My Ph.D Research Part2: Cryogenic Monolithic Interferometer for Phase-III TOBA

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Ando Lab Seminar

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Overview

- Cryogenics and monolithic interferometer are promised technologies for precision measurement, but none of the previous research combines them
- TOBA requires both of them
  - Cryogenic: reduce thermal noise
  - Monolithic interferometer: reduce readout noise from vibrations
- The realization of the cryogenic monolithic interferometer is essential for the development of Phase-III TOBA
- We demonstrated a prototype of the cryogenic monolithic headboard
  - Established a assembly method
  - Evaluate alignment drift
  - Investigate noise sources

Contents

- Motivation
- Previous research
- Design
- Assembly
- Evaluation

Setup of Phase-III TOBA

Active Vibration Isolation System

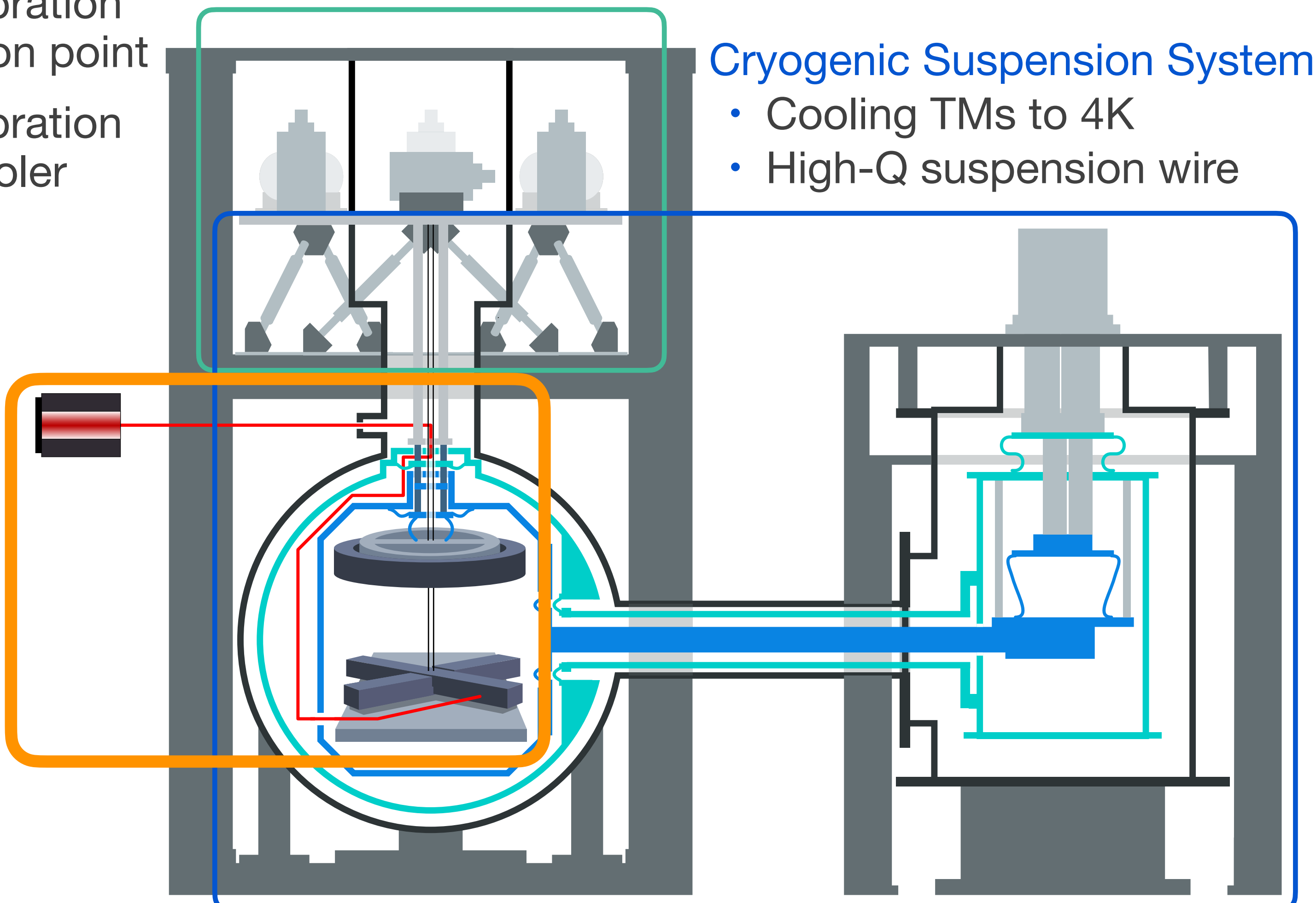
- Reduction of vibration at the suspension point
- Reduction of vibration induced cryocooler

Cryogenic Suspension System

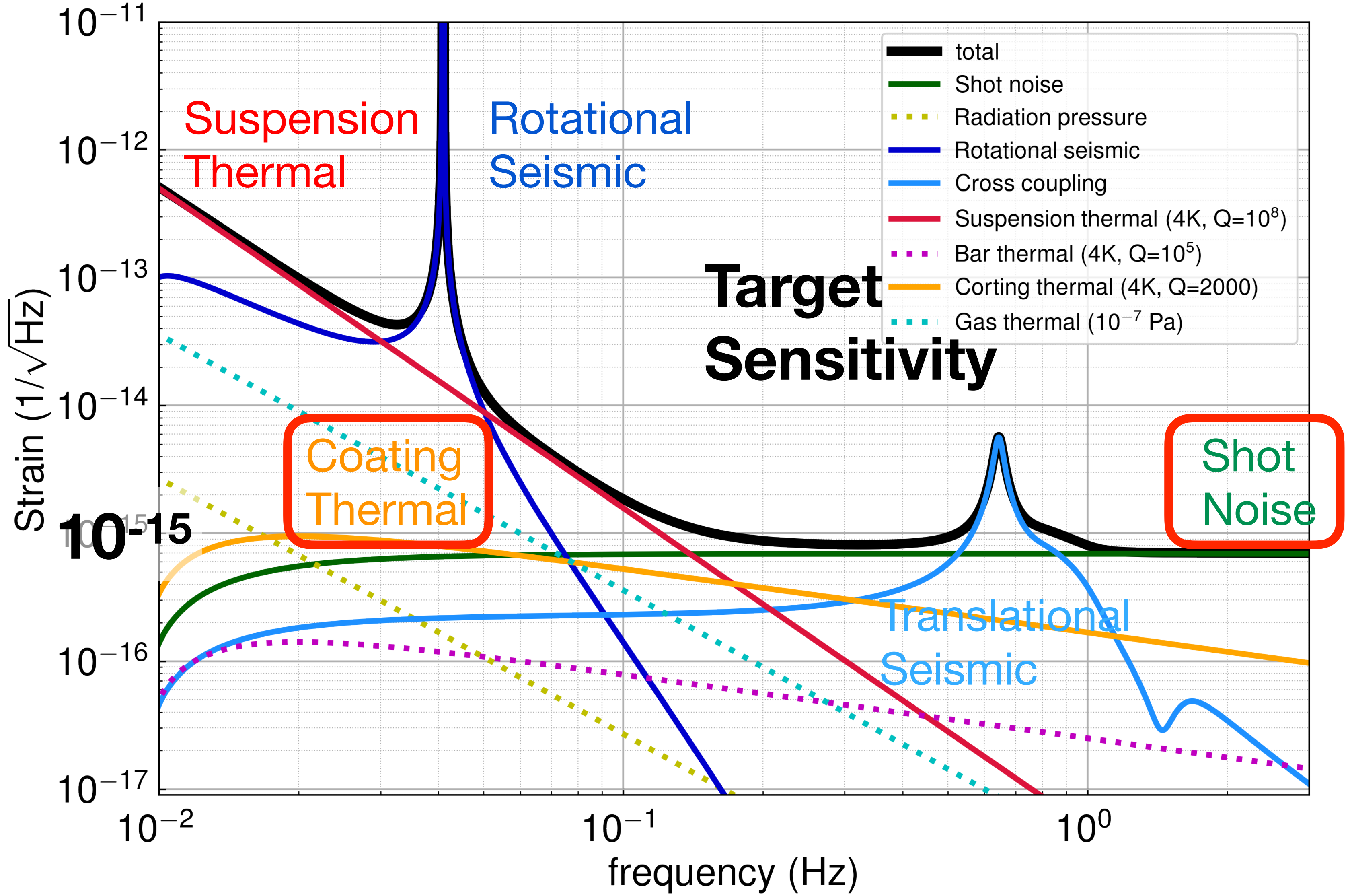
- Cooling TMs to 4K
- High-Q suspension wire

Optical System

- Rotation measurement by interferometer
- Monolithic interferometer



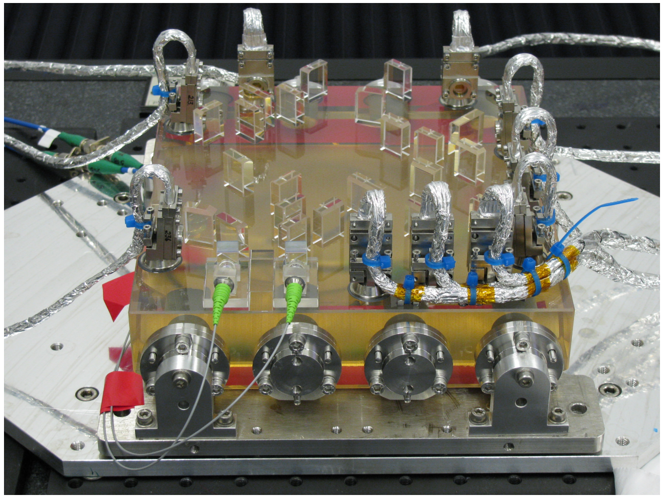
Design Sensitivity



Monolithic Interferometer

Monolithic Interferometer

- Optics are glued on a base plate directly
  - Large common mode rejection ratio
  - Small drift in long time duration
  - No way to tune alignment after gluing



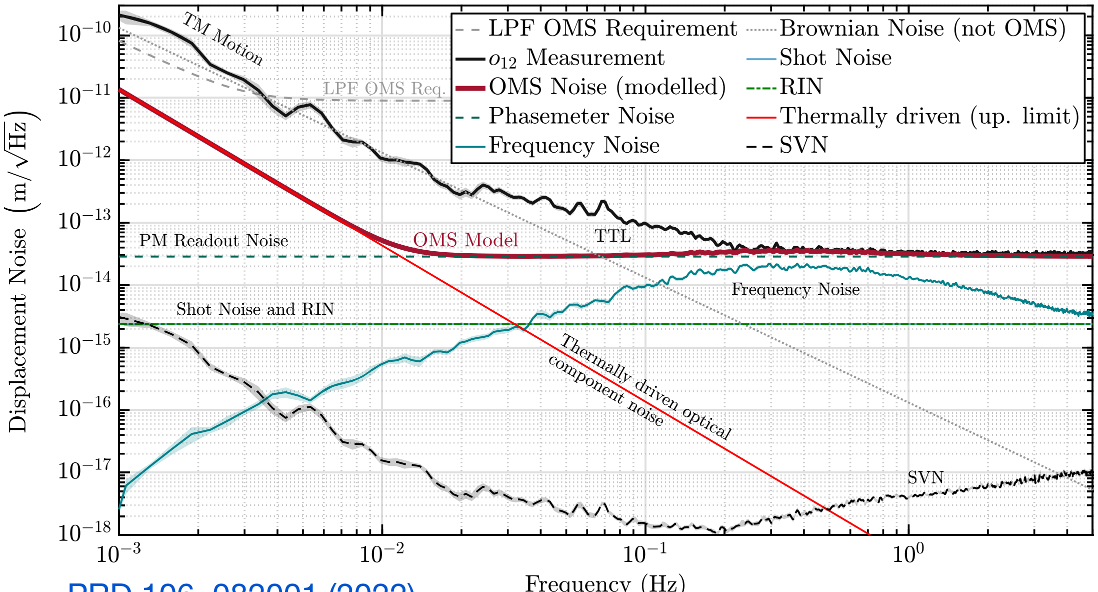
LISA Mission Proposal

LISA Pathfinder reached displacement sensitivity to

3.5 x10^{-14} m/√Hz @ 0.1 Hz

(w/o TM motion)

- Limited by
  - Noise of Phasemeter
  - Thermal coupling of optics



PRD 106, 082001 (2022)

