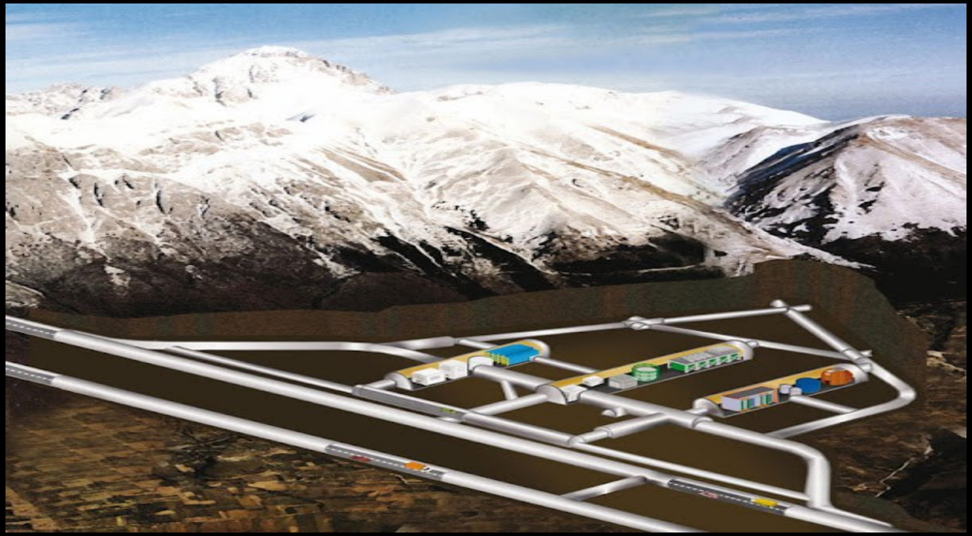
# A new underground seismic-isolation facility at LNGS

**Coordinating Institutions: GSSI & INFN – LNGS**

**Collaborators & Technical Advisors**

Tomislav Andric (GSSI), Carlo Bucci (INFN), Ilaria Caravella (GSSI), Daniele Cortis (INFN), Nicola D'Ambrosio (INFN), Massimiliano De Deo (INFN), Marco D'Incecco (INFN), Antonio Di Ludovico (INFN), Oliver Gerberding (University of Hamburg), Jan Harms (**PI**; GSSI), Jeff Kissel (LIGO Hanford), Alessandro Lalli (INFN), Brian Lantz (Stanford University), Laura Leonzi (INFN), Carla Macolino (Università di L'Aquila), Rich Mittleman (MIT), Conor Mow-Lowry (VU Amsterdam), Donato Orlandi (INFN), Stefano Pirro (INFN), Marco Ricci (Università di Roma La Sapienza), Jamie Rollins (Caltech), Jim Warner (LIGO Hanford)

# GSSI & INFN-LNGS



- A leading international research center and doctoral school
- GSSI'S new lab facilities

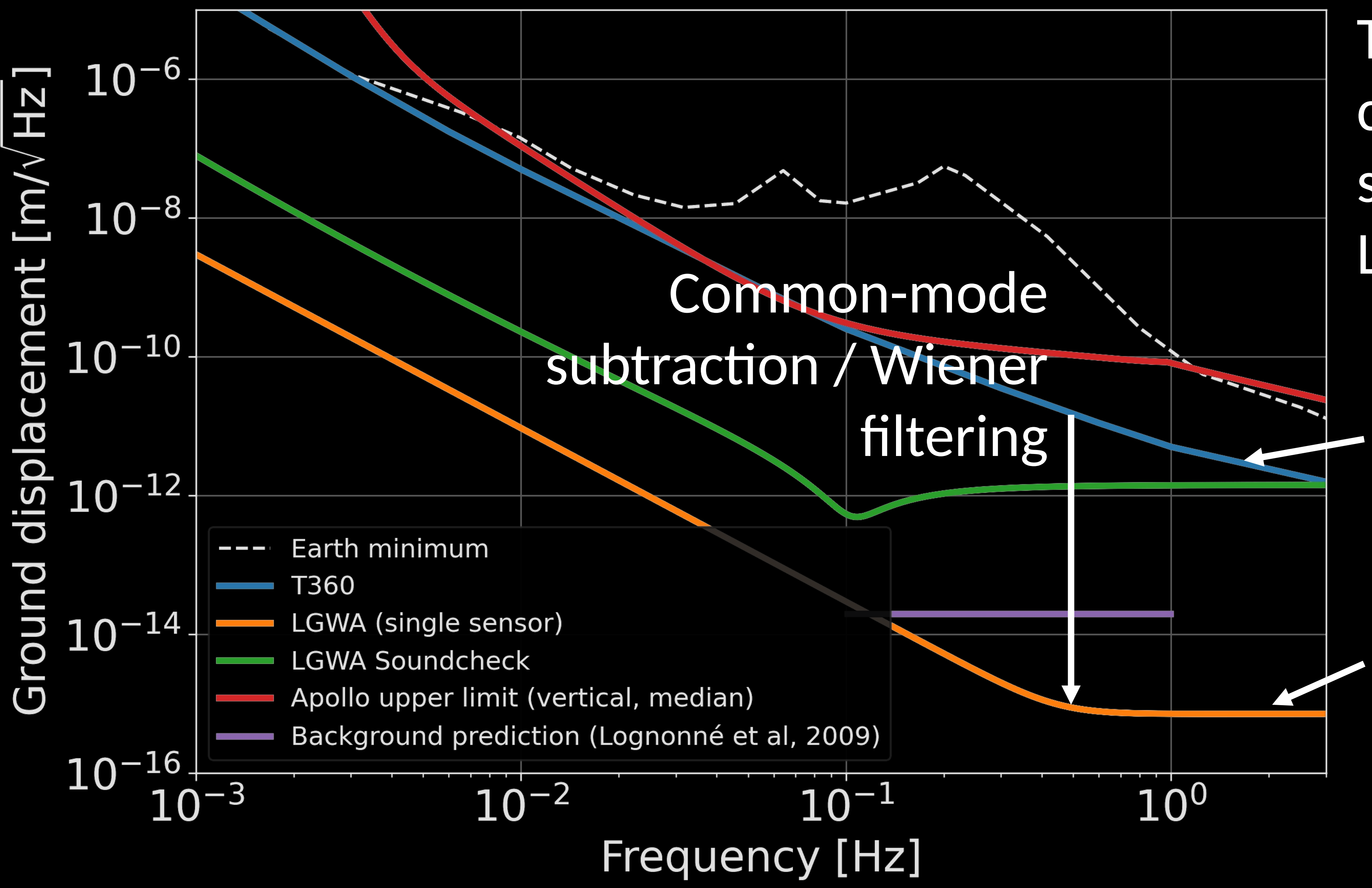
- LNGS – underground laboratory
- LNGS surface labs already accessible to us for work

# Profile

- Funding: PNRR-ETIC (1040k€ LNGS; 404k€ GSSI) and PNRR-Vitality - ASTRA (340k€ GSSI)

- Suspension mechanism of the seismometer's test mass - nontrivial
- Operating seismometers of such sensitivity would require an extremely low level of seismic disturbances - LNGS is a perfect/unique location to carry out these studies (low-noise, underground facility)
- Test platform for novel inertial sensors (room&cryo temperature)
- Test technologies, validate their performance, and ensure they meet the requirements before deployment on the Moon
- Development of vibration control and inter-platform control systems for the Einstein Telescope
- Installation and utilization of an underground environmental monitoring system

# GEMINI - LGWA

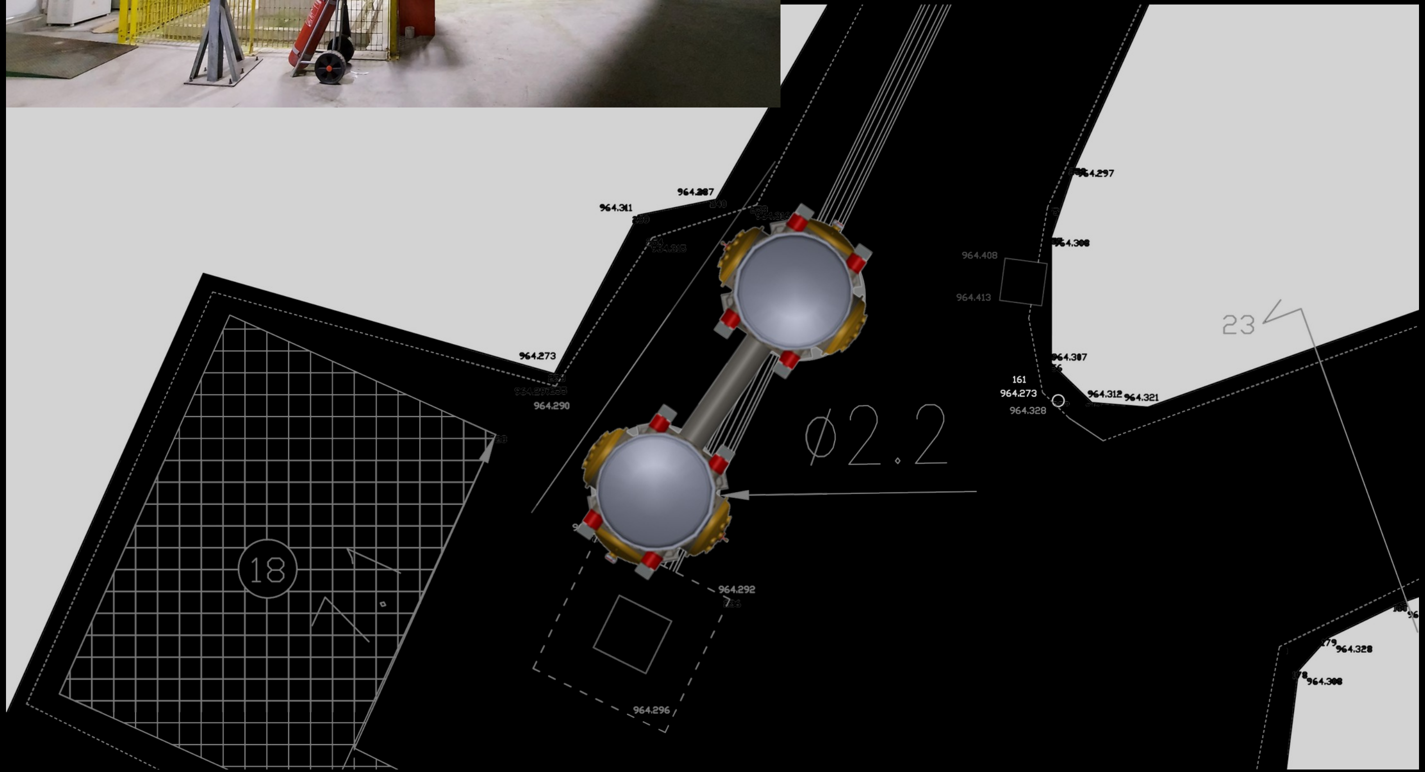



Test high-performance, cryo-temperature lunar seismometers for LGWA

Targeted GEMINI platform residual motion

LGWA sensor performance target

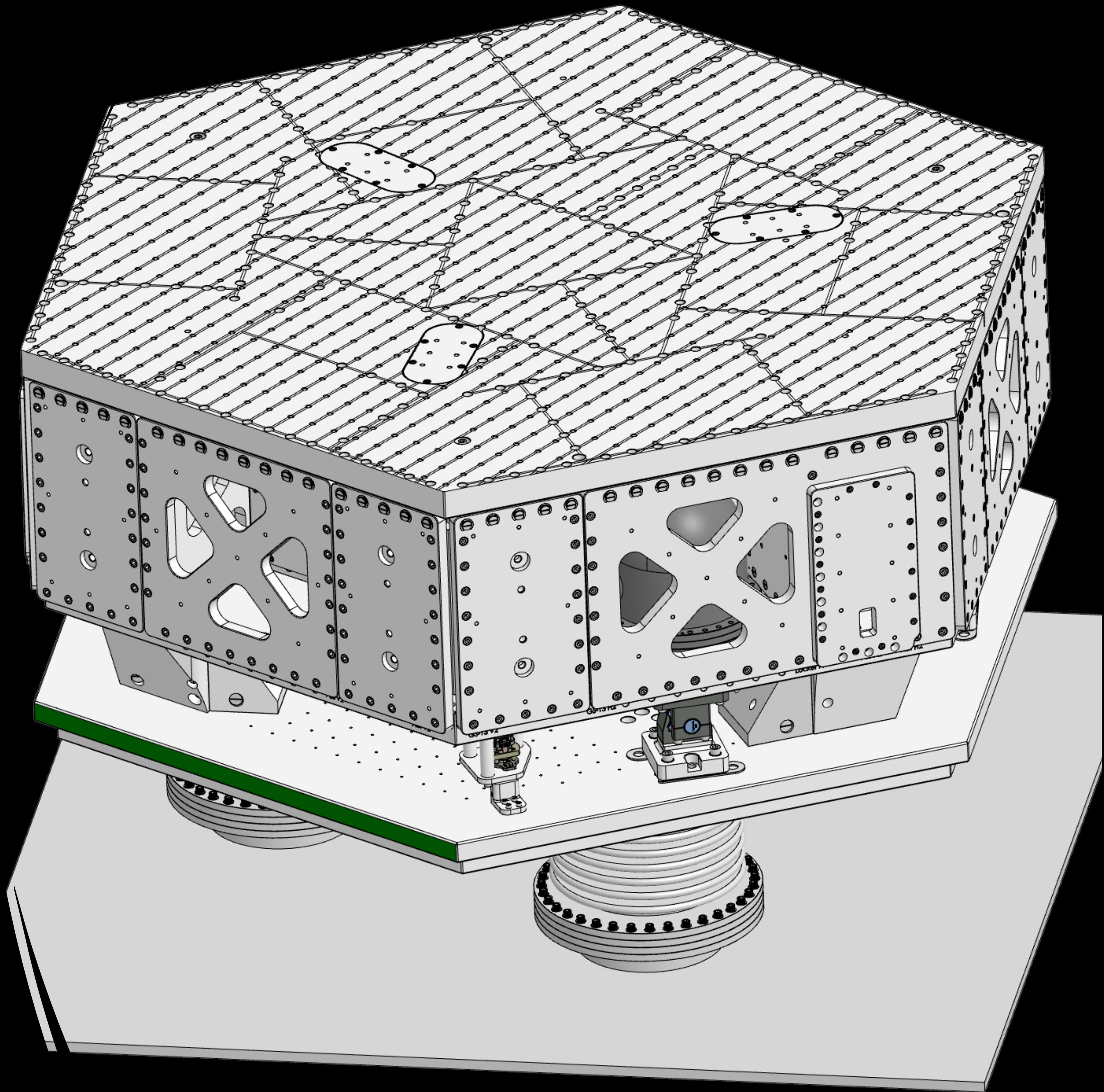
# Underground Laboratory

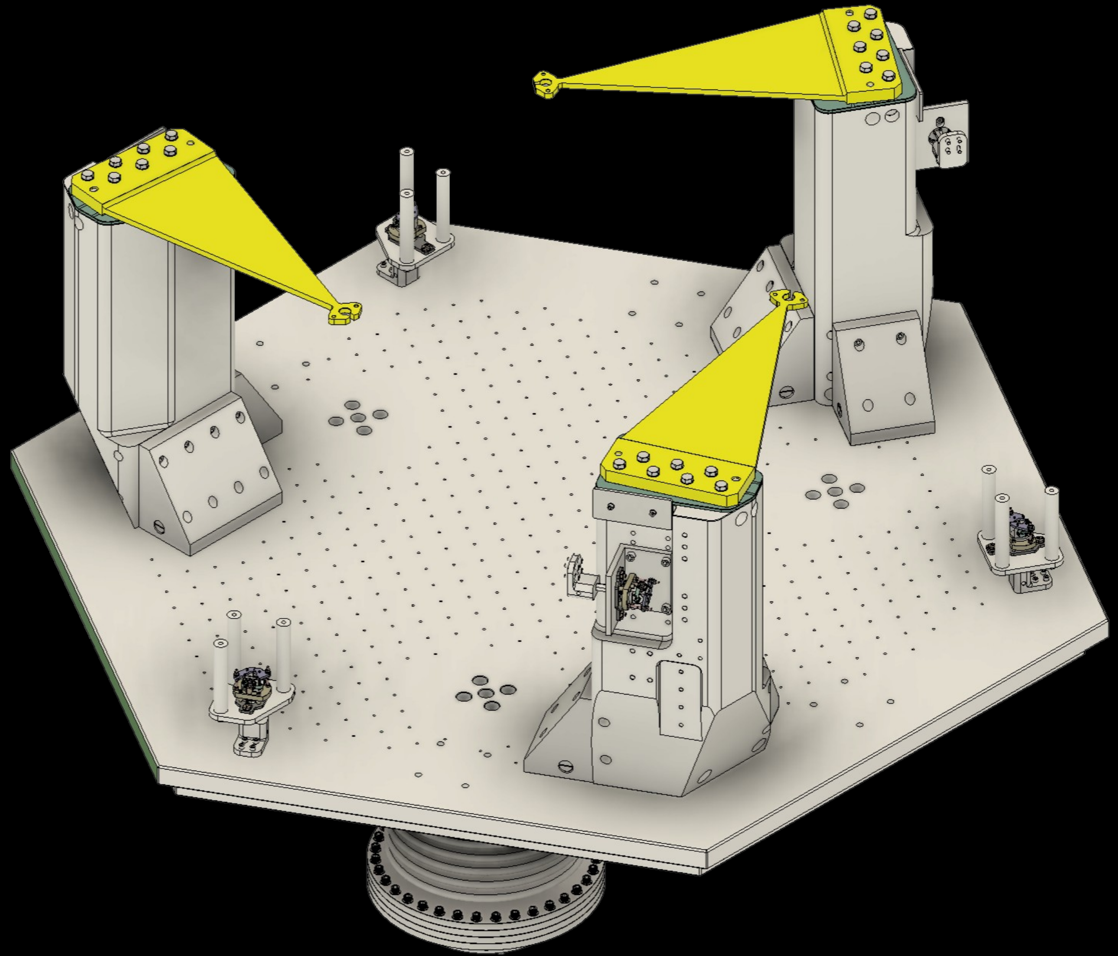

- Floor treatment
- Laminar-flow enclosures
- Lifting device for platforms and chamber segments
- Access to cooling water for cryocooler
- Timing signal from surface
- Low-latency data transfer to server at the surface

