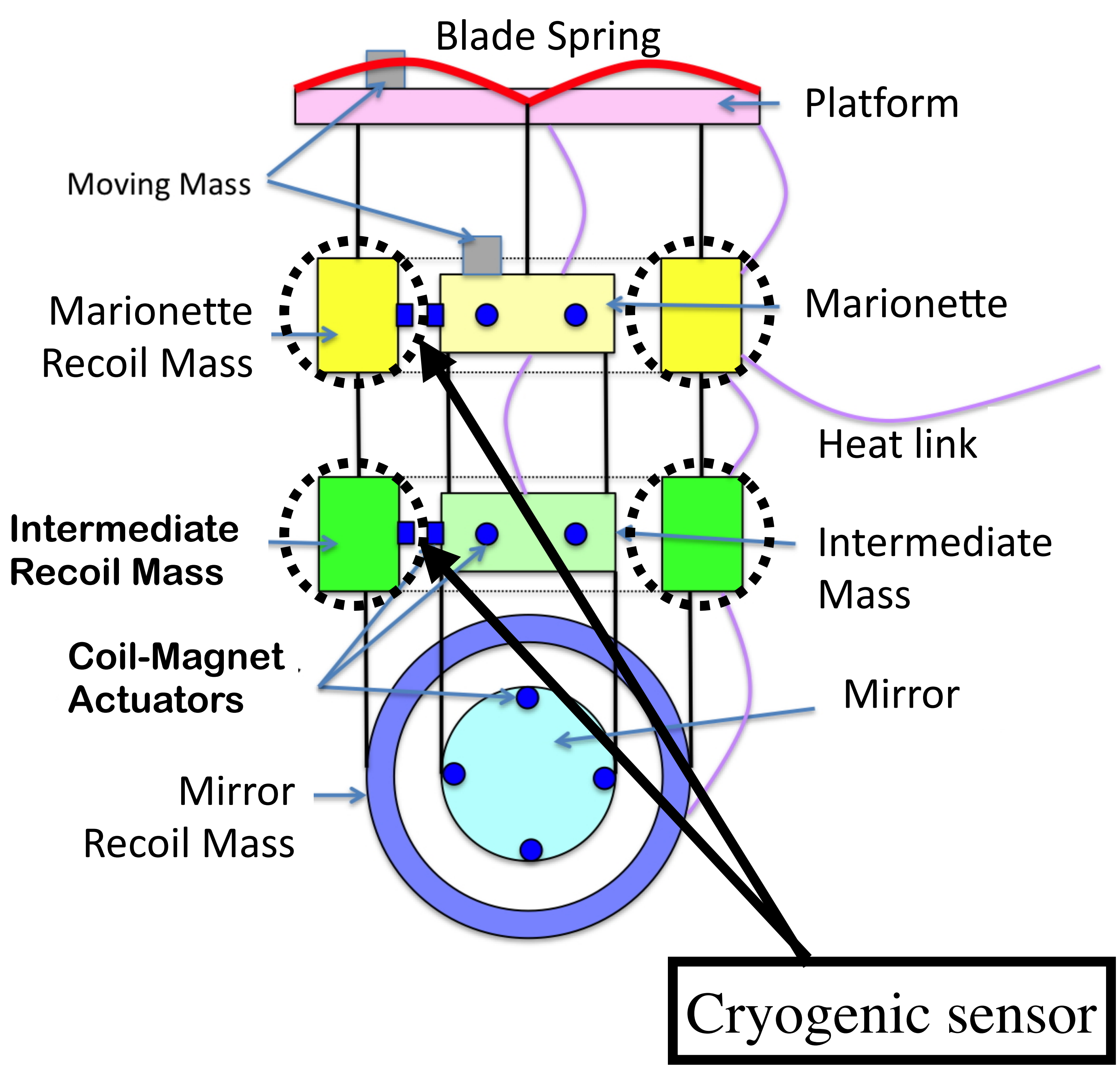
Back ground



- KAGRA has the mirror cooled down to 20 K.
- A mirror suspension cooled down to 20 K is called cryogenic payload.
- Cryogenic payload has a main chain and a recoil mass chain.
- The recoil mass chain is installed to reduce the vibration the main chain through the heat link.
- The damping control is necessary.

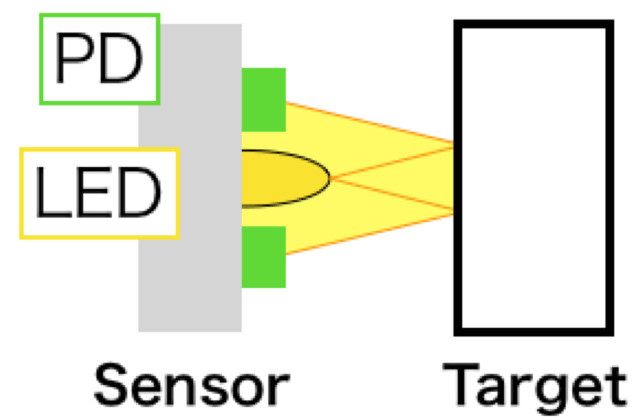
Cryogenic payload



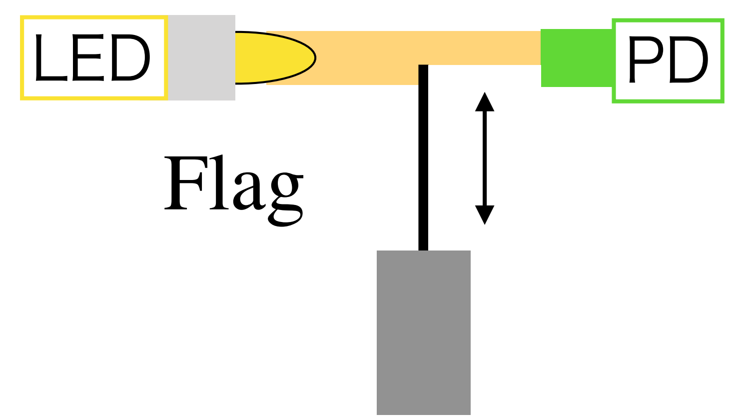
- The cryogenic payload has the feature to damp the resonance and to align the mirror.
- The moving mass is used for the mirror alignment.
- The sensor and the actuator is used for the damping control.
- The damping control consists of the feedback system.
- We need to develop the cryogenic sensor.

Suggested cryogenic sensor

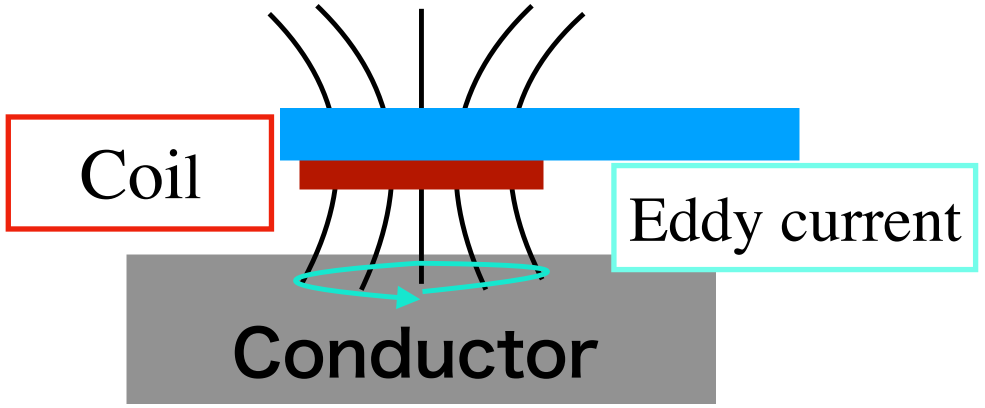
- Reflective photo sensor
 - Monitoring the change of the amount of reflective light as the displacement.



- Shadow sensor : OSEM
 - Monitoring the change of the light blocked by the flag as the displacement.



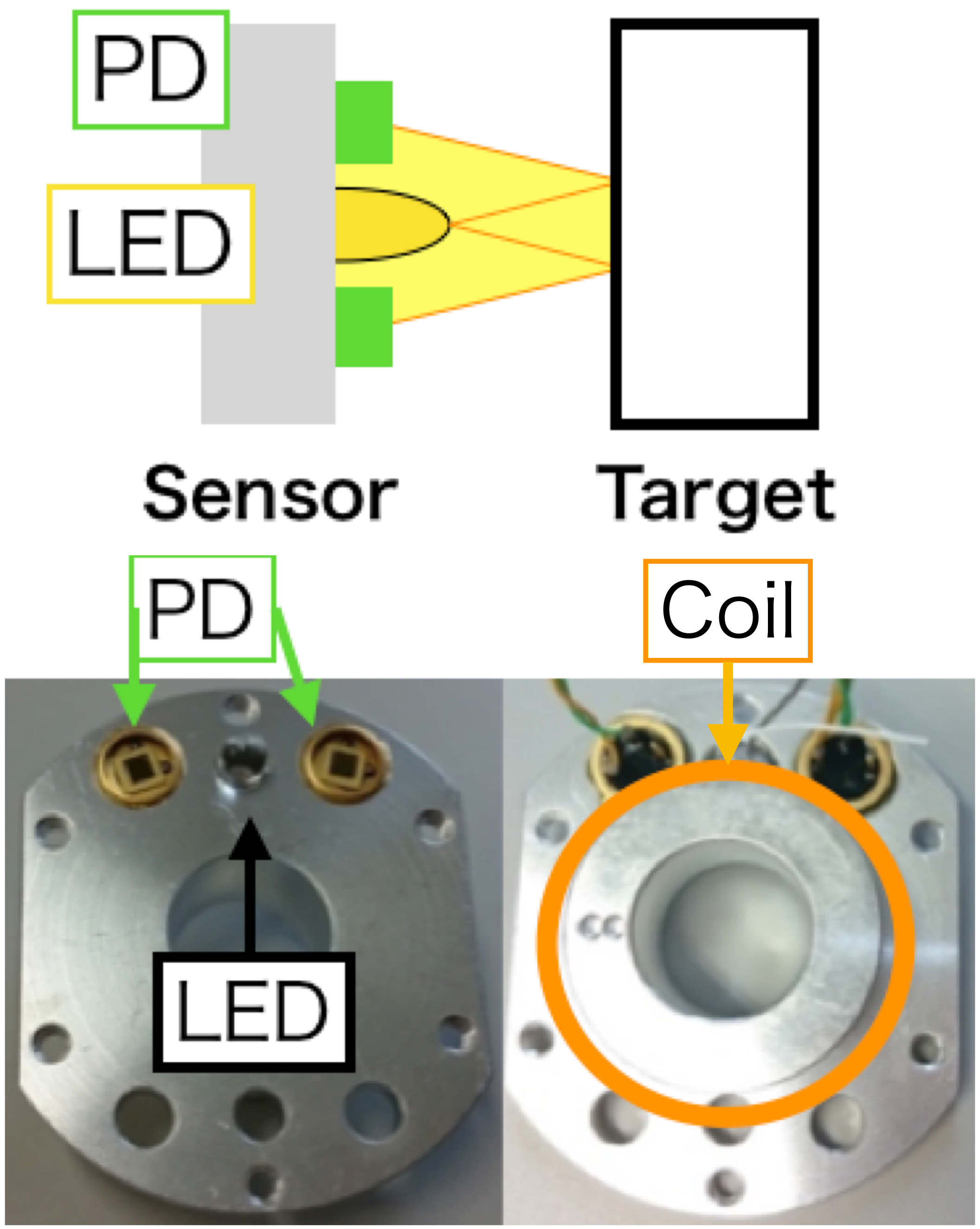
- Eddy current sensor
 - Monitoring the change of the resonance frequency of the circuit by the eddy current as the displacement.

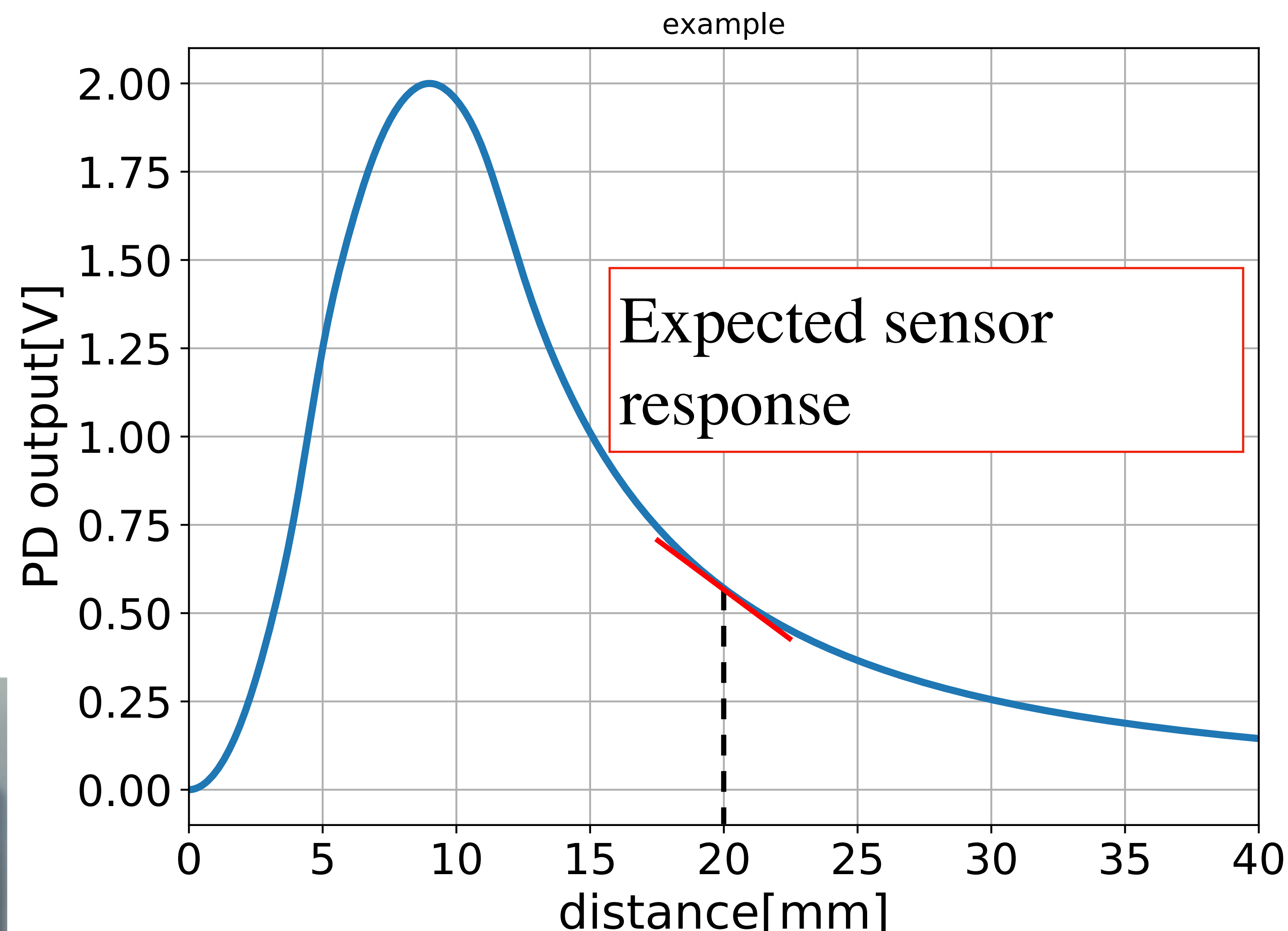


Cryogenic displacement sensor

KAGRA adopts the reflective photo sensor as the cryogenic displacement sensor.

- Wide dynamic range
- Thermal contraction





LED:LED1200E(Thorlabs)
PD:FGA21(Thorlabs)

InGaAs

Contents

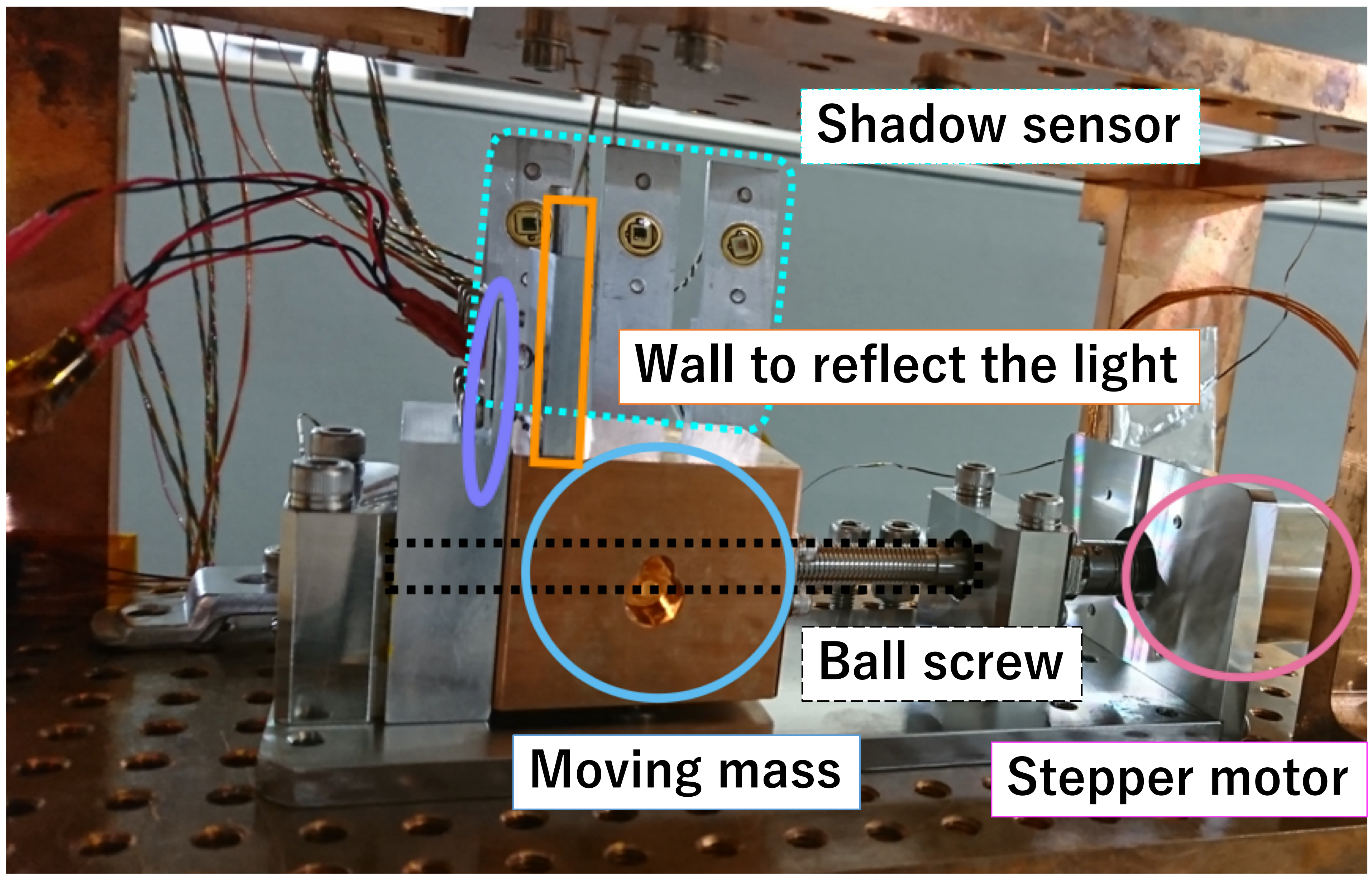
Setup of calibration

To establish the relationship between the reflective light and the relative distance.

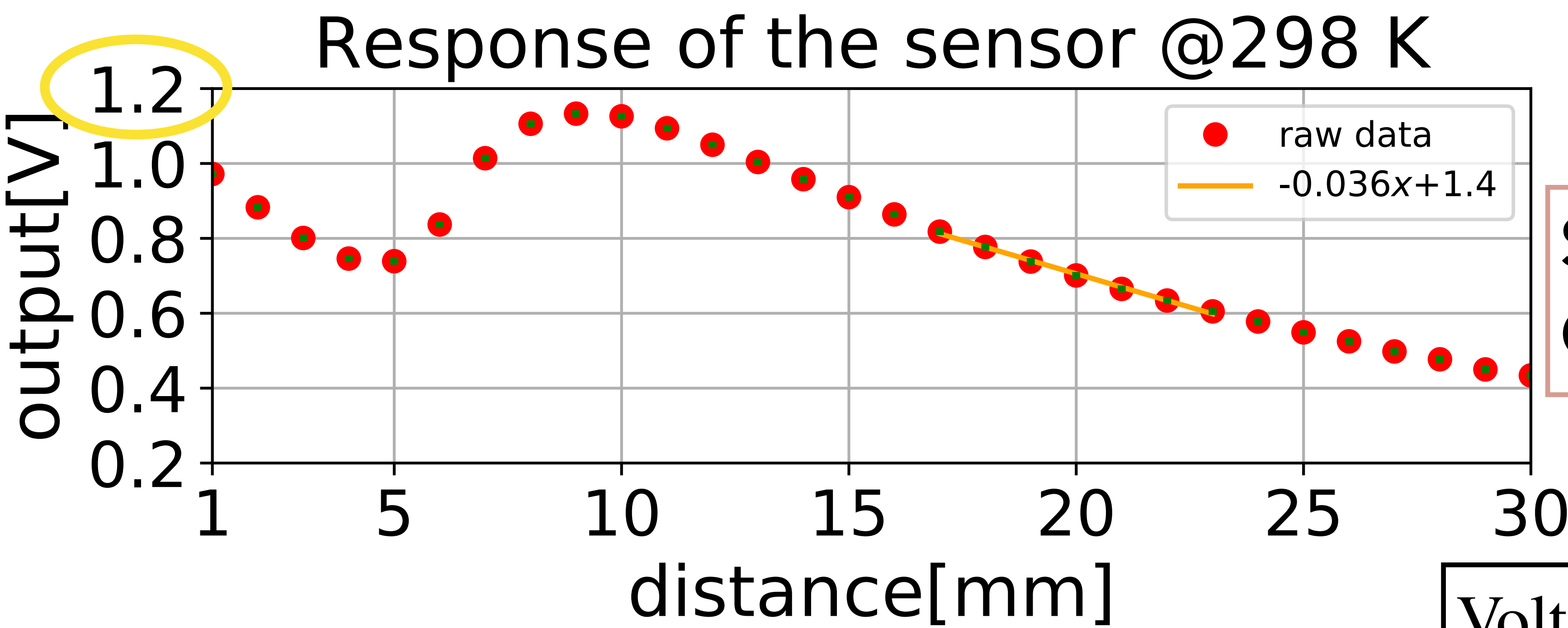
We calculated the distance shift of the moving mass by counting number of pulses sent to the stepper motor.

