Laser Wire Mechanical Design

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Noninvasive Beam Profile Monitor (Laser Wire) FDR

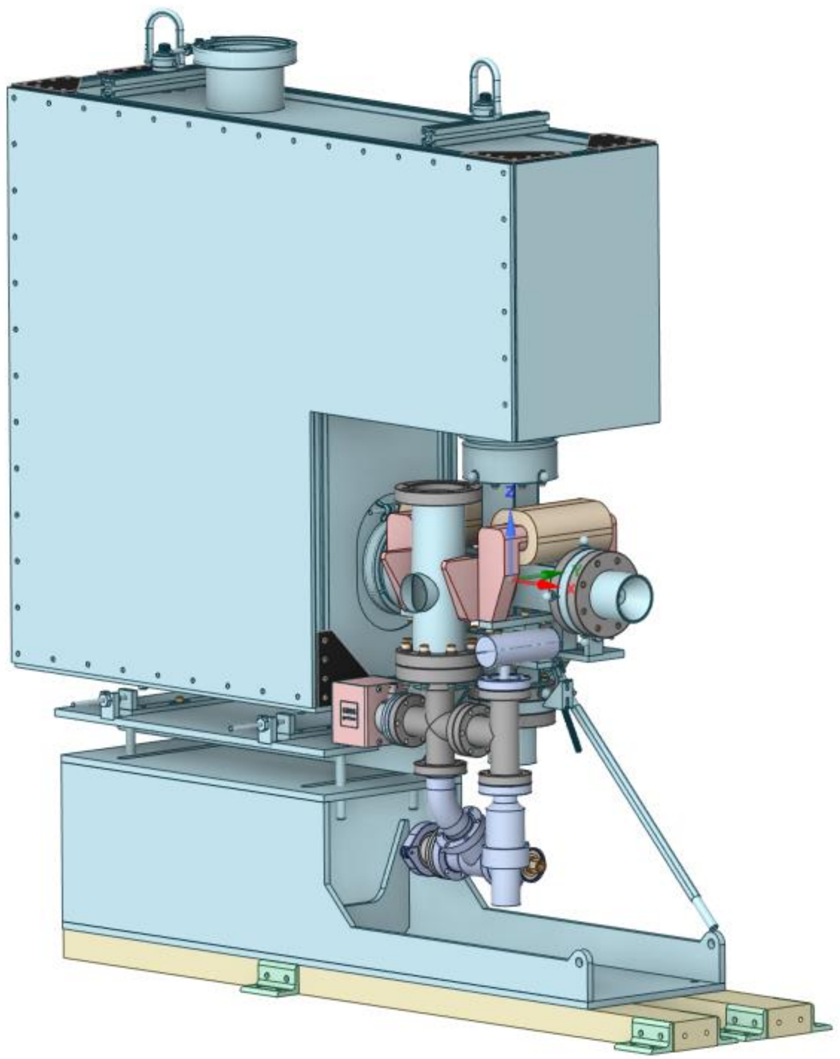
May 2-3 2024

PIP-II is a partnership of:

- US-DOE
- India-DAE
- Italy-INFN
- UK-STFC-UKRI
- France-CEA, CNRS/IN2P3
- Poland-WUST, WUT, TUL

Outline

- Mechanical System Requirements
- Mechanical Assembly Overview
- Operational PIP2IT System
- Space allocation and interfaces with Linac Installation and Vacuum Systems
- Vacuum Chamber Design and UHV specifications
- Quality Control
- Optical Boxes – Input and Dump
- Mechanical Validation Analyses
  - Structural
  - Thermal
  - Optical viewport risk analysis
- Installation Procedure
- Path Forward
- Summary



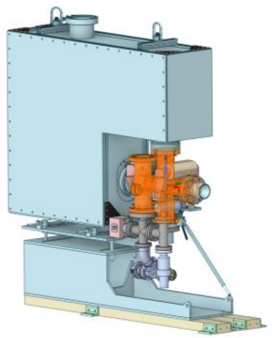
Technical Requirements per TRS ED0013714

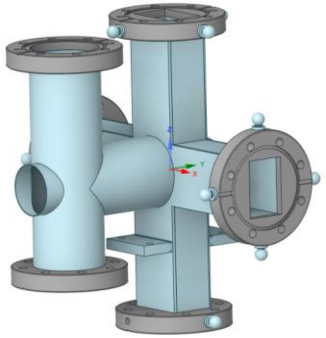
Requirement #	Requirement Statement
T-ED0013714-E001	Each laser station shall be designed to prevent the uncontrolled release of laser light.
T-ED0013714-E002	Each SCL laserwire station shall fit into the volumes defined by warm unit specifications.
T-ED0013714-E003	The laserwire stations shall not be a beamline aperture restriction and shall not have inner diameters less than the beam pipe apertures specified in each location.
T-ED0013714-E004	The free-space optics at each laserwire station shall keep the maximum average optical power density on the vacuum viewports to less than 3 W/cm^2
T-ED0013714-E005	Each laserwire station laser dump shall have a photodiode to indicate the presence of laser light.
T-ED0013714-E006	Each laserwire station shall not be baked or operated at temperatures exceeding 100°C (212°F).
T-ED0013714-E007	A magnetic field downstream of the laser interaction point shall be used to produce a vertical transverse deflect the photoionized electrons into an electron collector. The magnets should be capable of supplying a field up to 800 Gauss.
T-ED0013714-E008	All laserwire vacuum components shall meet PIP-II particle-free requirements and operate under ultra-high vacuum conditions.
T-ED0013714-E009	The laser optics boxes shall be removeable for repair and maintenance and access the beamline. Individual optics boxes shall be designed to allow removal without disturbing each warm unit assembly.
T-ED0013714-E010	Each laserwire station vacuum chamber shall have a port for a beamline vacuum pumping system.
T-ED0013714-E011	The material used to make components for any BI systems, located at enclosure locations subjected to radiation, shall be selected to be as radiation resistant as possible.
T-ED0013714-E012	Optical components of the laserwire profile monitor (including lenses, mirrors, vacuum viewports, and optical fibers) may require periodic replacements due to darkening from radiation exposure. Design of the laserwire system shall allow for these periodic replacements.

Mechanical Assembly Overview

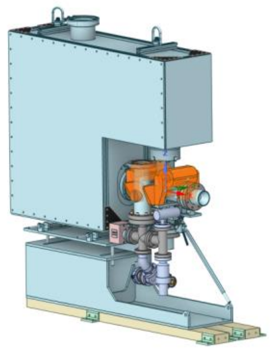
- Mechanical Assembly Overview – F10222031
  - UHV Vacuum Chamber with ports for:
    - Laser for 2 measurement profiles
    - Faraday cup
    - Vacuum pump and gauges
  - Dipole magnets
    - To bend electron trajectory into detector
  - Input optical boxes
    - Light-tight design with internal optical components

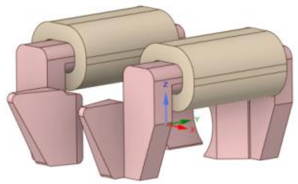
Vacuum chamber:



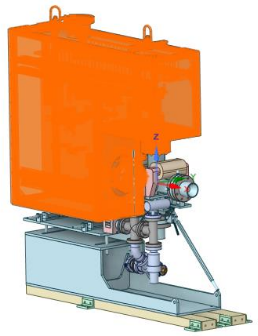


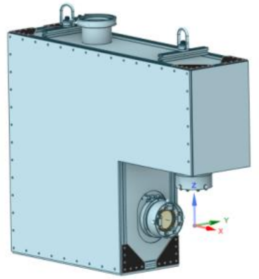
Magnets:





Input optical box:

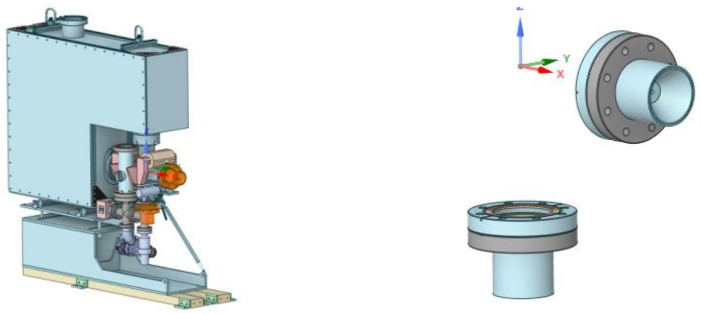




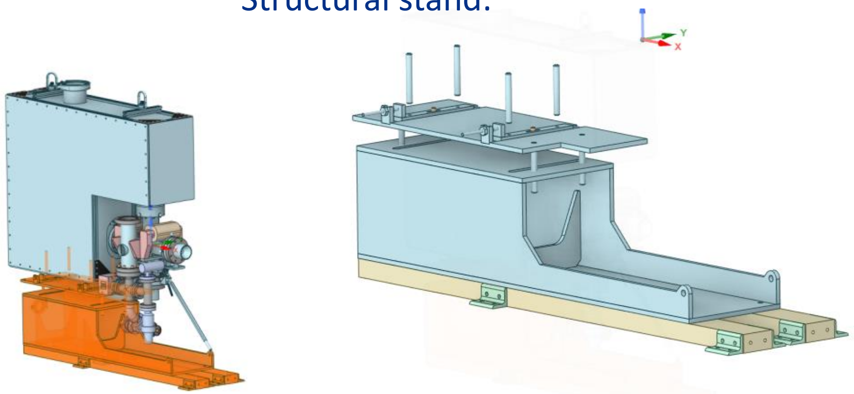
Mechanical Assembly Overview

- Mechanical Assembly Overview – F10222031
  - Laser dumps/dump boxes
    - Light-tight components to absorb output laser
  - Structural stand
    - With adjusting mechanisms that allow for installation procedure
    - Meets structural requirements: natural frequencies, stresses and deflections
  - Vacuum pumps and gauges
    - Scope of PIP-II Vacuum, not Beam Instrumentation
      - Combination Ion and NEG pump, Pirani and cold cathode gauges
    - Integrated into laser wire system assembly

