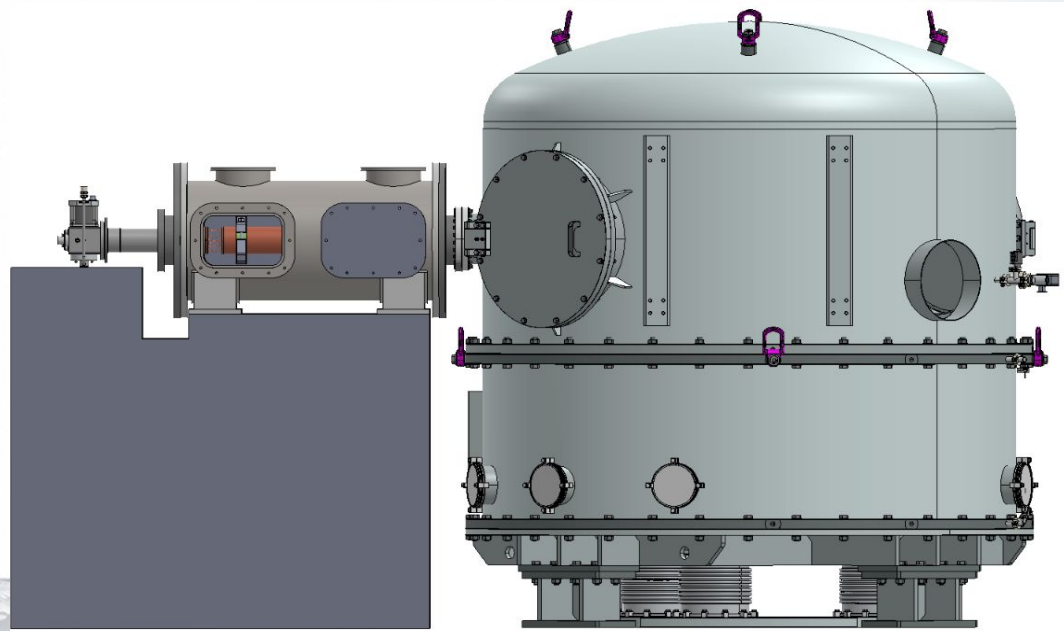
DEVELOPMENT OF A MOON EMULATOR

for High-Precision Testing of Lunar Accelerometers Operating Under Cryogenic Conditions

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PROJECT SCOPE

OBJECTIVE

Develop a Moon Emulator for high-precision testing of lunar accelerometers under controlled vacuum and cryogenic conditions.

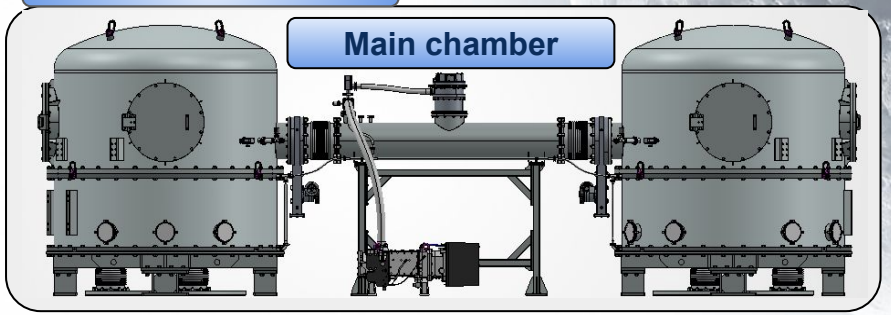
CURRENT FOCUS

Design and integration of the cryogenic subsystem with the existing GEMINI vacuum infrastructure.

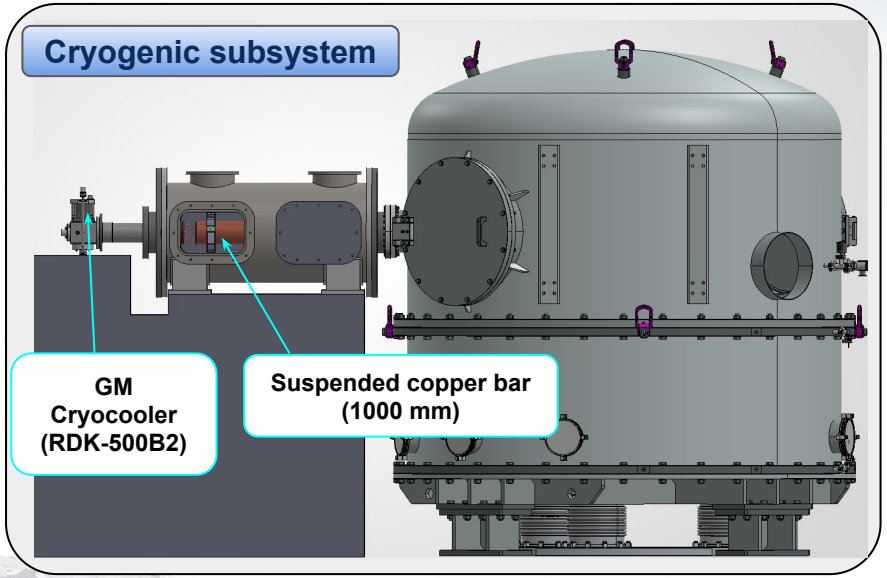
GEMINI CONTEXT

- Existing vacuum-chamber infrastructure
- Cryogenic sensor-test environment
- Integration interface for the Moon Emulator

GEMINI Infrastructure



Cryogenic subsystem



MOON EMULATOR: DESIGN REQUIREMENTS

Key requirements for a stable, cryogenic, low-vibration and vacuum-compatible test environment

LOW-VIBRATION ENVIRONMENT

- Suitable for high-performance lunar seismometer / inertial sensor testing
- Minimize vibration transmission from cryocooler and auxiliary systems
- Compatible with GEMINI vibration-control platform

CRYOGENIC ENVIRONMENT

- Target environment: **~40 K**
- Cryocooler-based cooling (e.g. RDK-500B2)
- Efficient thermal link to the cooled test region
- Stable and uniform cryogenic conditions in the sensor area