# GEM-VCP

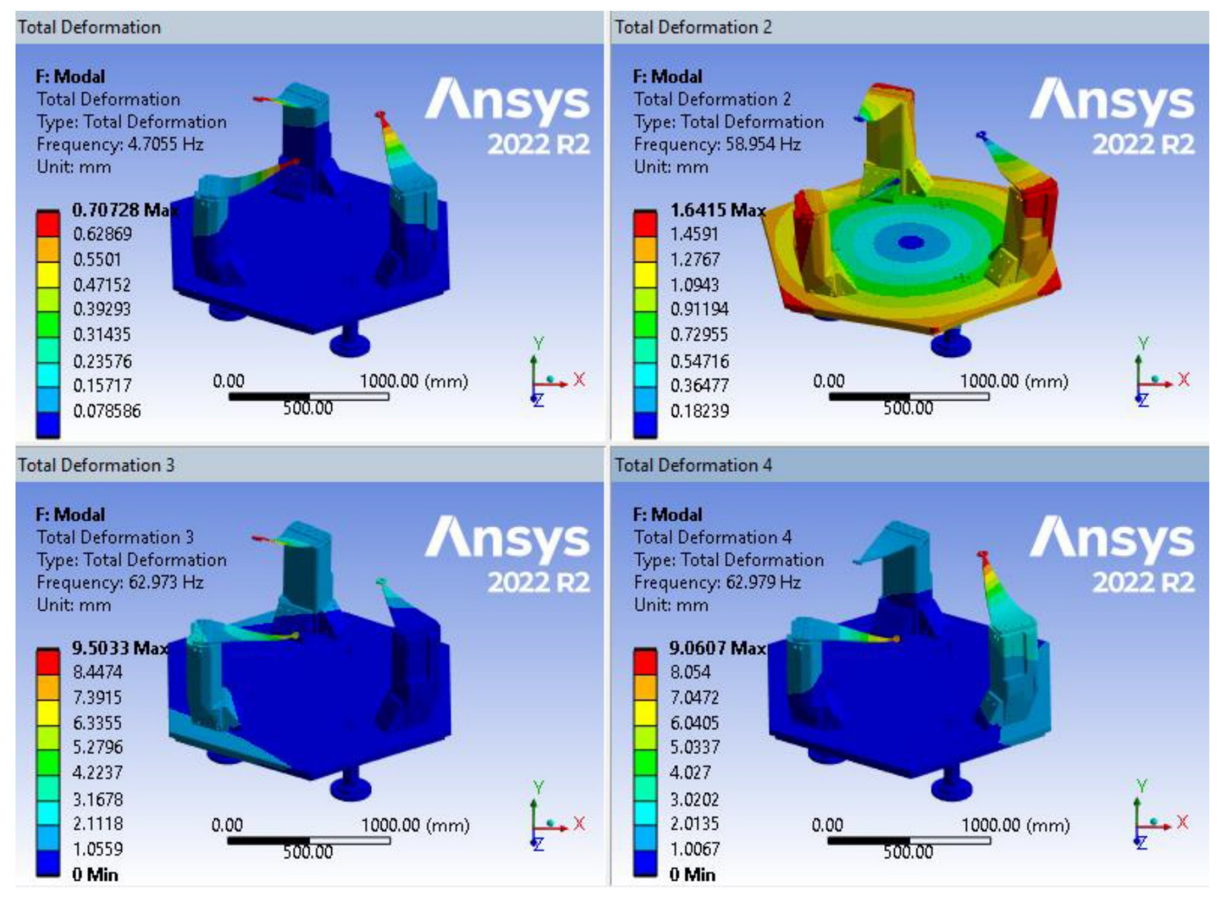
- GEMINI Vibration-control Platform
  - Starting point of the design: LIGO HAM-ISI - structural adjustments tailored for GEMINI's specific requirements.
  - Design modifications, vibration analysis, and executive drawings produced by LNGS mechanical engineers



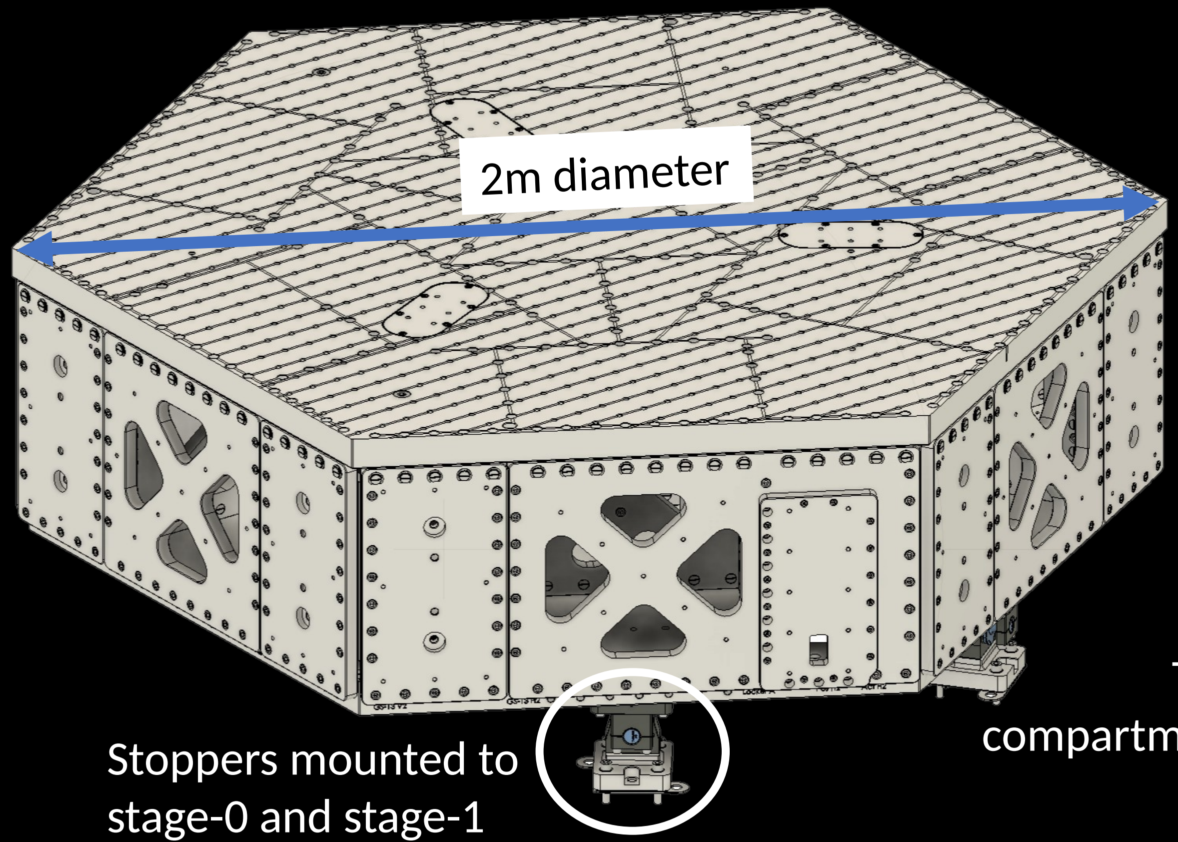
# GEM-VCP: Stage 0

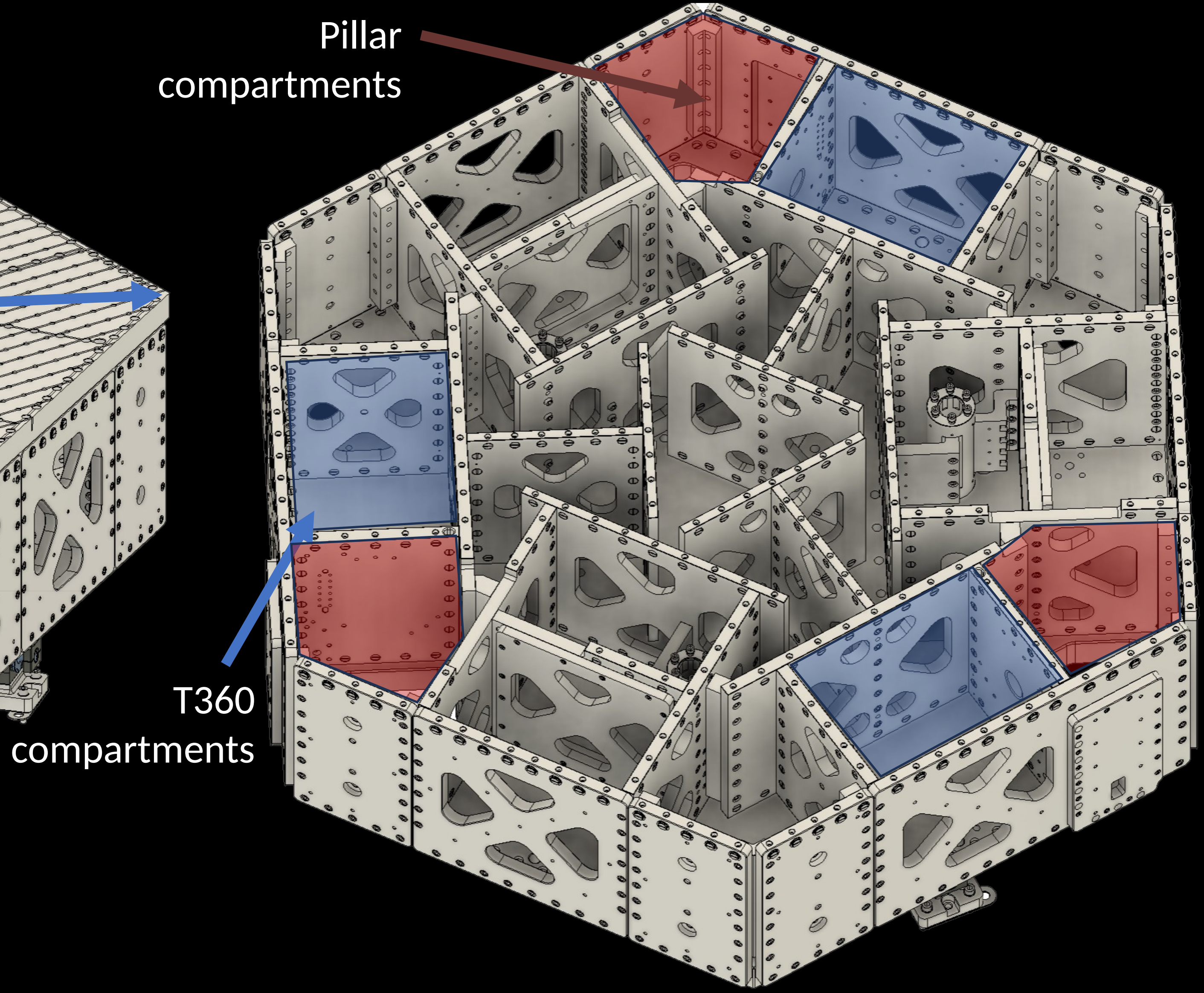


100Hz HAM-ISI (unconstrained)
60Hz GEM-VCP (under load)

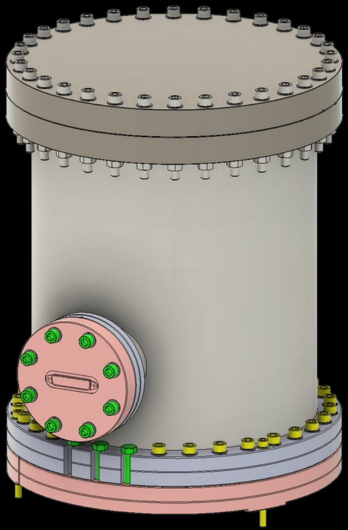


# GEM-VCP: Stage 1



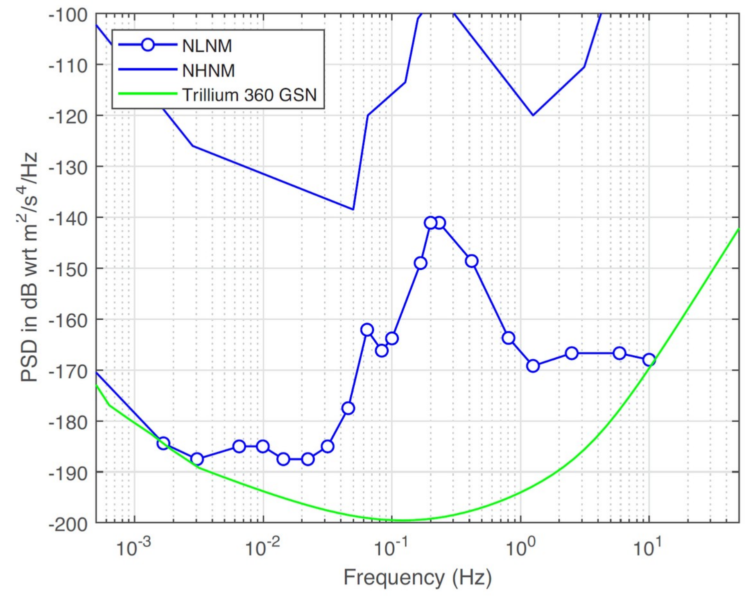



# Inertial Sensing

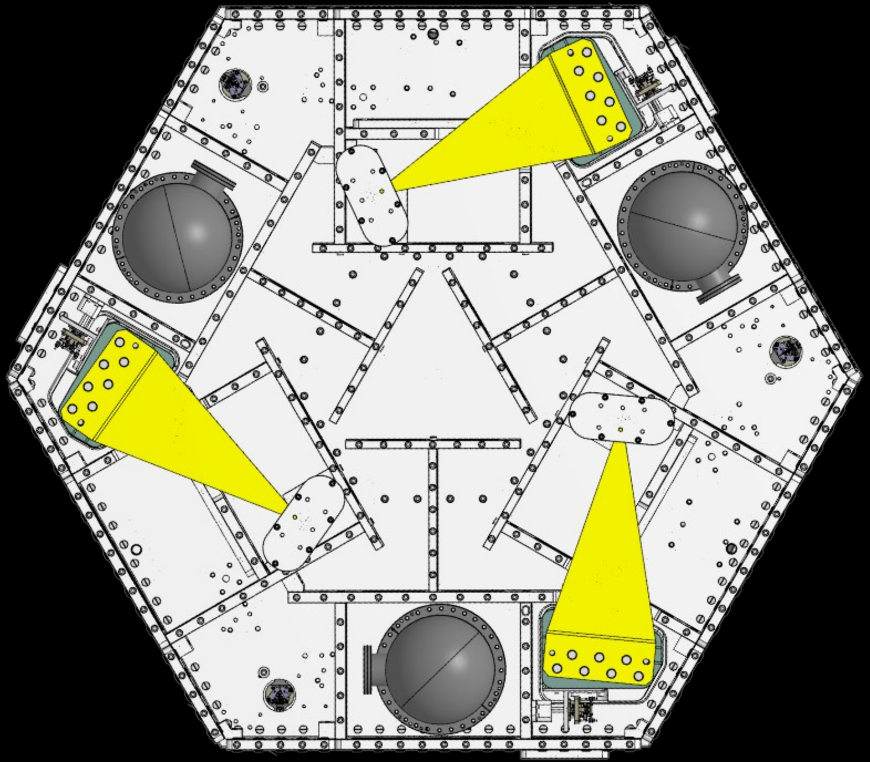


Vacuum pods
(to be ordered in
October 2024)

Nanometrics T360 GSN Vault
(3 per platform, 3 channels each)

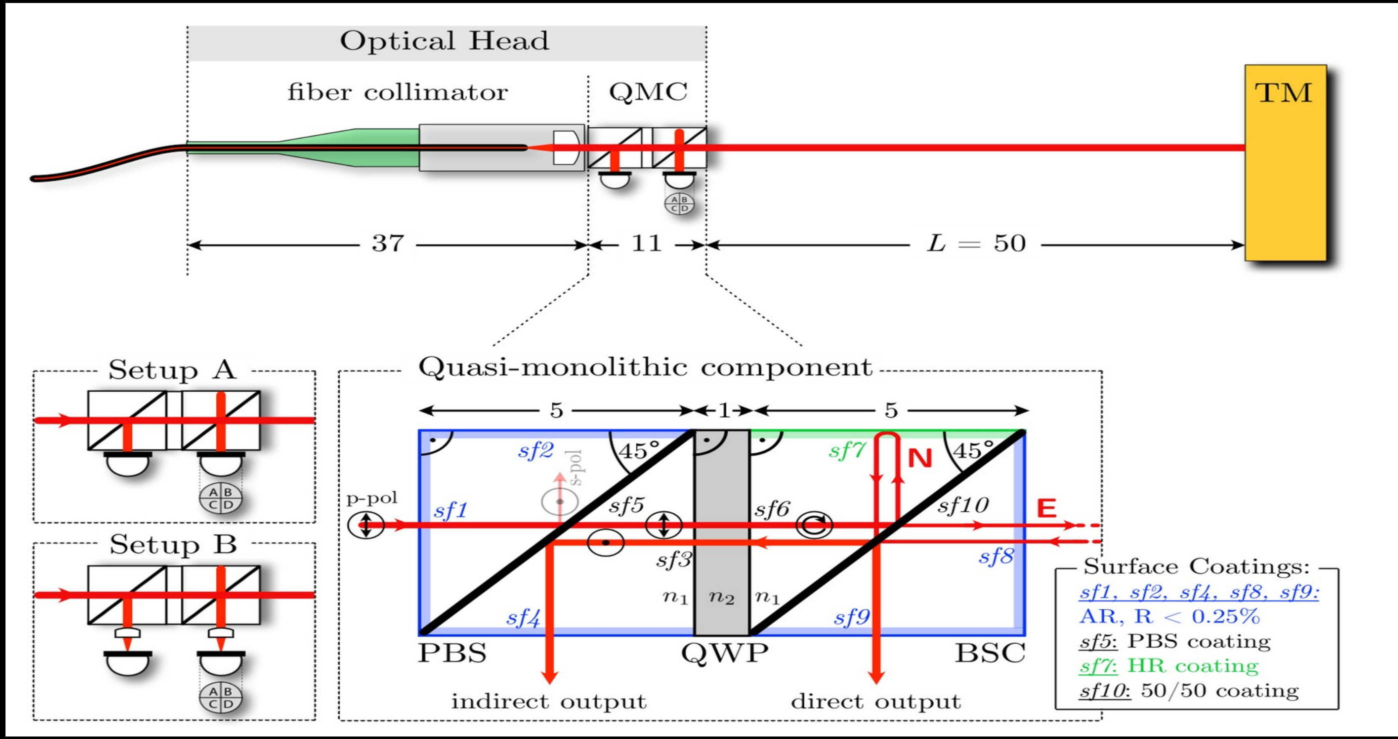



Integration in GEM-VCP



# Position Sensing: COBRI

COmpact Balanced Readout Interferometer - COBRI




- Required for platform alignment and positioning (precise displacement and motion sensing)
- Strong frequency modulation (set of sinusoidal phase modulations)
- Advanced digital readout algorithms to measure the phase shift induced by motion
- Needs to be blended with inertial sensing and control

- On-axis design with quasi-monolithic component
  Positive:
  - no misalignment in vacuum
  - Large linear range (several centimeters)

  Negative:
  - On-axis ghost beams cause nonlinearity

- Dual readout/balanced detection at the front
  - Lower readout noise by sqrt(2)
  - Enables scattered light reduction in post processing
  - Reduces residual amplitude modulation noise