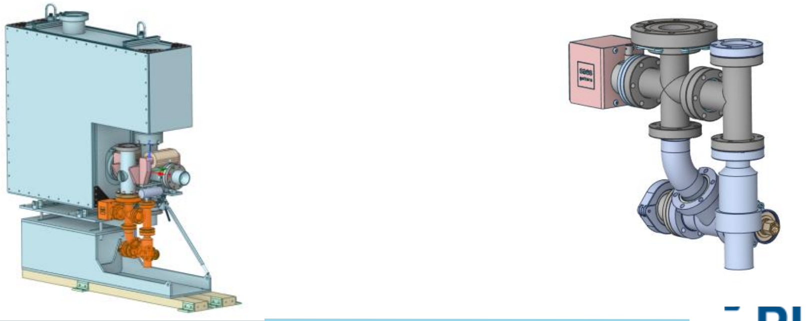
Laser dumps/dump boxes:



Structural stand:



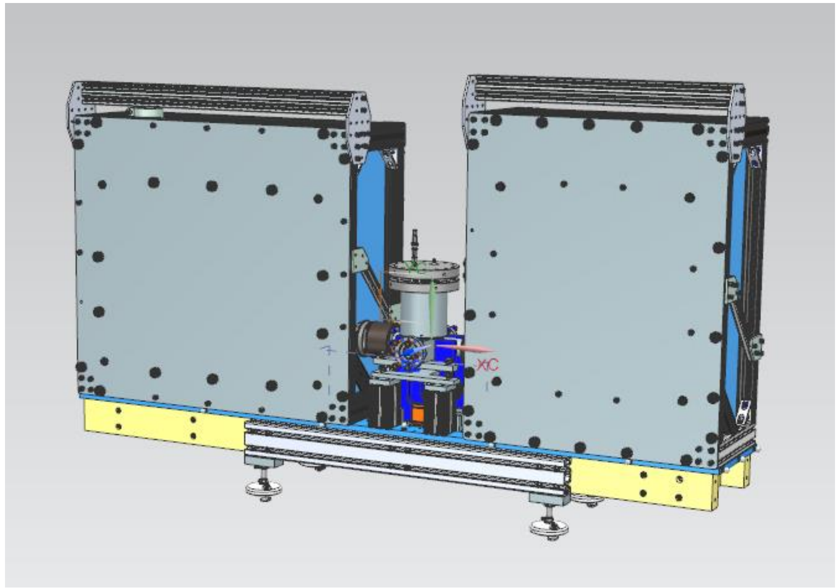
Vacuum pump and gauges (PIP-II Vacuum Scope):



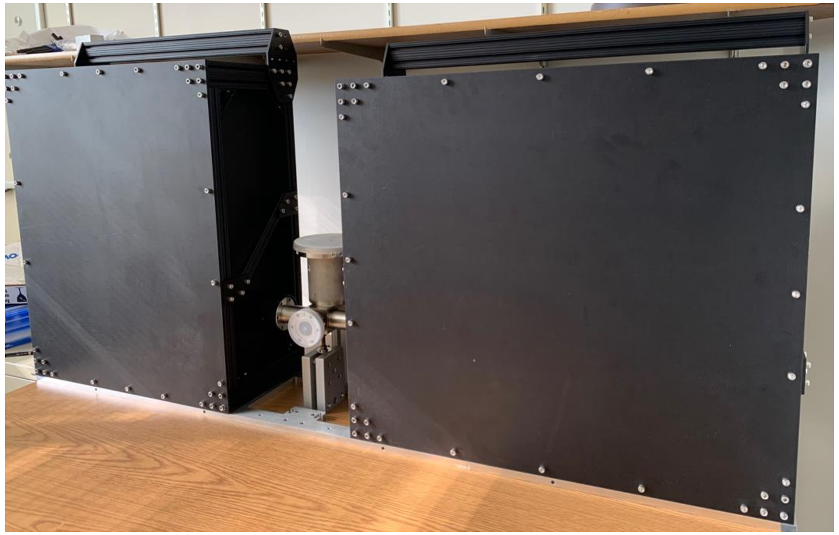
Operational PIP2IT System

- PIP2IT Laser wire mechanical assembly was built, installed and operated at PIP2IT validating most mechanical components for the PIP-II system
- Mechanical Assembly – F10054028
- Lessons Learned:
  - Internal system mechanical requirements
  - Assembly procedure
  - Light tightness
    - O-Rings, Lens tubes, and Safety switches
  - Installation and alignment procedures

