



NCU Michelson Interferometer Test Facility

On behalf of NCU & AS Gravitational Waves Research Group

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Gravitational Waves

'ripples' in space-time caused by
some of the most violent and
energetic processes in the
Universe.

Gravitational wave

Black hole

Spacetime

Mirror

Mirror

4 km

Interferometric Gravitational Waves Detector

a

b

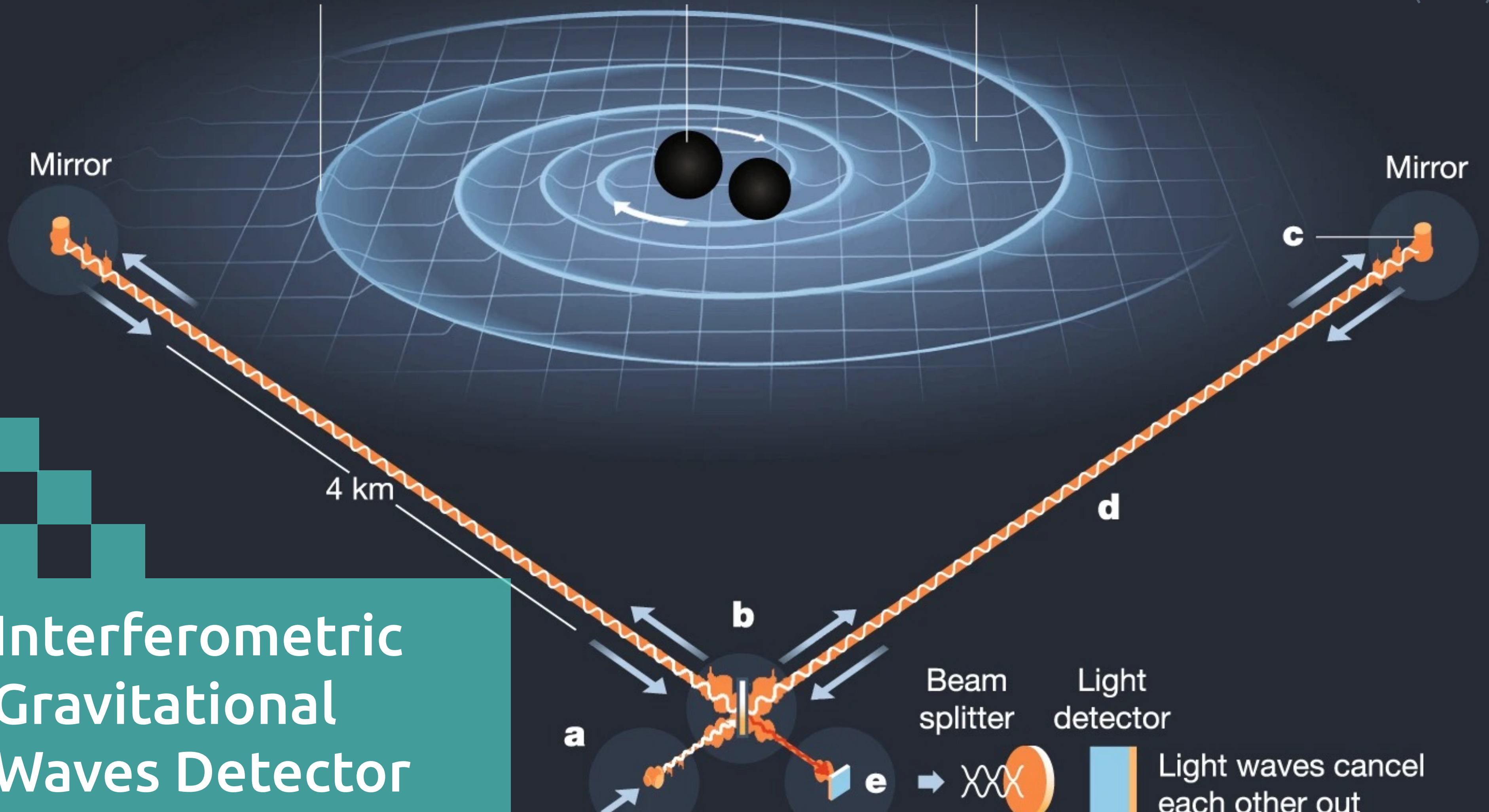
d

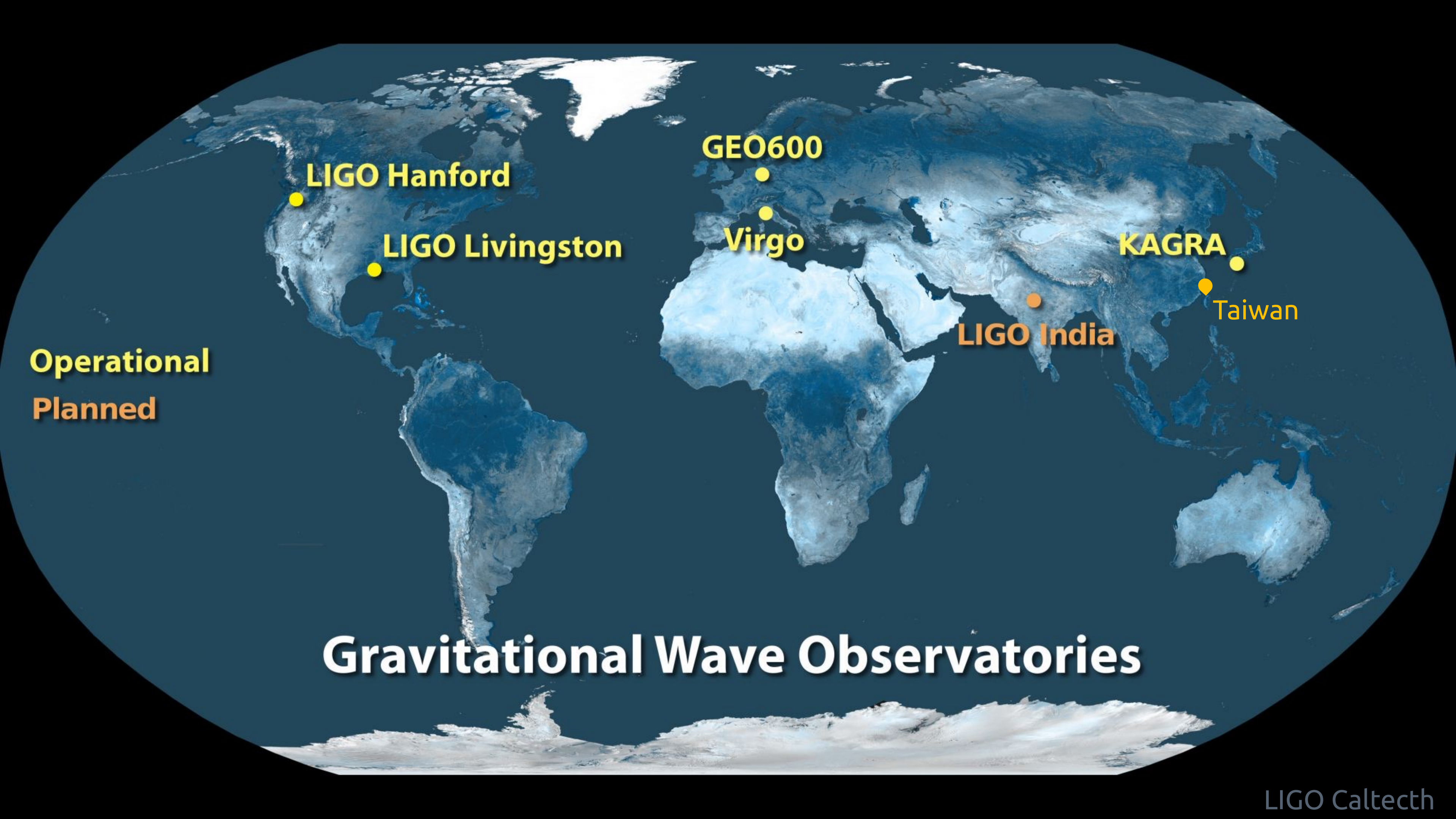
c

Beam splitter

Light detector

Light waves cancel each other out





LIGO Hanford

LIGO Livingston

GEO600

Virgo

LIGO India

KAGRA

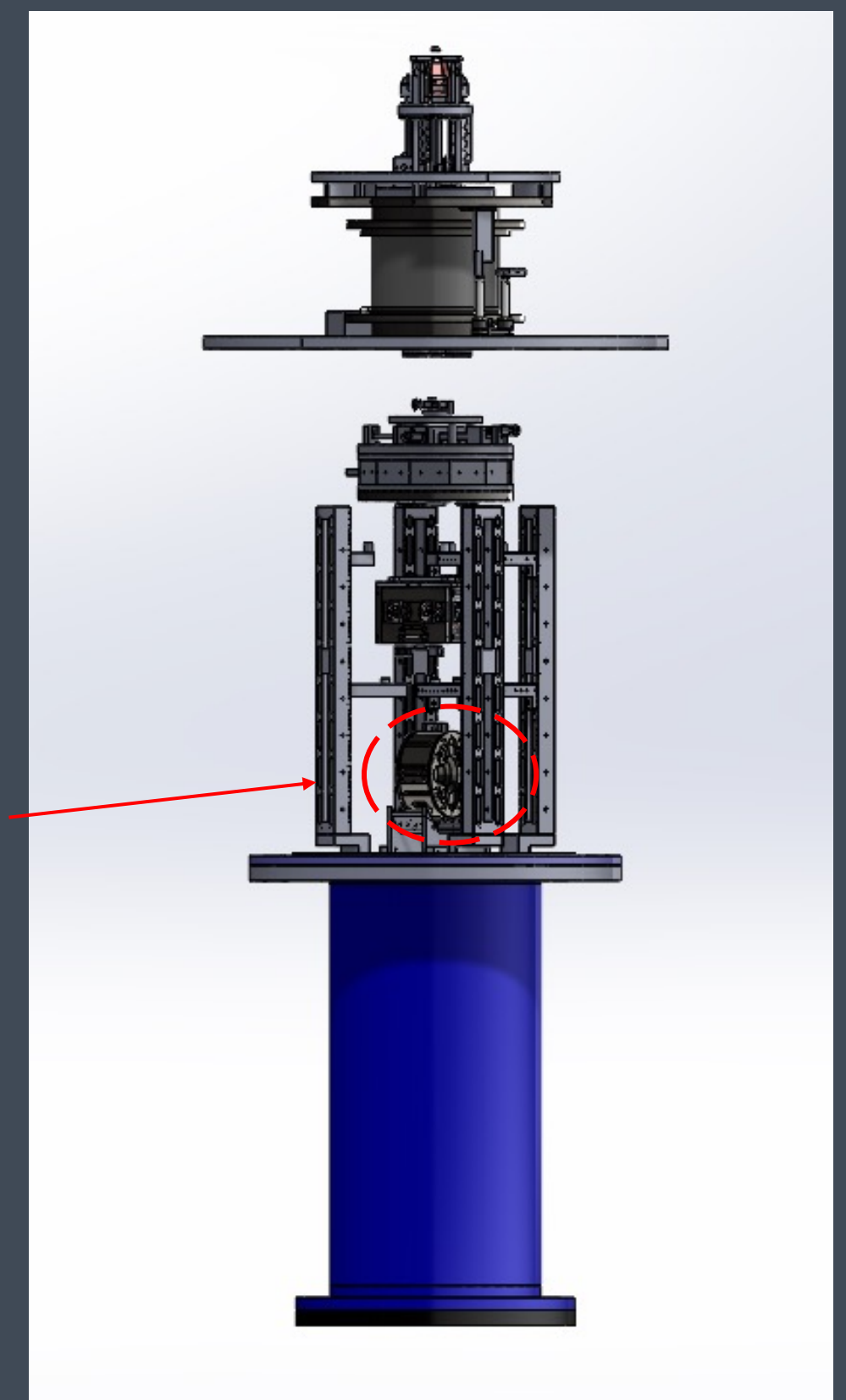
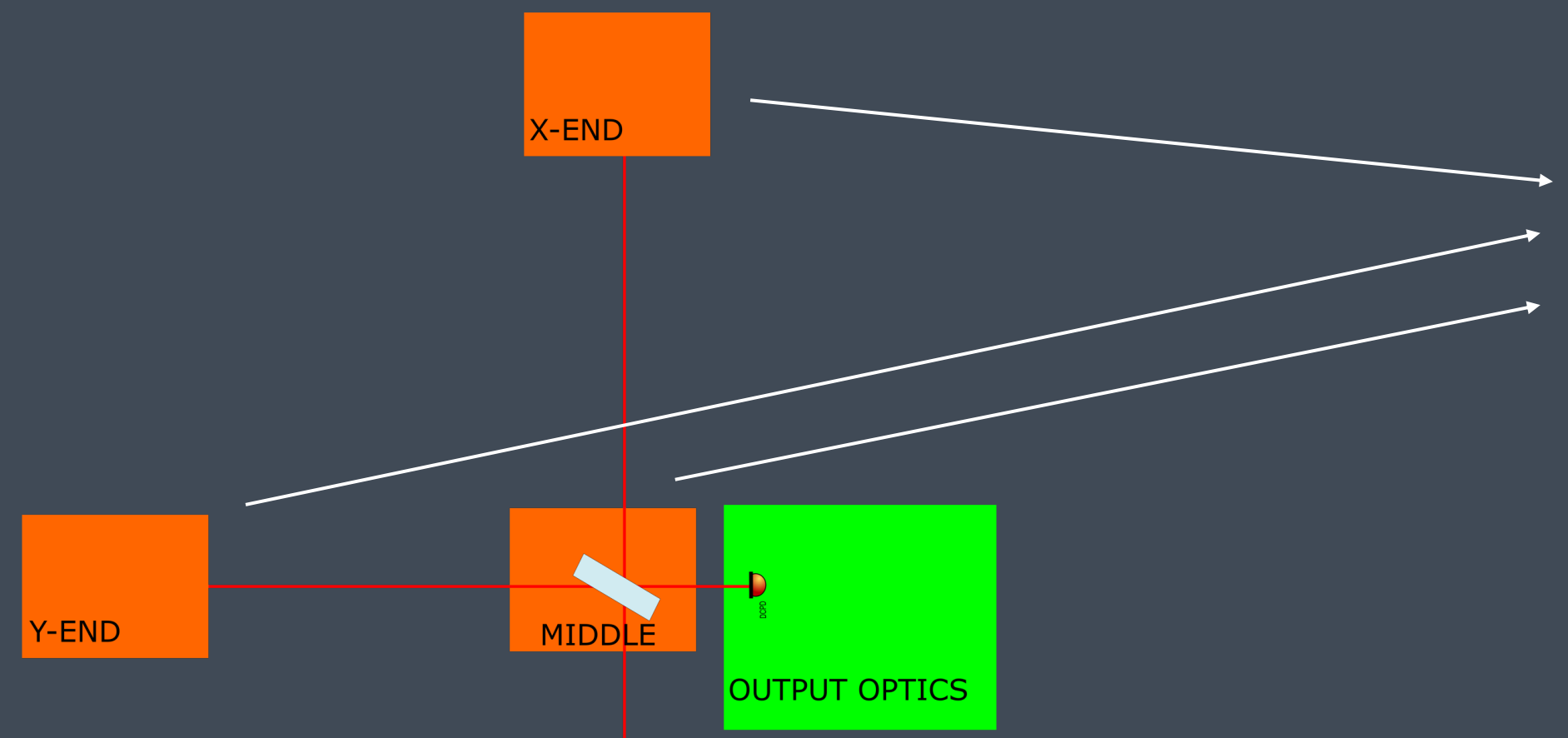
Taiwan