Ball screw system
- Ball screw
- Stepper motor
- Moving mass

LED & PDs

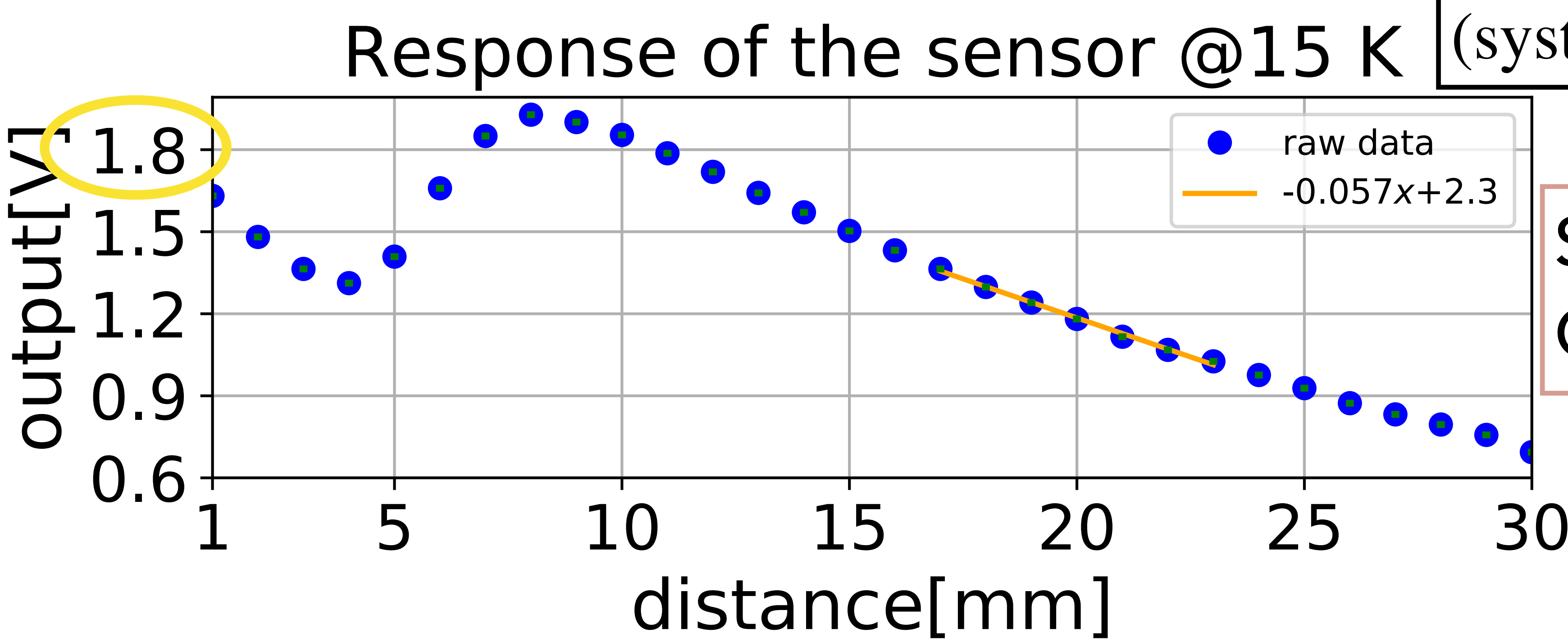


Results of calibration



Slope~ -0.036 ± 0.001 V/mm
Output(@20 mm) : 0.701 V

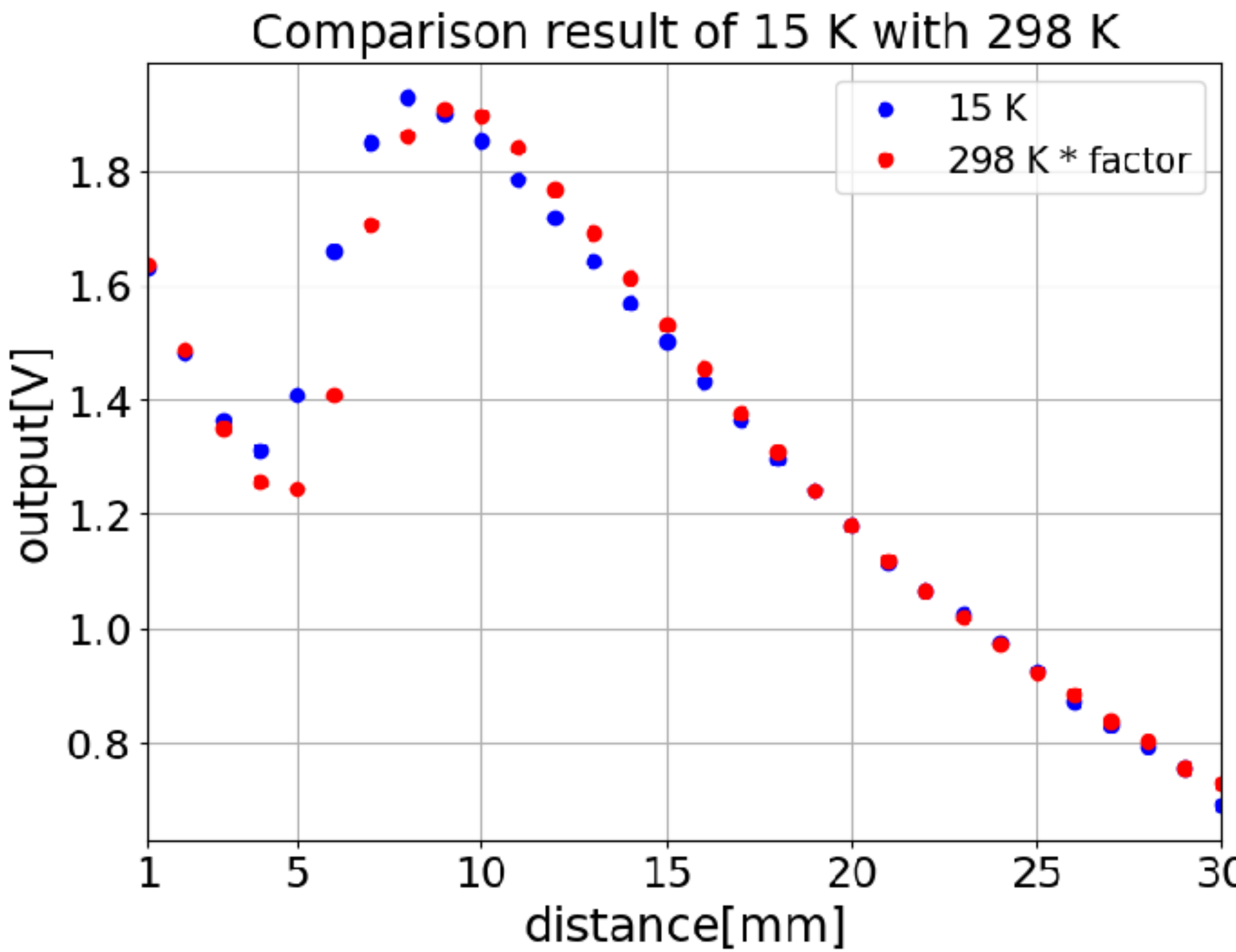
Voltage error ±2 mV (statistical)
Maximum distance error ± 0.05 mm (systematic)



Slope~ -0.057 ± 0.001 V/mm
Output(@20 mm) : 1.181 V

The sensor has the enough wide linear range for KAGRA.

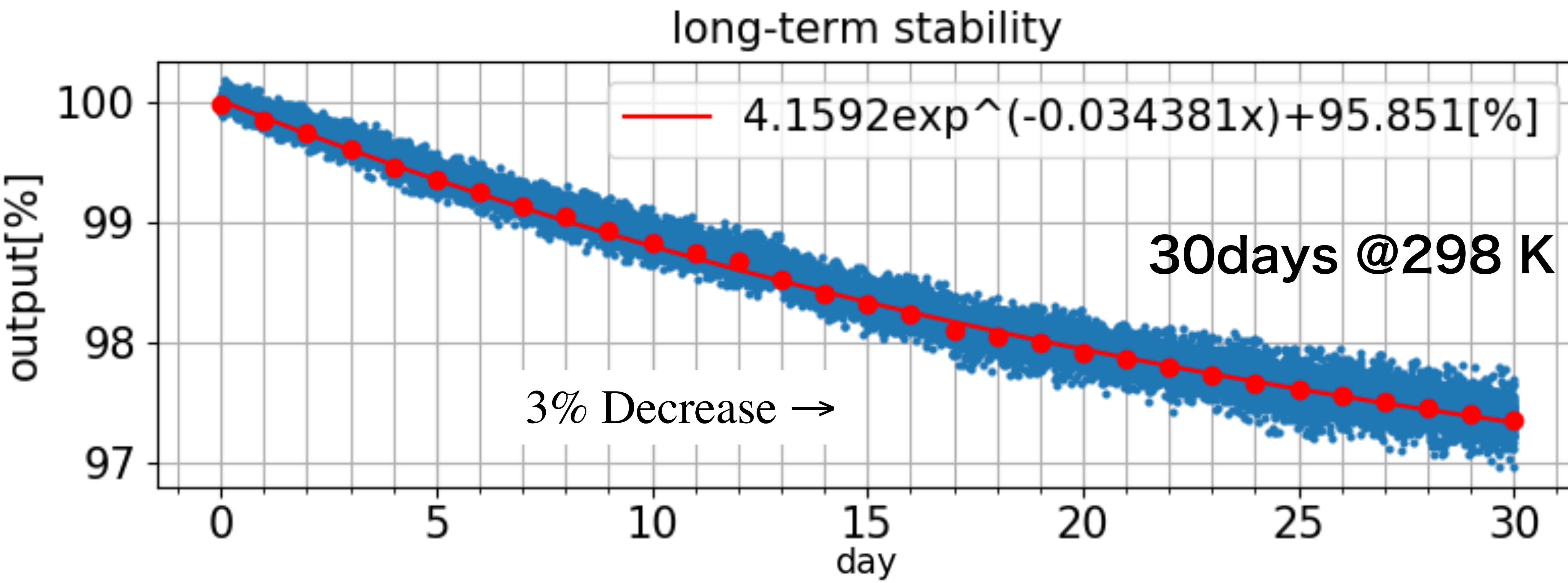
Temperature dependence of sensor response



Factor ~ 1.7

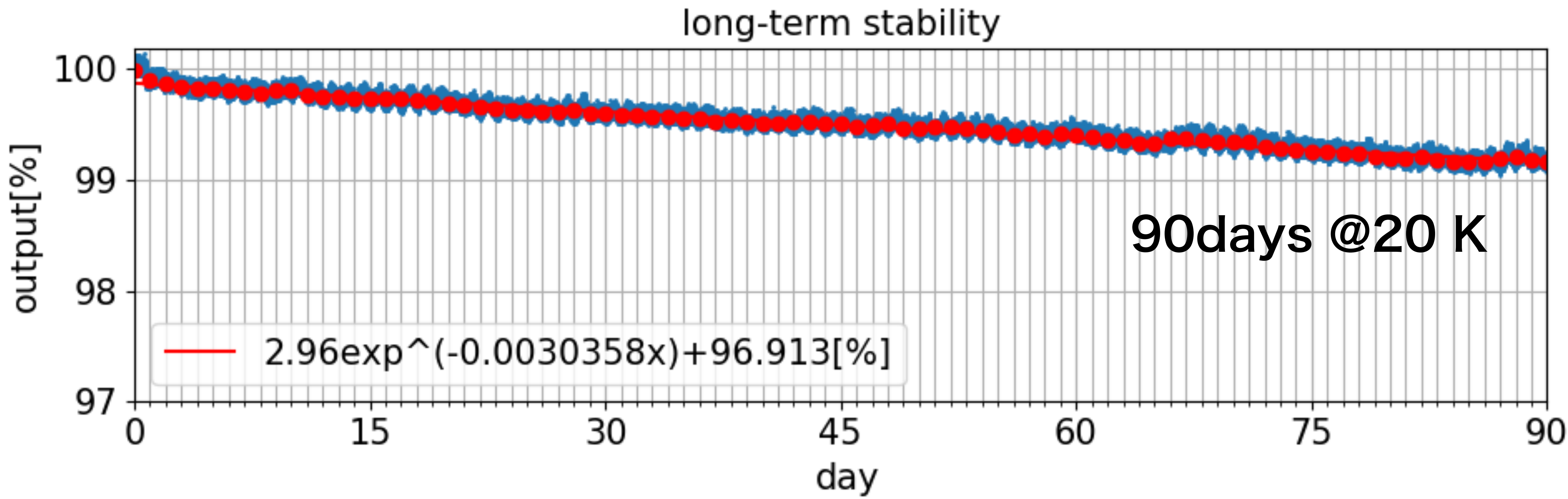
The sensor response at cryogenic temperature is proportional to that at room temperature.
→ We can estimate the response at cryogenic temperature from that at room temperature.

Long-term stability at 298 K



- We continued measuring the sensor output, fixed the target position at 20 mm.
- We removed the temperature fluctuation from the data.

Long-term stability at 20 K

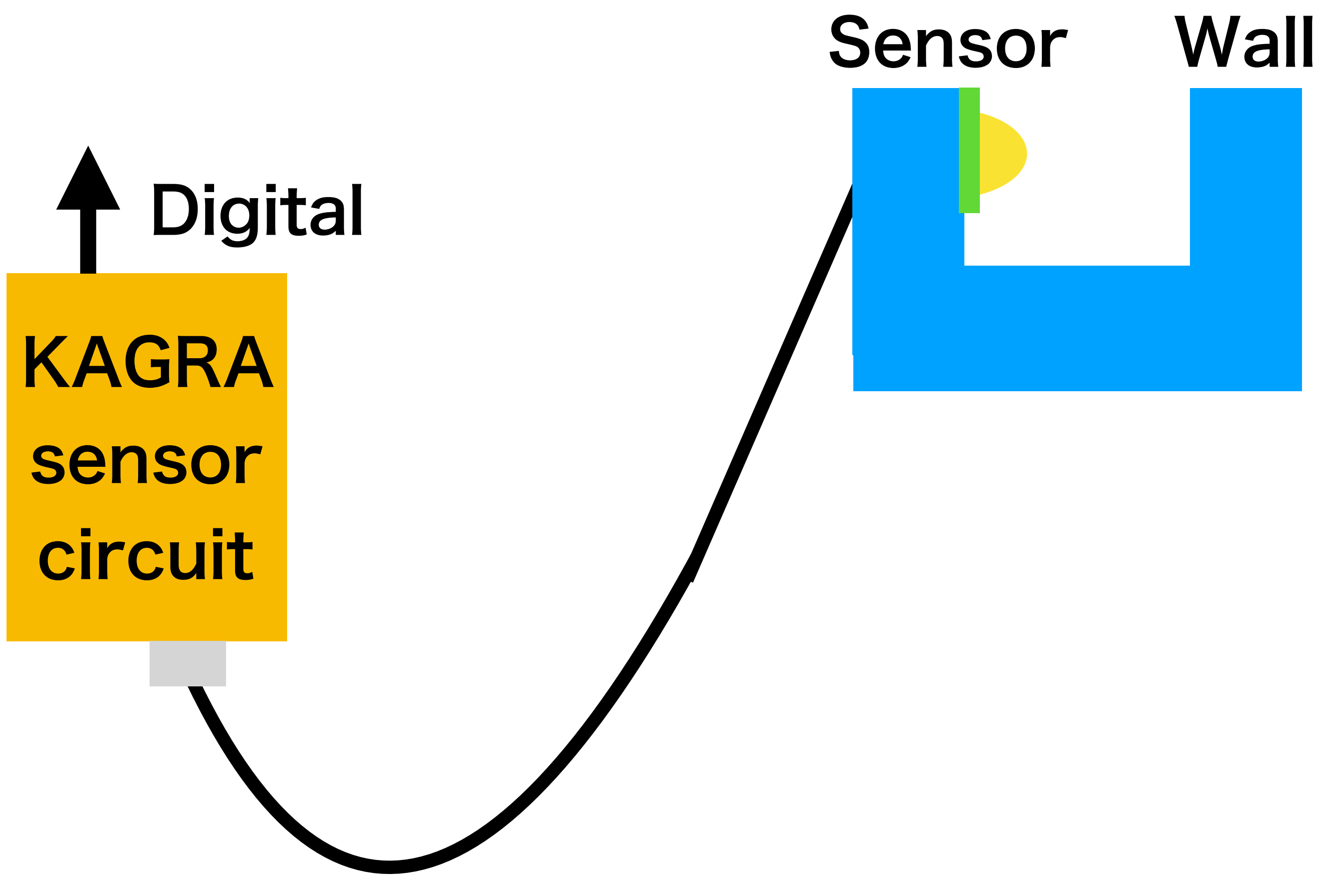


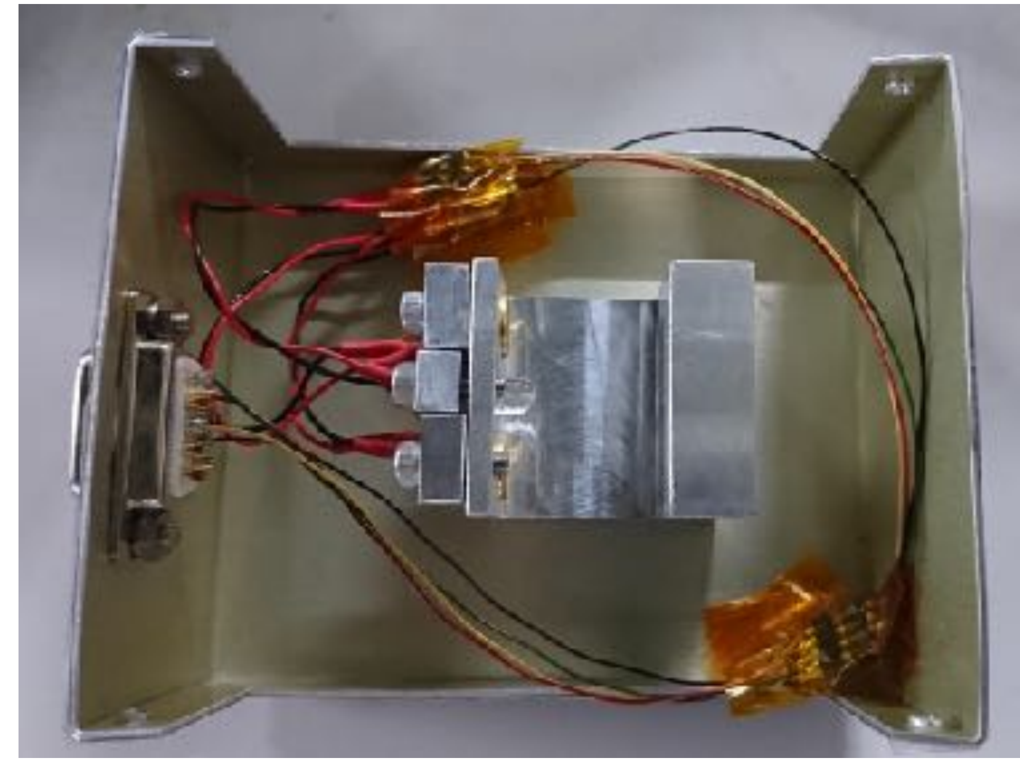
- We evaluated the long-term stability at cryogenic temperature.
- We kept the sensor temperature at 20 K with a heater.