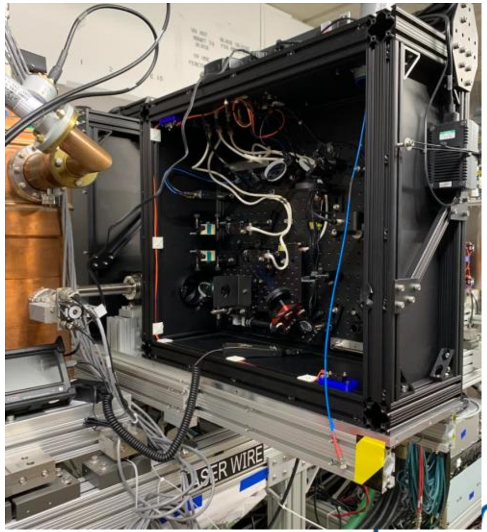
PIP2IT Mechanical Assembly: F10054028



PIP2IT Mechanical Assembly



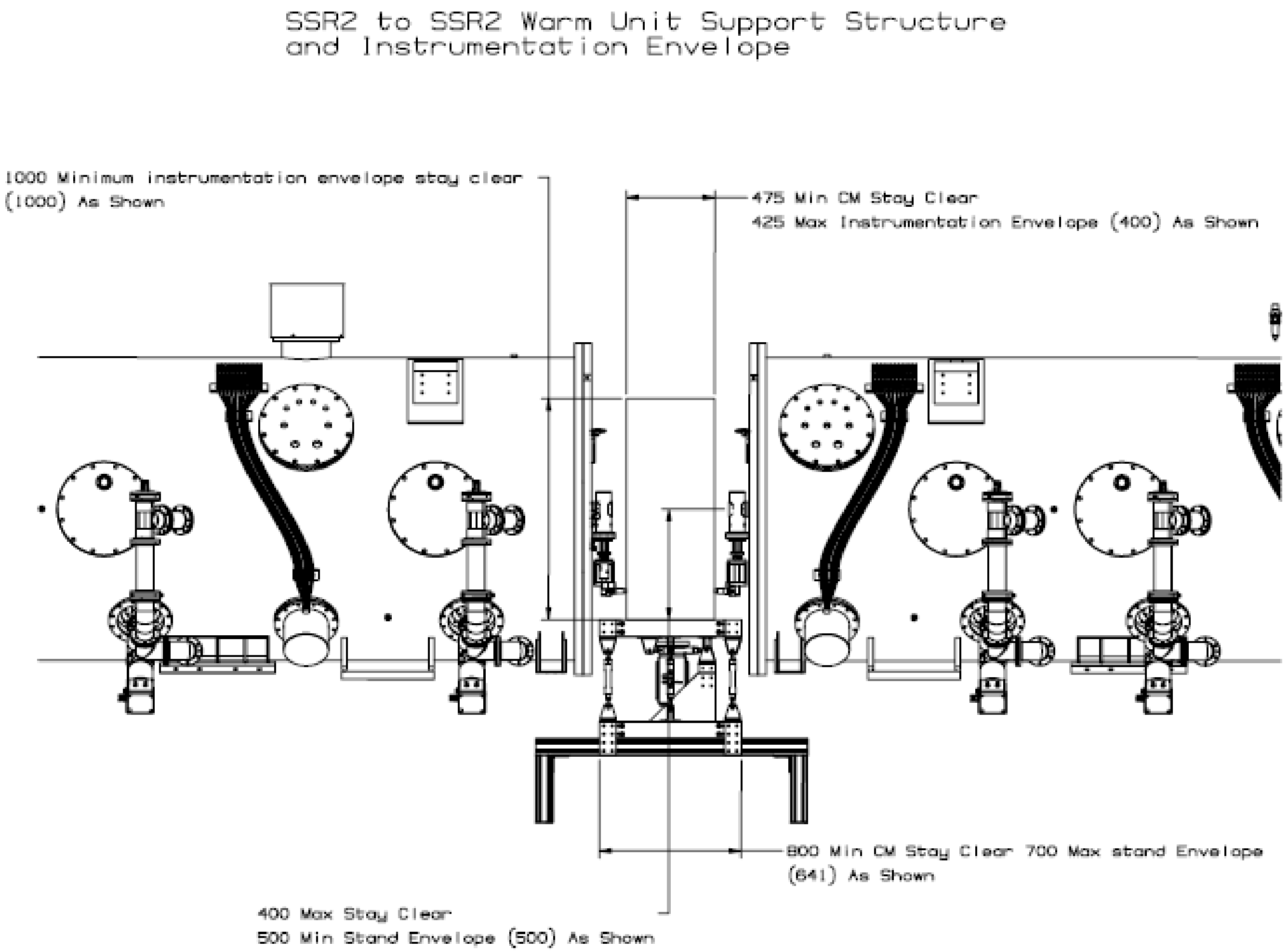
System Commissioning at PIP2IT



Space allocation and interfaces with PIP-II Linac Installation

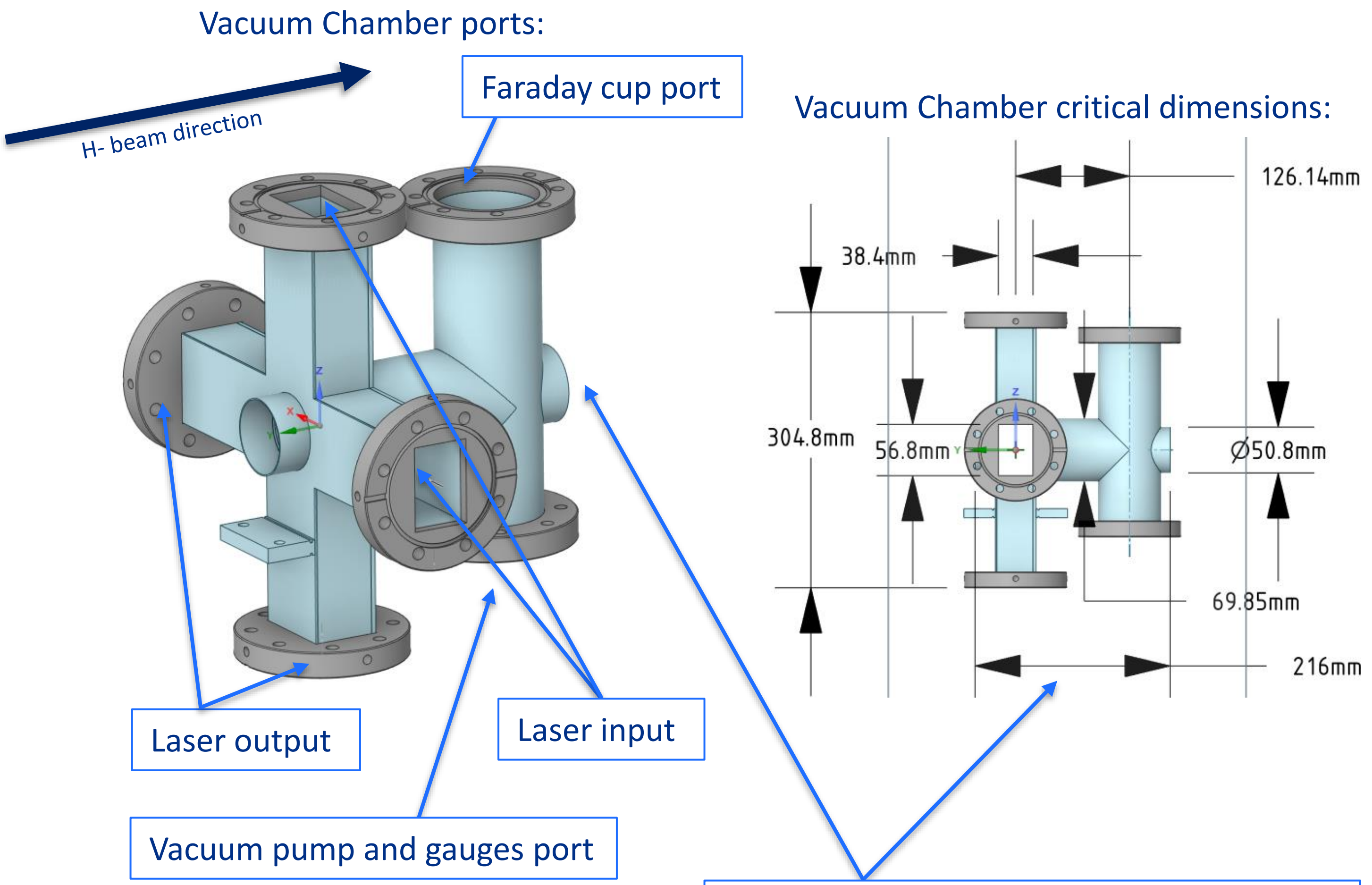
- Laser wire assembly must be **<=250mm longitudinally**
- Space allocation (not-to-exceed envelopes) for beam instrumentation assembly and interfaces with Linac Installation for 325 MHz warm units are documented in F0150993. 650 MHz warm units are less restrictive for space.
  - Interface plane from warm unit structure to laser wire stand also defined in this document

325 MHz warm unit instrumentation envelope, F0150993:



UHV Vacuum Chamber

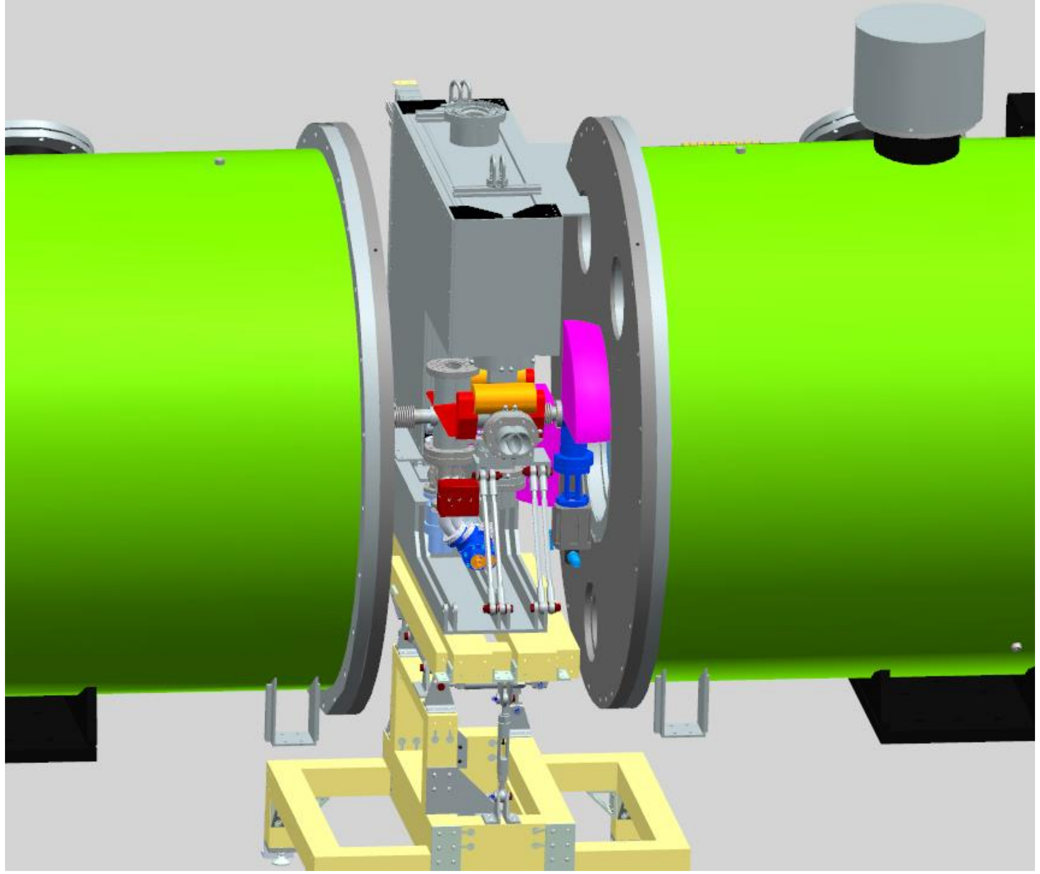
- Longitudinal distance defined by space allocation by PIP-II Linac Installation <= 250mm flange-to-flange
- Port dimensions and locations defined mostly by laser and electron trajectory requirements
- Material: 316L Stainless Steel for low magnetic permeability, 1/8in thick
- 4.5in CF flanges at all ports for laser, vacuum pump and gauges assembly, and faraday cup



Final design longitudinal distance is **250mm** and without flanges for integration with adjacent Beam Instrumentation BPMs and Vacuum bellows

Vacuum Chamber Design Integration in Warm Units

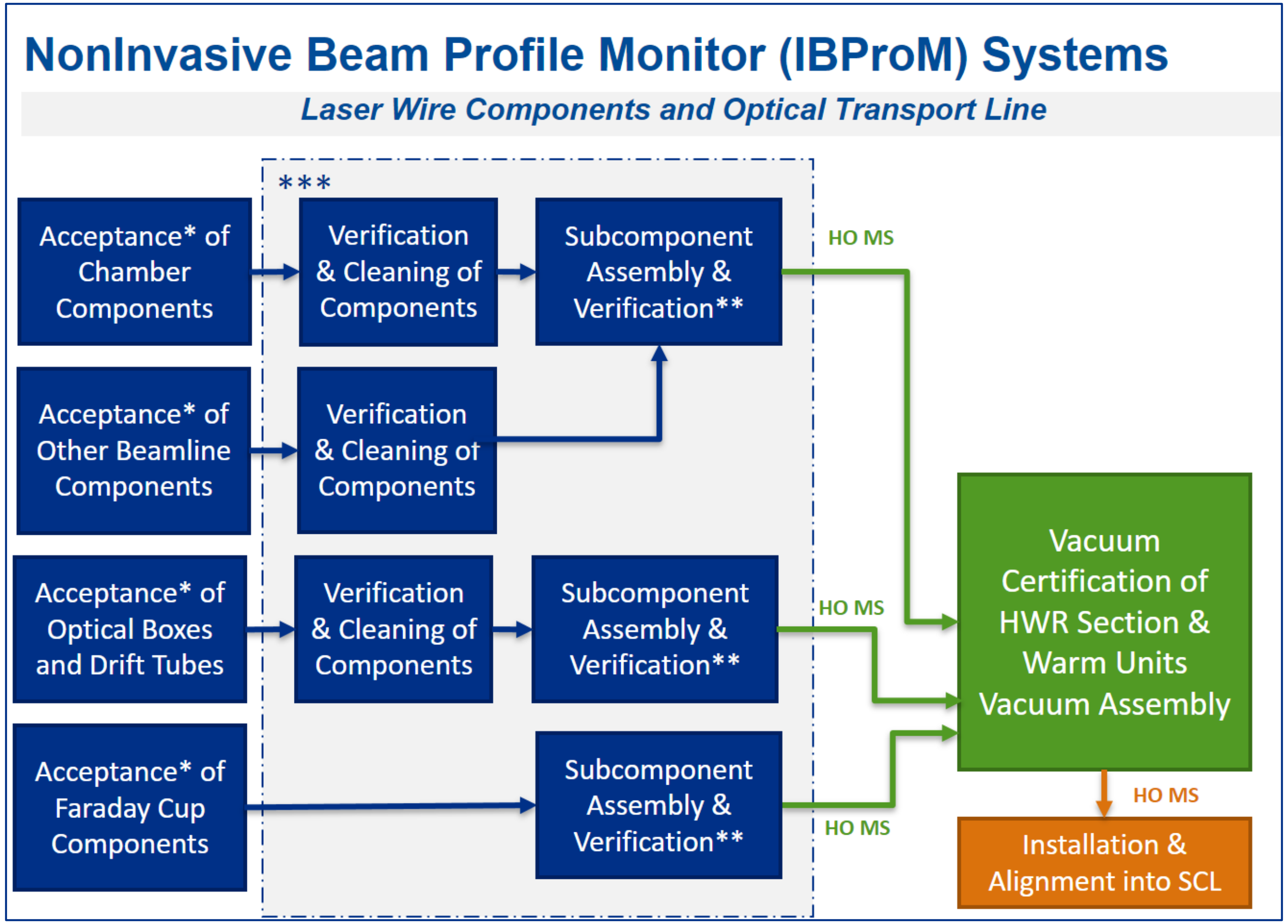
- Vacuum chamber will be integrated with the rest of the vacuum system in each warm unit by the PIP-II Vacuum group. This includes welded joints with:
  - Bellows and vacuum spools
  - BPMs
- Each warm unit between cryomodules has different configuration of beam instrumentation and magnets