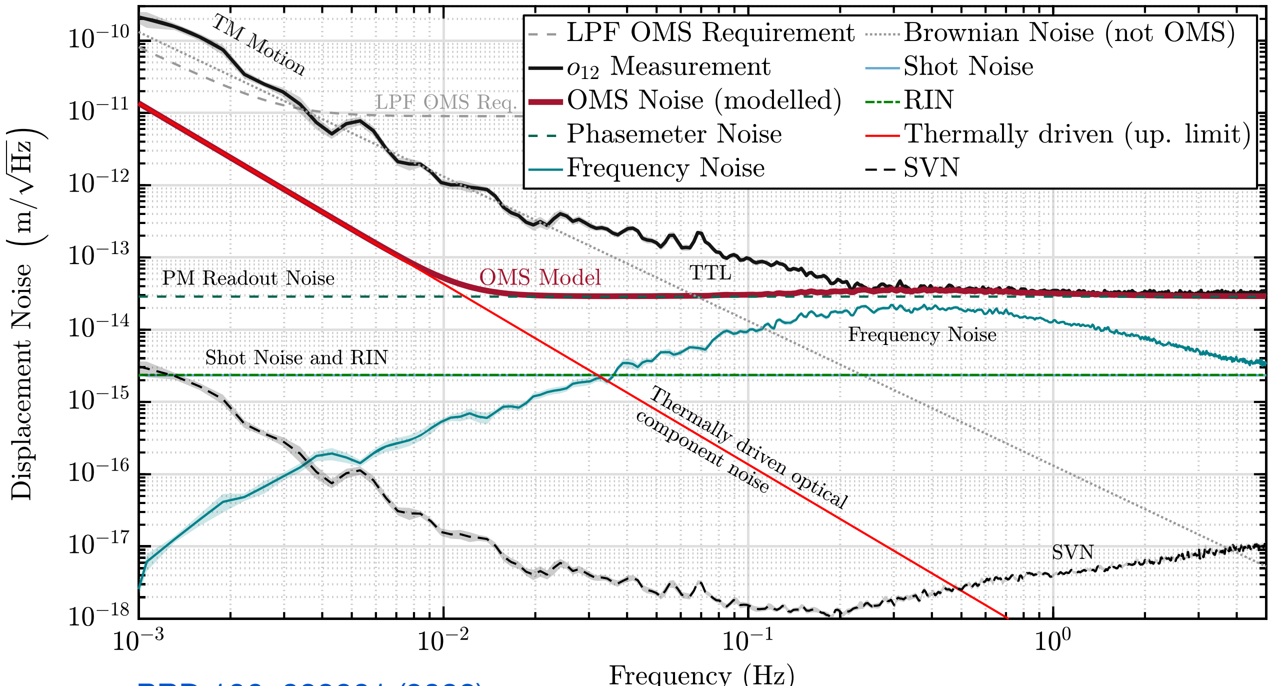
Cryogenic Monolithic Interferometer

Requirement for readout noise: **6 x 10^{-16} /√Hz** (**6 x 10^{-17} m/√Hz**)

- More stringent than LPF

Have to reduce

- Shot noise
- Frequency noise
- Thermal coupling
- Readout noise (Phasemeter)



PRD 106, 082001 (2022)

- Solve these issues by cryogenic monolithic interferometer

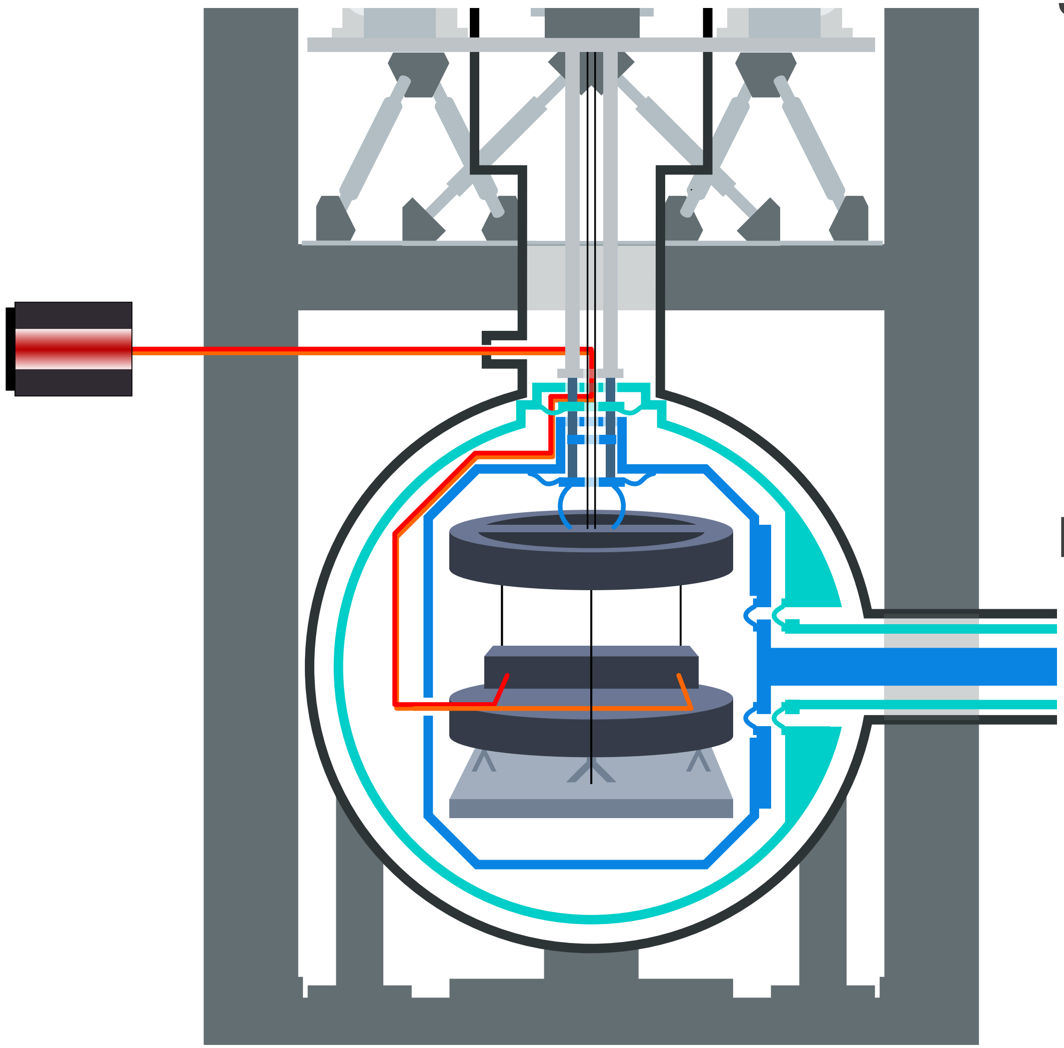
Cryogenic Monolithic Interferometer

What we have to solve:

- Component selection
  - Cryogenic compatible items
    - Optics: fused silica → sIlicon
    - Metals: have to avoid thermal failure
  - Detector: InGaAs not works for 1550nm at cry. temp. [Bajpai]
  - Bonding: HCB? Optical contact? Other glues?
  - Fiber injector: how to fabricate? What is suitable?
- Alignment drift
  - Few measurement data [Bajpai]

▶ Demonstration of a prototype to test (some of) these issues

Setup for Demonstration



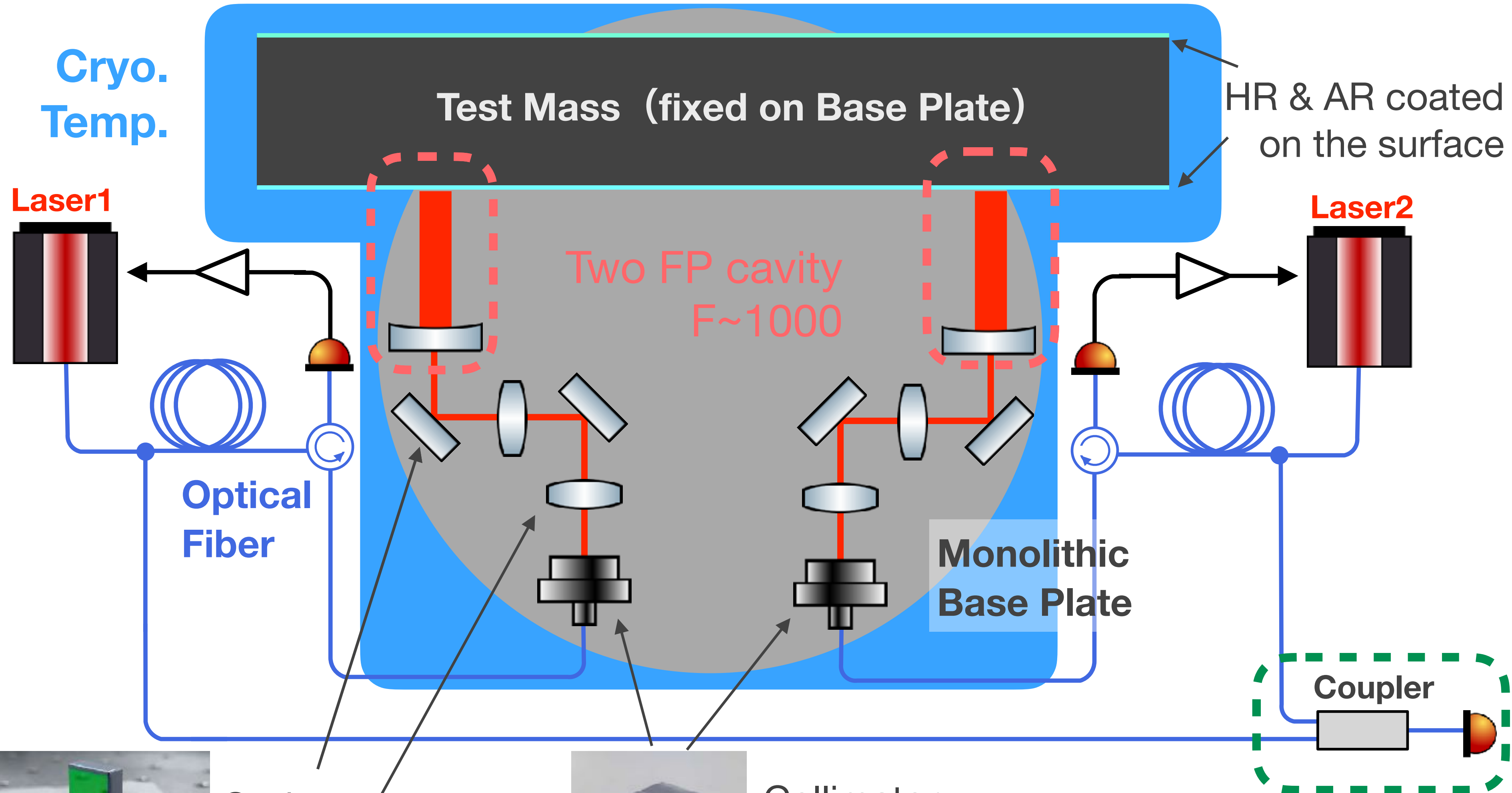
Simplification of the setup

- No suspended TM,
  fixed on OB
- OB suspension is 2-stage
- Laser light is introduced by optical fibers

Purpose

- Operation of monolithic interferometer at cryo. temp.
  - Evaluation of displacement noise
  - Alignment drift during the cooling