THERMAL PERFORMANCE

- Efficient heat extraction from test region
- Minimize parasitic heat loads (conduction, radiation, cables)
- Control temperature gradients
- Provide stable cryogenic test environment for duration of experiments

VACUUM ENVIRONMENT

- Operation inside GEMINI vacuum system
- Maintain required vacuum level (< 10^{-7} Torr as per GEMINI specification)
- Use vacuum-compatible materials, components and seals
- Minimize outgassing and leaks

GEMINI INTEGRATION

- Integrate cryobox, cryocooler and thermal link with existing GEMINI setup
- Compatible mechanical and vacuum interfaces (e.g. flanges)
- Minimize modifications to the existing GEMINI chamber
- Allow assembly, access and maintenance
- Compatible with installation and transport constraints

MECHANICAL SUPPORT

- Support and align the suspended copper bar (Ø108 mm, 1000 mm)
- Provide a robust and stable support structure
- Accommodate thermal contraction
- Allow assembly, access and maintenance

Design objective: Stable ~40 K environment | High vacuum | Low vibration | Reliable GEMINI integration

MOON EMULATOR: DESIGN CONCEPT

Cryogenic subsystem architecture and integration with GEMINI

CRYOCOOLER (RDK-500B2)

- Provides cryogenic cooling
- Connected to the cryobox through the bellows
- External support reduces direct mechanical coupling

LAMINAR BELLOW

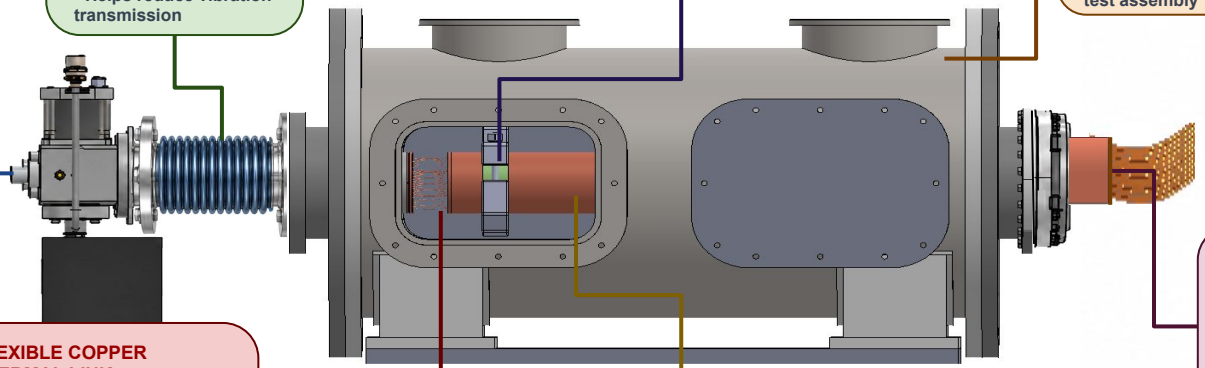
- Soft mechanical connection
- Provides flexibility between cryocooler and chamber
- Helps reduce vibration transmission

COPPER-BAR SUPPORTS

- Support and maintain bar alignment
- Accommodate thermal contraction
- Final suspension concept under development

CYLINDRICAL CRYOBOX

- Vacuum-compatible enclosure
- Houses copper bar and supports
- Houses the cryogenic test assembly



FLEXIBLE COPPER THERMAL LINK

- High thermal conductivity
- Connects cold head to copper bar
- Provides flexibility at the thermal interface

COPPER BAR

- Ø108 mm × 1000 mm
- Main thermal element
- Extends toward the GEMINI test region

GEMINI INTERFACE

- Mechanical and vacuum interface
- Connects Moon Emulator to GEMINI's test box with the copper links
- Minimizes modification of existing infrastructure

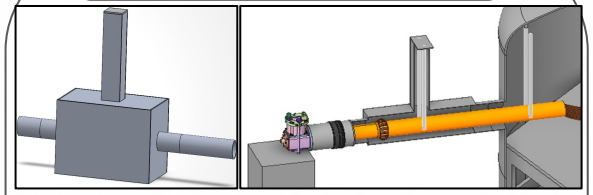
Functional Chain: GM Cryocooler → Laminar Bellows → Thermal Link → Copper Bar → GEMINI Test Region

DESIGN APPROACH: Locate the new cryogenic and support hardware outside the existing GEMINI main chamber, minimizing modifications to the existing infrastructure and simplifying integration and access.

DESIGN EVOLUTION & INTEGRATION STRATEGY

From initial concept to the current Moon Emulator design

INITIAL CONCEPT



- Rectangular cryobox concept
- Copper bar extending toward the GEMINI main chamber
- Preliminary arrangement of cryogenic components

Limitations Identified

⚠ **Rectangular geometry less suitable for external vacuum loading**

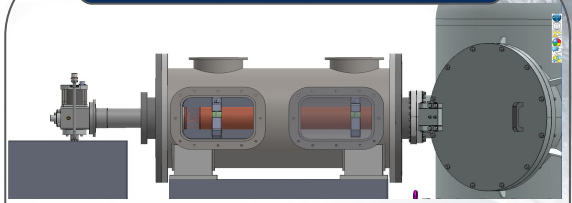
⚠ **Higher number of welded corners/joints increases fabrication complexity and potential leak paths**

⚠ **Integration inside the existing GEMINI main chamber would increase modification and access complexity**

KEY DESIGN DECISION

- Keep both copper-rod supports outside the GEMINI main chamber
- Minimize modifications to the existing GEMINI chamber
- Reduce integration risk and protect the main chamber integrity
- Improve accessibility of the support system for assembly and adjustment
- Simplify future maintenance and modifications
- Newly designed support hardware accessible outside the main chamber
- Fewer welded joints in the subsystem reduce potential leak paths