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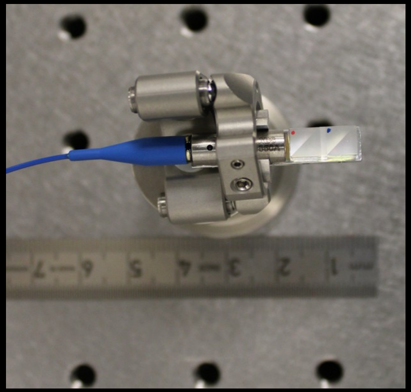
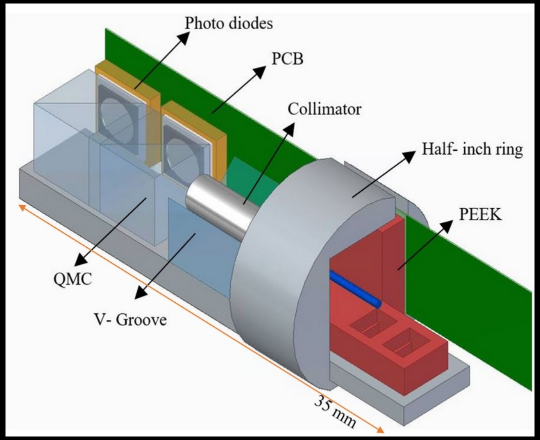


v2 design



# Cryo-box

GSSI — INFN Istituto Nazionale di Fisica Nucleare — GEMINI

## RDK-500B2 20K Cryocooler Series

### Performance Specifications

| Power Supply | 50Hz | 60 Hz |
|---|---|---|
| 1st Stage Capacity | 45 W @ 20 K | 50 W @ 20 K |
| Minimum Temperature[1] | <14 K | |
| Cooldown Time to 20 K[1] | <50 Minutes | <45 Minutes |
| Weight | 25.0 kg (55.1 lbs.) | |
| Dimensions (HxWxD) | 570 x 180 x 325 mm (22.4 x 7.1 x 12.8 in.) | |
| Maintenance | 8,760 Hours | |
| Regulatory Compliance | CE, UL/cUL | |

### Standard Scope of Supply

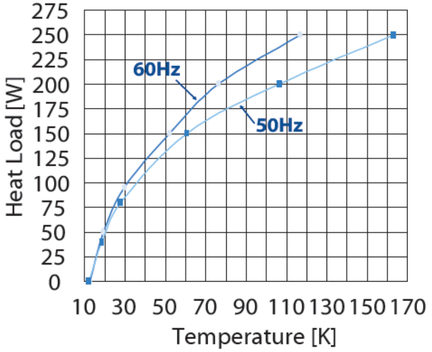
- RDK-500B2 Cold Head
- F-70LP/H Compressor
- Helium Gas Lines – 20 m (66 ft.)
- Cold Head Cable – 20 m (66 ft.)
- Power Cable – 5 m (16.5 ft.)
- Tool Kit

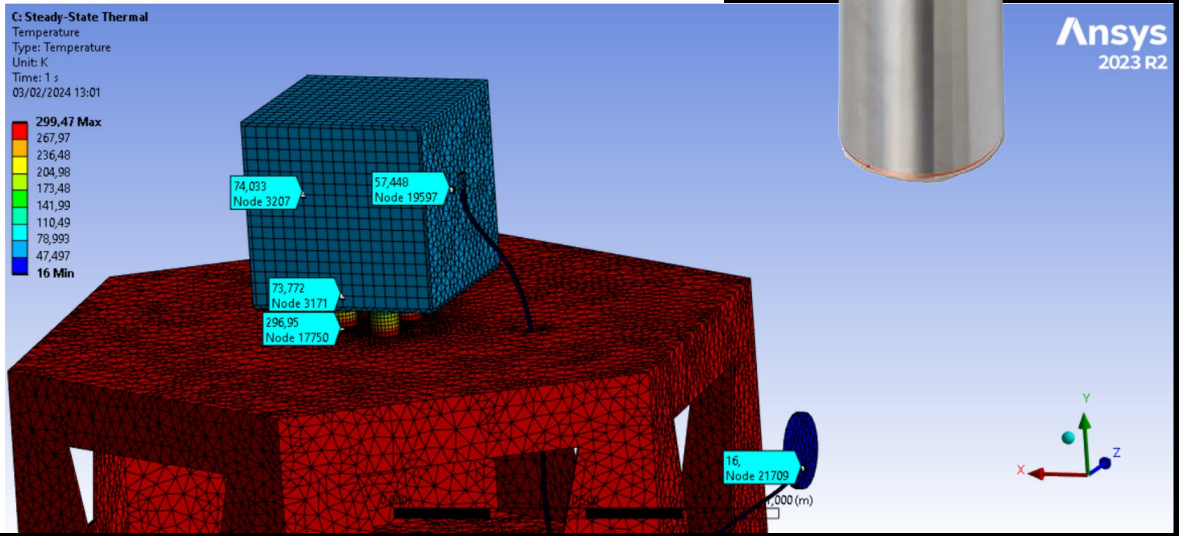
[1] *Lowest temperature and cooldown time are for reference only.*

Emulate 40K environment for lunar PSR payloads

**RDK-500B Cold Head Capacity Map (50/60 Hz)**

With F-70 Compressor and 20 m (66 ft.) Helium Gas Lines

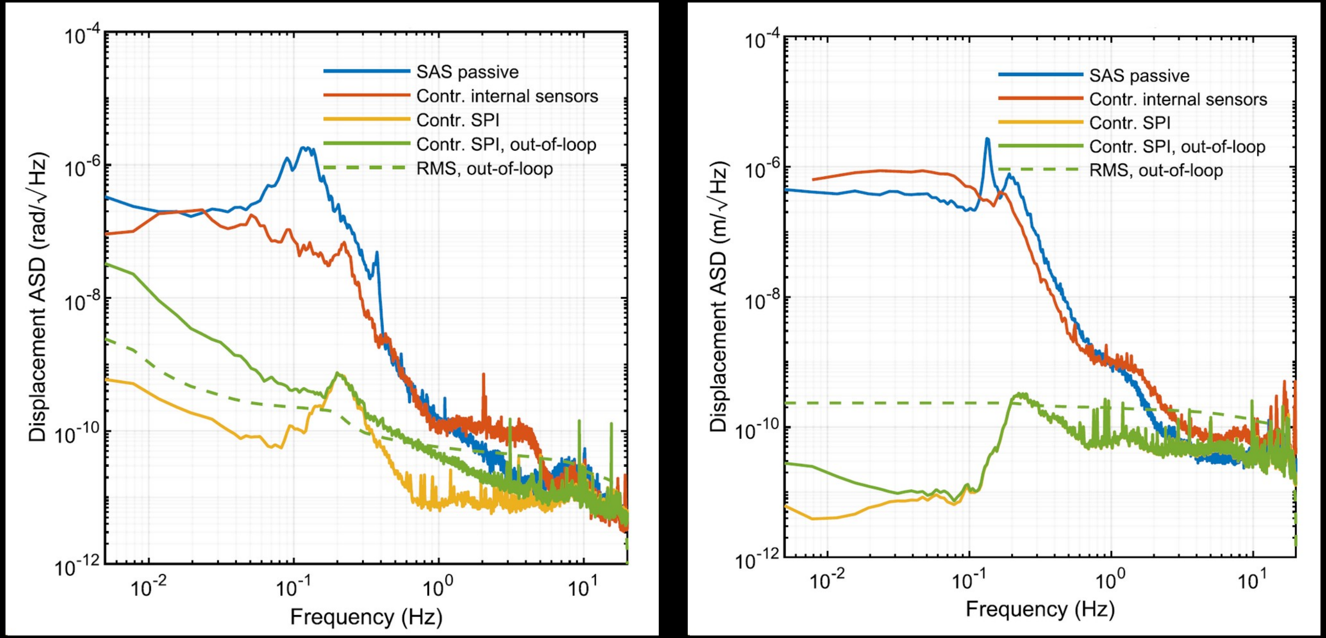



Thermal link will not be as shown in this simulation

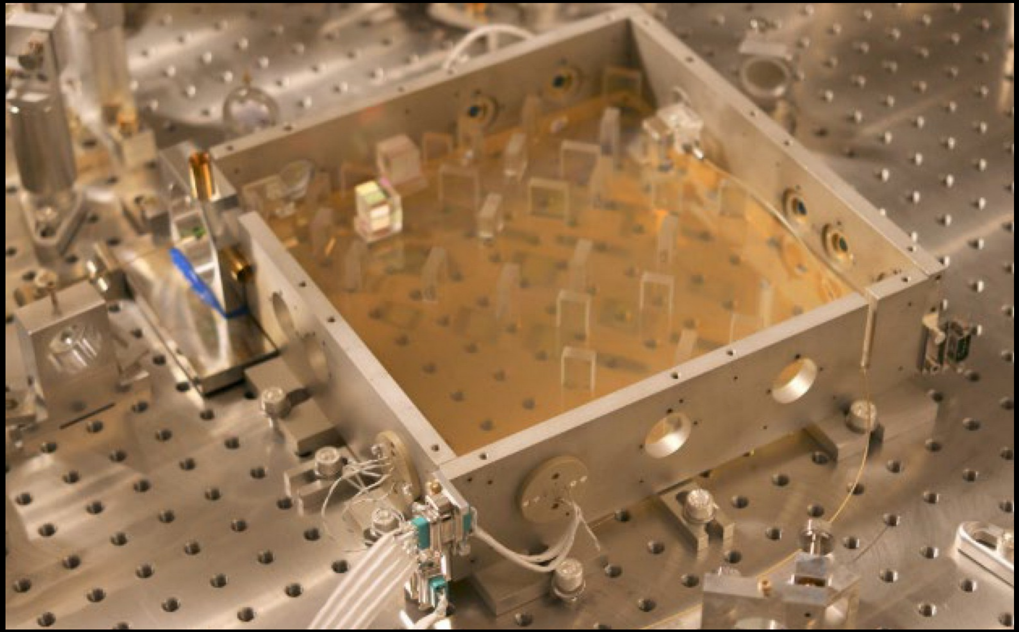
# Suspension-platform Interferometer (SPI)

Inter-platform sensing and control to reduce relative motion between platforms (displacement and angular)



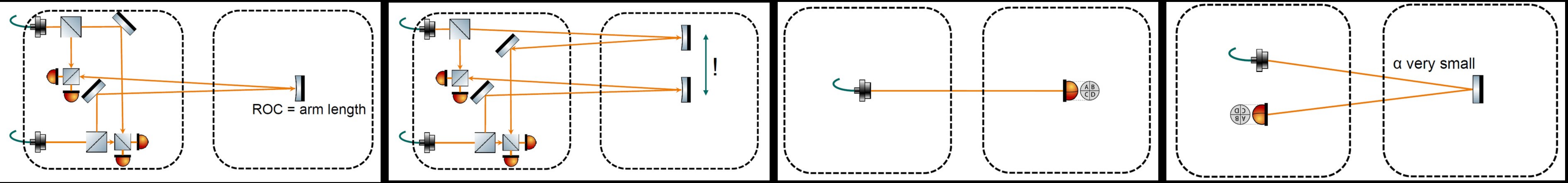

Koehlenbeck et al (2023)

SPI optical assembly



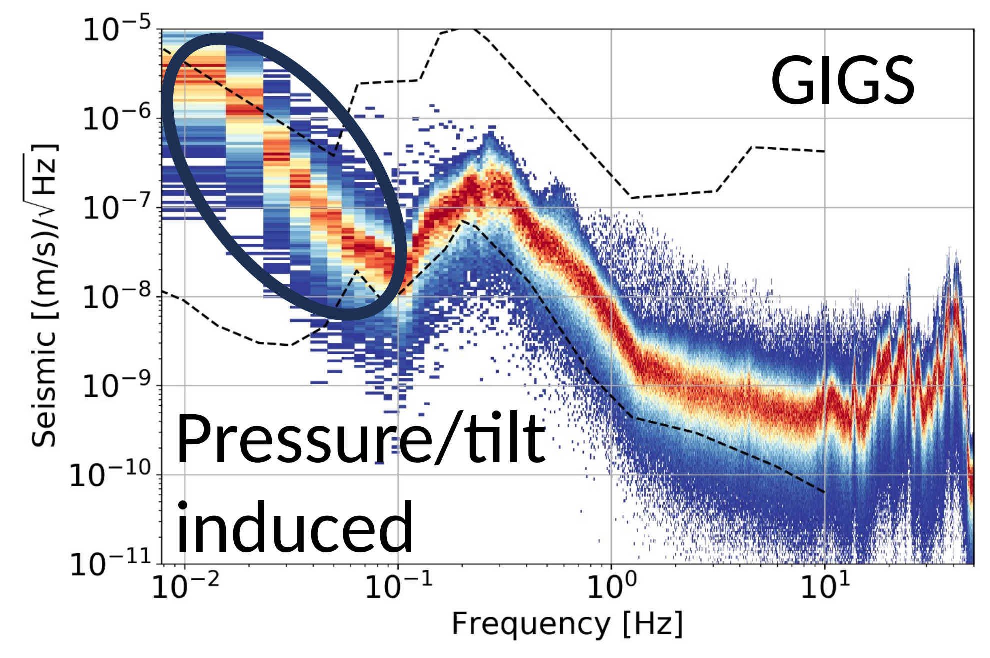
Koehlenbeck et al (2023)

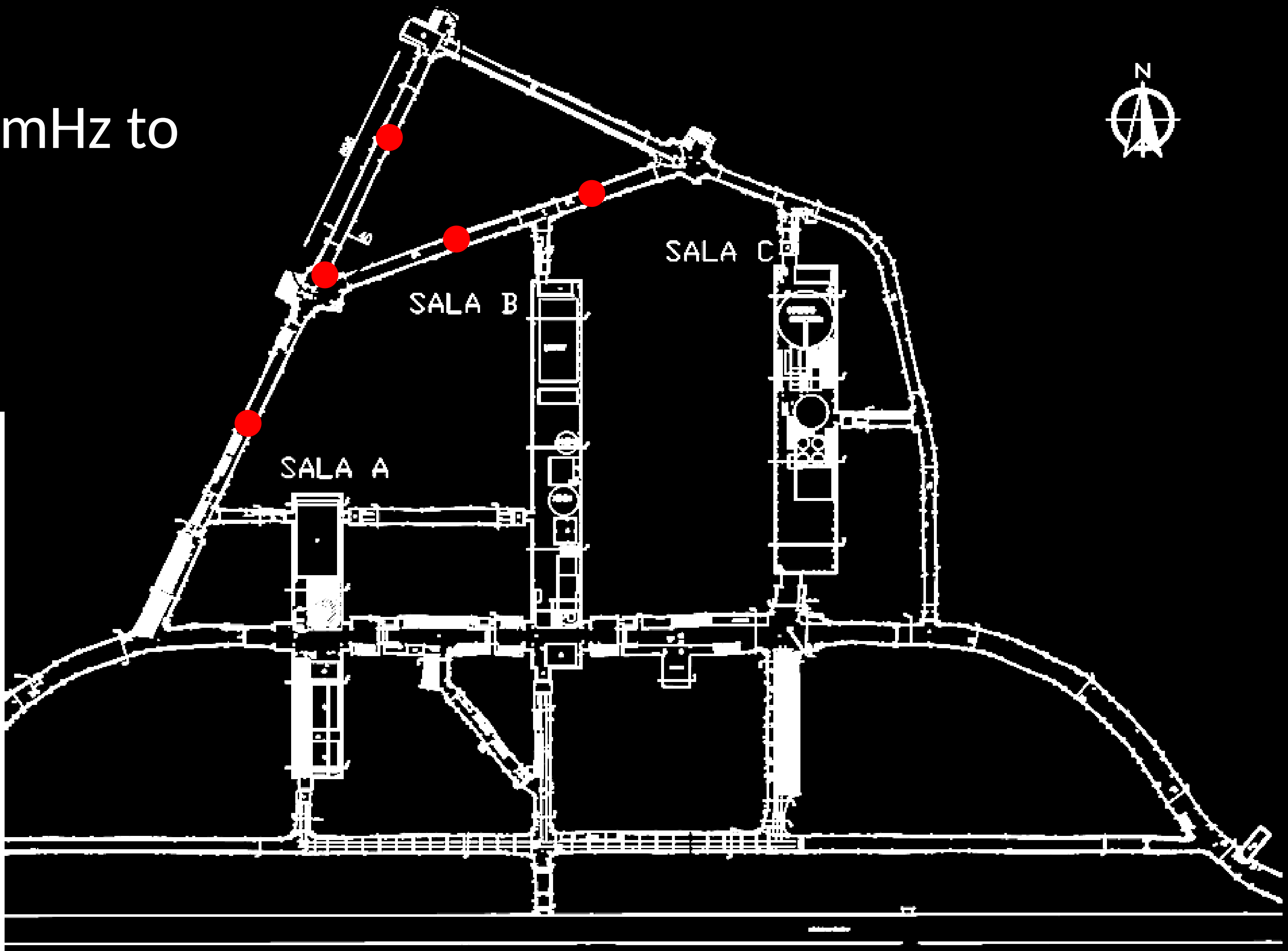
A few options for inter-platform sensing



# Environmental Monitoring System

Network of barometers for 1mHz to 1Hz observations (underground and surface)



# Tentative Timeline

## (assuming that funds are available when needed)

| | 2024 | | 2025 | | 2026 | | 2027 | | 2028 | |
|---|---|---|---|---|---|---|---|---|---|---|
| Site preparation | ■ | ■ | | | | | | | | |
| Installation of sensors and actuators on mechanical platforms (surface) | | | ■ | ■ | | | | | | |
| Testing of real-time system (surface) | | | ■ | | | | | | | |
| Installation of vacuum system | | | | ■ | | | | | | |
| Installation of electronics rack | | | | ■ | | | | | | |
| Installation of platforms into vacuum system | | | | | ■ | | | | | |
| Commissioning of active seismic isolation system | | | | | | ■ | ■ | | | |
| Installation of environmental monitoring system | | | | | | ■ | ■ | | | |
| Installation of cryocooler, thermal link, cryobox | | | | | | ■ | | | | |
| Installation of inter-platform interferometer (IPF) | | | | | | | | ■ | | |
| Commissioning of IPF | | | | | | | | | ■ | ■ |