Operational
Planned

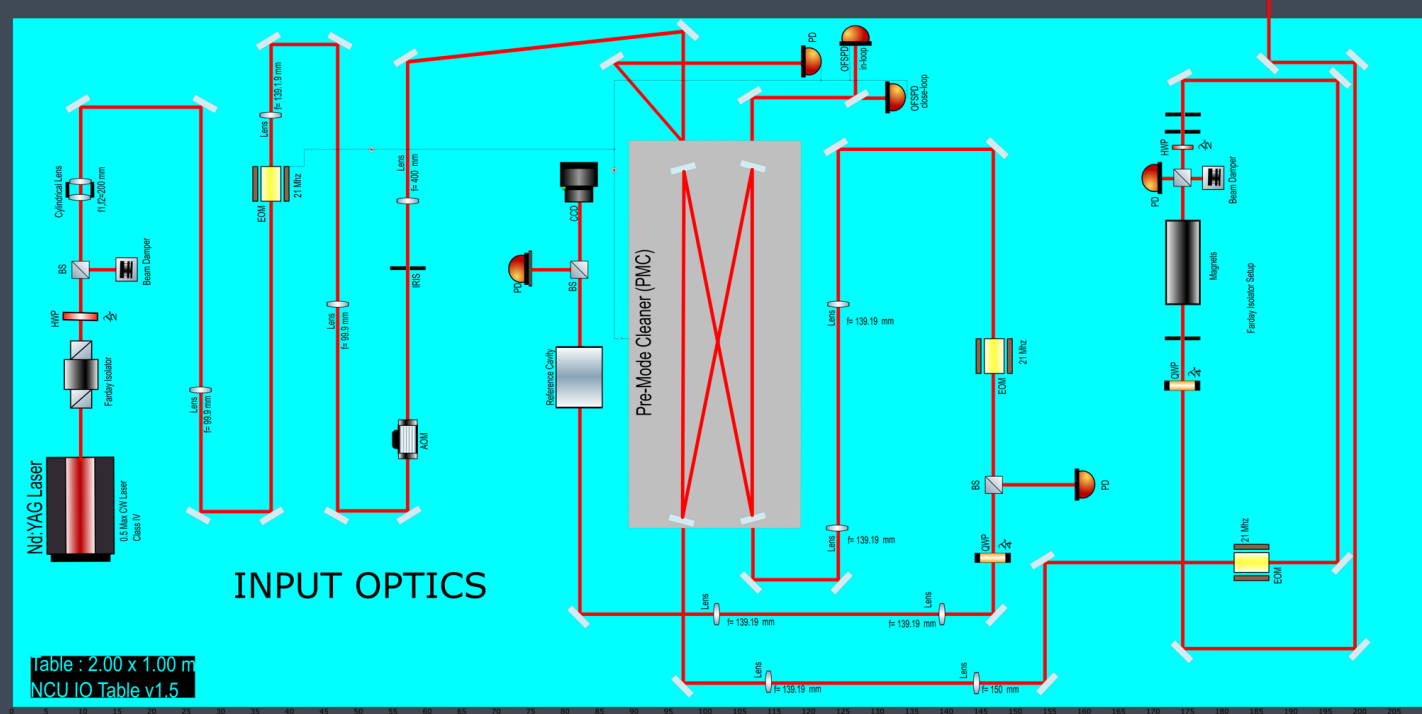
Gravitational Wave Observatories

NCU Michelson Interferometer

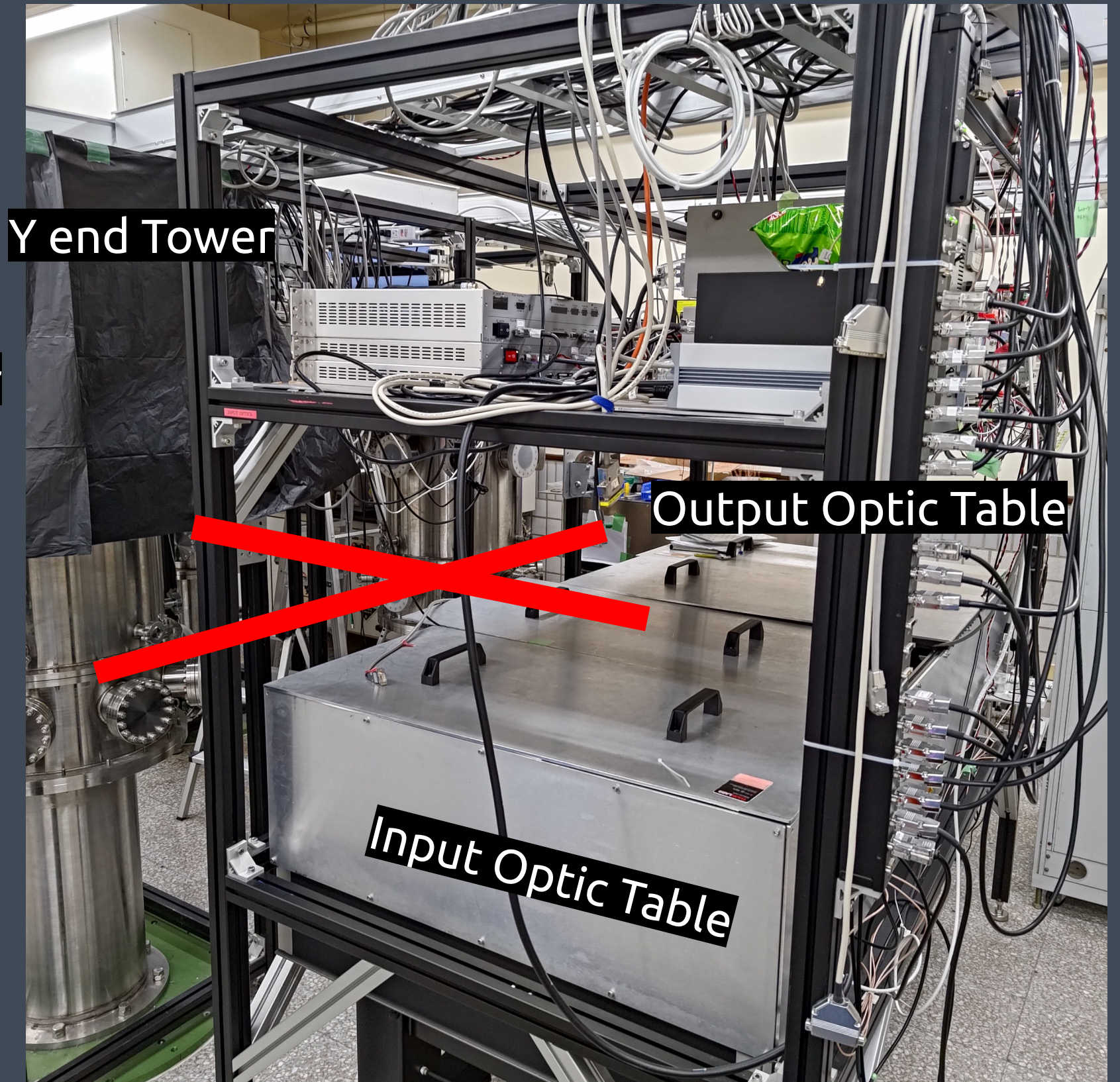
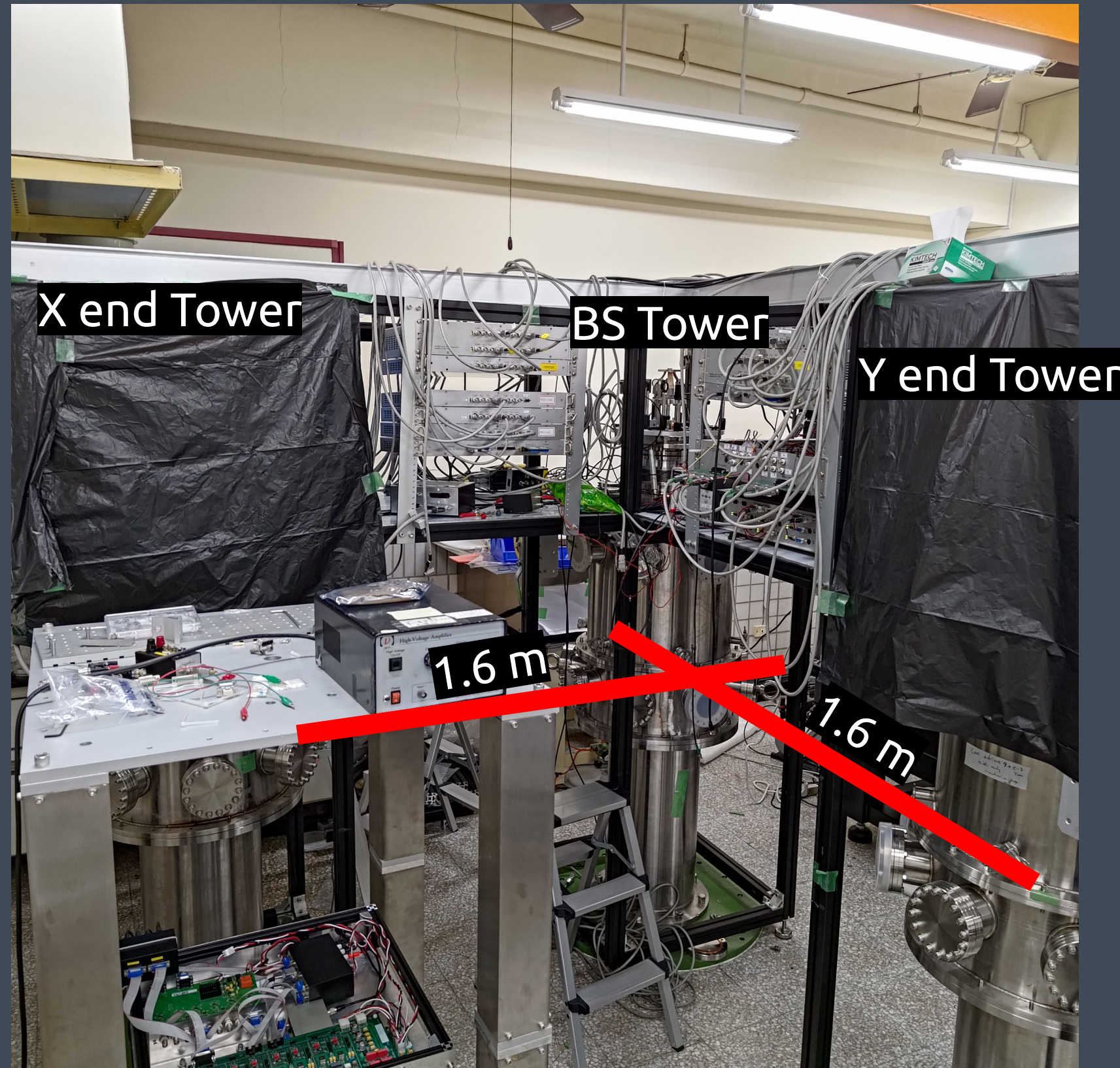
NCU MIF



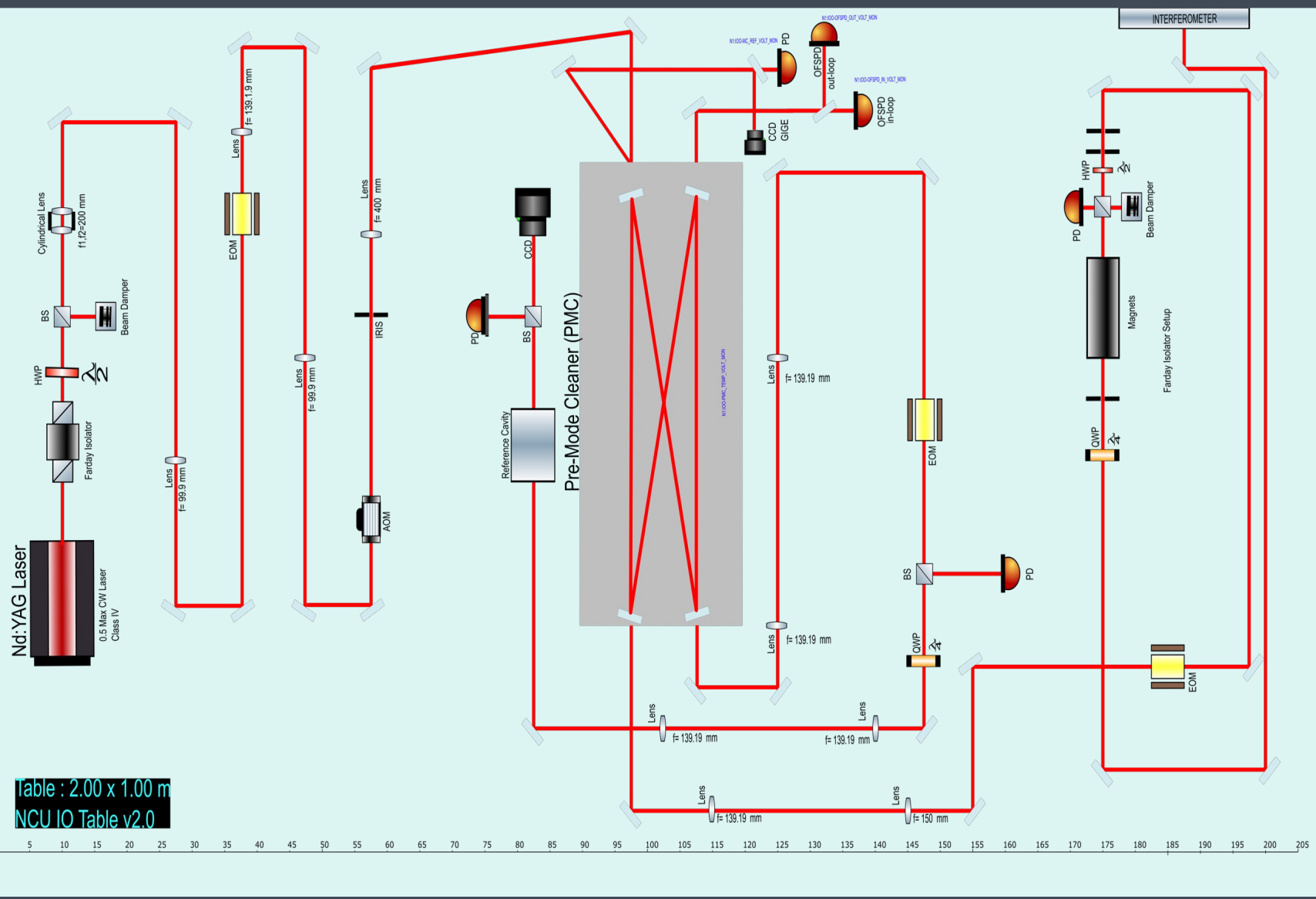
TM Mirrors and BS are suspended by multi-stages pendulum structure.