Conceptual Design

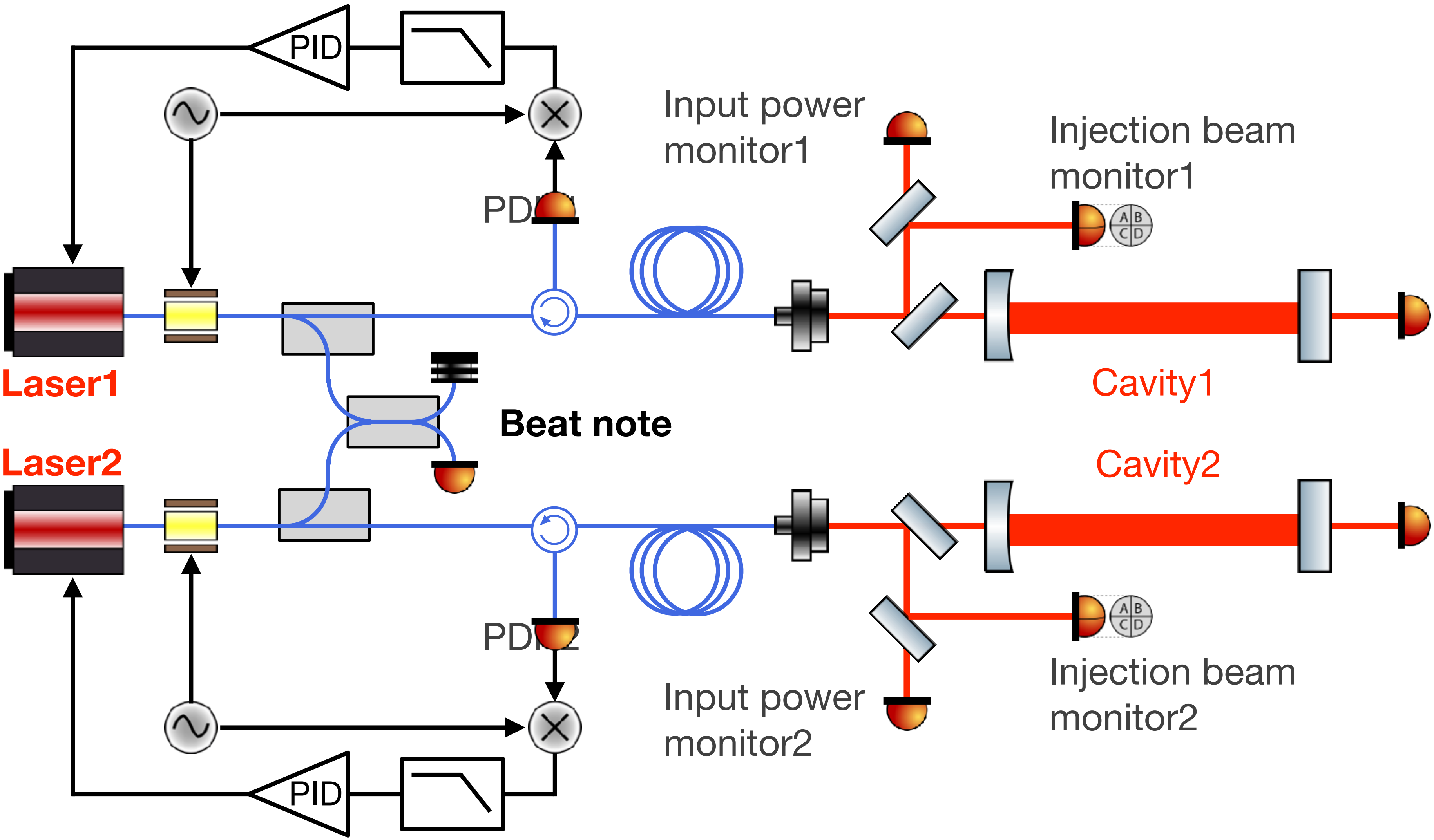


Optics:
made of silicon
TM, mirror, BS, lens

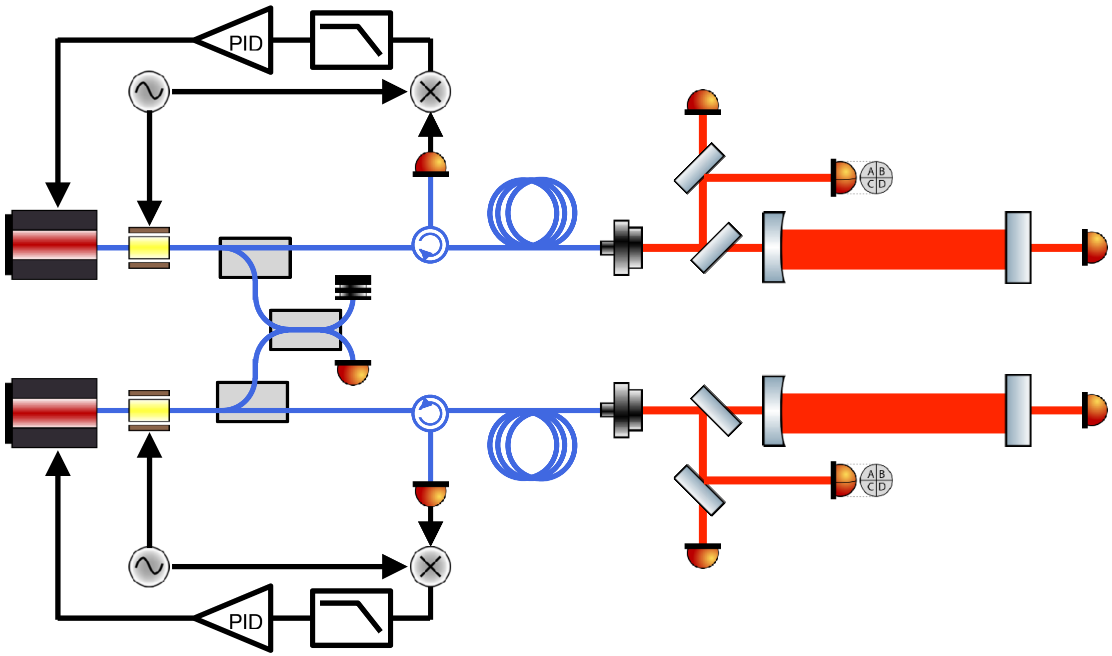
Collimator
with holder
made of invar

Differential displacement
signal from beat frequency

Optical Layout



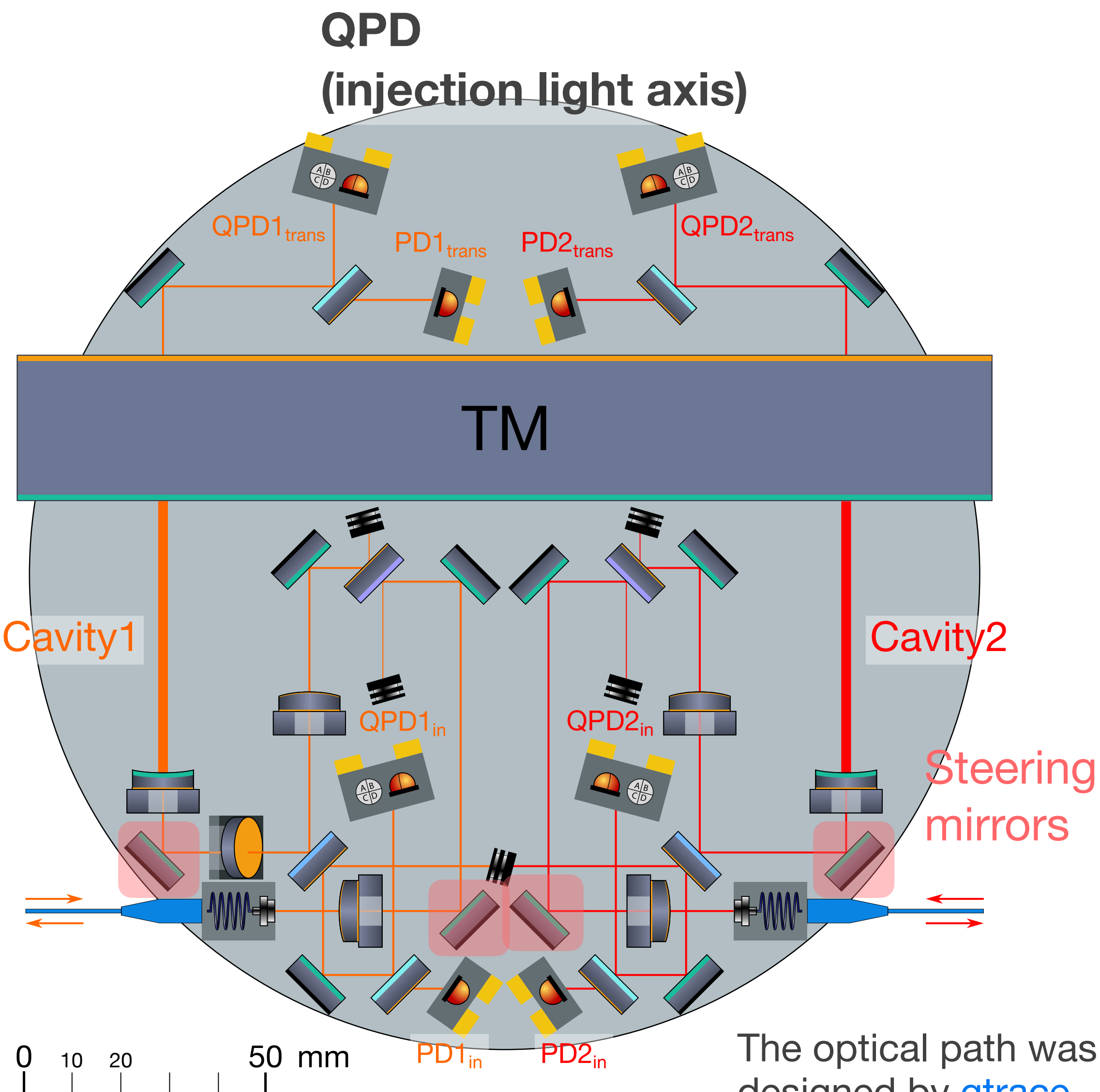
Parameters



Power	20 mW
Length	55 mm
Front Mirror Curvature	200 mm
End Mirror Curvature	∞
Front Mirror Reflectivity	99.5%
End Mirror Reflectivity	99.8%
Finesse	1045
FSR	2.7 GHz
FWHM	3 MHz

- Target: 4×10^{-17} m/√Hz @ 0.1Hz (differential)
- Would be limited by shot noise