# Full presentation

# A new underground seismic-isolation facility at LNGS

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# Profile

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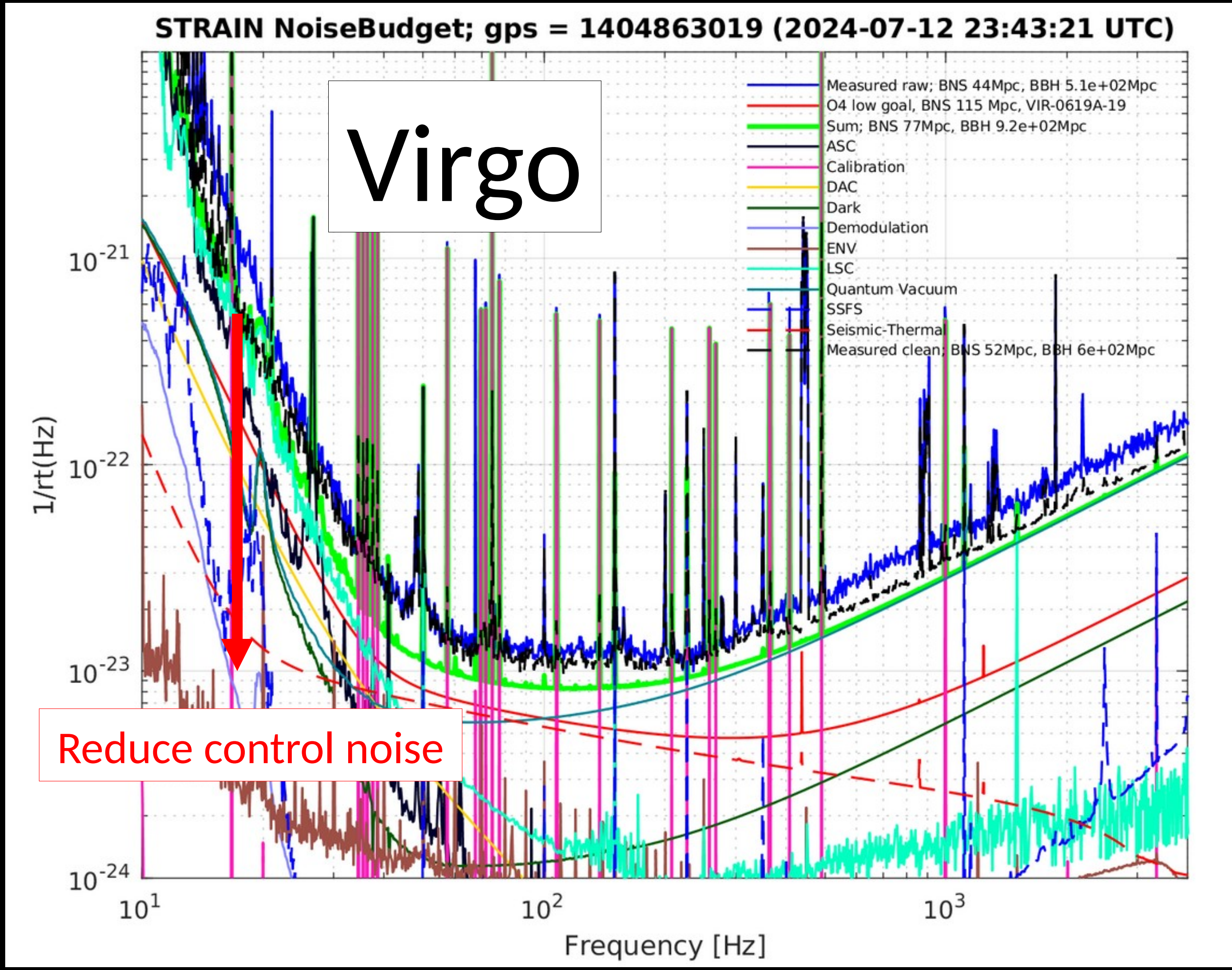
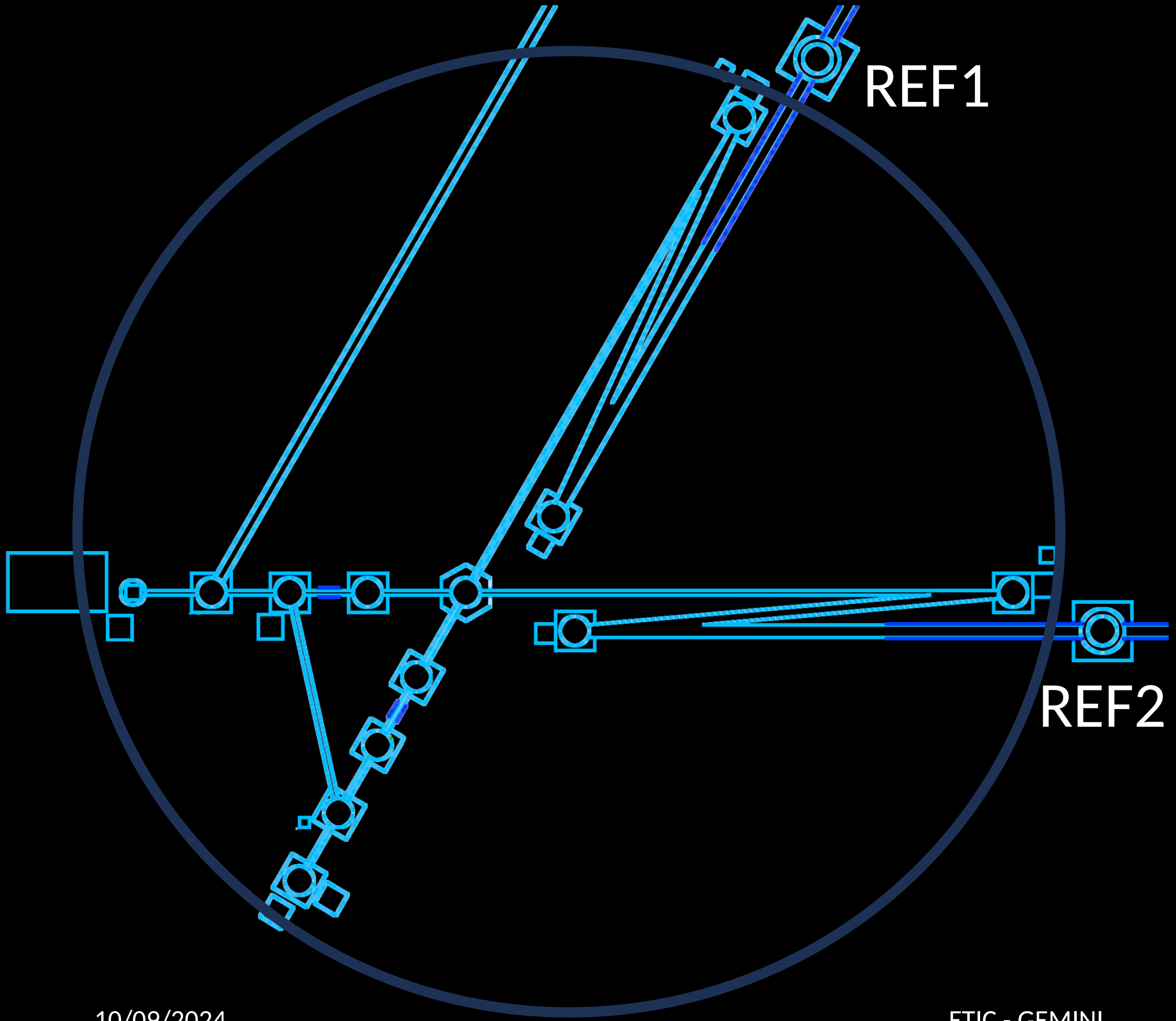
- Development of vibration control and inter-platform control systems for the Einstein Telescope; LNGS is a perfect/unique location to carry out these studies
- Test platform for novel inertial sensors (room&cryo temperature);
- Installation and utilization of an underground environmental monitoring system

# Scientific Goal 1: ET



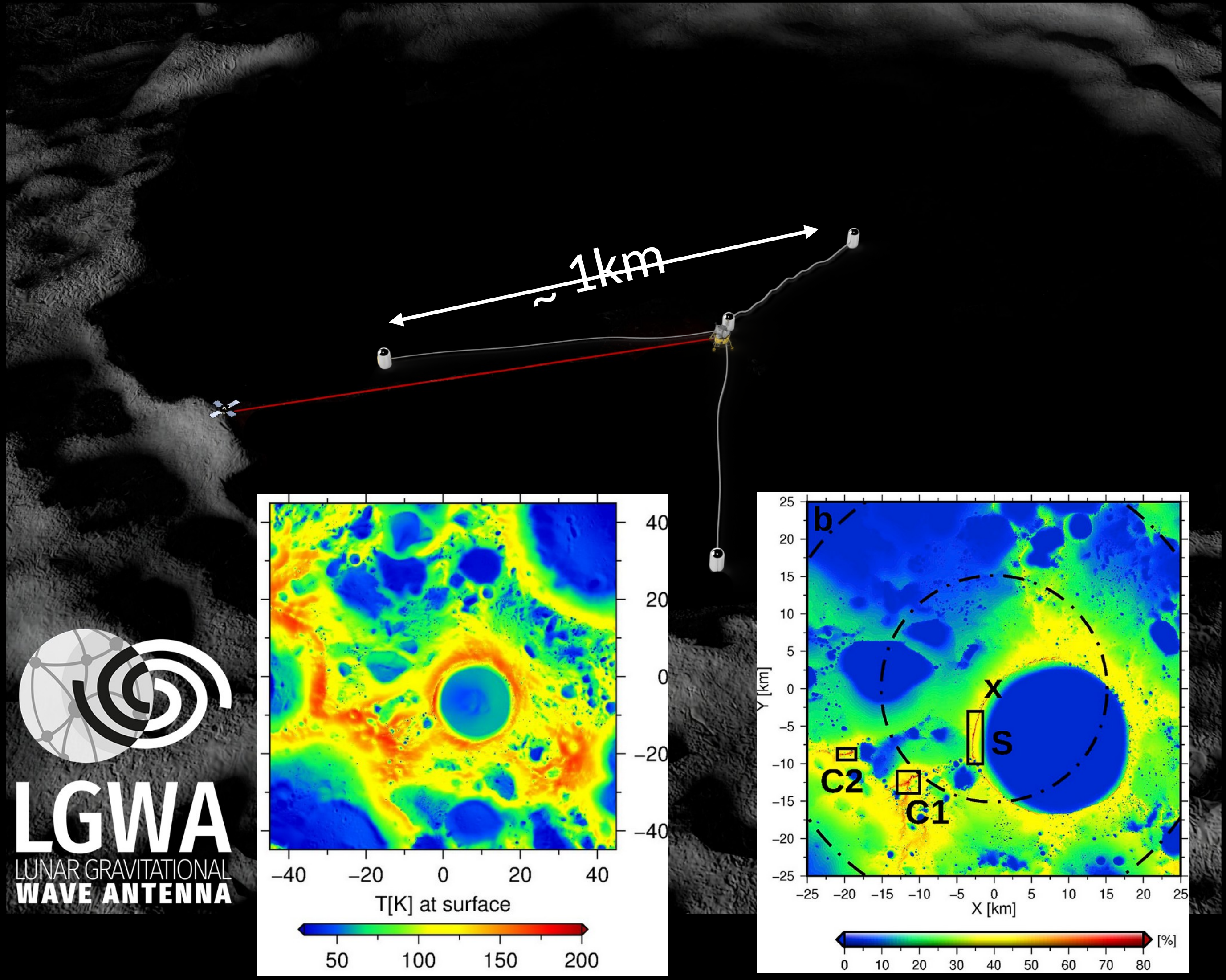

- Noise introduced by the control of length and alignment degrees of freedom can limit low-frequency sensitivity
- Develop an inter-platform motion control system to assist the ET length and alignment control of auxiliar degrees of freedom
- Enable ET-LF science case

# GEMINI - ET

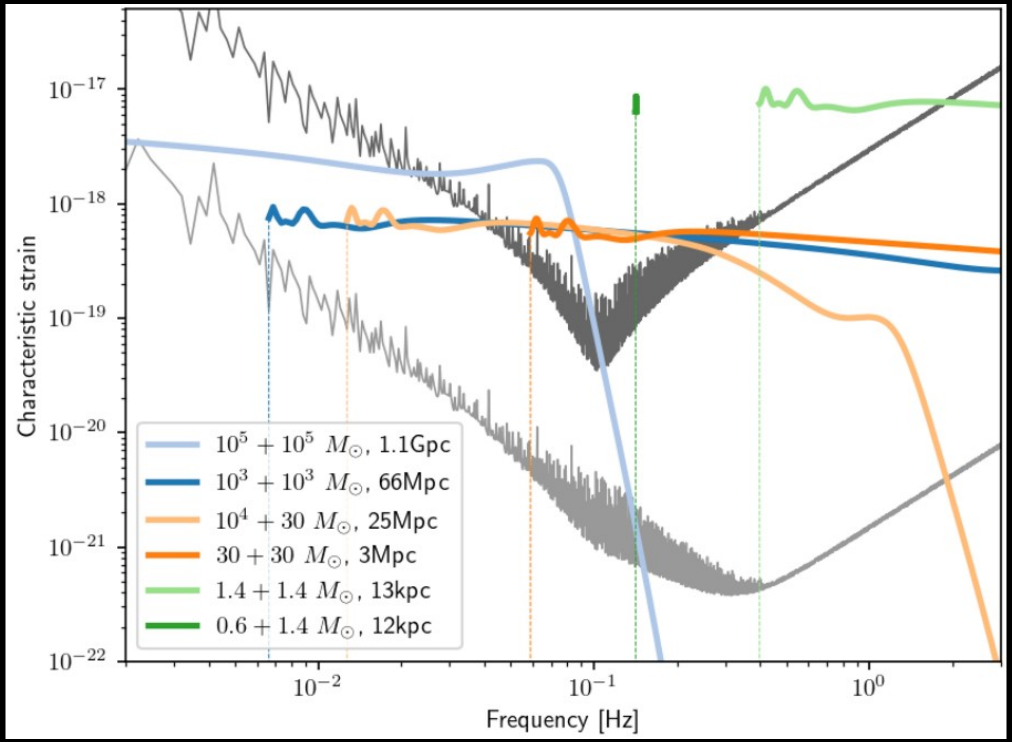



- Lock all suspension platforms into a common motion across the full central vertex of an interferometer
- Refer this optically rigid body to the two input masses