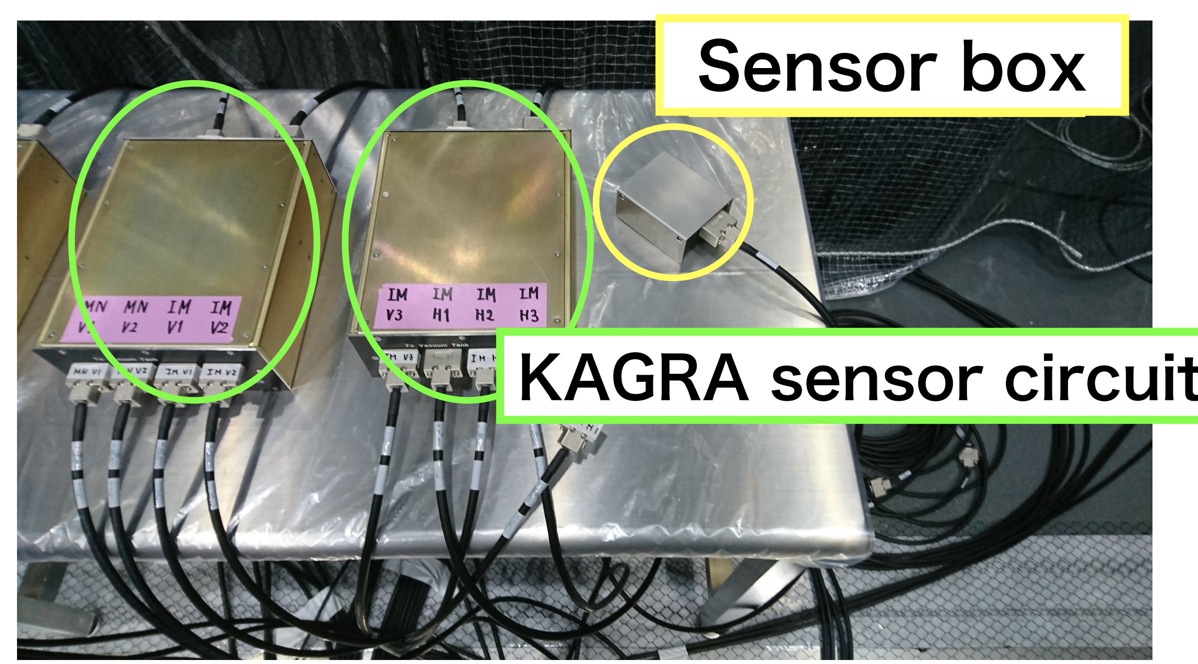
It only changed by about 0.8% even if it is used for 3 months at 20 K.

Contents

Noise measurement of KAGRA circuit







- We made the setup to measure the noise of the sensor.
- We measured the KAGRA circuit noise.

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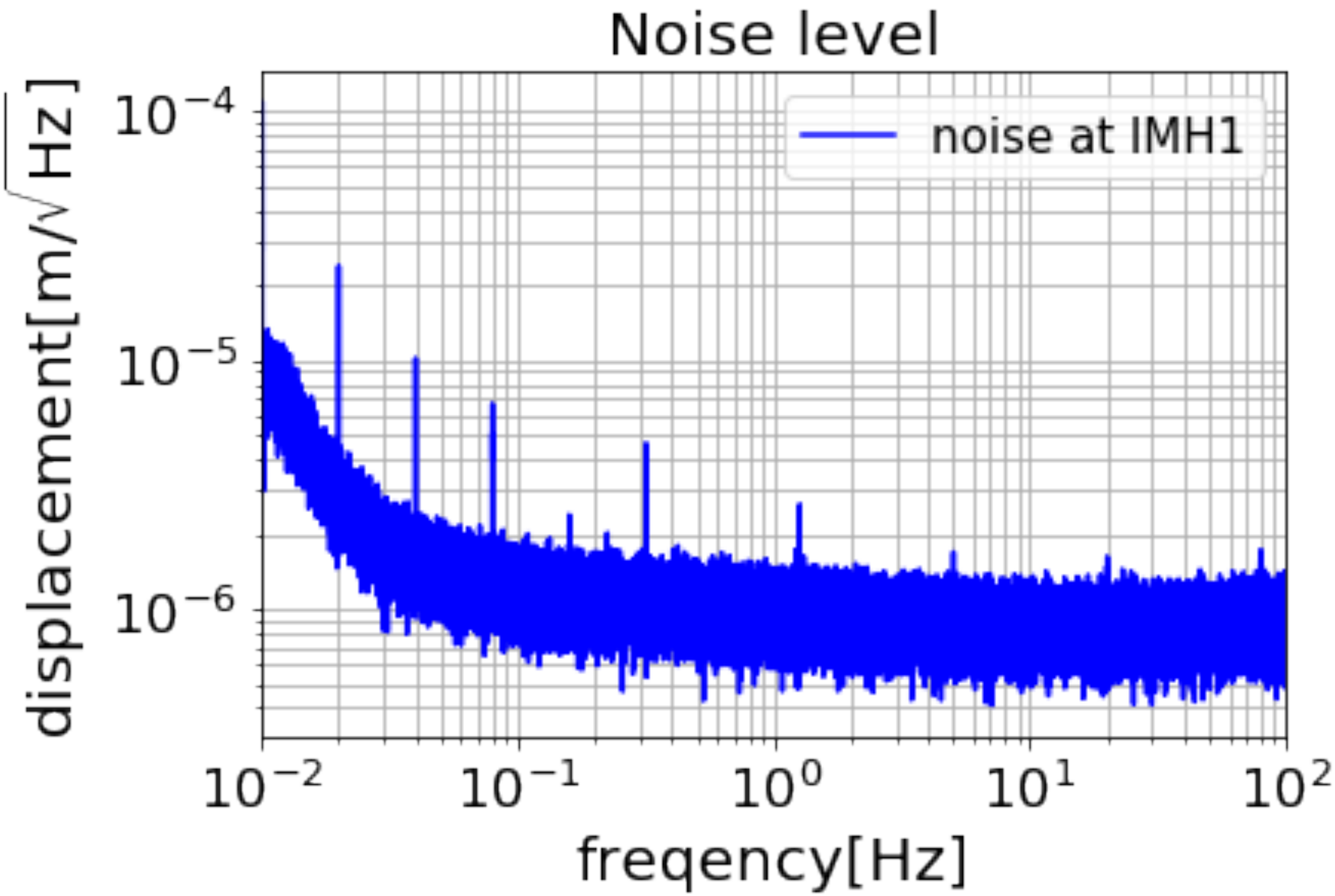
Evaluation of sensor noise level

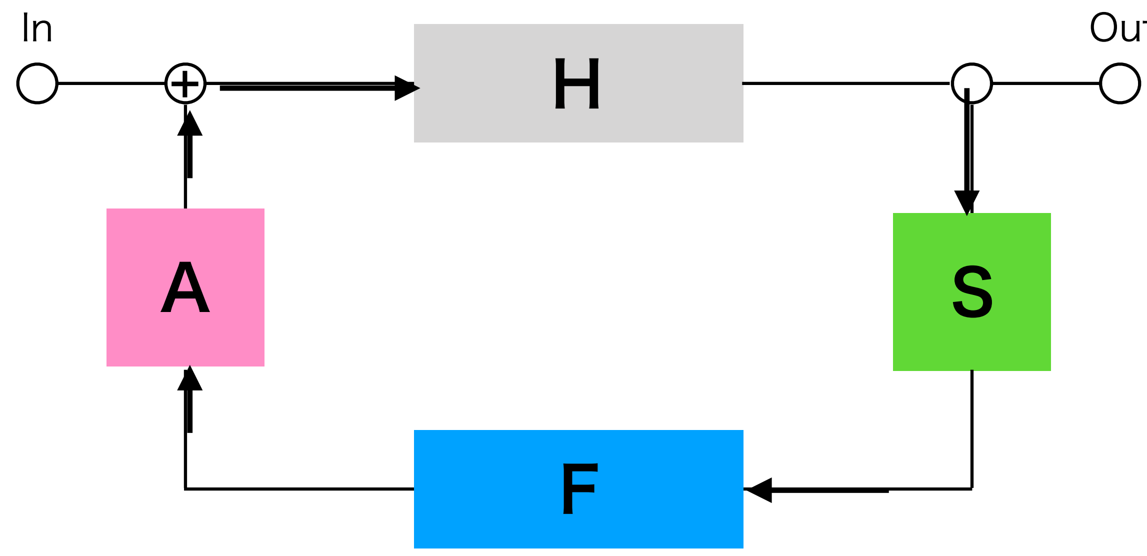


- We measured the noise at room temperature.
- In the frequency band 0.1 Hz to 100 Hz, the noise is 10^{-6} m/√Hz.

Contents

Damping filter

- The cryogenic displacement sensor is applied the damping control.
- Constitute the feedback system.
- Sensor noise feedback to the cryogenic payload.



H : suspension, S : sensor
F : filter, A : actuator

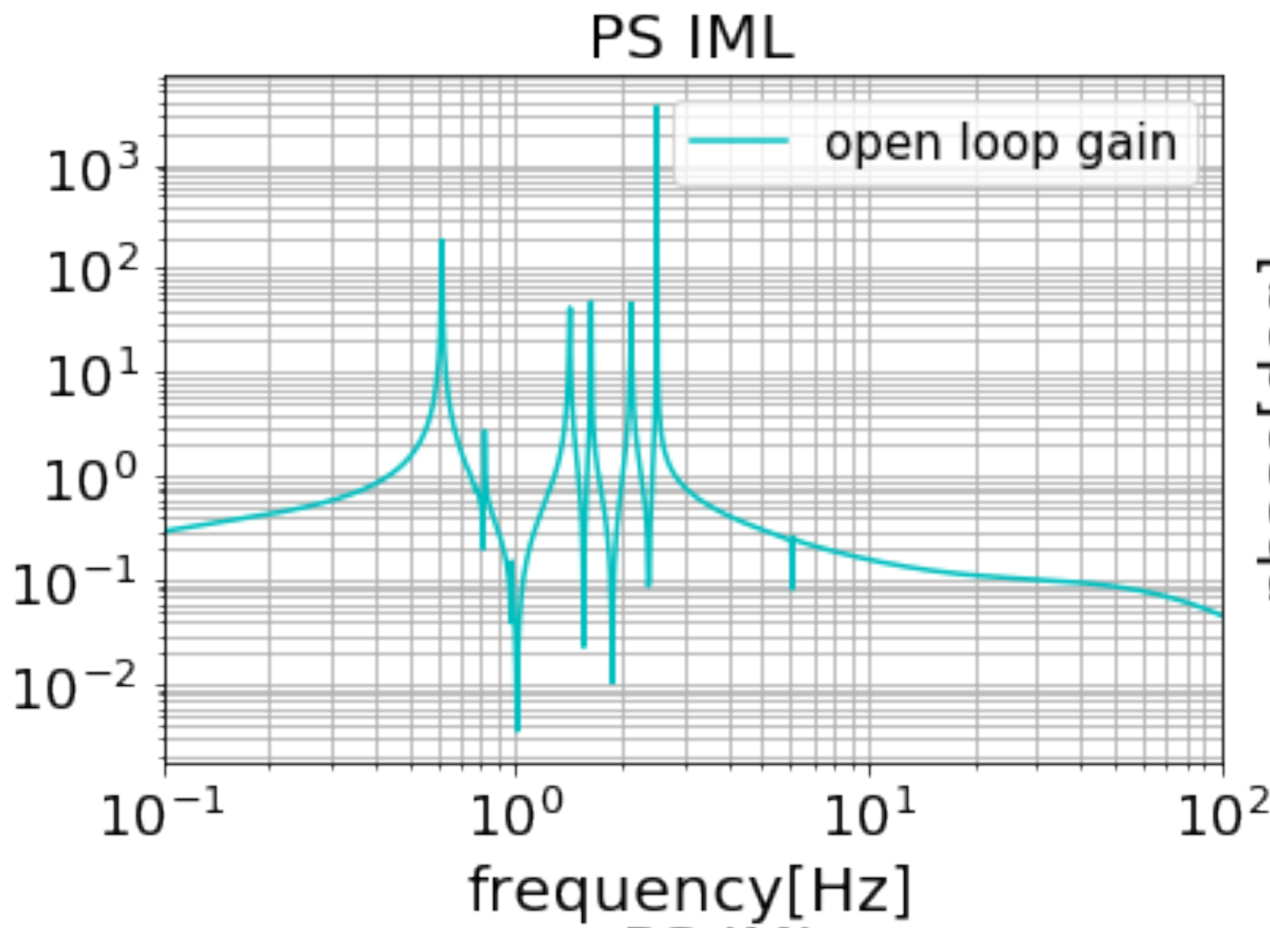
We use two types of damping control filter.

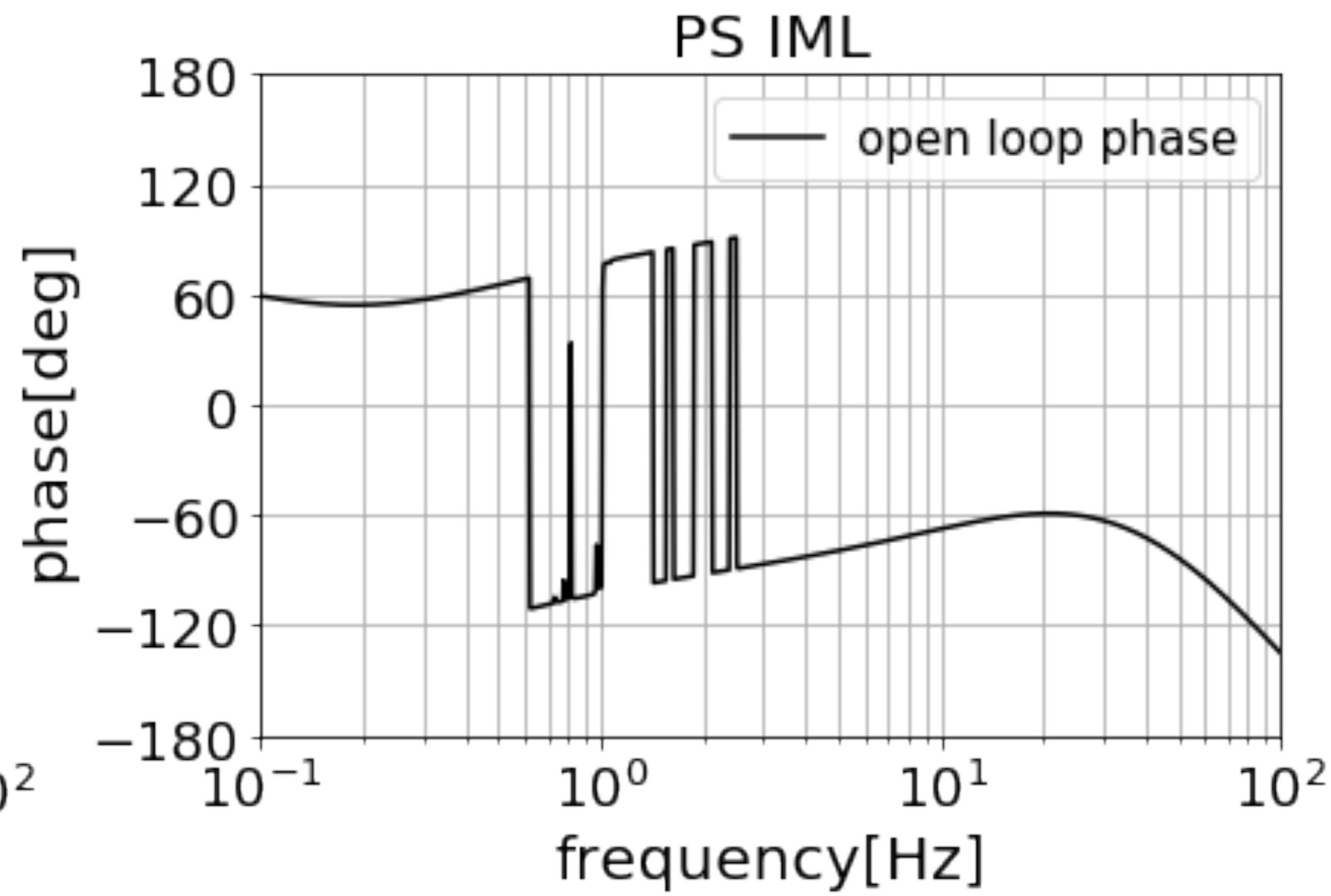
- For damping the resonance of the cryogenic payload.
  → 1/e decay time

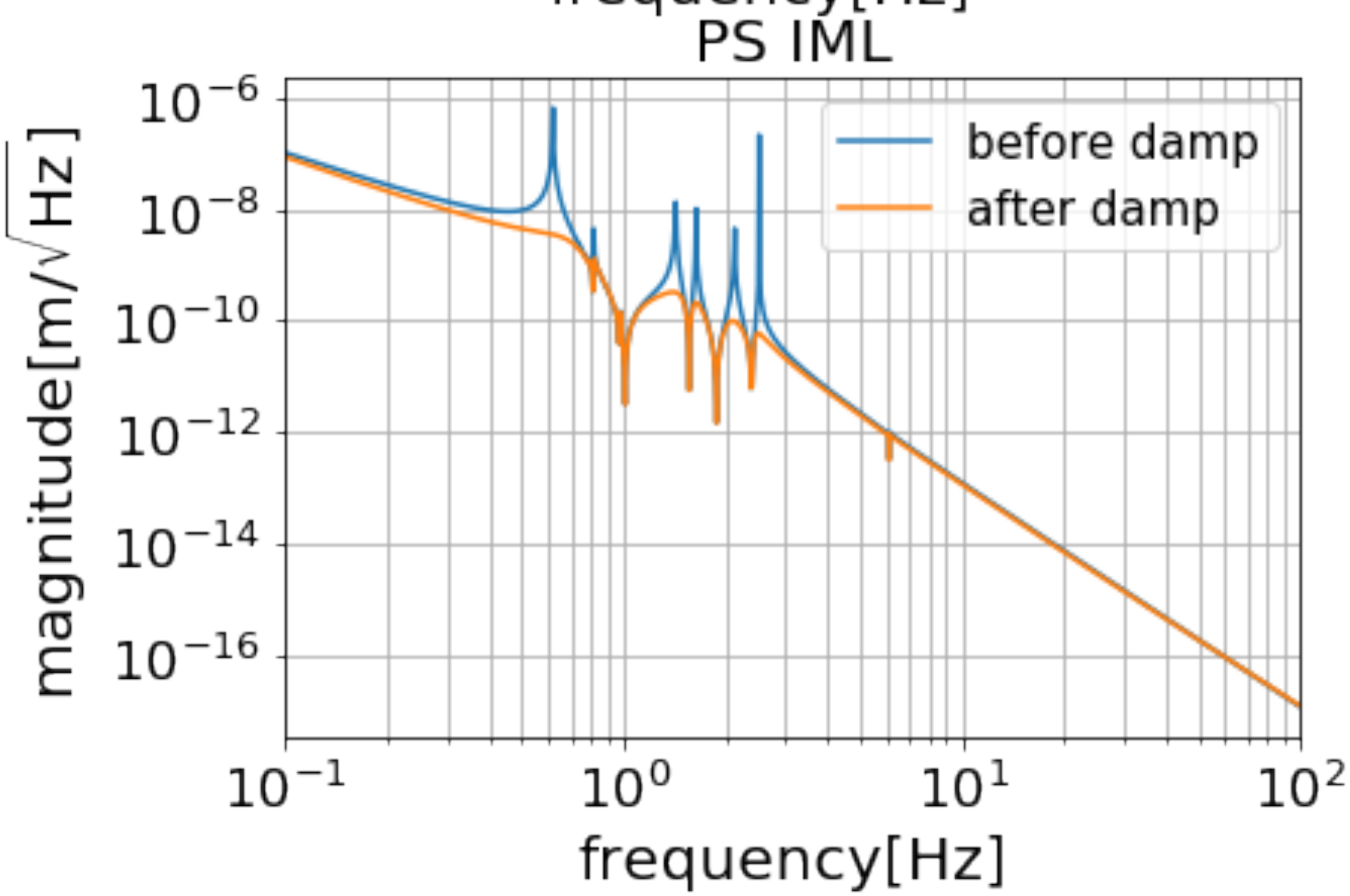
- For the damping control during the observation.
  → noise level

