The World's First Underground Facility for Inter-platform Control and Seismic Isolation in Gravitational-Wave Detection

Coordinating Institutions: GSSI & INFN – LNGS

Collaborators & Technical Advisors

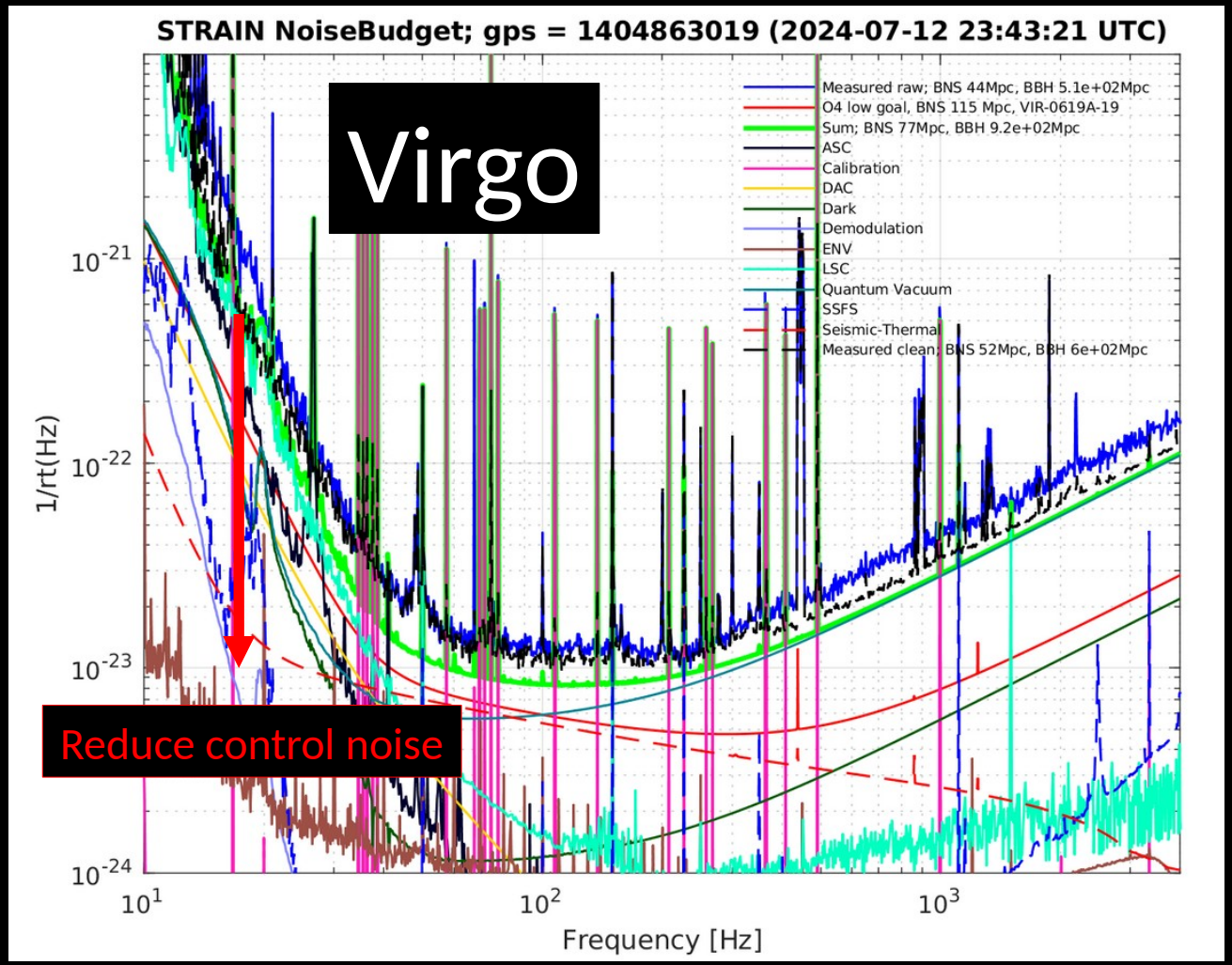
Tomislav Andric (GSSI), Carlo Bucci (INFN), Ilaria Caravella (GSSI), Daniele Cortis (INFN), Nicola D'Ambrosio (INFN), Massimiliano De Deo (INFN), Marco D'Incecco (INFN), Antonio Di Ludovico (INFN), Oliver Gerberding (University of Hamburg), Jan Harms (**PI**; GSSI), Jeff Kissel (LIGO Hanford), Alessandro 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)

Profile

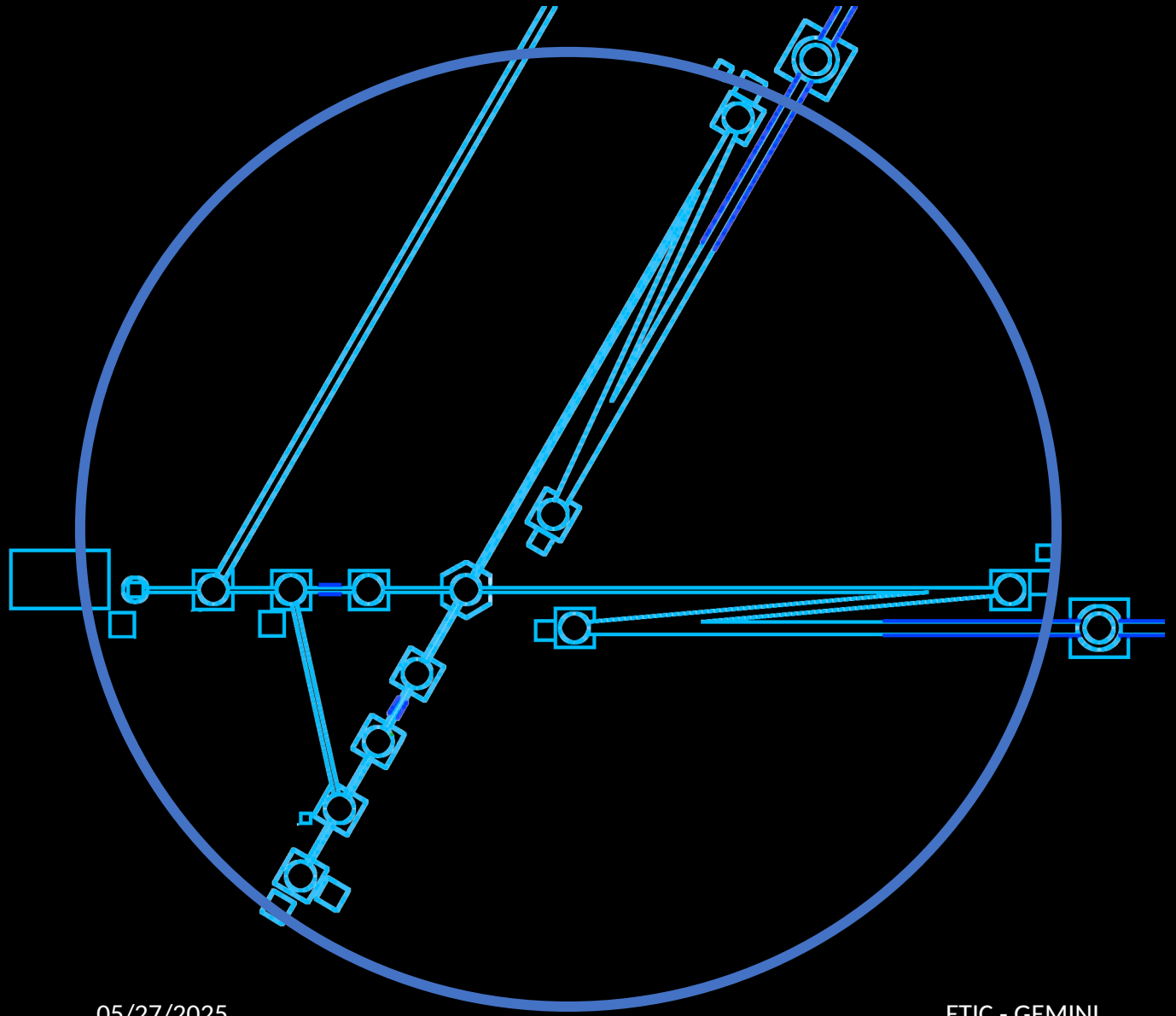
Scientific Focus:

- Development of vibration isolation and inter-platform control systems to support auxiliary DOF stabilization in ET
- Operation and validation of ultra-sensitive inertial sensors in a low-noise underground environment (LNGS)
- Platform for room-temperature and cryogenic testing of next-generation seismometers
- Deployment of a comprehensive underground environmental monitoring system
- Two operation modes:
  - ET Mode: Demonstrate control architecture for ET-LF auxiliary systems
  - LGWA Mode: Emulate lunar seismic and thermal environment for Moon-bound technologies

