Multi-Color Interferometry for Lock Acquisition of Laser Interferometric Gravitational-wave Detectors

レーザー干渉計型重力波検出器における動作点引込みのためのマルチカラー干渉技術

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Abstract

Background

Lock Acquisition problem in laser interferometric detector. This issue needs to be solved.

solution: Control using a multicolor interferometry

√ main laser1064 nm infrared

√a new auxiliary laser (532 nm green)

Main topics

√ 40 m baseline prototype experiment

√ Feasibility study in a km-scale detector

Contents

Contents

Gravitationl Wave Astronomy

Gravitational wave

- √ Predicted by General Relativity
- √ Propagation of spacetime distortion
- √ Radiated by accelerated mass
- √ No direct detection ever

To obtain a sufficiently big amplitude

a highly dense and accelerated source is necessary

➡ Astronomical wave sources

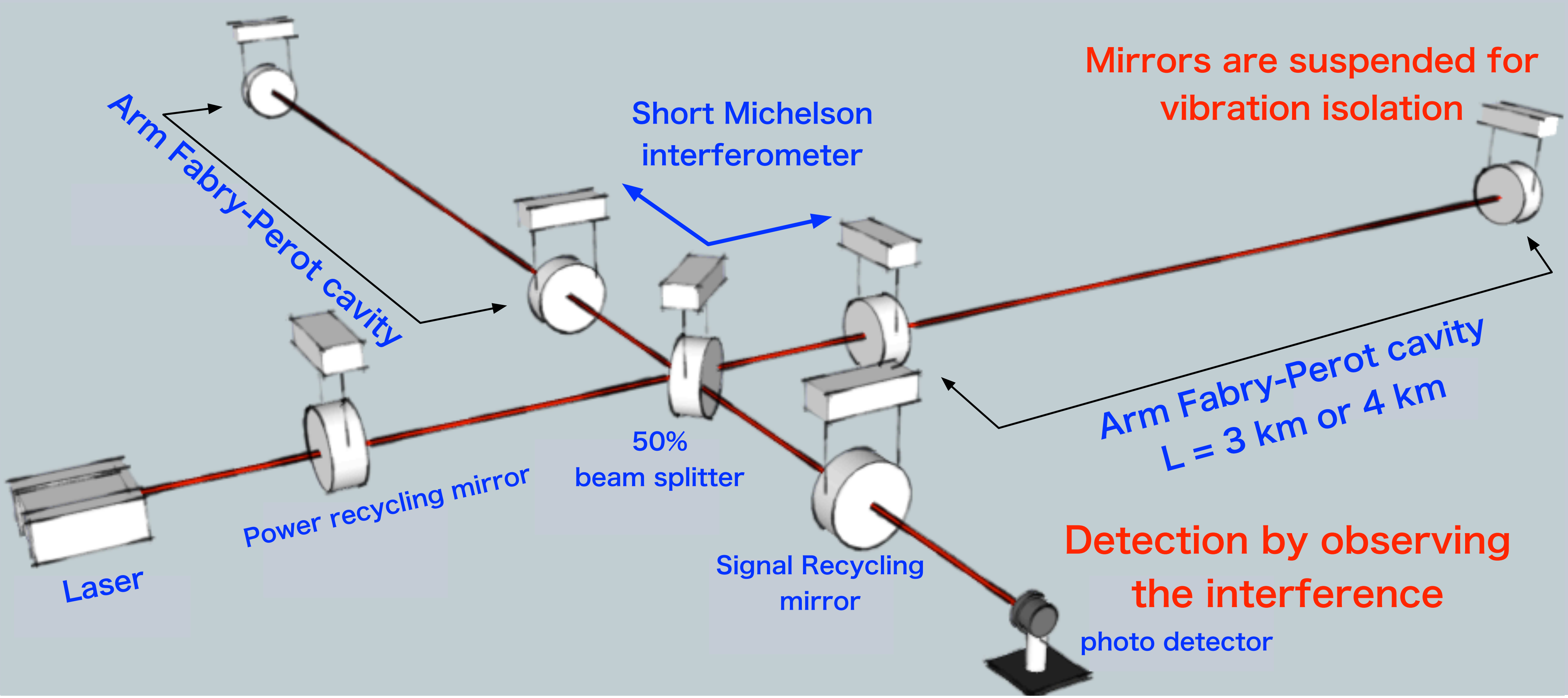
➡ A new window in astronomy : GW Astronomy

Large projects are ongoing around the world

➡ They will be detecting GWs
with a detection rate of ~ a few events/year

Laser Interferometric Detector

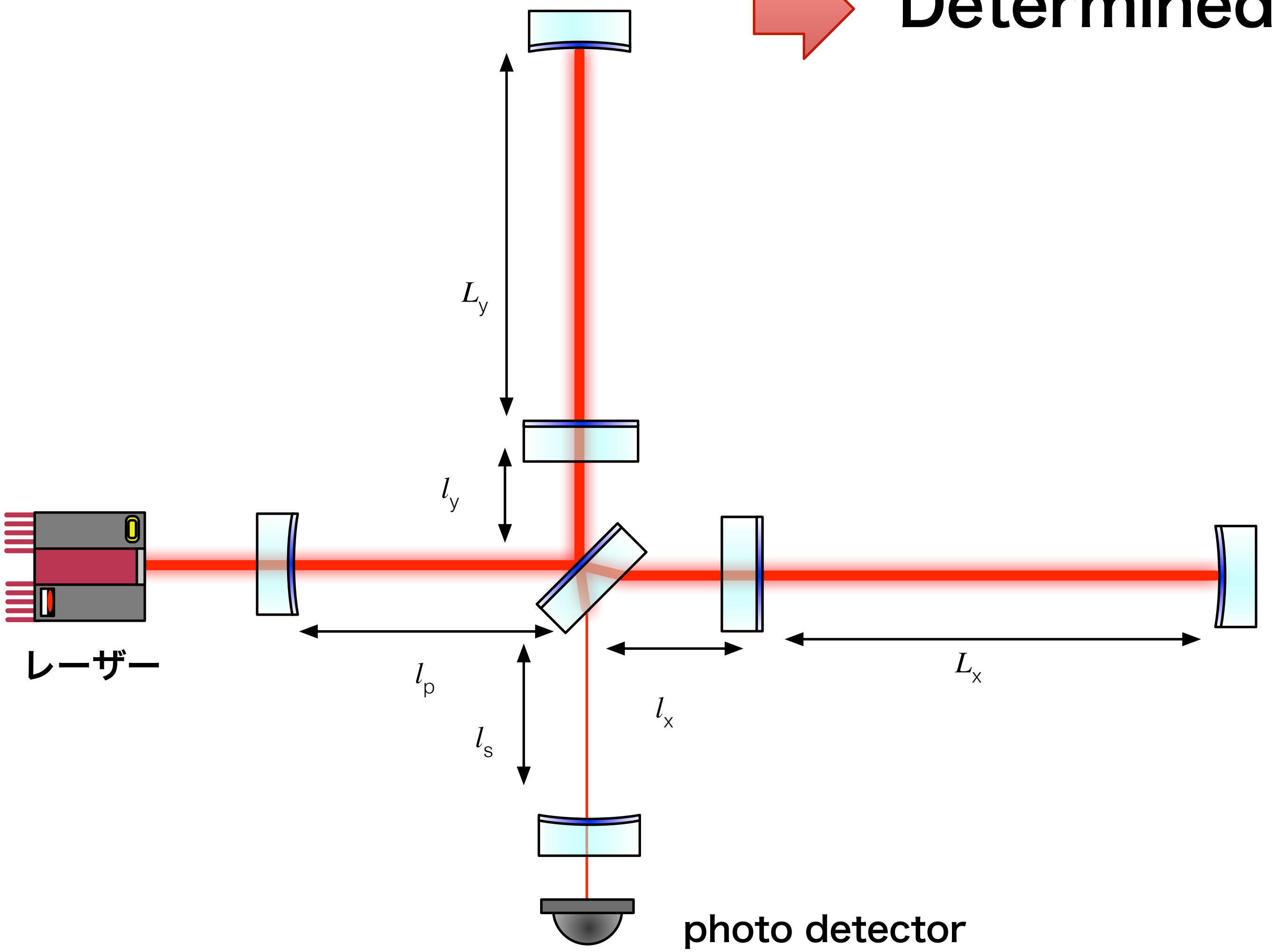
Advanced LIGO(USA), KAGRA(Japan), advanced VIRGO(France/Italy) under upgrade/construction and will be online ~ 2015



To Achieve Design Sesnsitivity

A certain interference condition must be satisfied

➡ **Determined by 5 lengths DOFs**



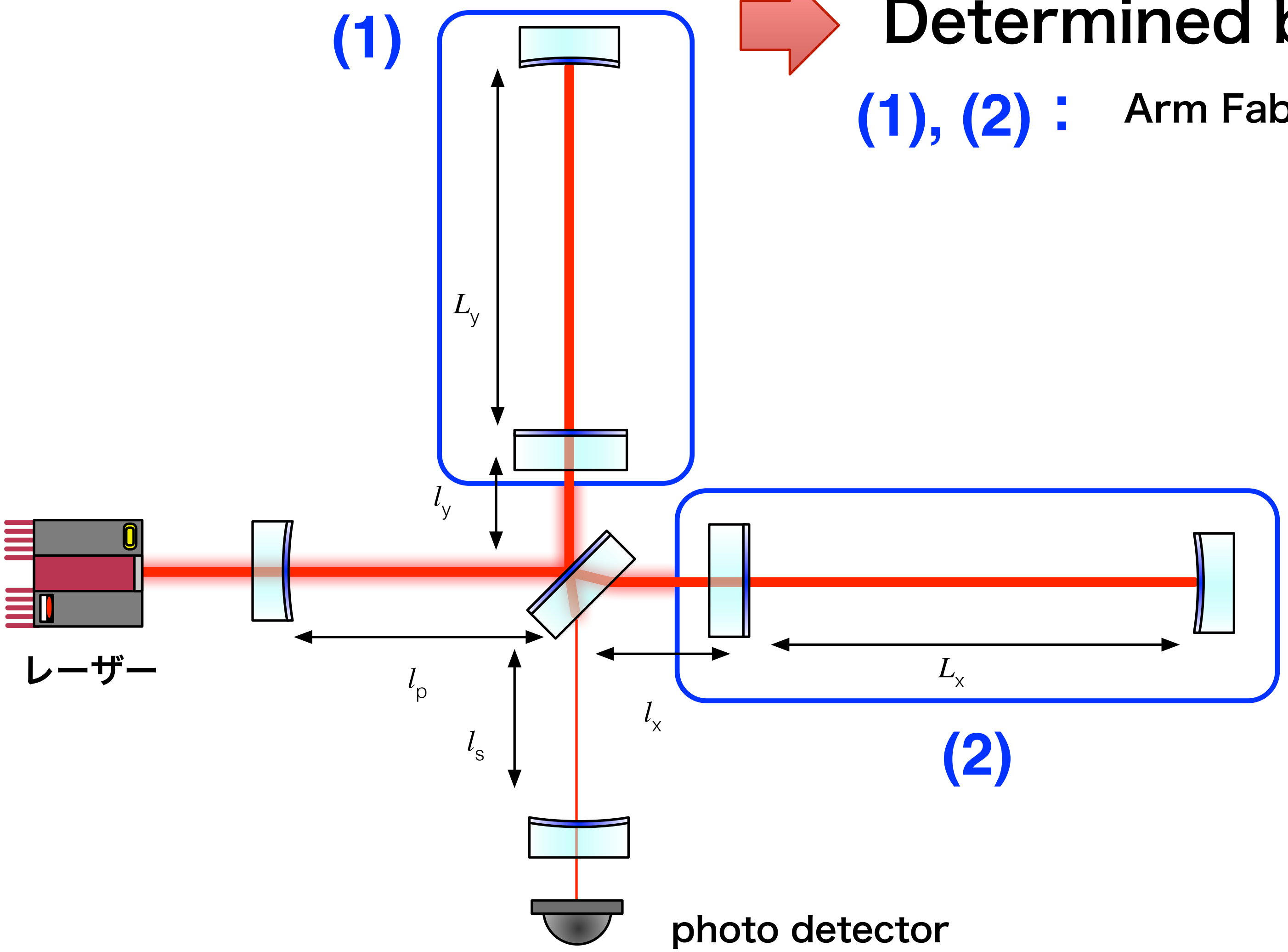
To Achieve Design Sesnsitivity

A certain interference condition must be satisfied

(1)

Determined by 5 lengths DOFs

(1), (2) : Arm Fabry-Perot cavity length



To Achieve Design Sesnsitivity

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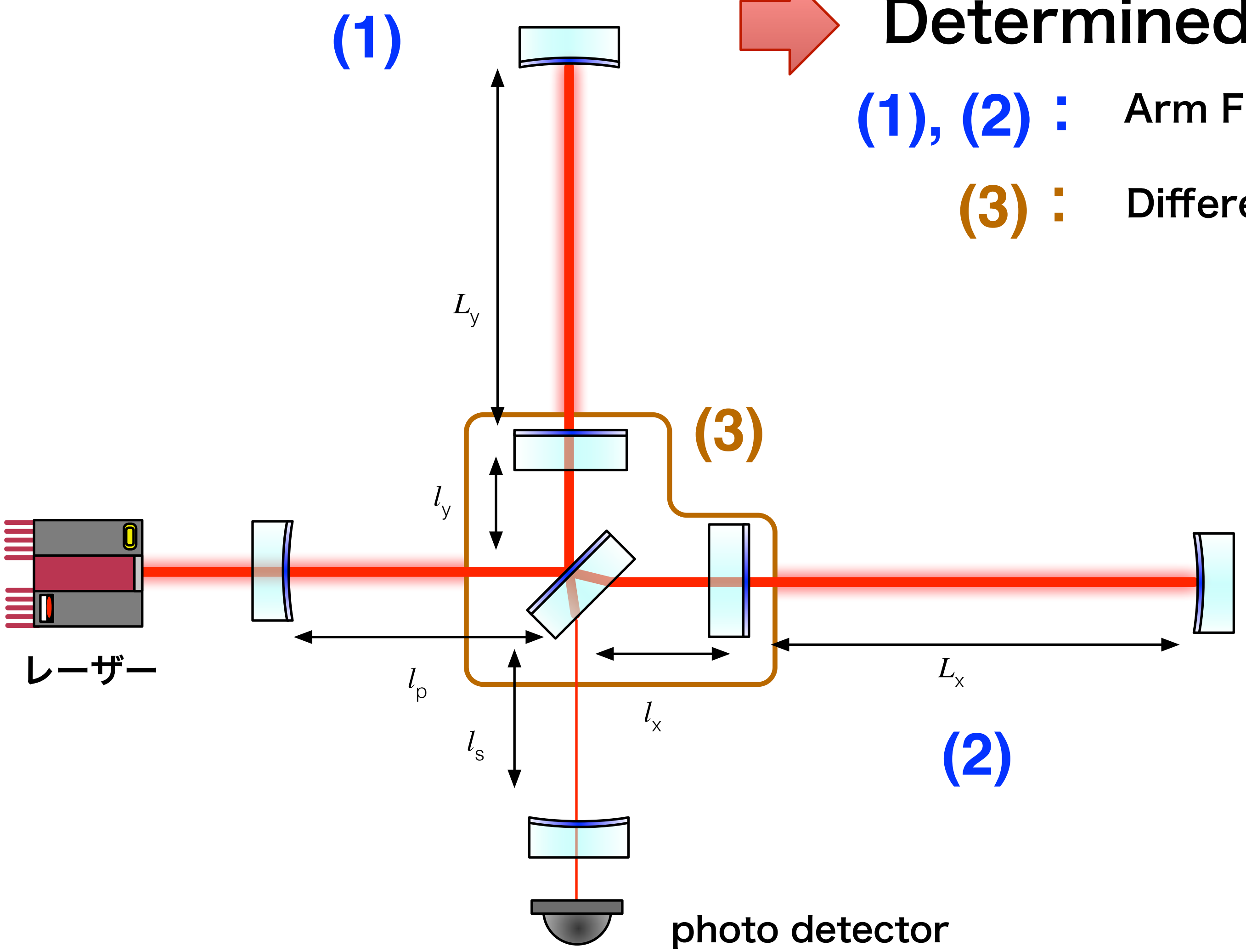
(1), (2) : Arm Fabry-Perot cavity length