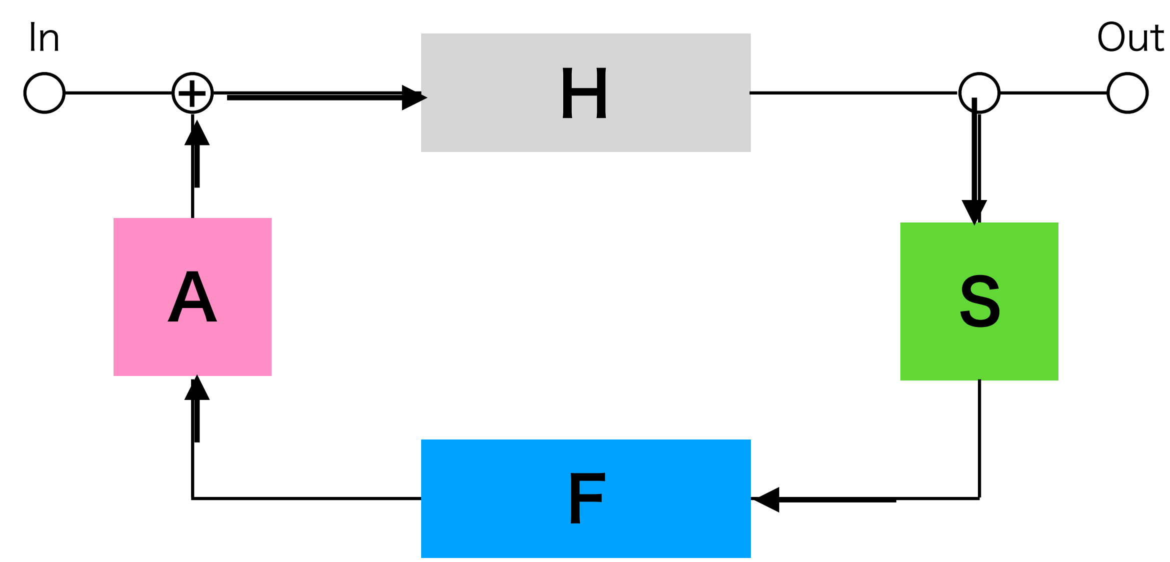
Ran the simulation

Filter for damping the resonance





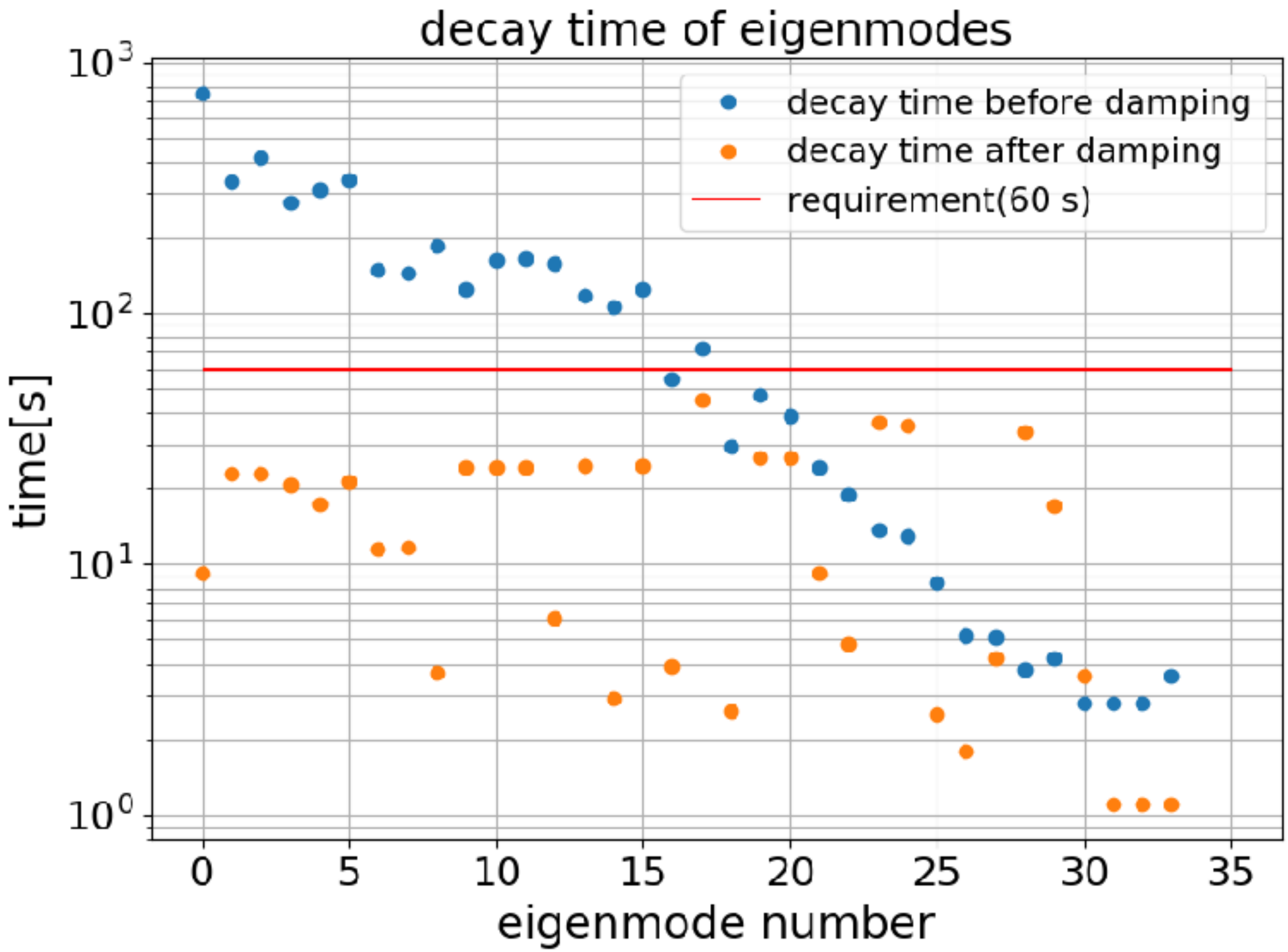




We simulated the total degrees of freedom(12) of IM, MN.

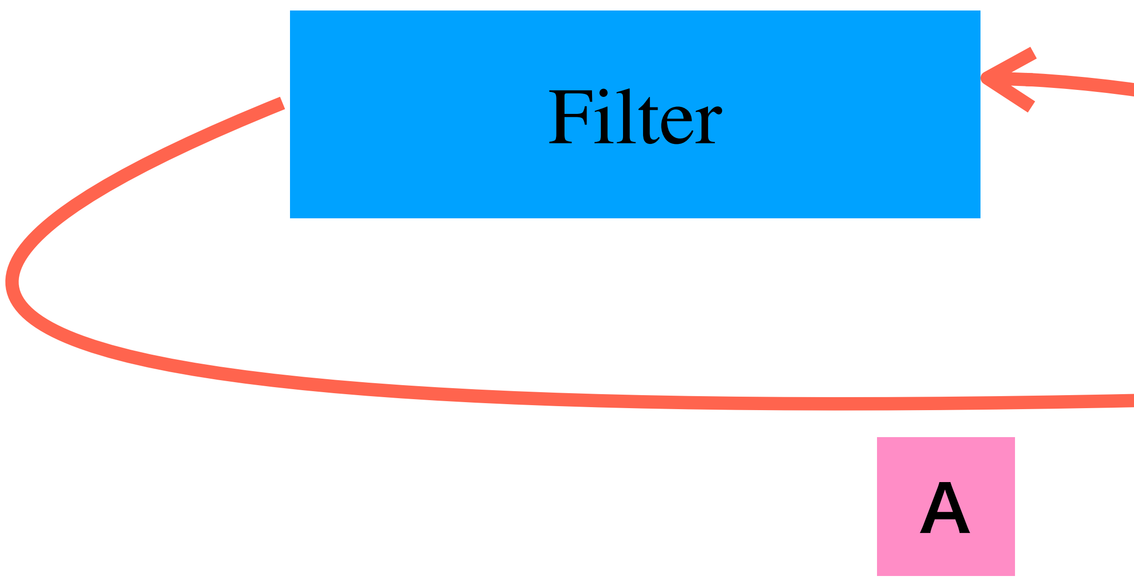
1/e decay time

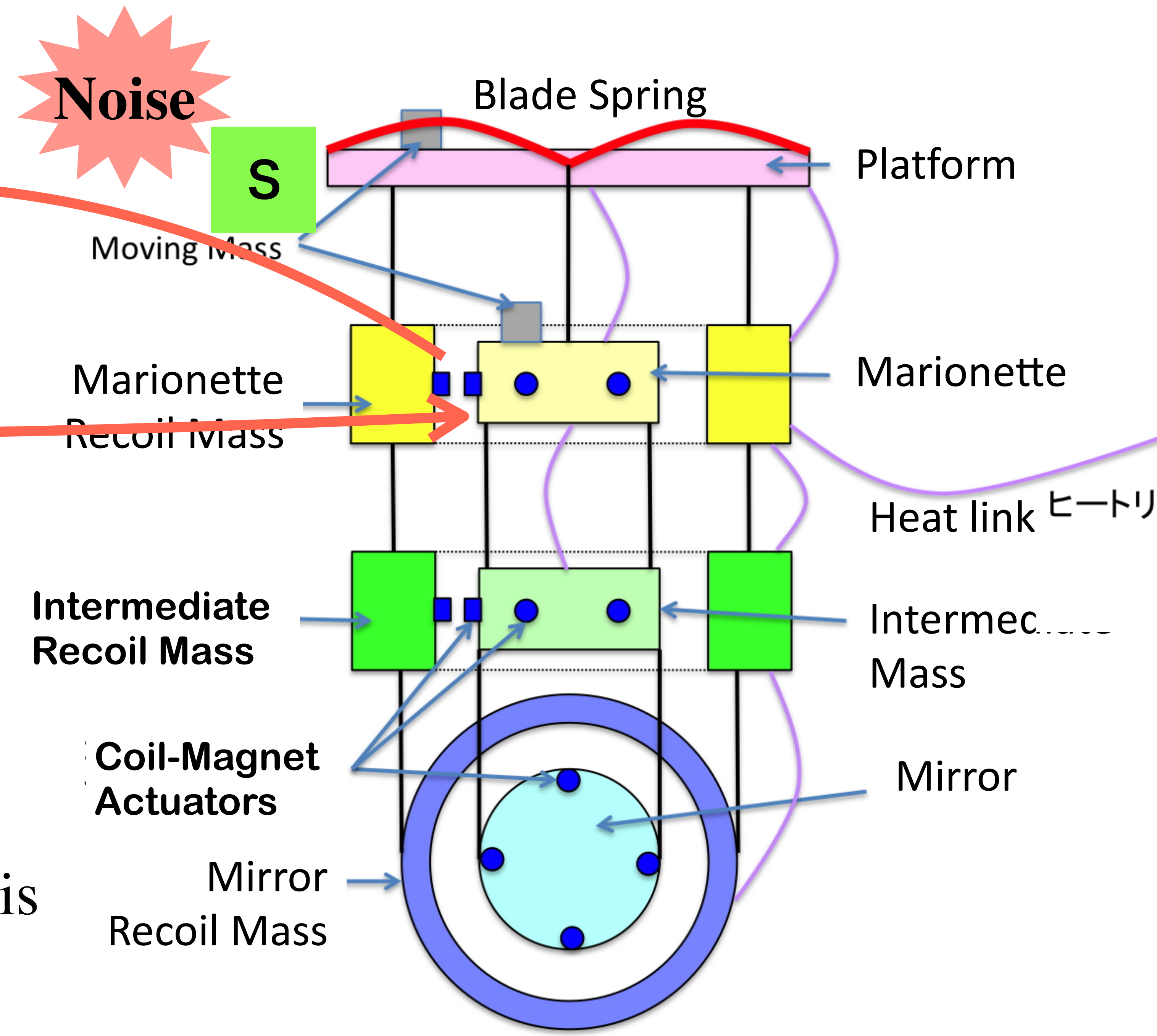
The blue points represent the decay time of the resonance of cryogenic payload.



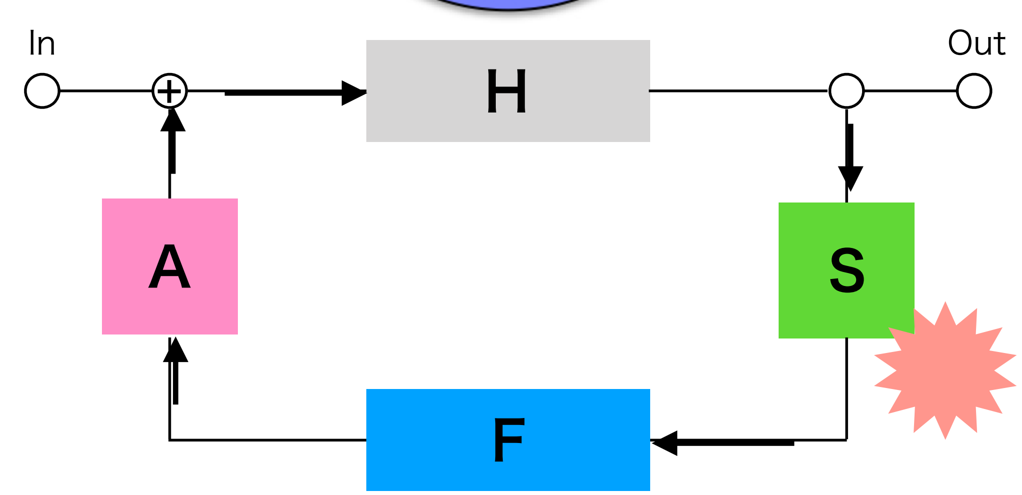
The time constant of 1/e decay time could be kept within 1 minute.

Sensor noise level



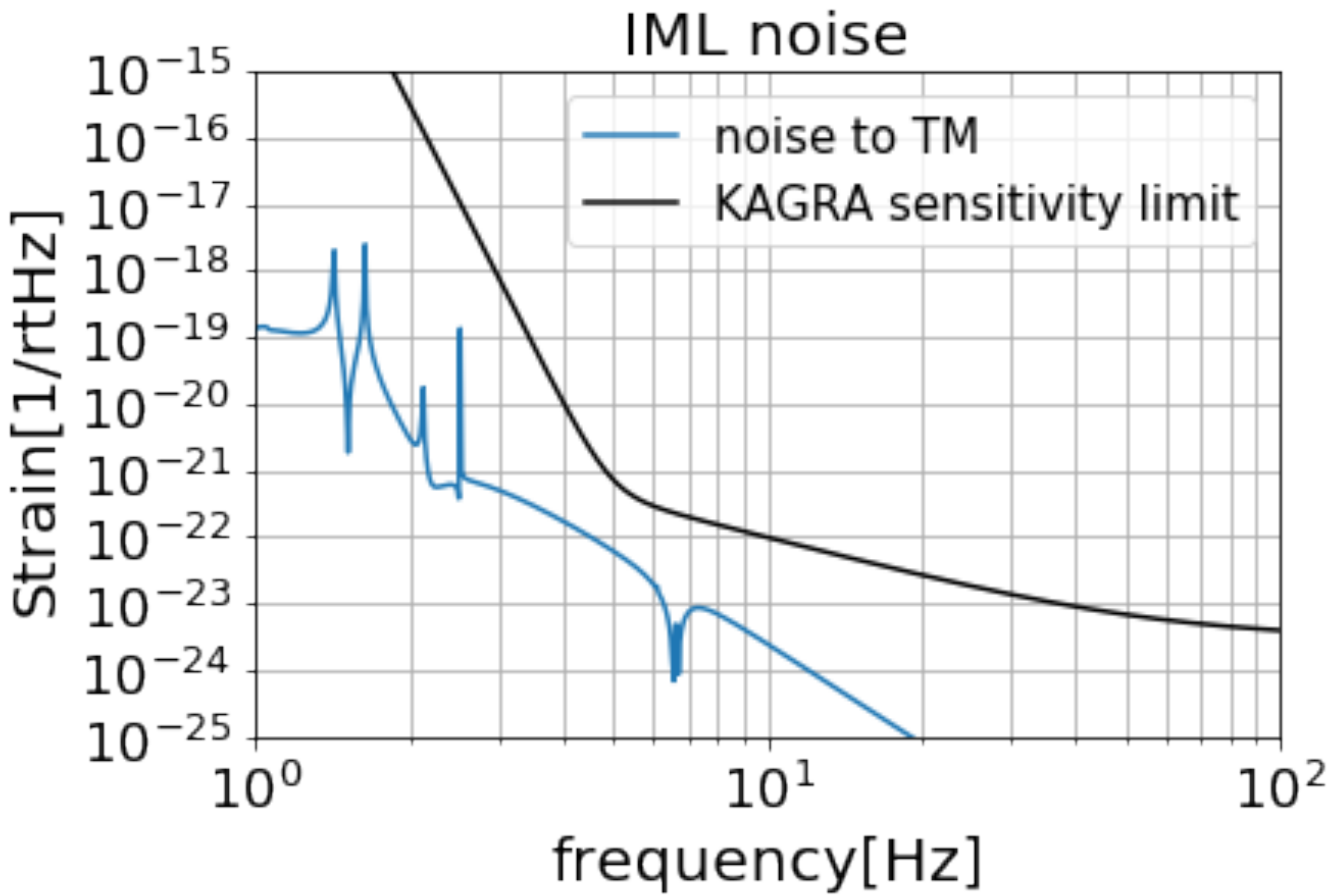


- Sensor noise feedback to the cryogenic payload.
- We arranged the filter to reduce this influence on KAGRA sensitivity.



Filter for the observation

Focus on transfer function and sensor noise from each suspension stage to the mirror.



It's suggested that the influence on KAGRA sensitivity is 1/10 at 10 Hz or more.

Contents

Summary

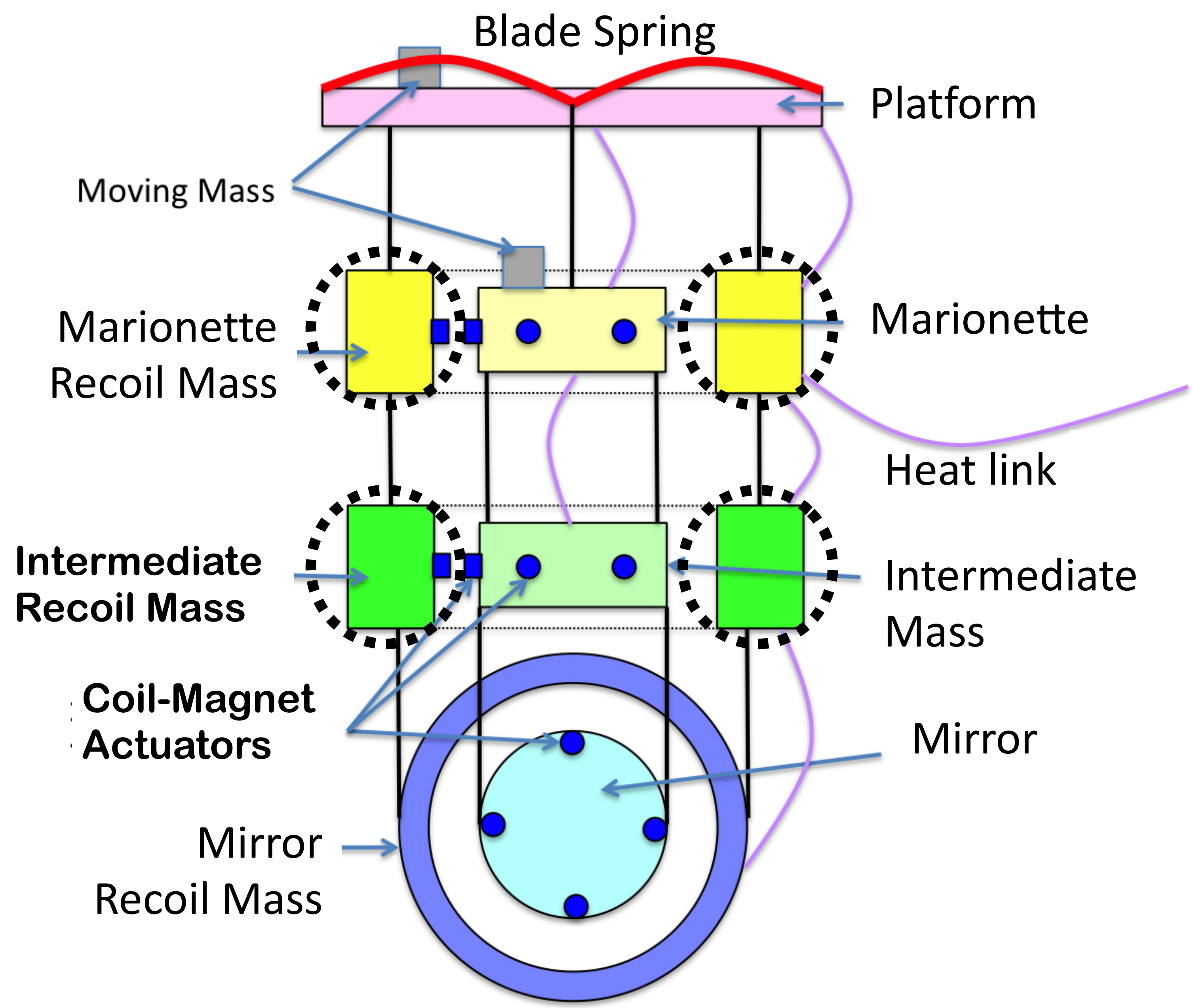
- We developed a cryogenic displacement sensor for KAGRA cryogenic payloads.
- Cryogenic displacement sensors are used for damping control of the cryogenic payload.
- We can estimate the sensor response at cryogenic temperature from that at room temperature.
- We developed two types of the damping control filter for damping the resonances.
- We concluded that the sensor realizes KAGRA stable operation.

Abstract

- We developed a cryogenic displacement sensor for KAGRA cryogenic payloads.
- Cryogenic displacement sensors are used for damping control of the cryogenic payload.

Cryogenic payload→

Cryogenic displacement sensors are installed on
Marionette Recoil mass : 6
Intermediate Recoil mass : 6



- We concluded that the sensor satisfies the requirements for use in KAGRA.