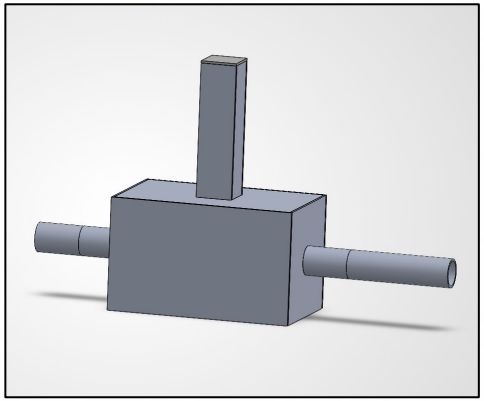
CURRENT CONCEPT

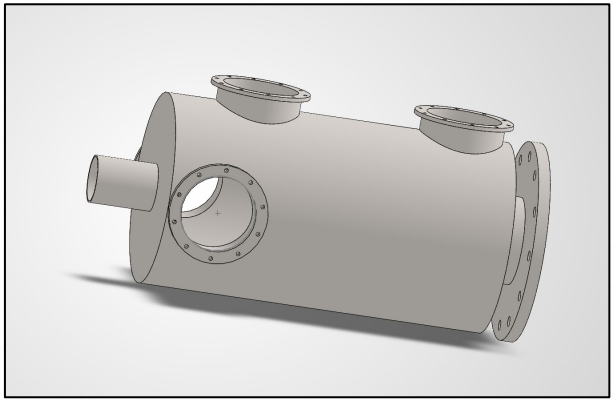


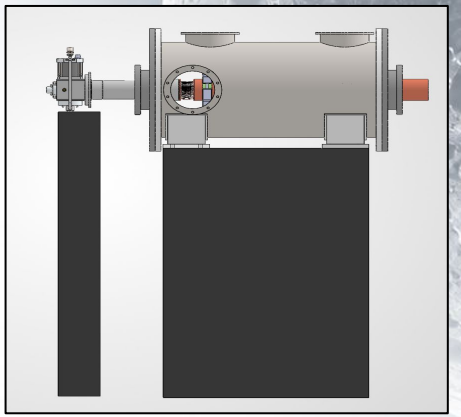
- Cylindrical stainless-steel cryobox
- Both copper-bar supports located within the external cryobox
- Copper bar extends toward the GEMINI test region
- Cryocooler integrated on the opposite side
- Easier access to newly designed components
- Reduced modifications to the existing GEMINI main chamber

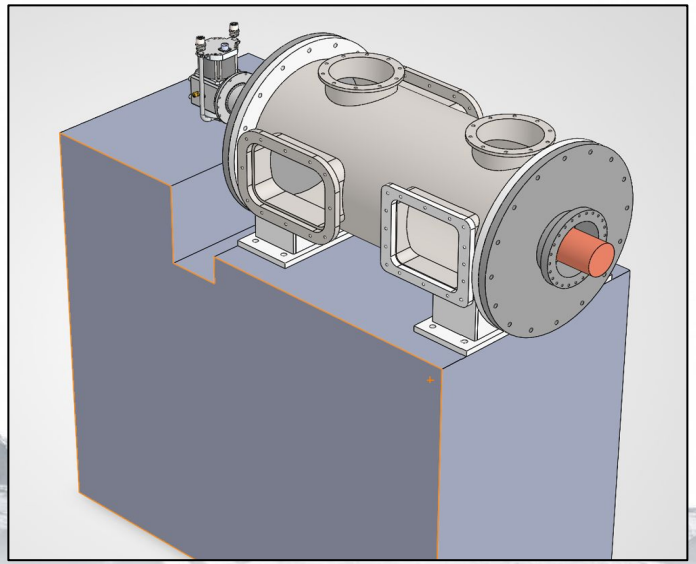
OUTCOME

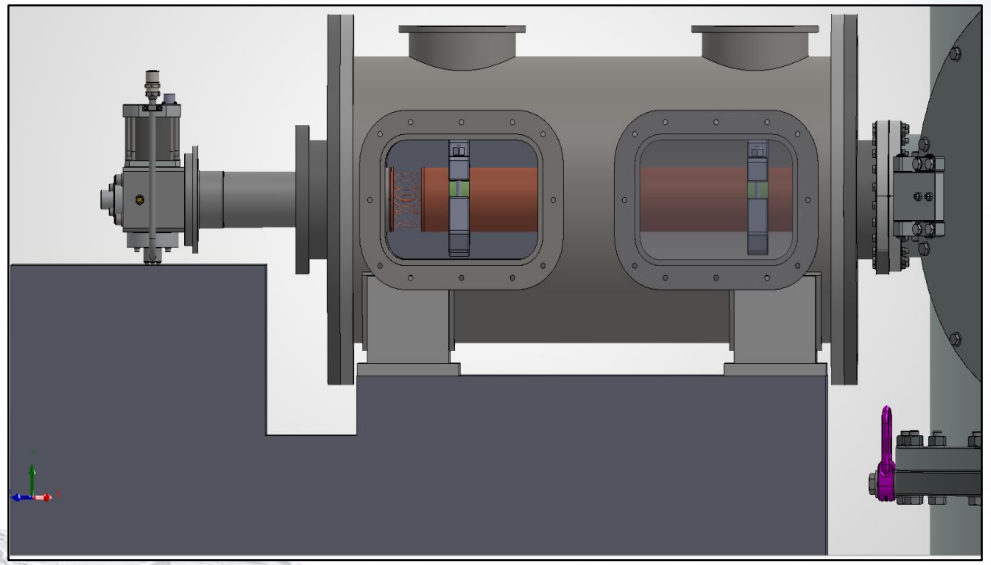
A more accessible and integration-friendly design with reduced intervention on the existing GEMINI chamber.