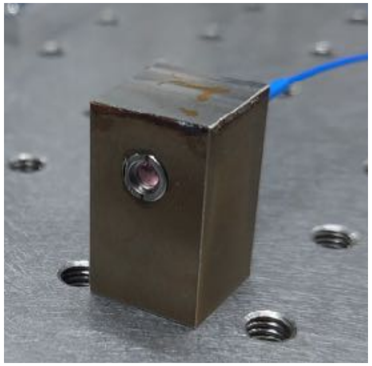
Optical Design



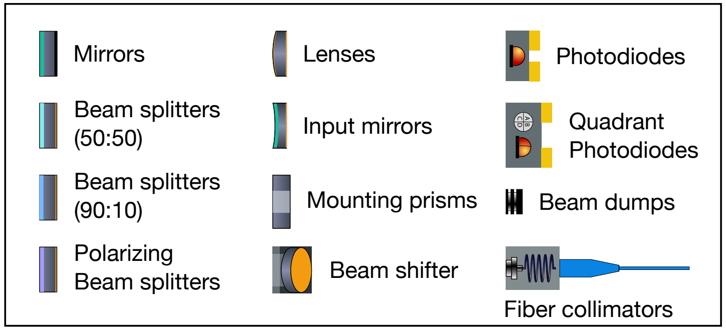
The optical path was designed by gtrace

PD

Lens

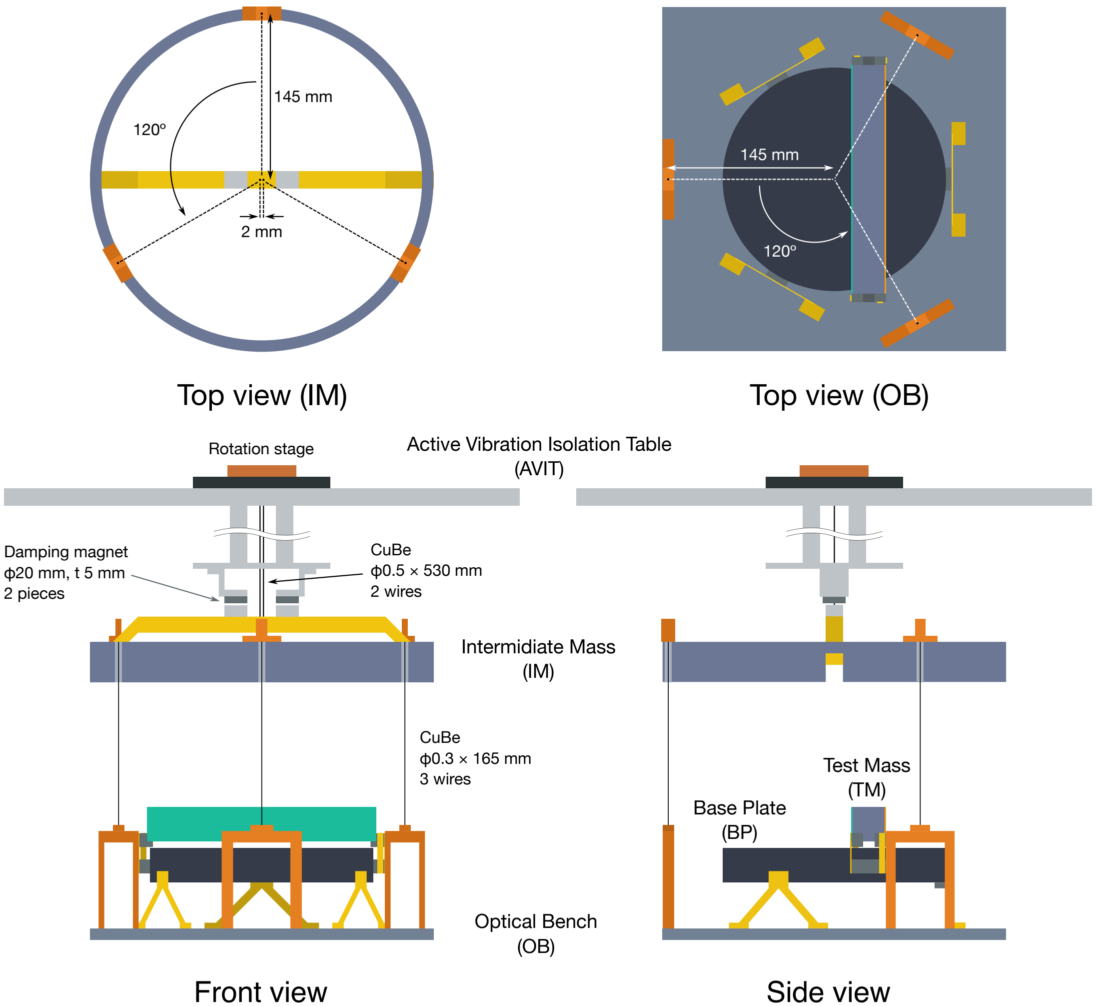


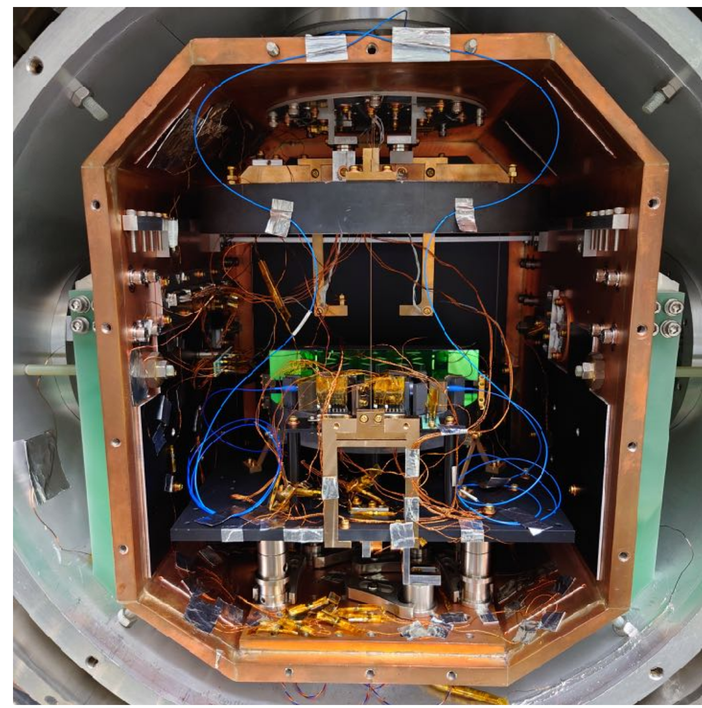
Collimator



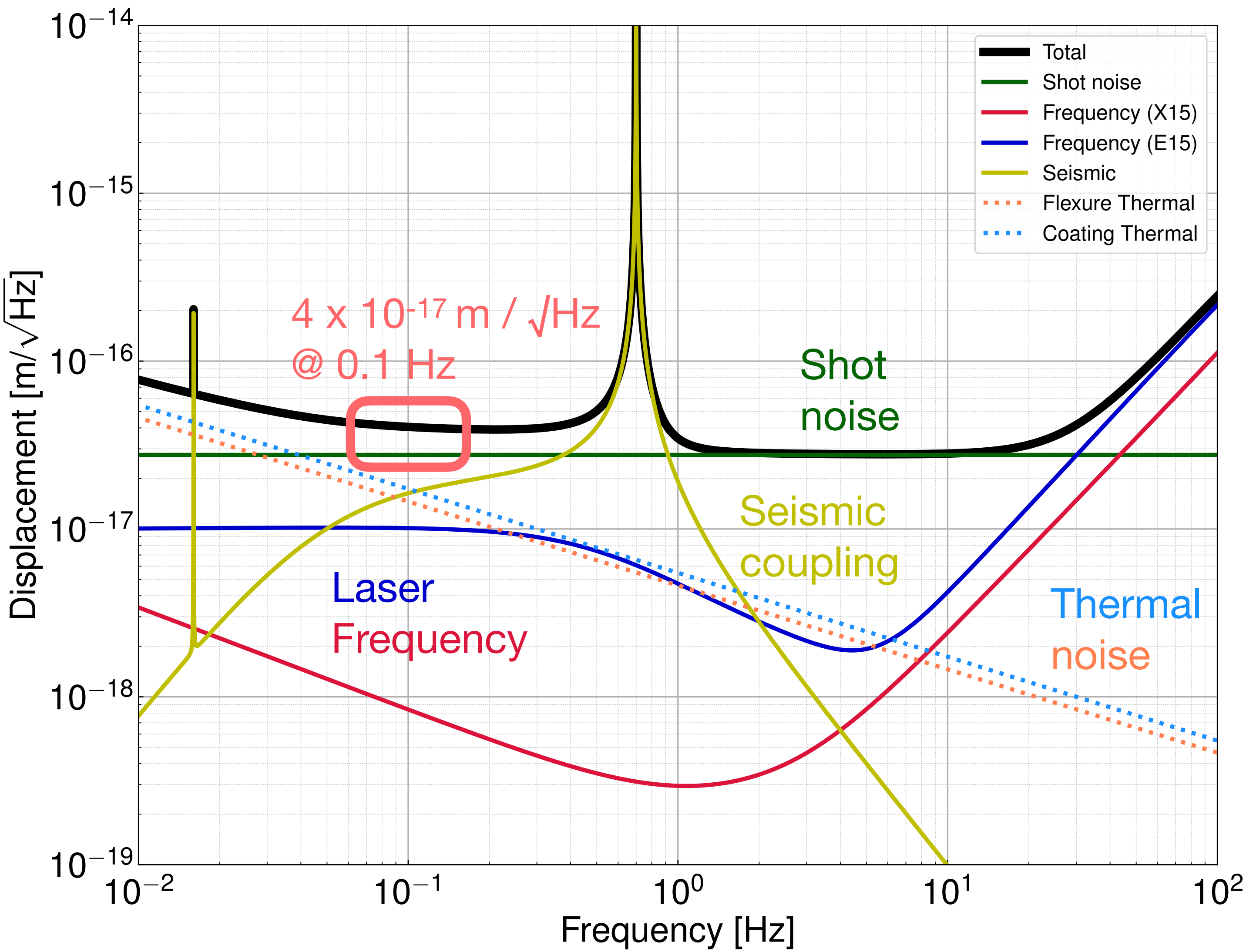
Suspension Chain

- Double-stage pendulum
- Supported by flexures





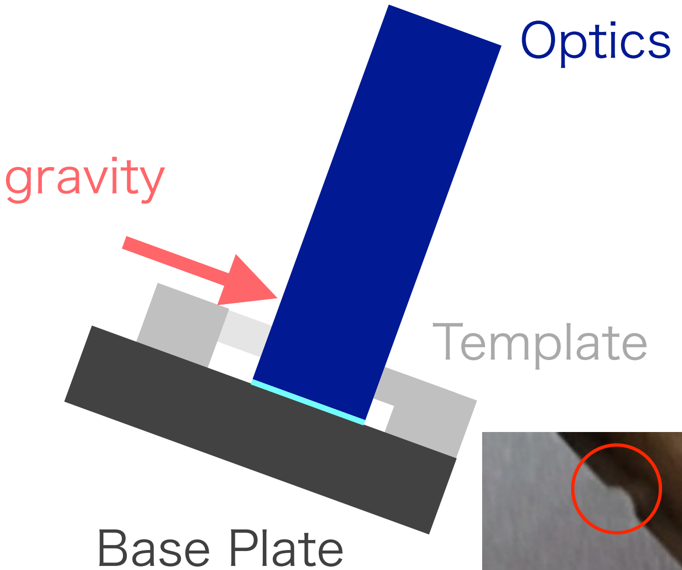
Design Sensitivity

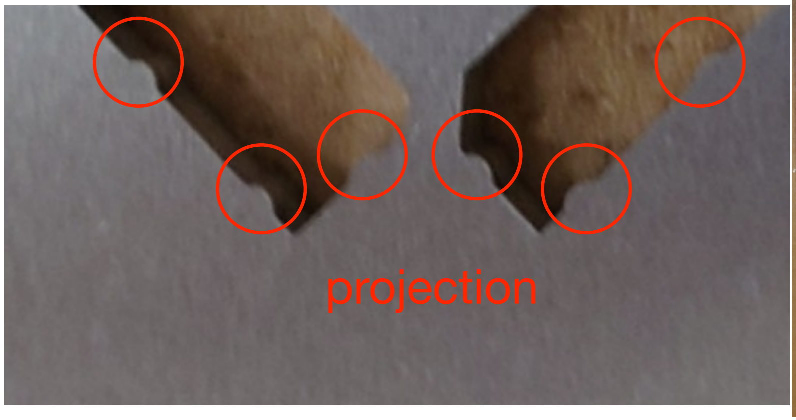


Template Bonding

Position of optics are defined by a template

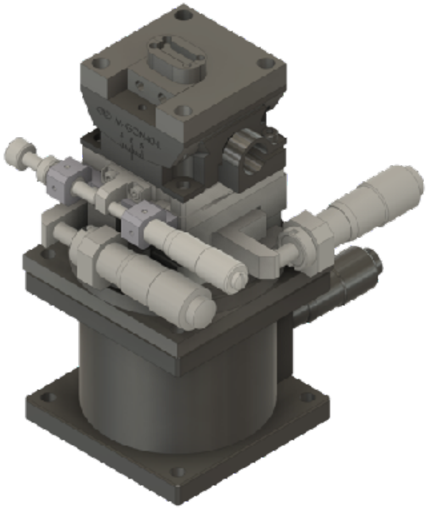
- Due to gravity optics glide on the bonding glue
- Stopped by projections on the template