NCU Michelson Interferometer



Input Optic



$$E(x,y) = A \exp(i\omega t)$$

Beam Intensity Phase

Mode cleaner Intensity Stabilization Frequency Stabilization

Current work in progress for PMC locking by John Chan (Msc student)

Digital Control System



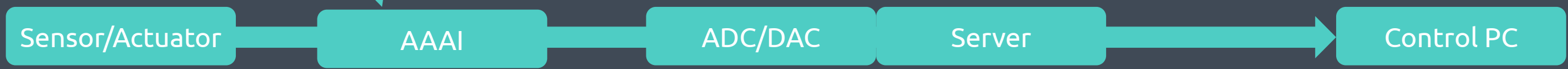
Sensor/Actuator

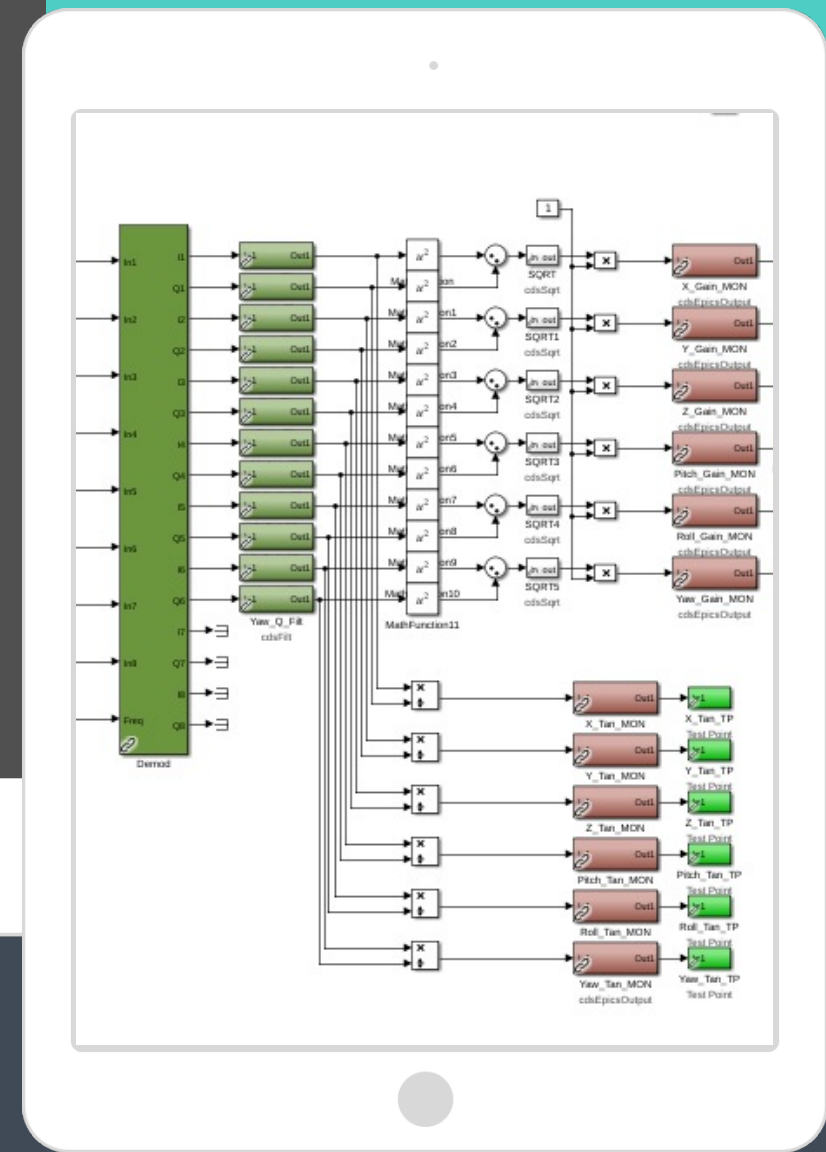
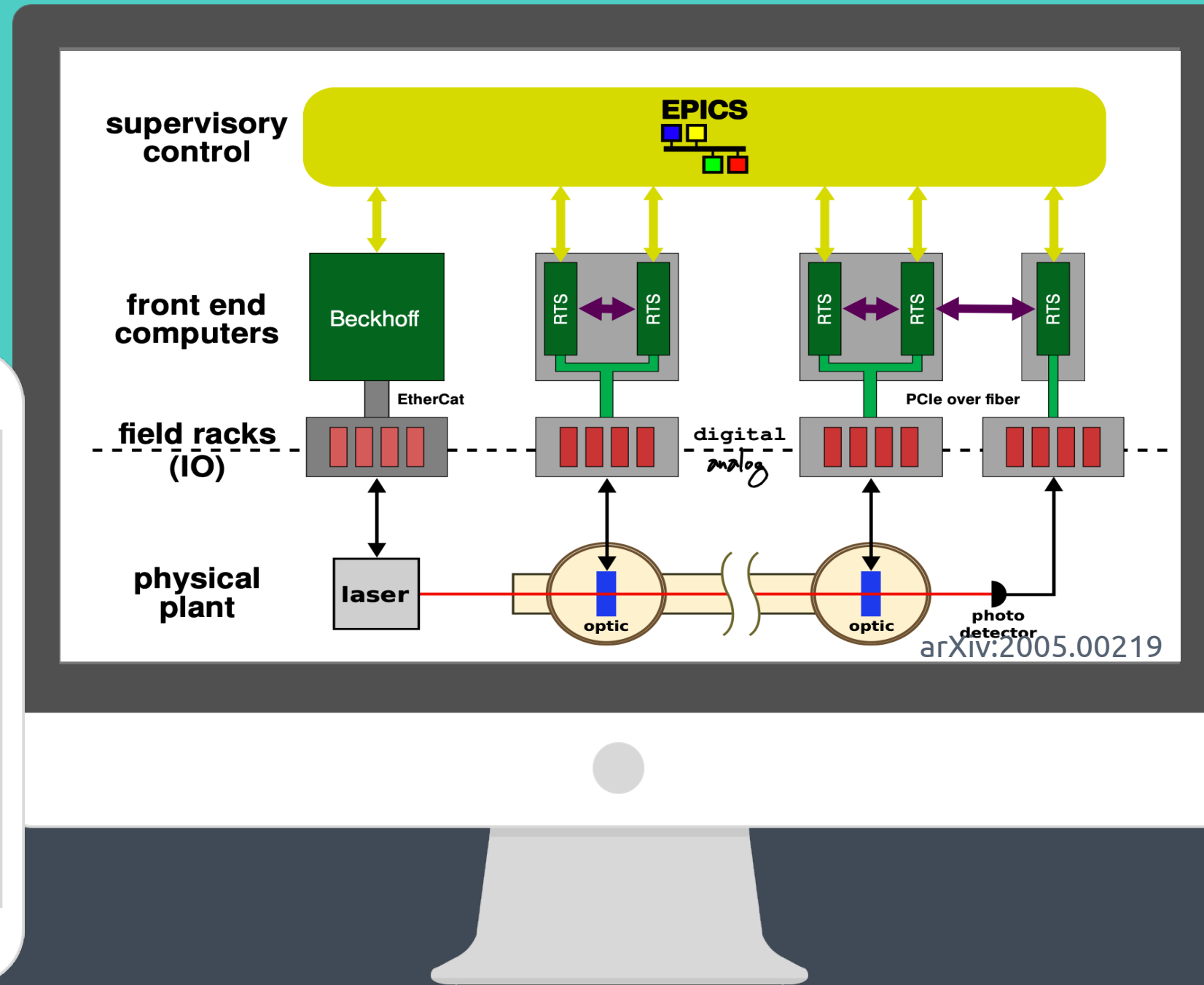
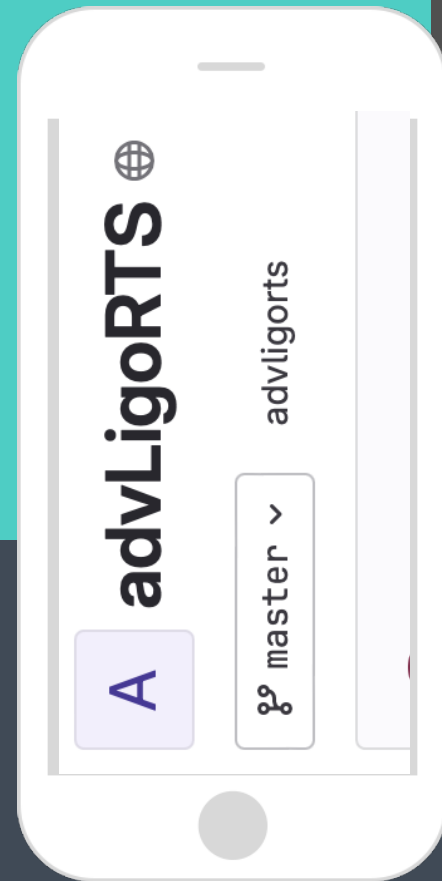
AAAI

ADC/DAC

Server

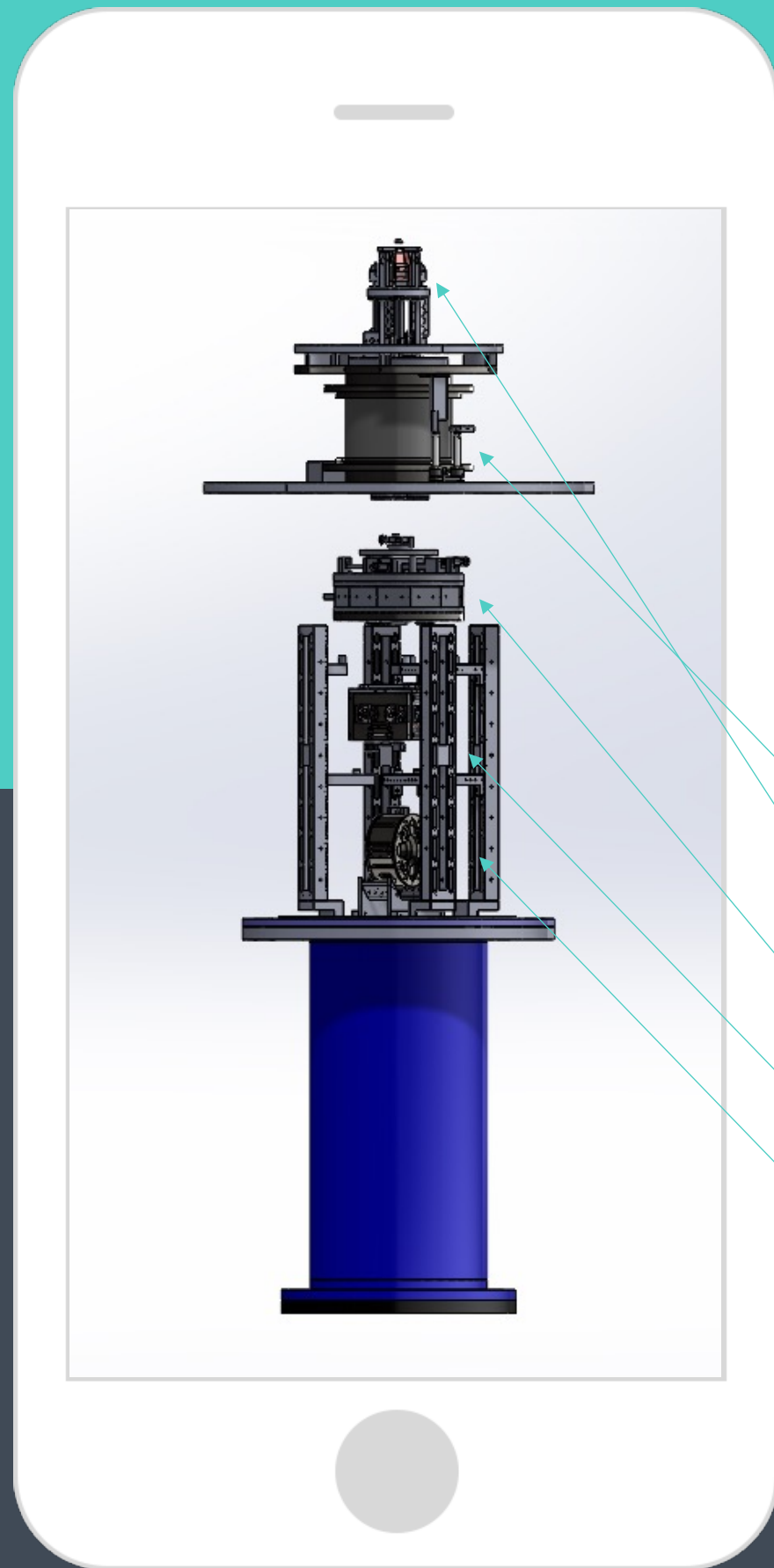
Control PC





Digital Control System

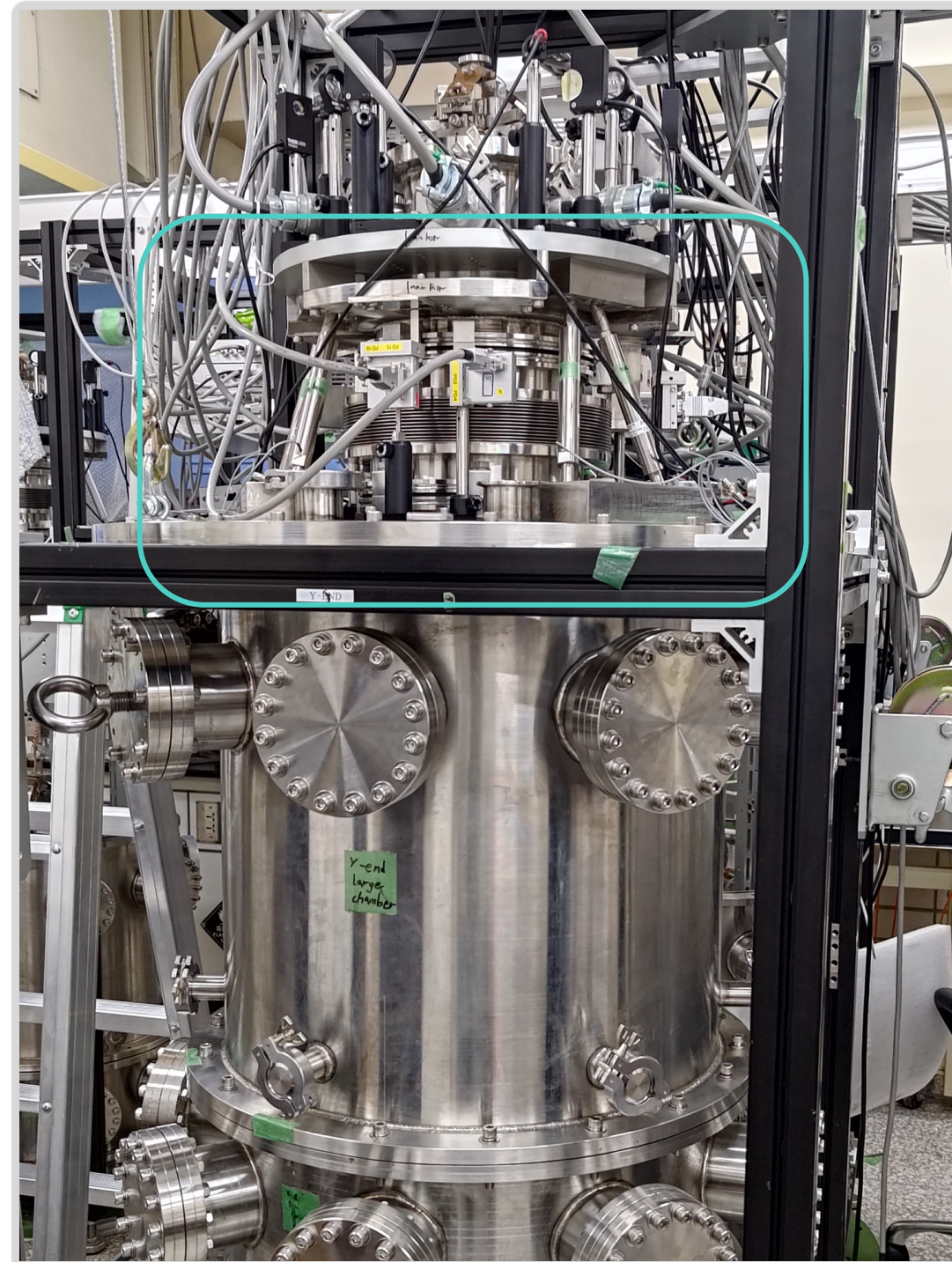
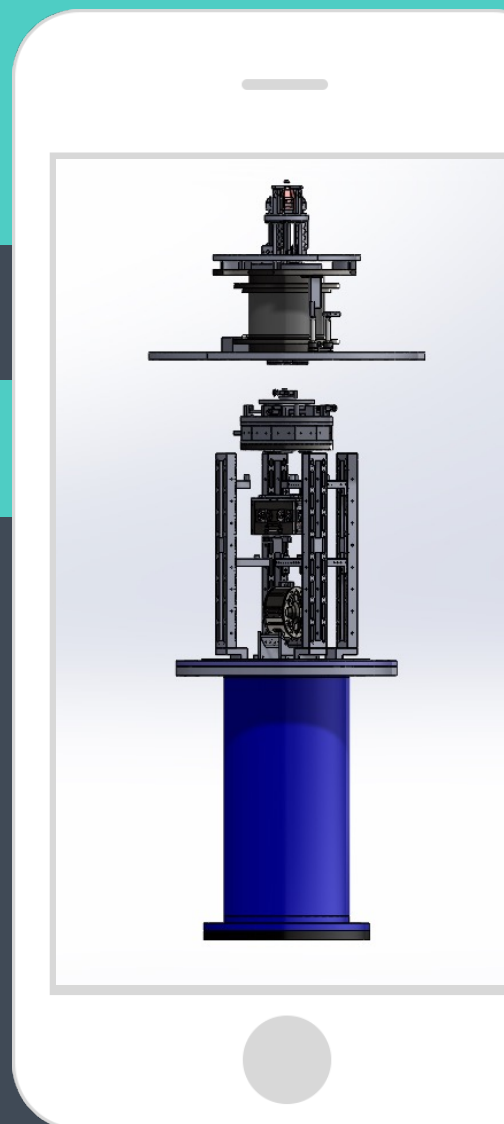
Our computing system use Debian and advLigoRTS (The Advanced LIGO Real-Time Digital Control and Data Acquisition System) which also uses EPICS (Experimental Physics and Industrial Control System).