Scientific Goal 1: ET

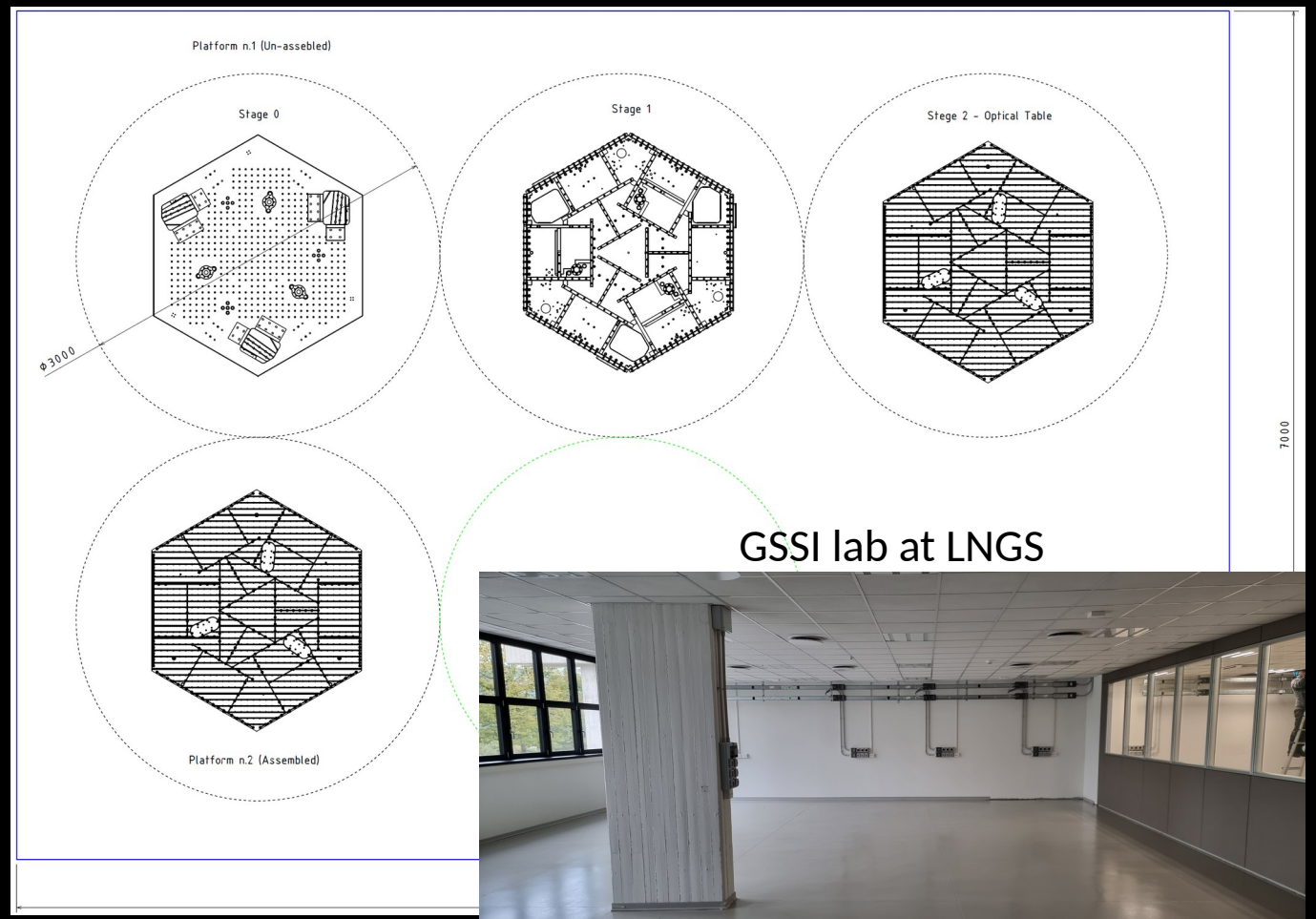


- Noise introduced by the control of length and alignment DOFs can limit LF sensitivity
- Develop an inter-platform motion control system to assist the ET length and alignment control of auxiliary degrees of freedom
- Lock all suspension platforms into a common motion across the full central vertex of an interferometer



- This enables stable control of auxiliary cavities
- Enable ET-LF science case
- Refer this optically rigid body to the two input masses

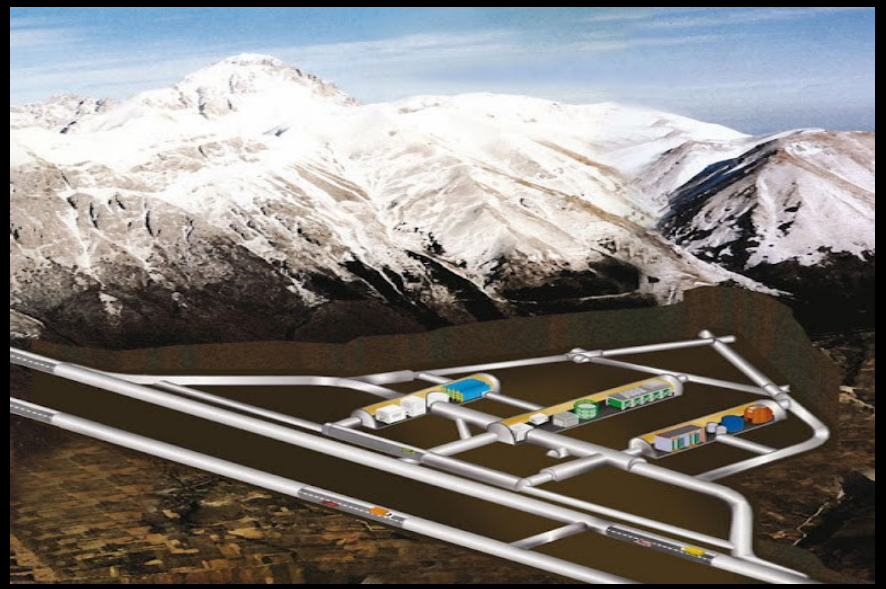
Surface Laboratory



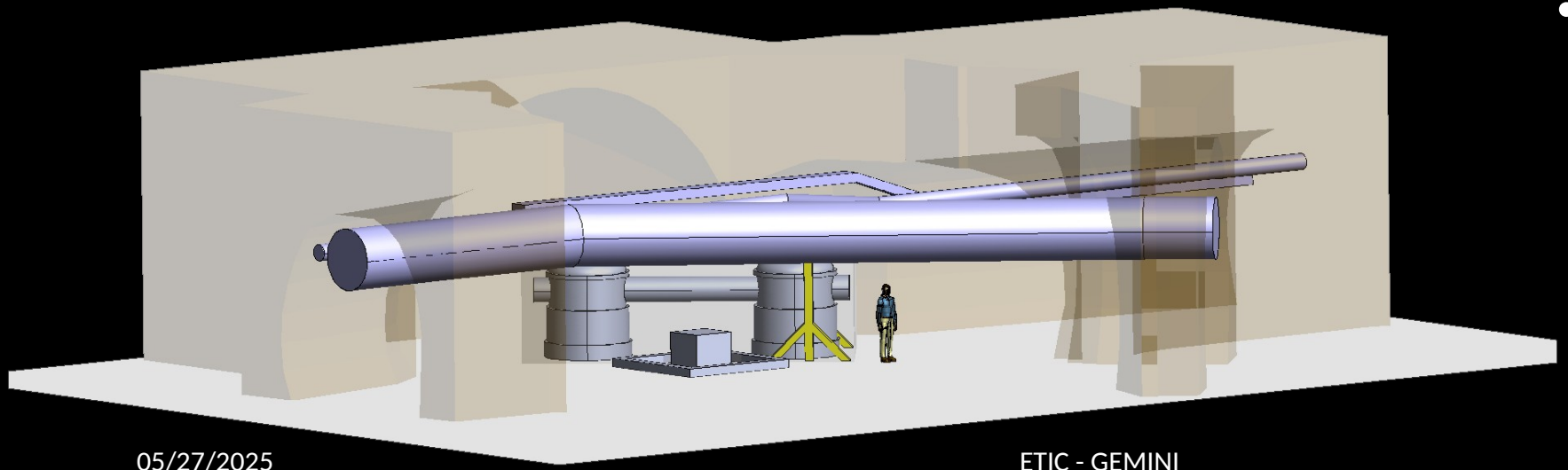
GSSI lab at LNGS

- 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

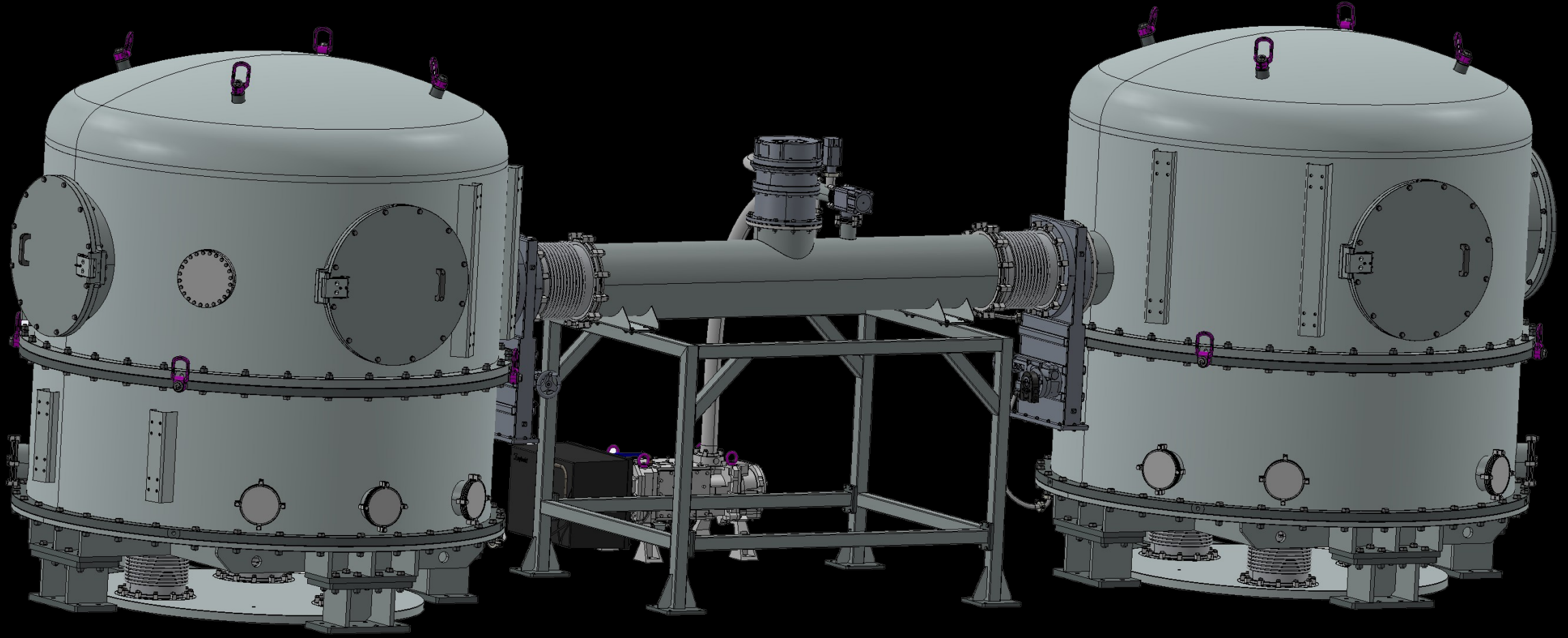


- Floor treatment
- Laminar-flow enclosures
- Lifting device for platforms and chamber segments
- Timing signal from surface
- Data transfer to server at the surface
- Preparation of the GEMINI hut: it will contain the control room and a room with clean environment to prepare installations into the GEMINI vacuum system