(3) : Differential length of Michelson



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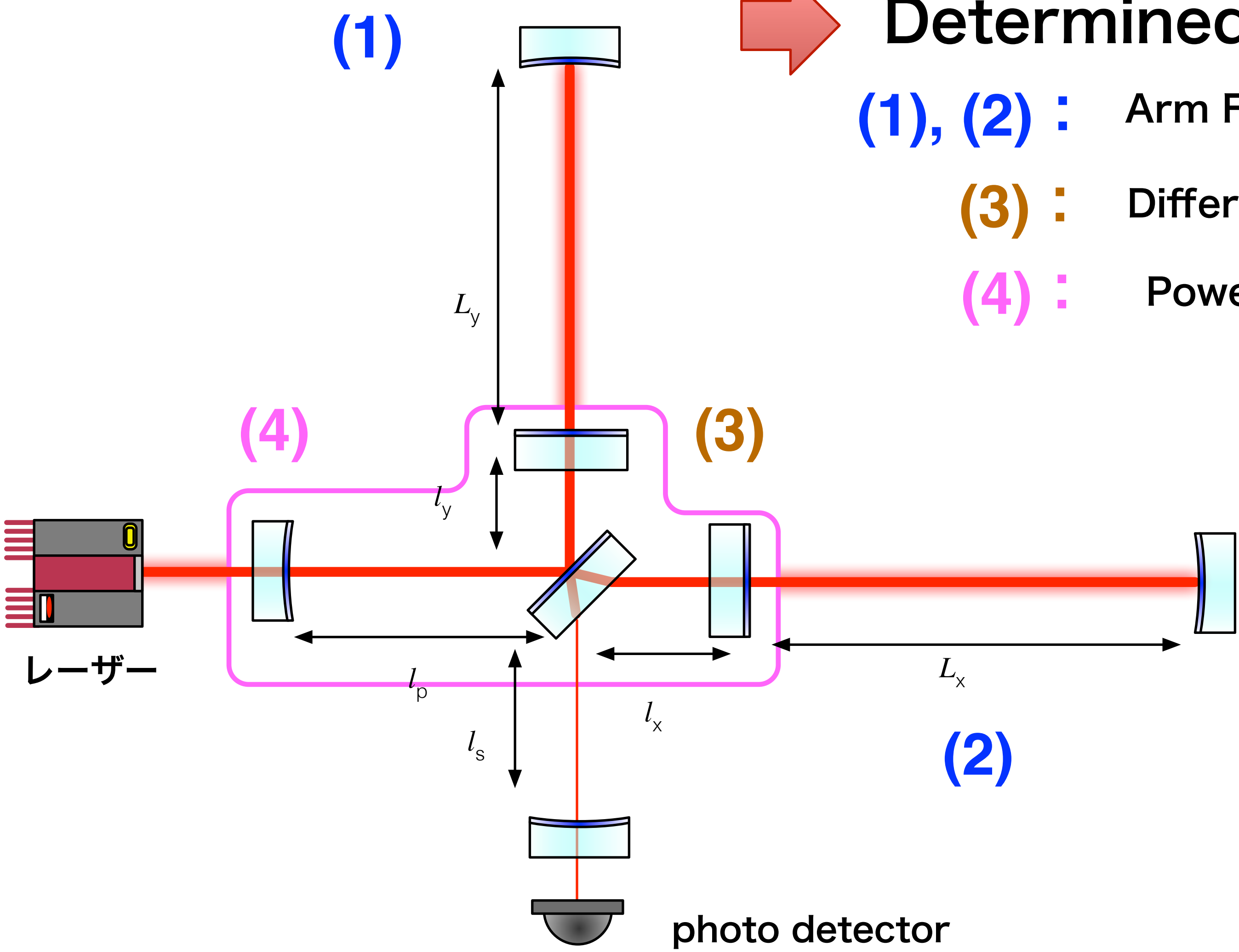

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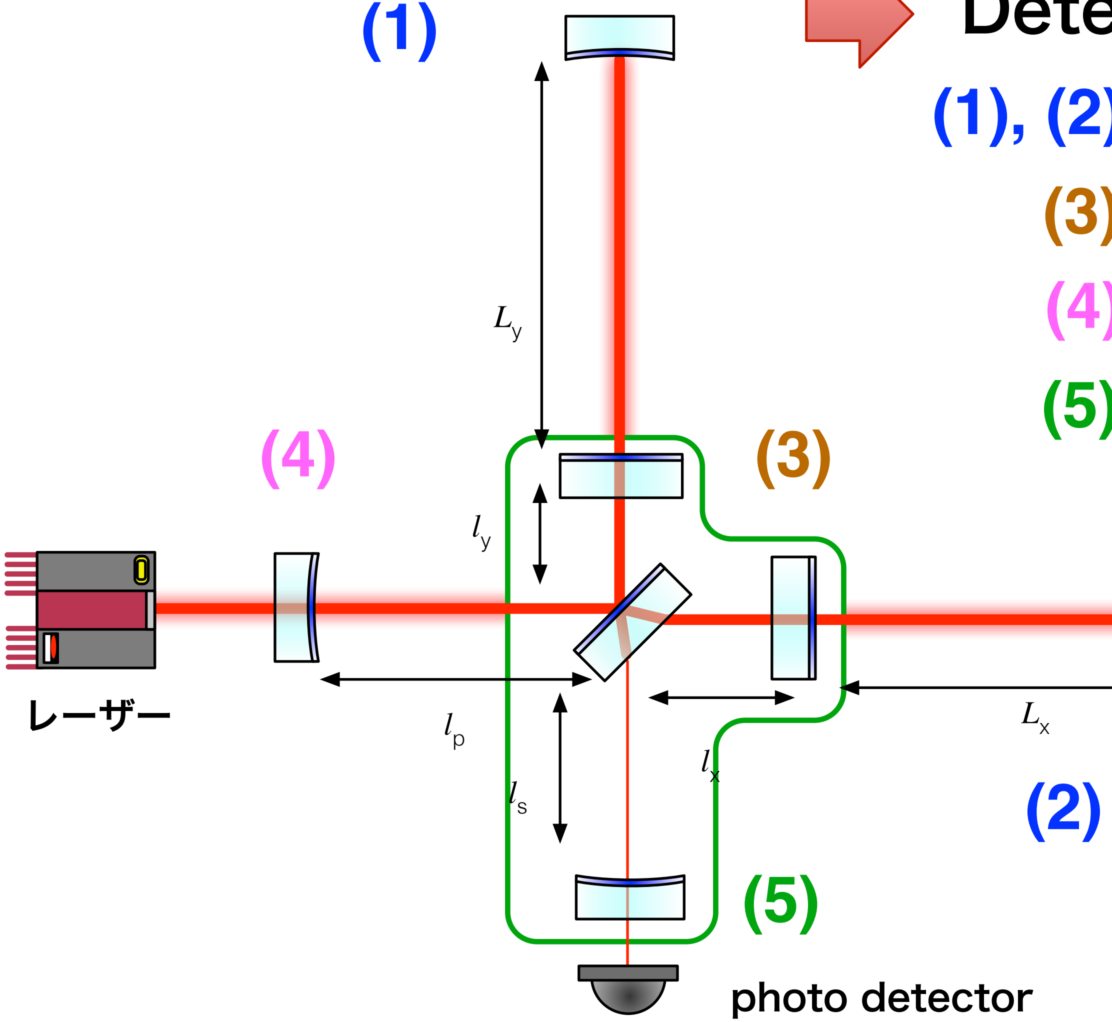


Determined by 5 lengths DOFs

(1), (2) : Arm Fabry-Perot cavity length

(3) : Differential length of Michelson

(4) : Power recycling cavity length

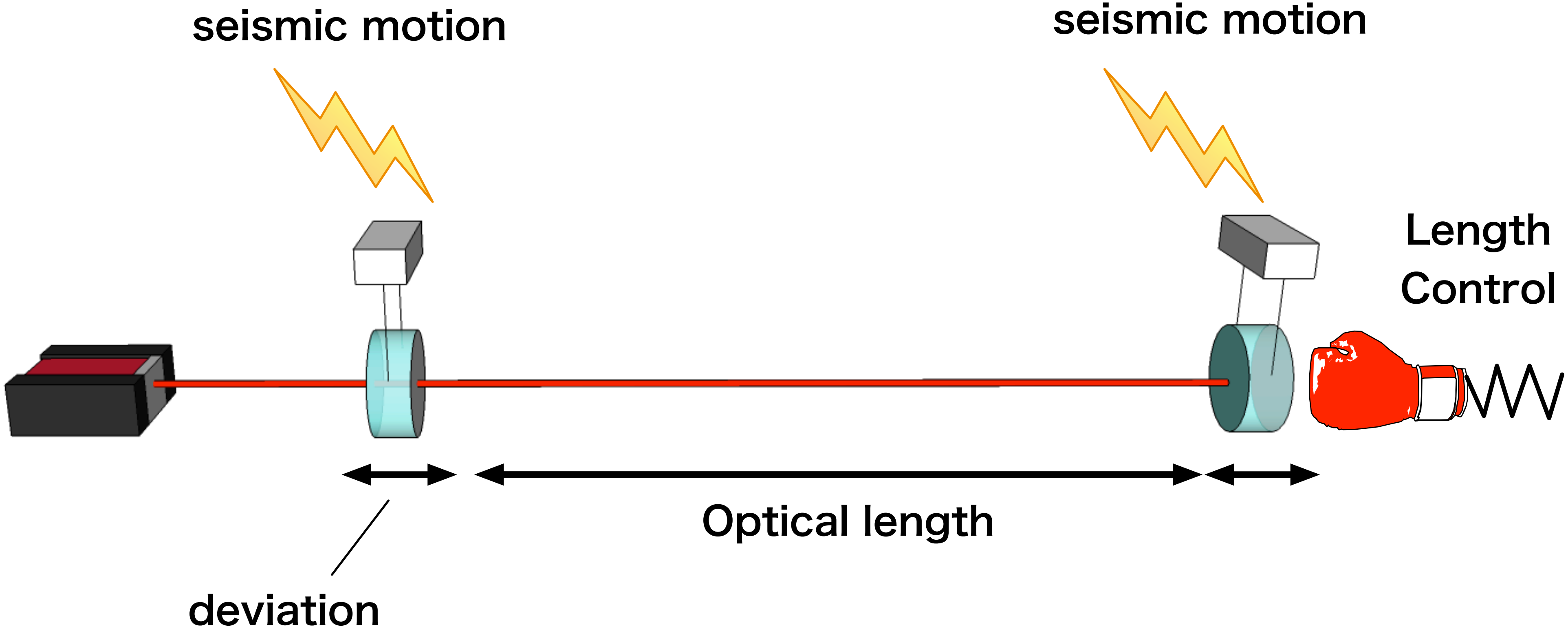
(5) : Signal recycling cavity length

In the previous detectors no signal recycling mirror existed and hence 4 DOFs

Necessary to Control Optical Length

√ Optical distance deviates due to disturbance

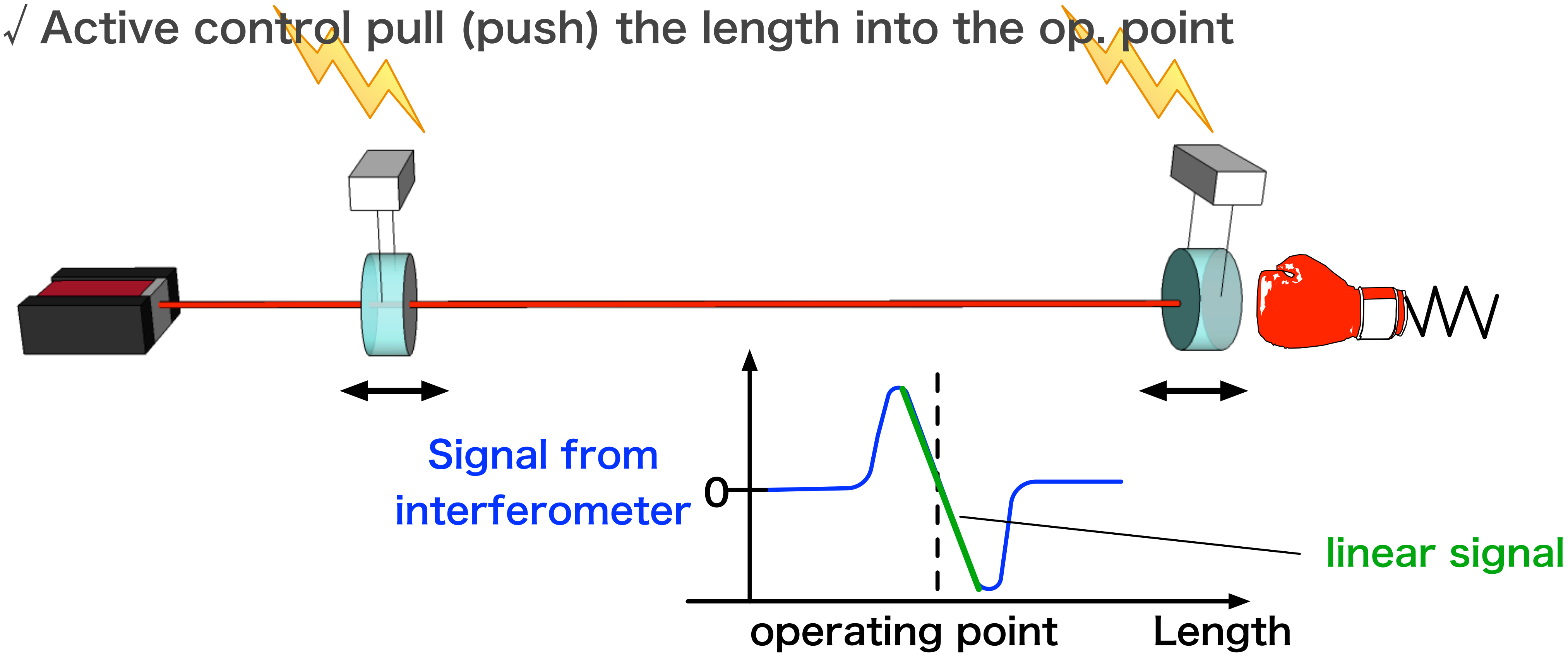
⇨ Active control to maintain a certain length