Vibration Isolation System

- Piezo Stage
- Top Stage (Inverted Pendulum Stage)
- PM Stage
- IM Stage
- TM Stage

To detect $h(t)$ GW, TM must remain as motionless as possible which should be isolated from the ground vibrational noise.



Active Vibration Isolation System

- 6 Piezo + 6 PD Panel (3 vertical + 3 Horizontal)
- Based on these sensor and actuator, we can reconstruct the motion of top plate in 6 DoF to do the feedback control.

AVIS – Piezo Stage MEDM

Y_end_AVIS.adl

Tue Nov 19 01:58:16 2024
1416032602

Y-end Piezo stage

Calibrated PD readout (mm): PD volt2mm

H1:	PD1 32.964561	V1:	PD7 31.660946
	PD2 29.958118		PD8 29.795773
H2:	PD3 32.227055	V2:	PD9 27.456274
	PD4 27.126696		PD10 32.902788
H3:	PD5 19.001992	V3:	PD11 29.258950
	PD6 24.285530		PD12 33.612028

PD Panels matrix

	H1	H2	H3	V1	V2	V3
X	0.1666	-0.3333	0.1666	0.0000	0.0000	0.0000
Y	-0.2886	0.0000	0.2886	0.0000	0.0000	0.0000
Z	0.0000	0.0000	0.0000	0.3333	0.3333	0.3333
PITCH	0.0000	0.0000	0.0000	-0.002	0.0000	0.0021
ROLL	0.0000	0.0000	0.0000	0.0008	-0.0016	0.0008
YAW	-0.002	-0.002	-0.002	0.0000	0.0000	0.0000

Matrix Diagonalization

	X	Y	Z	PITCH	ROLL	YAW
X	1.0992	-3.733	2.7705	-1051.	-2067.	-1264.
Y	-1.137	12.437	-9.316	1912.6	4337.6	1860.7
Z	0.6280	-4.053	4.2647	-694.5	-1290.	-510.7
PITCH	-0.000	0.0307	-0.025	6.3836	11.295	4.9013
ROLL	-0.001	0.0355	-0.025	5.7013	14.975	7.2080
YAW	-0.000	0.0147	-0.012	3.1306	6.6645	3.9039

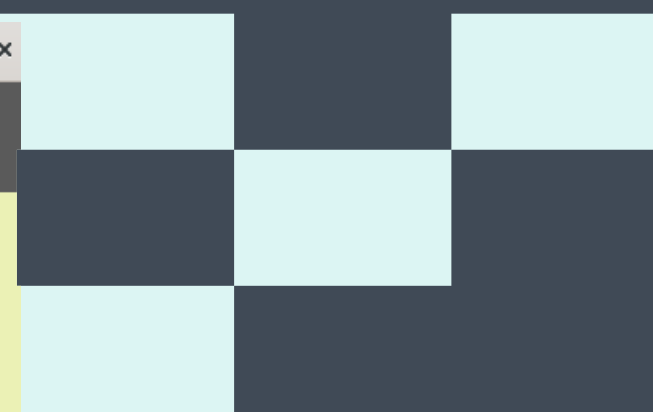
Line Injection Demodulator

	Freq	Gain	Switch
X	0.500	3.9	0.0
Y	0.500	4.4	0.0
Z	0.500	15.0	0.0
PITCH	0.500	10.2	0.0
ROLL	0.500	10.0	0.0
YAW	0.500	7.0	0.0

Piezo matrix

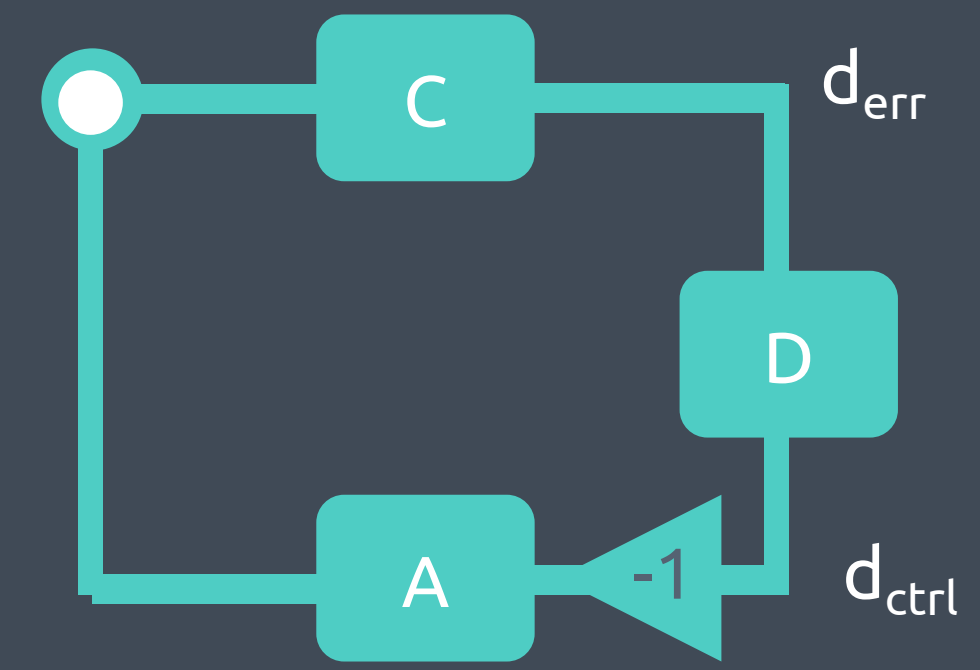
	X	Y	Z	PITCH	ROLL	YAW
P1	0.6439	-1.1153	0.1786	-0.4819	-0.1200	-0.6439
P2	-0.6439	1.1153	0.1786	-0.1368	0.4774	0.6439
P3	-1.2879	0.0000	0.1786	0.3450	-0.3570	-0.6439
P4	1.2879	0.0000	0.1786	-0.3450	-0.3570	0.6439
P5	0.6439	1.1153	0.1786	0.1368	0.4774	-0.6439
P6	-0.6439	-1.1153	0.1786	0.4819	-0.1200	0.6439

Diagram of piezo stage with actuators (P1-P6) and sensors (H1-H3, V1-V3).



MEDM
Motif Editor and Display Manager is a GUI for designing and implementing control screens which display the values of EPICS process variables.

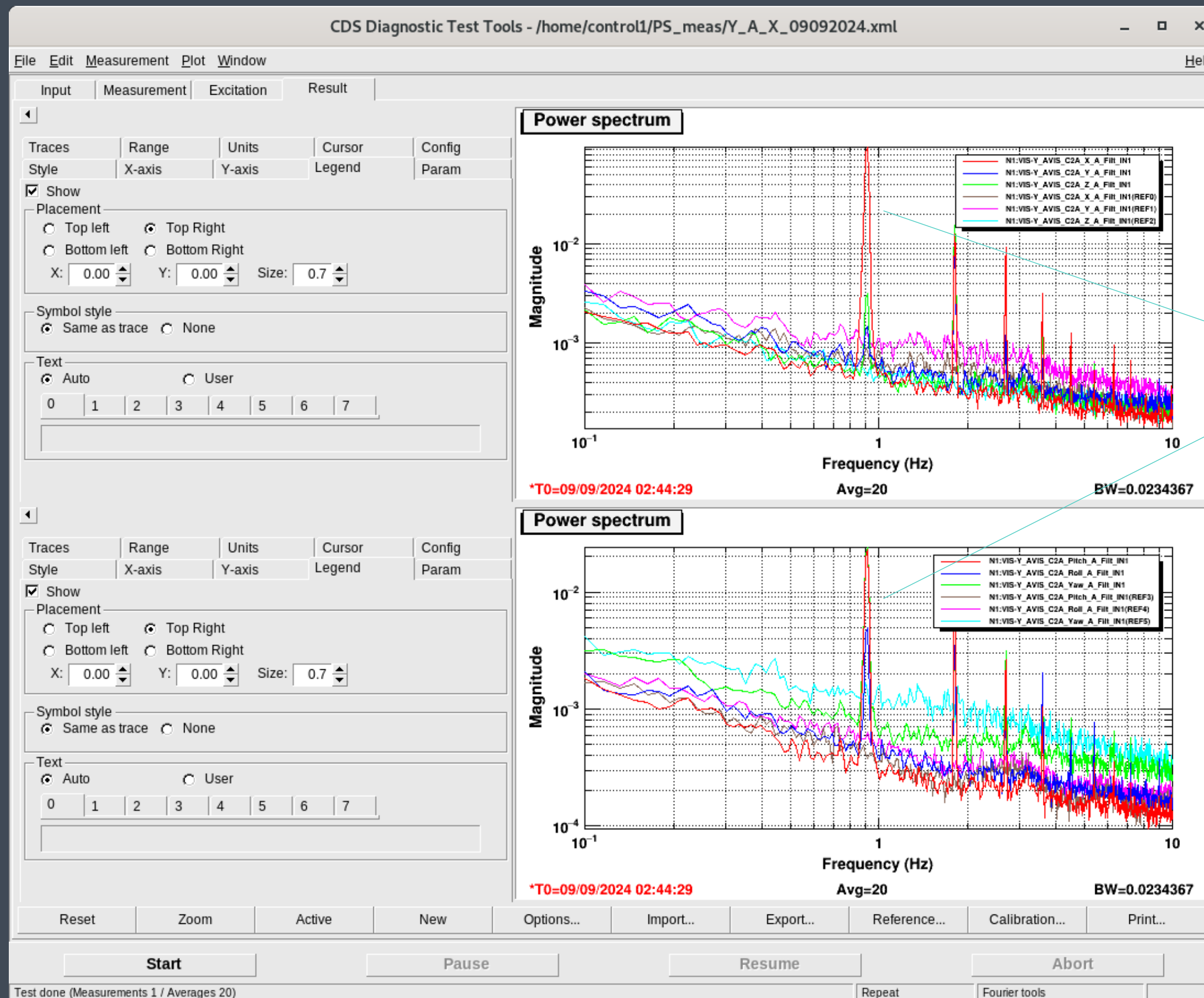
We reconstruct 6DoF motion (X, Y, Z, Pitch, Roll, Yaw) based from the sensors and actuators.



Cross-Contamination on 6 DoF



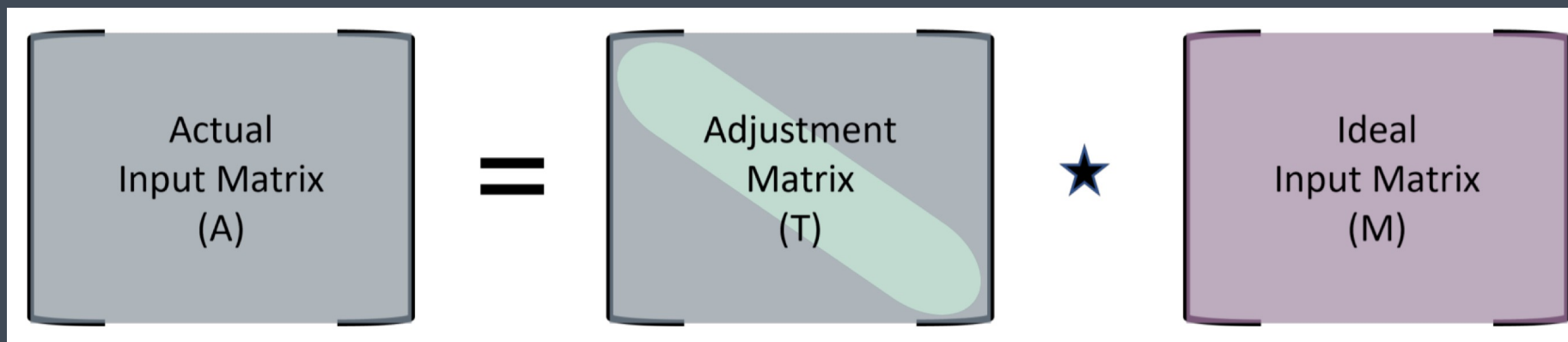
Diagonalization



We injected 0.9 Hz signal on X from the actuators, however from the output of sensor matrix, it showed 0.9 Hz peaks on all 6 DoF.

Diaggi – a tools developed by LIGO to measure power spectrum and transfer function.

Diagonalization



H.C. Hsu

In reality, our actual input matrix is not equivalent to Ideal input matrix, therefore we need to measure the adjustment matrix to calculate its inverse matrix so that we can diagonalize our input matrix.

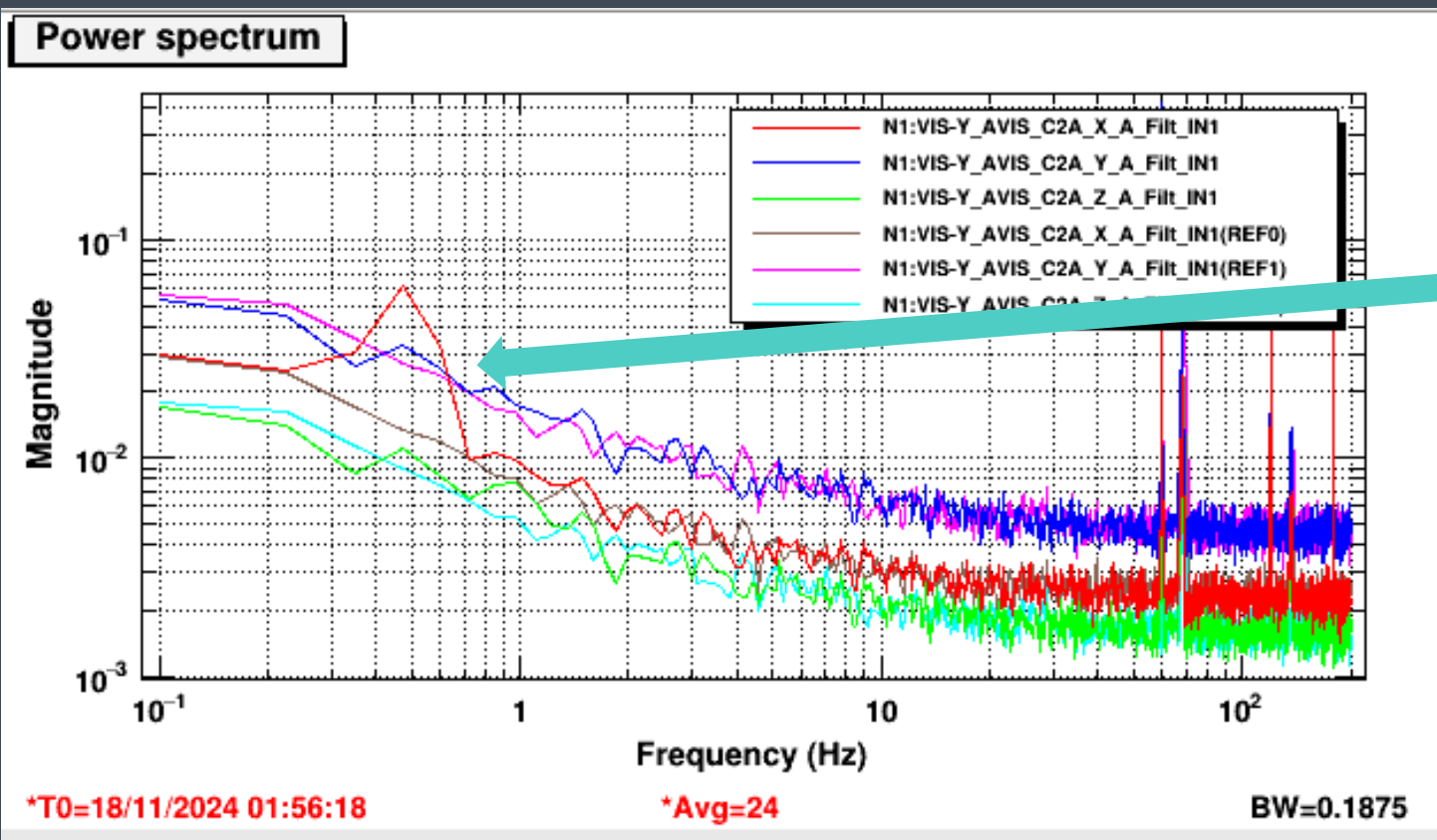
DoF Filts	Matrix Diagonalization							DoF Filts
	X	Y	Z	PITCH	ROLL	YAW		
0.004979	X	1.0992	-3.739	2.7709	-1051.	-2067.	-1264.	0.202642
0.026036	Y	-1.137	12.437	-9.316	1912.6	4337.6	1860.7	-0.061102
-0.013367	Z	0.6280	-4.053	4.2647	-694.5	-1290.	-510.7	-0.032202
0.000087	PITCH	-0.009	0.0307	-0.026	6.3836	11.299	4.9013	-0.000073
-0.000037	ROLL	-0.001	0.0353	-0.029	5.7013	14.979	7.2080	-0.000771
-0.000274	YAW	-0.000	0.0147	-0.012	3.1306	6.6649	3.9039	-0.000493

```

piezo_diagonalization.py x
Yend > python3 piezo_diagonalization.py > ...
1  #!/usr/bin/env python3
2  # -*- coding: utf-8 -*-
3  """
4  Created on Sun Oct 6 4:59 PM 2024
5
6  @author: M Maarif, Avani, Hsiang-Yu
7  """
8  import sys
9  import os
10 import numpy as np
11 from datetime import datetime
12 import epics
13 import time
14 import utils
15 from utils import Matrix, ReadChans
16 import sys
17
18 args =sys.argv
19
20 # Input Parameters
21 if len(args) < 2:
22     print('Please enter the frequency (args[1]) and time range (args[2])!')
23     sys.exit()
24
25 freq = float(args[1])
  