Control flow of interferometer

- The cryogenic payload reduces some noises and aligns the mirror.
- It has the proper feature for the interferometer control on below each phase.

- **Controls on each suspension** — Local control phase

1/e decay time < 1min.

- **Lock the interferometer** — Global control phase

Active control to mirrors.

- **Observation** — Observation phase

Control noises don't affect the sensitivity.

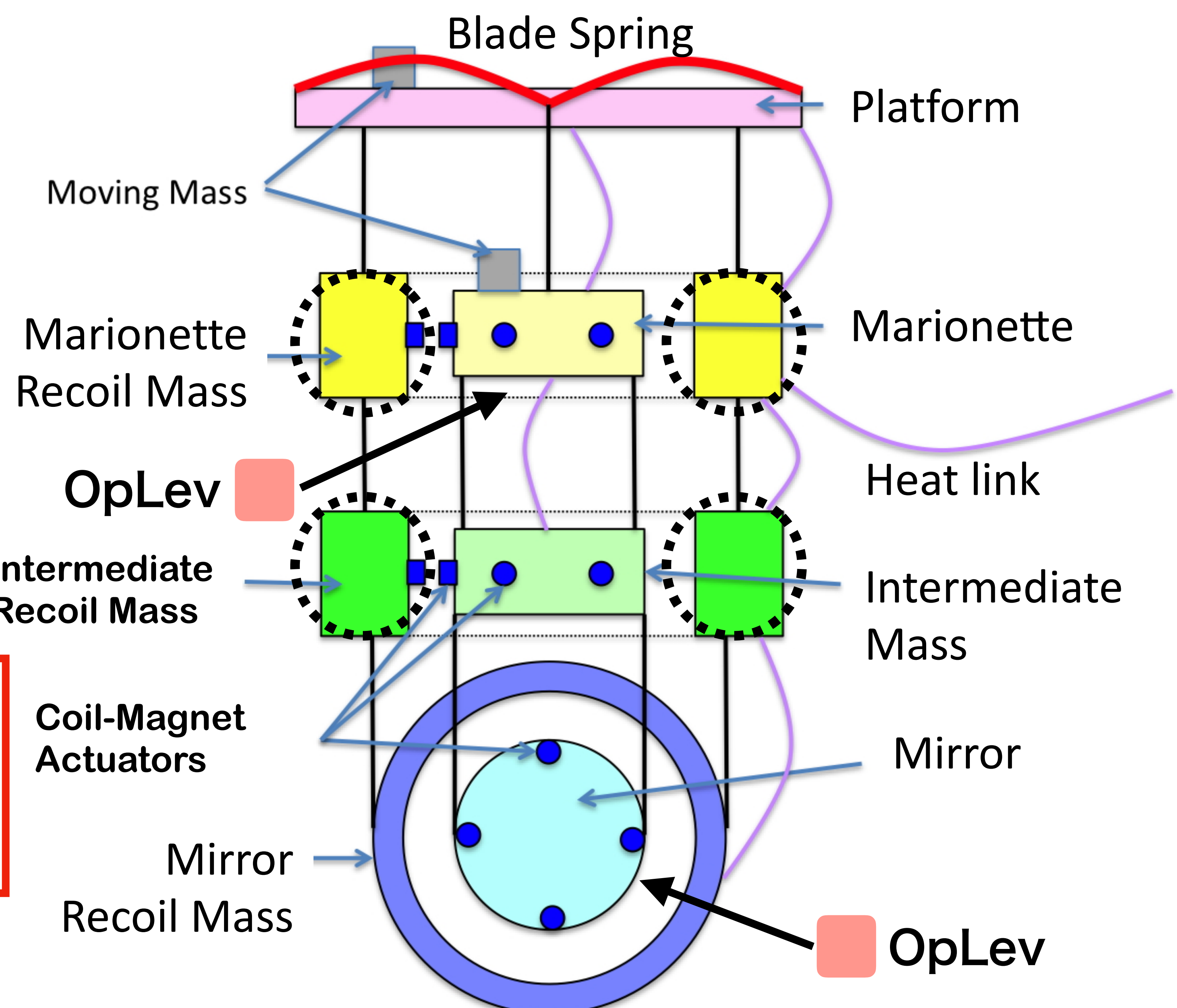
Sudden Vibration

Role of Cryogenic payload

- **To align the mirror**
  - Using Optical Lever (OpLev) and displacement sensor.
  - From these monitoring, it aligns the mirror by using moving mass.

- **To damp the resonance**
  - Using coil-magnet actuator.
  - Damping control.

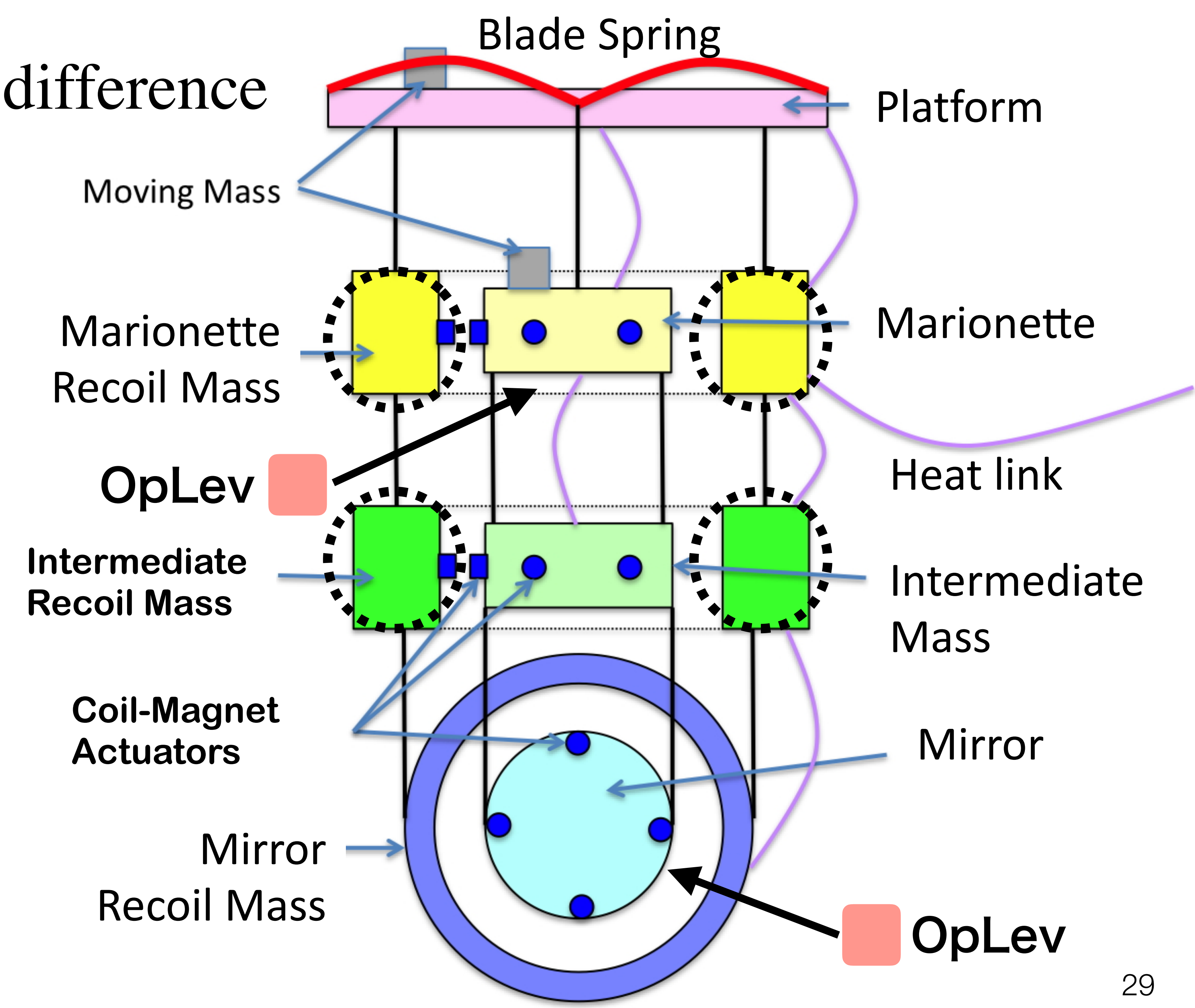
In the sensor systems, we hadn't develop the cryogenic displacement sensor.



Requirements and Requests for the sensor

★Work at cryogenic temperature(20 K).
★Non-contact and an large dynamic range.
★Linear ranges

- Influence of individual difference
- Long-term stability
- Noise levels



Requirements and Requests for the sensor

Requirements and Requests

★Work at cryogenic temperature(20 K).
★Non-contact and an large dynamic range.
★Linear ranges : 20 mm ± 3 mm, linearity 5%
•Influence of individual difference < 50%
•Long-term stability ~ 1 year
•Noise levels

To do list

1.Calibration
2.Evaluating individual difference
3.Long-term measurement
4.Making damping control systems

Contents

Requirement

★Non-contact and an large dynamic range.

★Linear ranges : 20 mm ± 3 mm, linearity 5%

Contents

Requests

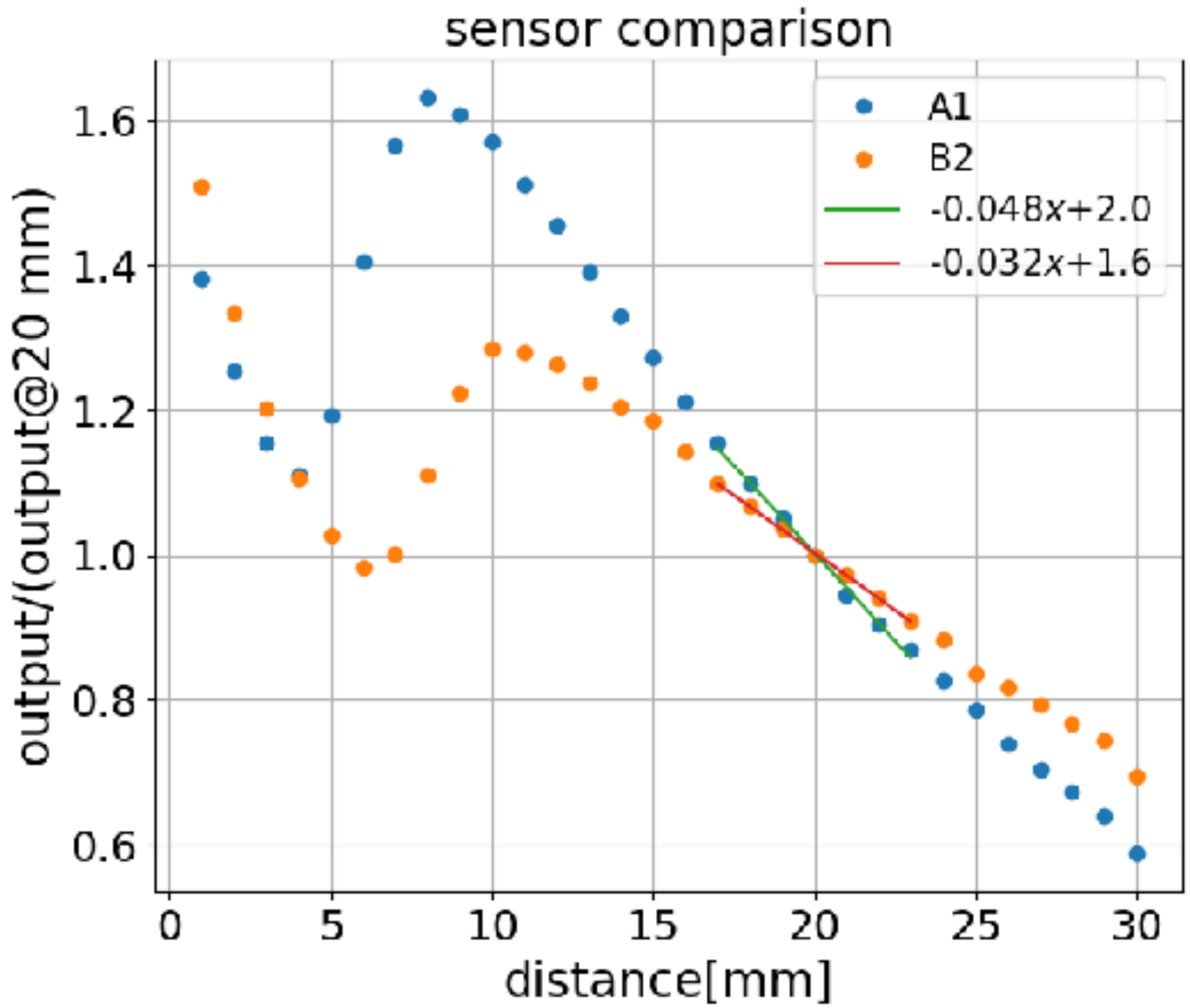
- Influence of individual difference < 50%

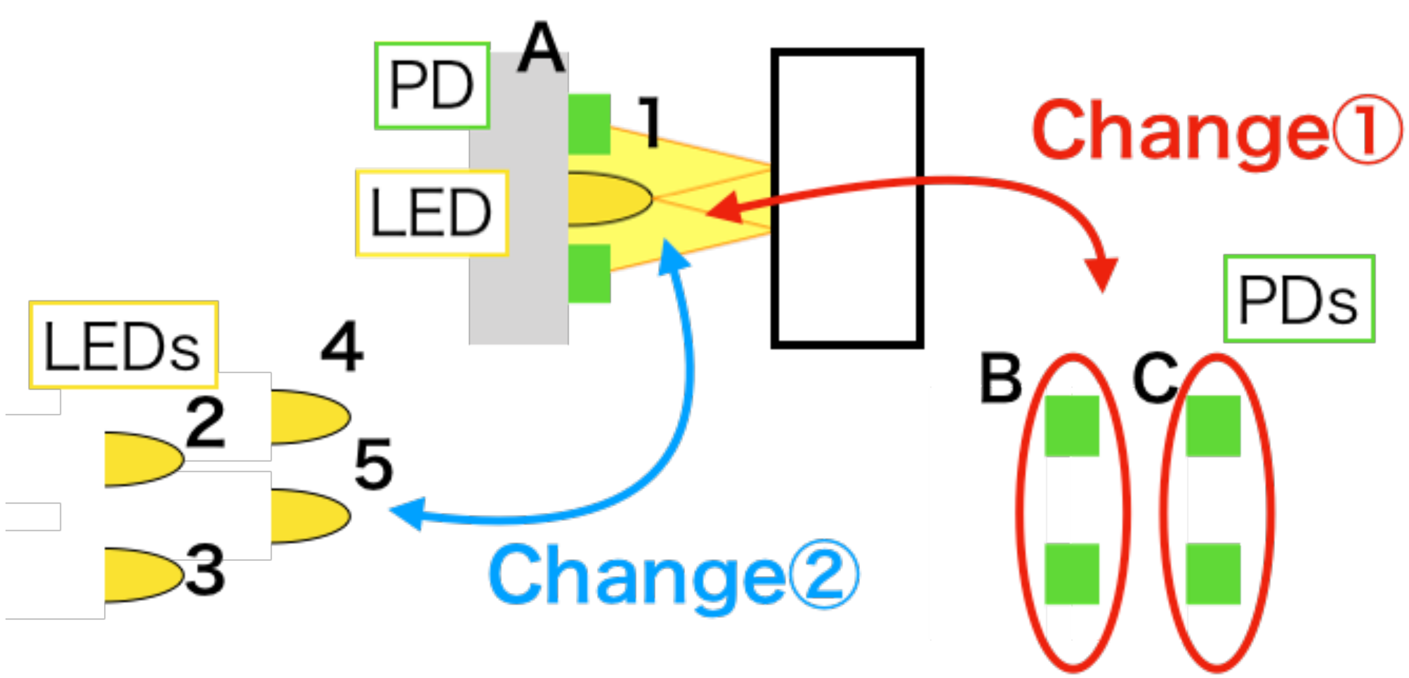
Individuals difference of cryogenic sensor

We calibrated two sensors that PDs and an LED are different.

→normalized slope is different ~ 30%
(normalized slope means the slope divided by the output at 20 mm.)

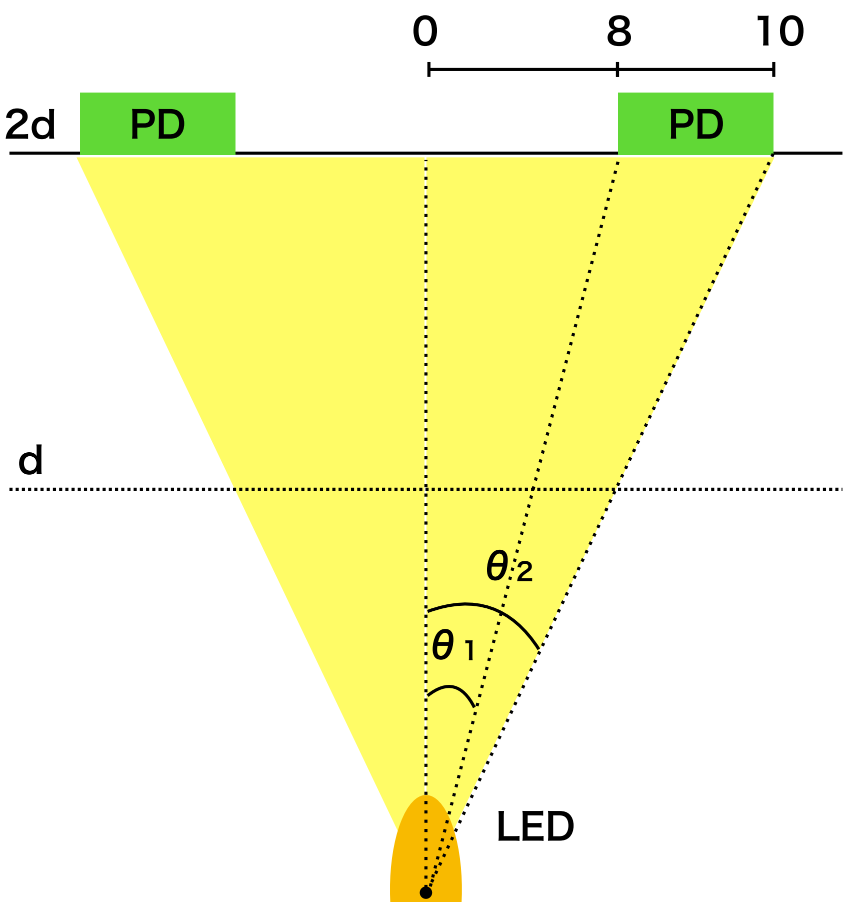
→the sensor has individuals diffrence.





Installation error is small.
→ We checked the PD and the LED.