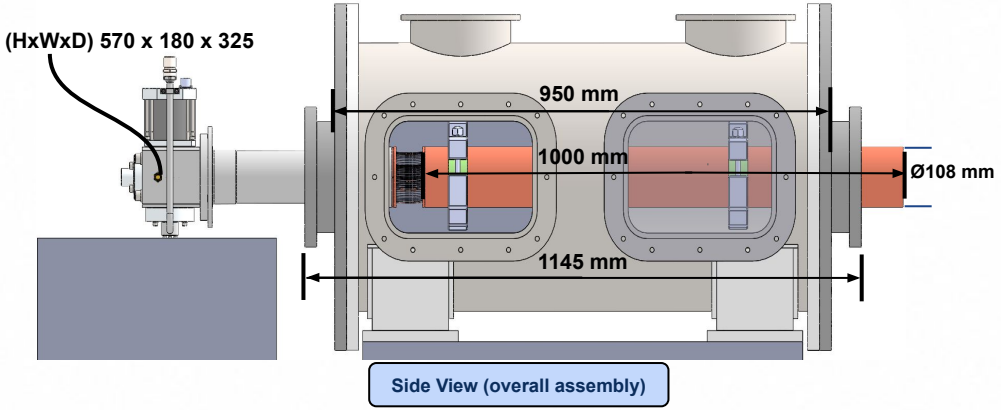




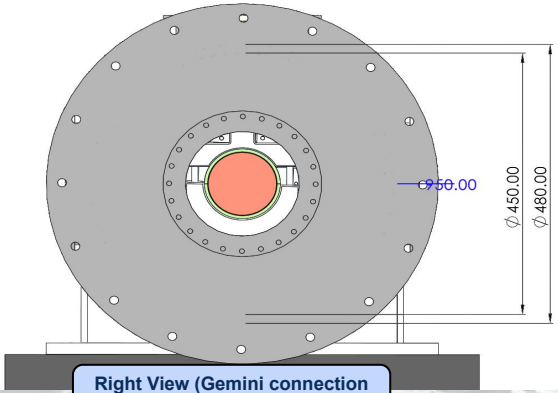


CURRENT CRYOBOX: MECHANICAL DESIGN

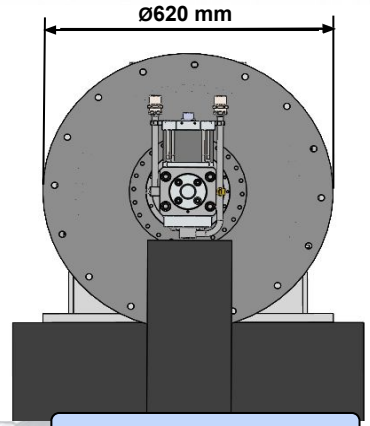
Current geometry and principal mechanical parameters



Side View (overall assembly)



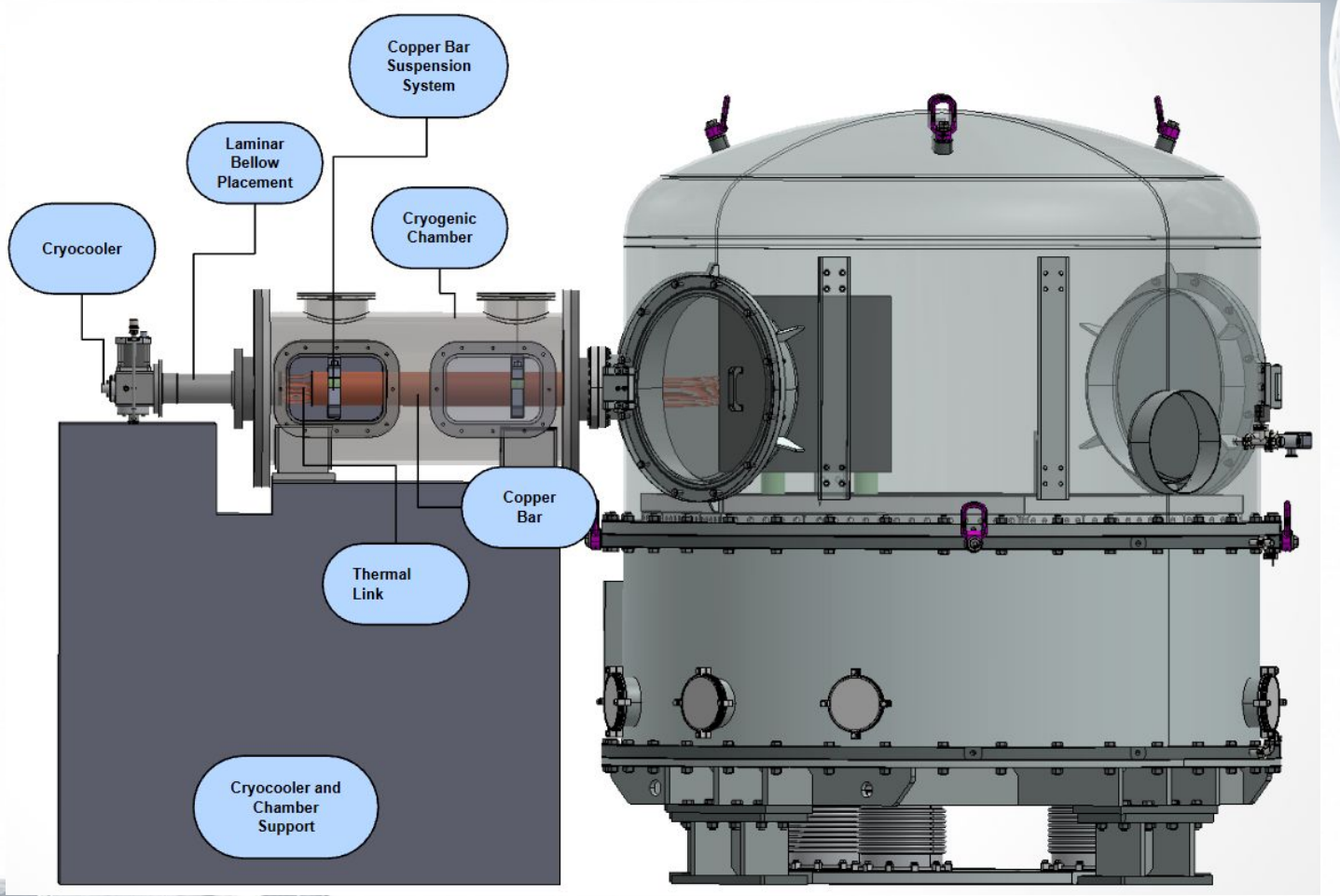
Right View (Gemini connection side)