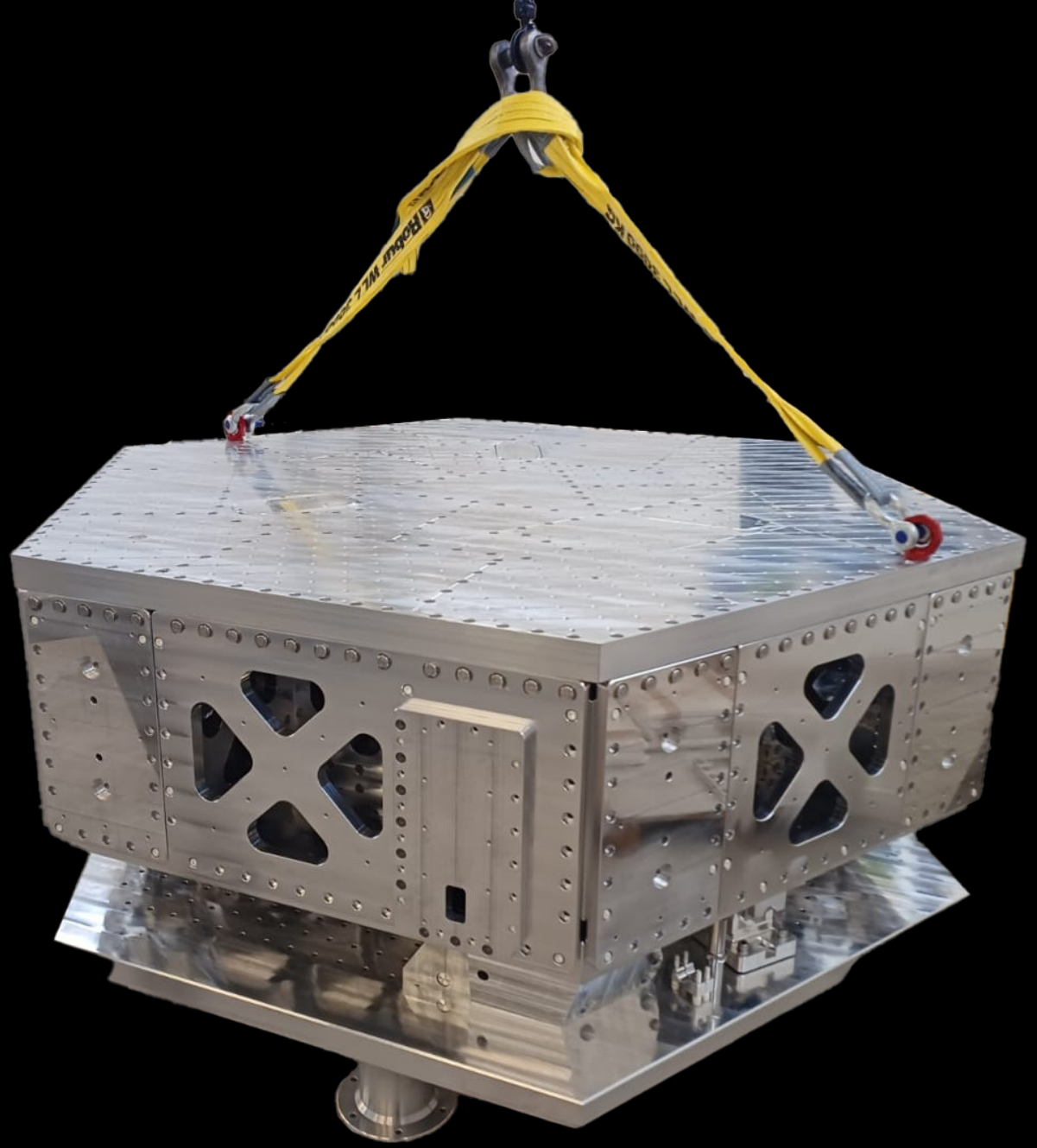
Vacuum System

Two chambers connected by vacuum pipe.
Tunnel entrance dimensions put strong limitations on chamber geometry.

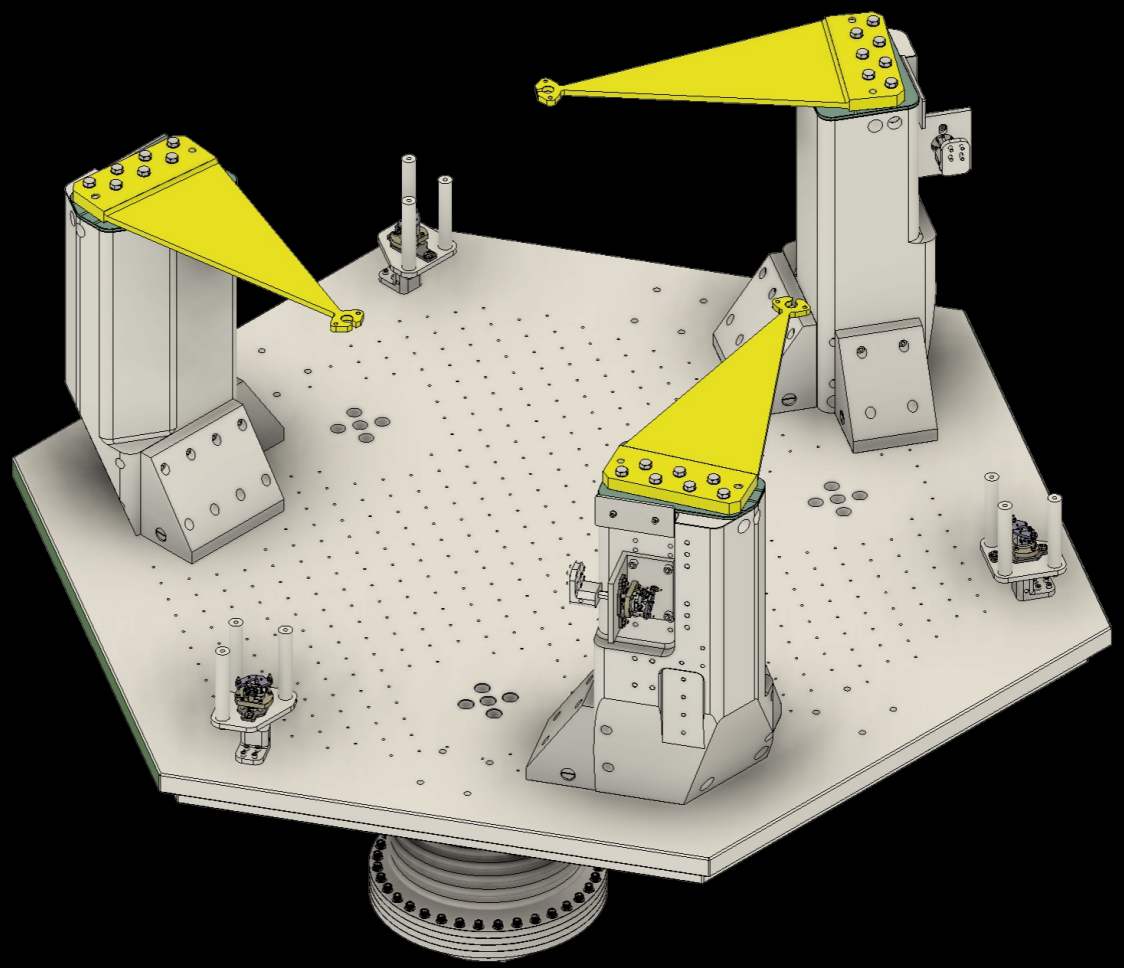


GEM-VCP

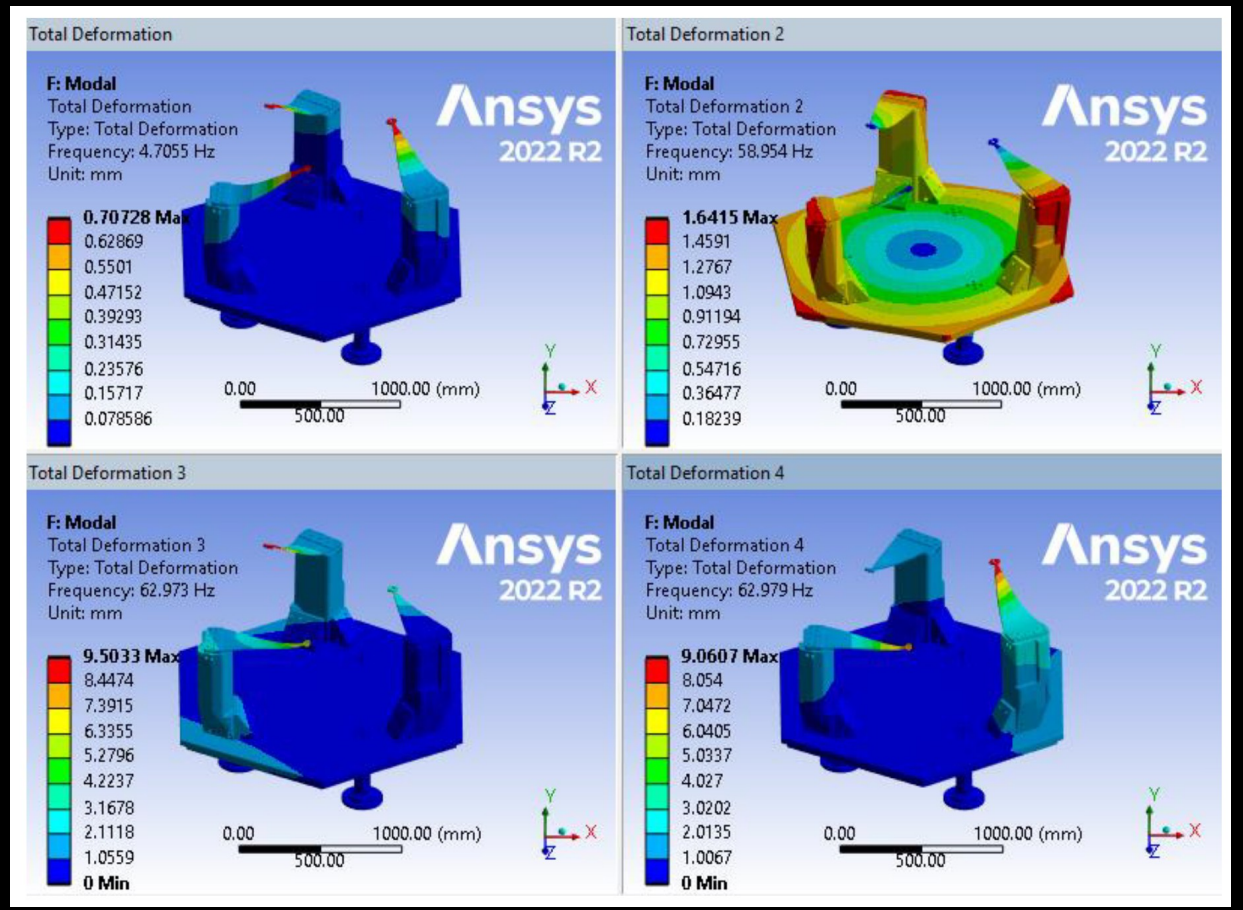
- GEMINI Vibration-control Platform
  - Starting point of the design: LIGO HAM-ISI - structural adjustments tailored for GEMINI's specific requirements.
  - Design modifications, vibration analysis, and executive drawings produced by LNGS mechanical engineers