```

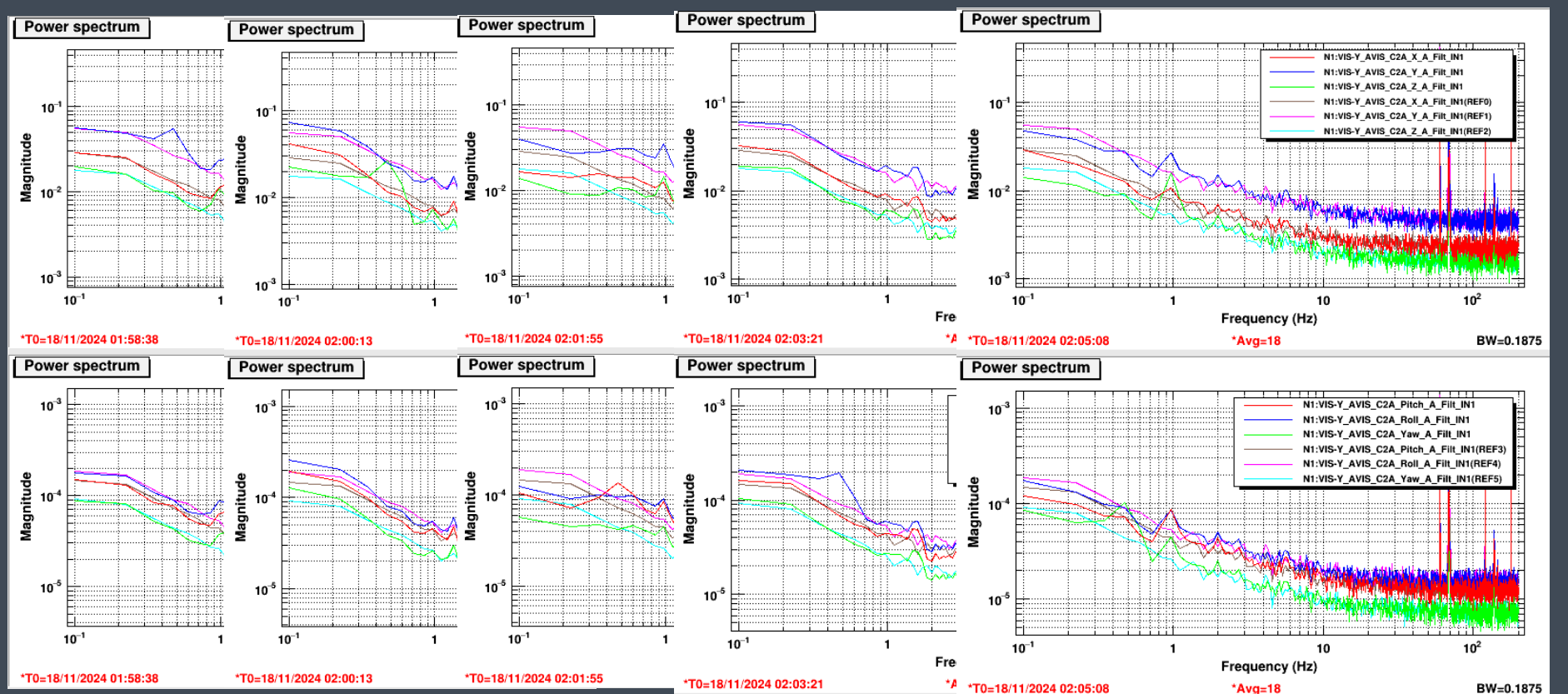
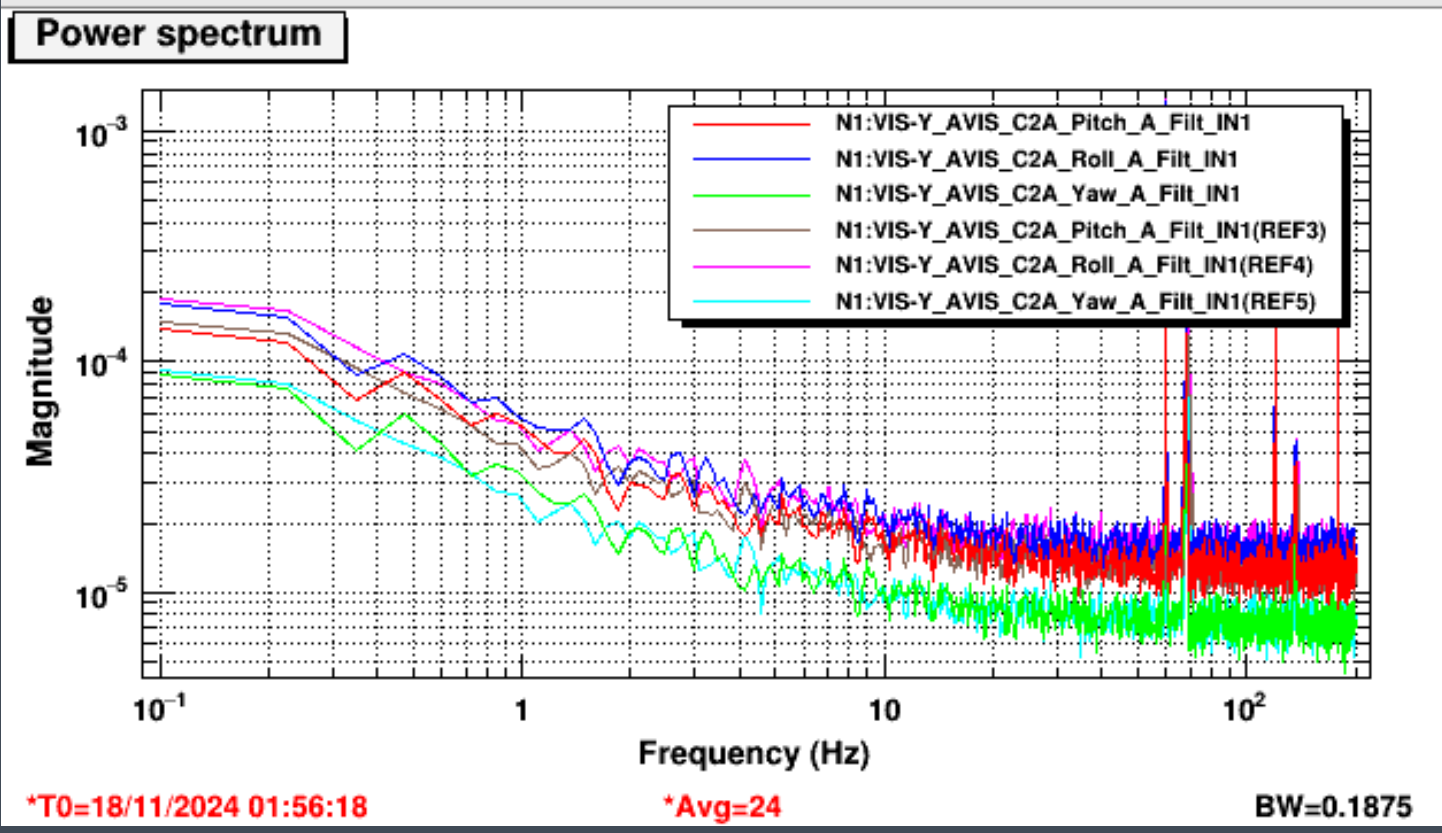
The process to calculate inverse matrix from demodulation is done automatically by python code.

Diagonalization Result

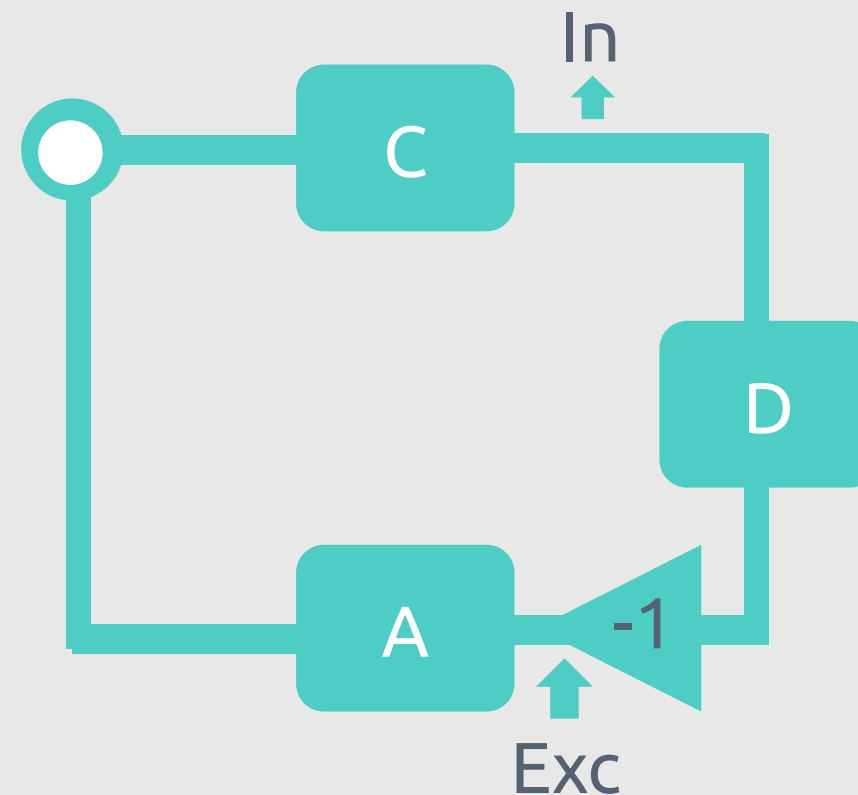
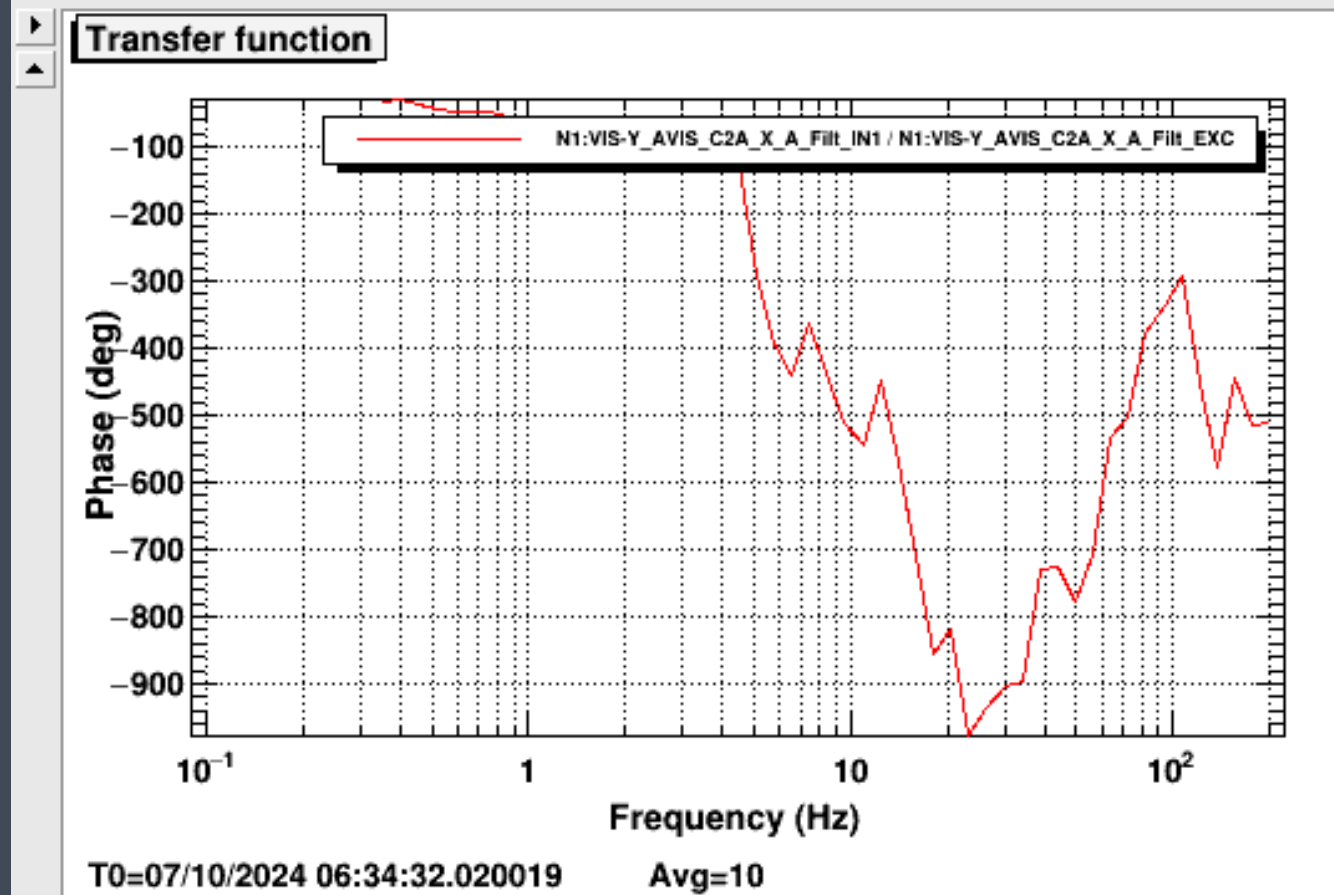
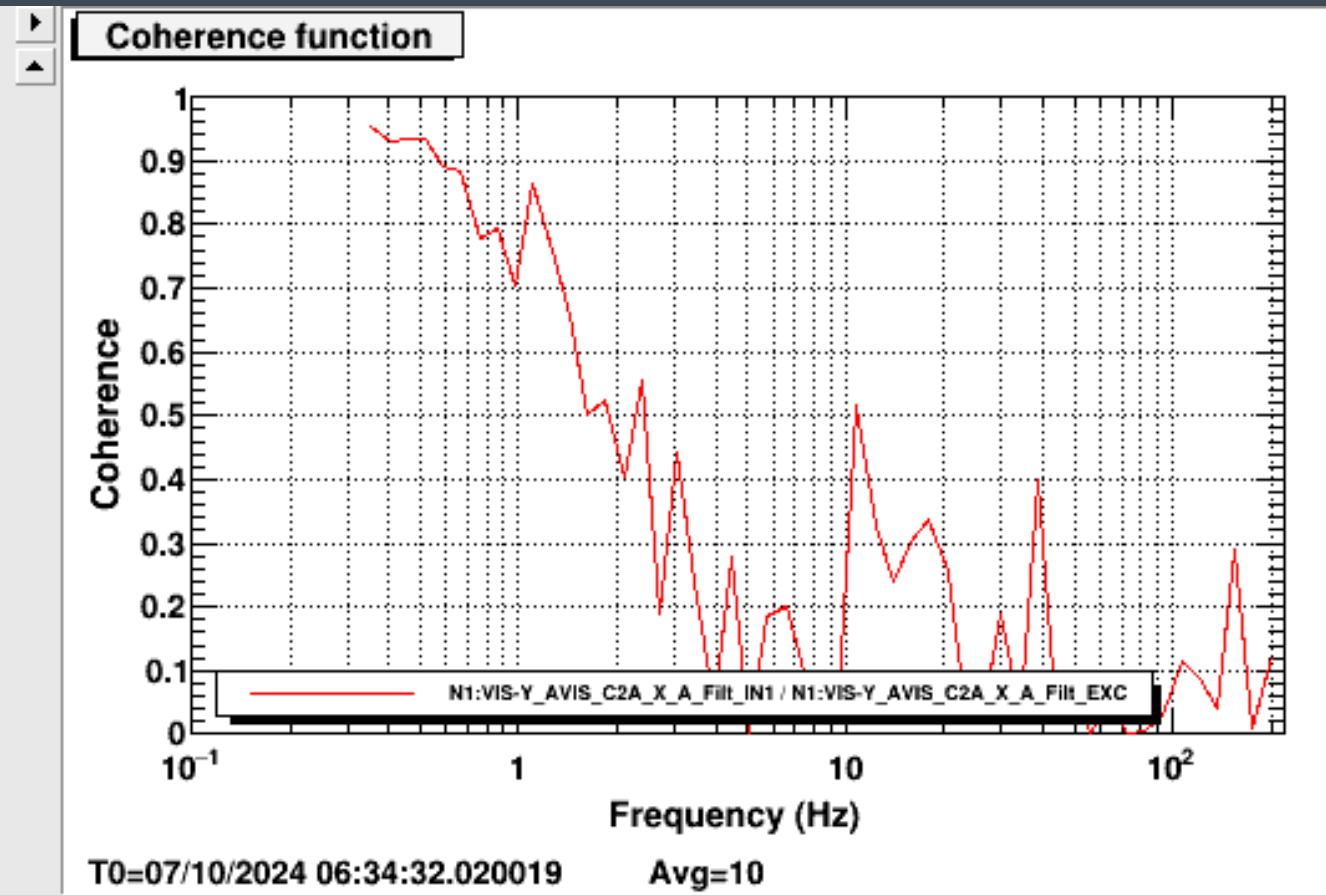
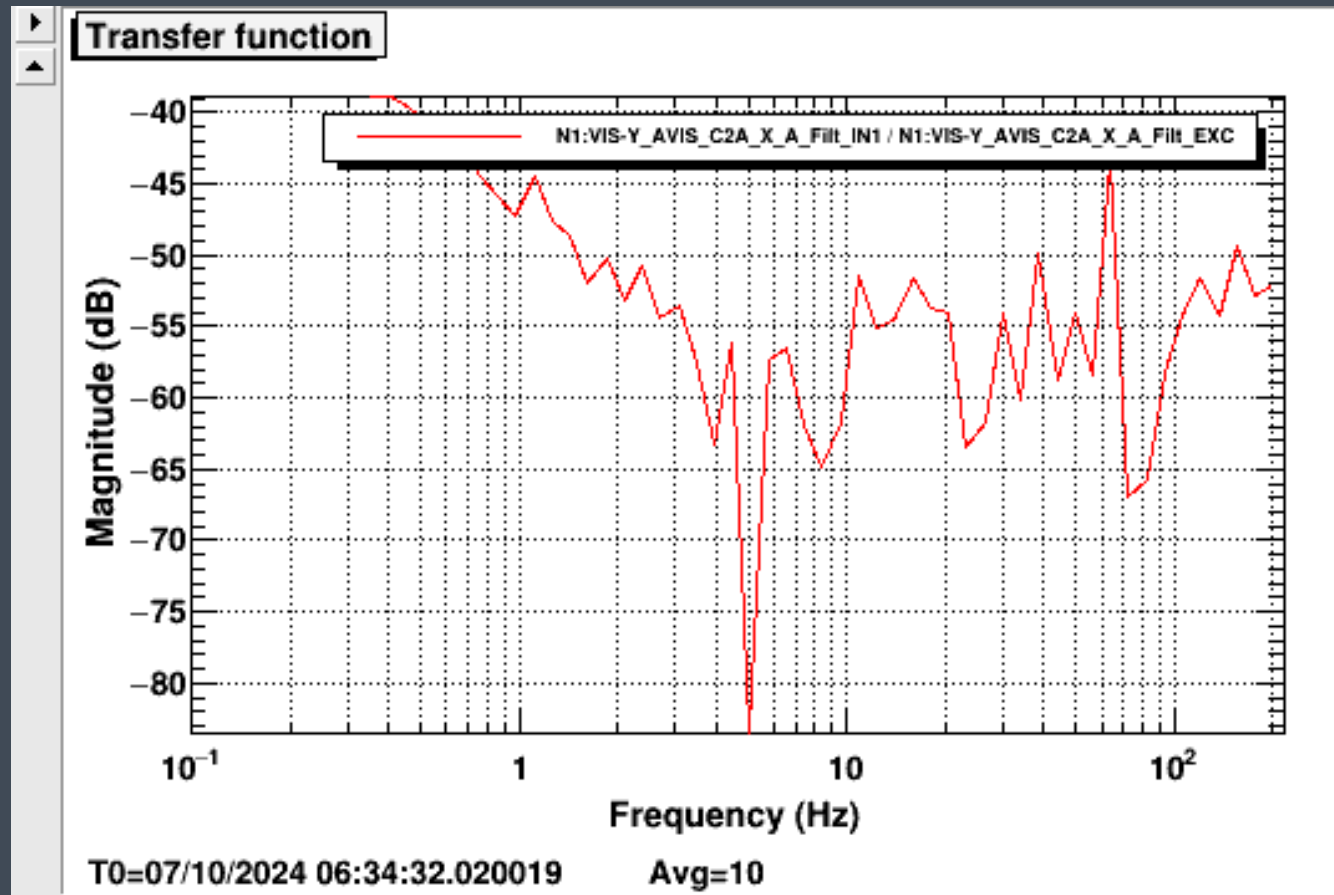