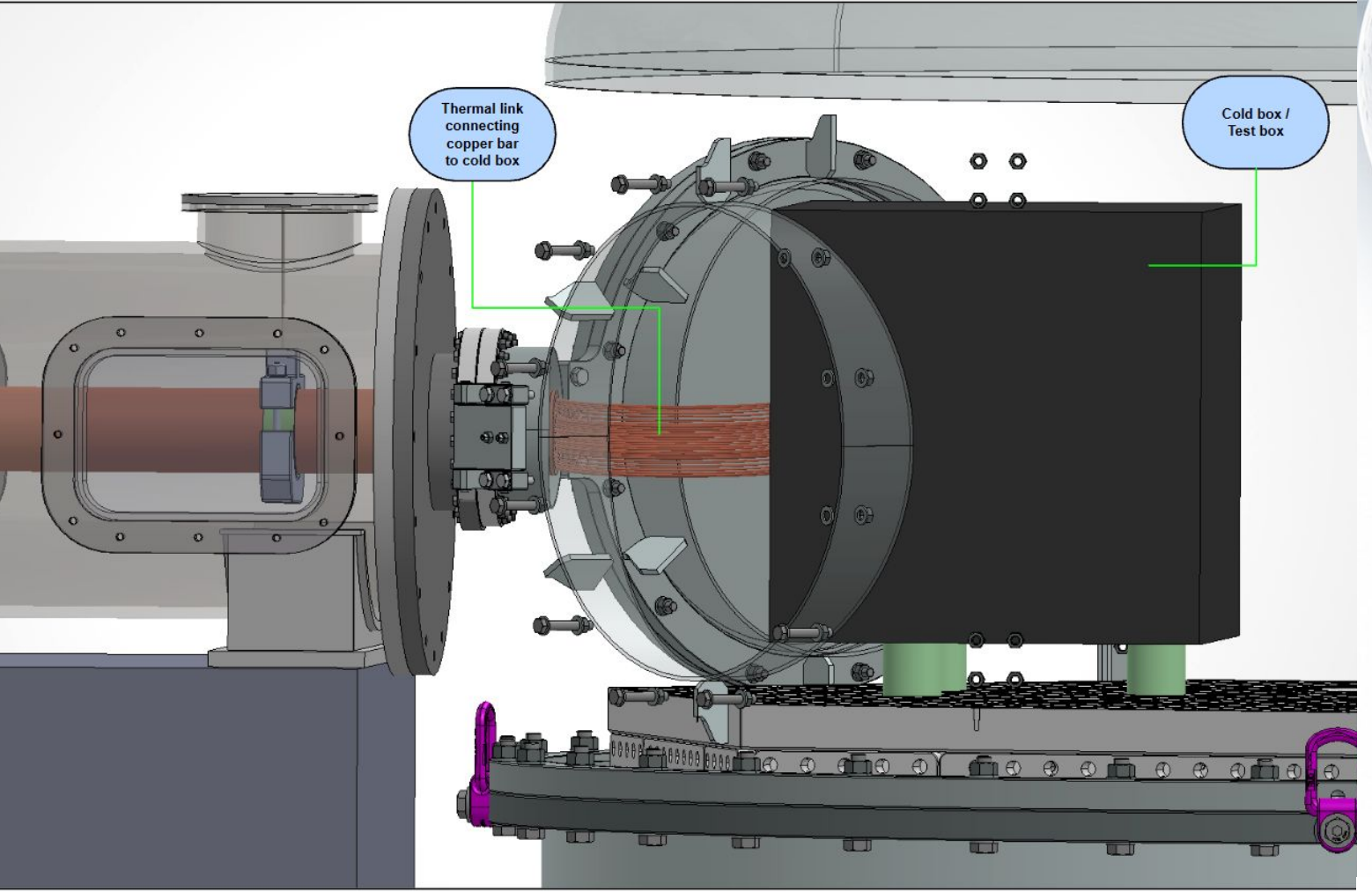


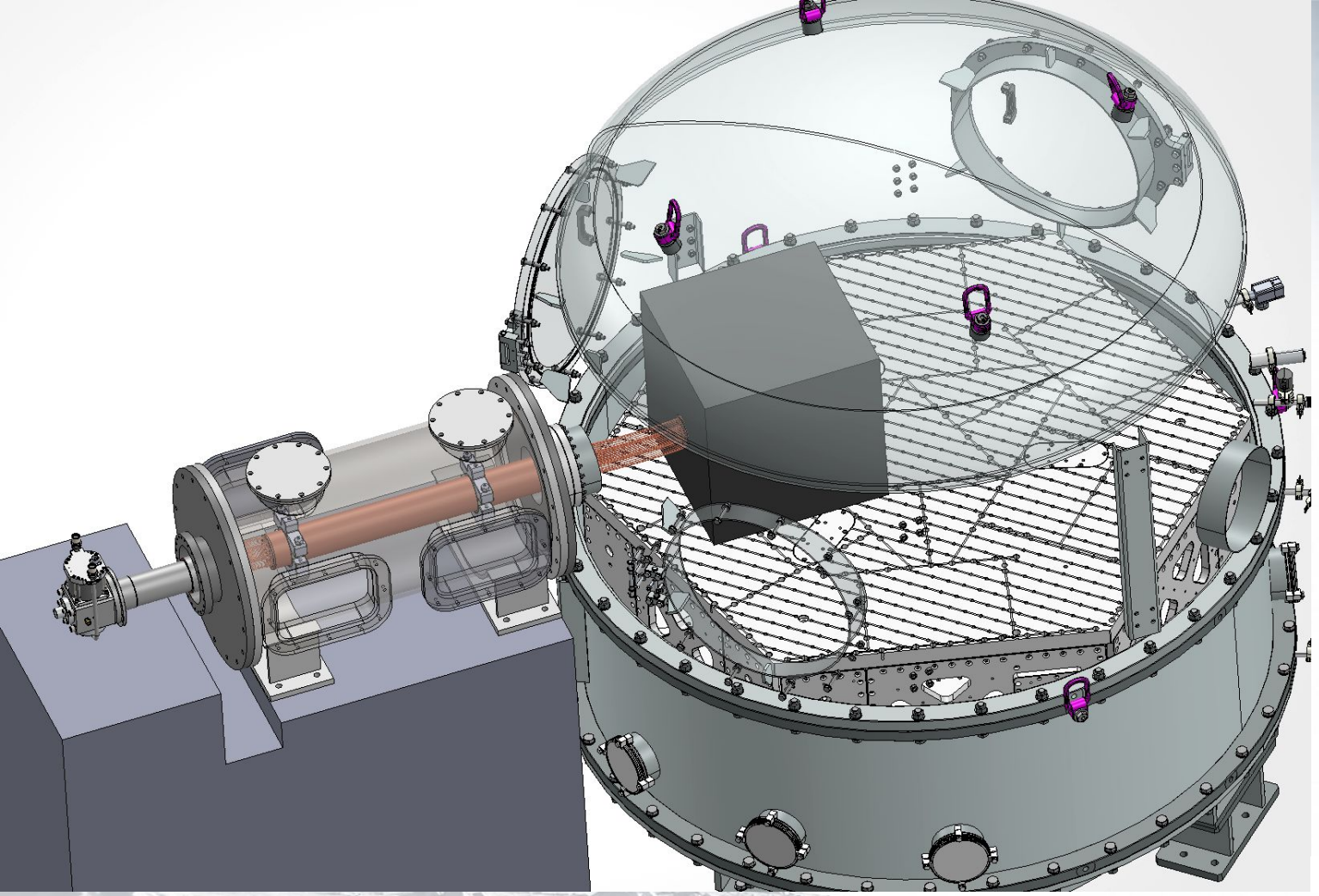
Left View (cryocooler end)