Lock Acquisition

A process to bring the length to the operating point

- √ Signal from interferometer is nonlinear
- √ linear signal available only in the vicinity of op. point
- √ Due to the seismic noise it spontaneously pass across the op. point
- √ Active control pull (push) the length into the op. point



Lock Acquisition is NOT easy

Full lock proceeds step by step

√ All 5 DOF won't be in the vicinity of the operating point spontaneously
√ We lock one DOF and then lock another DOF sequentially
√ Arm cavities are locked at the very end of the progression
√ It needs to suppress residual motions so that one can pass the control to the observational sensors

⇒ **Not easy to lock the arm cavities**

Two main factors

Nonlinearlity	optically coupled cavities

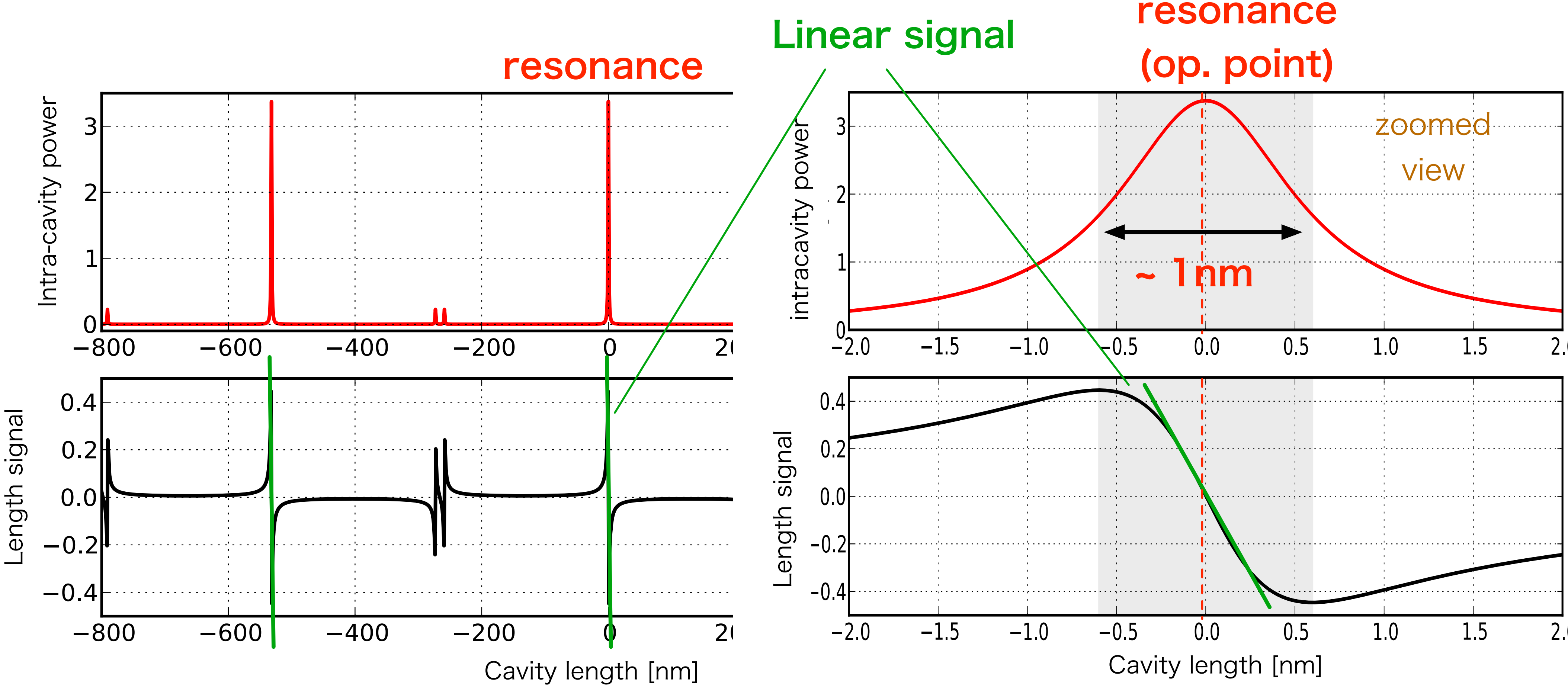
* addition of SRM makes the interference condition more complicated

Difficulty 1 : Nonlinearity

Difficult to stop the mirror within the resonance linewidth

√ Ground motion ~ order of 100 nm

√ We have to confine the length within 1 nm

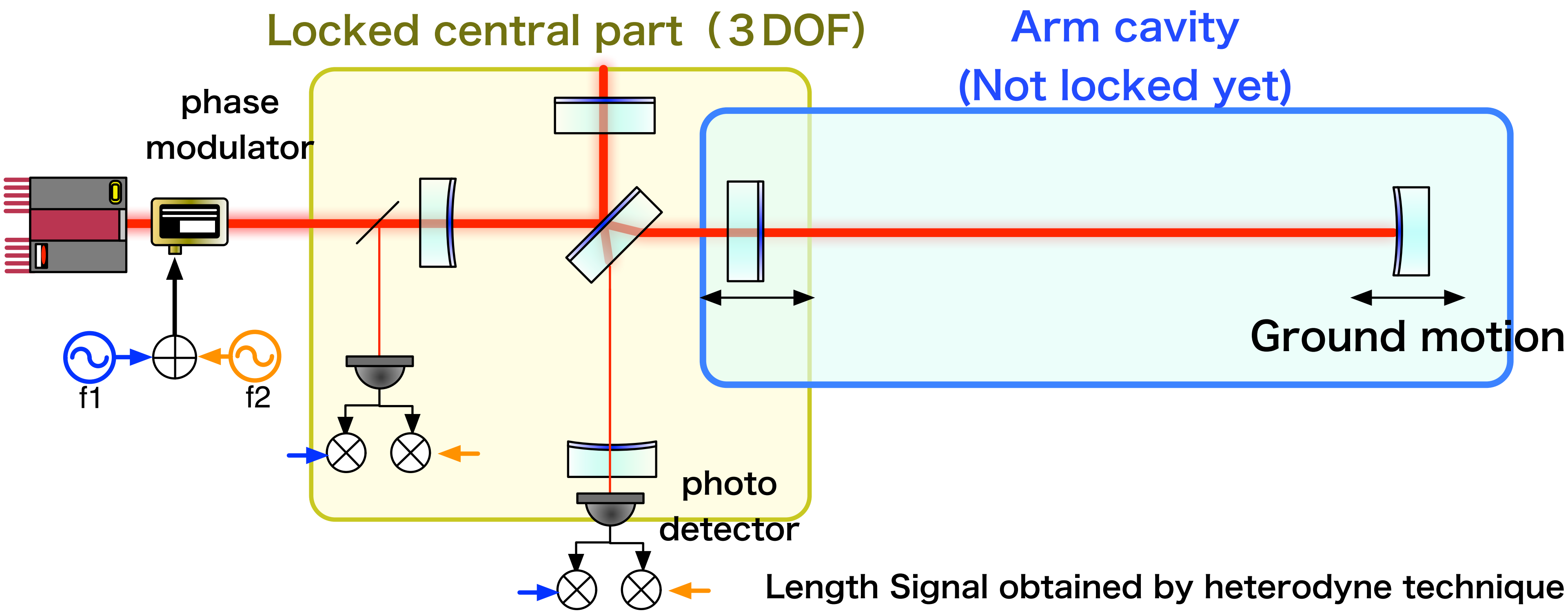


Difficulties 2 : coupled cavities

√ Arms occasionally couple with the central part

➡ Dramatically changes the interference of the central part

➡ Disturbance in the signal : control of the central part gets destroyed.



Need a New Idea

It is unclear if we can achieve full lock acquisition

Bad things can happen

√ If arms motion get excited (e.g. big ground motion)

You cannot stop the mirrors and the central part frequently gets destroyed.

√ In the future in more sensitive detectors

Actuators becomes weaker and more difficult to lock

⇒ It is time to change the strategy

Summary of Background

√ Necessary to maintain a certain interference condition

√ Active control suppresses the optical length deviation

√ Linear signal available only in the vicinity of resonances

√ Full lock is a step-by-step progression

√ (1)Nonlinearity and (2) coupled cavities complicate locking of the arm cavities

√ Necessary to develop a new scheme

Contents

Motivation of Multicolor Interferometry

Points to be fixed

Arms were not under control

Arms were freely swinging

Solution

Newly adding a wide range sensor should allow us to control arm cavities independently

What kind of sensor ?

- √ Measures optical length ➡ Laser interferometry
- √ Couples only with Arms ➡ Dichroic mirror + other wavelength
- √ Syncs with main laser ➡ SHG (Second Harmonic Generation)

Muli-Color Interferometry

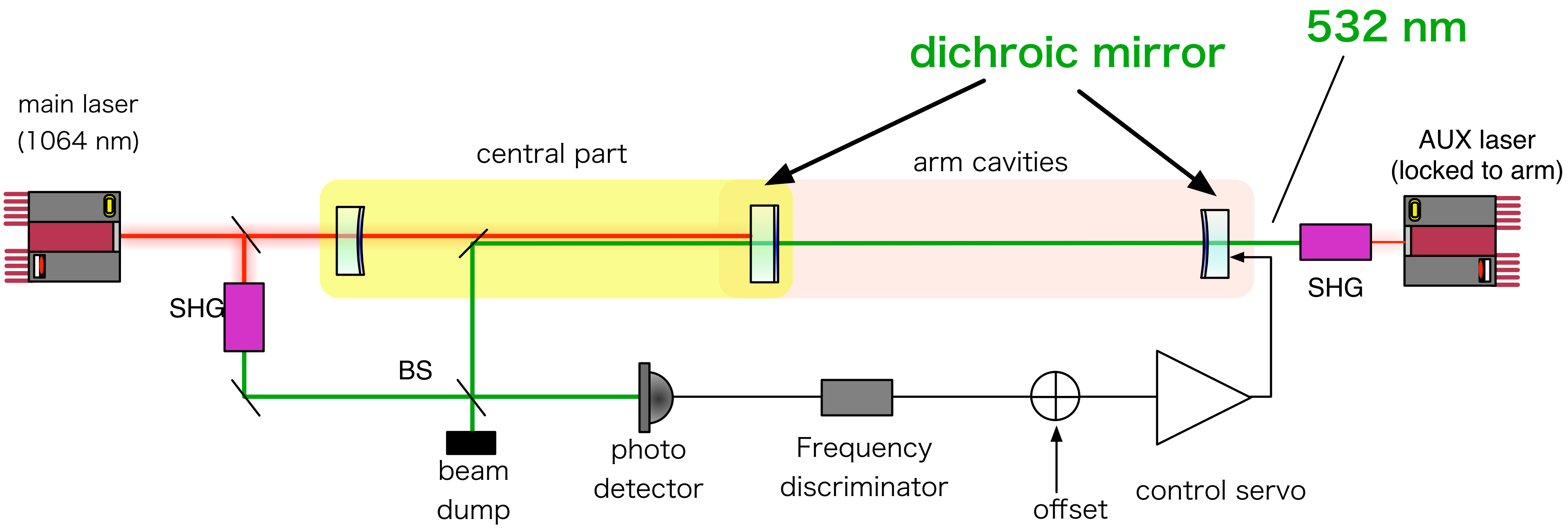
√ Idea existed in the past. A dedicated design done in 2009

√ Senses motion of the arms "indecently" in "wide range"

A frequency-doubled laser is placed at the end of the arms

The arm mirrors are designed to be dichroic

Injection of the green light from the back of the arm



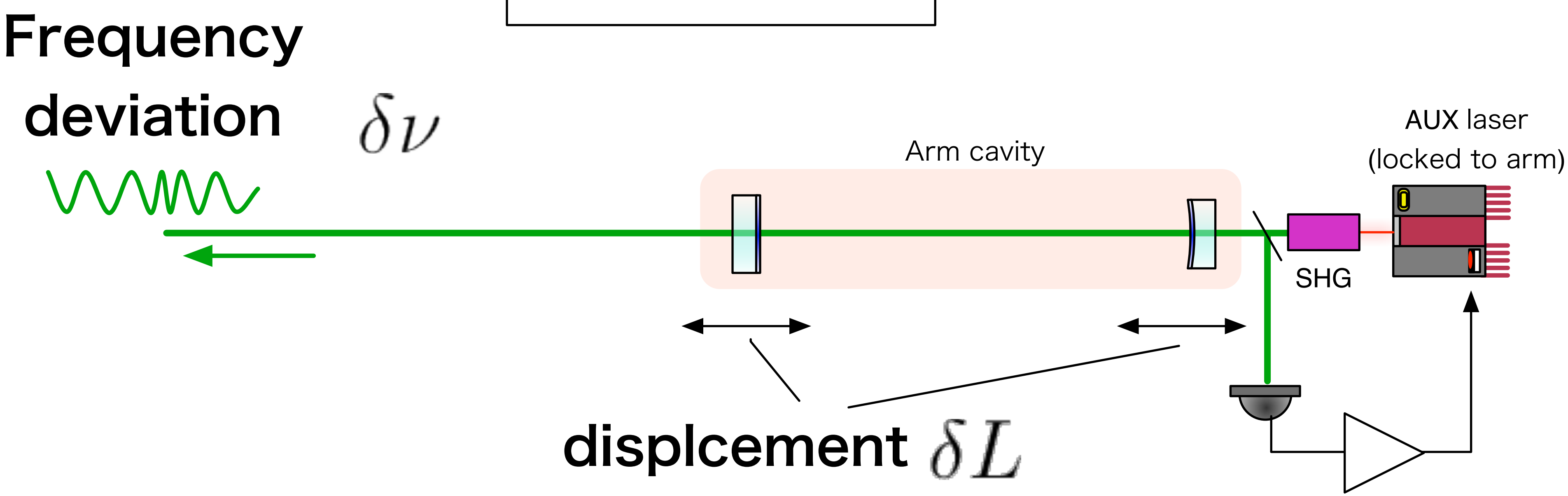
Laser Freq. Carries the Length Info

√ AUX laser is locked the arm length

This forces the AUX laser to follow the arm motion

Frequency of the transmitted laser carries the displacement information

$$\delta\nu \propto \delta L$$



Main Laser as Freq. Reference

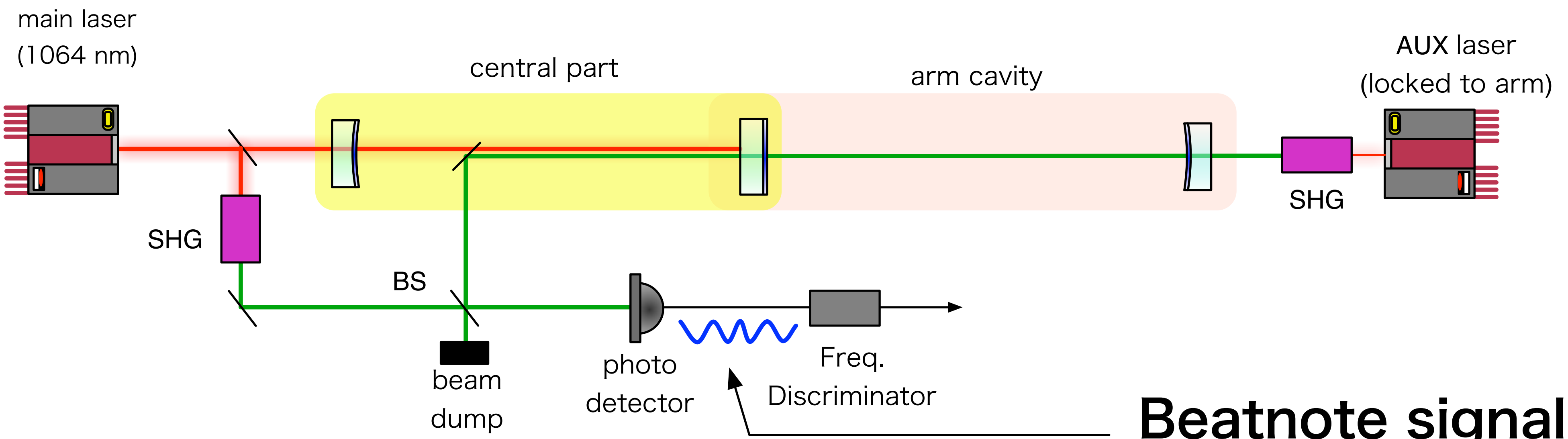
√ What is the reference when you measure the length?