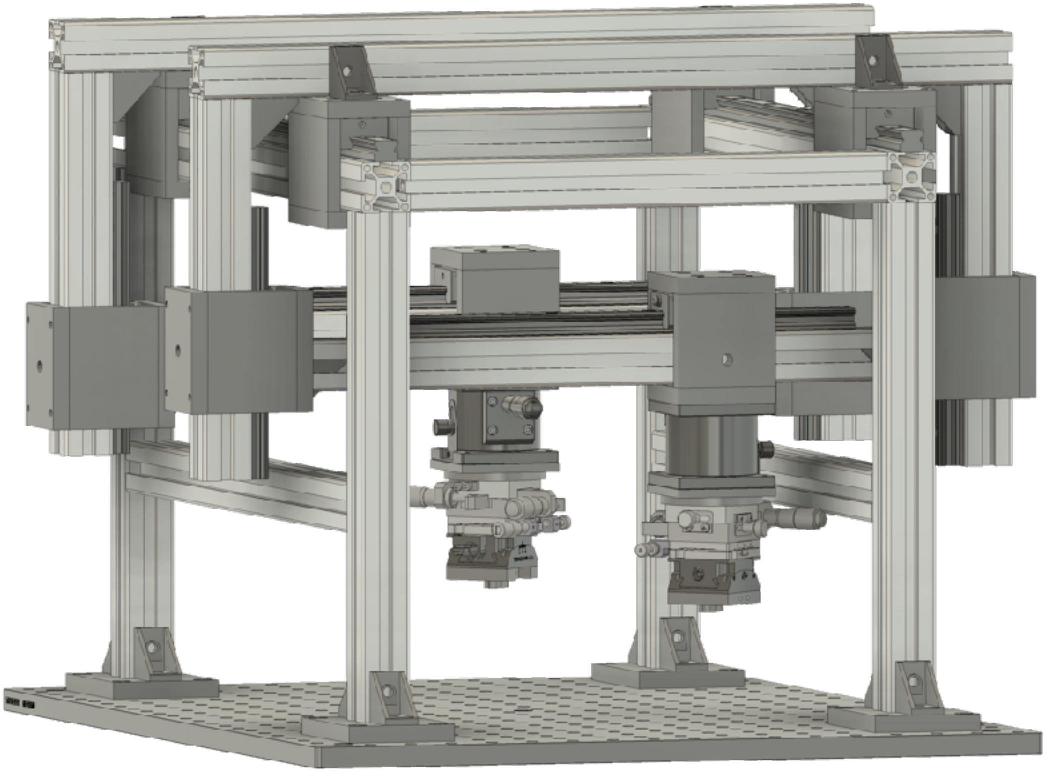


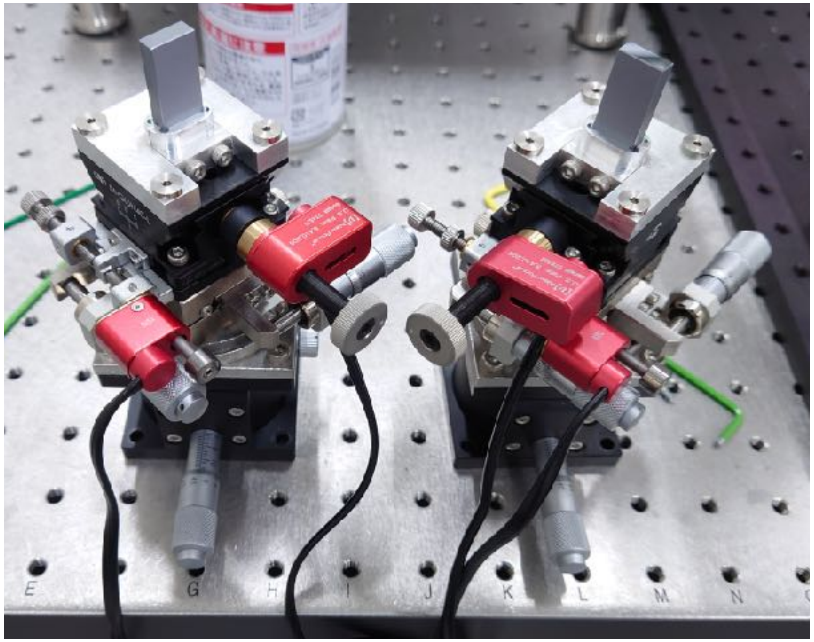


Fine Stage Alignment

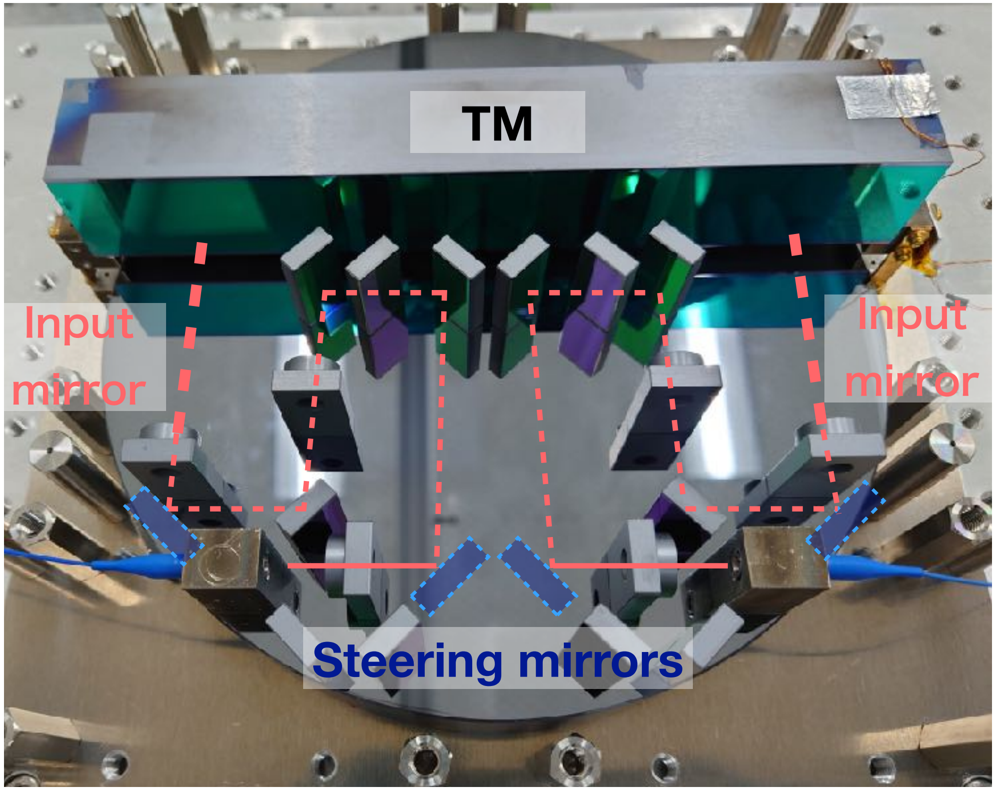
- Adjustable stages
  in 5 DoF (x, y, z, pitch, yaw)
- 3 manual (x, y, z),
  2 picomotors (pitch, yaw)



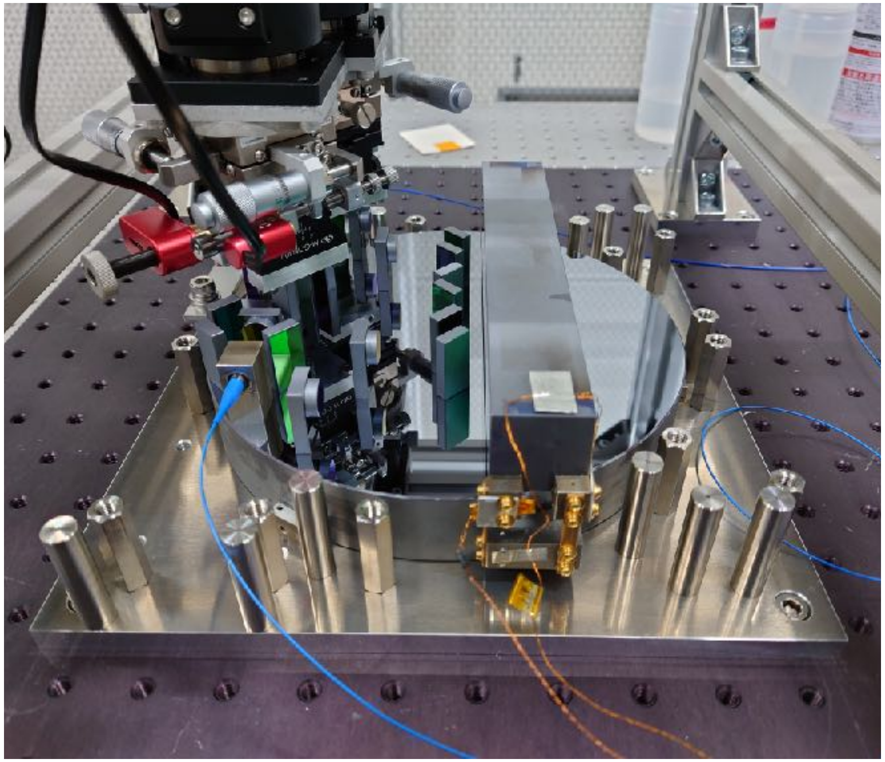




Alignment

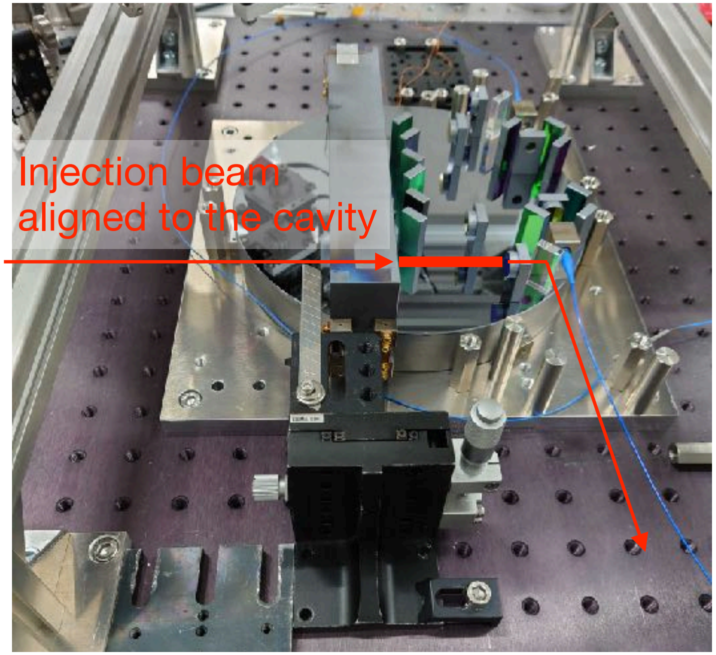


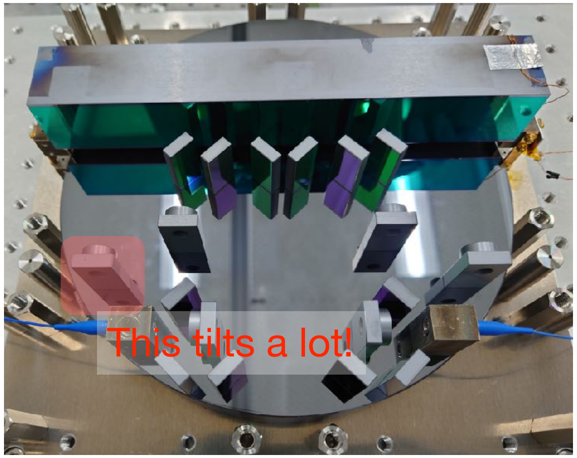
Template Gluing
→ Fine alignment

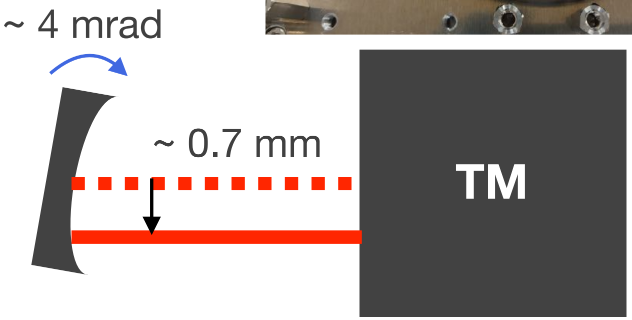


Problems with Alignment

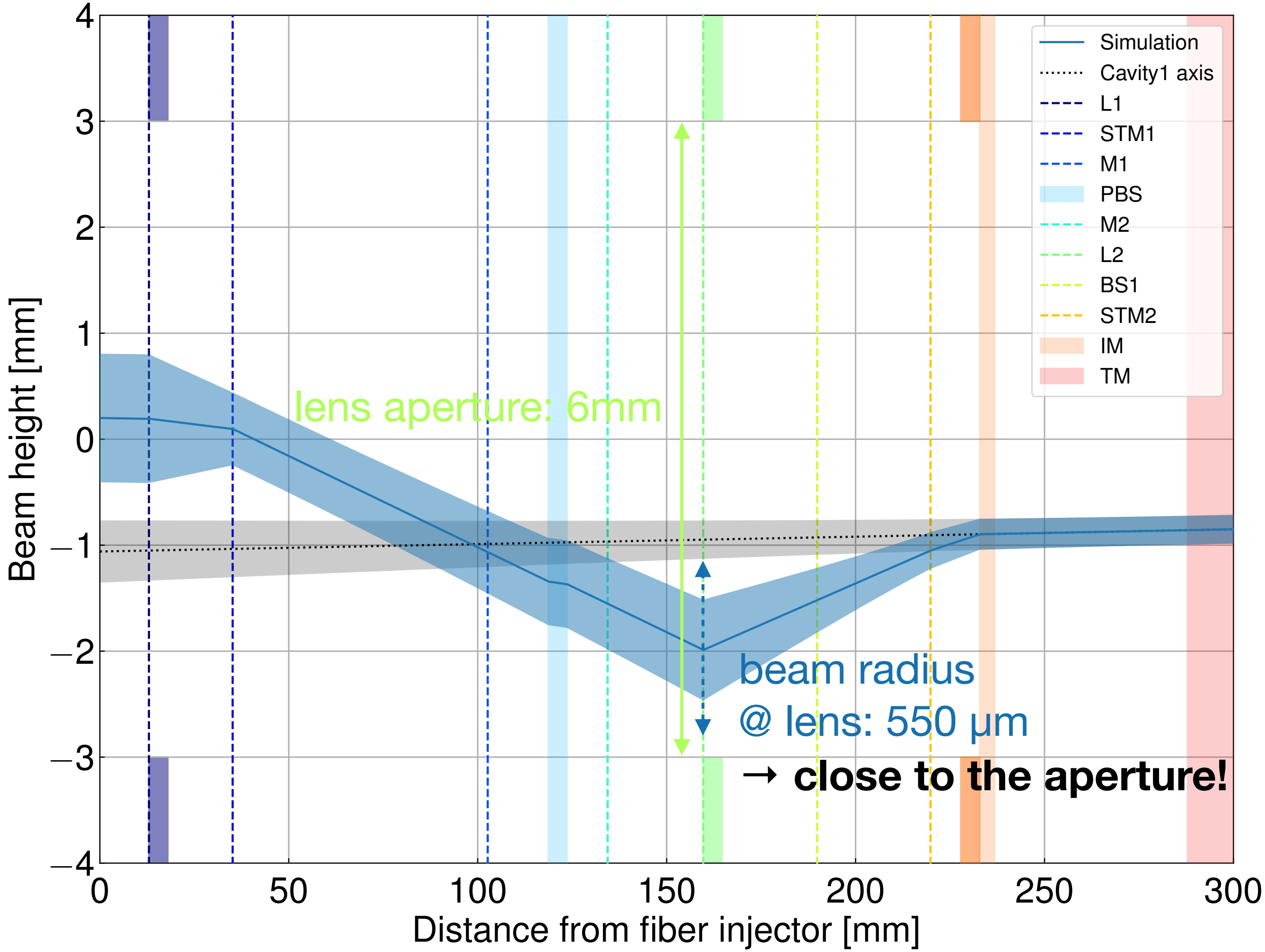
- In November 2022, tried the alignment first time
  - Maximum mode matching ratio is ~ 52%
  - Input beam seemed clipped at a mode matching lens
- Measured beam axis tilt & height by injecting laser backwards
  - One of input mirror (IM) tilts ~ **4 mrad**
  - TM & the other IM tilt < 1mrad