DESIGN PARAMETERS	
CRYOBOX (VACUUM VESSEL)	
Material	SS304
Configuration	Cylindrical vacuum vessel
Outer diameter (OD)	480 mm
Inner diameter (ID)	450 mm
Wall thickness	15 mm
Overall assembly/interface length	1145 mm
COPPER BAR	
Material	Copper
Diameter	Ø108 mm
Total length	1000 mm
CRYOCOOLER	
Type	Gifford–McMahon (GM) cryocooler
Model	RDK-500B2
Cooling stages	Two-stage
Connection to cryobox	Laminar bellows
Thermal connection	Flexible copper thermal link
Moon Emulator target	~40 K

Current design configuration:
Dimensions subject to final interface and structural verification.


Copper Bar Suspension System
Laminar Bellow Placement
Cryocooler
Cryogenic Chamber
Copper Bar
Thermal Link
Cryocooler and Chamber Support


Thermal link connecting copper bar to cold box
Cold box / Test box



Analytical vs Numerical Structural Verification

Cryogenic Vacuum Chamber (SS304)

Analytical Calculation

Cylindrical Shell under External Pressure

Input Parameters

External pressure (atmospheric)	p = 0.10132 MPa
Mean shell diameter	D□ = 465 mm
Wall thickness	t = 15 mm
Material	SS304
Material properties	E = 193 GPa, v = 0.29

Cylindrical Shell Formulas (Thin Shell Theory)

Hoop (circumferential) stress:

$$\sigma_h = \frac{pD_m}{2t} = \frac{0.10132 \times 465}{2 \times 15} \approx 1.57 \text{ MPa}$$

Longitudinal (axial) stress:

$$\sigma_L = \frac{pD_m}{4t} = \frac{0.10132 \times 465}{4 \times 15} \approx 0.79 \text{ MPa}$$

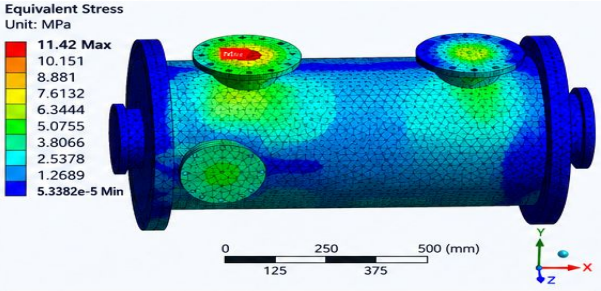
Analytical equivalent (von Mises) stress:

$\sigma_{v□} = \sqrt{(\sigma□^2 + \sigma□^2 - \sigma□\sigma□)}$

$\sigma_{v□} = \sqrt{(1.57^2 + 0.79^2 - 1.57 \times 0.79)} \approx 1.36$ MPa

ANSYS Simulation Results

Static Structural Analysis (External Pressure)



Key ANSYS Results

Maximum equivalent (von-Mises) stress	11.42 MPa
Minimum equivalent stress	5.3382×10^{-5} MPa
Average equivalent stress (whole model)	1.33 MPa
Maximum total deformation	0.01697 mm
Minimum total deformation	0 mm
Applied external pressure	0.10132 MPa
Material	SS304 – Cryobox (E = 193 GPa, ν = 0.29)

Comparison and Discussion

Result	Analytical (Cylindrical Shell)	ANSYS (FEA)
Equivalent stress (global)	1.36 MPa	~1.33 MPa (average)
Maximum local stress	Not captured (in ideal shell)	11.42 MPa
Maximum deformation	—	0.01697 mm

OBSERVATIONS

- **Global agreement:** Analytical equivalent stress (**~1.36 MPa**) is close to the ANSYS average equivalent stress (**~1.33 MPa**).
- **Local stress:** ANSYS captures a local maximum of **11.42 MPa** near a geometric discontinuity, which is not represented by the ideal shell equations.
- **Small deformation:** Maximum total deformation is **0.01697 mm** under the current simplified boundary conditions.
- **External-pressure stability is evaluated separately through eigenvalue buckling analysis.**