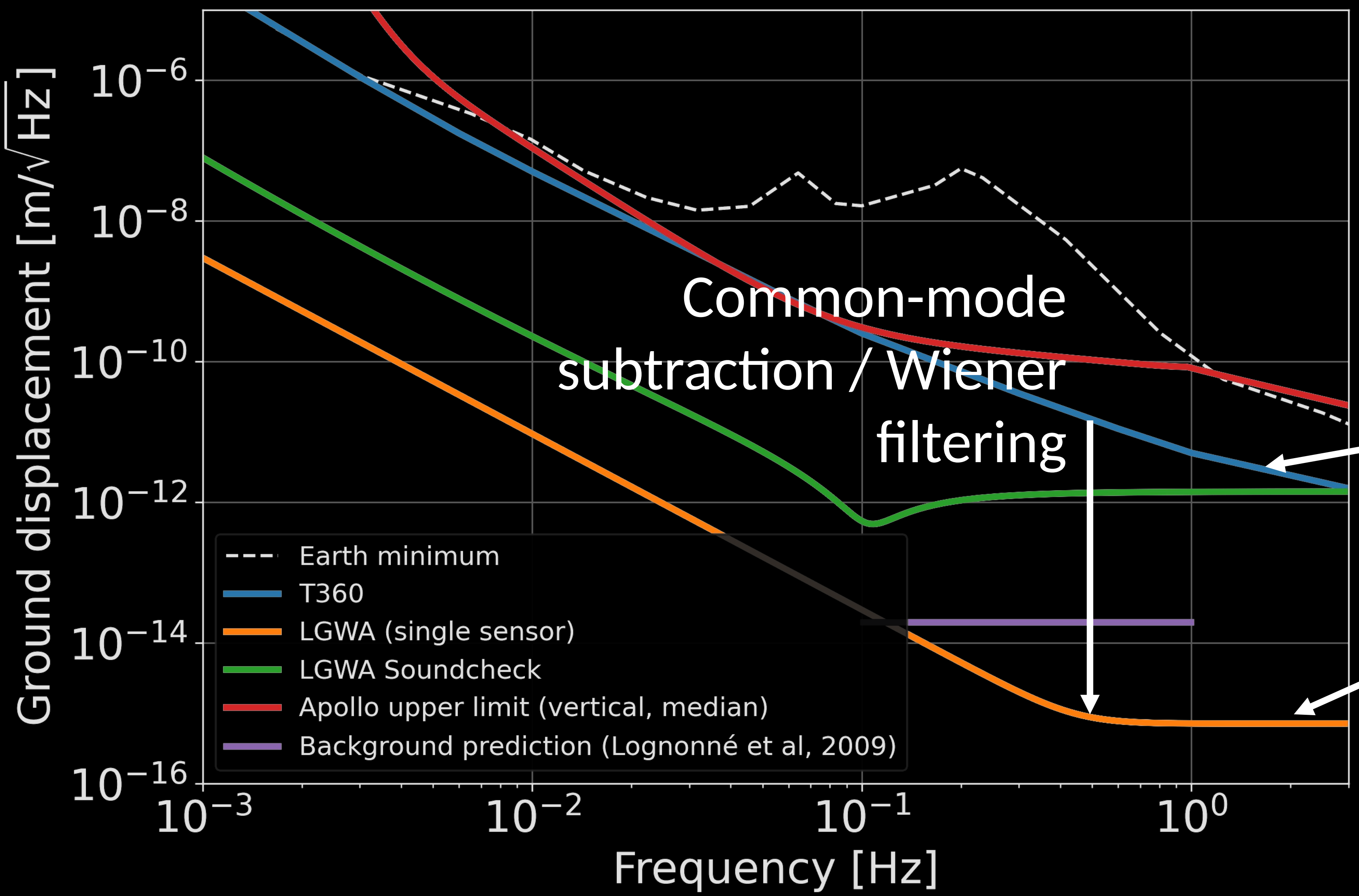
# Scientific Goal 2: LGWA




Decihertz gravitational-wave detection on the Moon



# GEMINI - LGWA

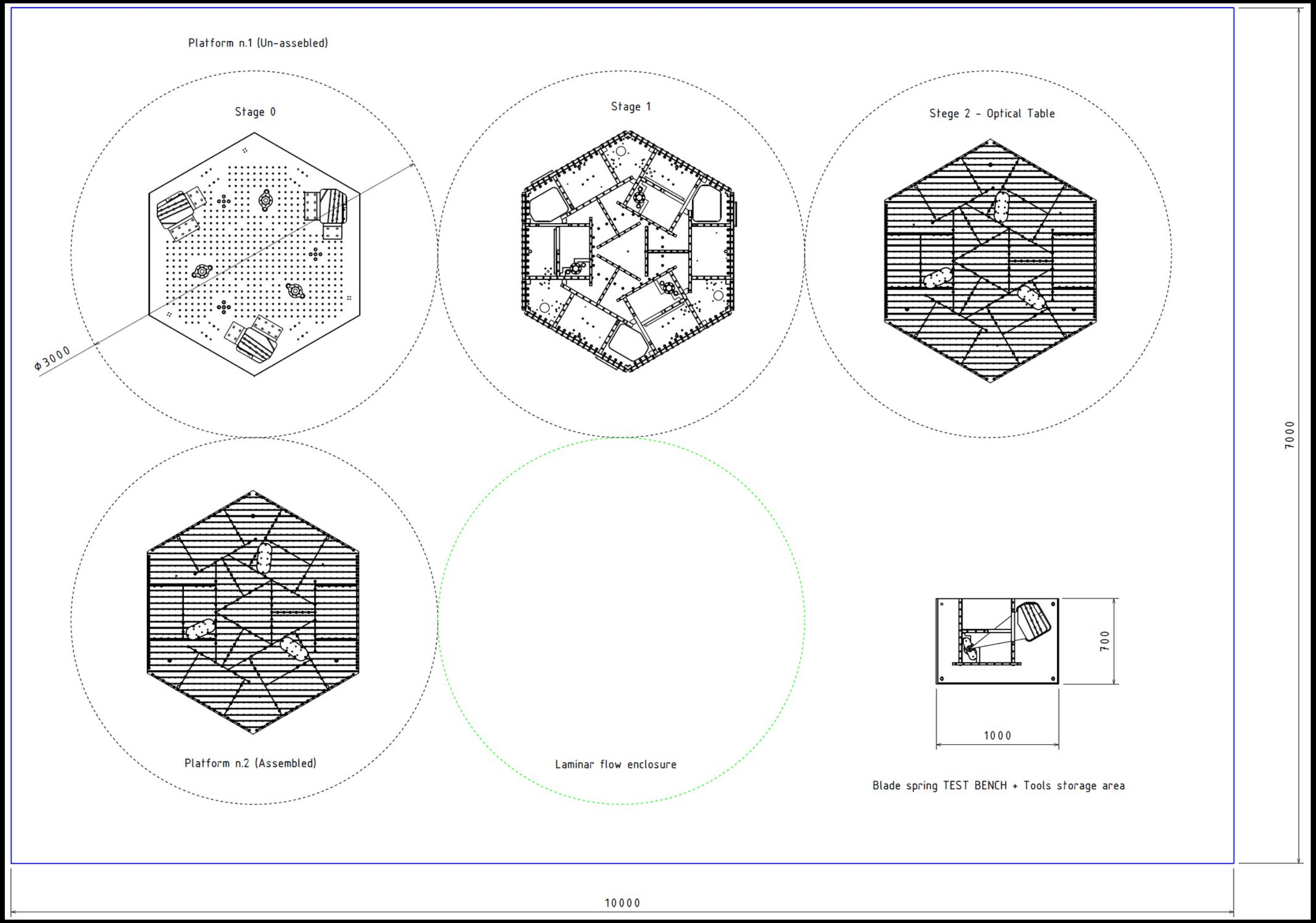



Test high-performance, cryo-temperature lunar seismometers for LGWA

Targeted GEMINI platform residual motion

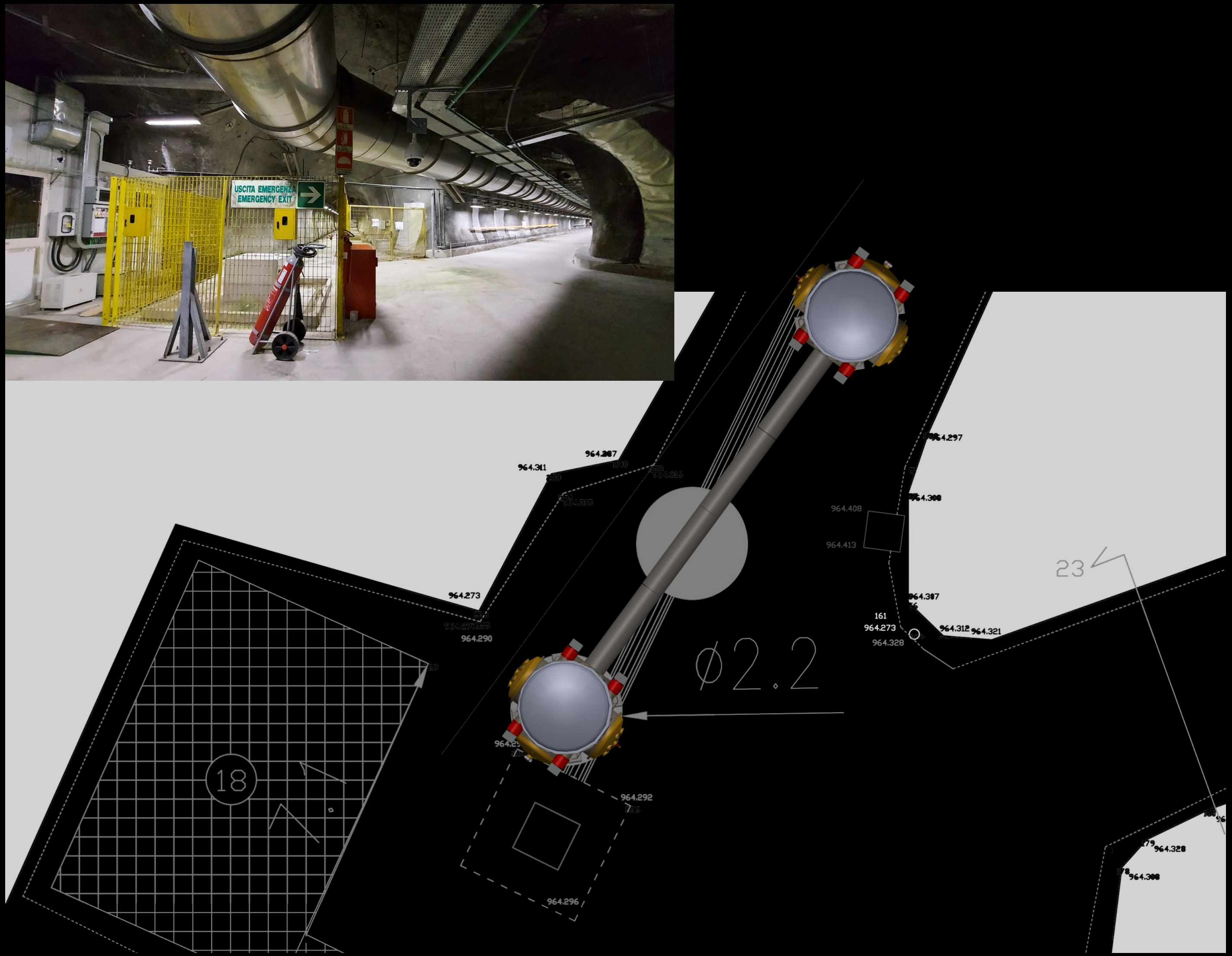
LGWA sensor performance target

# Surface Laboratory




- Integration of sensors and actuators on stage-0 and stage-1 platforms
- Installation and test of real-time system
- Test of control system
- Test stand for spring-blade material characterization
- Assembly and testing in clean environment

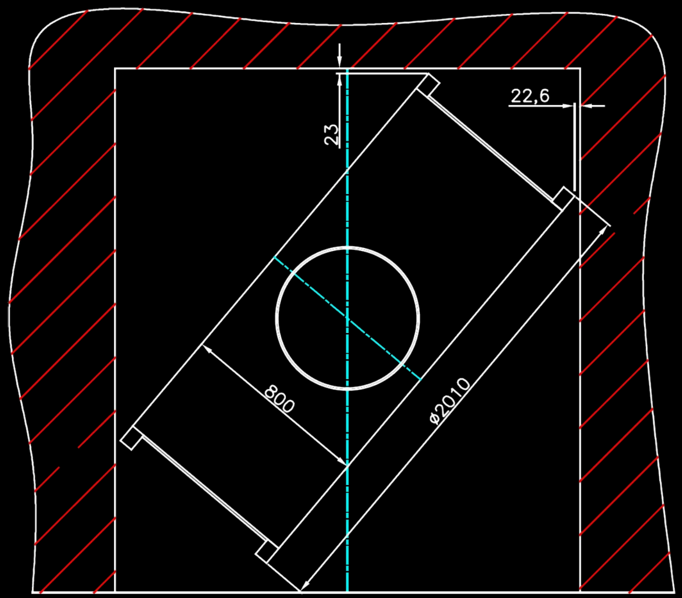
# Underground Laboratory

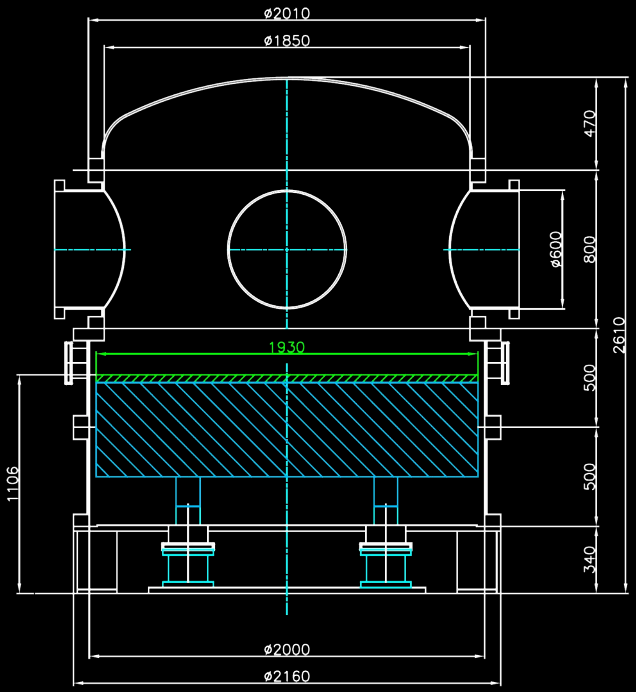


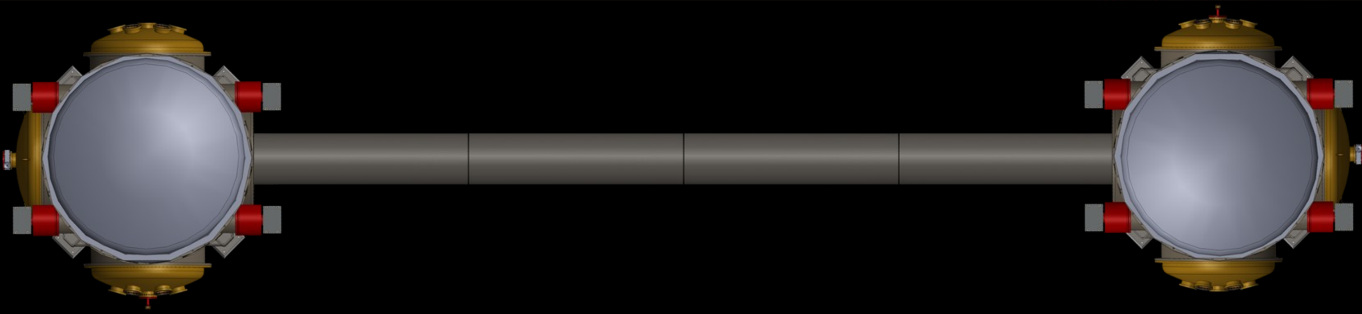

- Floor treatment
- Laminar-flow enclosures
- Lifting device for platforms and chamber segments
- Access to cooling water for cryocooler
- Timing signal from surface
- Low-latency data transfer to server at the surface

# Vacuum System

## Initial simulation



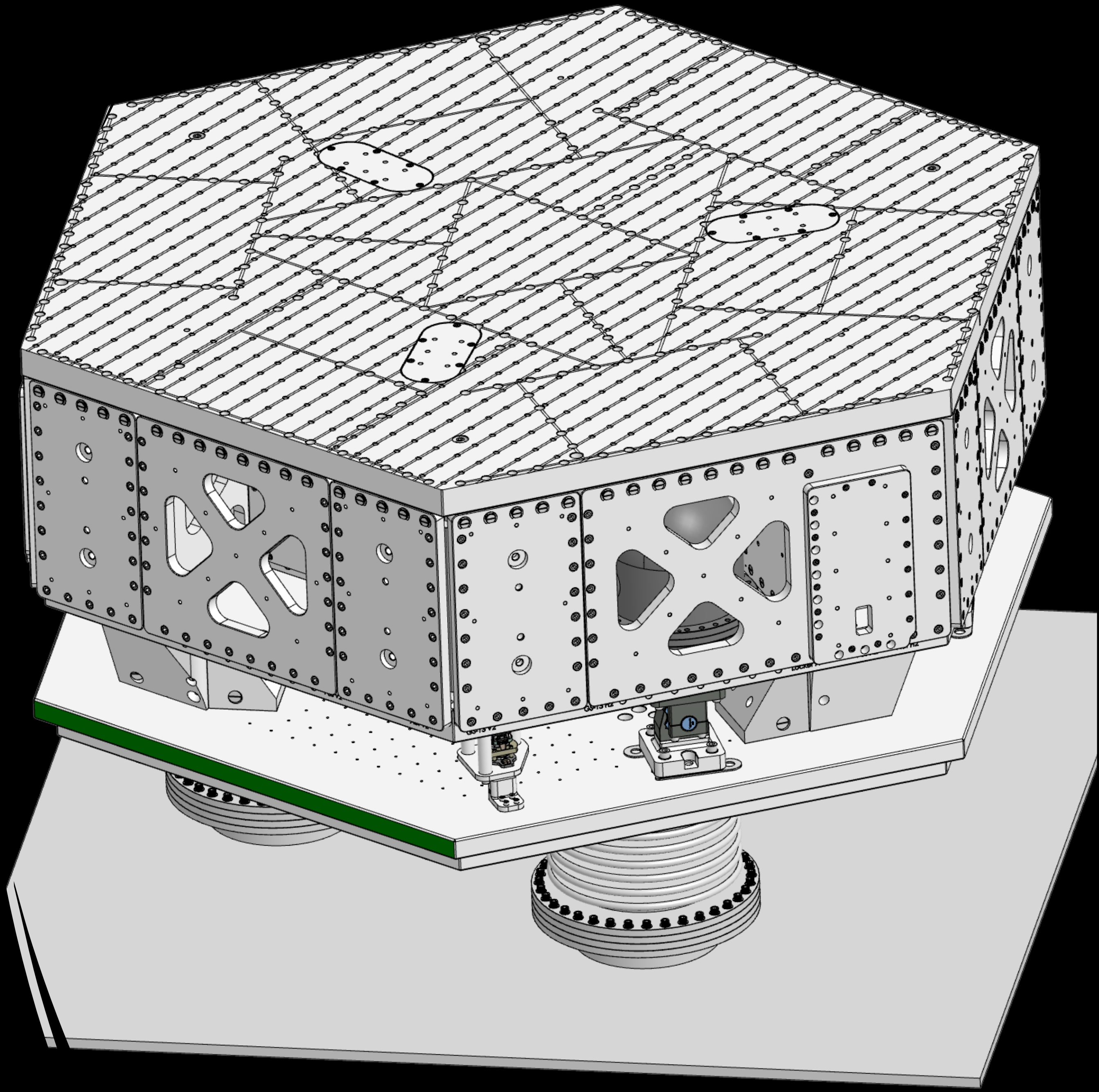



Two chambers connected by vacuum pipe.

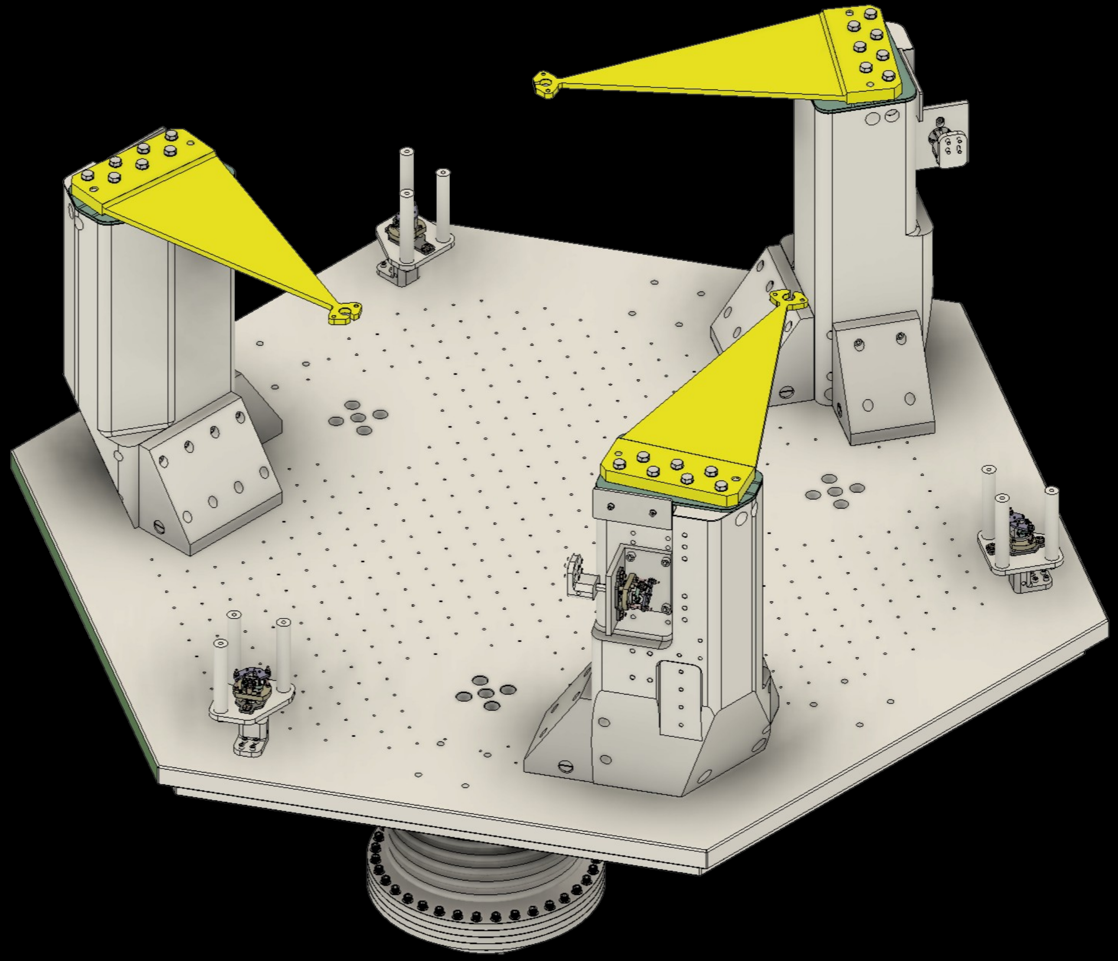
Tunnel entrance dimensions put strong limitations on chamber geometry.