Now, only X shows the peak when we injected signal on X.

And it happens for all other DOFs

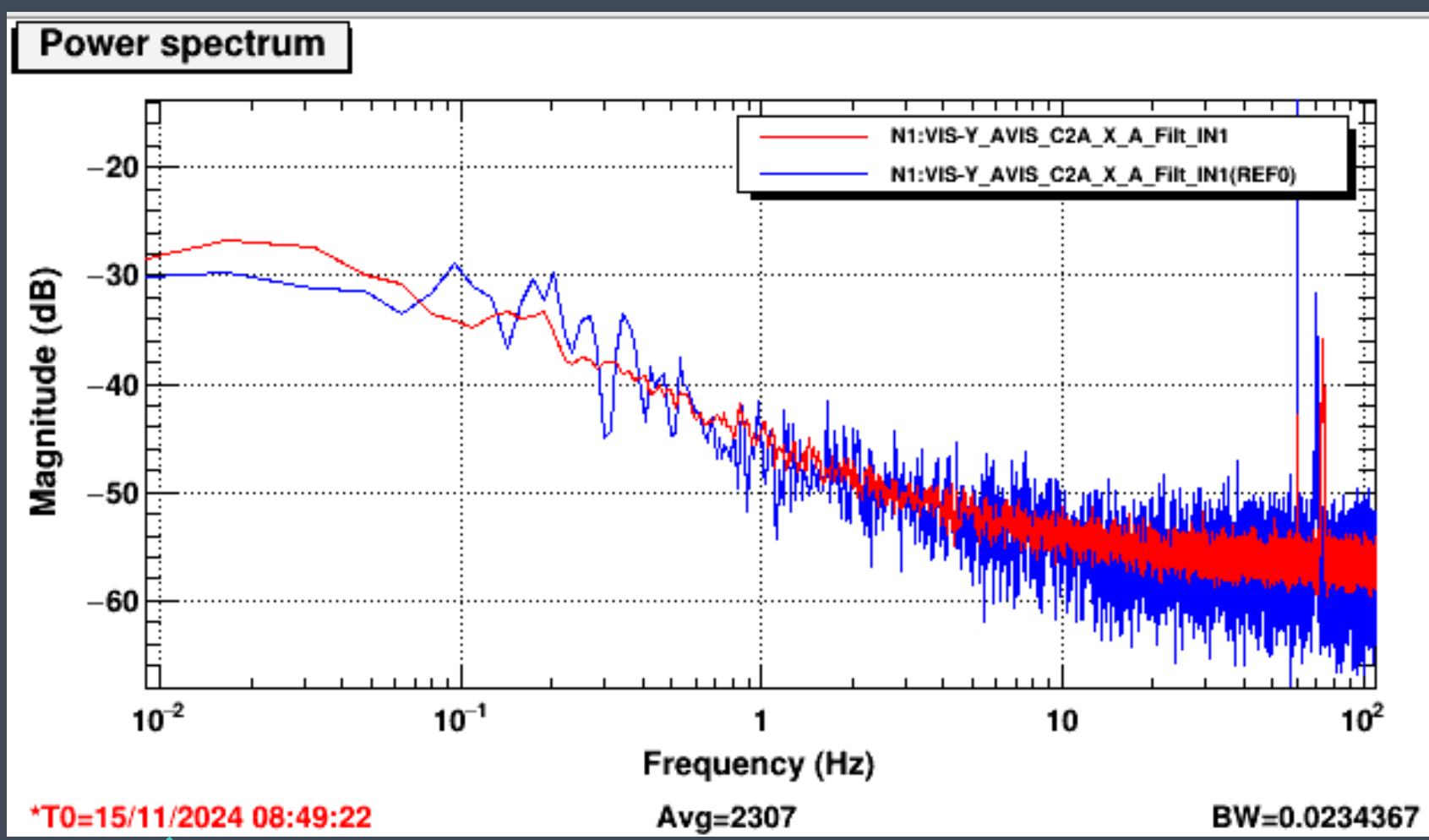


Transfer Function Measurement

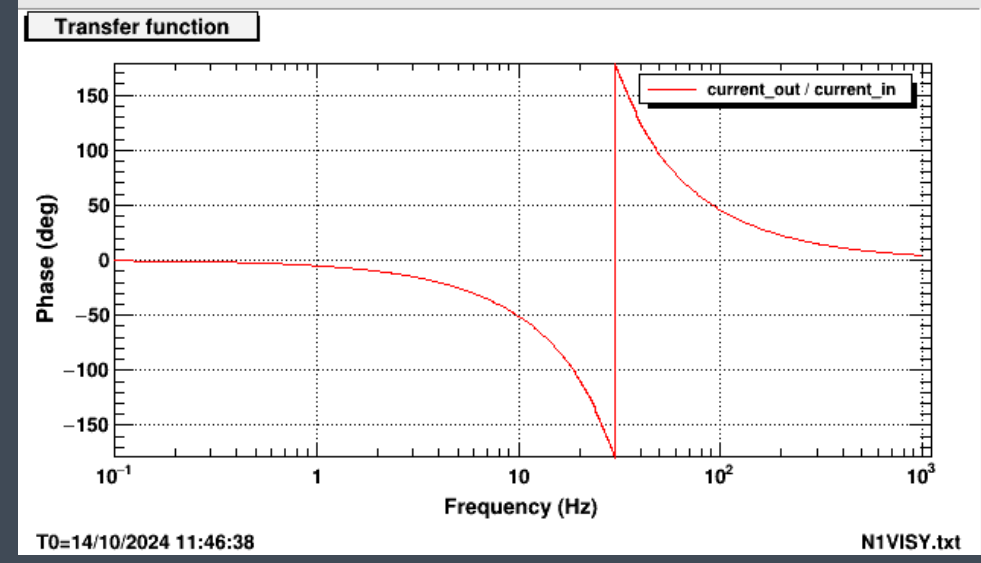
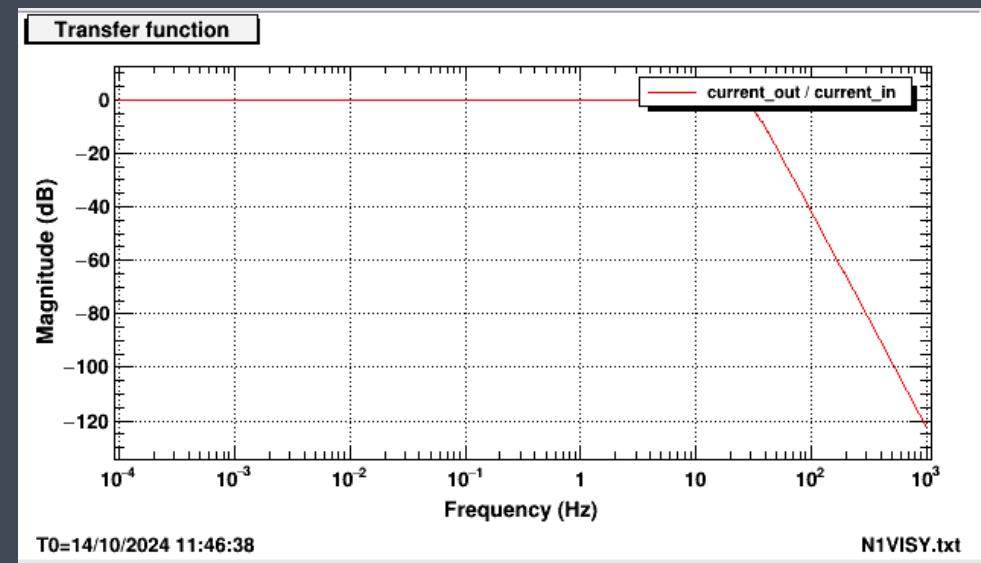
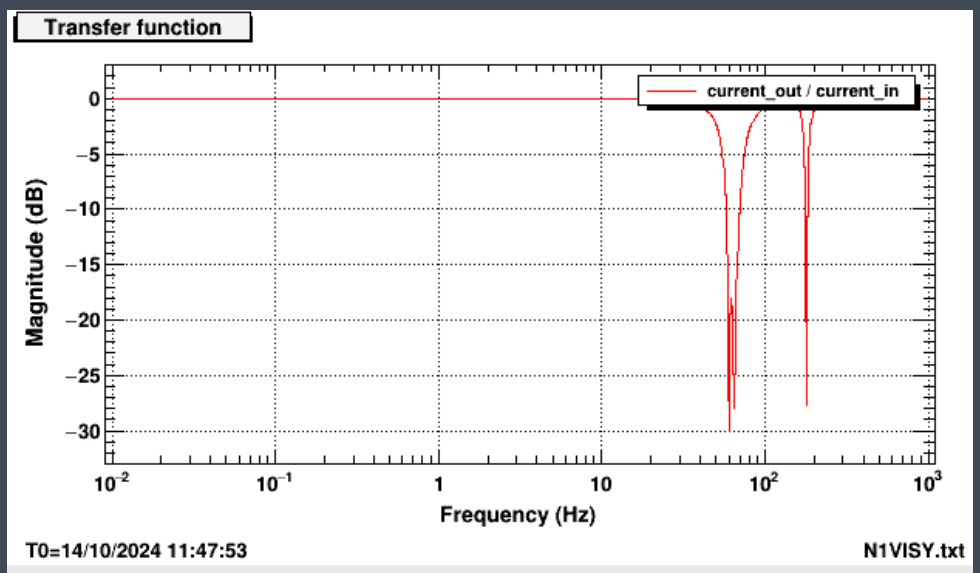


After achieving diagonalization, we measured TF for each DoF to check the coherence function. Based on this TF, we can design digital filters to do feedback control.