UHV Vacuum Chamber Assembly and QC

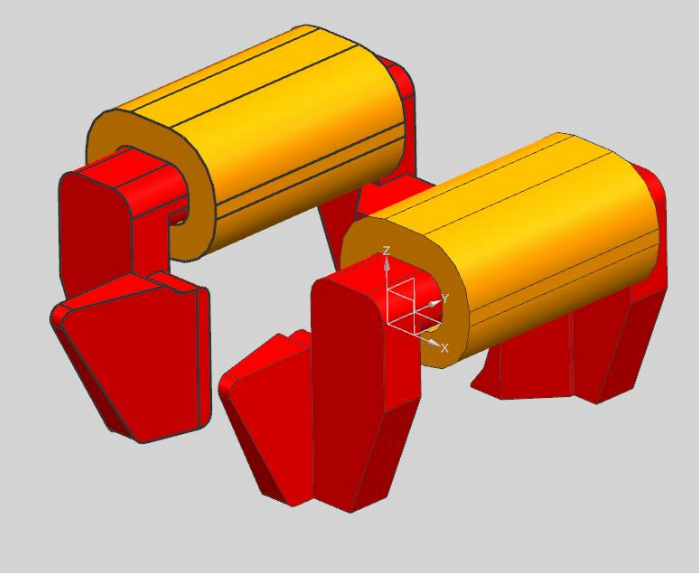
- Vacuum chamber will be fabricated, cleaned and assembled following AD-Mechanical Support Department procedures for particle-free UHV: ED0003571- Producing Very Low-Particulate UHV Components
  - Particle-free UHV work will be performed by qualified technicians
  - Laser wire team will manage the vacuum cleaning and assembly activities of vacuum chamber components and then hand off to PIP-II Vacuum for integration into the warm unit vacuum assemblies

Particle-free UHV Assembly and QC process. Courtesy of Aisha Ibrahim



Magnets

- Designed by Randy Thurman-Keup
- Integrated within the space constraints of full assembly
- 22.8 Watts of maximum heat generation at laser wire locations of higher beam energies
- Thermal testing conducted to calibrate a heat transfer finite element model for defining heat transfer conductance between coils and magnet cores
  - Thermal conductance between coils and magnet core calculated to be: **100W/m^2K**
  - Standard 7 W/m^2K free convection coefficient to room temperature air

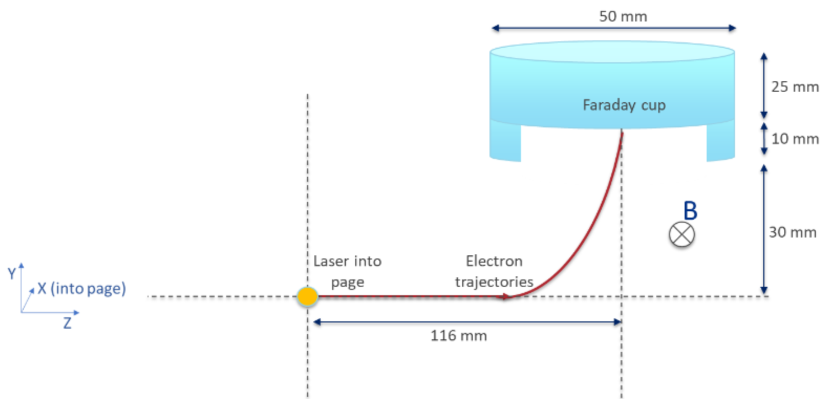


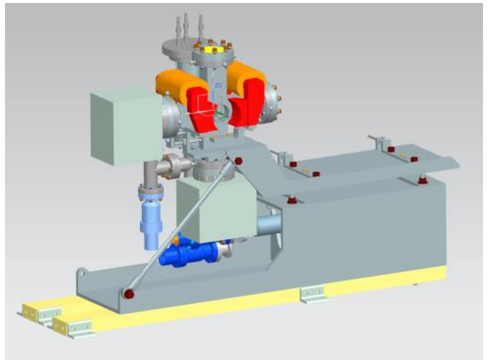
Thermal testing of magnet assembly for analysis correlation:

Faraday cup status (part of last 10% of the design)

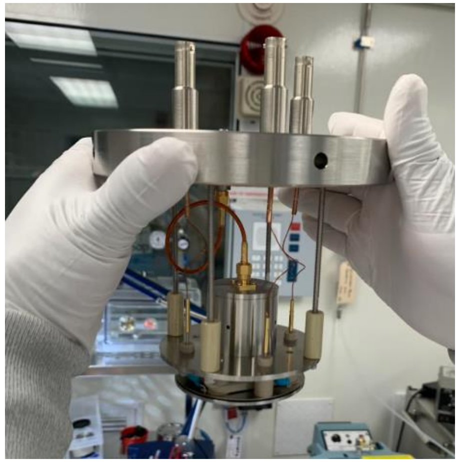
- Operational faraday cup designed and built for PIP2IT system
- Faraday cup mechanical design for PIP-II will be simpler than for PIP-II
- Dimensions and materials input for final design of PIP-II faraday close to complete
- Design of joints and materials will follow Particle-free UHV best practices

Current design input, courtesy of Sajini Wijethunga:

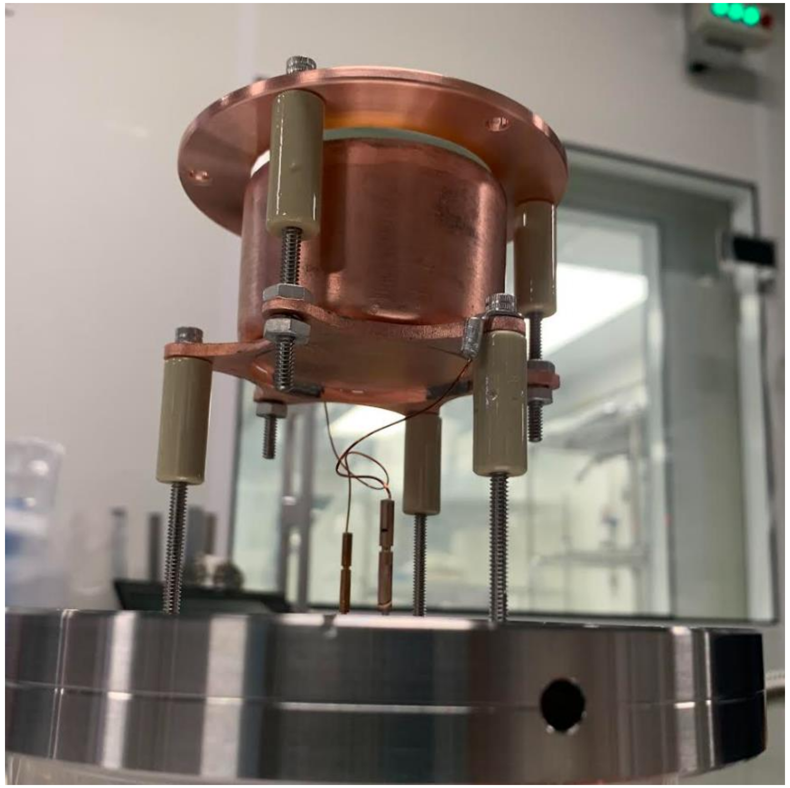




PIP2IT Microchannel plate option:

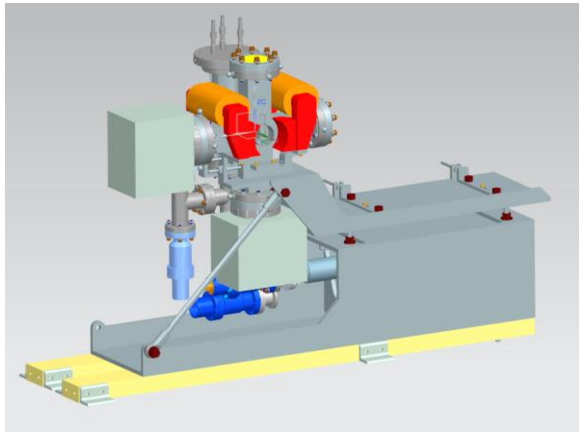


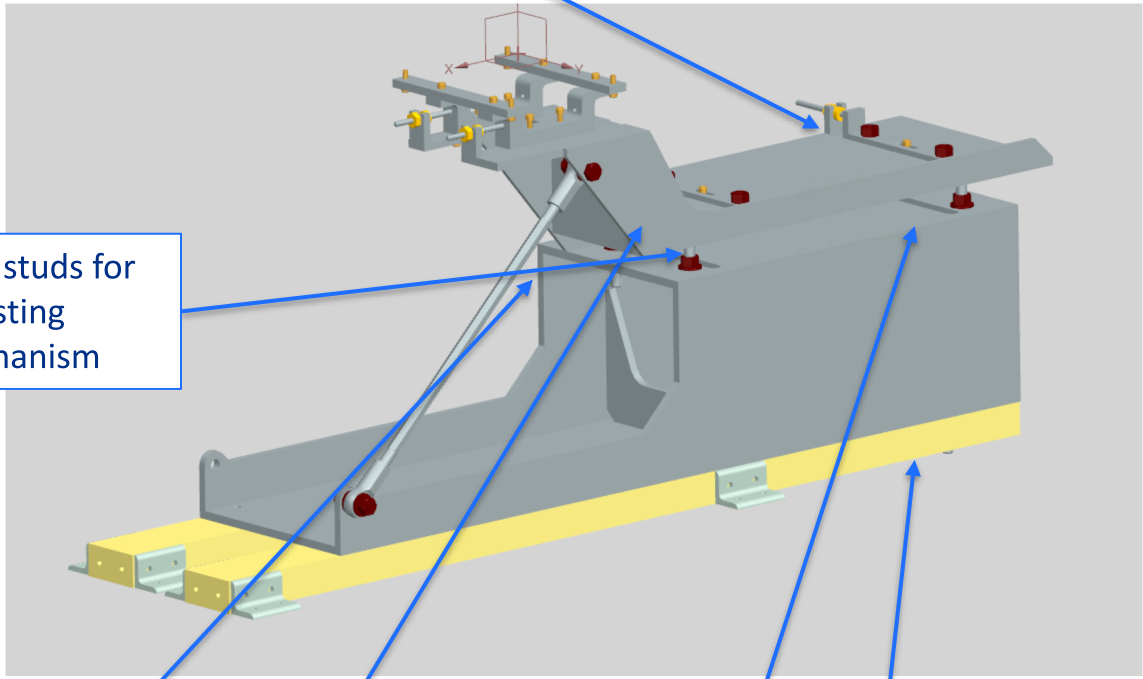
Operational PIP2IT Faraday cup:



Stand Assembly

- Stand assembly designed to:
  - Support mass of vacuum chamber and attached components considering their center of mass
  - Meet structural requirements: natural frequencies, stresses and deflections
  - Accommodate the planned installation and alignment procedure
  - Material: 6061 Al





Independent adjustment for optical box

3/8” studs for adjusting mechanism

Optional strut to be attached after installation and alignment for increasing natural frequencies

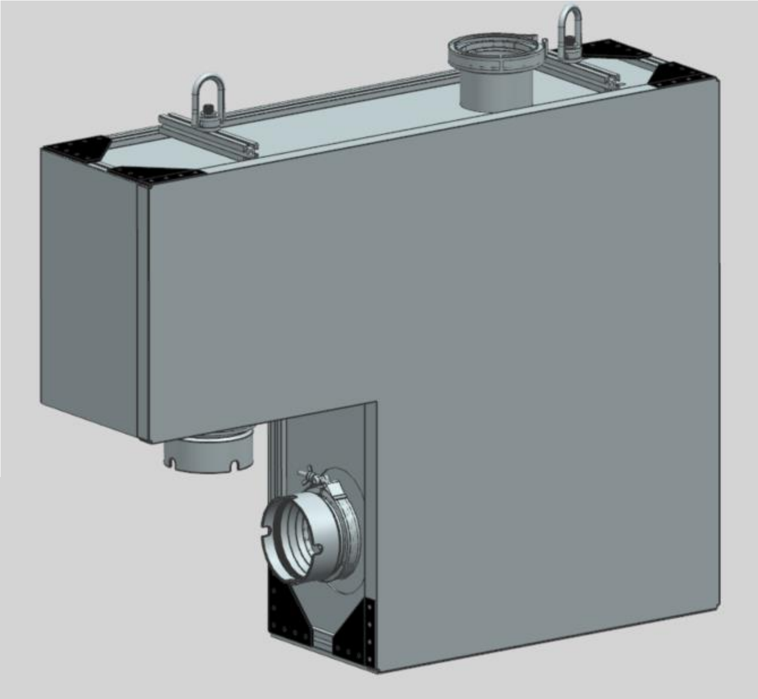
Structure optimized for statically supporting mass, and for meeting natural frequency requirements

8020 frame interfaces with warm unit structure

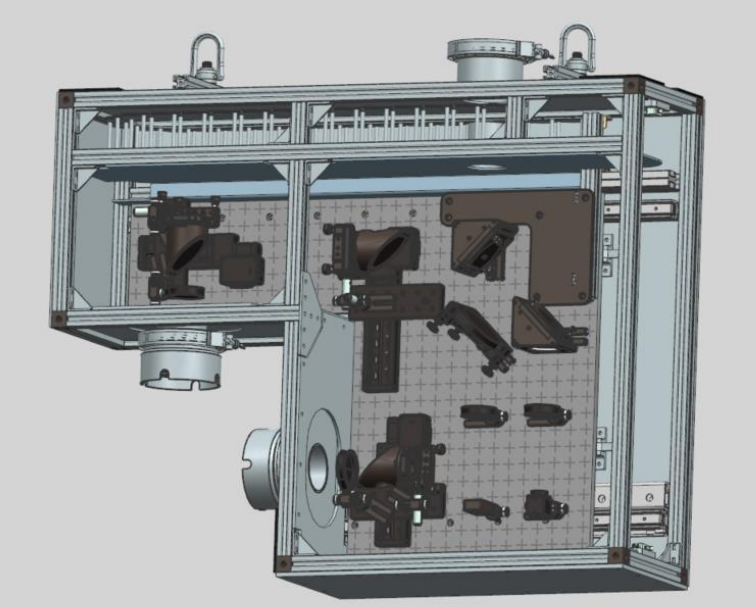
Adjustment for vacuum chamber with attached components including vacuum pump and magnets

Input Optics Box – Requirements

- Input Optics Box requirements:
  - Allow two-dimensional profiling of beam
  - Contain only radiation resistant materials
  - “Light tight” connections at interfaces
  - Prevent release of laser light
  - Removable cover/panel for maintenance of optics
    - Interlocked to safety system
  - Rail system



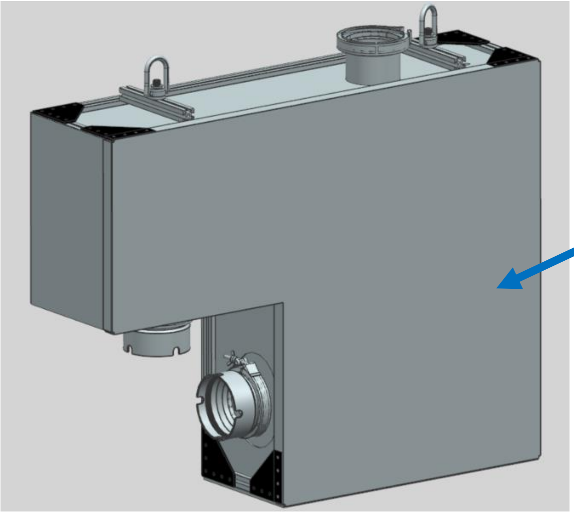
Teamcenter #: F10225016

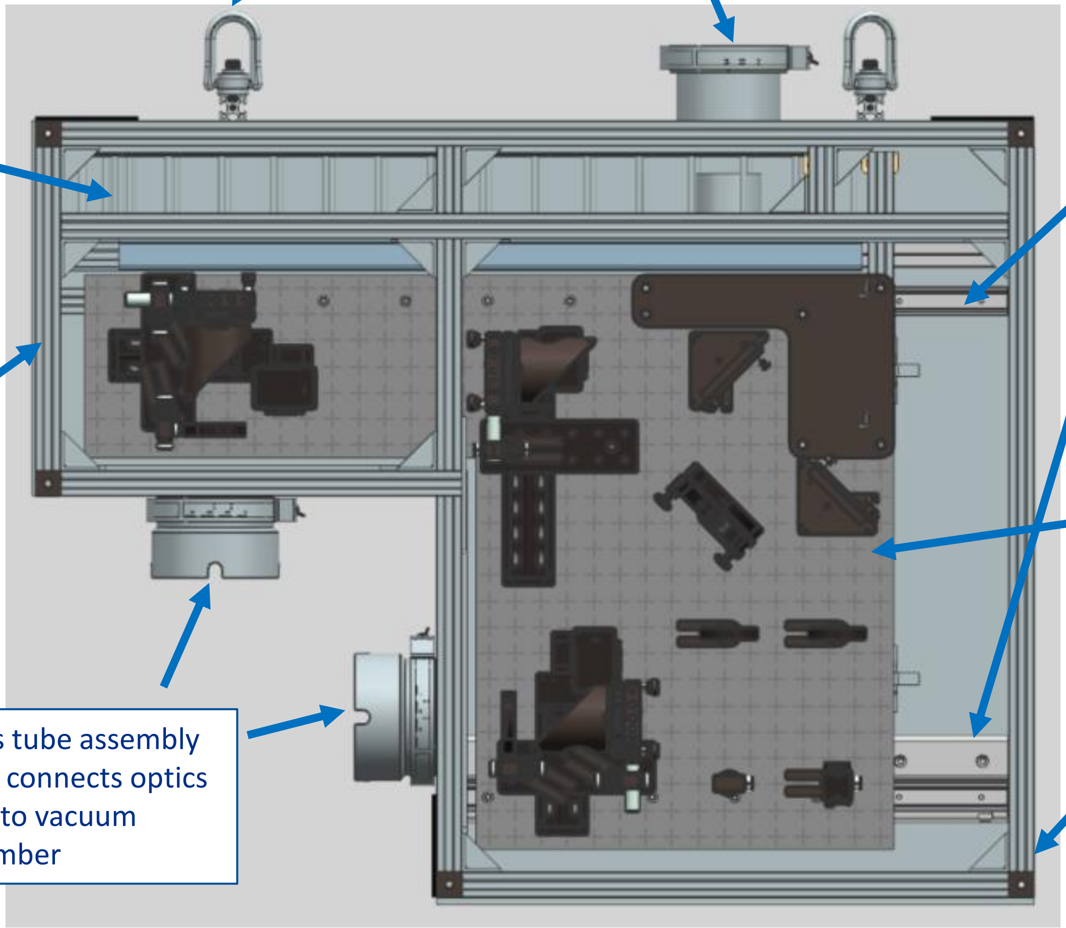


Optics Box w/ cover removed

Input Optics Box – Design Features

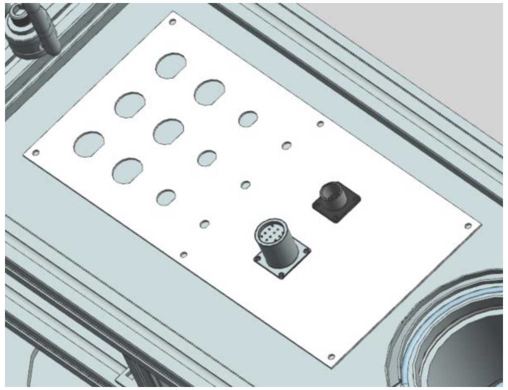
- Input Optics Box features:
  - T-slot aluminum construction
  - 6061 Aluminum panels and interface tubes
    - Panels: 1/8”-1/4” thick
    - Black anodized
  - One removable panel
    - Combined front (upstream) and side panel
  - Rail system