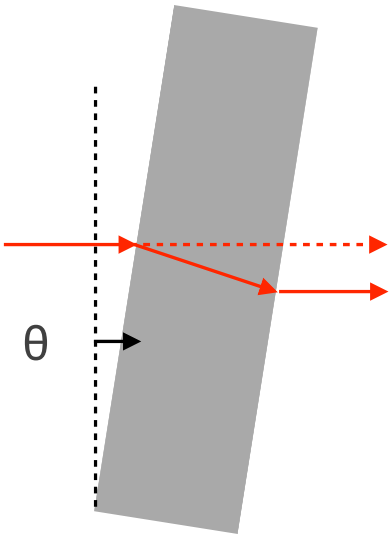


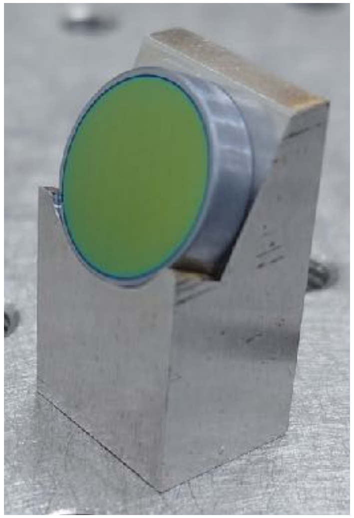
Beam Spot Simulation

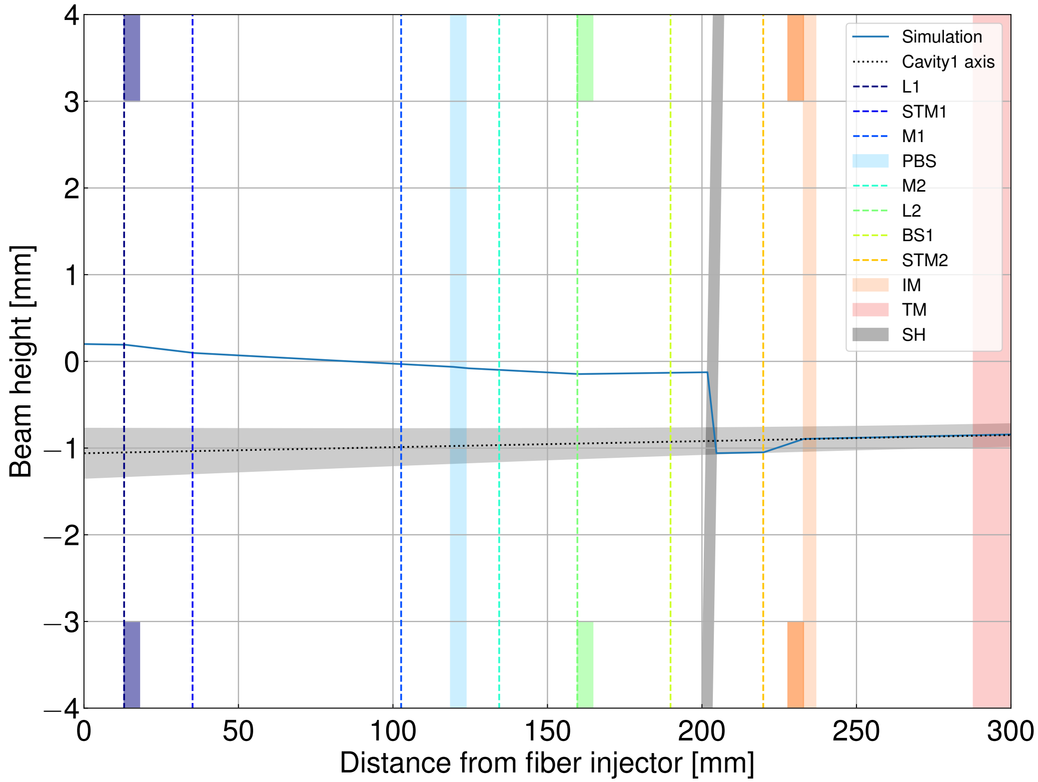


Beam Shfting

- Decided to add a shifting plate to modify the incident beam

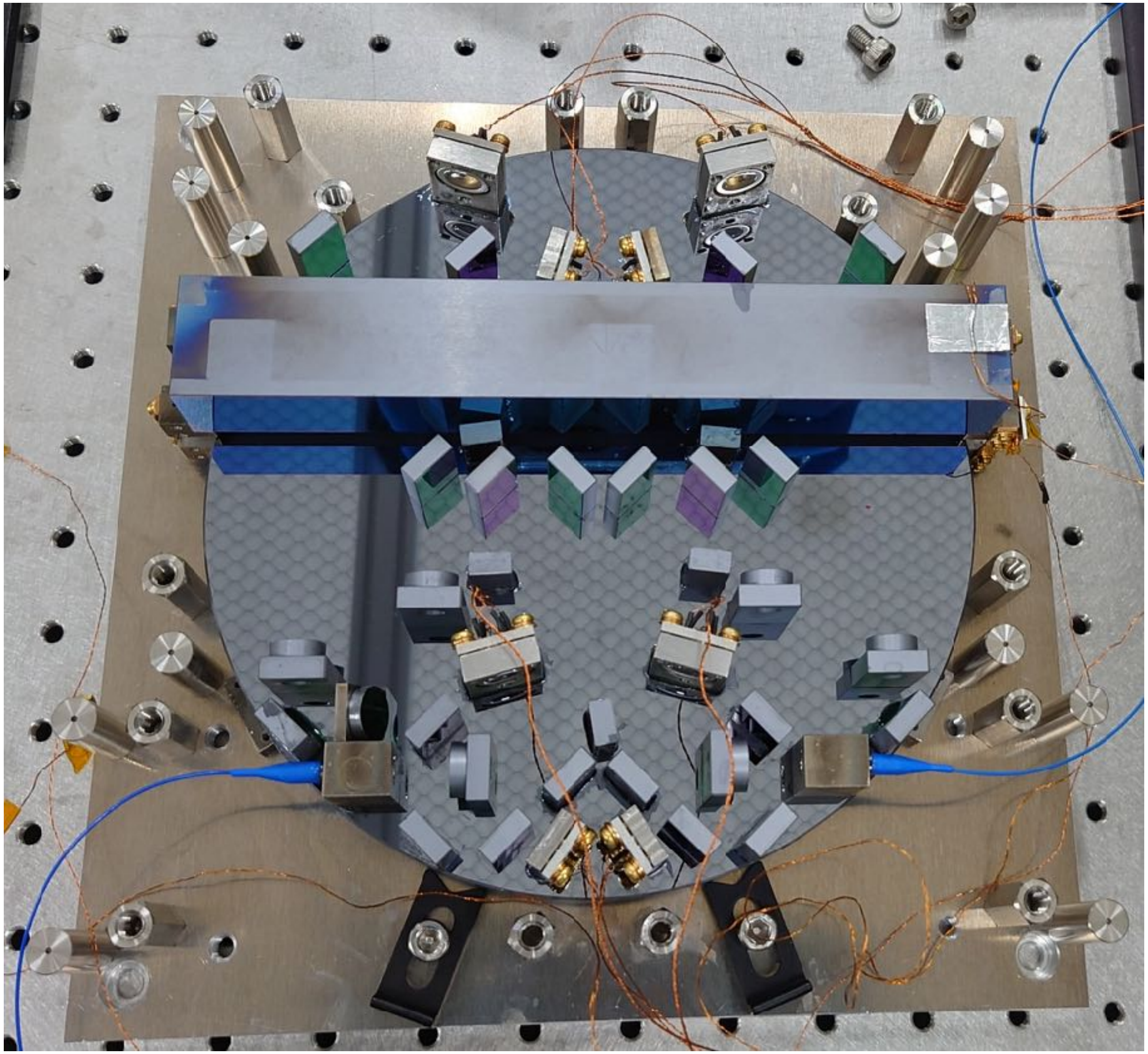






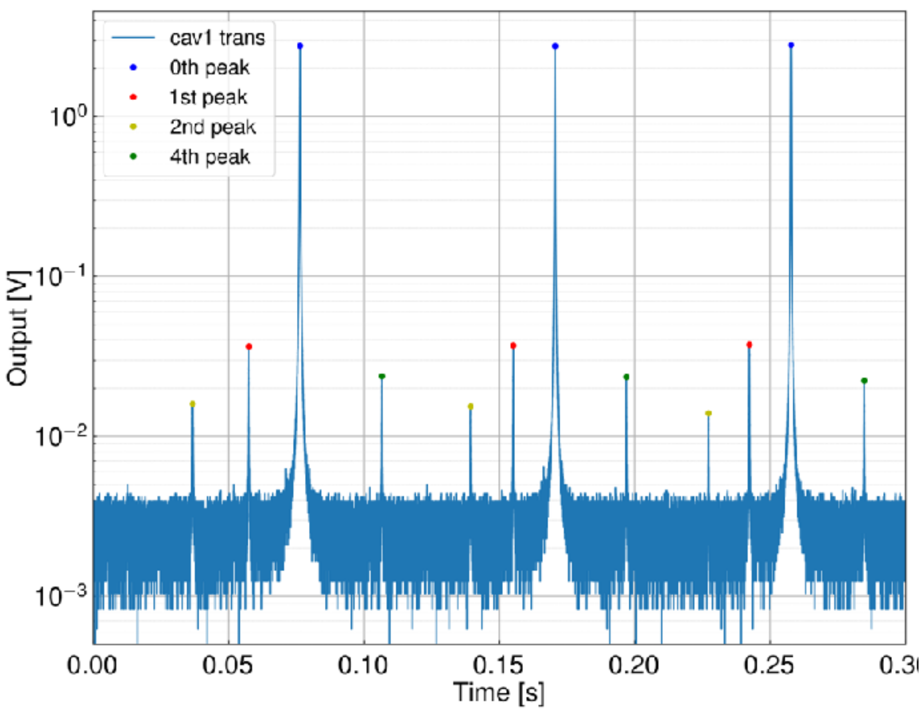
- Thorlabs WG80530, Φ12.7mm x t 3mm
- AR coating on both sides by Sigma-koki

After alignment

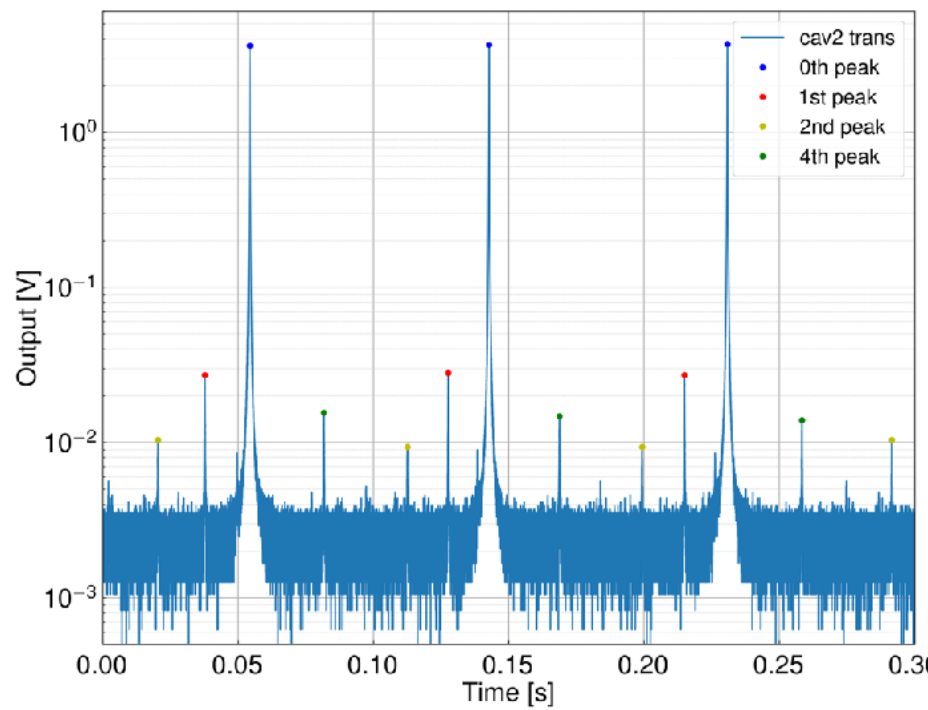


Mode Matching Ratio

- Cavity scan by changing the laser frequency
- Designed mode matching ratio: ~ 99%