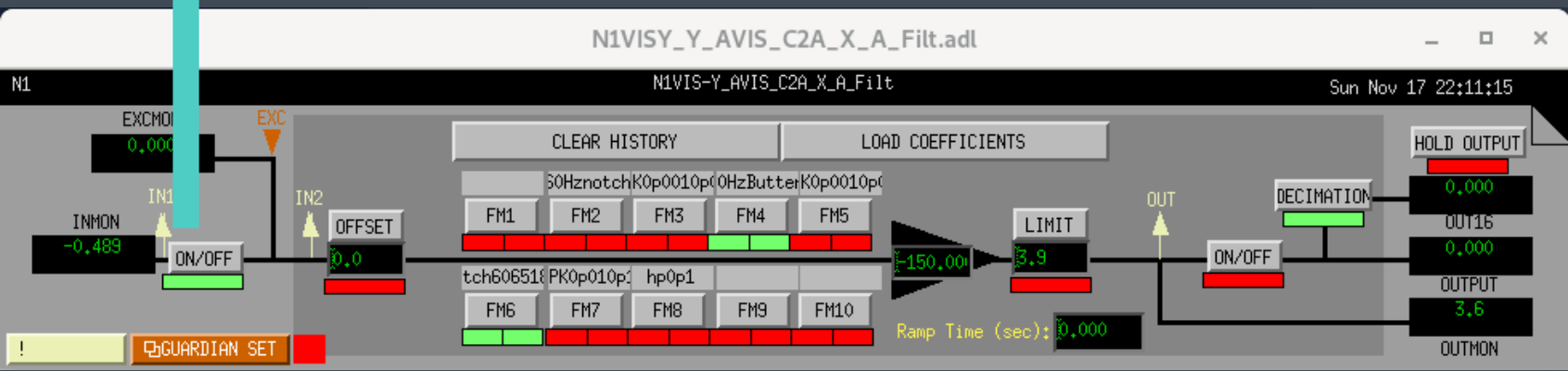
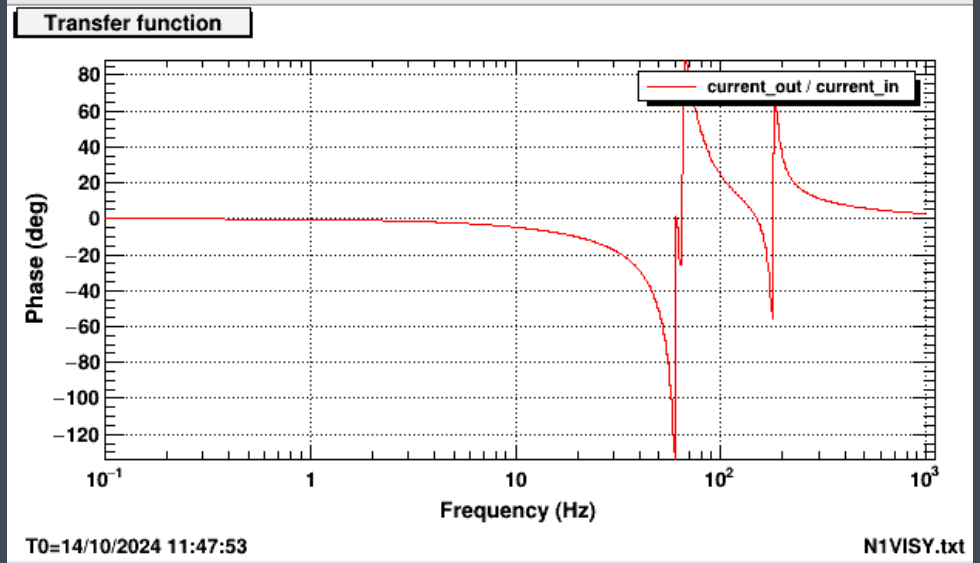
Foton Filter Design



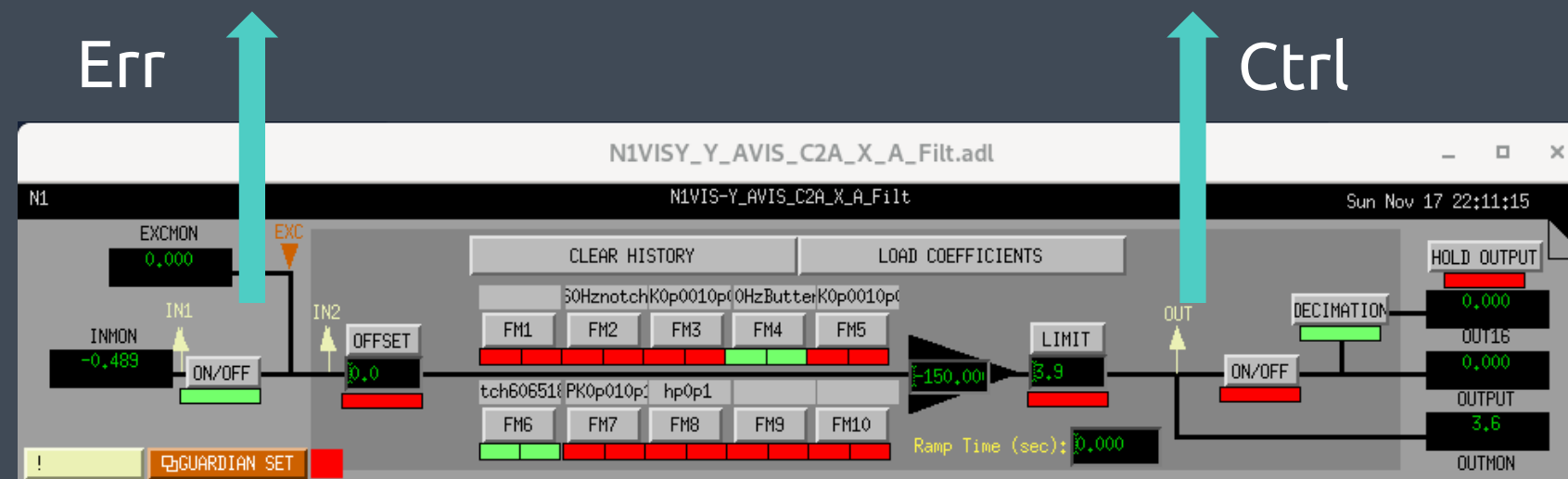
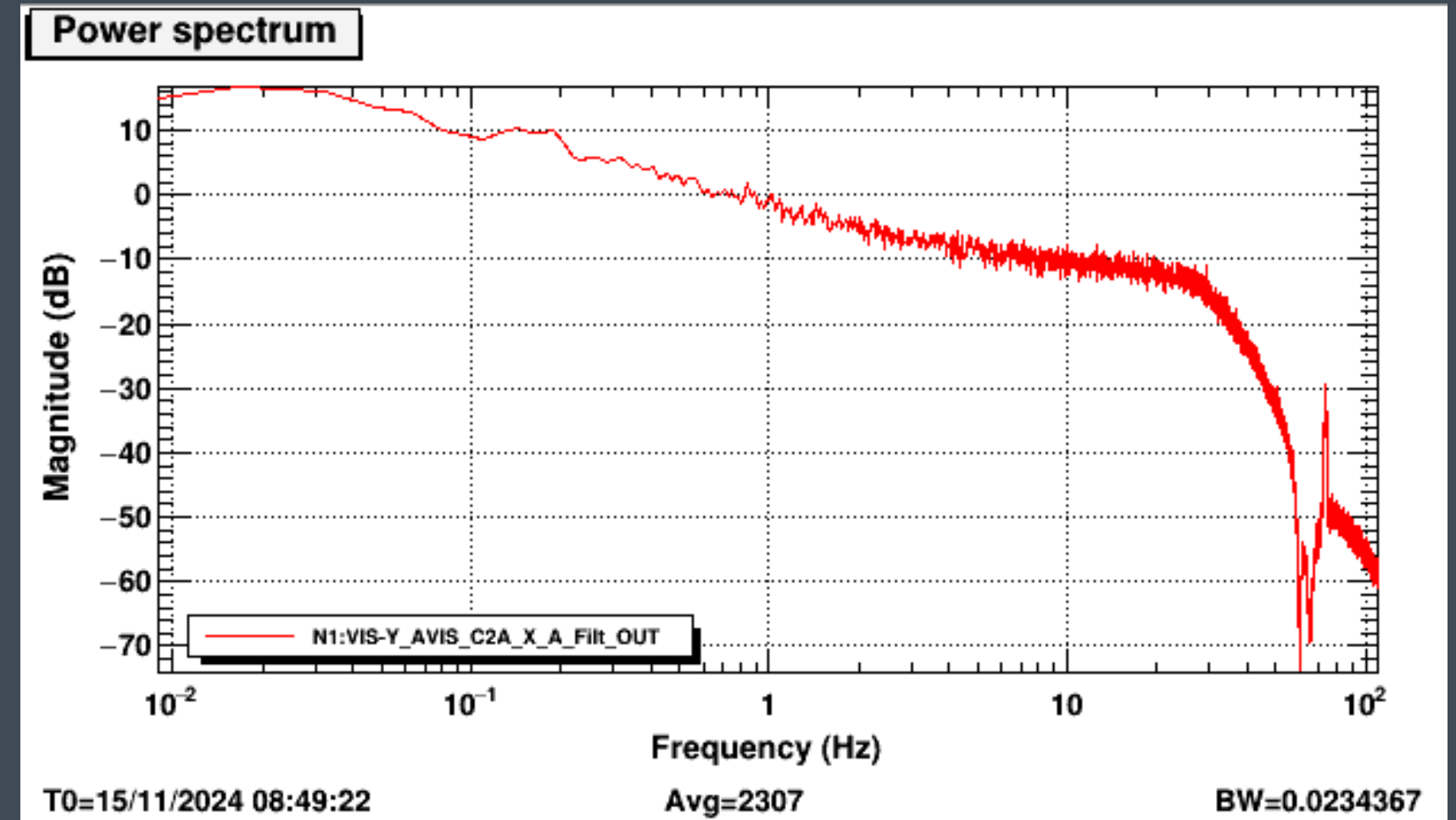
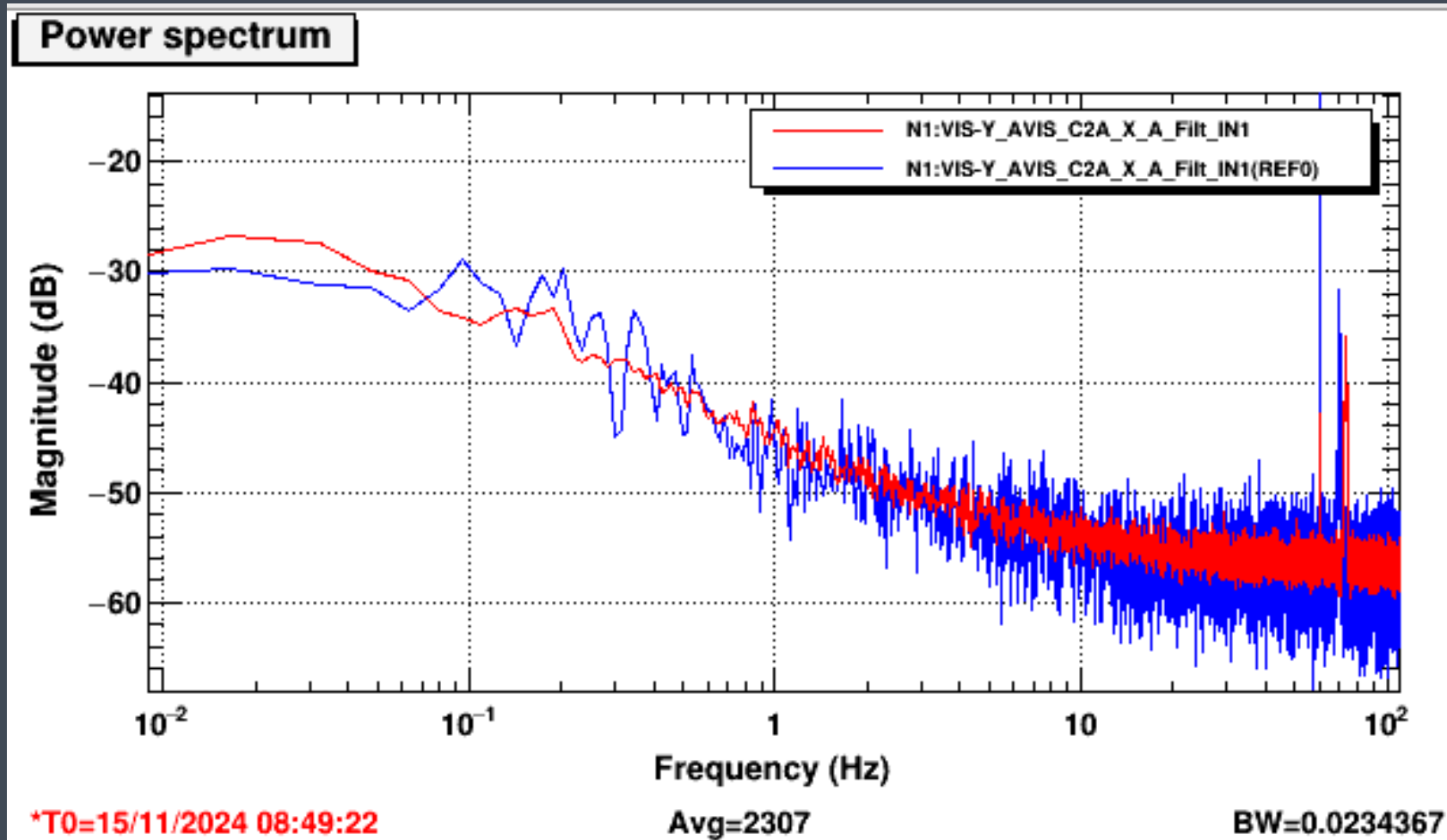
Notch filter
60 Hz, 180 Hz; Q:30