Frequency of the main laser

√ Beatnote frequency by the two fields

Frequency comparison of the main and AUX laser

The length is read and the main laser serves as reference



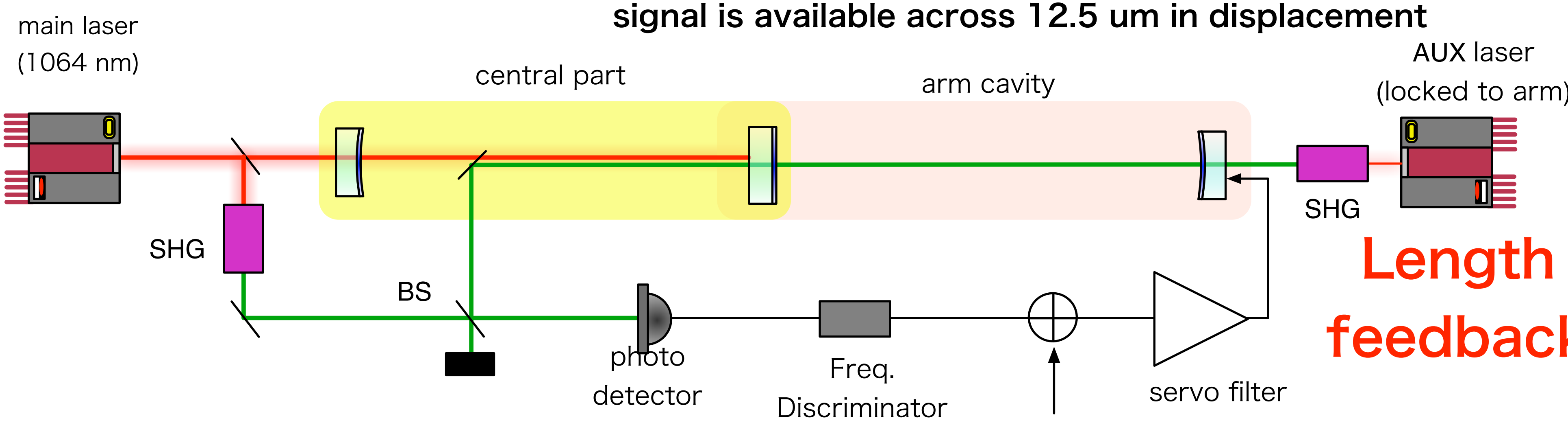
Wide Linear Range is Good

It can control the length in a wide range
It allows us to optically decouples the arms from the rest

Solves the coupled cavity issue !

√ the arm length can be read as long as the beatnote can be detected

In the case of the 40m arm length the signal is available across 12.5 um in displacement



Length feedback

Length adjustment with an offset

Summary of Multicolor Technique

√ Robust lock by independently controlling the arms

√ A new sensor with a different wavelength laser

√ AUX laser carries the displacement information

√ A wide linear range by the frequency detection

√ Arm length can be (1)stabilized and (2)controlled
in a wide length range

√ the nonlinearity and coupled cavity issues are solved

Contents

1. Background
2. Lock Acquisition
   with Multi-Color interferometry
3. **Experimental demonstration in prototype**
4. Evaluation of Stability
5. Conclusion

The motivation

Multicolor interferometry for Arm Length Stabilisation will be used in Advanced LIGO and KAGRA

A prototype test is necessary !

√ Demonstration of the technique
√ Stability evaluation (must be smaller than 1 nm)
√ Estimation of the performance in the 4 km interferometer

→ A test was conducted at a LIGO prototype
＊only a single arm was used

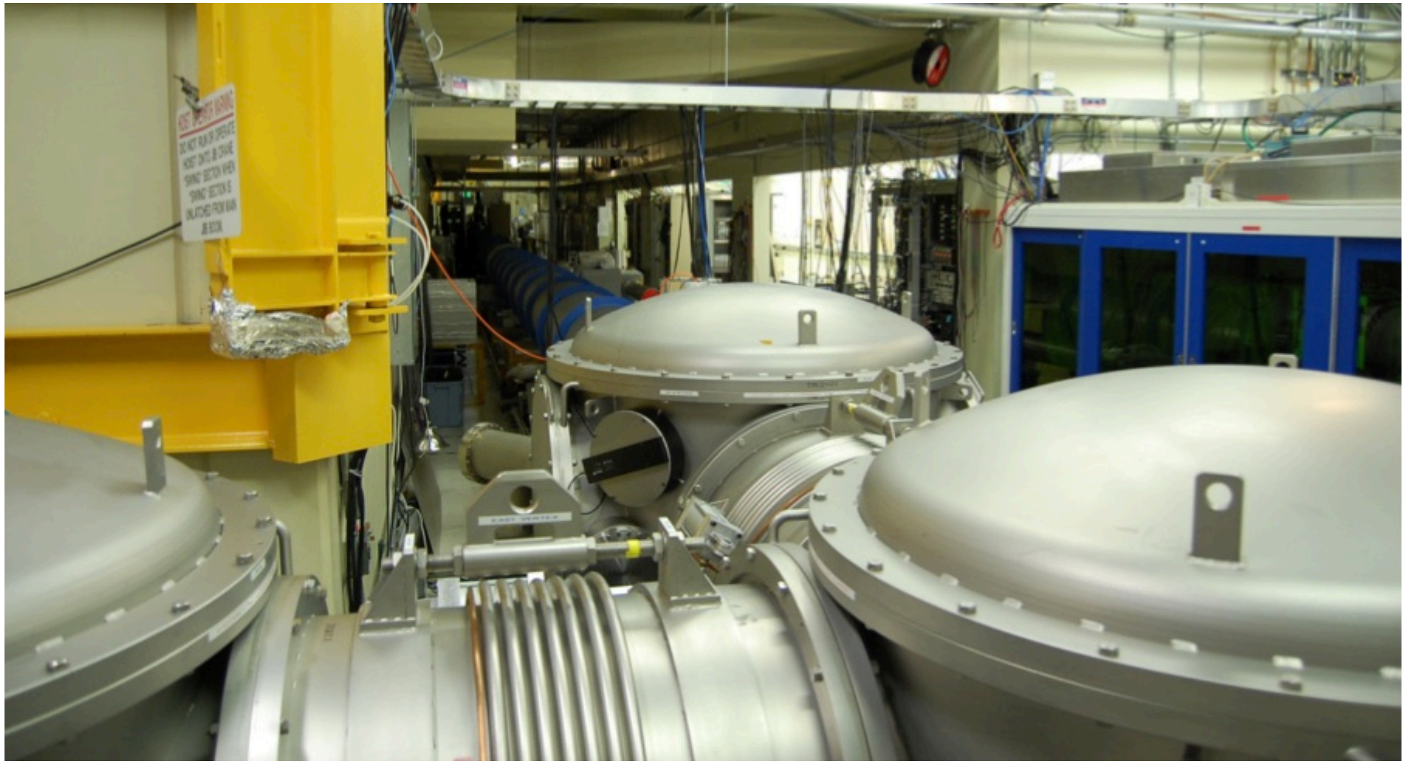
40 m baseline interferometer

Only one full prototype for Advanced LIGO

√ on the campus of California Institute of Technology

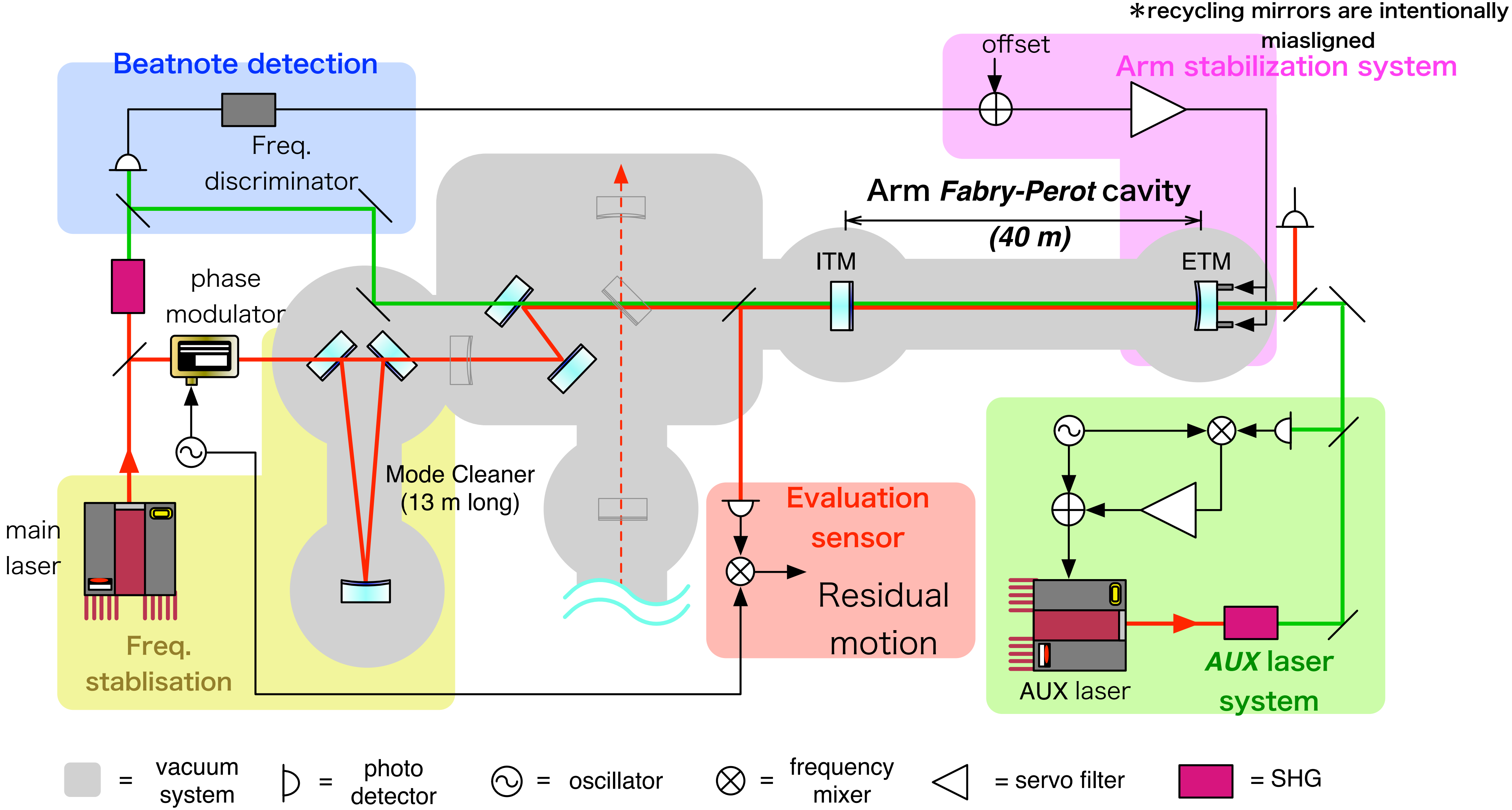
√ Testbed for the length control of Advanced LIGO