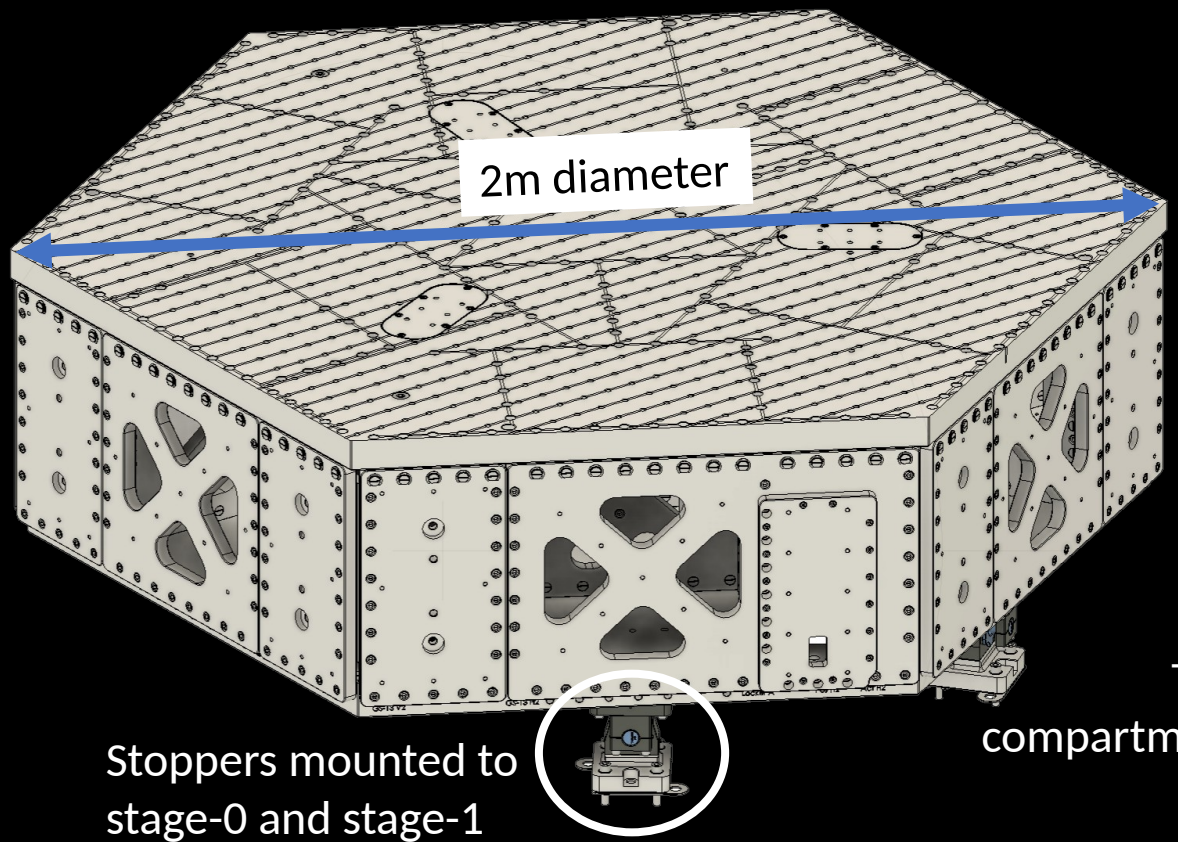
GEM-VCP: Stage 0

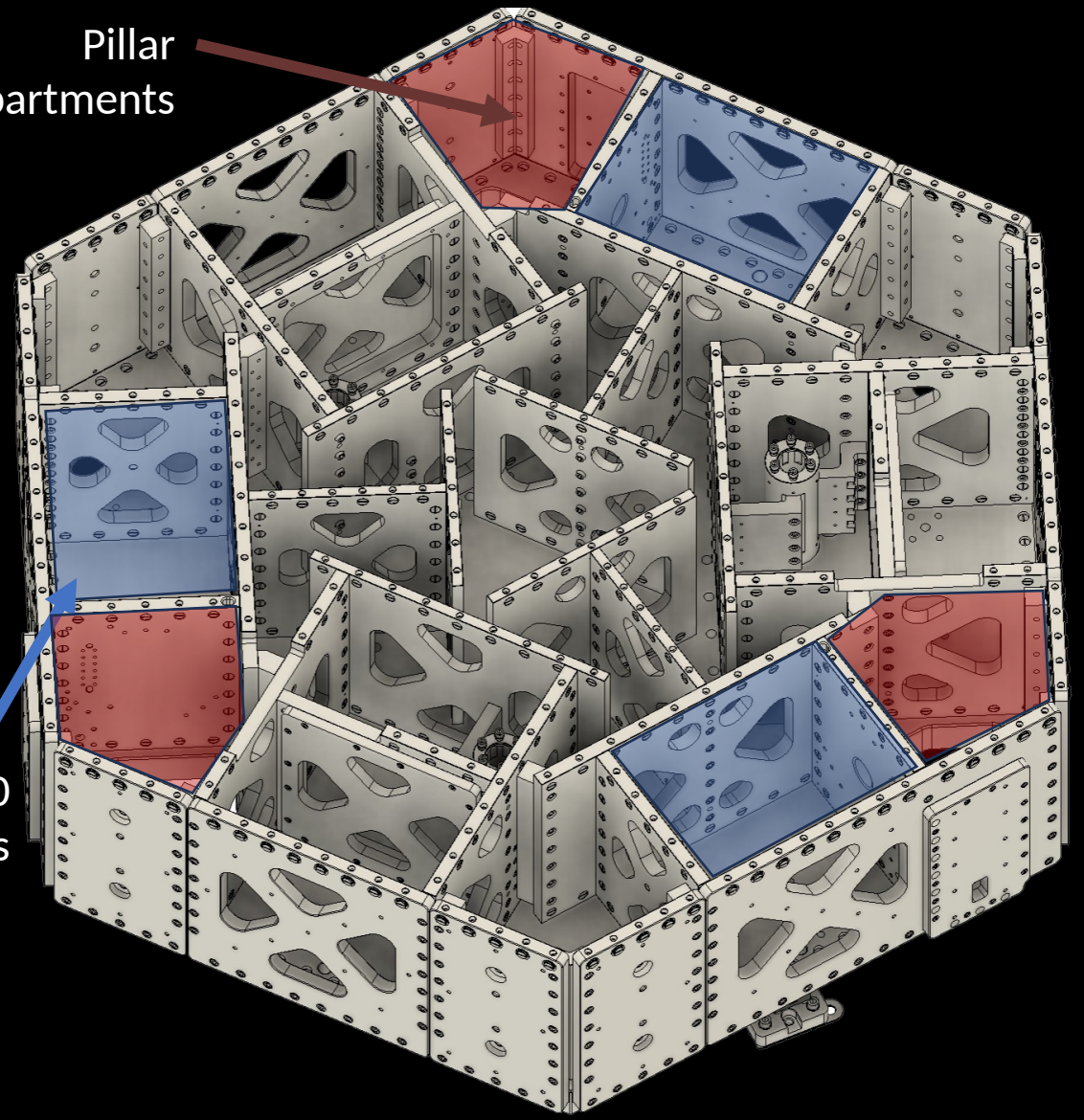


100Hz HAM-ISI (unconstrained)
70Hz GEM-VCP (under load)