# GEM-VCP

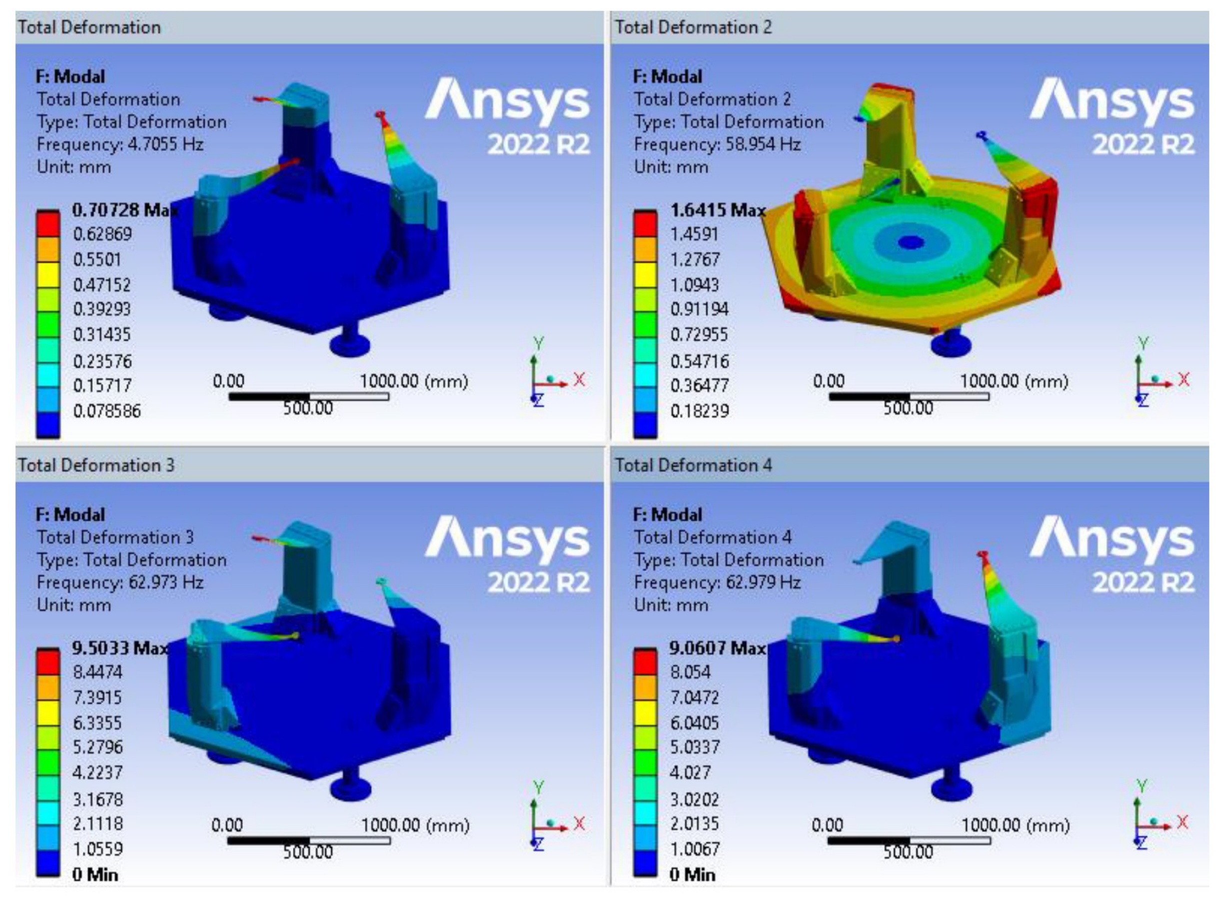
- GEMINI Vibration-control Platform
  - Starting point of the design: LIGO HAM-ISI
  - Design modifications, vibration analysis, and executive drawings produced by LNGS mechanical engineers



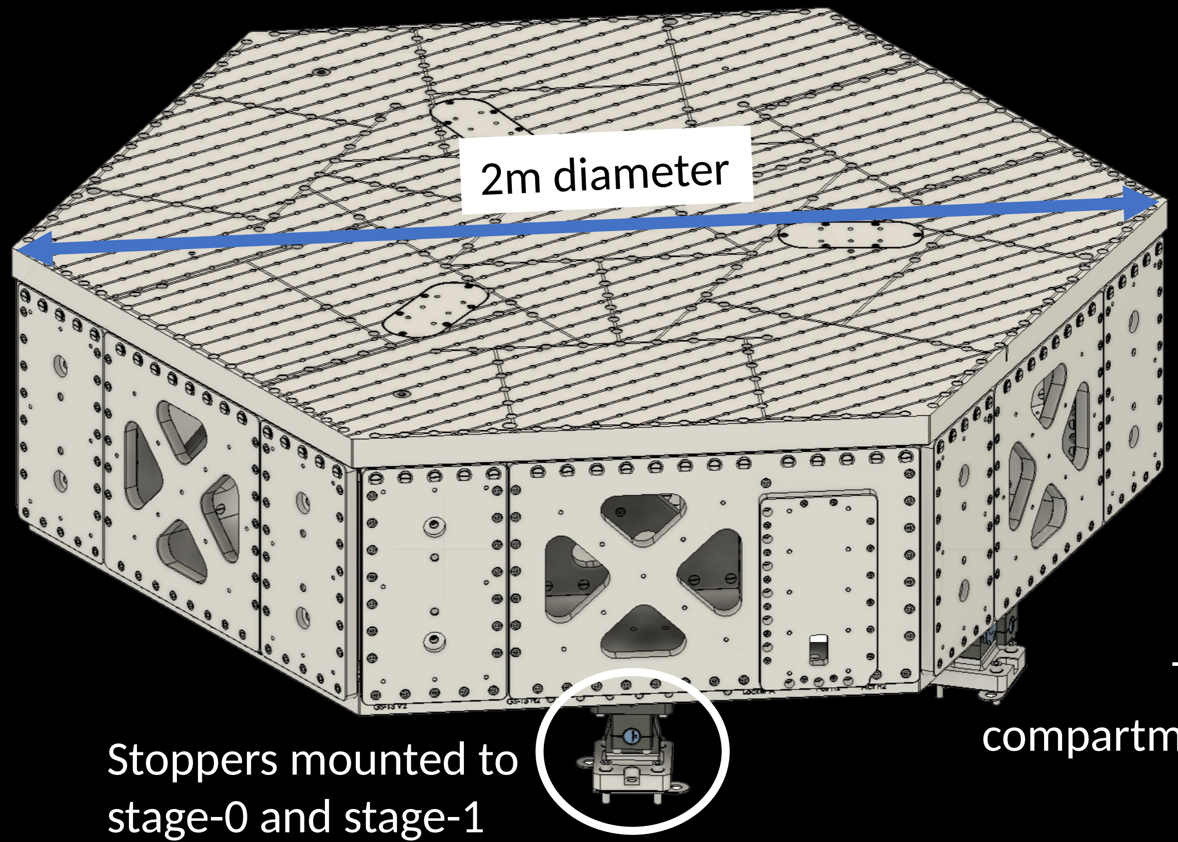
# GEM-VCP: Stage 0

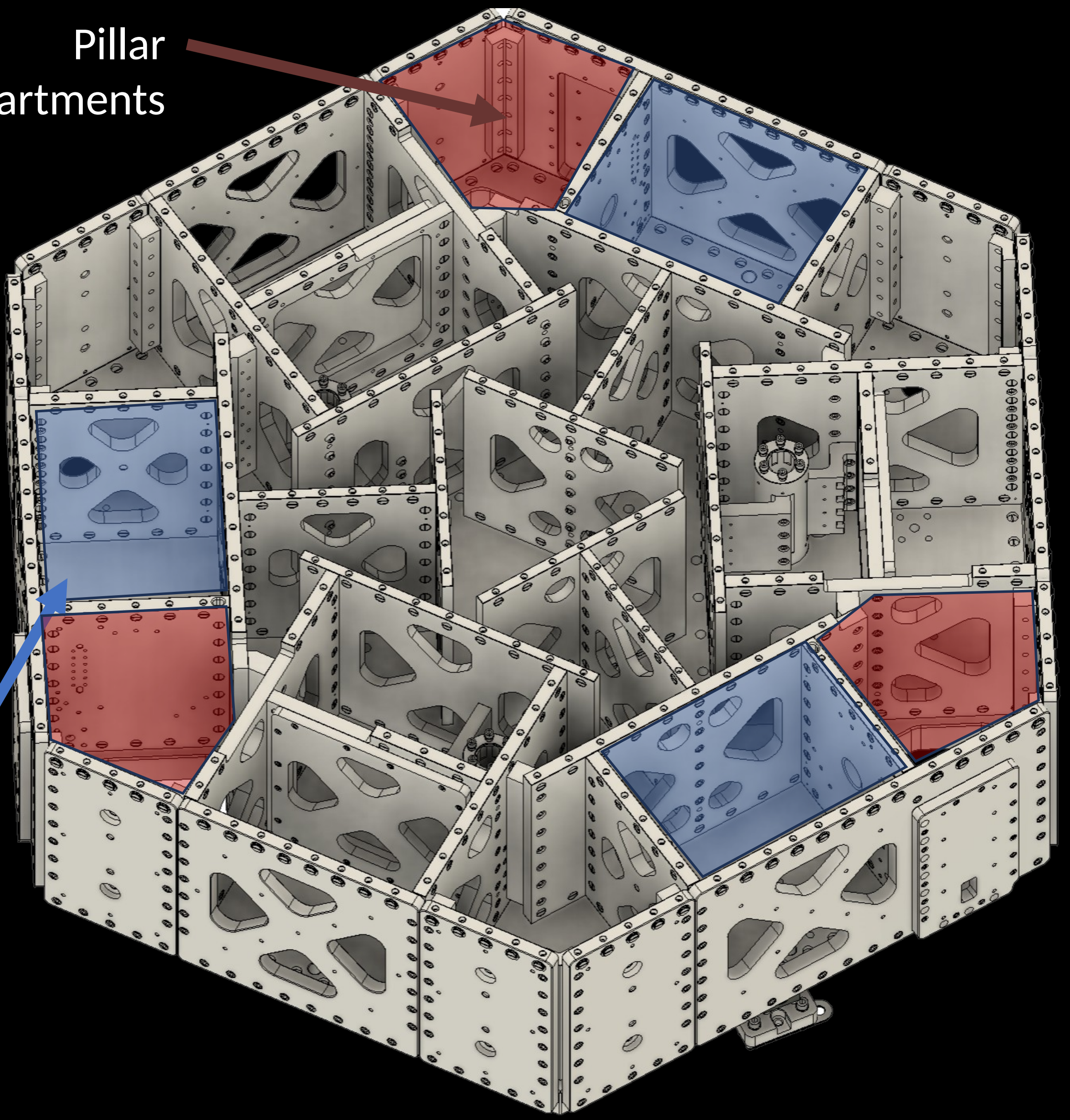


100Hz HAM-ISI (unconstrained)
70Hz GEM-VCP (under load)

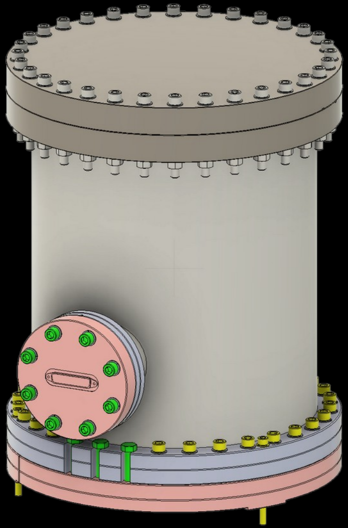


# GEM-VCP: Stage 1



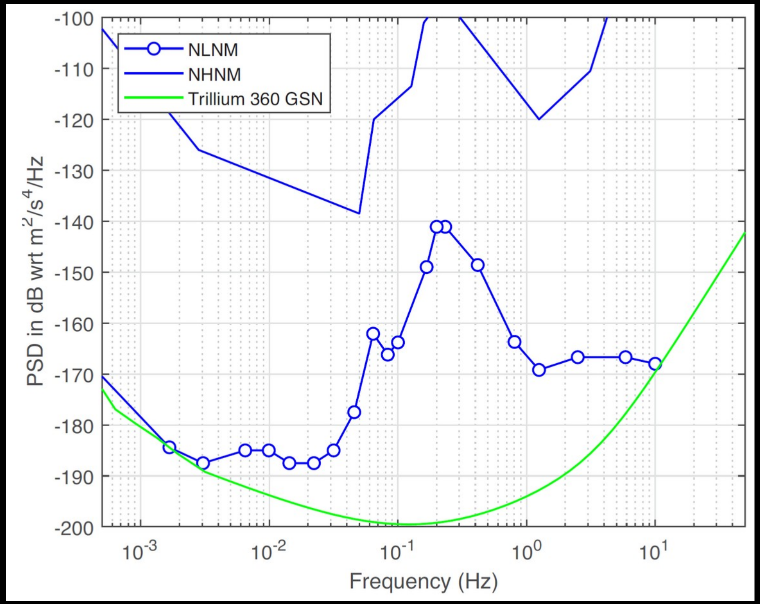



# Inertial Sensing

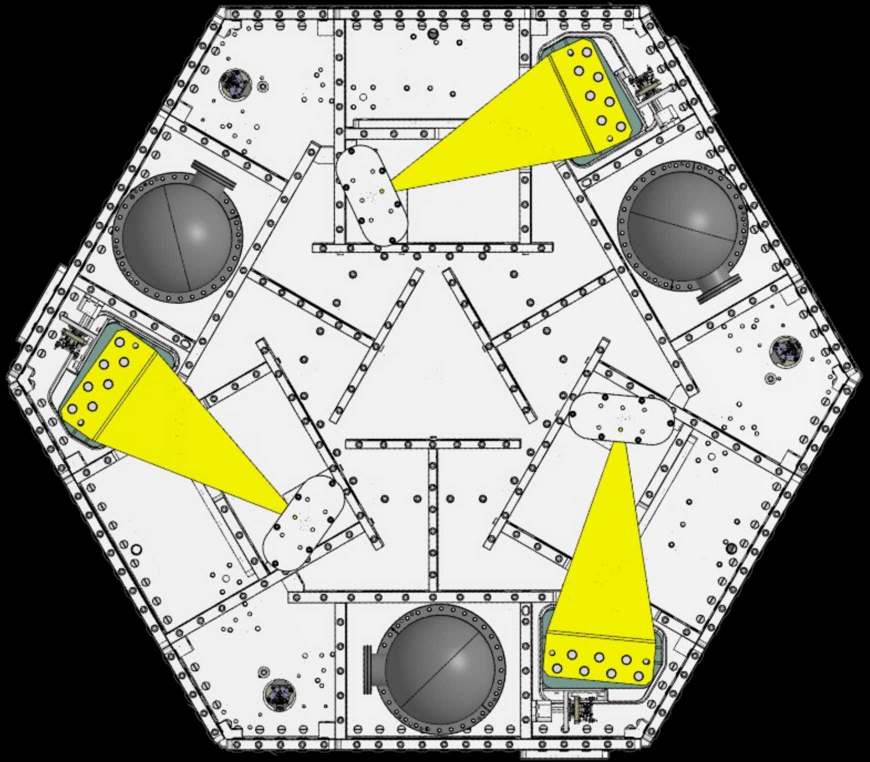


Vacuum pods
(to be ordered in October 2024)

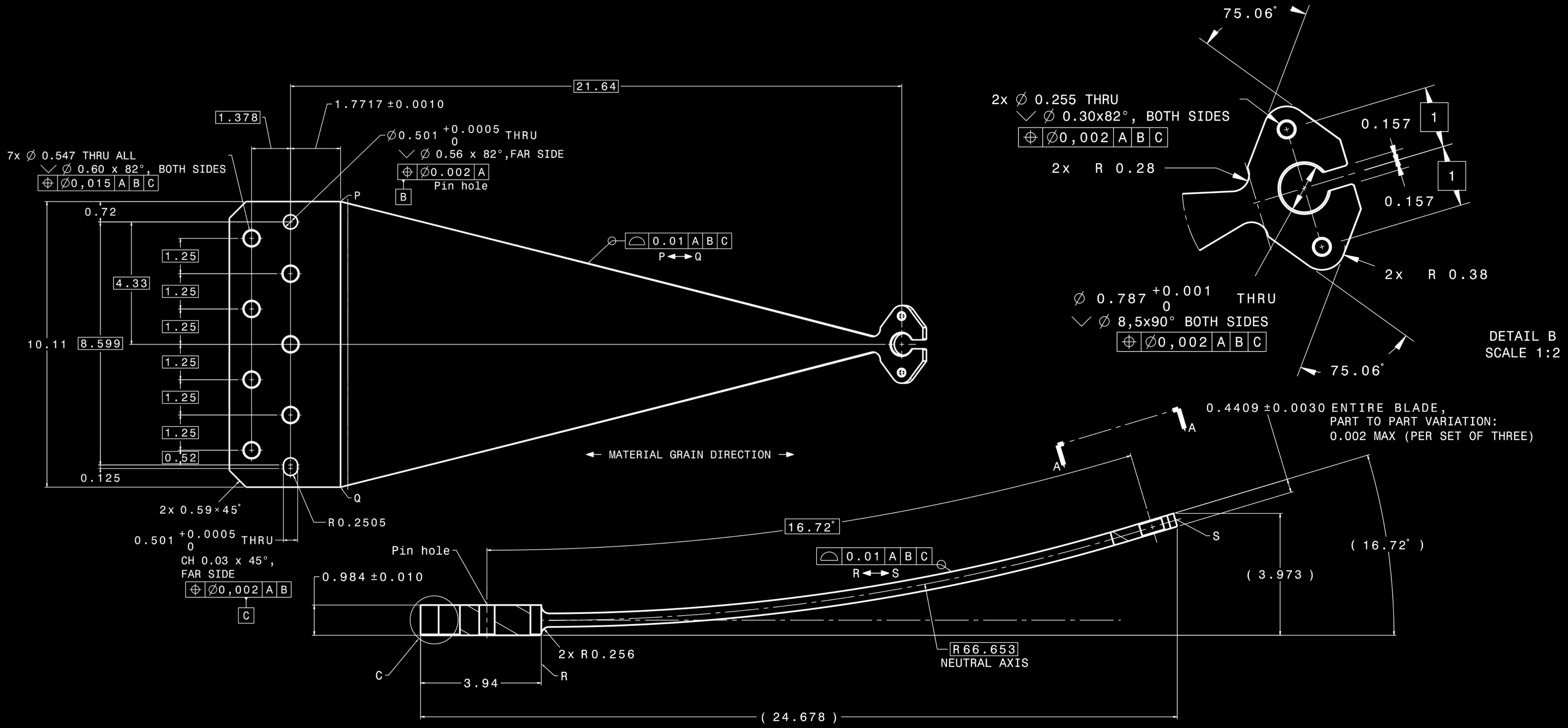
Nanometrics T360 GSN Vault
(3 per platform, 3 channels each)