Model for response of reflective photo sensor

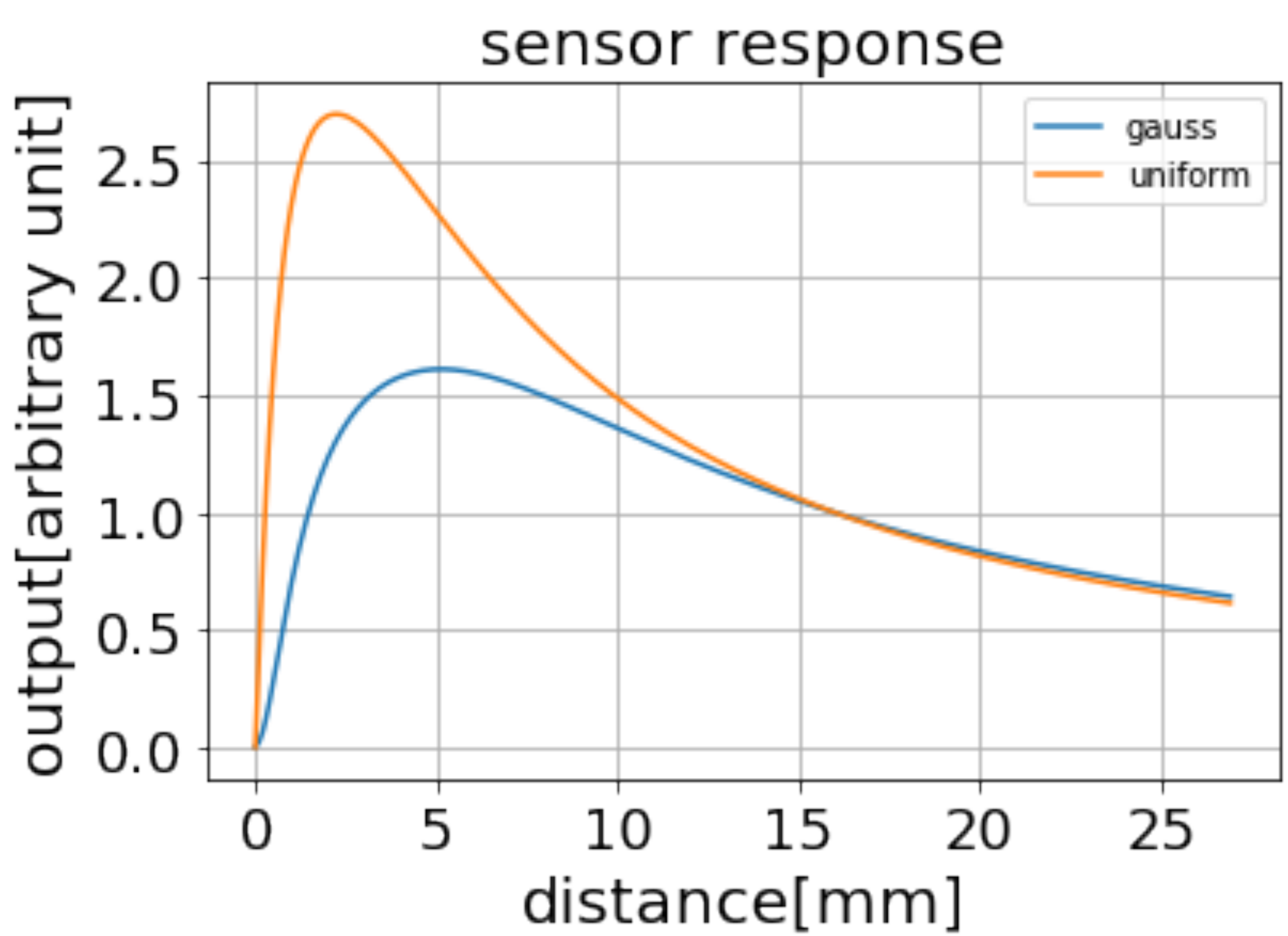


- The distance between the PD and the LED is 9 mm.
- A PD size is ϕ2.
- We think mirror image reversal of how it reflects.

$$P(d) = 2\sum_{n=1}^{n} a^n \int_{\theta_{n1}}^{\theta_{n2}} F(\theta)d\theta$$

a : reflectance,

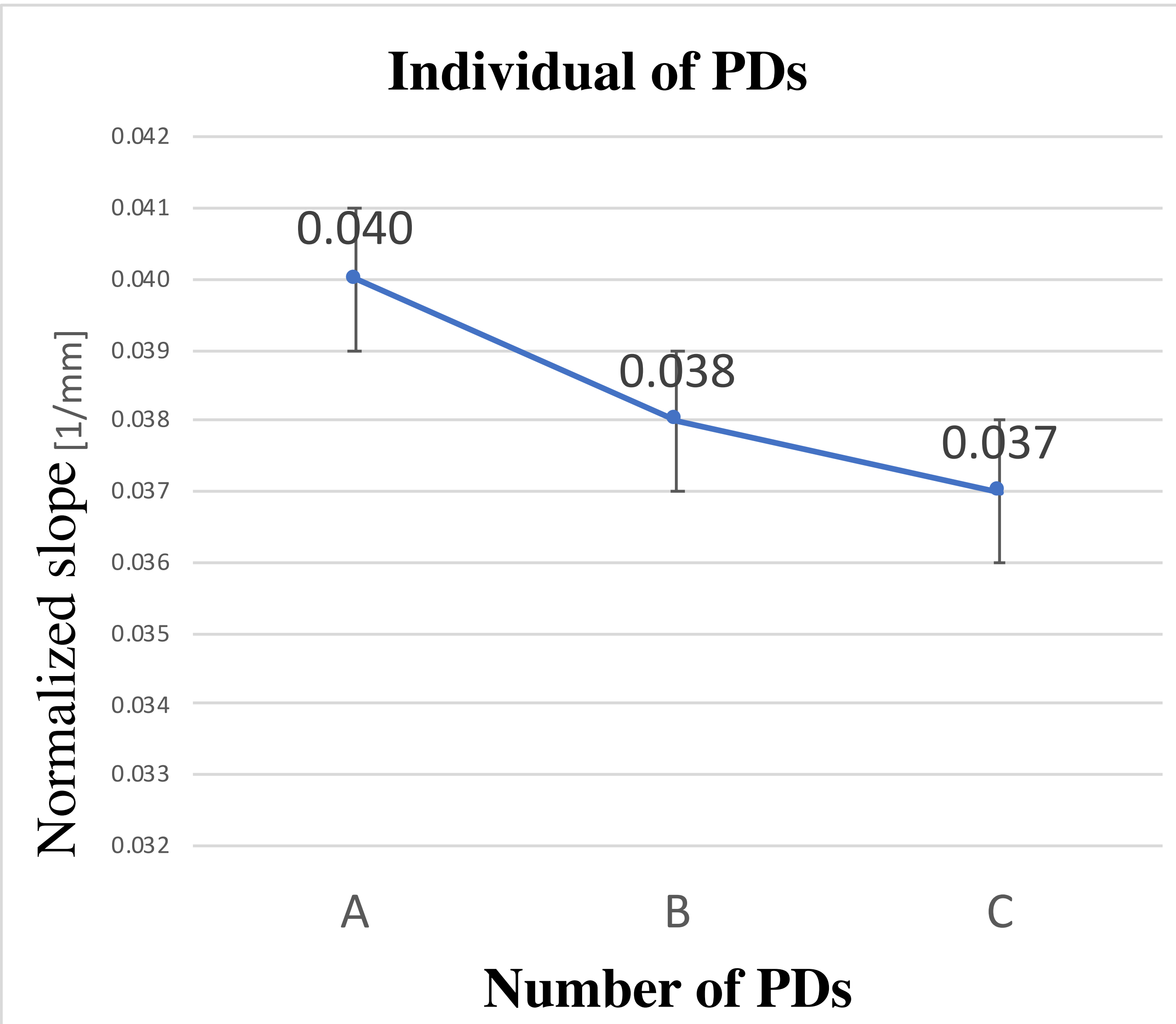
n : number of reflects

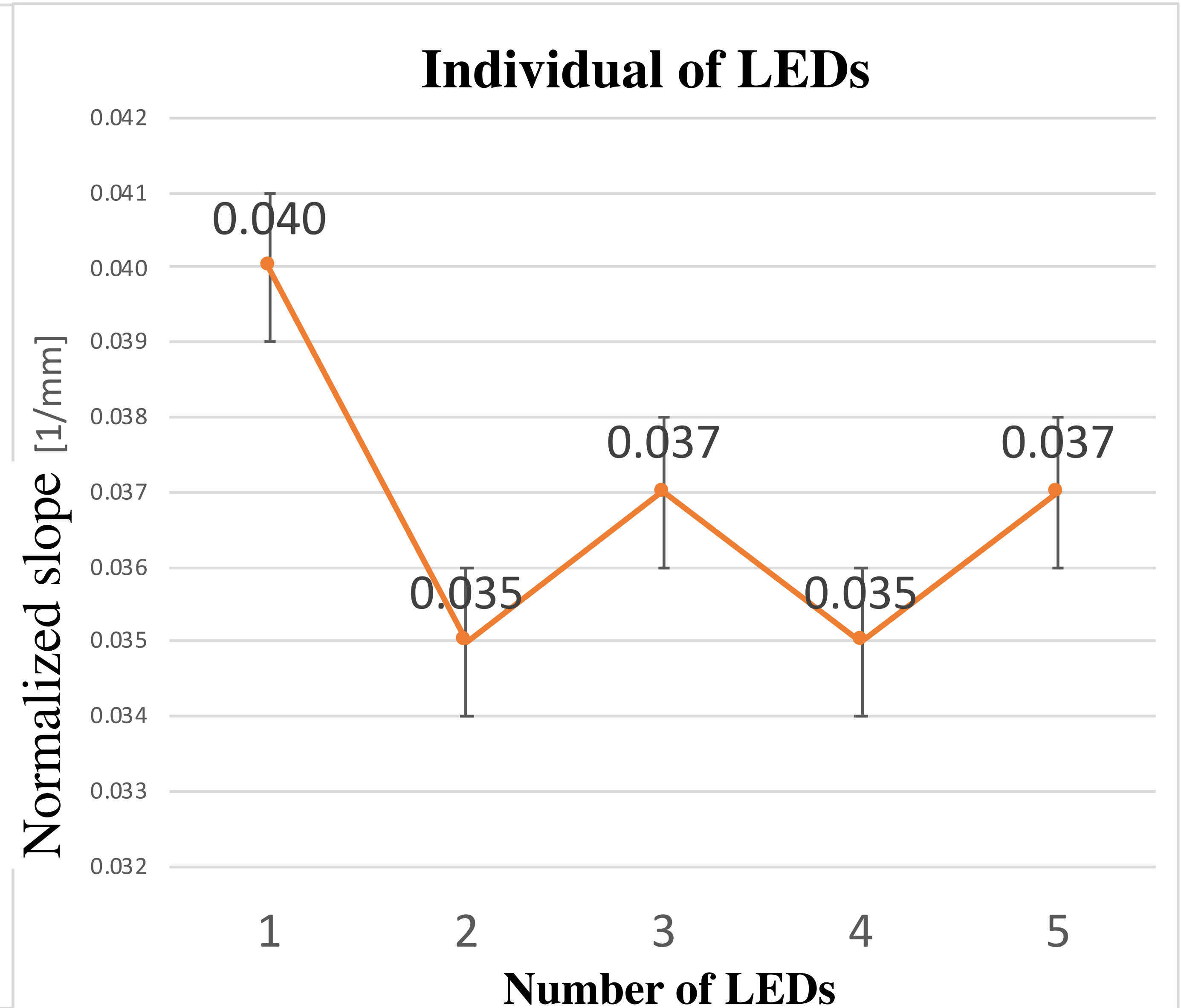


It is expected that the response of the sensor largely depends on the shape of the beam $F(\theta)$.

→ Focus on LED beam profiles.

Individuals difference of PDs and LEDs

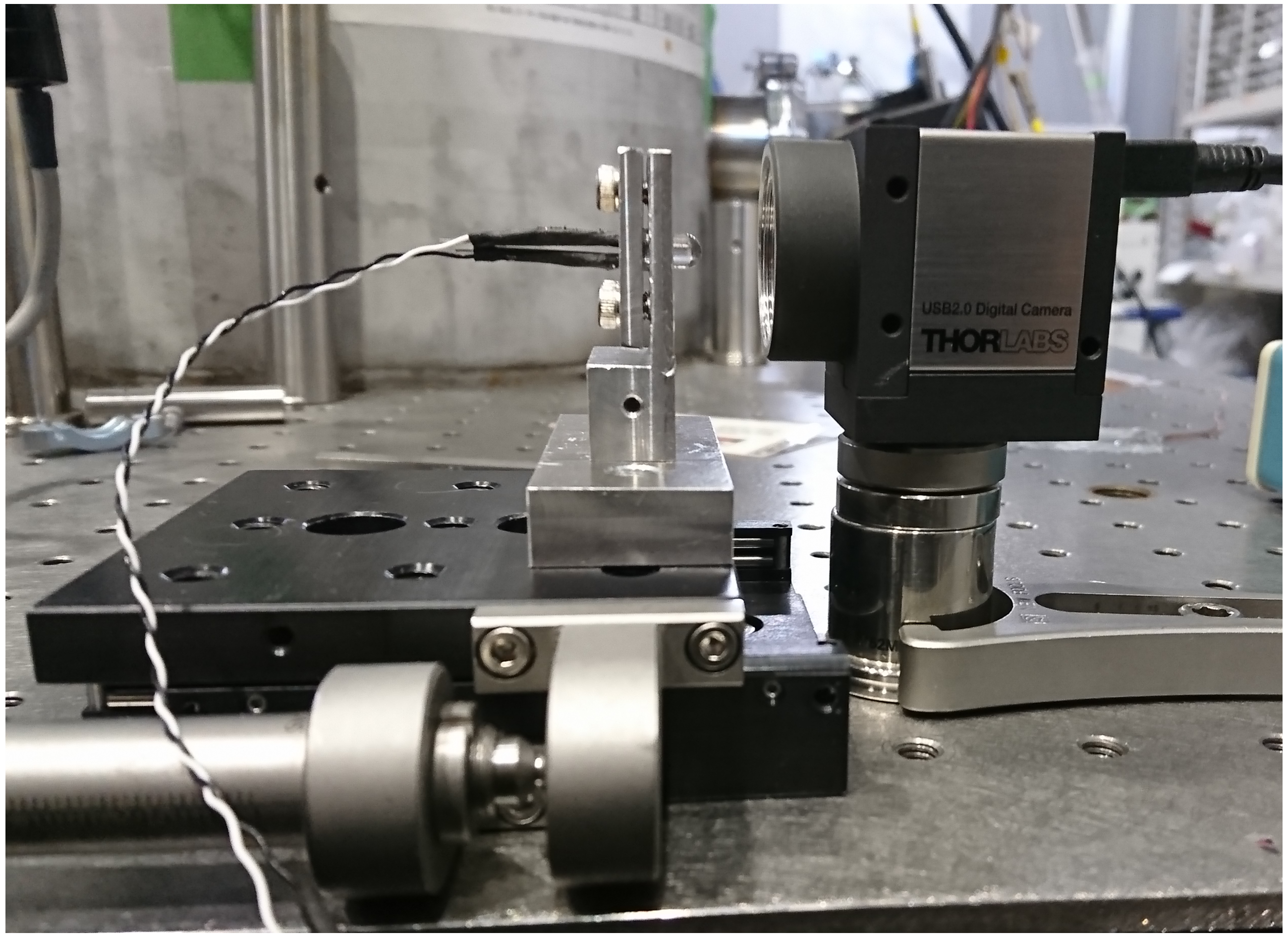




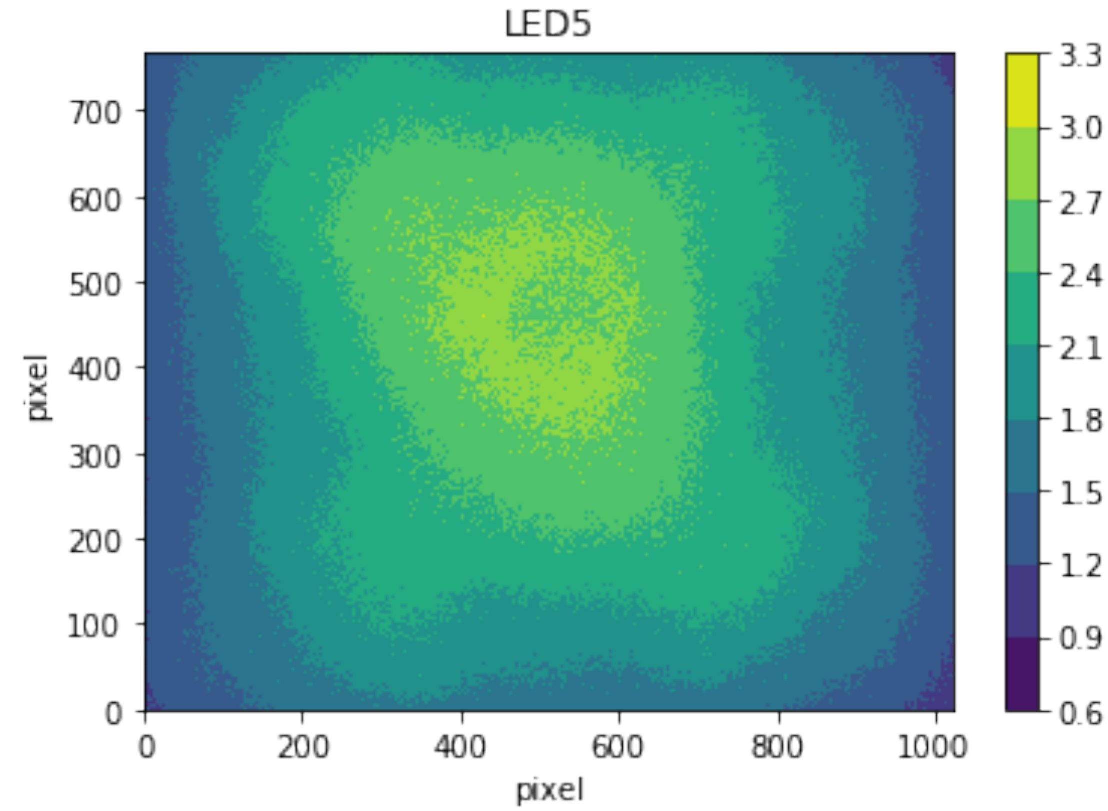
- Maximum error due to individual difference of PDs～7%
- Maximum error due to individual difference of LEDs～13%

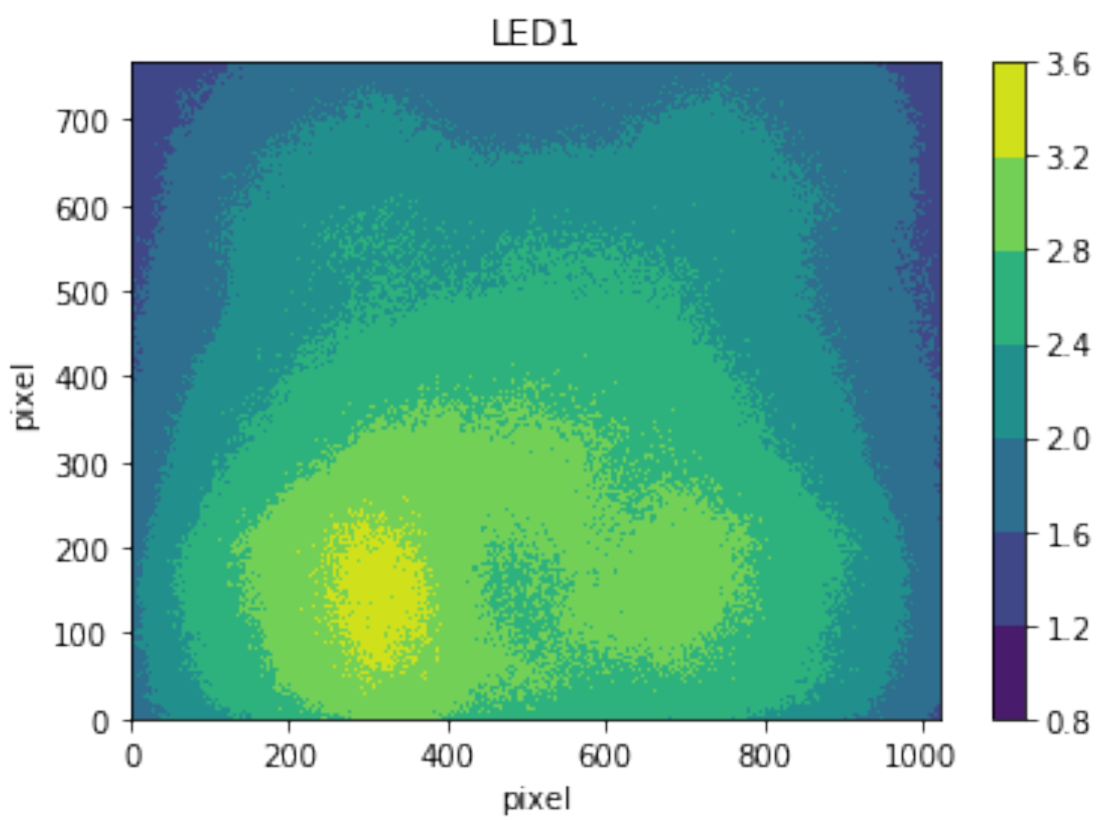
→ The LED individual difference is more effective.