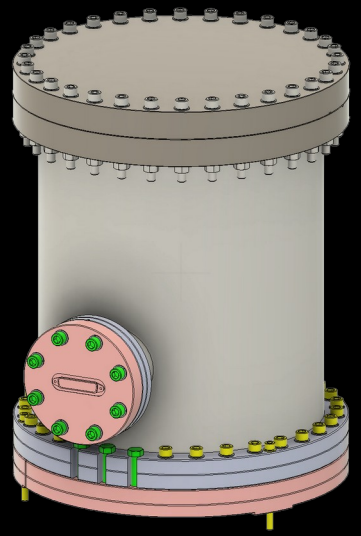
GEM-VCP: Stage 1



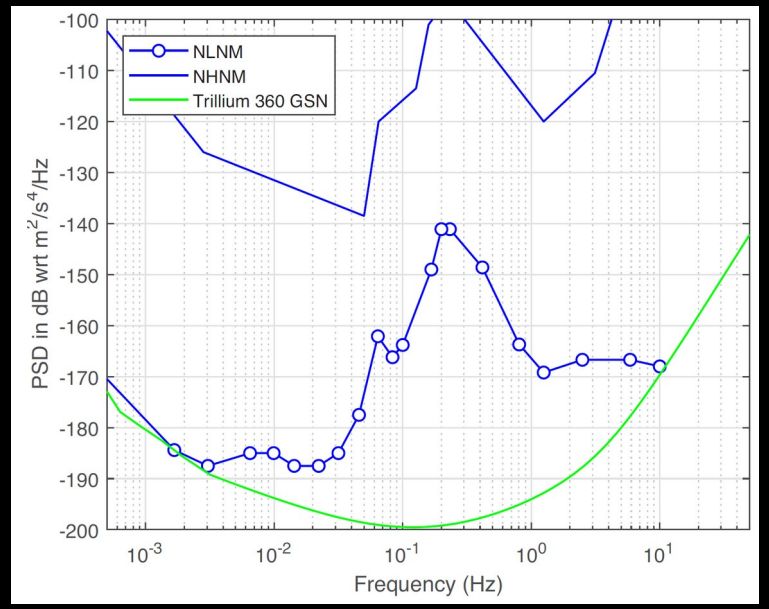


Inertial Sensing

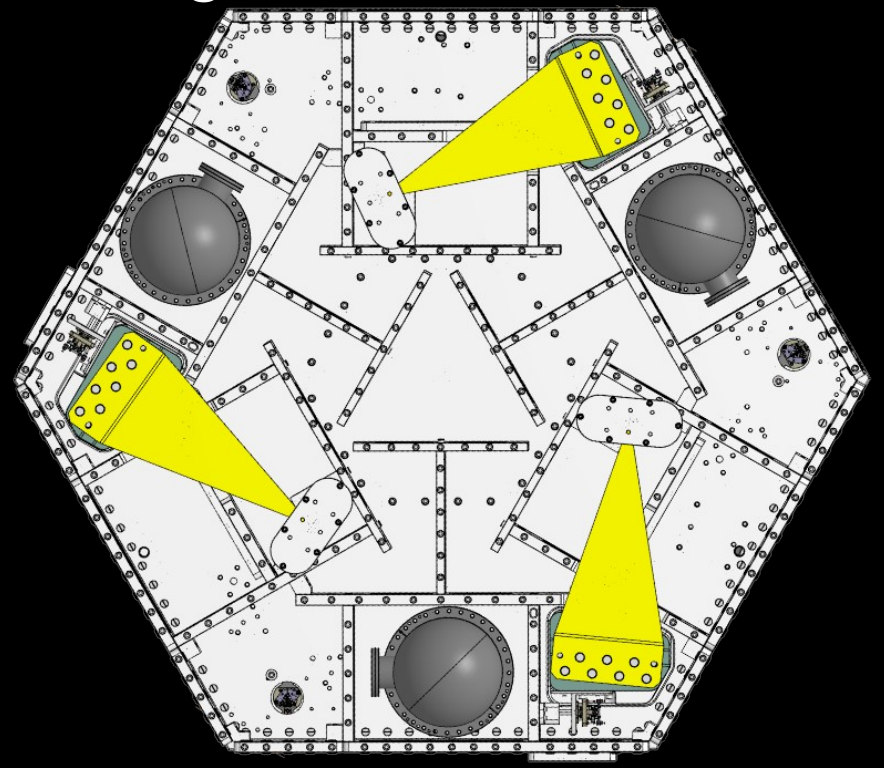
Vacuum pods



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



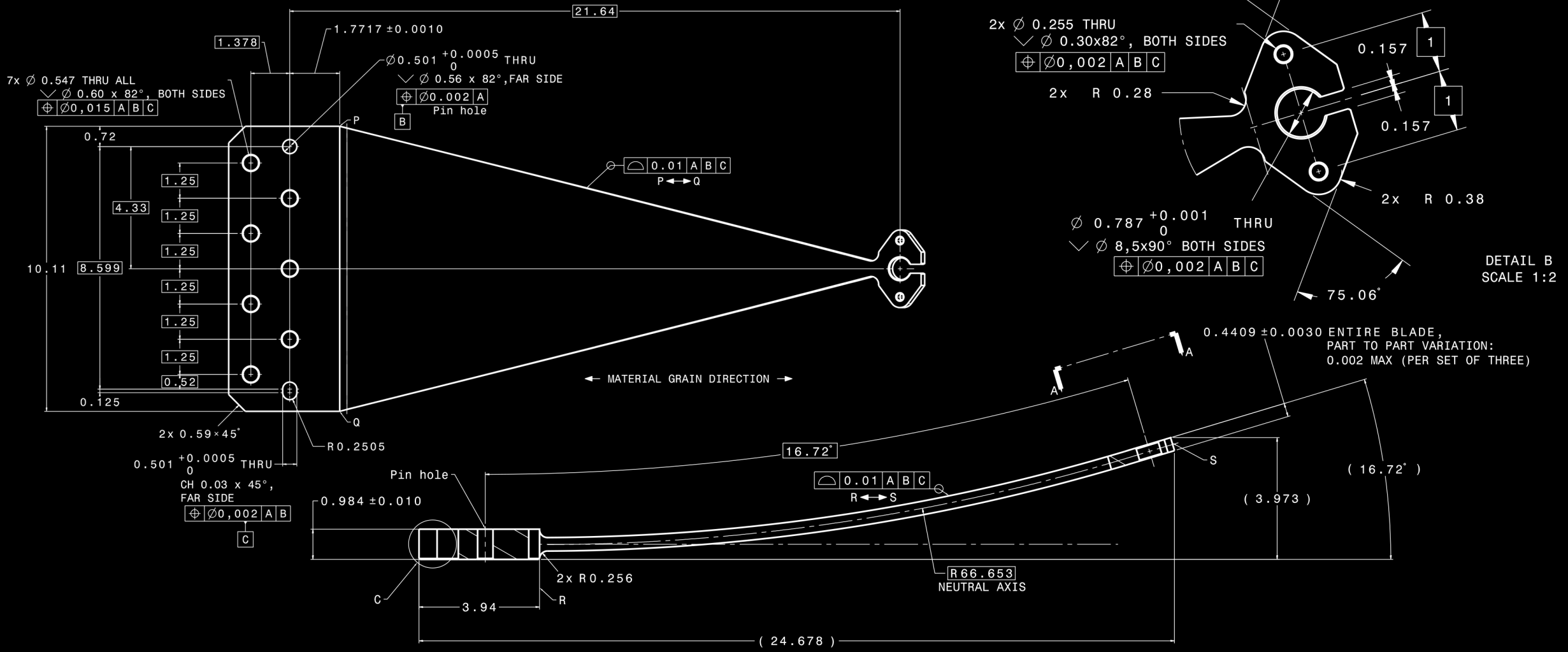
Integration in GEM-VCP



Spring Blades

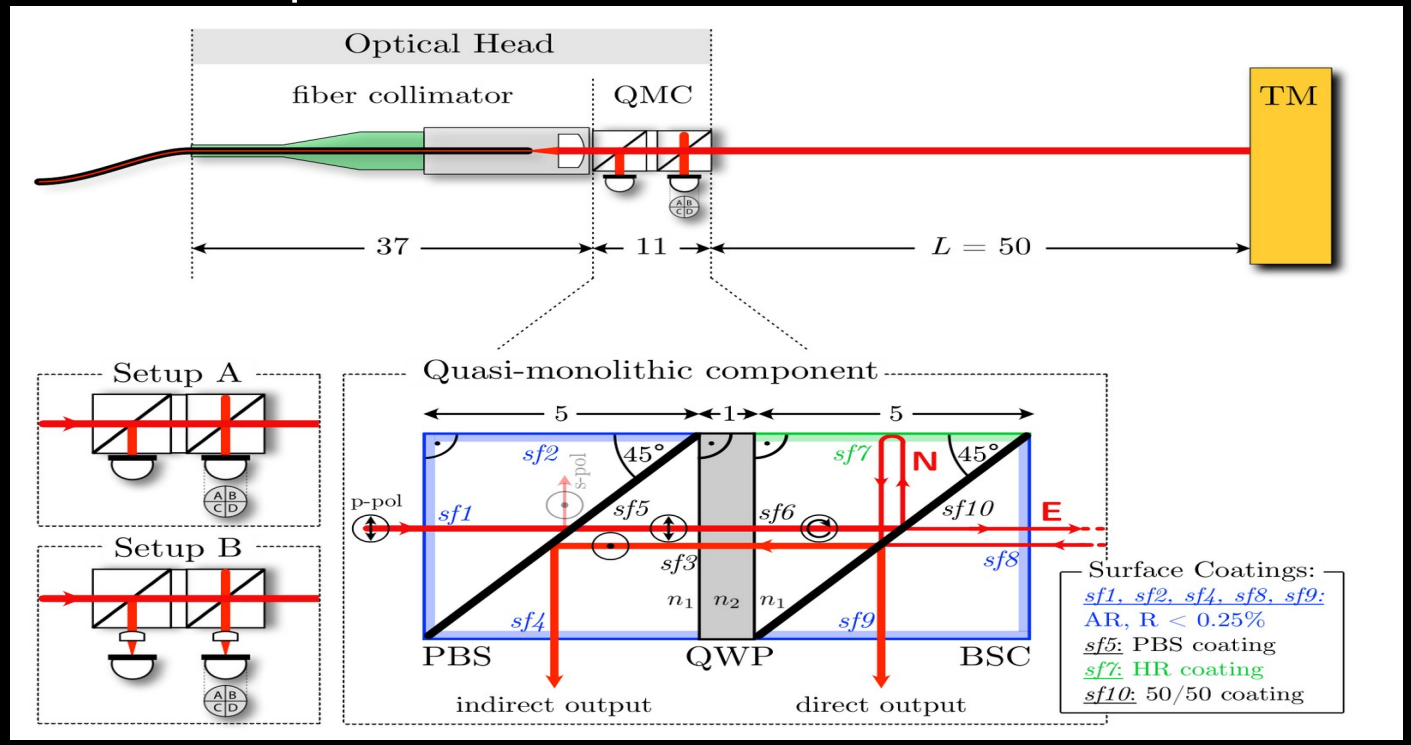
Ti-19 meets design specs (strength, fatigue, stability) for supporting the load

Full-load test still needed to validate mechanical performance before integration



Position Sensing: COBRI

COmpact Balanced Readout Interferometer - COBRI

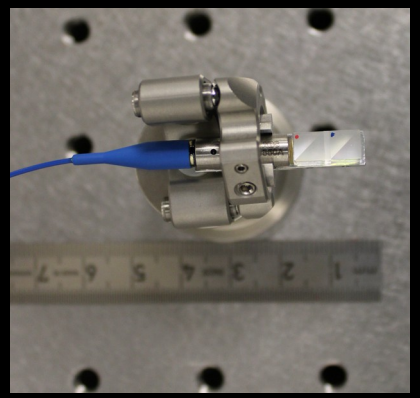


- Required for platform alignment and positioning
- Utilized together with inertial sensing

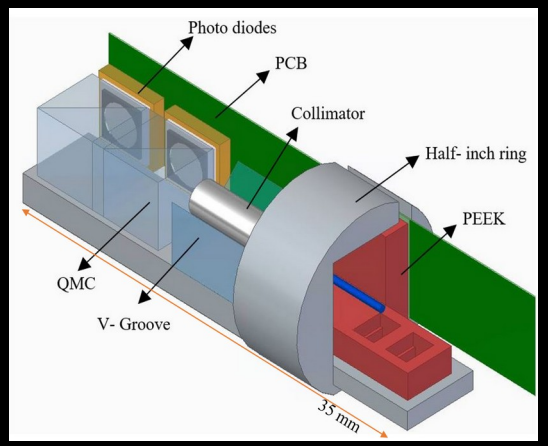
- On-axis design with quasi-monolithic component
  Positive:
  - no misalignment in vacuum
  - Large linear range (several centimeters)

  Negative:
  - On-axis ghost beams cause nonlinearity

O. Gerberding, K.-S. Isleif Sensors 2021, 21(5), 1708



v2 design



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	

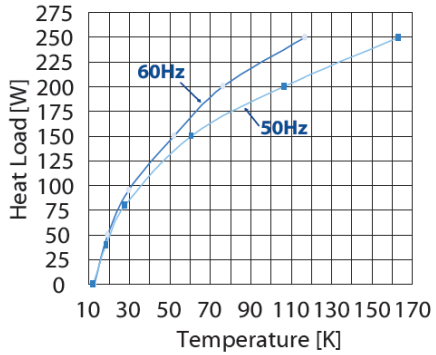
Standard Scope of Supply

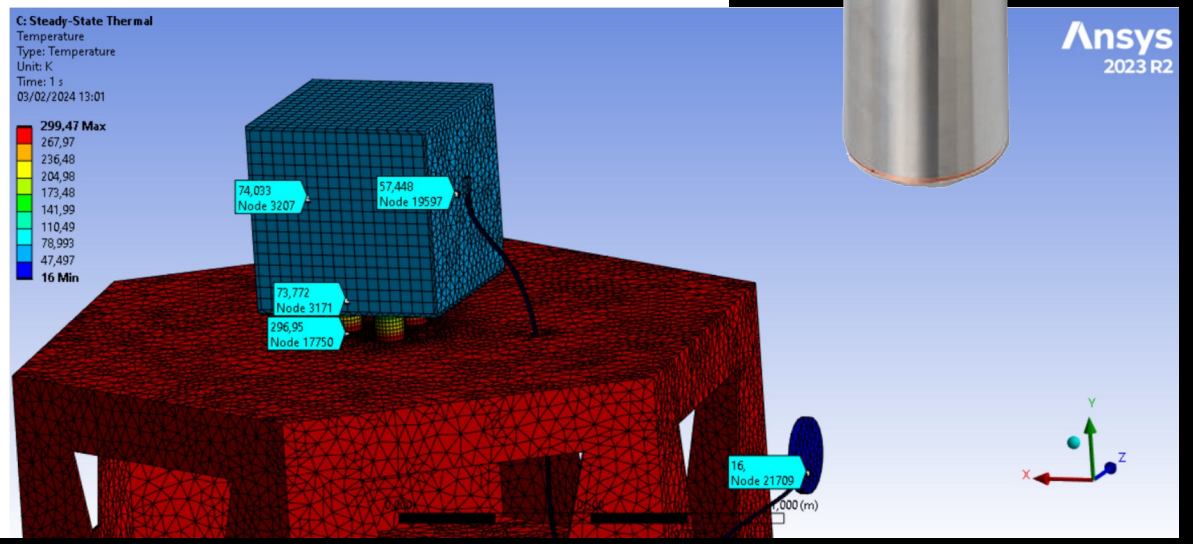
- RDK-500B2 Cold Head
- F-70LP/H Compressor
- Helium Gas Lines – 20 m (66 ft.)
- Cold Head Cable – 20 m (66 ft.)
- Power Cable – 5 m (16.5 ft.)
- Tool Kit