CONCLUSION

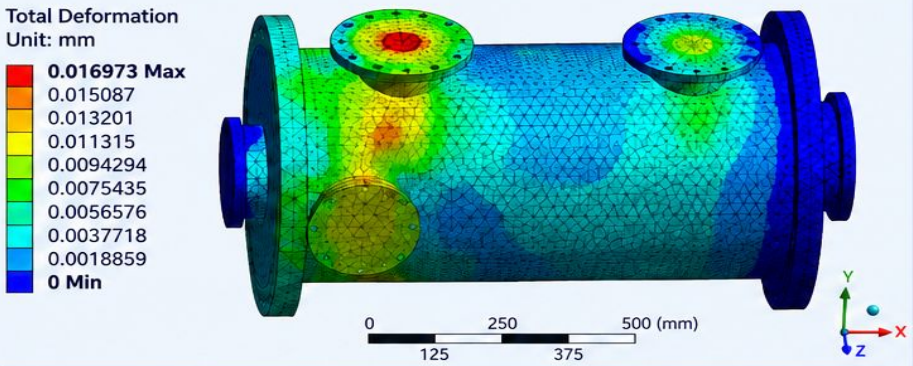
OUTCOME

A more accessible and integration-friendly design with reduced intervention on the existing GEMINI chamber.

STATIC STRUCTURAL ANALYSIS — RESULTS

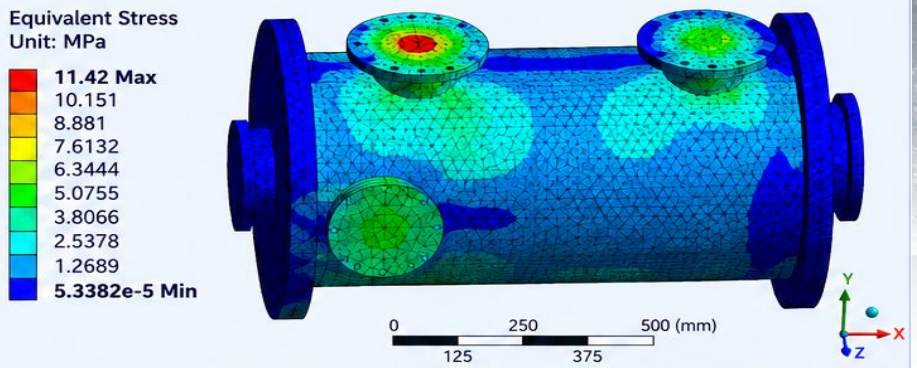
External atmospheric pressure loading — current simplified boundary-condition case

Total Deformation



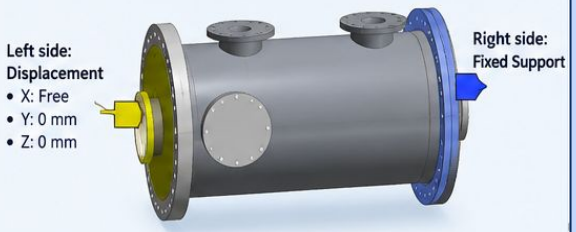
Maximum Total Deformation: 0.01697 mm
Minimum: 0 mm

Equivalent (von-Mises) Stress



Maximum Equivalent (von-Mises) Stress: 11.42 MPa
Minimum: 5.3382 × 10^{-5} MPa

Boundary Conditions



Analysis Setup

External pressure	0.10132 MPa
Right flange	Fixed Support
Left-side displacement	X: Free, Y: 0 mm, Z: 0 mm
Material	SS304
Analysis type	Linear Static Structural
Model	Cryobox assembly (9 bodies)

Key Takeaways

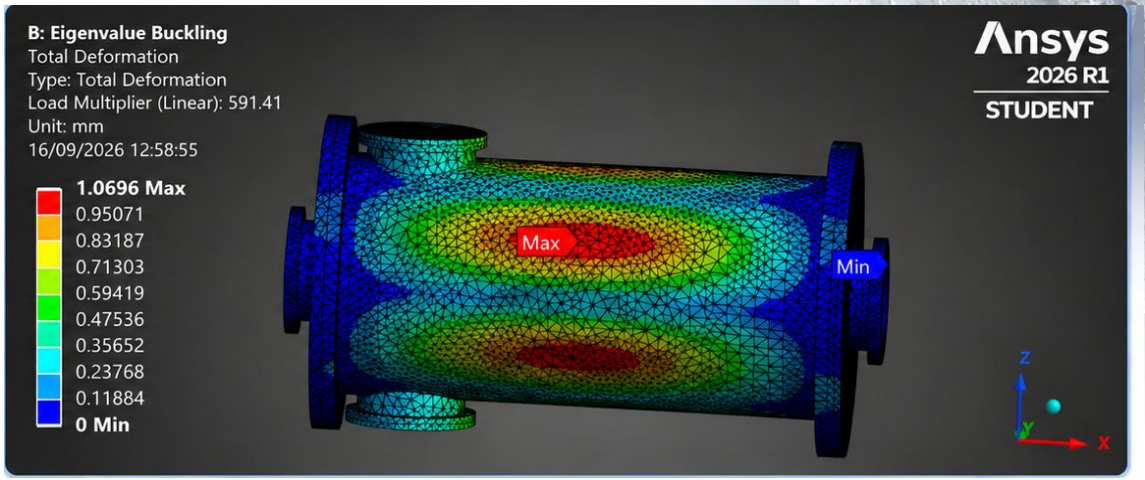
- Maximum total deformation is **0.01697 mm** under the current boundary conditions.
- Maximum equivalent (von Mises) stress is **11.42 MPa**, occurring near the left upper nozzle region.
- The peak stress is localized around geometric discontinuities, while lower equivalent stresses occur across most of the shell.
- Results are **preliminary and dependent on the current simplified boundary conditions**.
- External-pressure stability is assessed separately through eigenvalue buckling analysis.