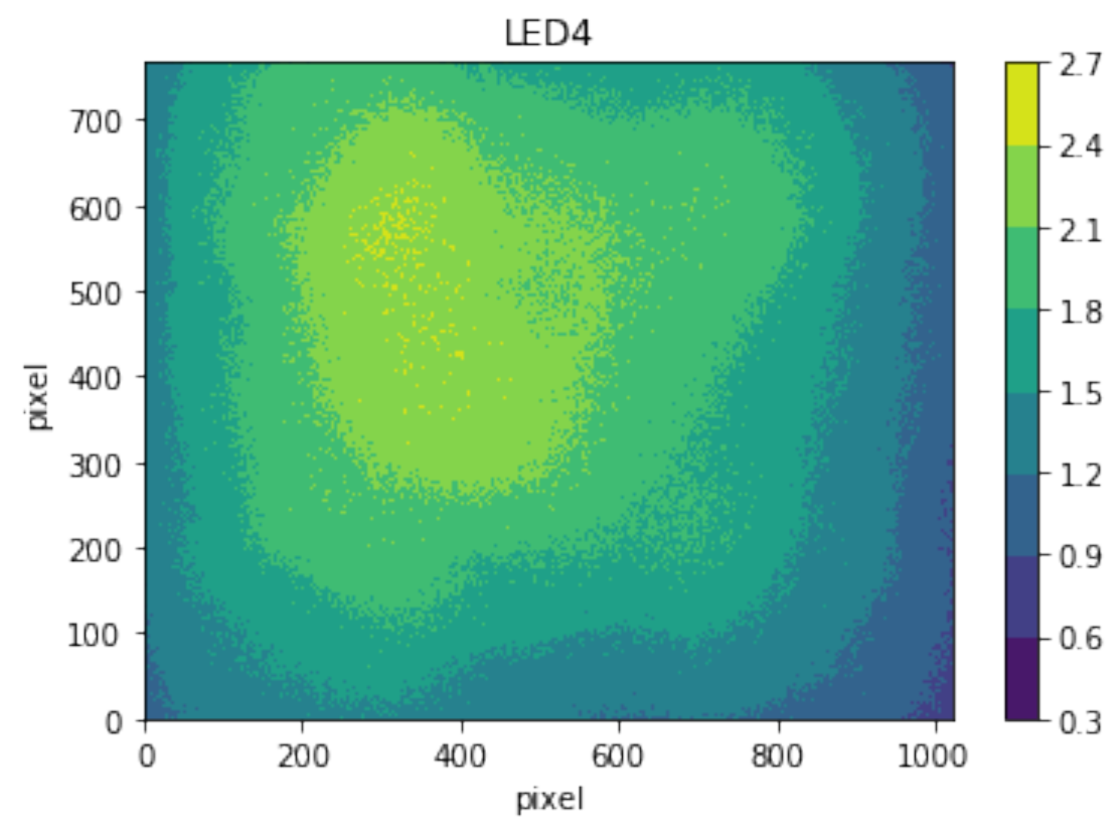
Beam profiles of LED



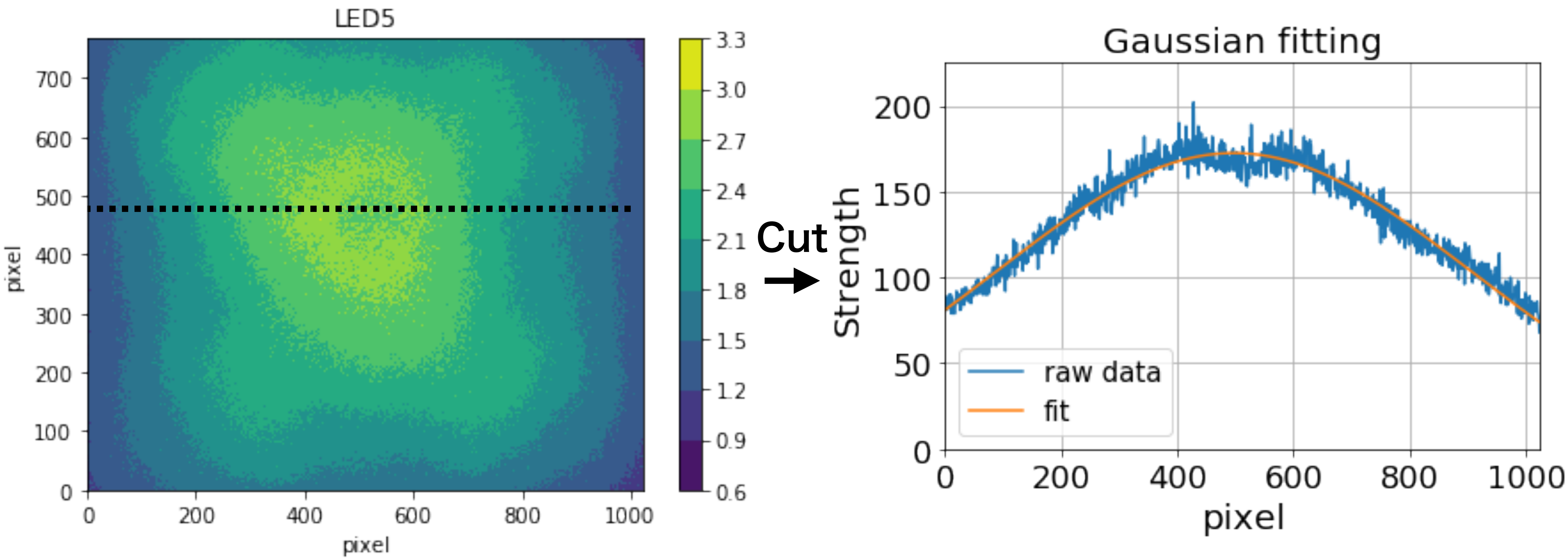
Shooting LED beam with CCD camera
Quantification by image analysis.







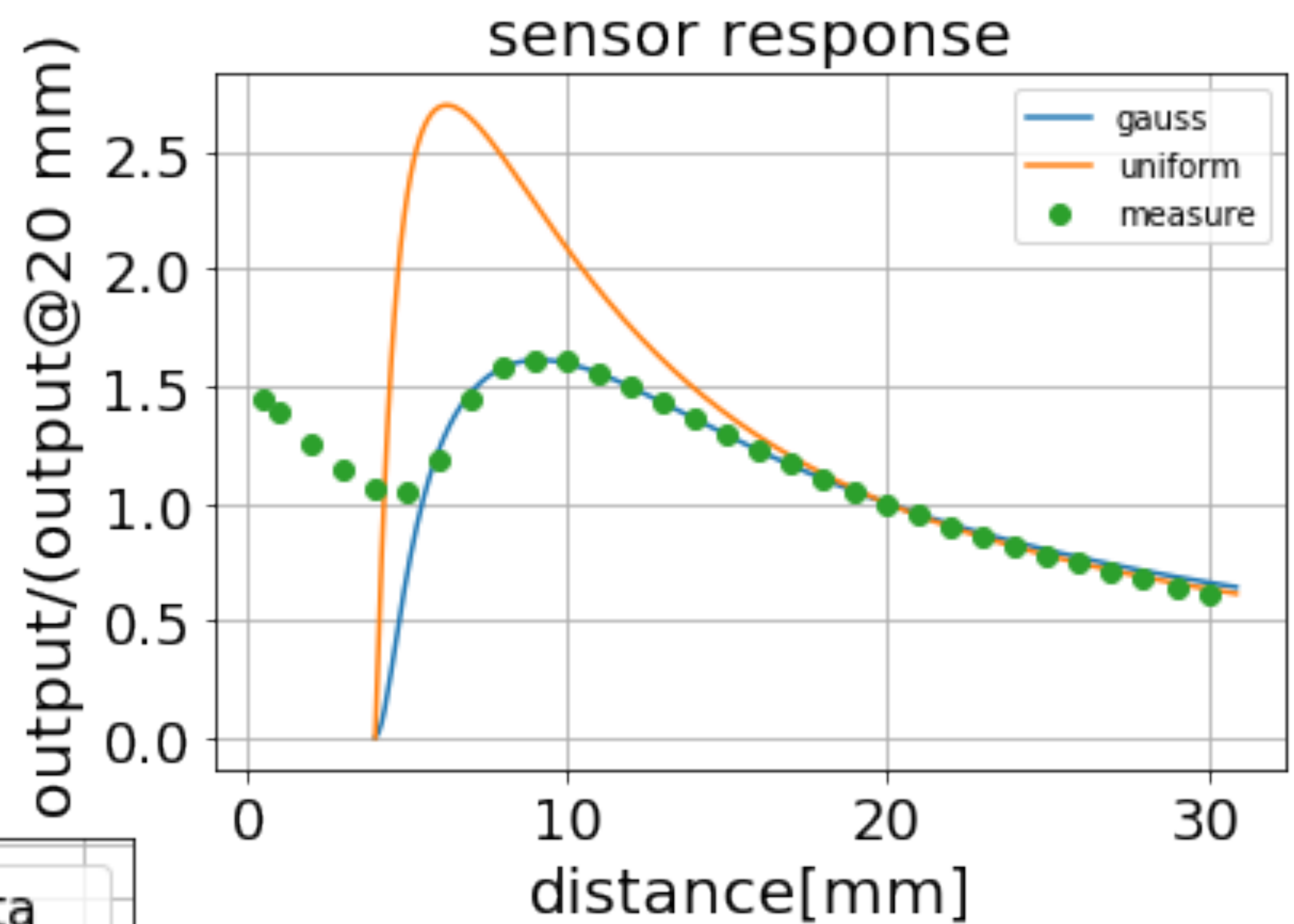
Fitting of beam profiles



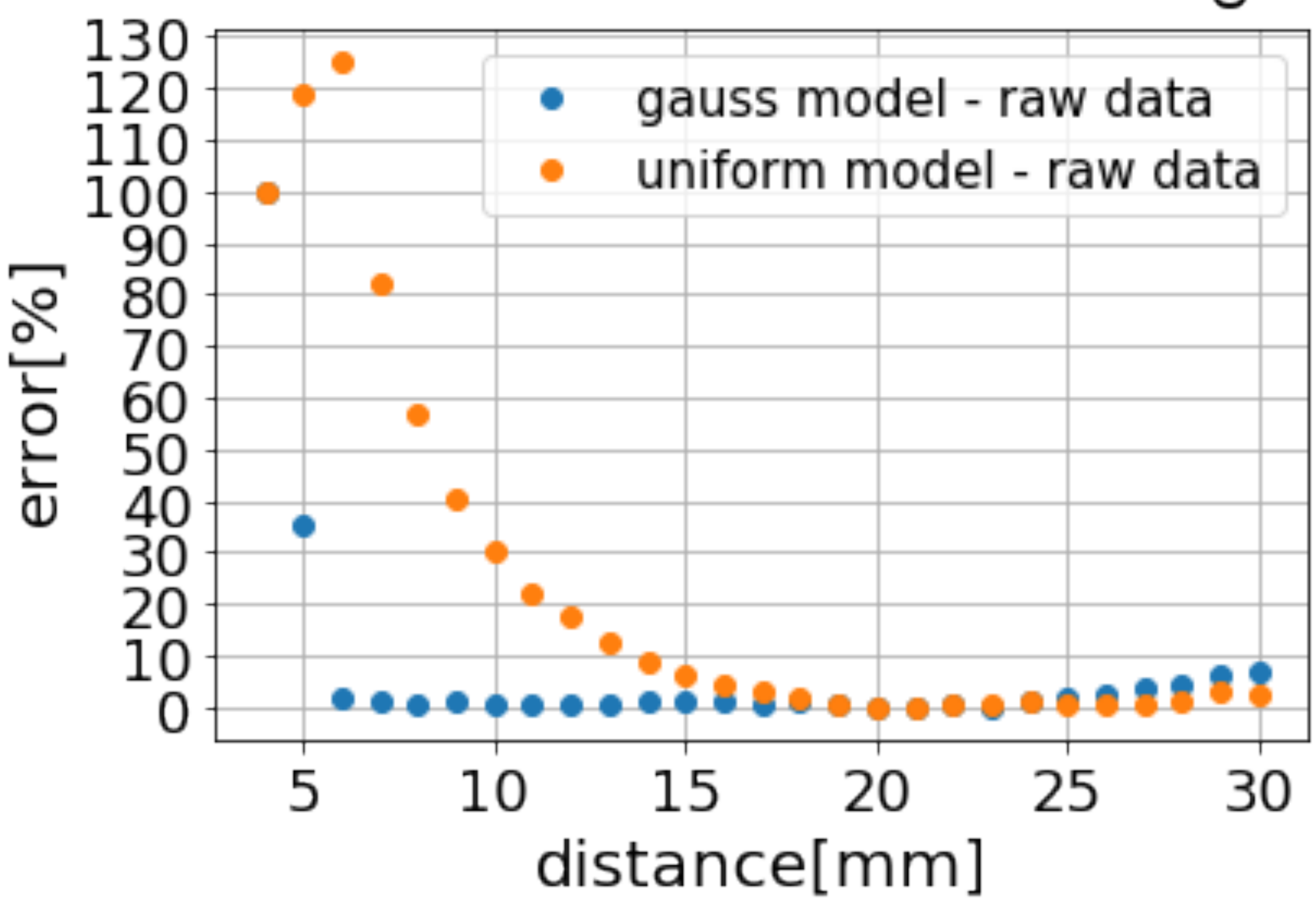
→ Gaussian fitting is better.

Evaluation of Model

The outputs is normalized.
The parameter is fixed;
Reflectance : a=0.975
Number of reflects : n=100

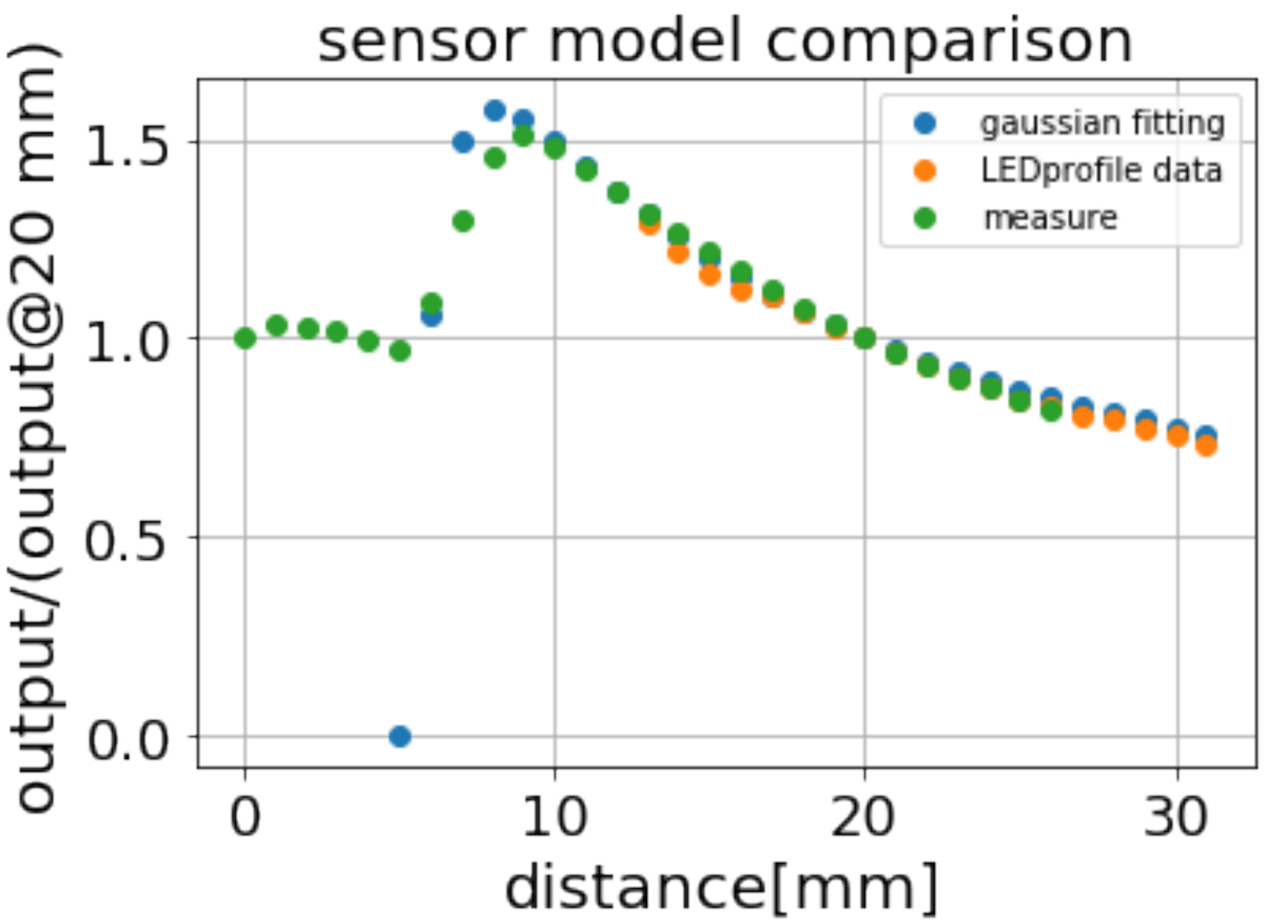


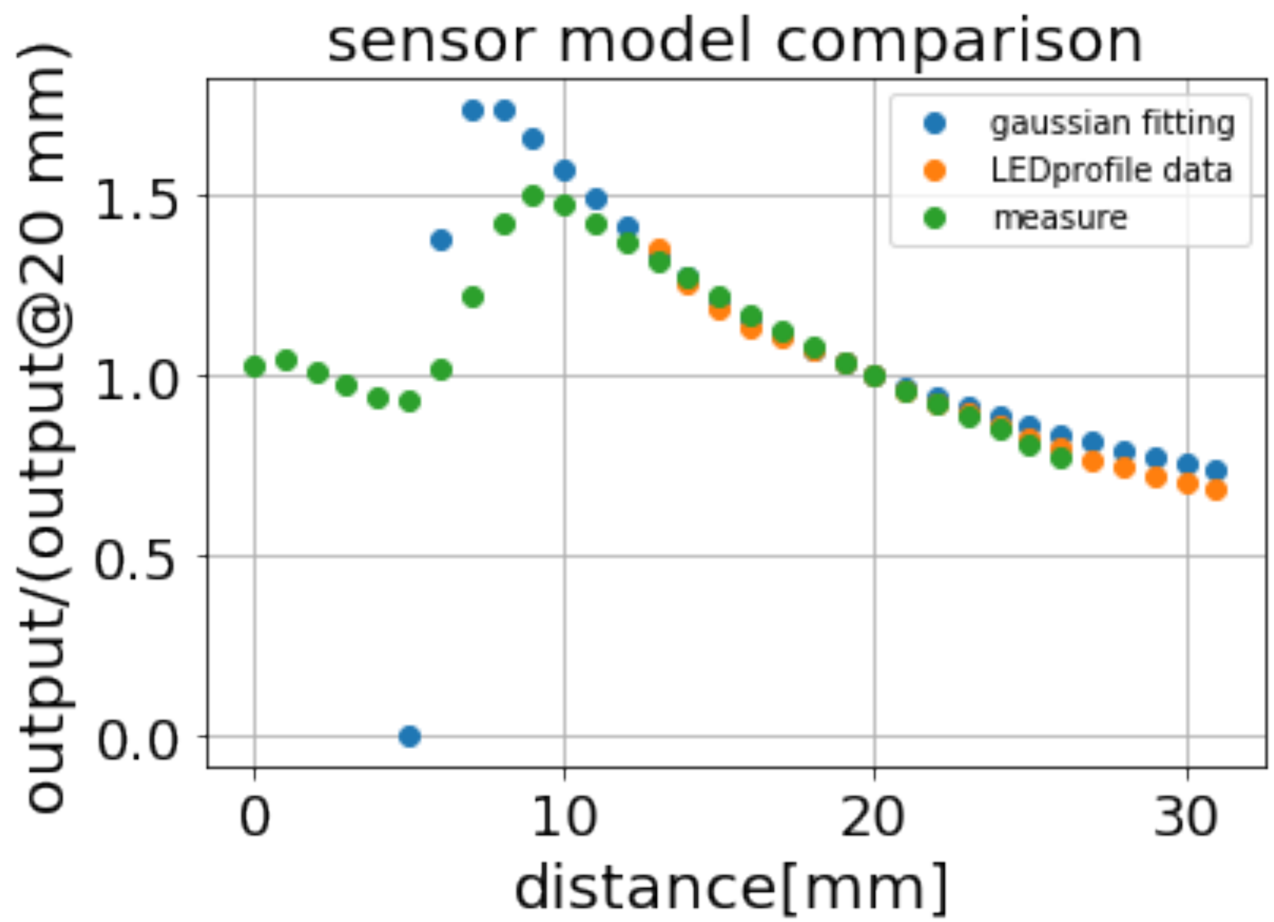
relative difference



The relative difference between gauss model and raw data is less than 10%.

Model and LED beam profiles





gaussian fitting : gaussian fitted raw data → $F(\theta)$
LEDprofile data : raw data → $F(\theta)$

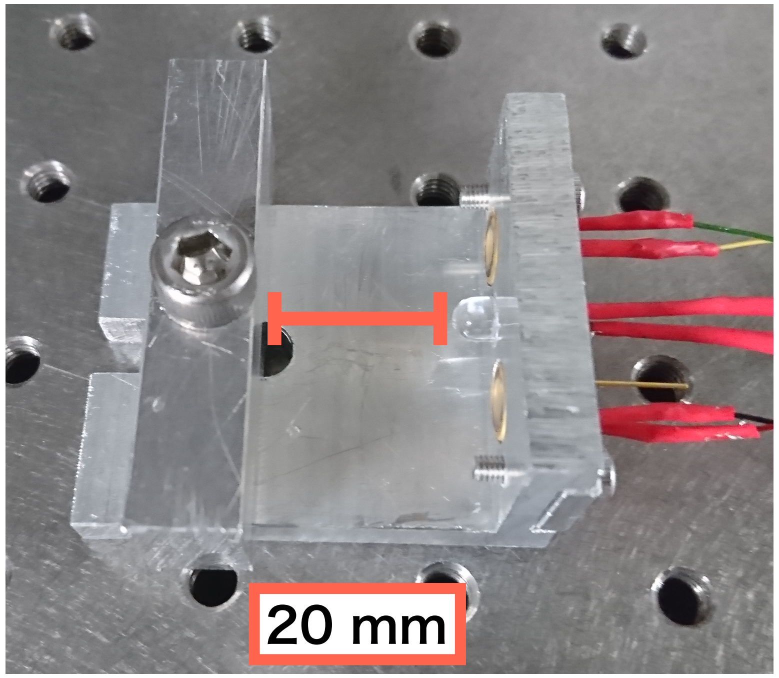
Both the linear range relative distance is less than 2%.
Calibration is possible by using the LED beam profile and this model.