[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

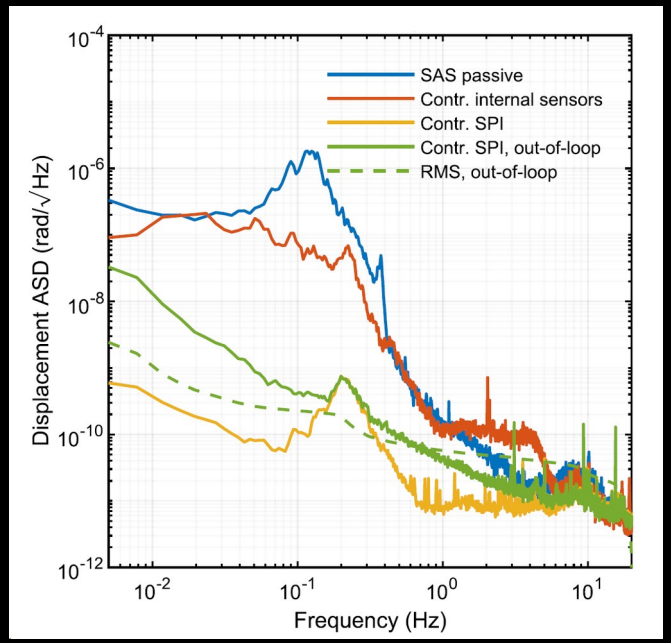


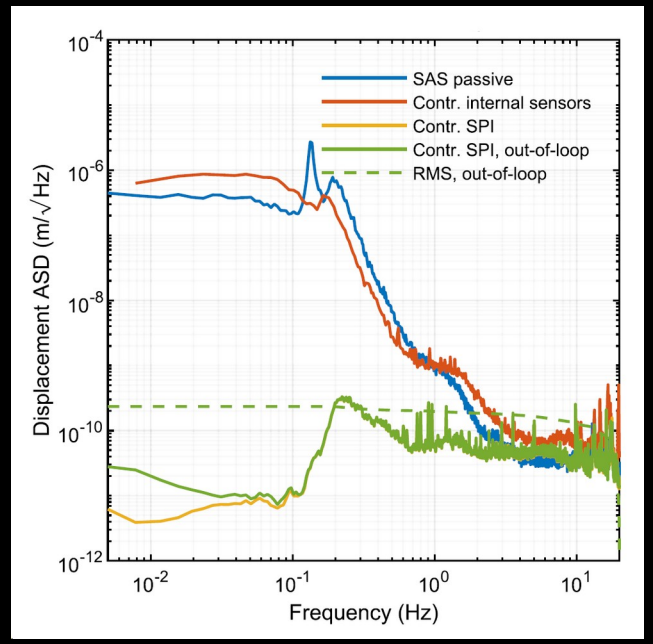


Thermal link design: Minimizing the length of the flexible braided copper section is essential

Suspension-platform Interferometer (SPI)

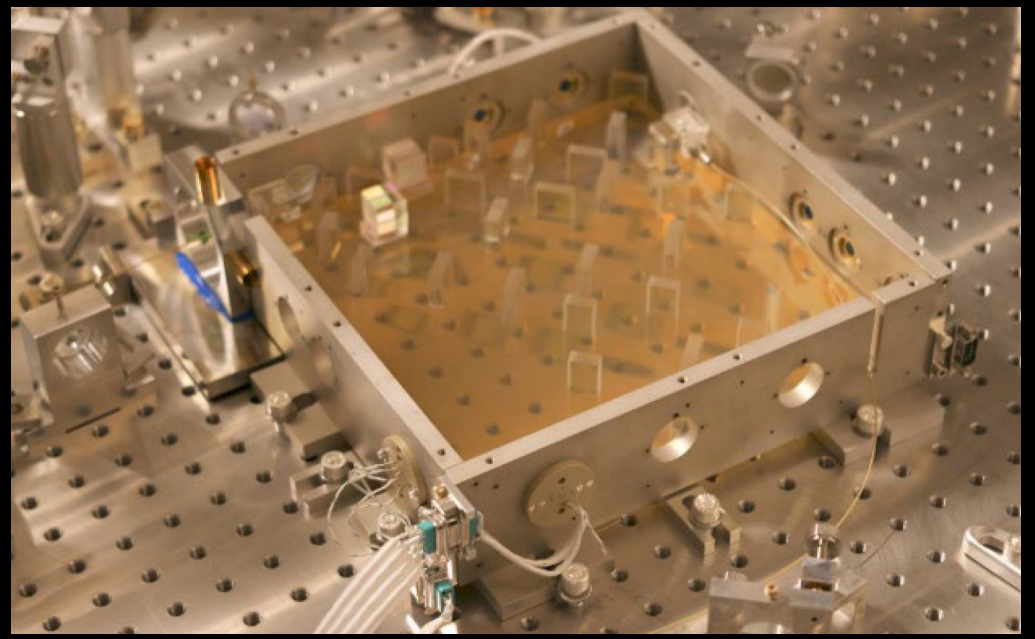
Inter-platform sensing and control to reduce relative motion between platforms (displacement and angular)



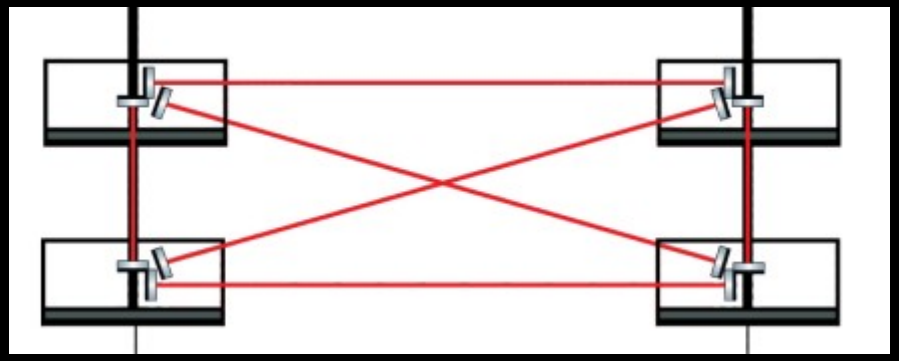


Koehlenbeck et al (2023)

SPI optical assembly



Koehlenbeck et al (2023)

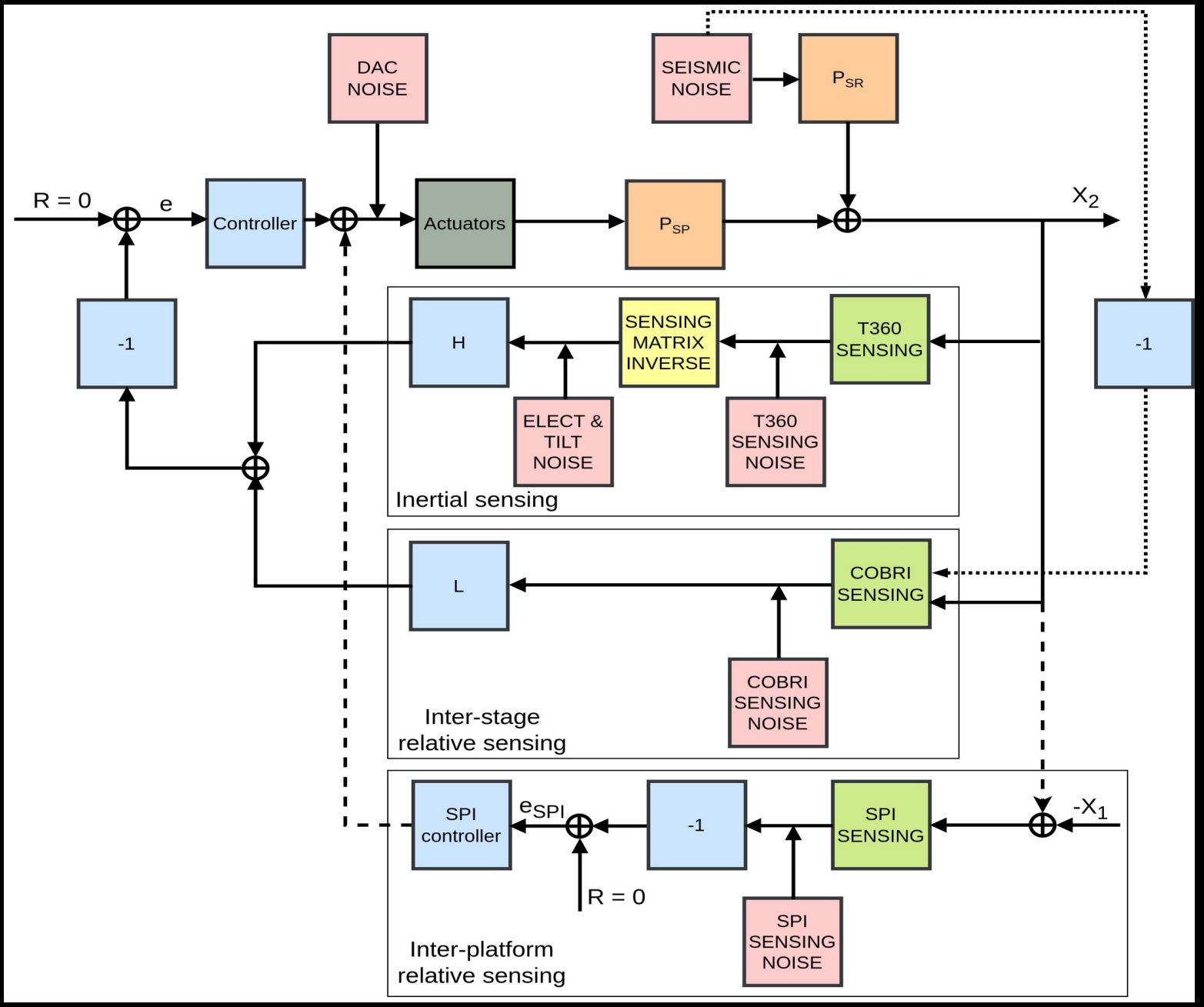


Harms et al (2013)