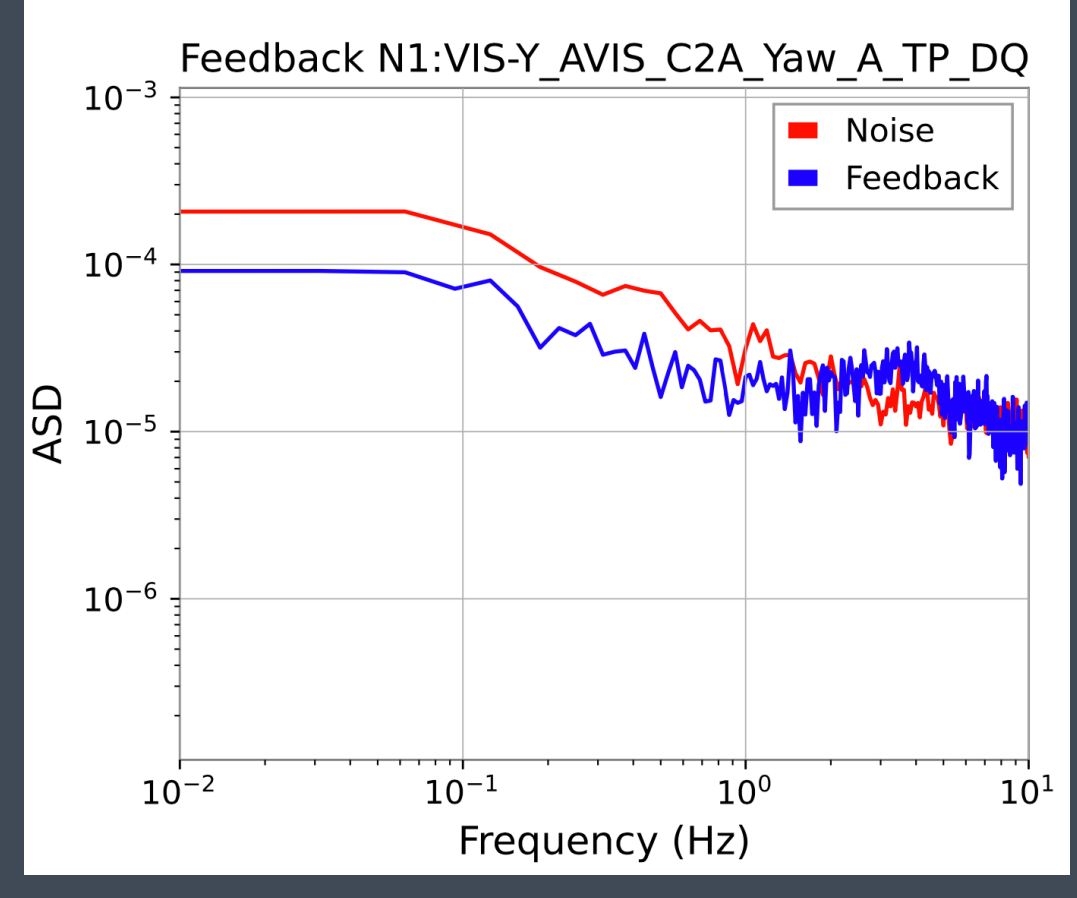
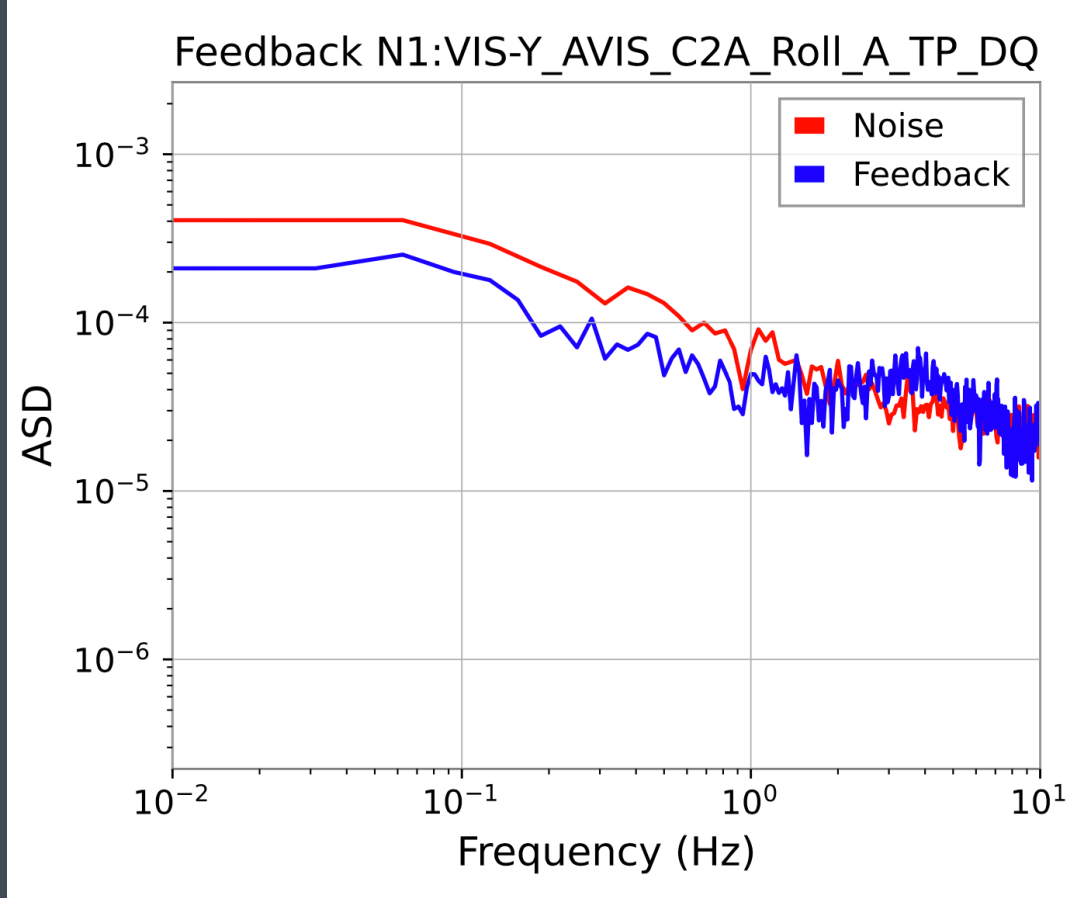
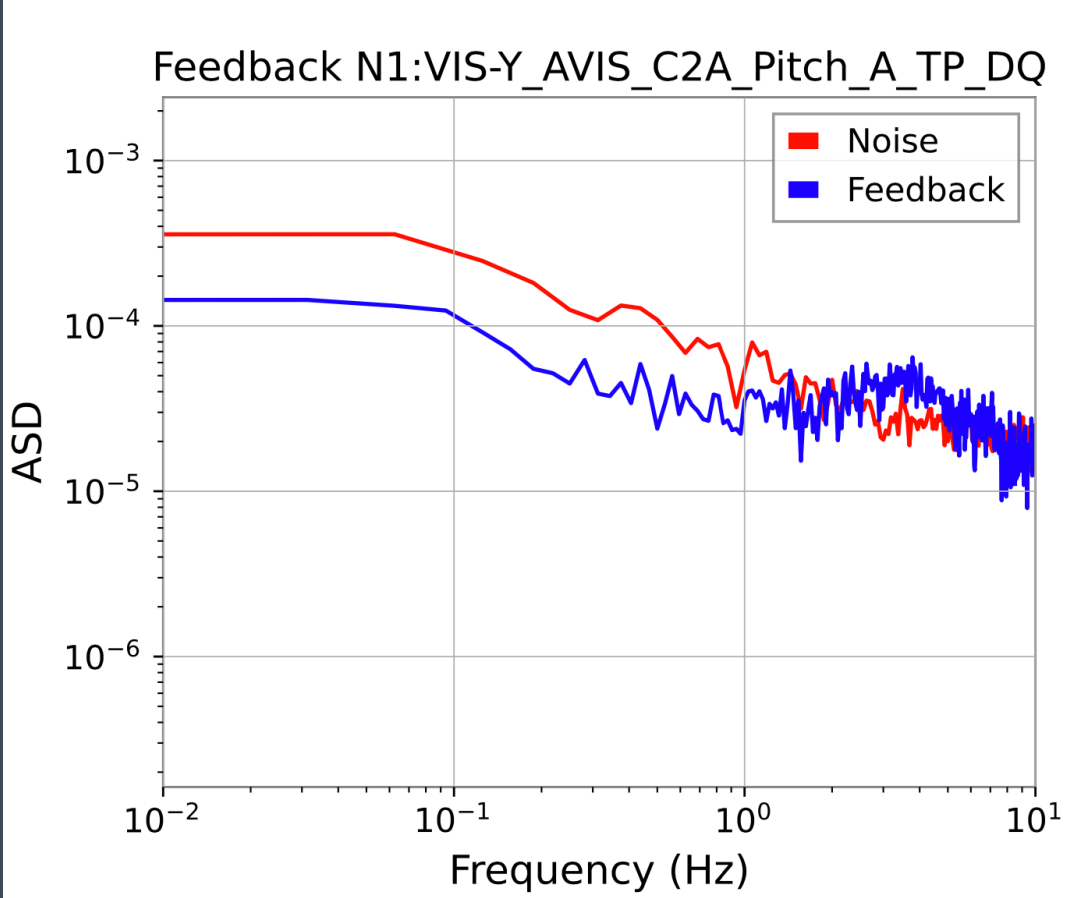
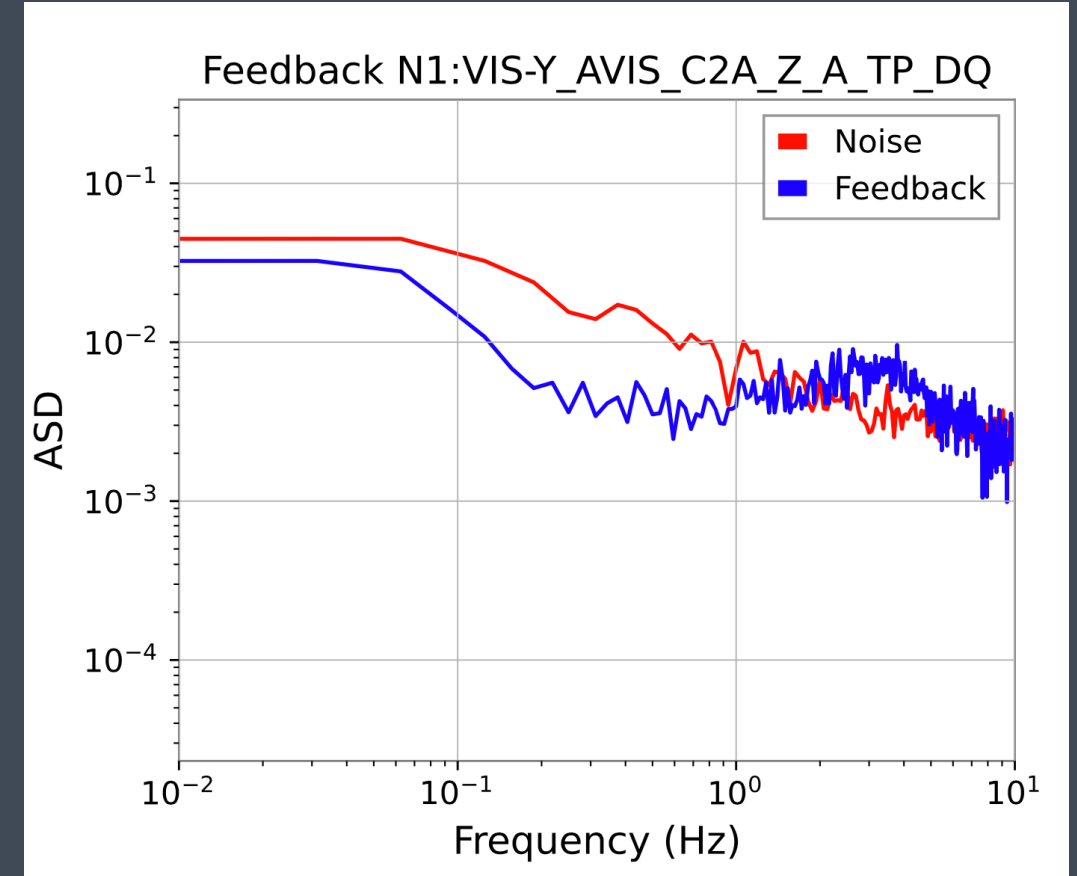
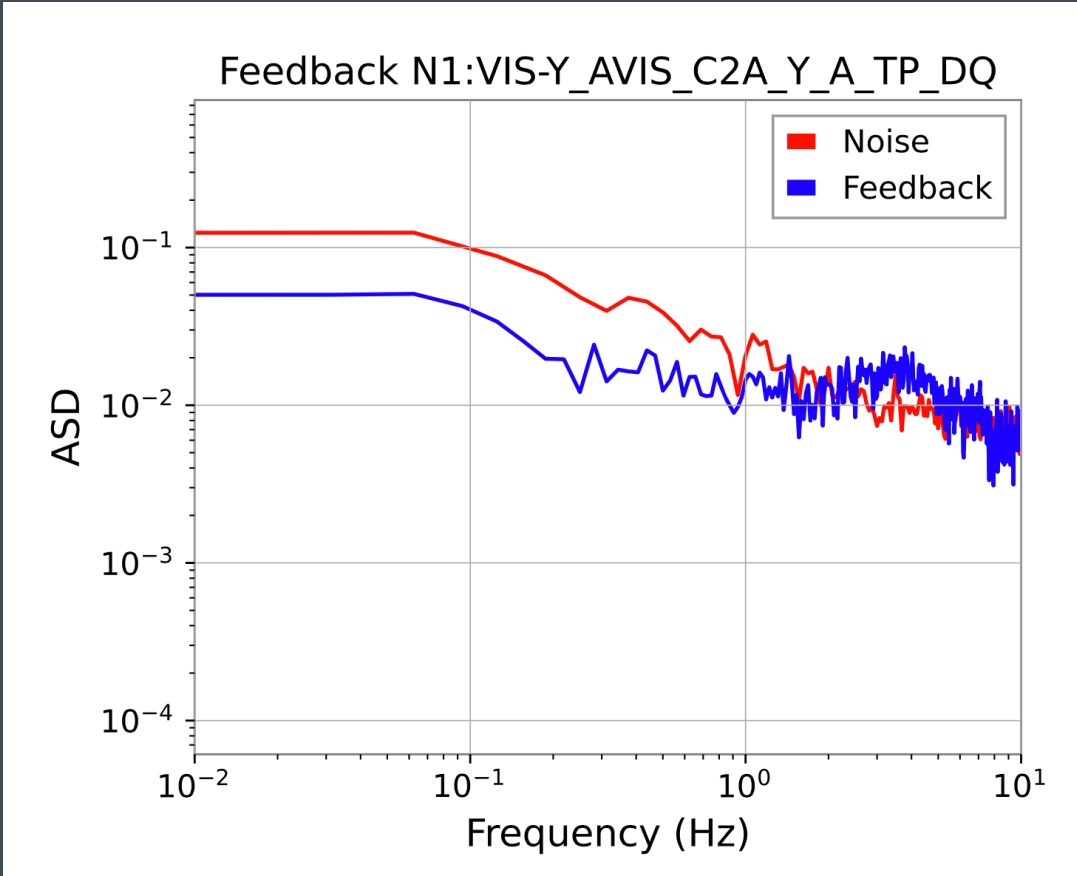
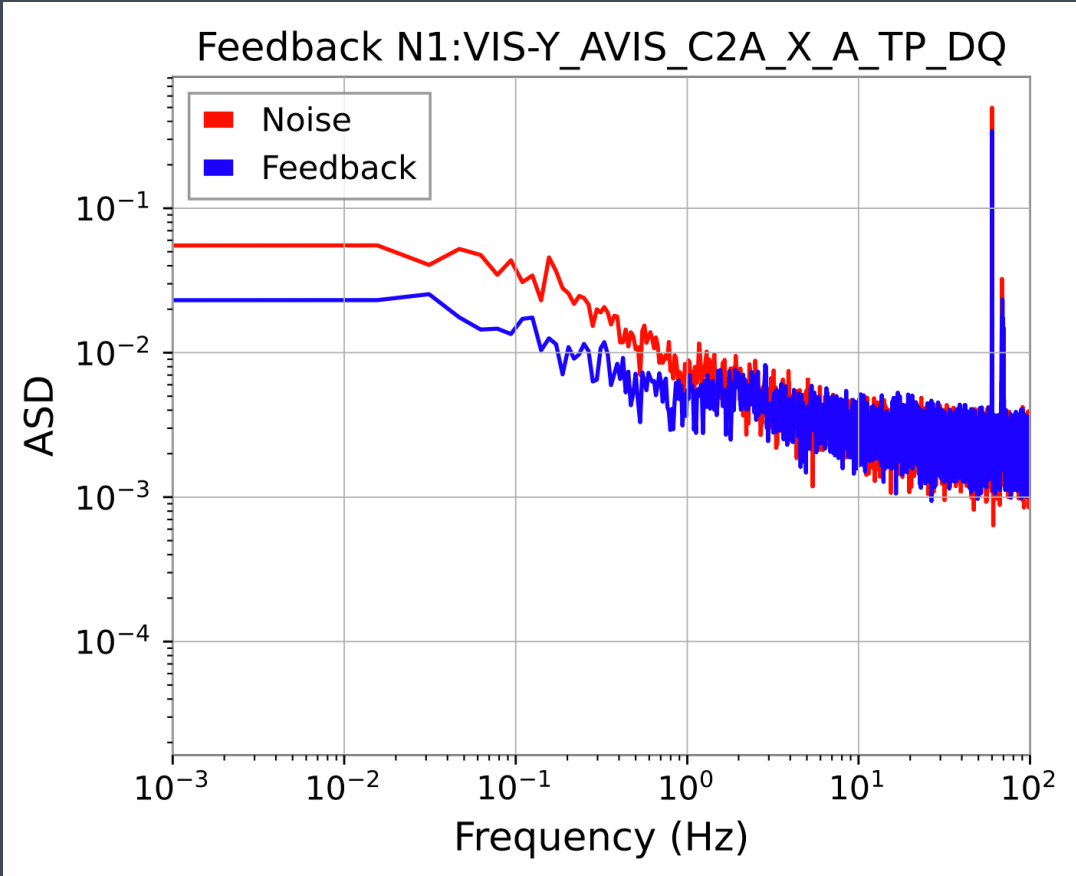
Butterworth
Low pass filter
Fcut:30 Hz 4th order



Control Signal



Feedback Control 6 DoF Simultaneously



Current Status for MIF

- **Xend** – Diagonalization and Feedback Control for Top Stage. (Dennis, Yoyo)
- **Center** – Installing chasis and cables connection to DGS. (Eason Lin)
- **Yend** – Commissioning D Filter for Piezo stage and Diagonalization for Top Stage.
(M Ma'arif)
- **Input Optics** – Improving PMC locking. (John Chan)

Thank you!