EIGENVALUE BUCKLING ANALYSIS

Preliminary external-pressure stability assessment

Analysis Setup

Parameter	Value
Analysis type	Prestressed Eigenvalue Buckling (Linear)
Reference pressure (from static analysis)	0.10132 MPa
Buckling mode	Mode 1
Load multiplier, λ_1 (Linear)	**591.41**
Linear critical-pressure equivalent	**≈ 59.92 MPa**
Mode-shape amplitude (displayed)	1.0696 mm (scaled / normalized)
Material	SS304 (E = 193 GPa, v = 0.29)



Key Observations

- Mode 1 gives a linear eigenvalue load multiplier of **591.41**.
- The corresponding linear critical-pressure equivalent is **≈ 59.92 MPa** based on the reference pressure of 0.10132 MPa.
- The displayed mode shape shows the predicted buckling pattern of the cylindrical shell (mode-shape amplitude = 1.0696 mm, scaled/normalized).
- Eigenvalue buckling analysis provides an idealized linear stability estimate and does not account for geometric imperfections, material nonlinearities or post-buckling behavior.

Conclusion

The analysis indicates a high idealized elastic buckling multiplier for the current model; however, eigenvalue buckling does not represent the actual collapse pressure.

Preliminary linear stability result – nonlinear imperfection-sensitive and/or code-based external-pressure verification is required for final design qualification.

CURRENT STATUS & REMAINING WORK

Progress achieved and remaining work toward a fully verified Moon Emulator

CURRENT STATUS - PROGRESS ACHIEVED

Overall Moon Emulator architecture defined
Cryogenic subsystem concept developed for integration with the existing GEMINI infrastructure.

Cylindrical cryobox concept developed
Current cylindrical vacuum-vessel geometry and principal interfaces defined.

Detailed CAD model developed
Cryobox assembly includes cryocooler interface, thermal-link region, copper bar and GEMINI-side interface.

Cryocooler & copper-bar arrangement established
RDK-500B2 cryocooler and Ø108 × 1000 mm copper bar incorporated into the current design.

GEMINI integration strategy established
Cryogenic and support hardware arranged outside the existing GEMINI main chamber to minimize modifications.

Preliminary structural verification completed
Analytical shell calculations and static structural FEA completed for the current model.

Preliminary buckling assessment completed
Prestressed linear eigenvalue buckling analysis performed for external atmospheric pressure.

Current Design Status:
Preliminary mechanical architecture established and structurally assessed for the current model.

REMAINING WORK - NEXT STEPS

Finalize Copper-Bar Support Concept
Define final geometry, materials, suspension/fixation method and interfaces.

Confirm Final Dimensions & Interfaces
Freeze critical dimensions, tolerances and GEMINI interface details.

Complete Thermal & Heat-Load Analysis
Evaluate conduction, radiation, parasitic heat loads and expected temperature distribution.

Verify Thermal Contraction Accommodation
Evaluate differential contraction between copper and stainless-steel components.

Finalize Vacuum Interfaces & Sealing
Define flange, sealing, bolt-pattern and leak-tightness requirements.

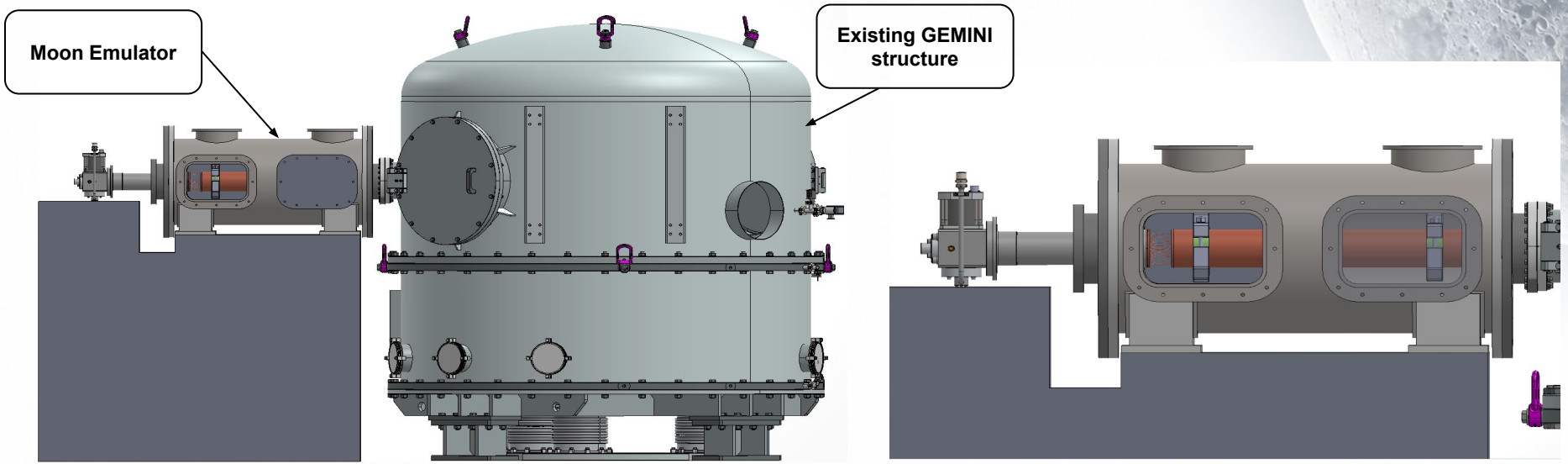
Refine Structural Verification
Improve support/boundary-condition representation and assess local structural details.

Complete External-Pressure Verification
Perform nonlinear imperfection-sensitive and/or code-based buckling assessment.

Finalize Manufacturing & Assembly Concept
Define fabrication, joining, installation and maintenance strategy.

CONCLUSIONS

Current outcome of the Moon Emulator mechanical design study



DESIGN CONCEPT ESTABLISHED

Cylindrical Moon Emulator architecture developed for integration with the existing GEMINI infrastructure.

CRYOGENIC ARCHITECTURE DEFINED

Cryocooler, bellows, flexible thermal link and copper test bar incorporated into the current design.

PRELIMINARY MECHANICAL VERIFICATION COMPLETED

Analytical, static FEA and linear eigenvalue buckling assessments completed for the current mechanical model.

The current design provides the mechanical basis for the next phase of Moon Emulator development and GEMINI integration.

THANK YOU

Questions & Discussion

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