√ Demonstration of the length control schemes

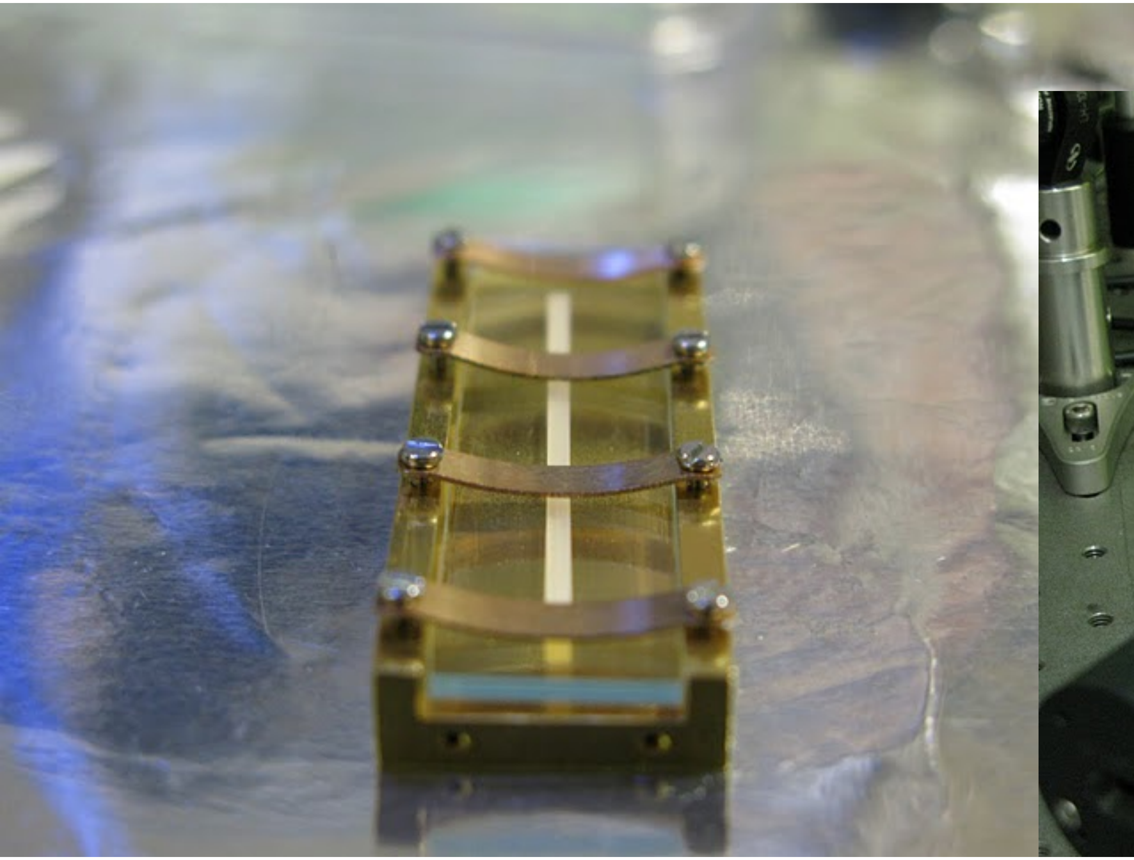


The Setup

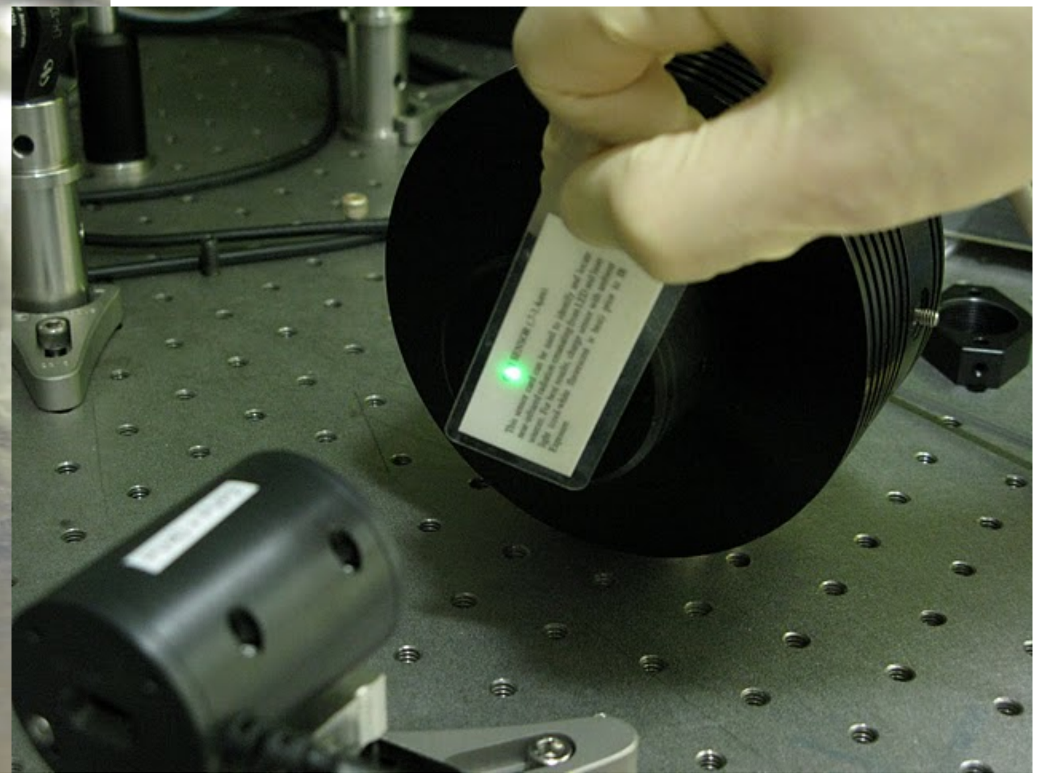
40 m arm cavity of the prototype was used



Pictures : SHG (Second Harmonic Generation)

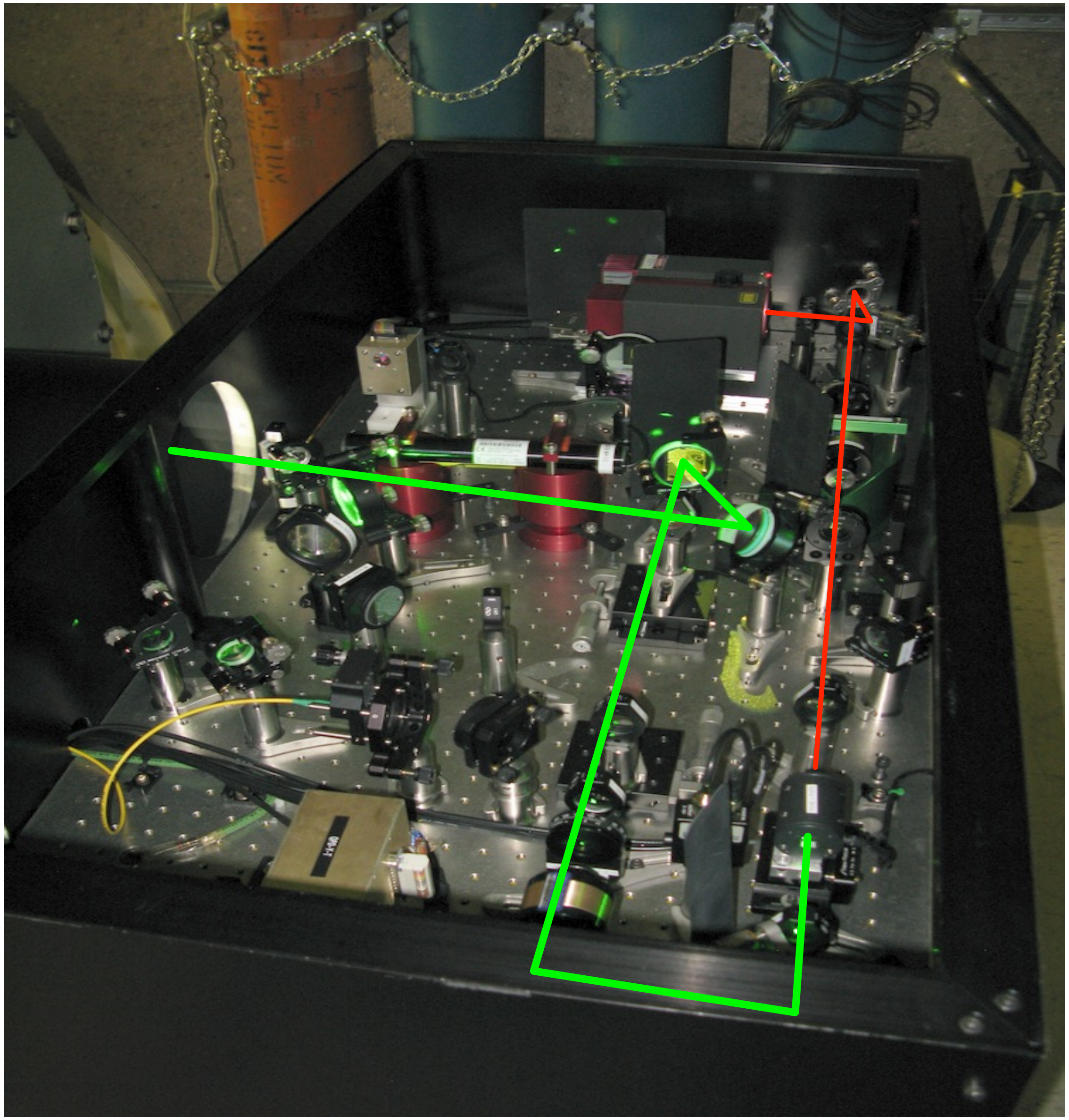


1x1x30 mm
PPKTP



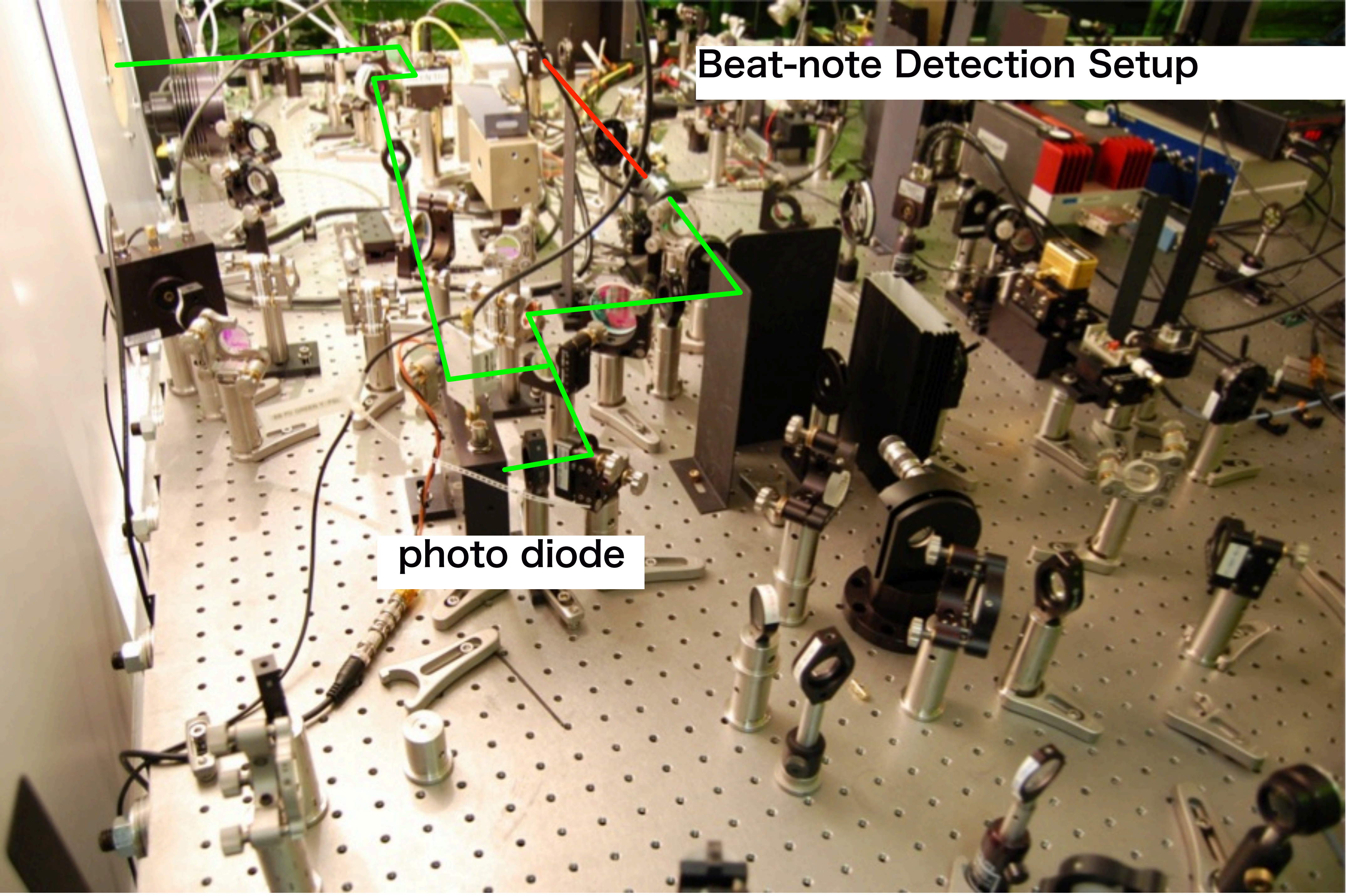
The green light
generated from the crystal
mounted in the oven

Pictures: AUX laser setup



~ 1.2 mW into the arm cavity

700 mW 1064 nm laser


Beat-note Detection Setup
photo diode

Automation by Digital System

Lock Acquisition

- √ Many operators will run the interferometers
- √ People will lock the interferometer Many times during commissionings

⇨ Necessary to automize the sequence

What have been done

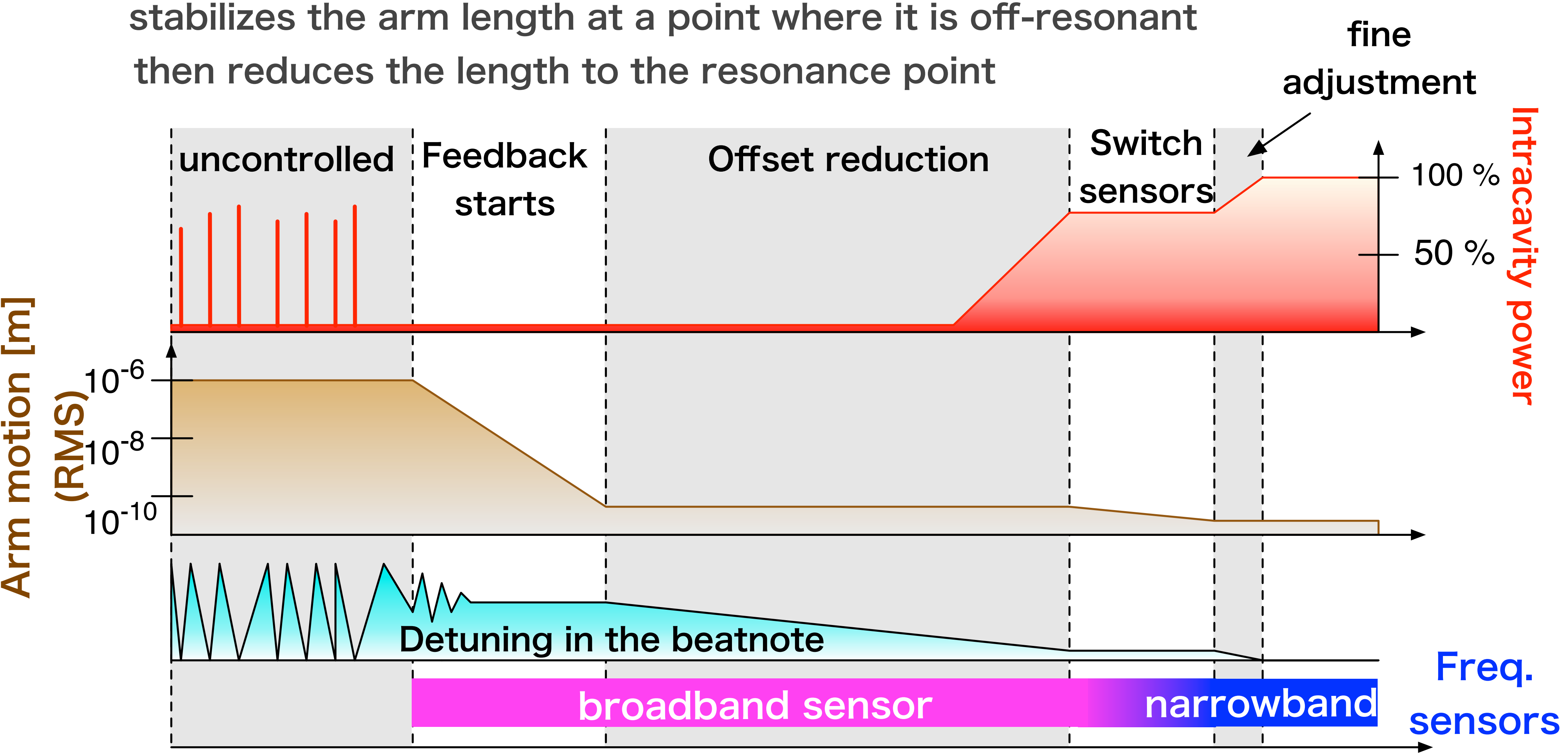
- √ Automation by utilizing script language
- √ Making the control sequential