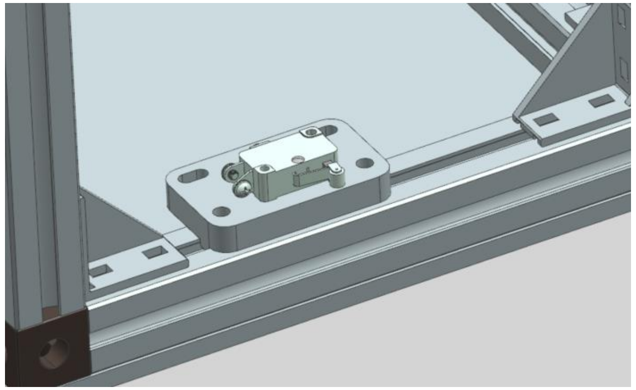


Input Optics Box – Light Tight Design and Laser Safety

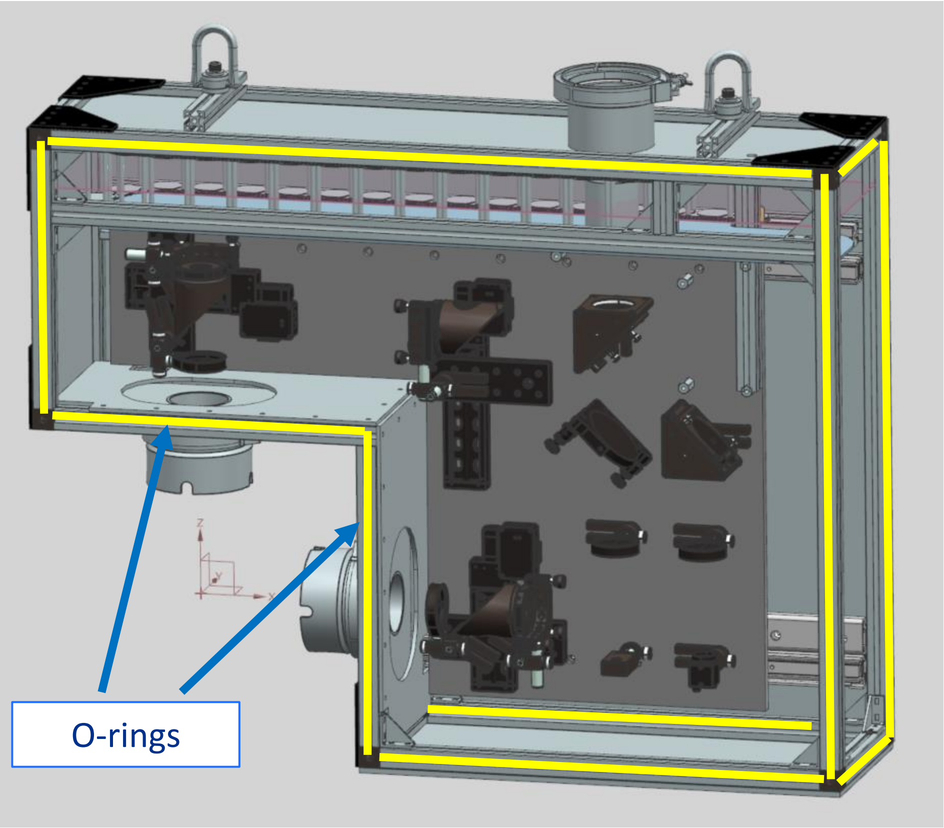
- O-rings along the edges of the 80/20 slots to seal and secure the panels
  - Radiation resistant EPDM elastomer o-rings will be used
- All panels will be black-anodized to reduce reflection
- Limit switches integrated with the removable panel
- Cable panel will be added on top



Cable panel

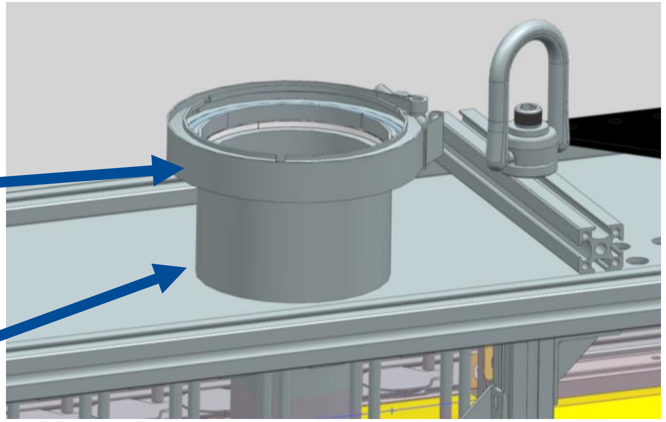


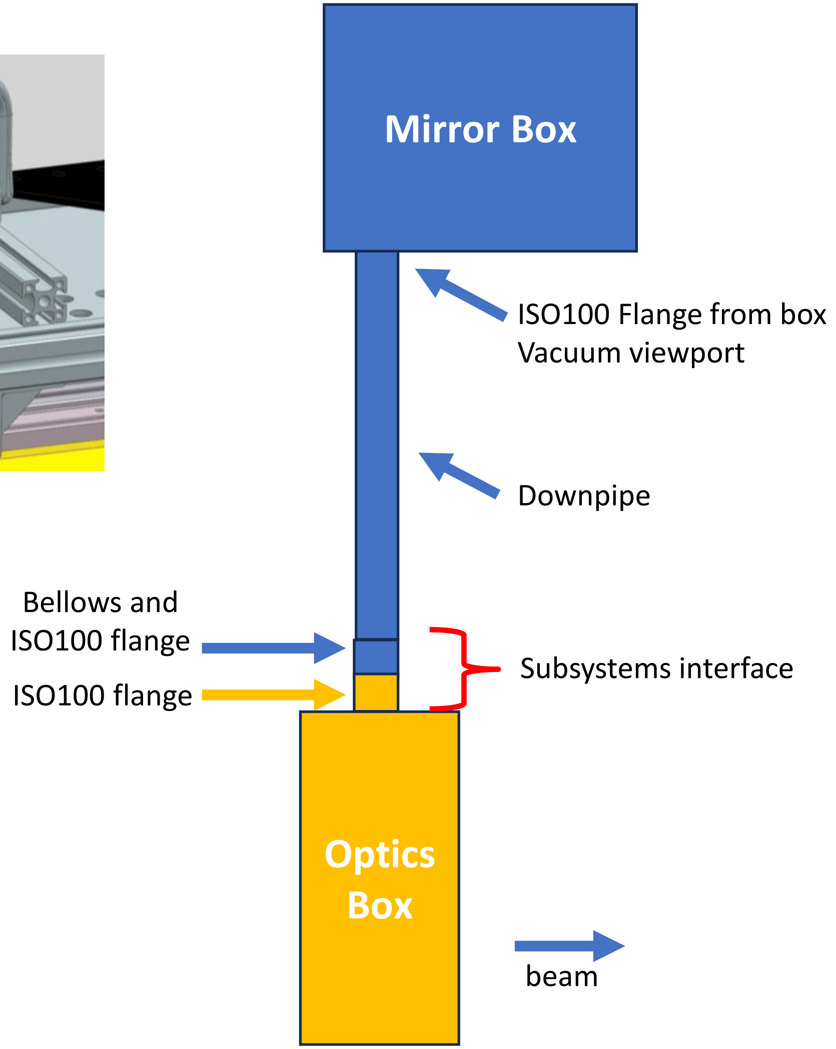
Limit/safety switch



Input Optics Box – Interface w/ Optical Transport Line

- Interface with Optical Transport Line:
  - Optics Box: ISO NW100 vacuum flange, centering o-ring, and banded clamp
    - Aluminum tube welded to optics box to support components
  - Optics box will <u>not</u> be under vacuum
  - Optics box will <u>not</u> see any vacuum load