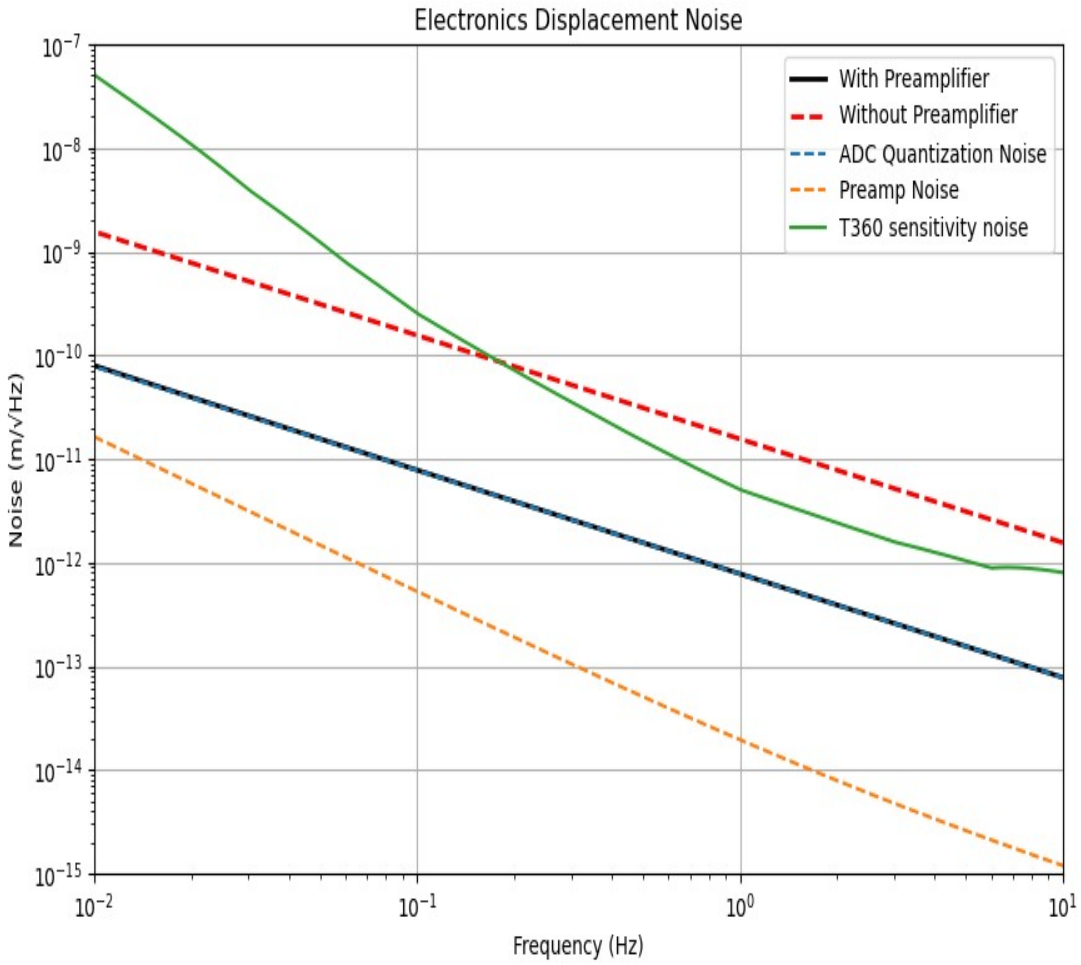
Optical Rigid Body concept using a network of interferometric cavities between stage-0 and stage-1 of both suspended platforms

Multi-cavity topology allows us to measure and suppress all 6 differential DOFs enforcing quasi-rigid motion across platforms