Automation method can be applied to aLIGO

Automated Lock sequence

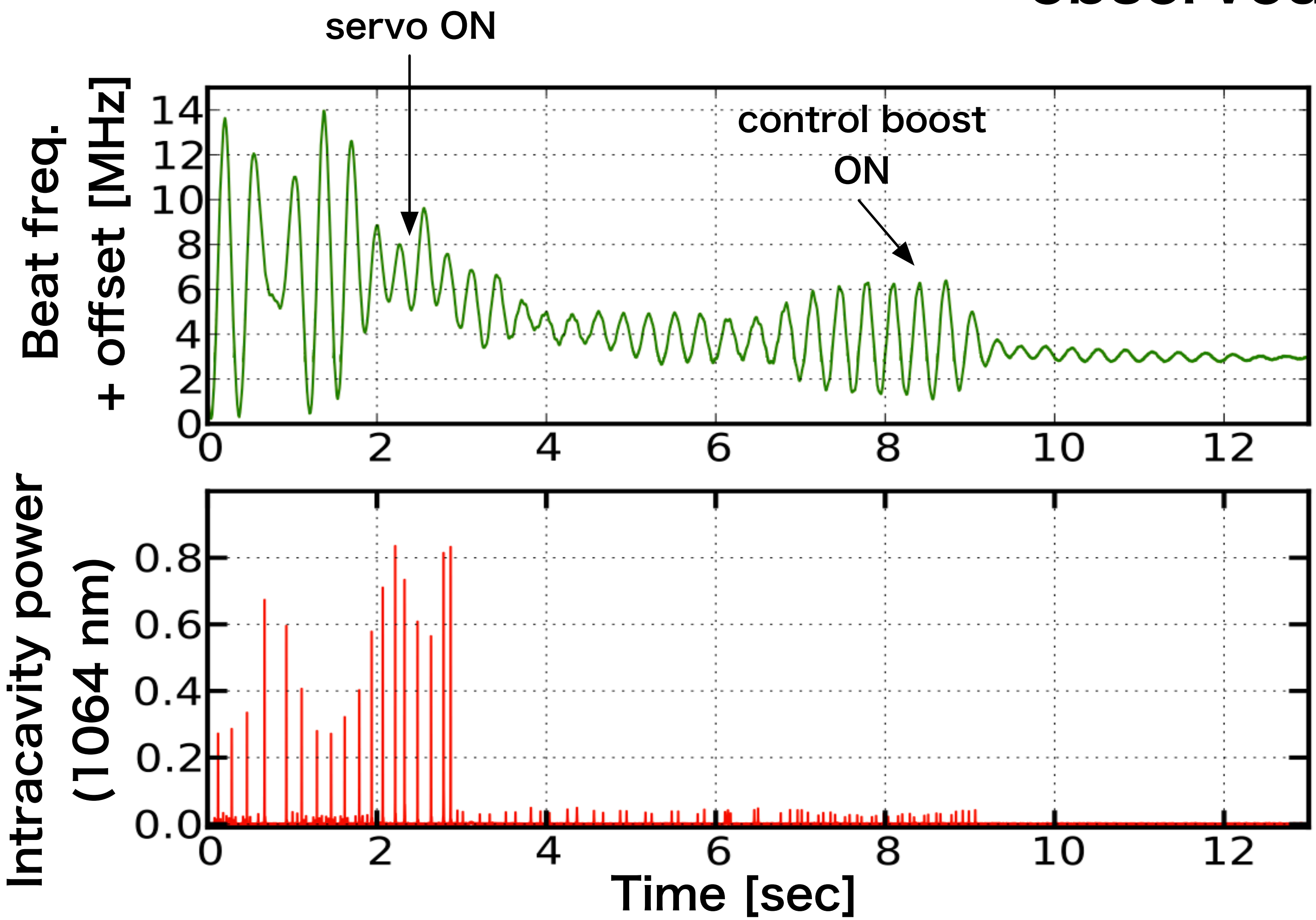
Brings the length to resonance automatically

stabilizes the arm length at a point where it is off-resonant
then reduces the length to the resonance point



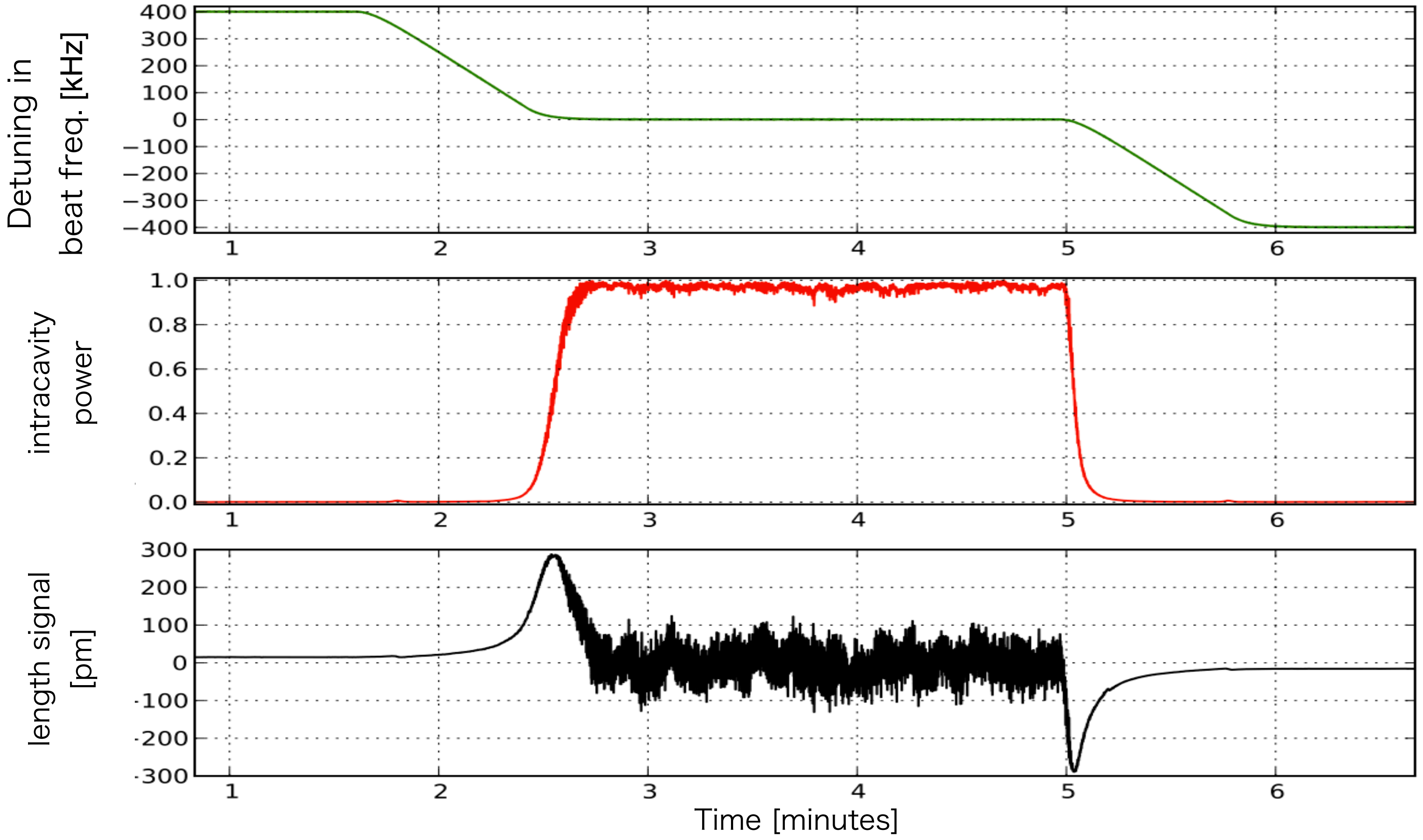
Arm Length Stabilised !

Length stabilisation ⇨ NO ocasional resonance observed



Length can be tuned to arbitrary point

allows us to decouple the arms from the central part



Summary of prototype test

√ Demonstration at the 40 m baseline prototype

√ A single Fabry-Perot arm cavity was used

√ Automation of the lock sequence performed

√ Demonstration of the wide range control

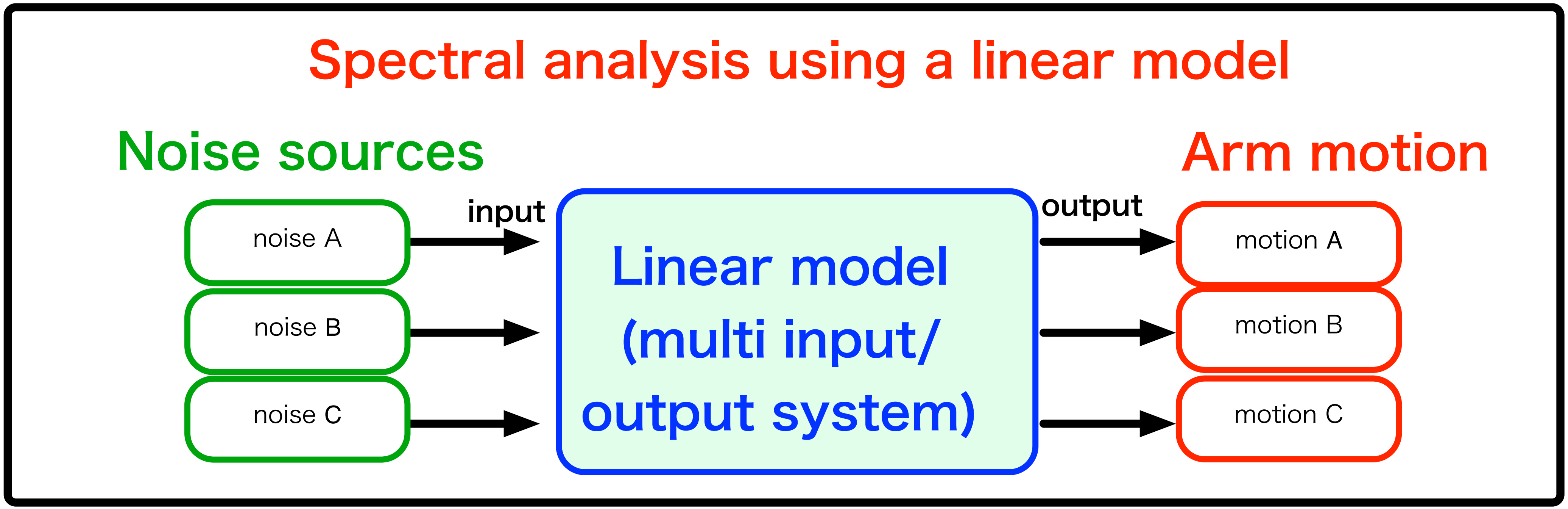
Contents

Evaluation of residual motion

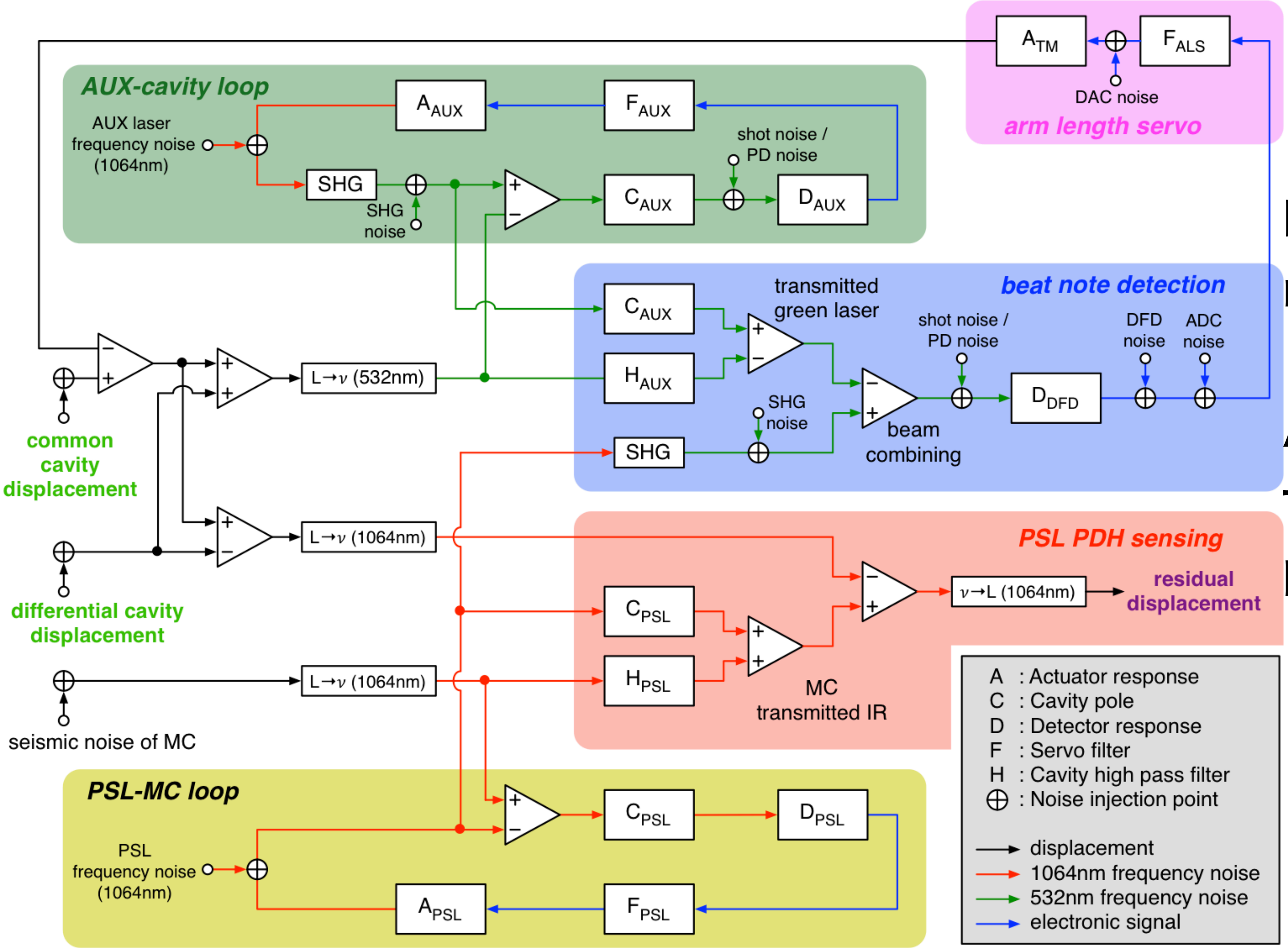
Demonstration was successful

- How good is the stability ?
- What kind noise contributes the residual motion ?
- Still good in Advanced LIGO ?