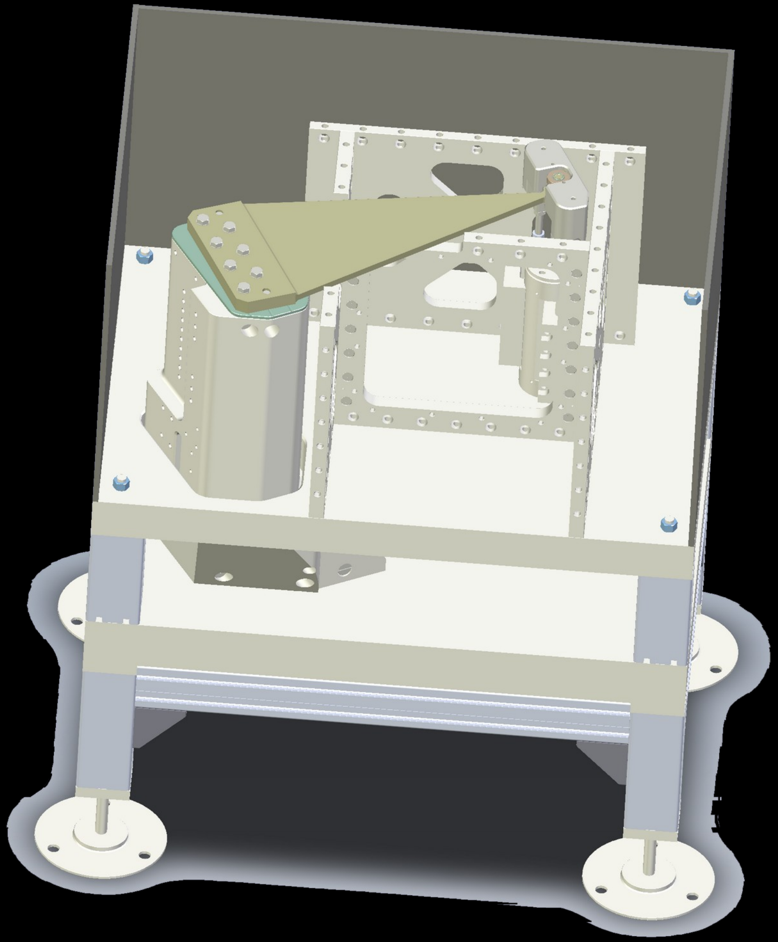

Integration in GEM-VCP



# Spring Blades
(HAM-ISI: maraging steel, GEM-VCP: t.b.d.)



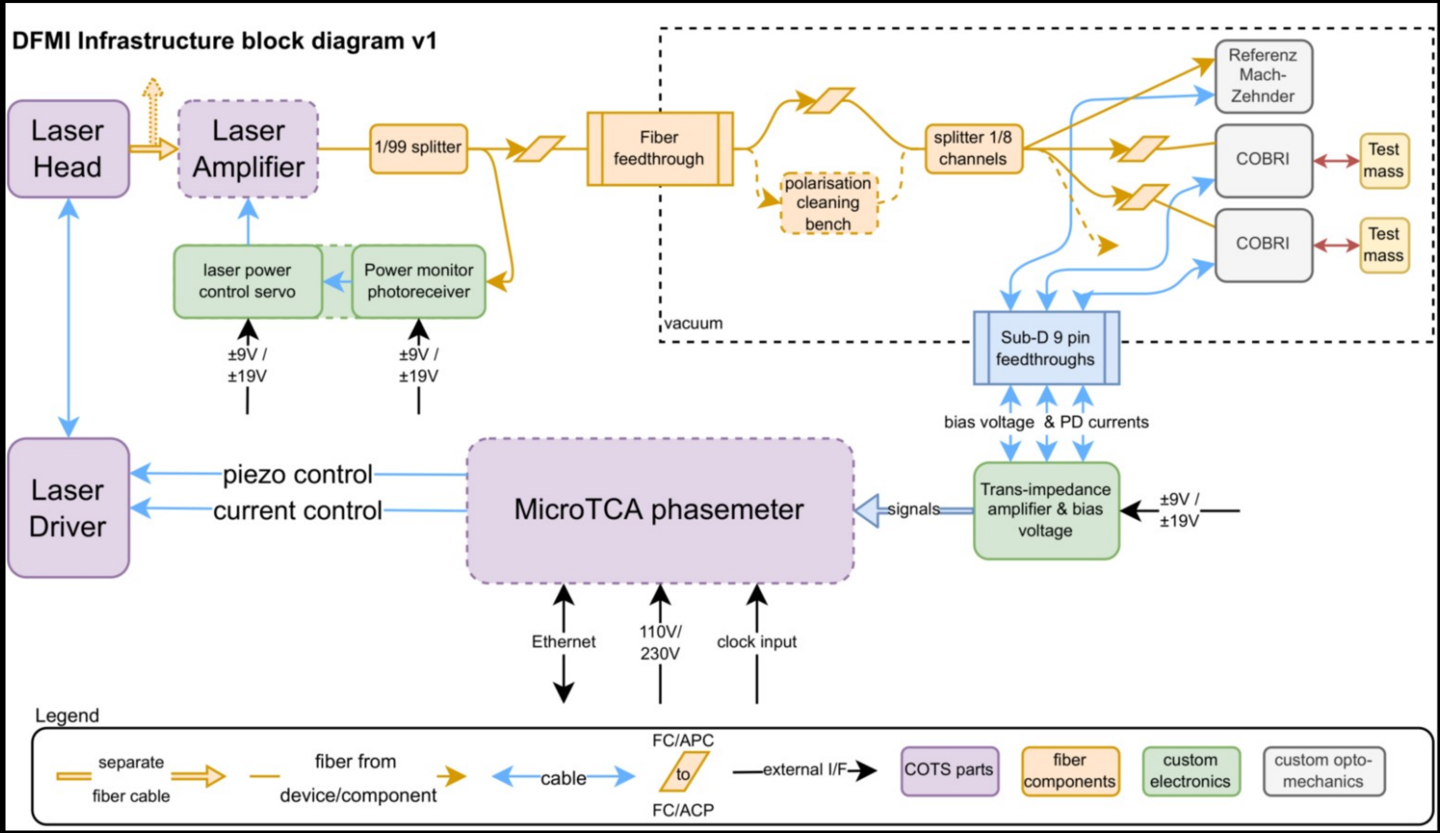
# Spring-blade Test Stand



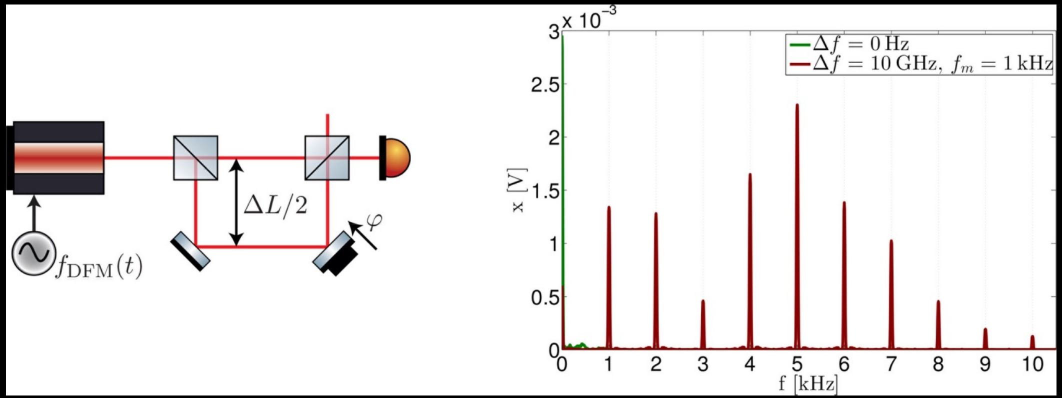
- Affordable maraging steel is hard to get
- Characterize new materials for the GEM-VCP spring blades
- Executive drawings of mechanical structure ready
- Quotes were obtained for sensors, data-acquisition and software
- Order expected by October 2024

# Position Sensing: DFMI

## Deep Frequency Modulation Interferometry



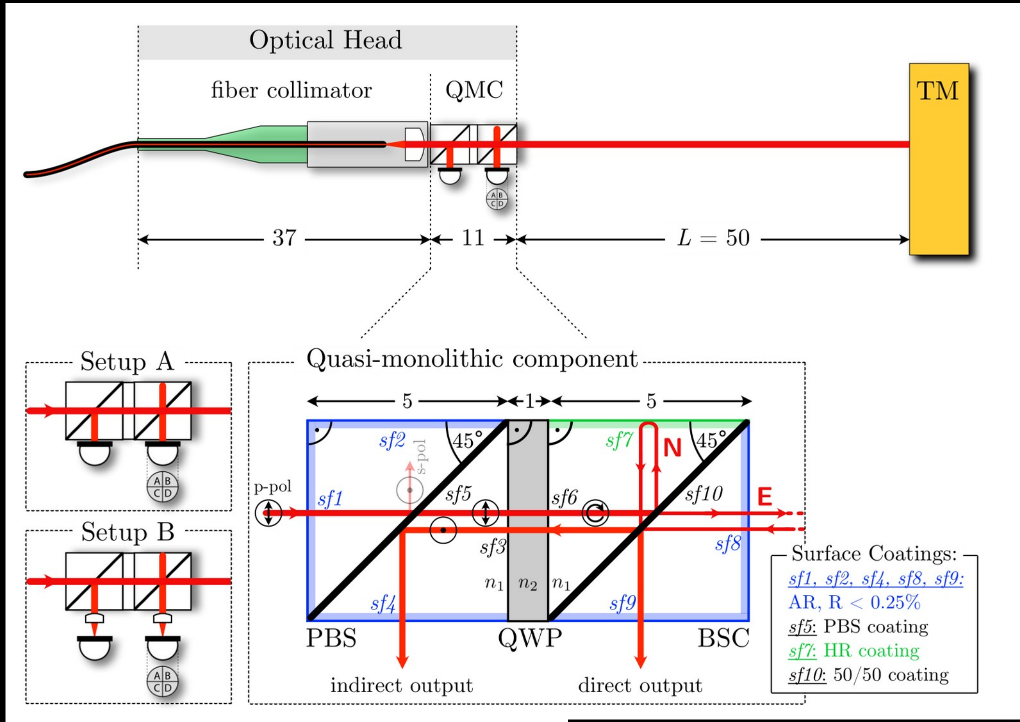

Gerberding (University of Hamburg)

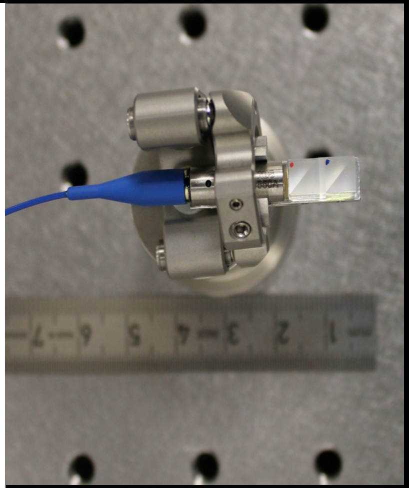


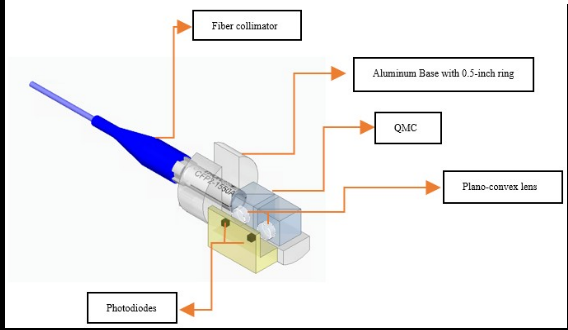

- Required for platform alignment and positioning
- Needs to be blended with inertial sensing and control

# Position Sensing: Optical Head

COmpact Balanced Readout Interferometer - COBRI



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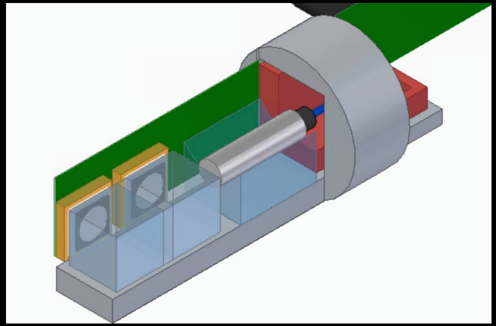
v2 design

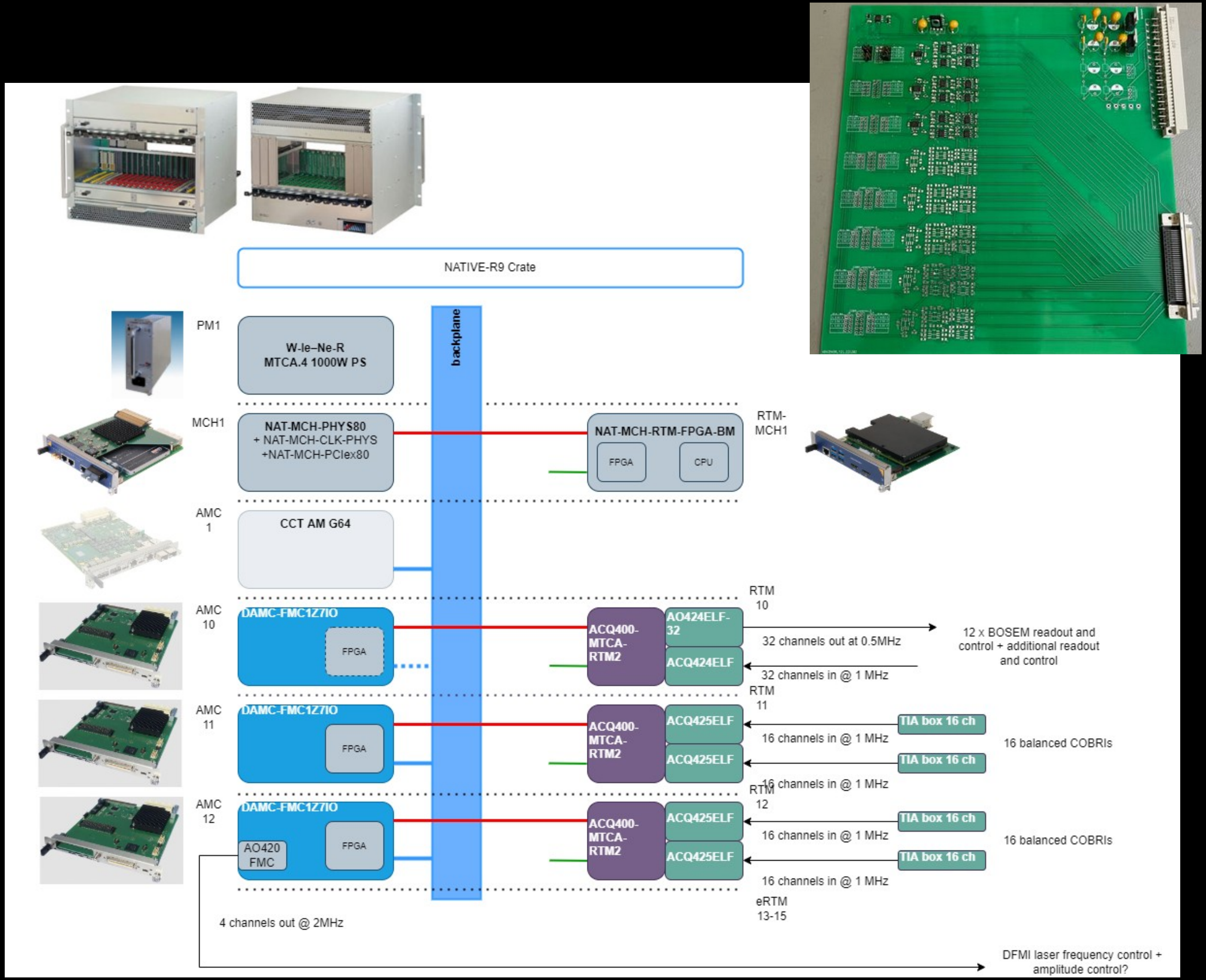


- On-axis design with quasi-monolithic component
  Positive:
  - no misalignment in vacuum
  - Large linear range (several centimeters)

  Negative:
  - On-axis ghost beams cause nonlinearity
- Dual readout/balanced detection at the front
  - Lower readout noise by sqrt(2)
  - Enables scattered light reduction in post processing
  - Reduces residual amplitude modulation noise

# Position Sensing: Control Hardware

- Phasemeter with FPGAs running in MicroTCA
- Commercial hardware (FPGAs, ADCs, DACs)
- Self-made trans-impedance amplifier electronics (outside of the vacuum, driving the ADCs)
- Processing split between FPGA and CPU
- One crate can host up to 160 COBRIs




Gerberding (University of Hamburg)

# Voice-coil Actuators

The best choice of VCA still needs to be determined

BEI Kimco

| | |
|---|---|
| Total Stroke | 12.7 mm |
| Continuous Stall Force | 43.15 N |
| Peak Force | 142.34 N |
| Actuator Constant | 9.03 N√W |

H2W Technologies

| | |
|---|---|
| Total Stroke | 24.0 mm |
| Continuous Stall Force | 87.0 N |
| Force @ 10% Duty | 261 N |
| Actuator Constant | 13.1 N/√W |

# Cryo-box

## RDK-500B2 20K Cryocooler Series

### Performance Specifications

| Power Supply | 50Hz | 60 Hz |
|---|---|---|
| 1st Stage Capacity | 45 W @ 20 K | 50 W @ 20 K |
| Minimum Temperature[1] | <14 K | |
| Cooldown Time to 20 K[1] | <50 Minutes | <45 Minutes |
| Weight | 25.0 kg (55.1 lbs.) | |
| Dimensions (HxWxD) | 570 x 180 x 325 mm (22.4 x 7.1 x 12.8 in.) | |
| Maintenance | 8,760 Hours | |
| Regulatory Compliance | CE, UL/cUL | |

### Standard Scope of Supply

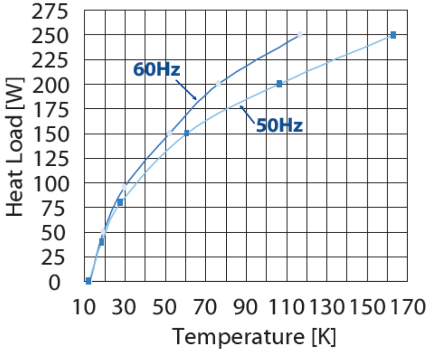
- RDK-500B2 Cold Head
- F-70LP/H Compressor
- Helium Gas Lines – 20 m (66 ft.)
- Cold Head Cable – 20 m (66 ft.)
- Power Cable – 5 m (16.5 ft.)
- Tool Kit

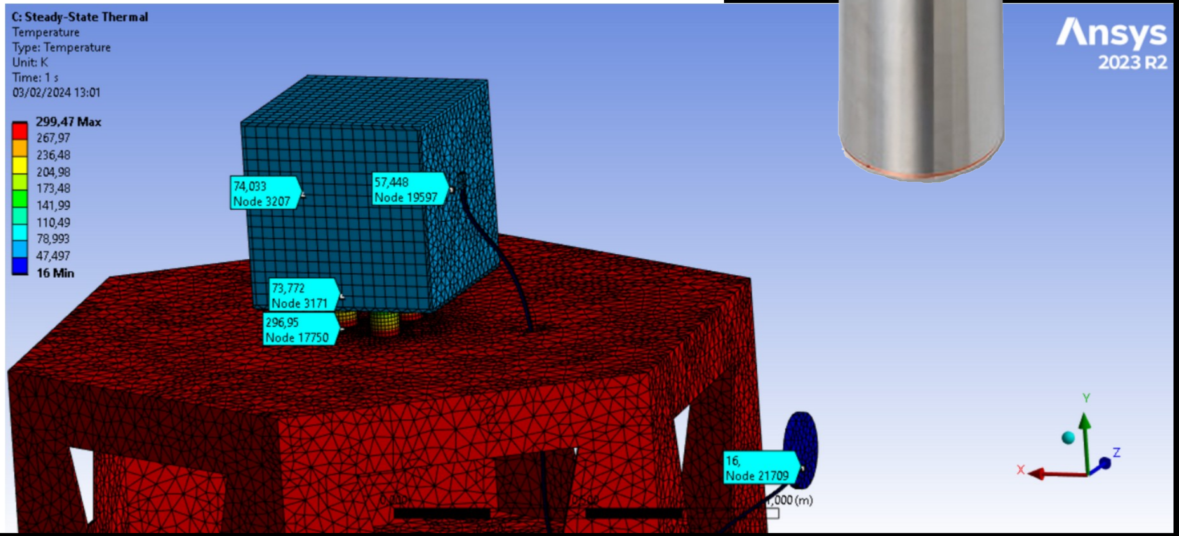
[1] *Lowest temperature and cooldown time are for reference only.*

Emulate 40k environment for lunar PSR payloads

**RDK-500B Cold Head Capacity Map (50/60 Hz)**

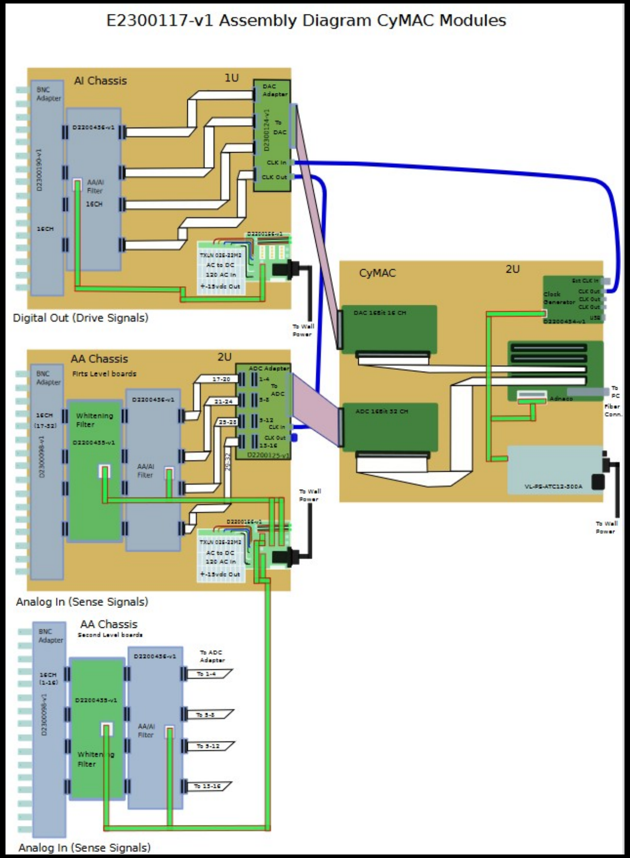
With F-70 Compressor and 20 m (66 ft.) Helium Gas Lines