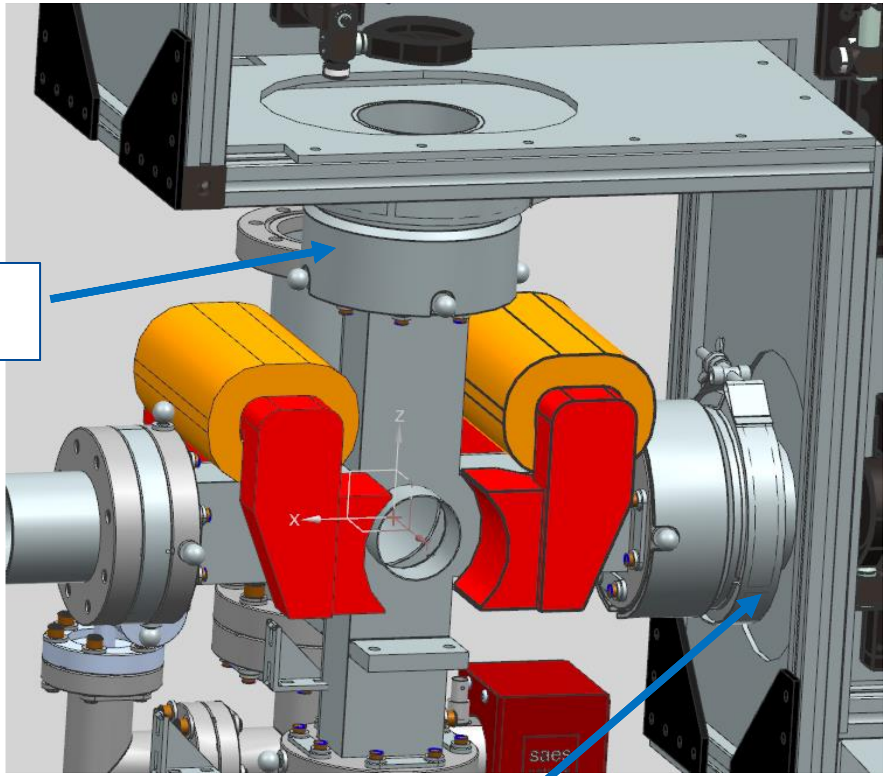




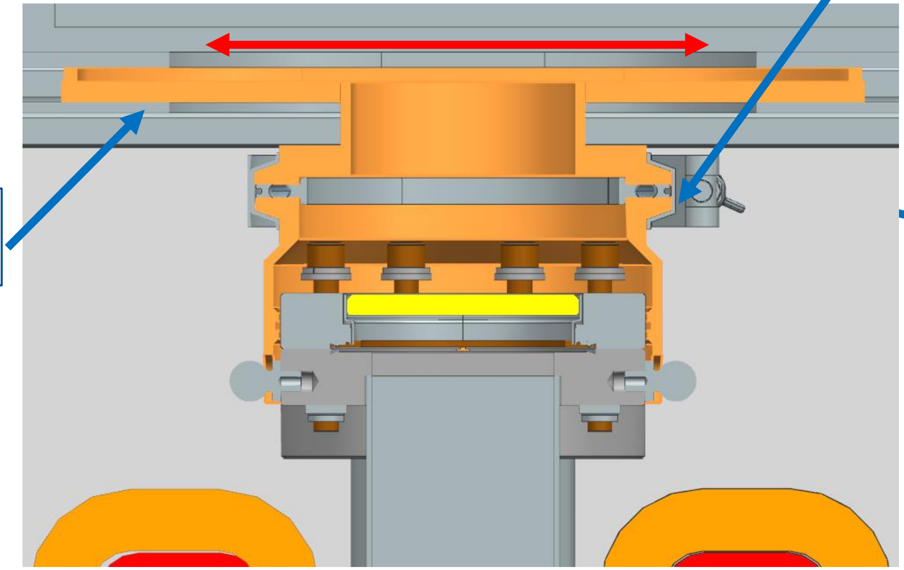
Input Optics Box – Interface w/ Vacuum Chamber

- Interface with vacuum chamber:
  - Lens tubes slide over vacuum flange
  - O-rings used to seal the connection
  - Banded clamp and centering o-ring add extra seal
  - Sliding shutter and shutter tube
    - Allows for horizontal or vertical adjustment of the lens tubes to align with vacuum flanges

Lens tube w/ slots to cover flanges



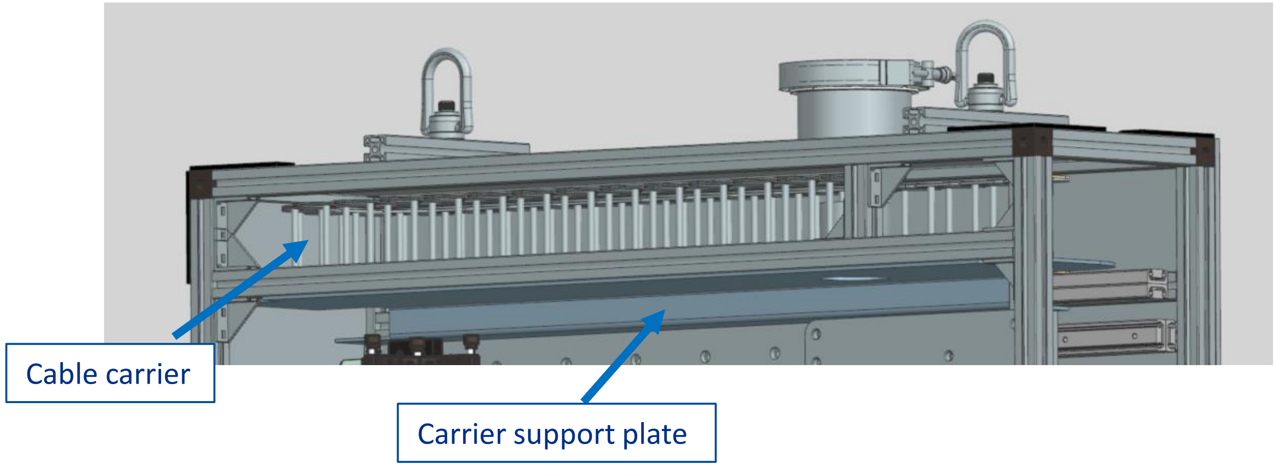
Sliding shutter tube for horizontal adjustment

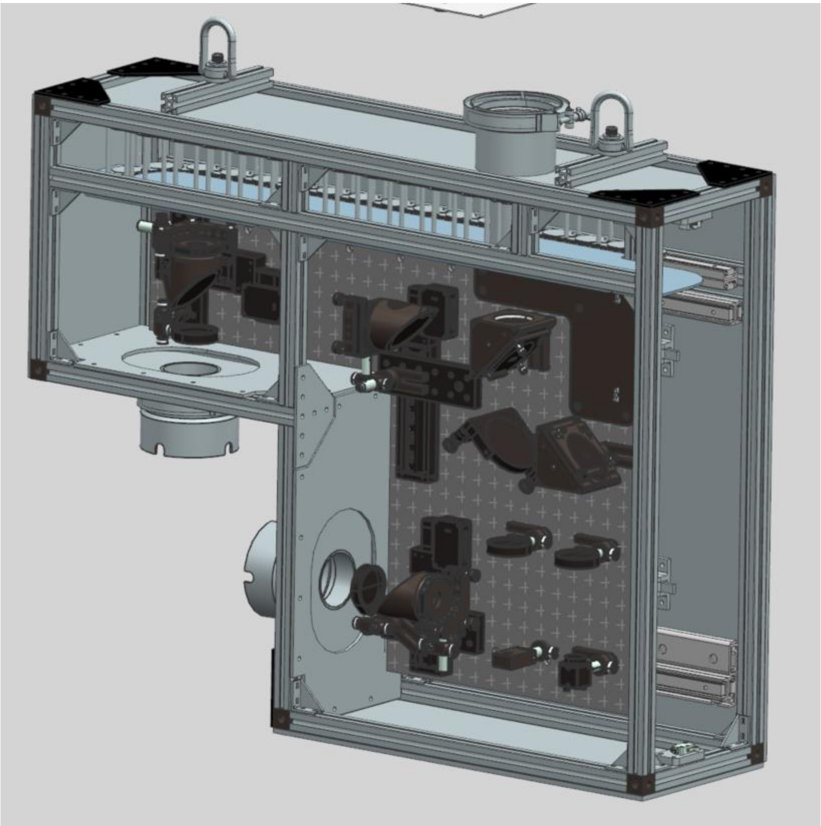


Banded clamp to secure lens tube and sliding shutter

Input Optics Box – Maintenance Features

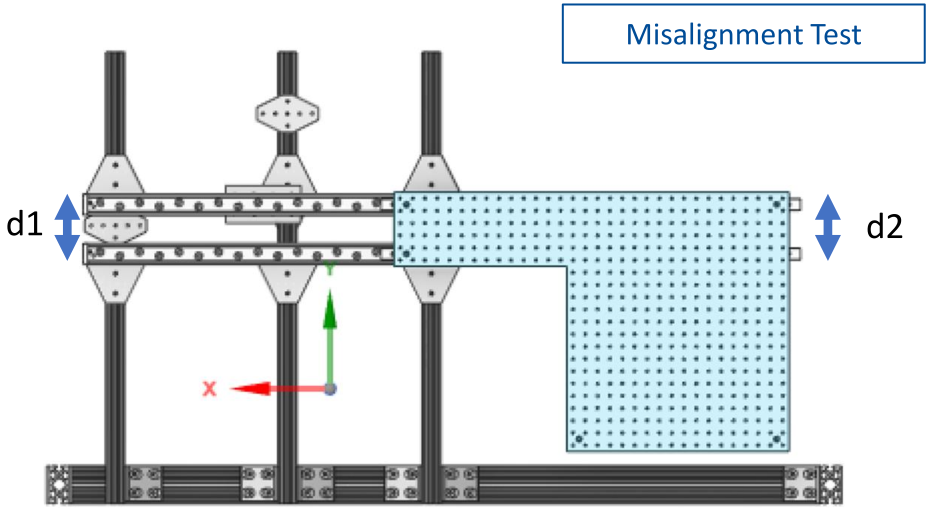
- Rail system and removable cover panel
  - Allow optical components to be replaced w/o removing entire box from laserwire station
  - Not expected to be opened often (~1/year)
  - Rails can be unlubricated
    - Will lubricate with radiation hardened grease
- Cable carrier
  - Organize cables when breadboard is slid in and out