Contents

Requests

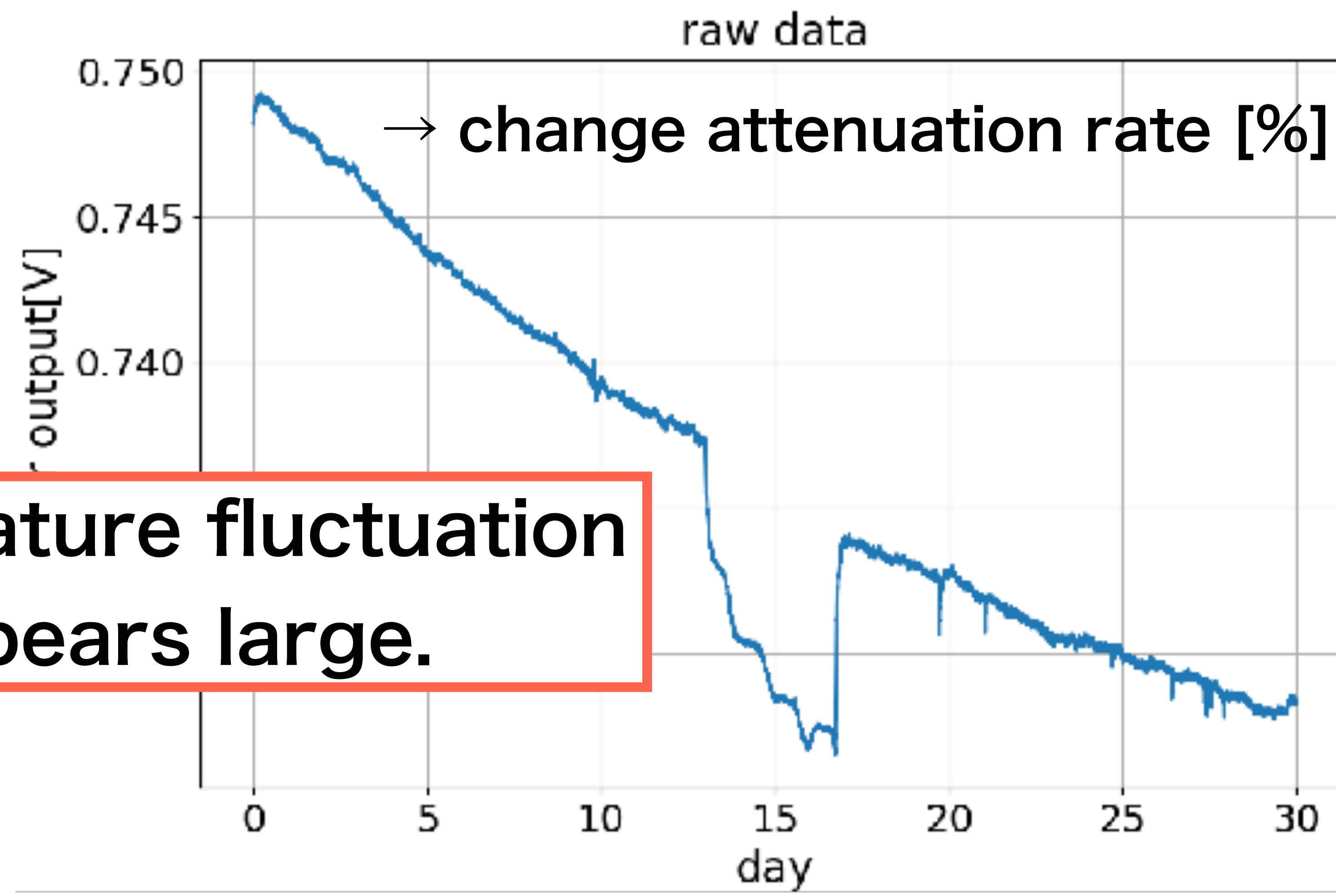
- Long-term stability ~ 1 year

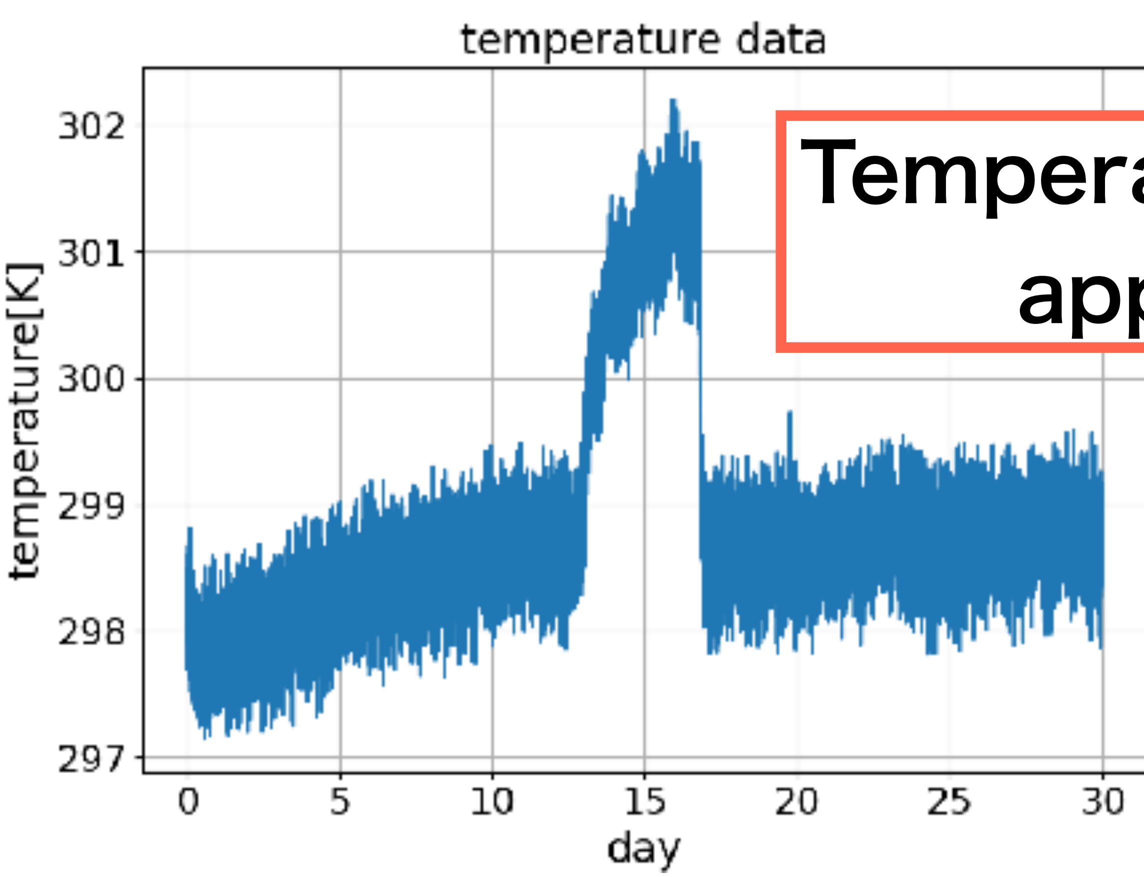
Long-term stability of cryogenic sensor



Relative distance is fixed 20 mm.
Measured the temperature around the sensor.

We evaluated the fitting with chi-squire test.





Temperature fluctuation appears large.

We removed the temperature fluctuation from the data by fitting.

Summary of development

★Working on cryogenic temperature(20 K).

★Non-contact and an large dynamic range : 13 mm~

★Linear ranges : 20 mm ± 3 mm

- Influence of individual difference ~ 30%
- Long-term stability ~ 3 months
- Noise levels ← Next topics.

Requirements and Requests for the sensor

Requirements and Requests

- ★Working on cryogenic temperature(20 K).
- ★Non-contact and an large dynamic range.
- ★Linear ranges : 20 mm ± 3 mm, linearity 5%
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- Long-term stability ~ 1 year
- Noise levels

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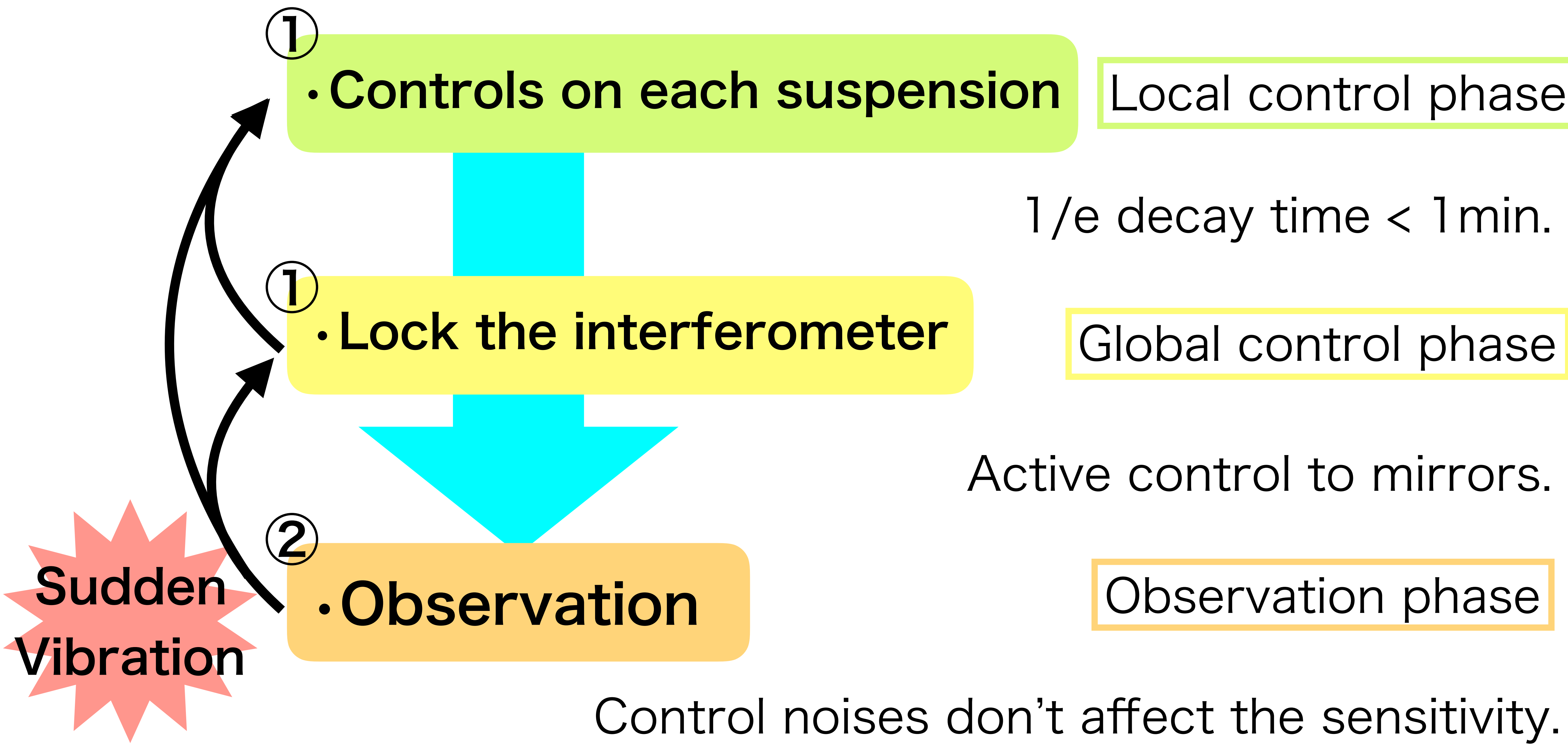
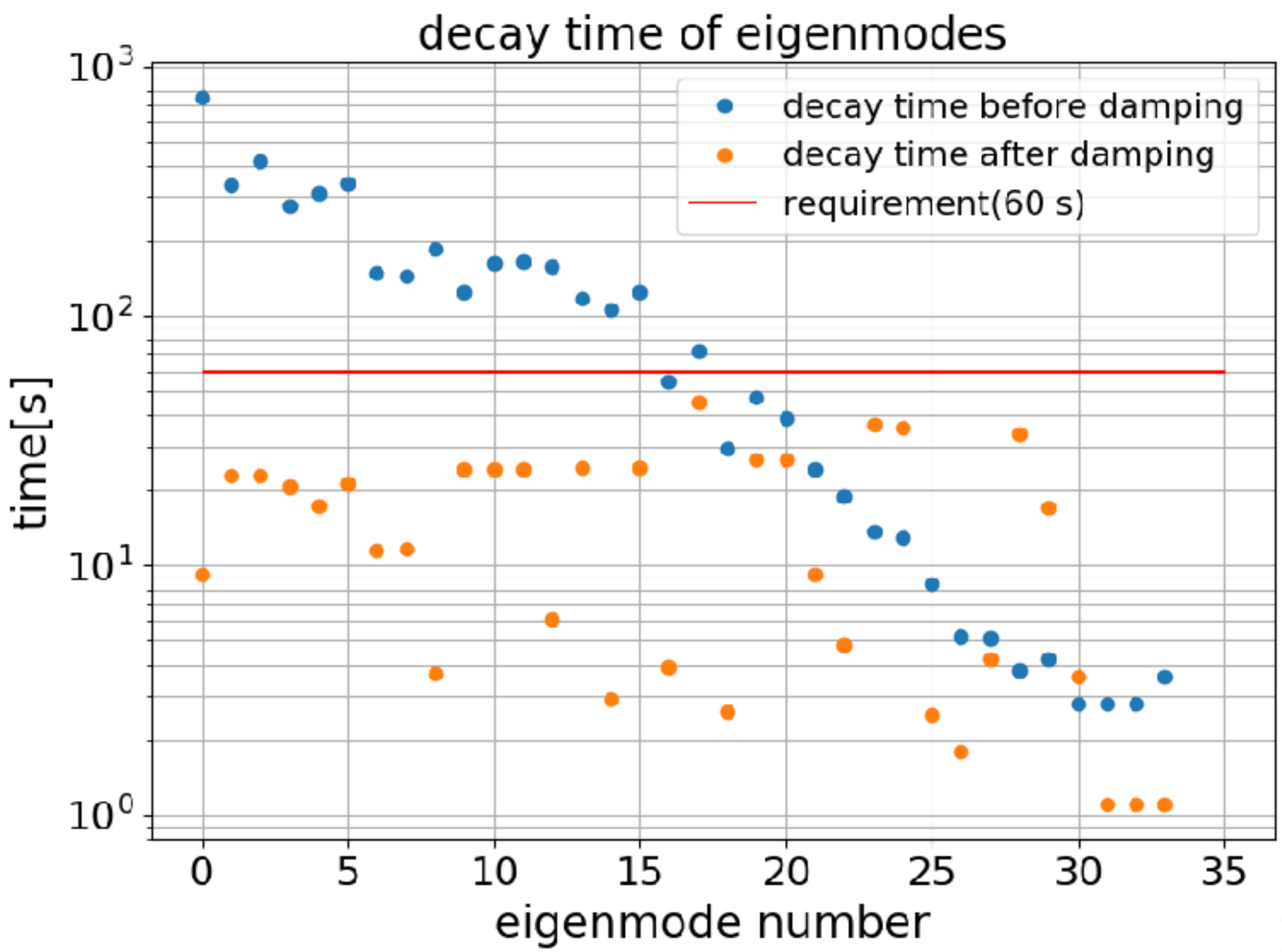
Control flow of interferometer

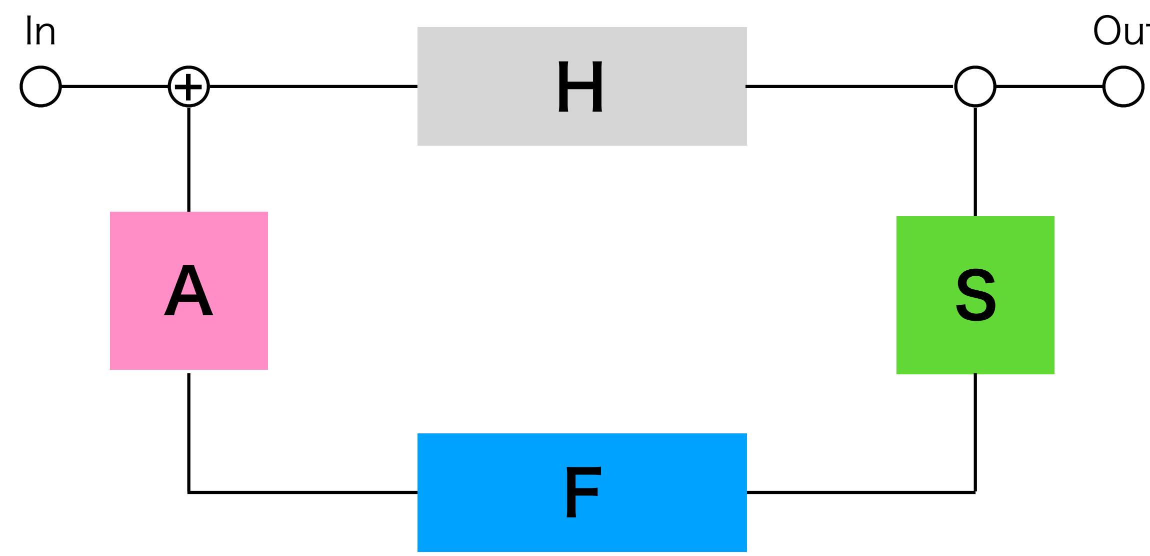
- The cryogenic payload reduces the some noises and aligns the mirror.
- It has the proper ability for the interferometer control on below each phases.



We use two types of damping control filter.

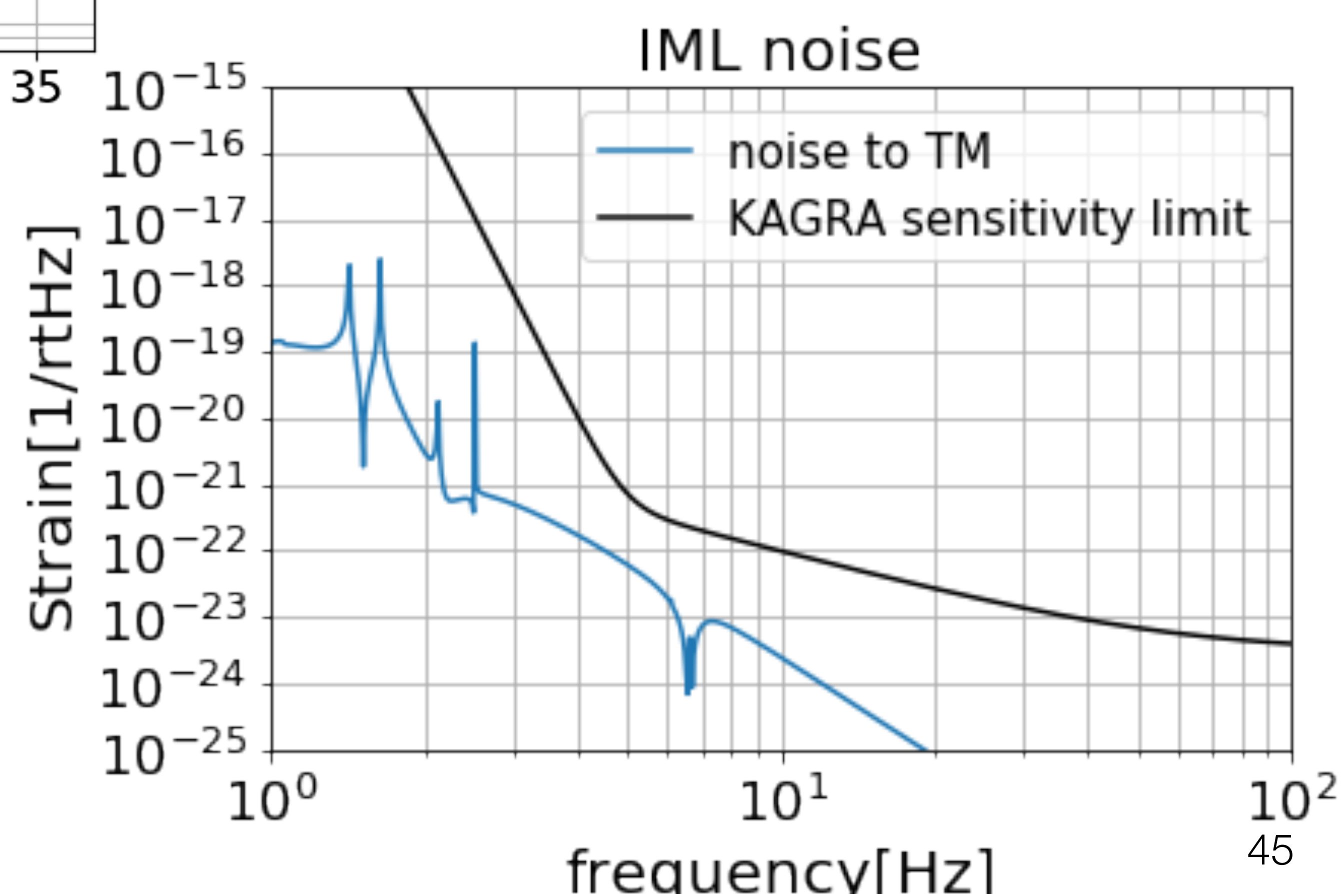
Damping simulation





↑Damping simulation is successful.

Noise level is clear. →



Summary

Development

- ★Working on cryogenic temperature(20 K).
- ★Non-contact and an large dynamic range : 13 mm~
- ★Linear ranges : 20 mm ± 3 mm
- Influence of individual difference ~ 30%
- Long-term stability ~ 3 months

Applications

- Noise levels → clear
- Damping simulation → successful

The cryogenic displacement sensor satisfies the requirements and the requests for use in KAGRA.