Thermal link will not be as shown in this simulation

# Real-time System

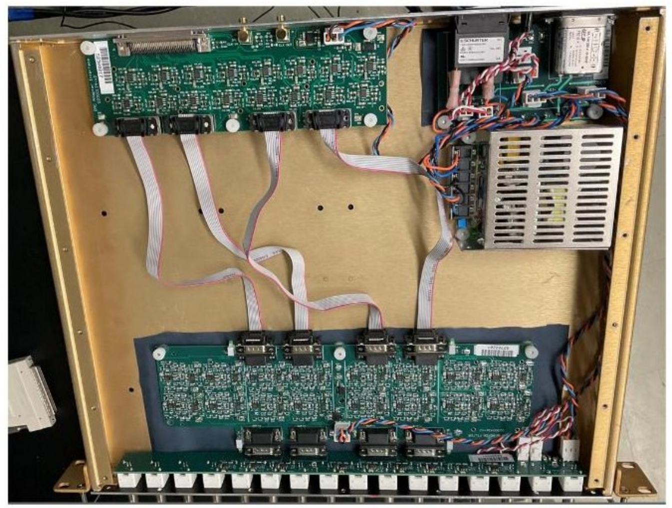




- LIGO's CyMAC with minor modifications
- Readout of up to 64 differential channels (24 diff position channels, 18 diff inertial channels, environmental monitors, on-table sensors)
- Output of up to 16 differential channels (12 coils)

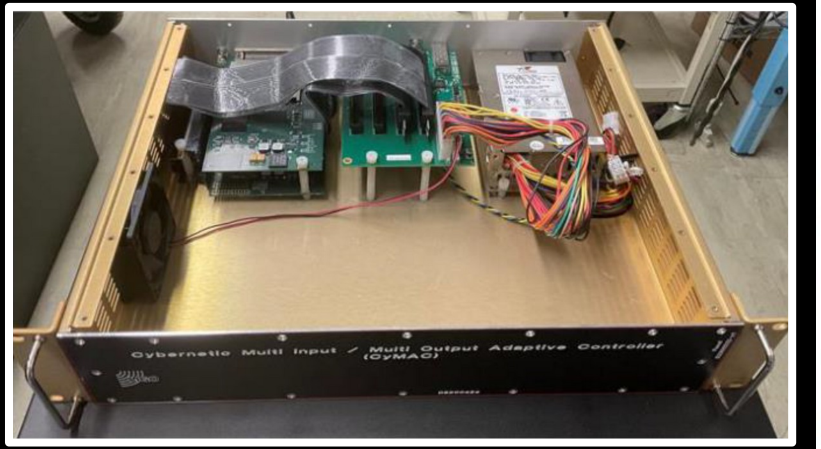
Main components: ADC/DAC, timing, anti-aliasing / anti-imaging, front-end computer, whitening filters

# Real-time System: Chasses

Analog-output chassis

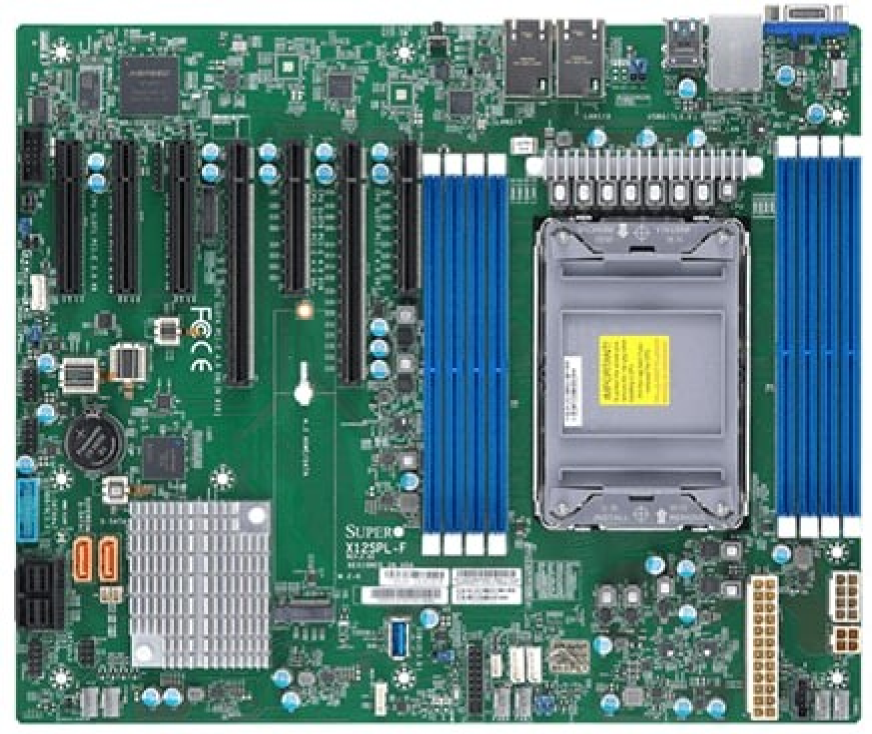


CyMAC (ADC/DAC/CLK)




Front-end computer

X12SPL-F motherboard, Xeon W-3323 CPU



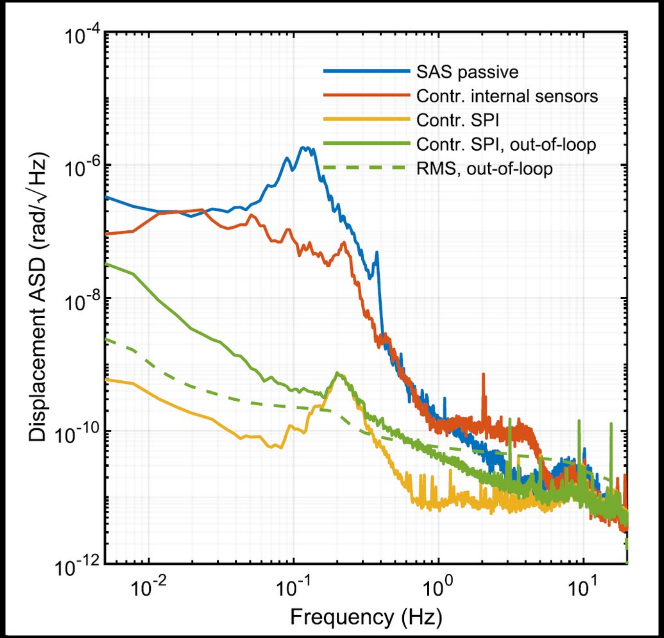
Analog-input chassis

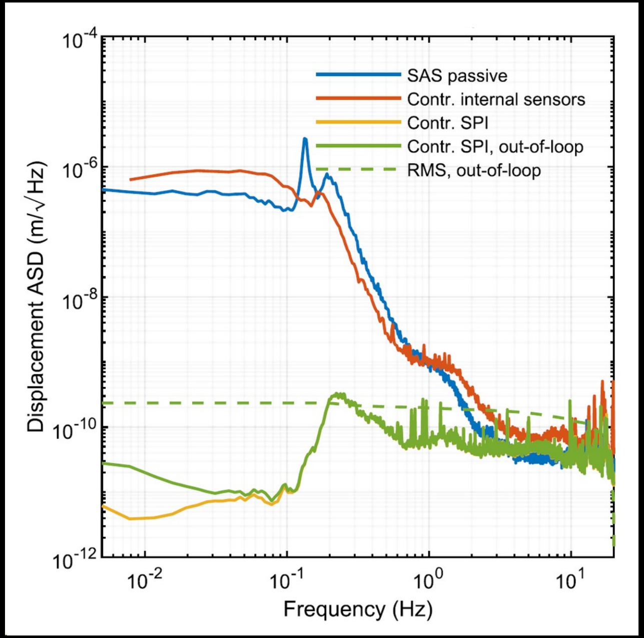
Additional electronics:

- Preamplifiers (input)
- Coil-drivers (output)
- MicroTCA (for fibers)
- Cryo system
- Pump system

# Suspension-platform Interferometer (SPI)

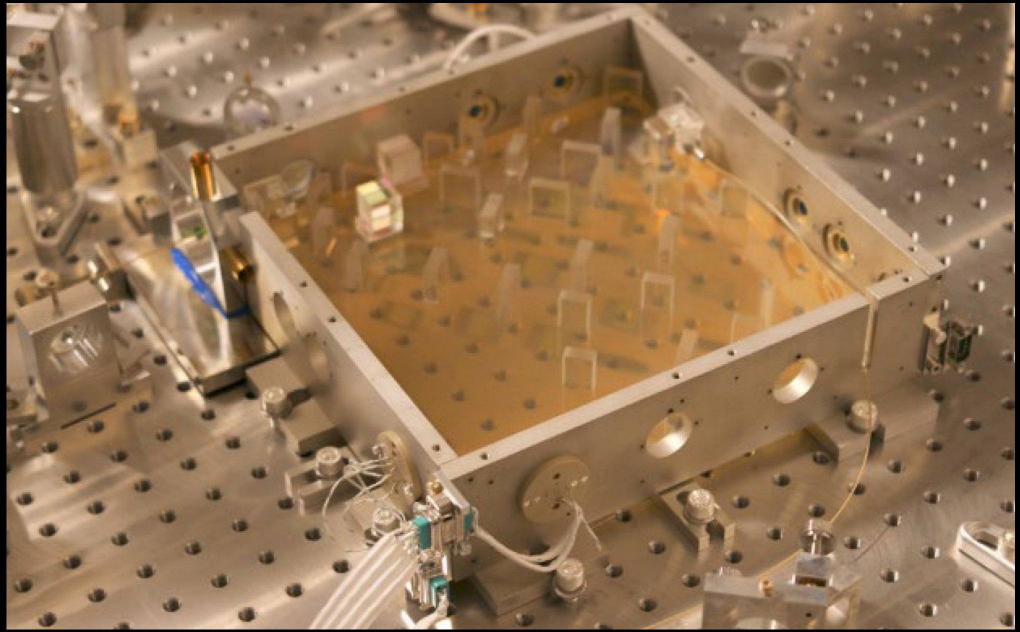
Inter-platform sensing and control to reduce relative motion between platforms (displacement and angular)



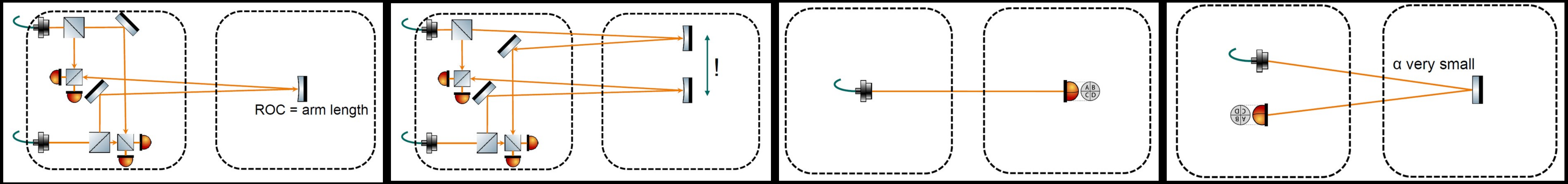

Koehlenbeck et al (2023)

SPI optical assembly



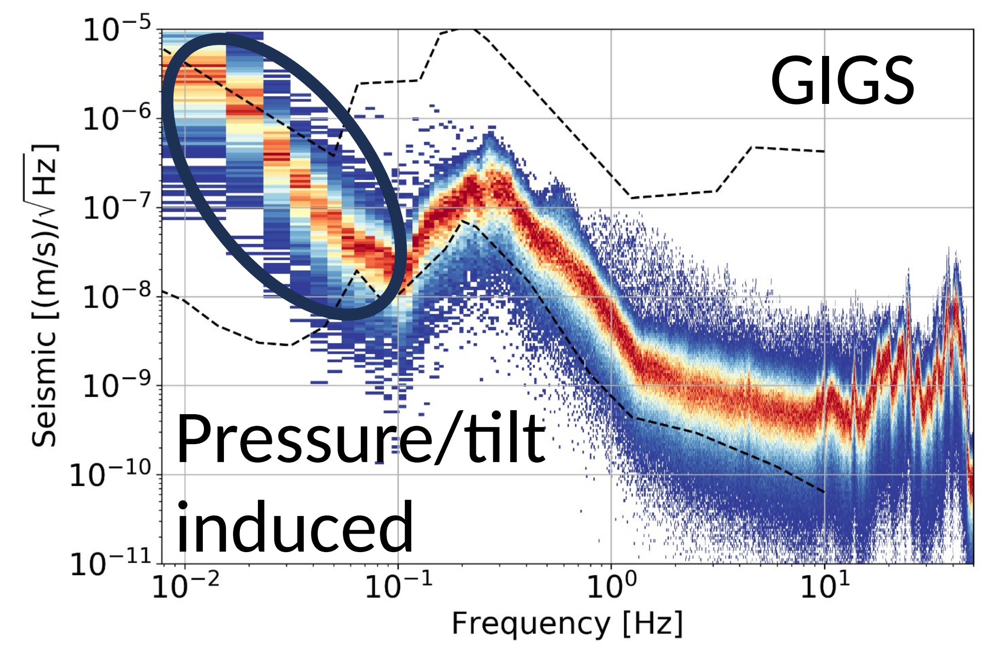
Koehlenbeck et al (2023)

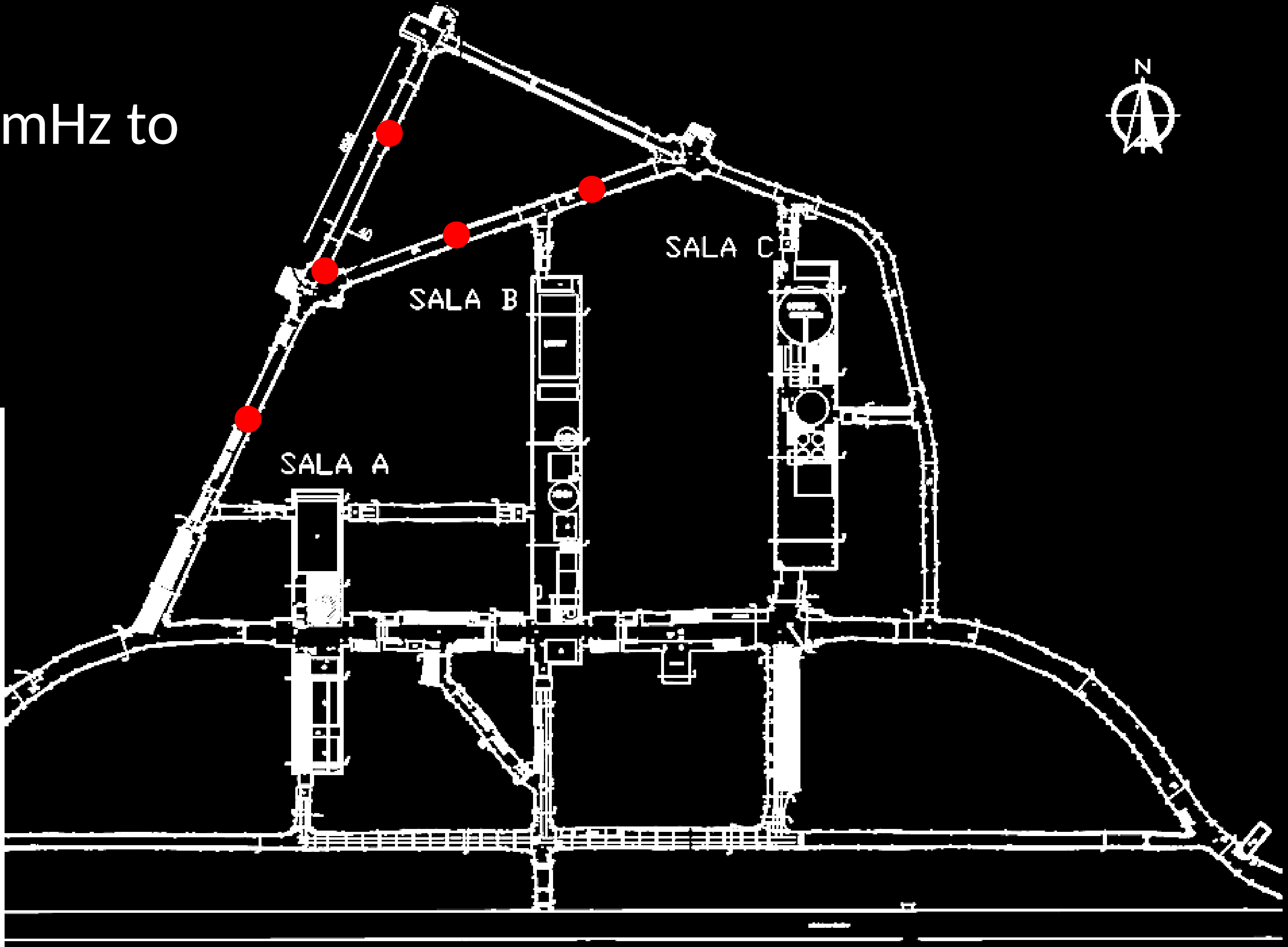
A few options for inter-platform sensing



# Environmental Monitoring System

Network of barometers for 1mHz to 1Hz observations (underground and surface)



# Missing Components

- Electronics (to be ordered in October 2024)
- Vacuum pods (to be ordered in October 2024)
- Cryocooler + equipment for thermometry
  (last items to be ordered in September 2024)
- Cryolink and cryobox
  (to be ordered in 2024/2025)
- Compact laser-interferometric position sensors
  (to be ordered in December 2024)

No funding available yet for (in order of urgency):

- Actuators
- Spring blades + test stand
- Barometer/microphone array
- Inter-platform interferometer

# Required Personnel

- Integration and commissioning of actuators and position sensors (1-yr senior, 1-yr early career)
- Test and optimization of control system, creating user interface (1-yr senior, 3-yr early career)
- Characterizing spring blades (0.2-yr senior, 1-yr early career)
- Designing, order, and installing cryolink and cryobox (0.2-yr senior, 2-yr early career)
- Design, order, installing, and commissioning of inter-platform interferometer (1-yr senior, 3-yr early career)

# Tentative Timeline

(assuming that funds are available when needed)

| | 2024 | | 2025 | | 2026 | | 2027 | | 2028 | |
|---|---|---|---|---|---|---|---|---|---|---|
| Site preparation | ■ | ■ | | | | | | | | |
| Installation of sensors and actuators on mechanical platforms (surface) | | | ■ | ■ | | | | | | |
| Testing of real-time system (surface) | | | ■ | | | | | | | |
| Installation of vacuum system | | | | ■ | | | | | | |
| Installation of electronics rack | | | | ■ | | | | | | |
| Installation of platforms into vacuum system | | | | | ■ | | | | | |
| Commissioning of active seismic isolation system | | | | | | ■ | ■ | | | |
| Installation of environmental monitoring system | | | | | | ■ | ■ | | | |
| Installation of cryocooler, thermal link, cryobox | | | | | | ■ | | | | |
| Installation of inter-platform interferometer (IPF) | | | | | | | | ■ | | |
| Commissioning of IPF | | | | | | | | | ■ | ■ |