Evaluation



The Linear Model



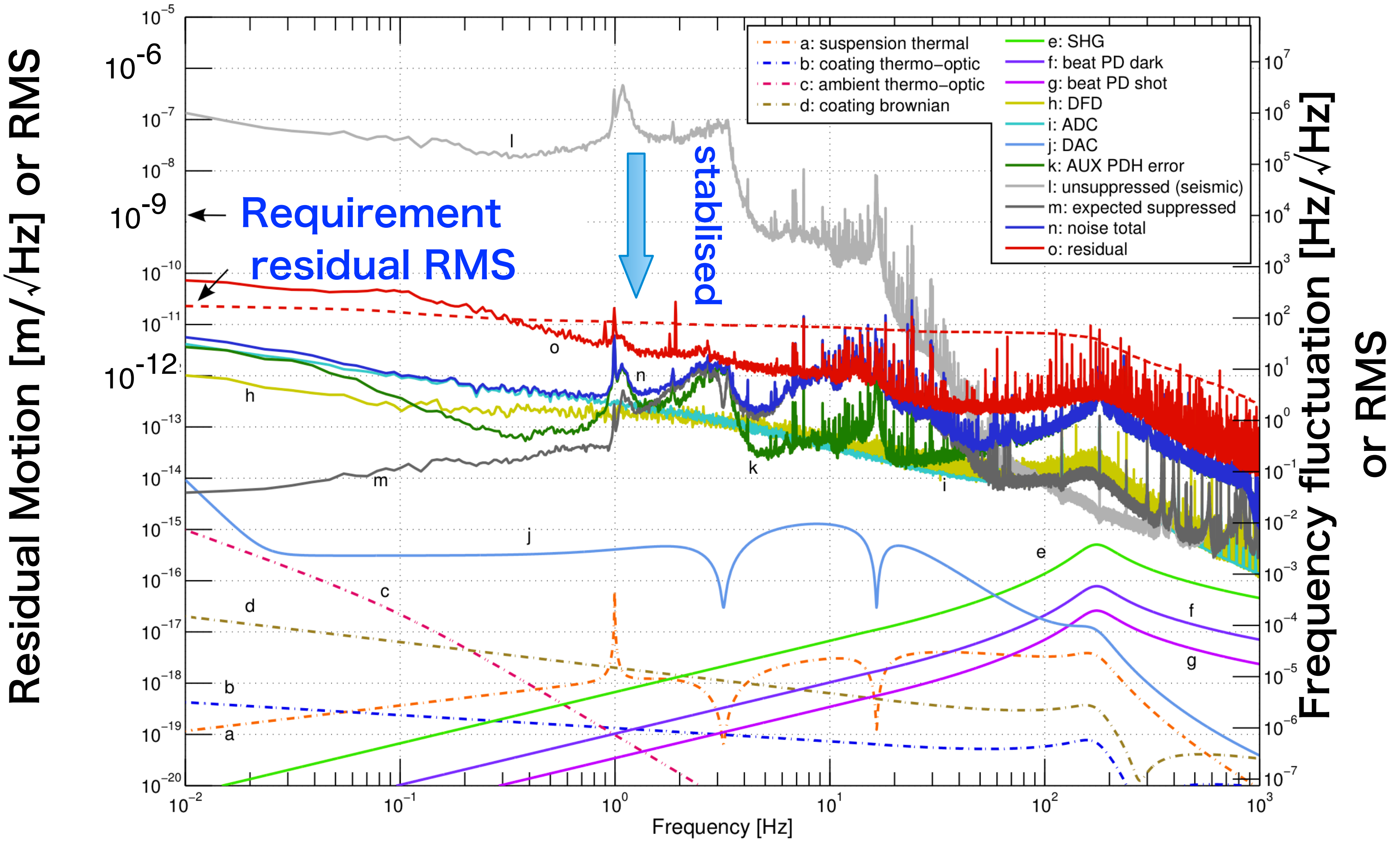
Based on several measurement.

Allows to simulate the noise propagation

Stability in Prototype Test

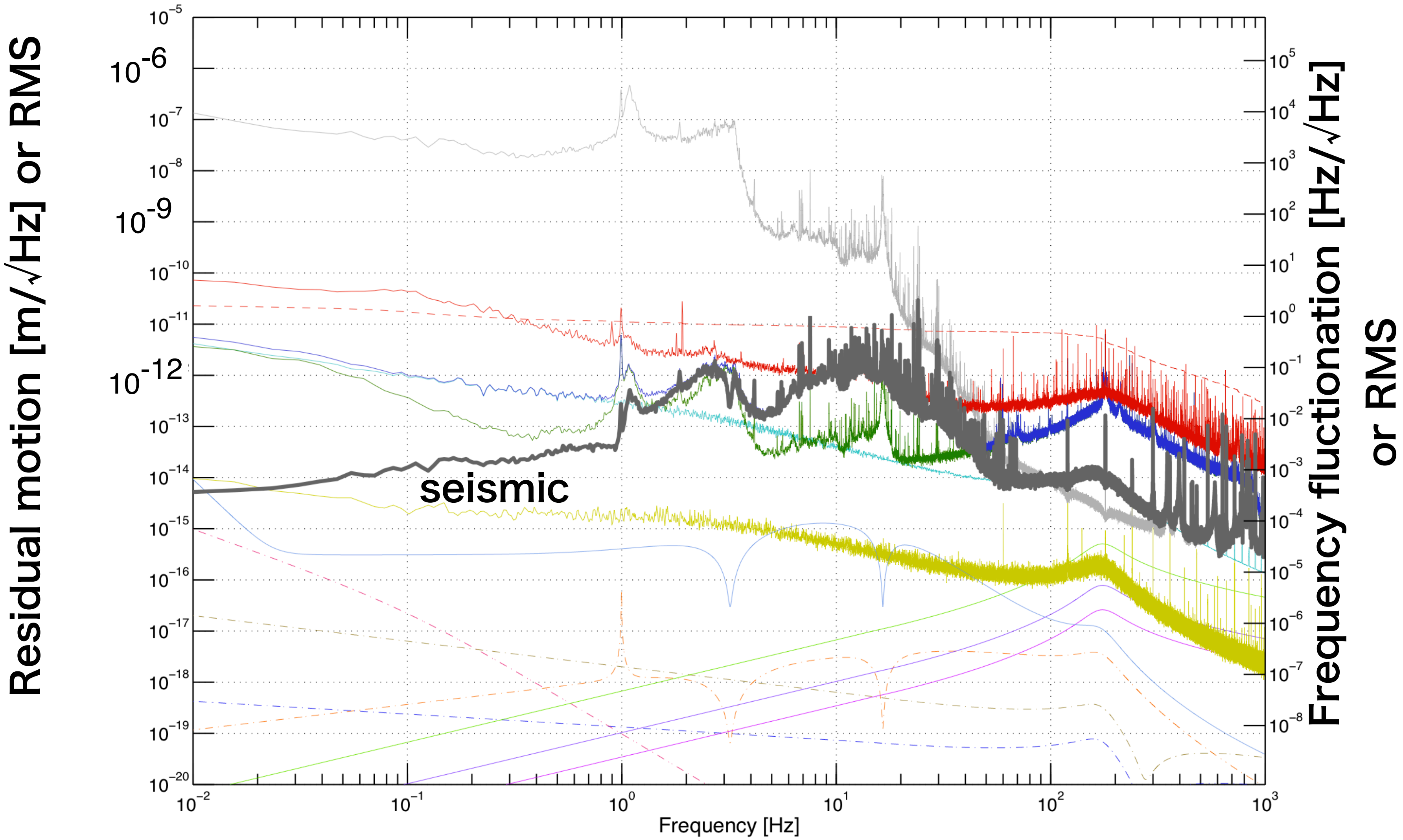
Residual = 24 pm in RMS, surpassing requirement of 1nm

Low and high freq. noise not identified



Main noise 1/3 : Seismic Noise

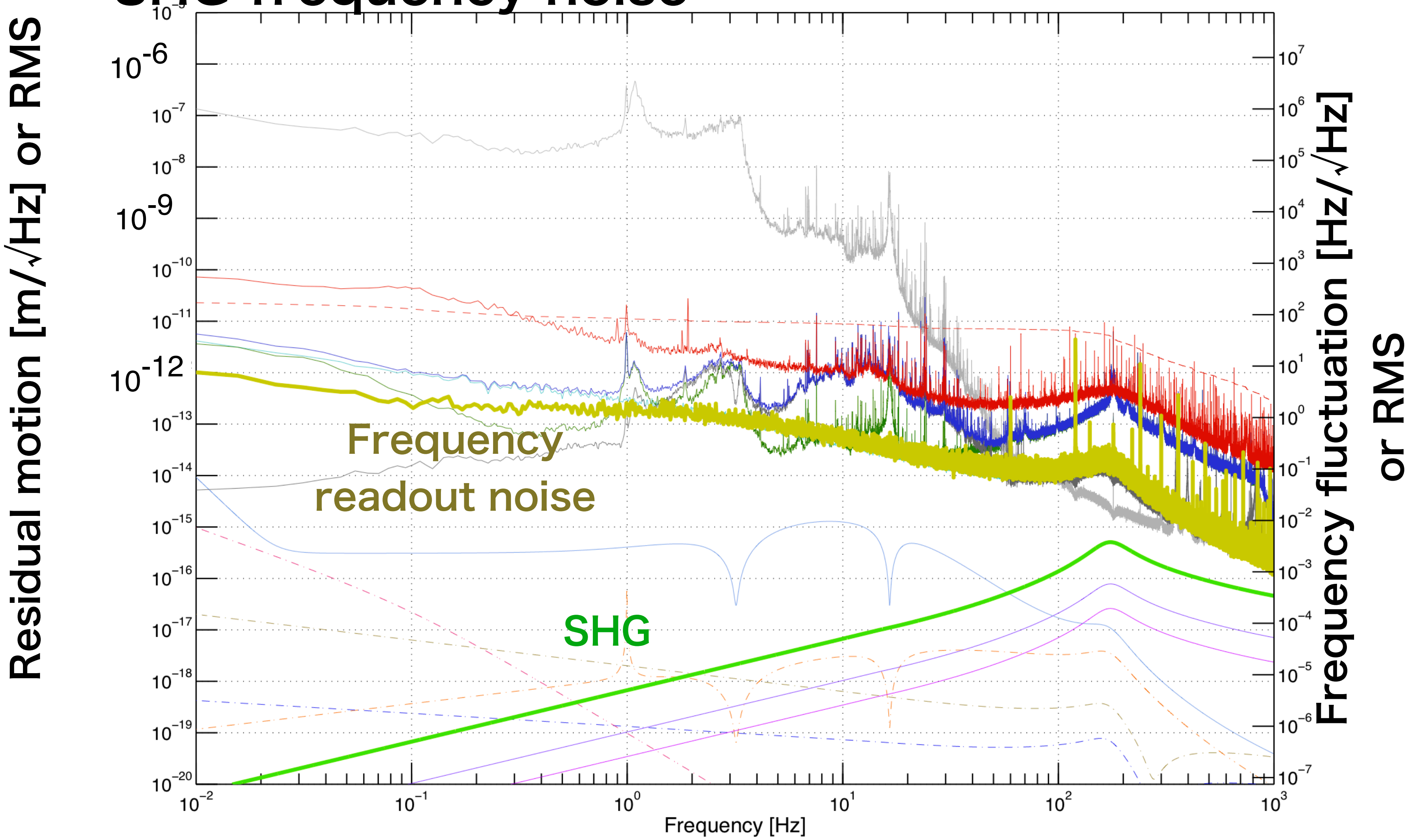
contributes at around10Hz



Main noise 2/3 : Readout and SHG noise

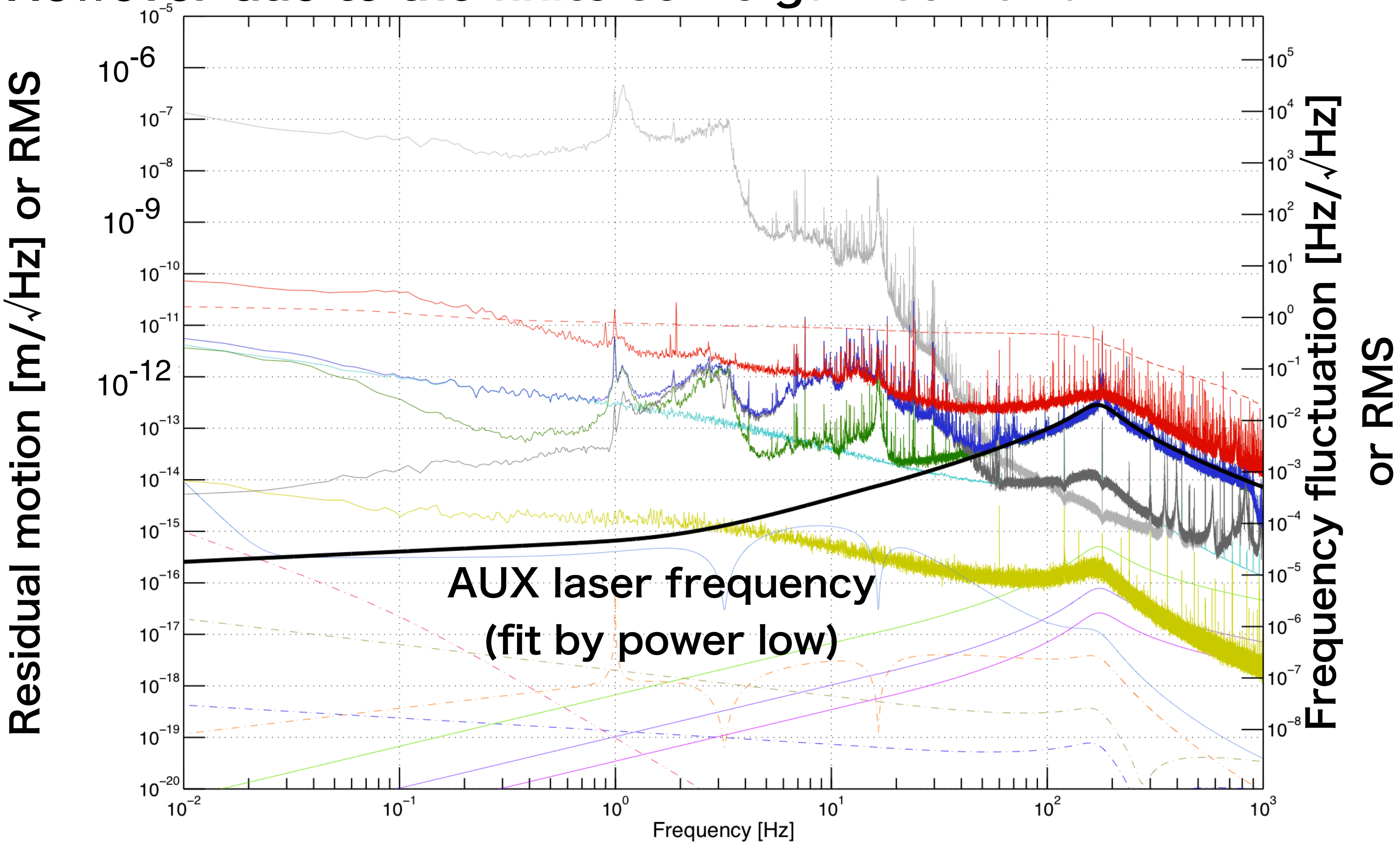
Frequency readout (limited by electronics noise)

SHG frequency noise



Main noise 3/3 : AUX laser

ideally the AUX laser noise can be suppressed to zero.
However due to the finite servo gain some remains.



Residual Motion in advanced LIGO

Prototype test was successful

then in the case of Advanced LIGO ?