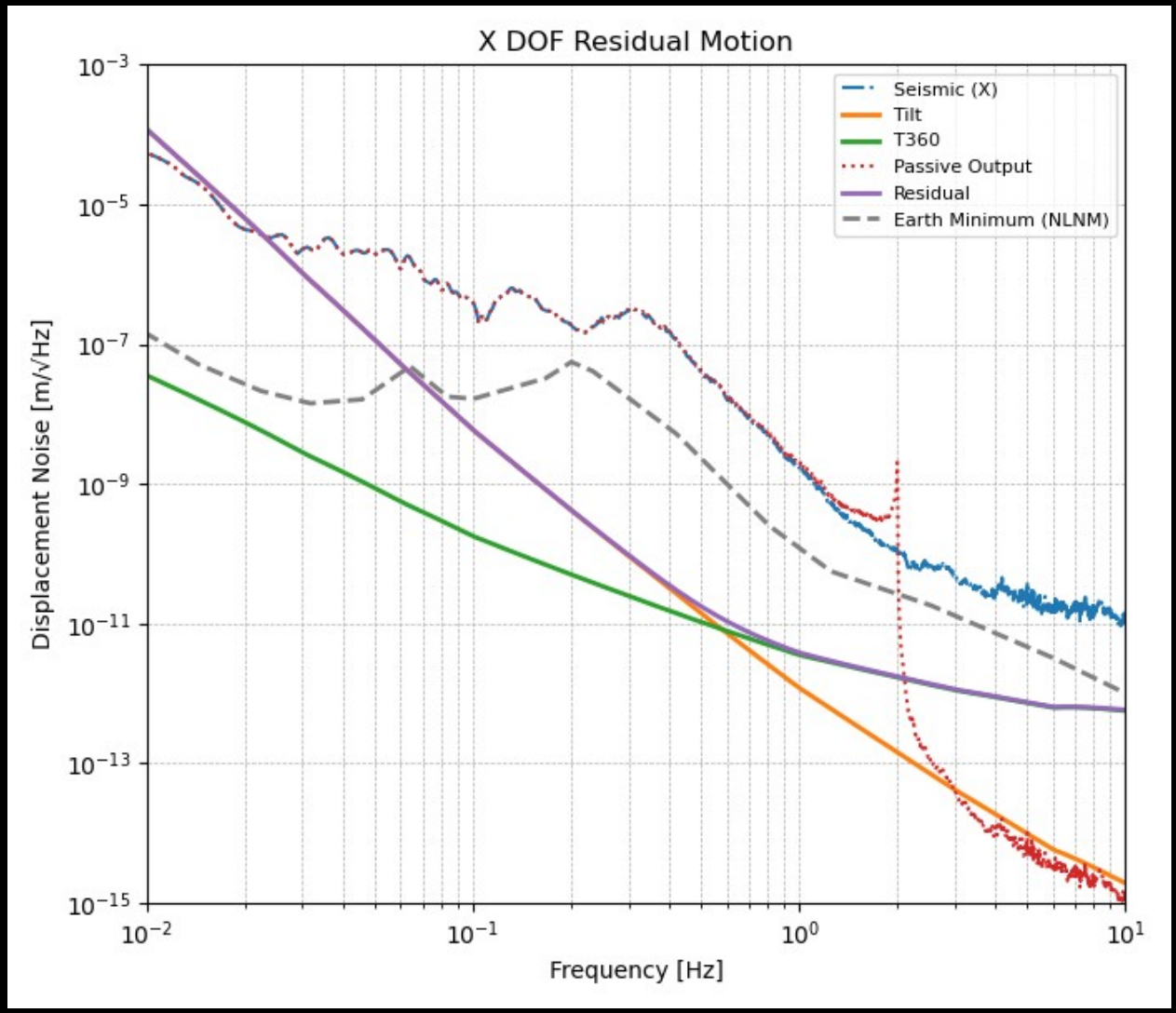
Simulations



Simulations

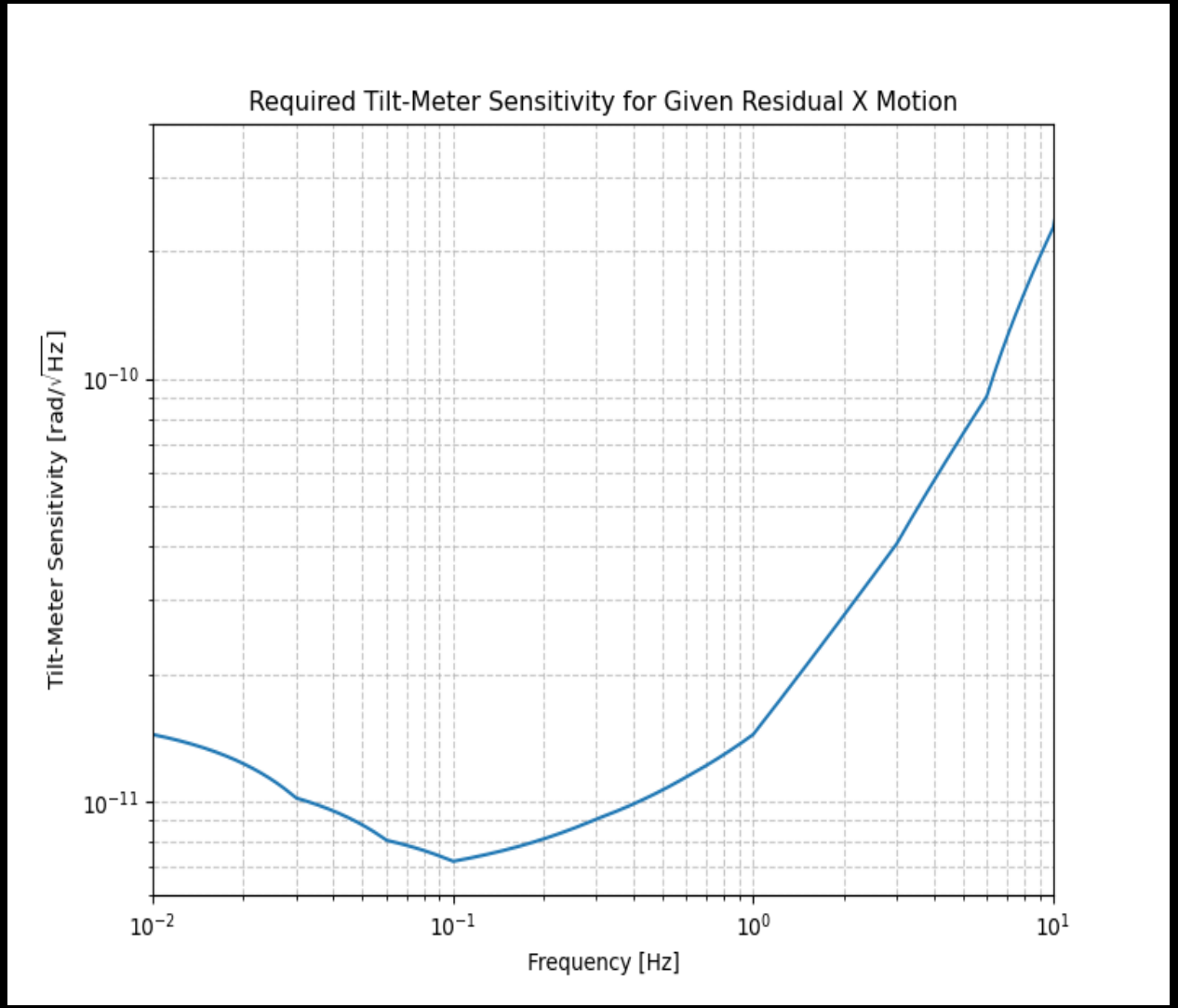


a) Electronics displacement noise

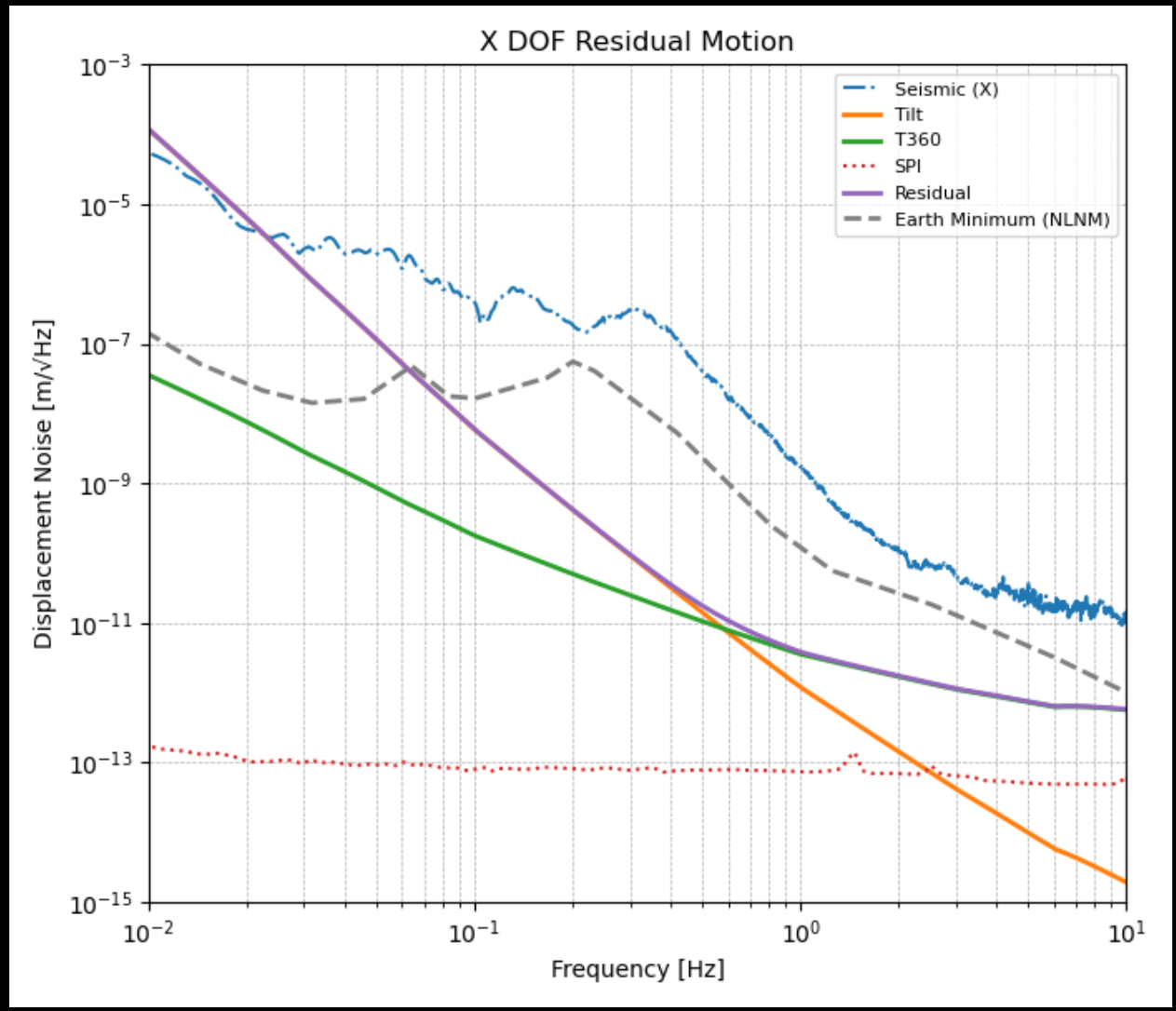


b) Leader platform residual motion

Simulations



c) Required tilt-meter sensitivity



d) Follower platform residual motion

Simulations

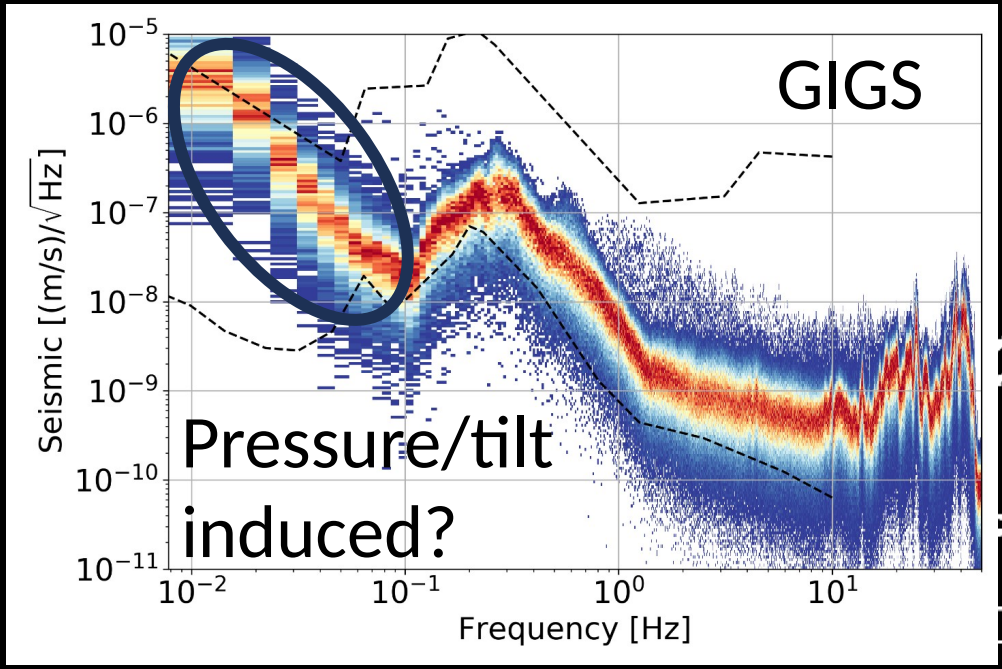
GEMINI: The World's First Underground Facility for Interplatform Control and Seismic Isolation in Gravitational-Wave Detection

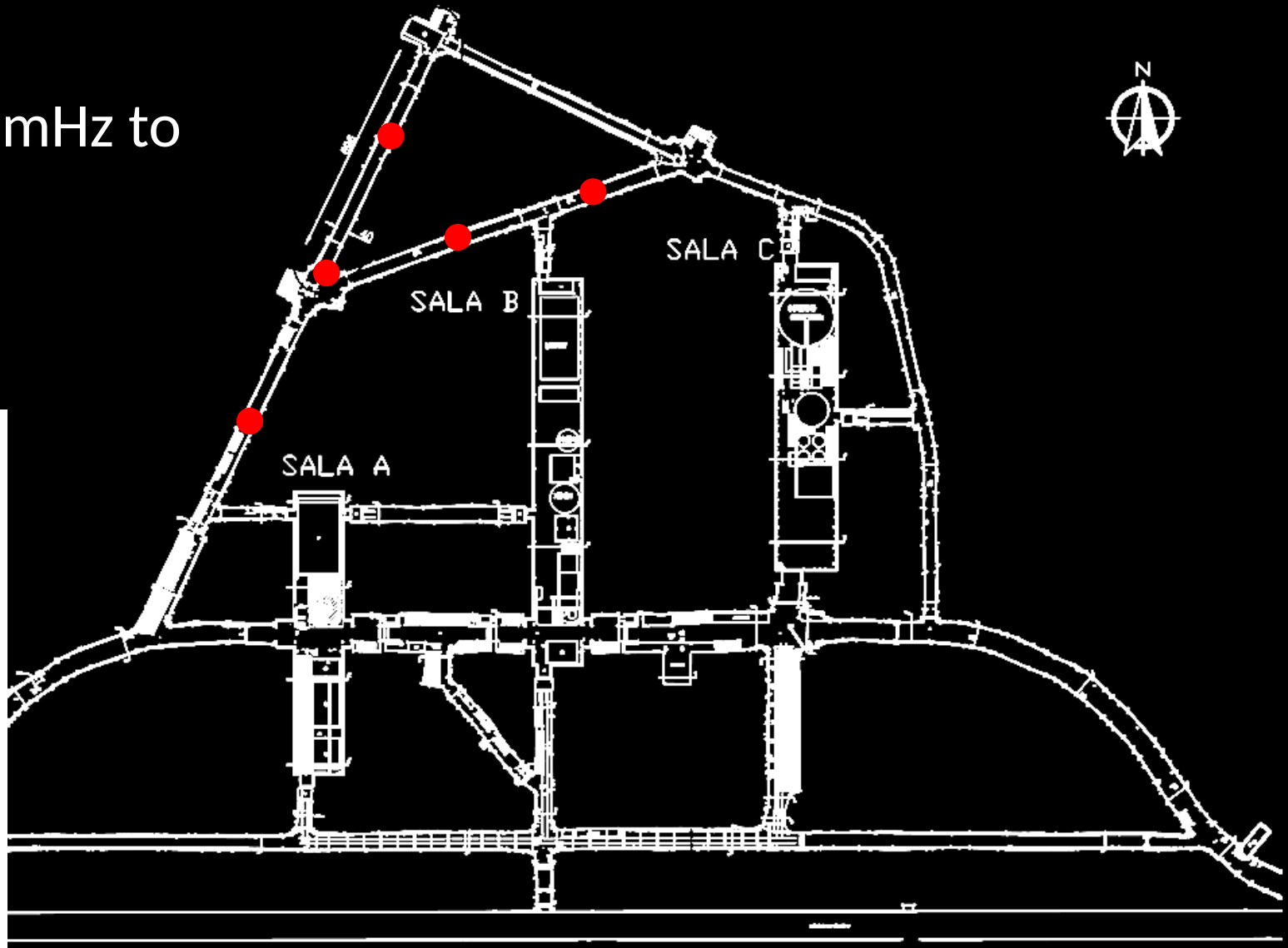
Abstract

GEMINI is an underground research and development facility dedicated to advancing seismic isolation and control technologies for future gravitational-wave observatories, including the Einstein Telescope (ET) and the Lunar Gravitational-Wave Antenna (LGWA). This paper presents the technical design and theoretical framework of GEMINI's active seismic isolation platforms, including detailed noise budget analyses, performance predictions, and residual platform motion evaluations. The GEMINI platforms are designed to achieve unprecedented vibration isolation, targeting residual motion levels across the 1 mHz to 10 Hz frequency band, making them the quietest platforms of their kind. In the context of ET, GEMINI will enable the development and validation of inter-platform control strategies essential for the stabilization of auxiliary degrees of freedom in the interferometer's central

Environmental Monitoring System

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





Tentative Timeline

	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				