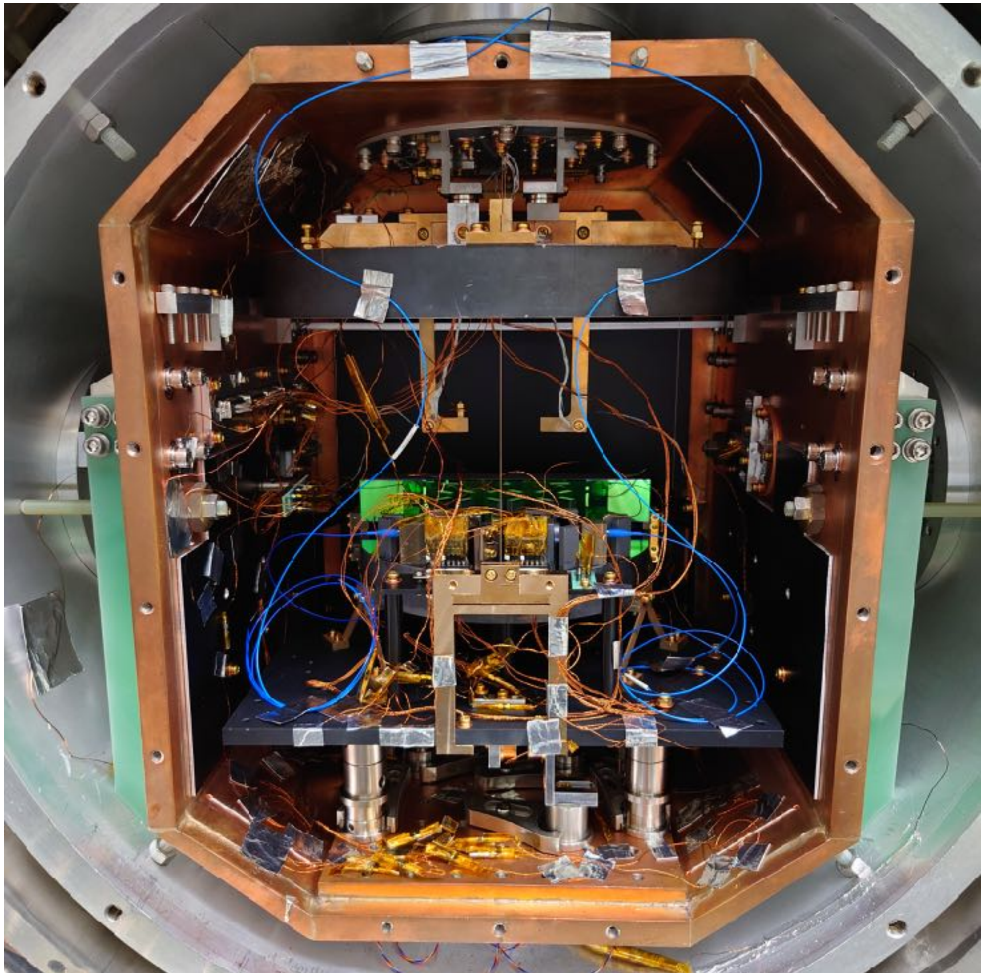
Cavity1 (w/ beam shifter): 95.9 %

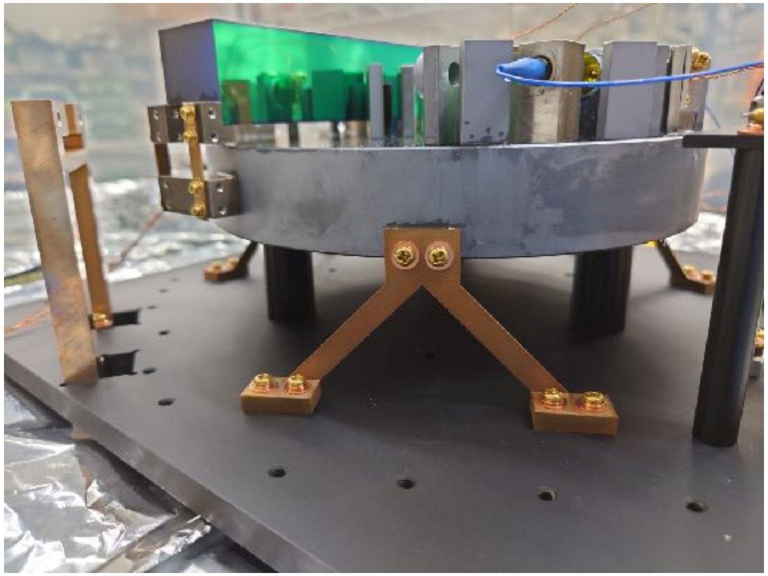


Cavity2 (no beam shifter): 97.8 %

- No problem about alignment

Installation



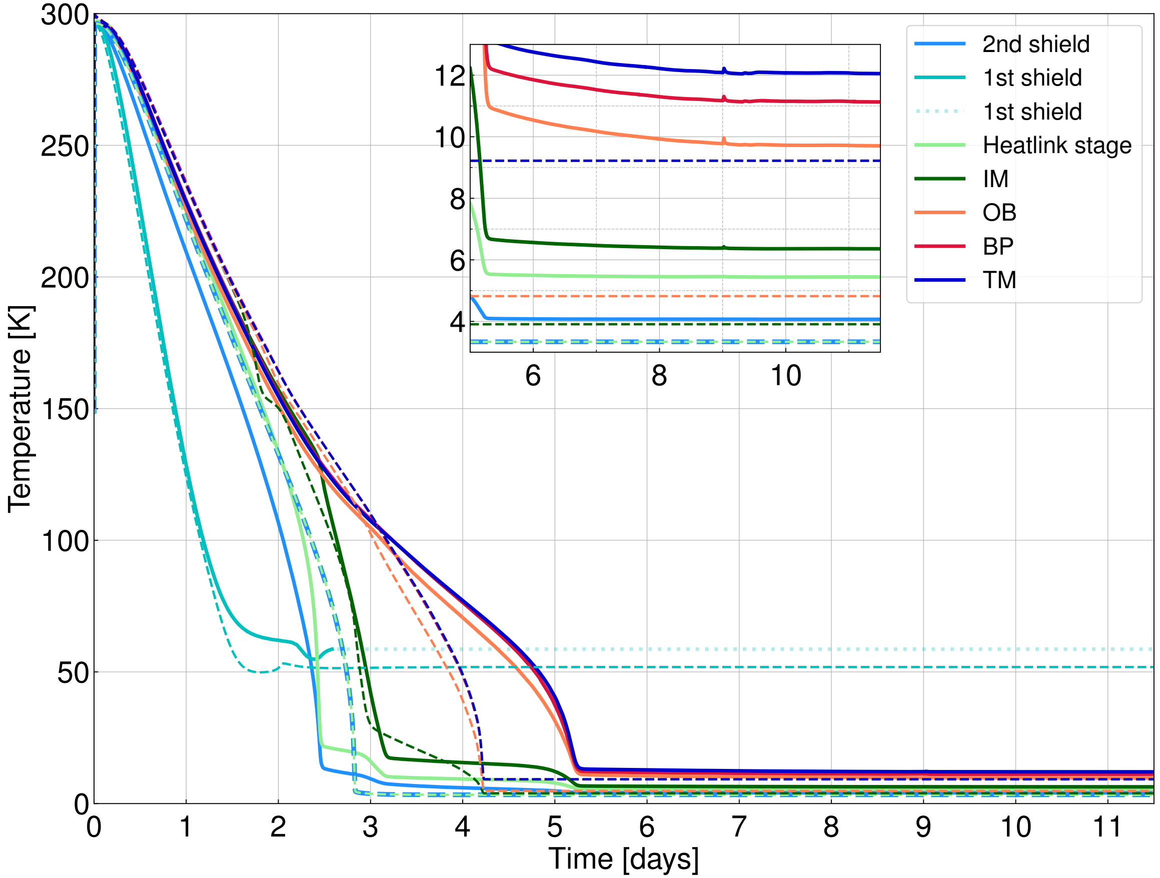


Supported by flexures

Cooling

Cooled down to 12 K in ~ 10 days

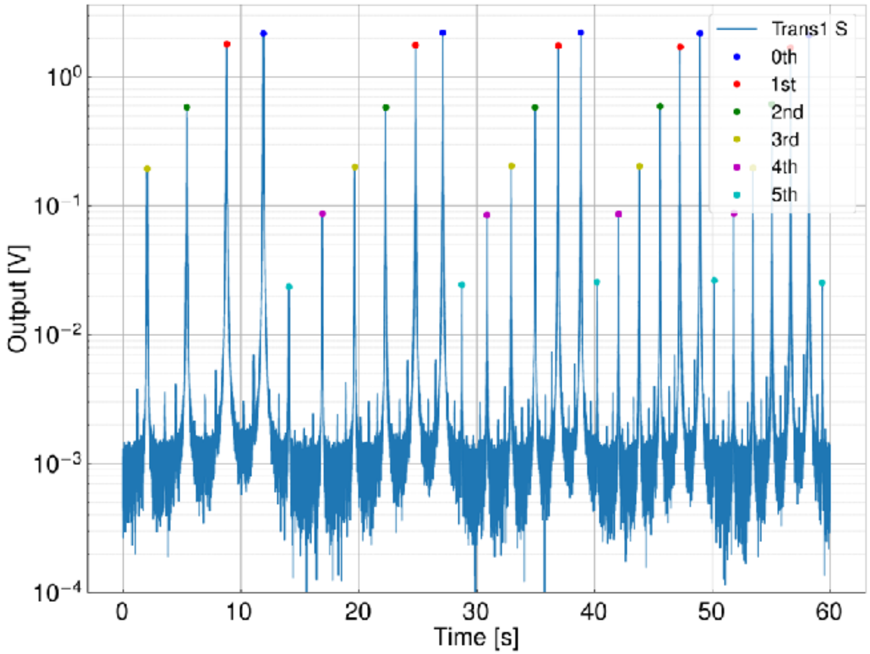
- Design: down to 9 K in 6 days
- Bad heat contact of the heatlinks?
- Absorption of light?

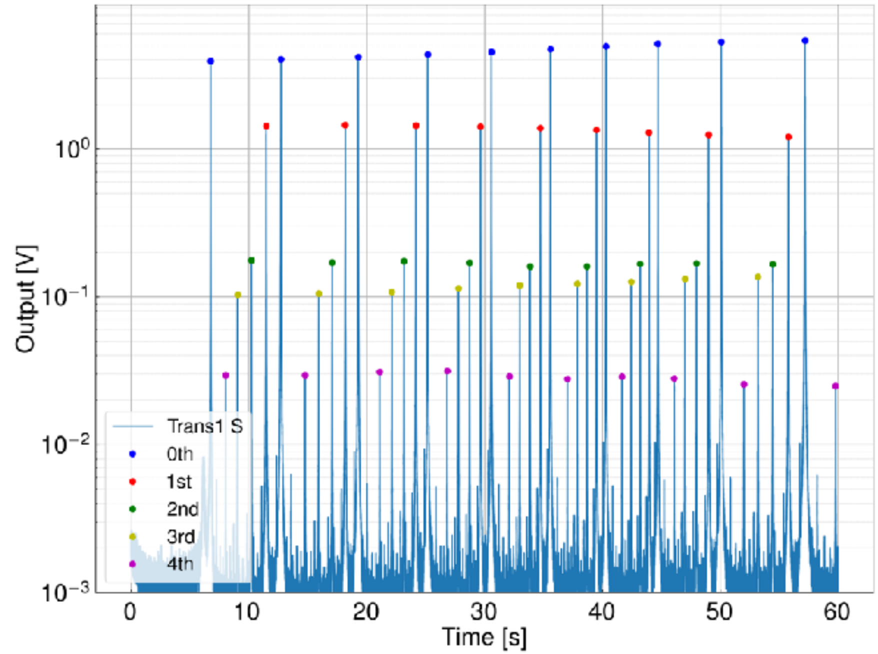


Alignment Drift

Mode matching ratio:

- Cavity1: 95.9 % → 47.2 %
- Cavity2: 97.8 % → 74.8 %

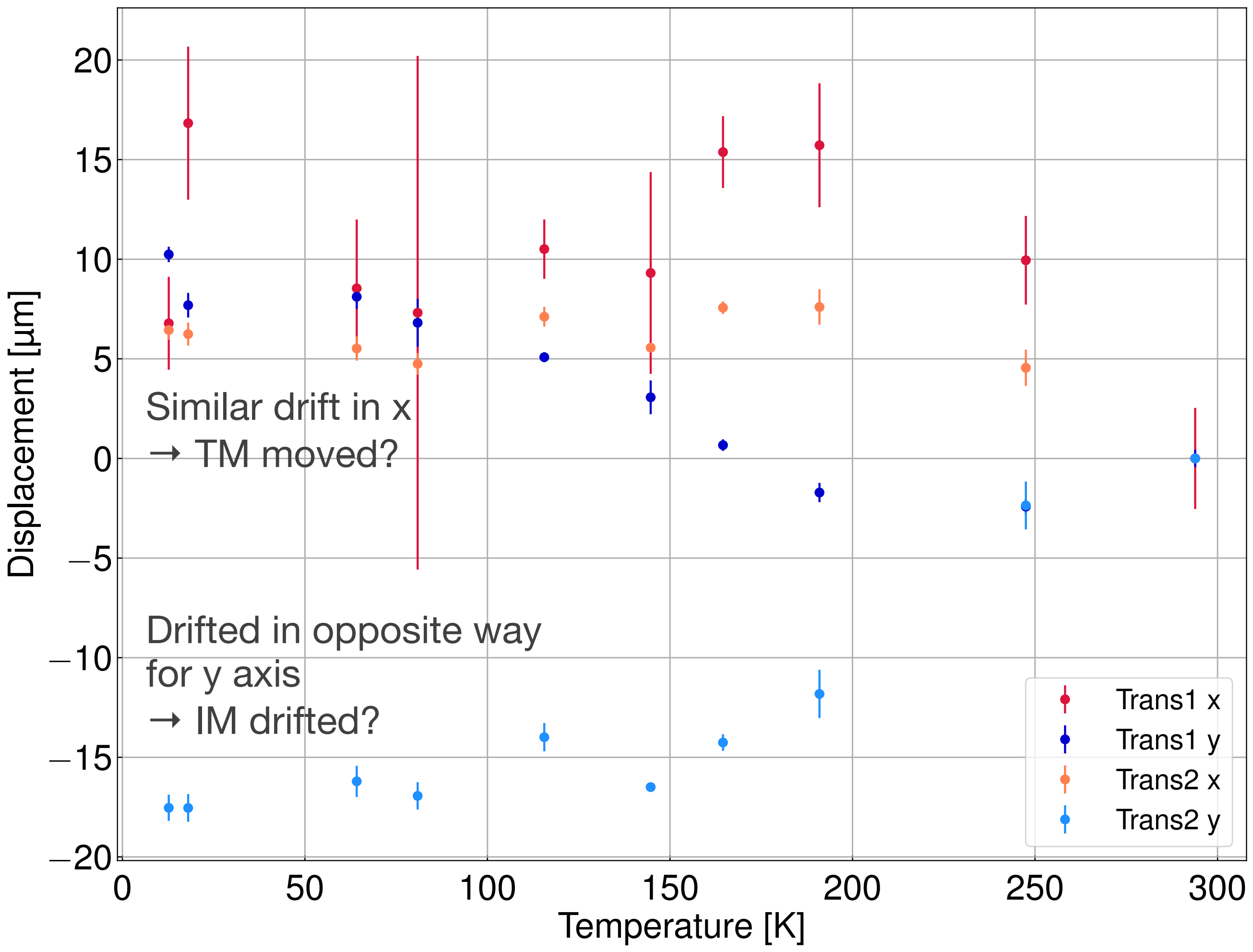




- Drift of the input beams?