Due to the length difference (40 m vs. 4 km)

Frequency-related noise becomes 100 time relevant

Confirmed that it can still meet the requirement

√ AUX laser frequency noise

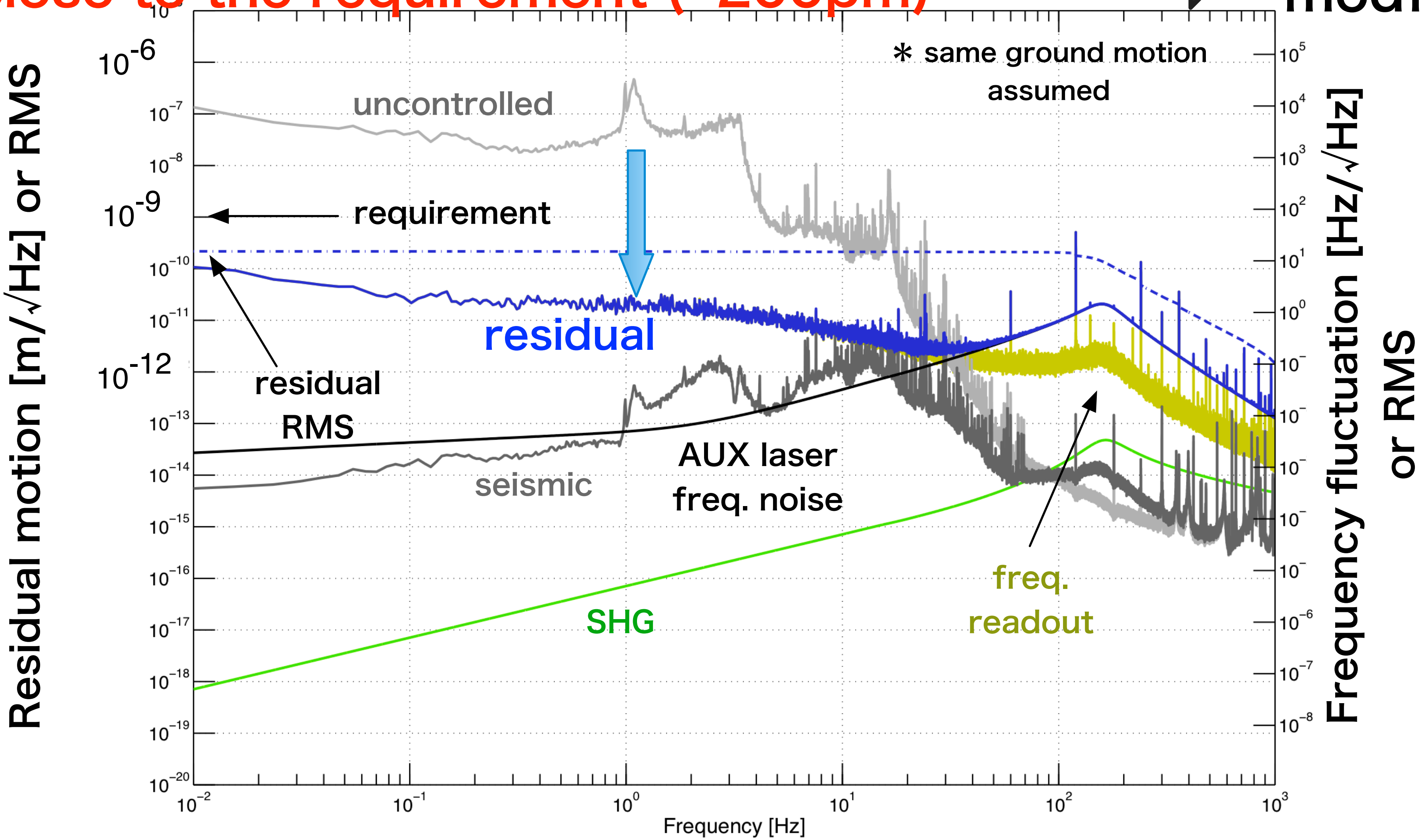
AUX laser needs to be controlled more tightly (modification in the servo design)

√ Beatnote readout noise

narrow-range/high sensitivity detector is needed

Residual motion in 4 km arm 2/2

if the same system is applied the residual is close to the requirement (~200pm) ⇨ needs a modfication

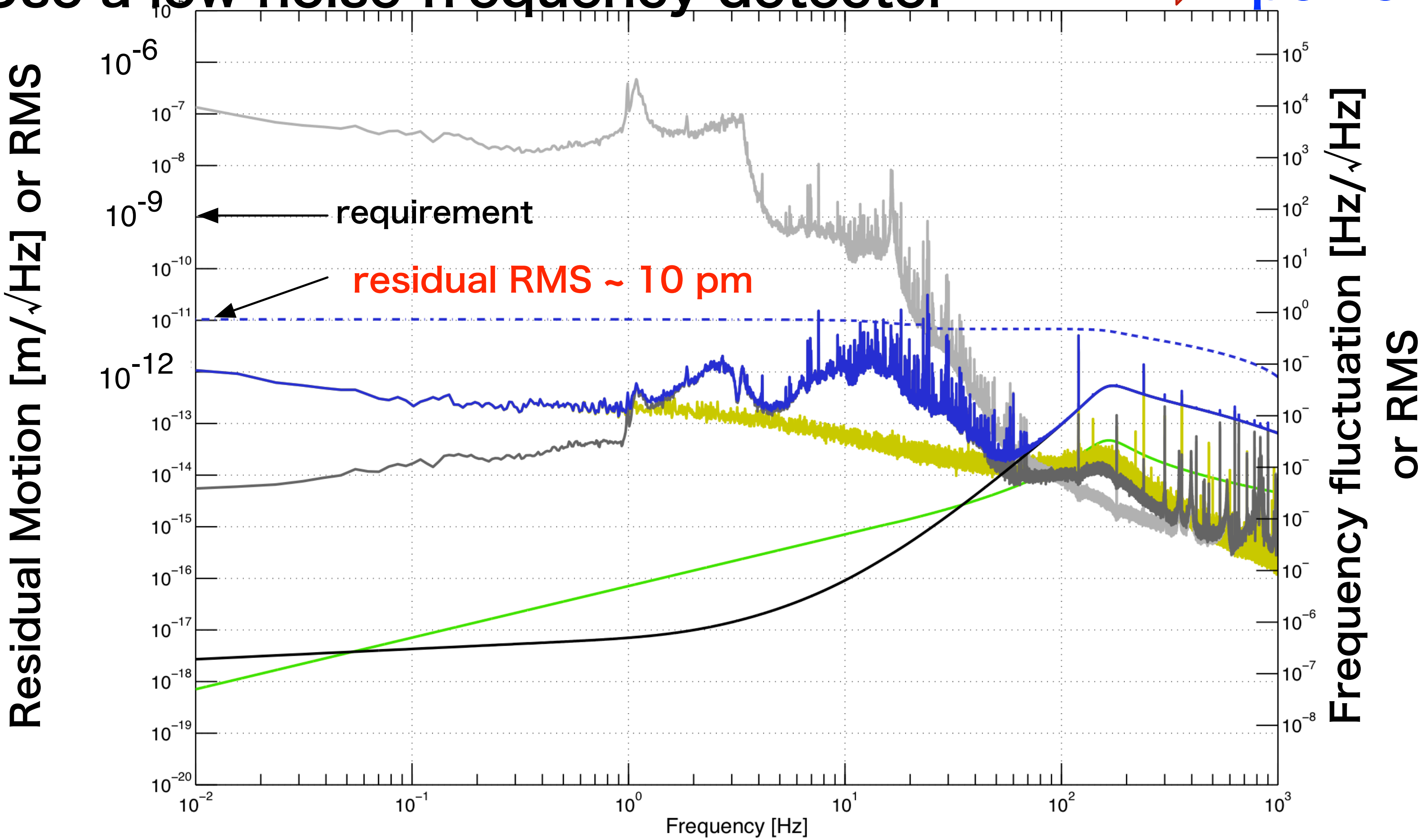


Residual motion in 4 km arm 2/2

Refine the AUX laser control loop

Use a low noise frequency detector

➡ better performance



Summary of the evaluation

√ Achieved a stability of 24 pm surpassing the requirement of 1 nm

√ Noise analysis based on a linear model

√ Estimated the residual motion in a 4 km arm

√ AUX laser and frequency readout noise will be more relevant in the 4 km case

√ Confirmed that the technique can be applied to advanced LIGO

Contents

Conclusion

A lock acquisition technique necessary for the laser interferometer was established.

Gravitational wave Astronomy will start soon.

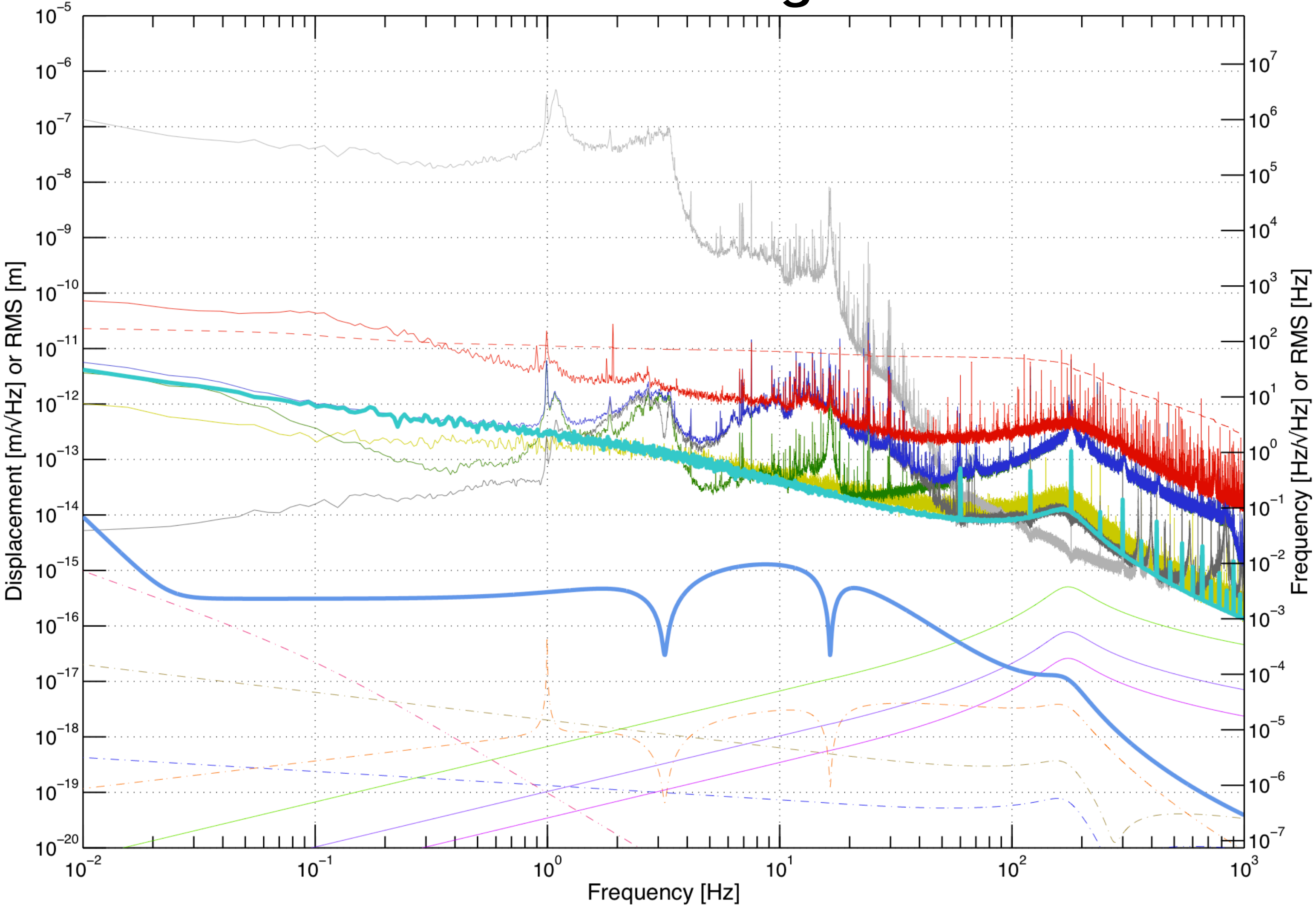
終わり

fin.

Appendix: ADC/DAC noise

ADC for frequency readout.

DAC for the length actuator.

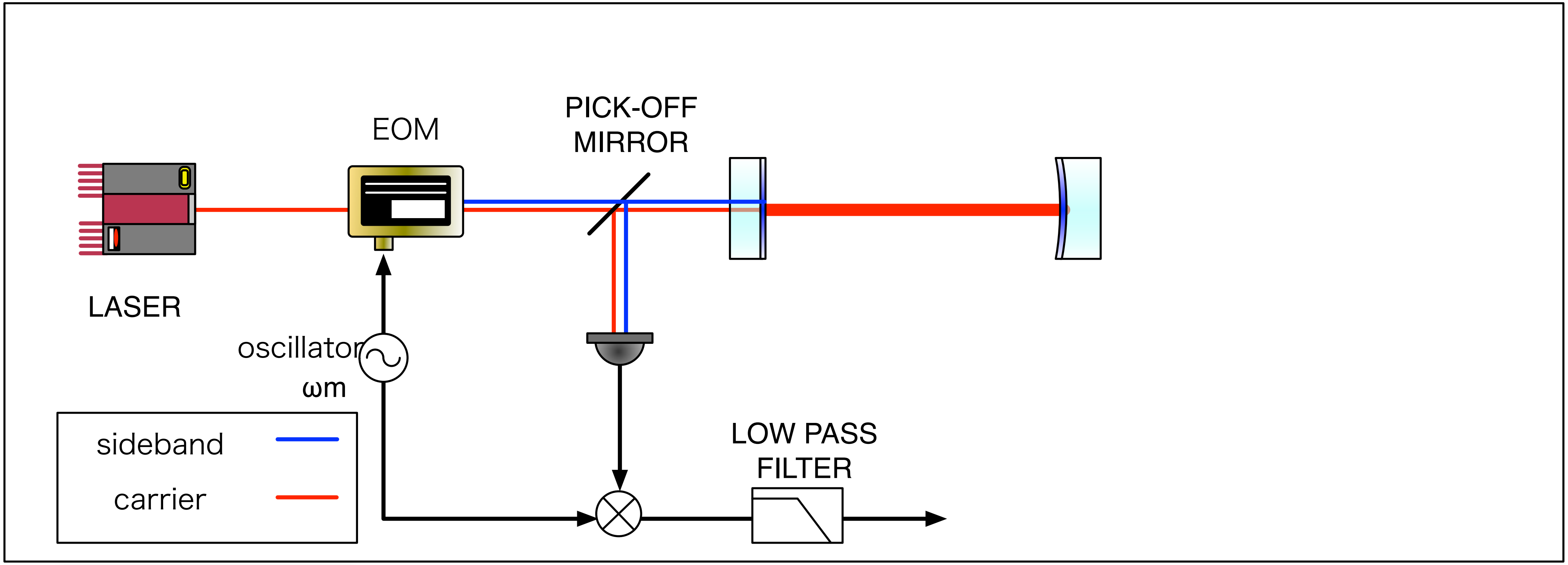


Appendix: Heterodyne length sensing

√ sideband doesn't get in the cavity

Act as local oscillator field

√ photo detection squares the field and down converts the frequency to ω_m



Some locking approaches

	single Fabry-Perot	coupled cavities	new hardwares	features
Digital Interferometry[1]	○	△	a few	wide linear range readouts coupled cavities noisy
Guided Lock [2]	○	×	nothing	wide linear range not great for coupled cavities
Multi-Color Interferometry	○	○	many	wide linear range readouts coupled cavities lots of new hardwares

○ = OK   △ = intermediate   × = not good

[1] Optics Letter, 32(22):3355 (2007)
[2] Optics Letter, 20:2463 (1995)

Delay-Line Frequency Discriminator