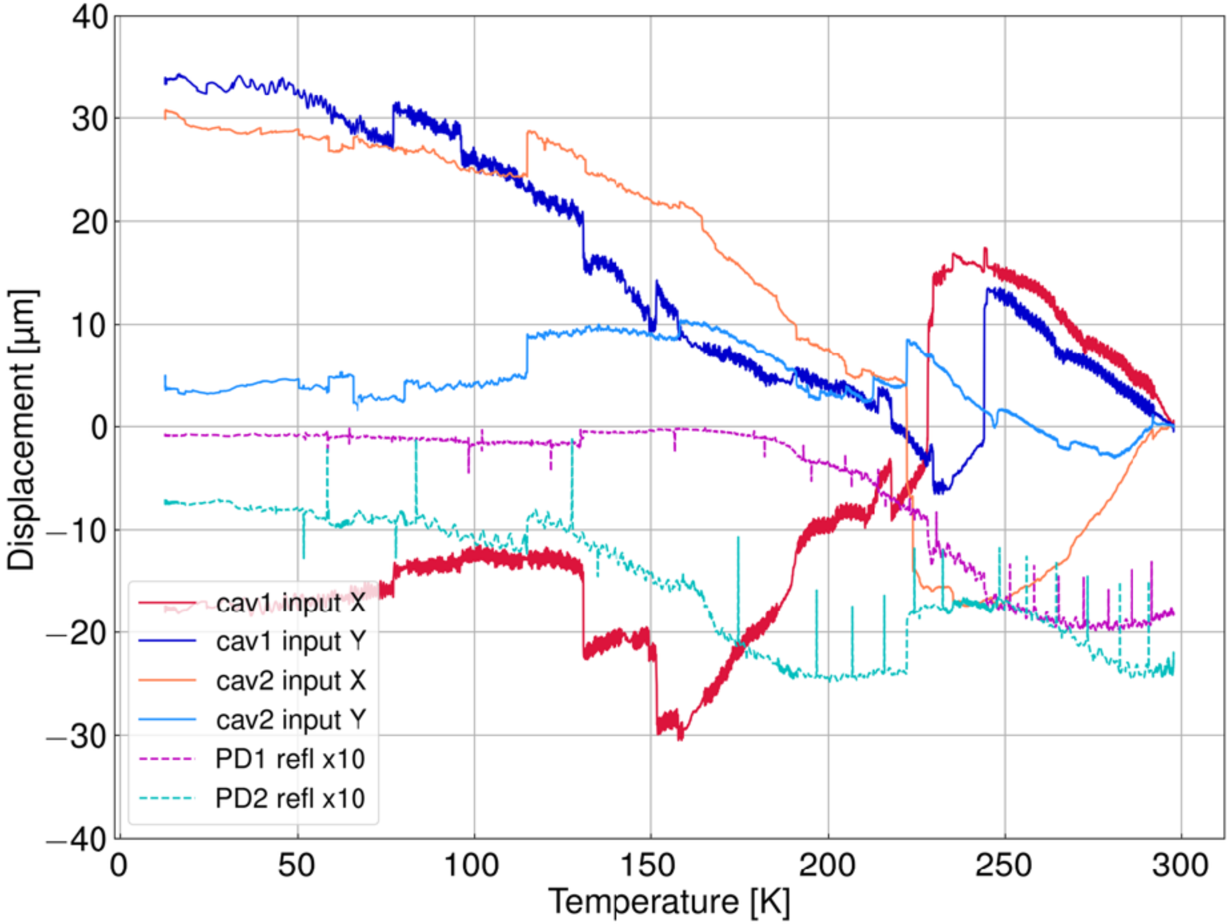
Beam Spot on Transmission Port

- Monitored by QPDs on the transmission port



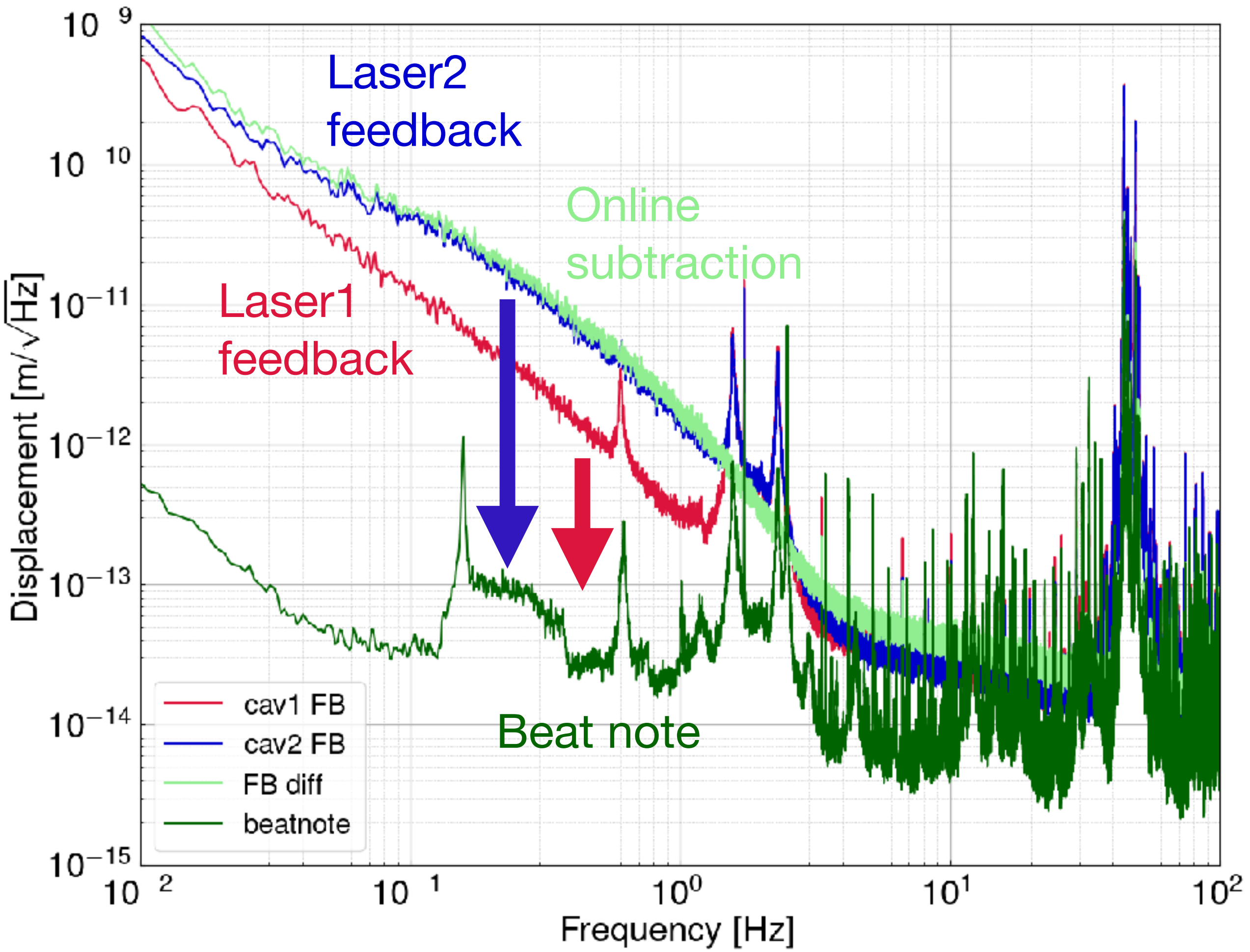
Beam Spot on Input port

- The beam spot drift is similar (20-40μm) for both cavity, but quite different behavior for refl power and mode matching
- Sudden jumps are also seen



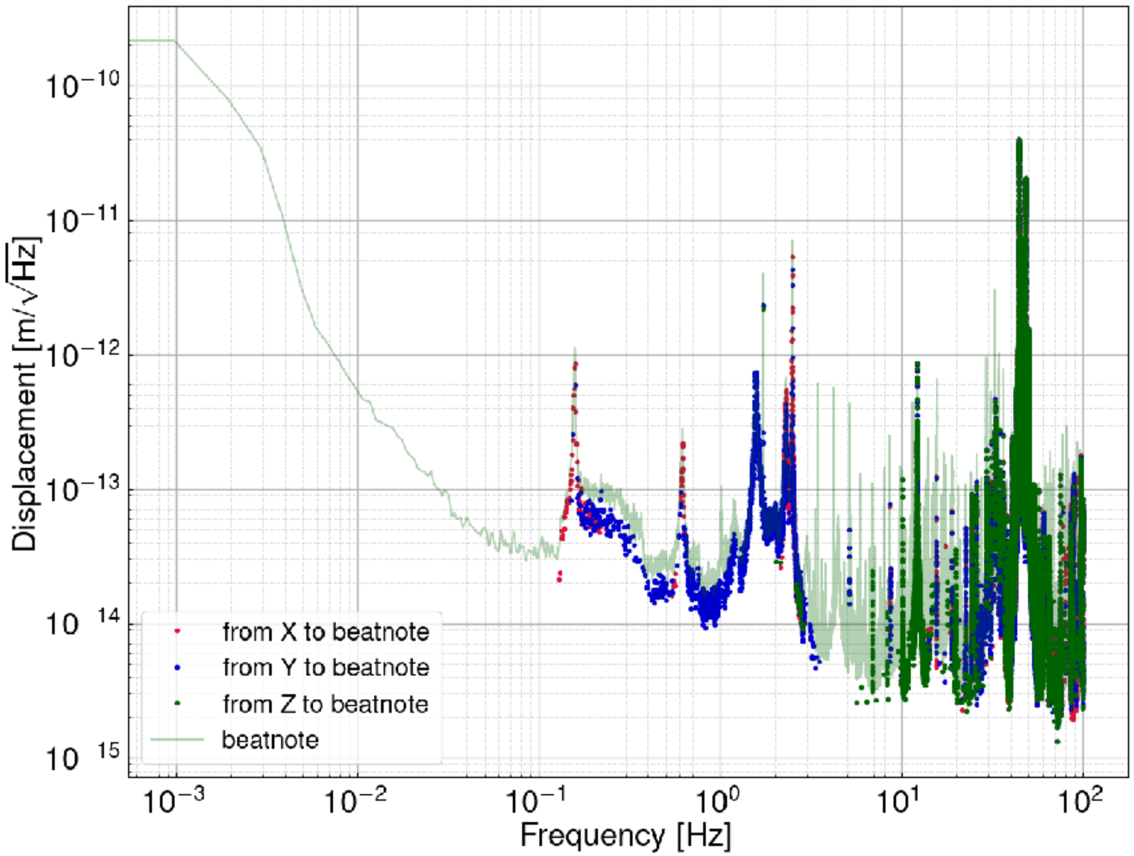
Beat note measurement

- Achieved **3 x 10^{-14} m/√Hz @ 0.1 Hz**
- Frequency noise is suppressed as expected



Seismic Noise Coupling

- 0.1 - 10 Hz: horizontal axis (x, y, yaw)
- Around 17 Hz: vertical axis (z)
- Around 50 Hz: vertical axis (z) + tilt (pit, roll)



Conclusion

- We demonstrated the cryogenic monolithic interferometer
  - Full monolithic breadboard
    - **First achievement**
  - Establishment of assembly scheme
    - Component investigation
    - Alignment procedure
  - Operated at cryogenic temperatures
    - Keep enough alignment for locking the cavity
    - Stable locking, more than 1 day
  - Achieved sensitivity: **3×10^{-14} m/$\sqrt{}$Hz @ 0.1 Hz**
    - Almost the same level as LPF
    - 500 worse than the target sensitivity

Outlook

- Issues for future
  - Alignment drift
    - Further investigation is necessary for improvement
    - Intense work for cryogenic fiber injector might be necessary
  - Vibration coupling
    - Vertical seismic isolation is necessary
    - ▶ Oshima-san will solve the issue?
    - Vibration from the coolers?
    - ▶ AVIT is essential for reduction of the noise
  - Cooling performance
    - Bad heat contact results in slower cooling speed
    - For future this may interrupt the experiment

Fin