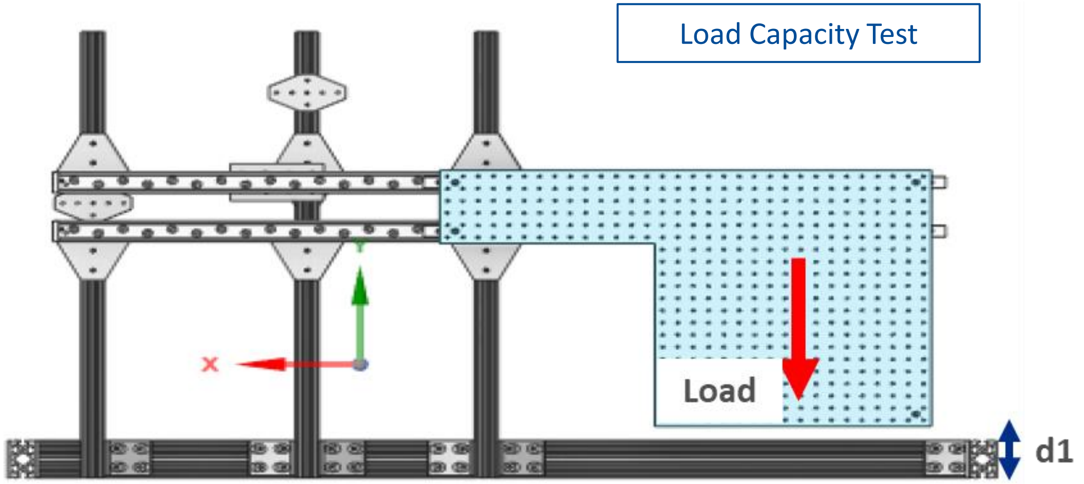




Input Optics Box – Top Rail Selection

- Considered 3 telescoping rail options
- Required features:
  - Radiation resistant material
  - Full extension of breadboard outside the box
  - Low profile
  - Handle expected and accidental loads
    - Nominal vertical loads and bending
- Bought and tested pairs of each rail option to determine the best option
  - Misalignment test
  - Load capacity test



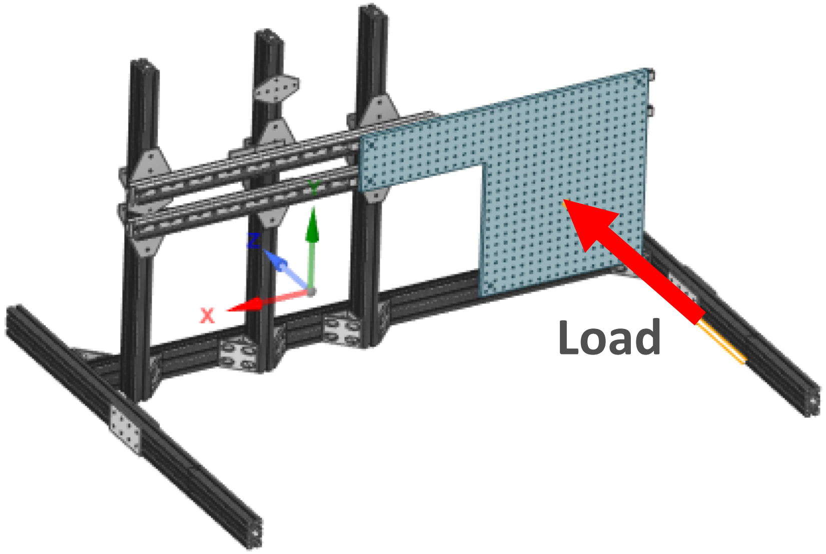


PIP-II

Input Optics Box – Top Rail Selection

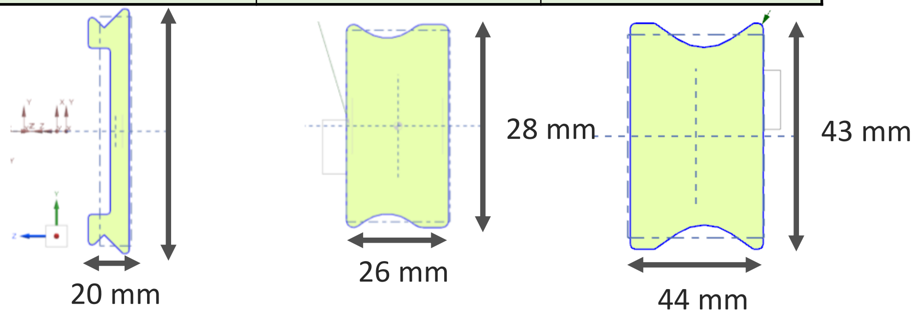
- Rail Bending Validation
  - Ensure that the rails can handle any accidental transverse loading when rails are fully extended
    - i.e. pushing against the board
  - Used bending stress formula for calculation
  - Result: all three rails could withstand accidental loading without permanently deforming

Bending Stress: $\sigma_b = \frac{My}{I}$



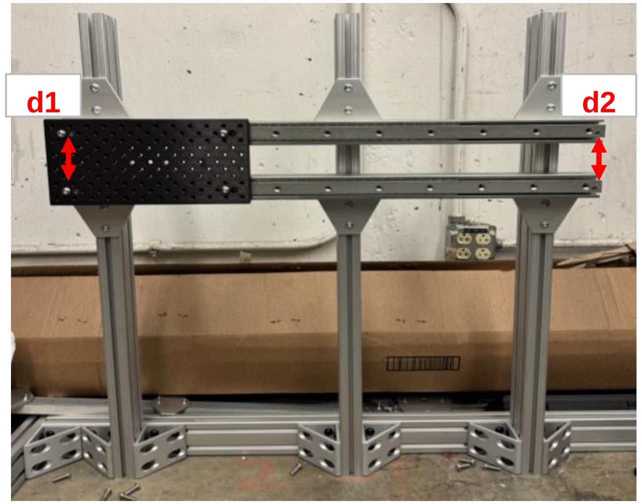
Rail	Sliding Sys. Rail	Rollon	McMaster
$I_{y'}$ (mm^4)	376.92	514.34	4541.82
Material	Aluminum	Steel	Steel
Yielding Force (N)	118.73	219.26	1074.41
Yielding Force (lbsf)	26.69	49.28	241.50

Rail arm cross sections



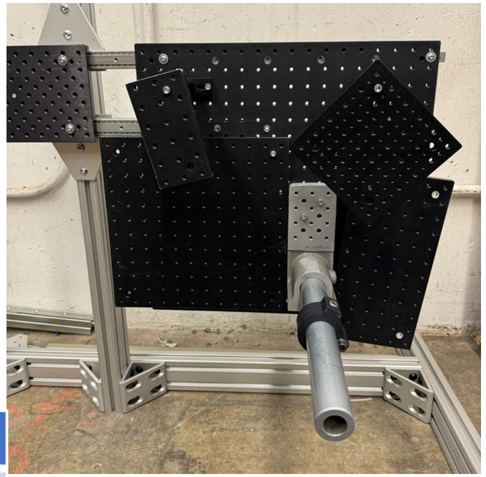
Input Optics Box – Top Rail Selection

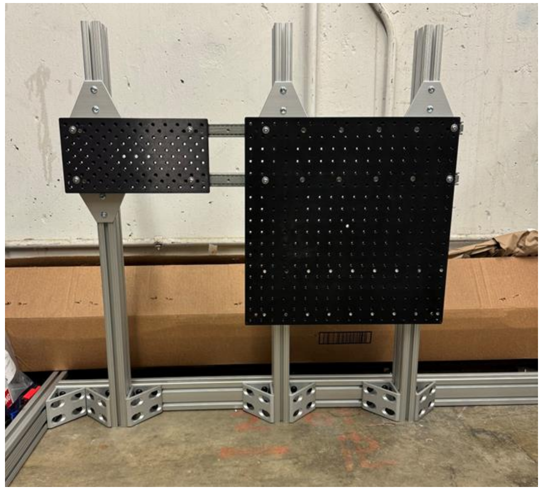
- Misalignment/Parallelism Test:
  - Purpose: Determine the allowable misalignment between the two rails
  - Result: Misalignment of rails did not inhibit operation for all three options
- Load Capacity Test:
  - Purpose: Observe and determine deflections when breadboard is loaded, and rails are extended
    - Ensure rails still return to original position
  - Result: Minimal vertical deflection. Some transverse deflections observed
    - Ideal to add more stability near bottom of breadboard



Misalignment Test

Rail Option	Allowable Misalignment
McMaster	2 mm
Rollon	6 mm
Sliding Systems	3 mm





Load Capacity Test

Rail Option	Max. Deflection
McMaster	2.61 mm
Rollon	2.89 mm
Sliding Systems	3.07 mm

Input Optics Box – Top Rail Selection

Rail Option	1	2	3
Company	McMaster Carr/Rollon	Rollon	Sliding Systems
Load Capacity (kg)	290	144.75 (pair)	135 (pair)
Stroke Length (mm)	866	866	830
Width/profile (mm)	44	26	20
Unlubricated option (Y/N)	Y	Y	Y
Material	Zinc-plated Steel	Zinc-plated Steel	7075 T6 Aluminum

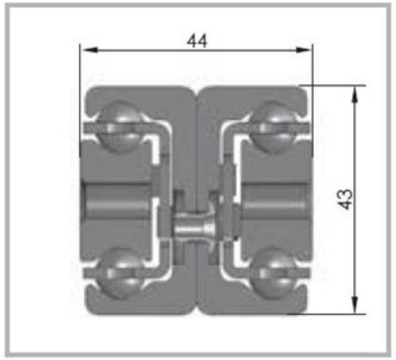


Fig. 17

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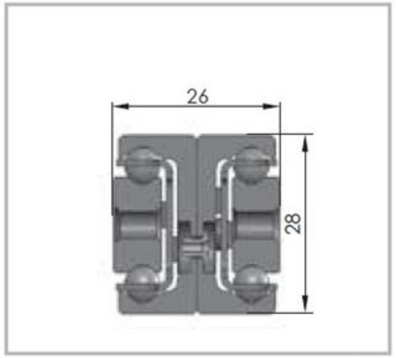

Fig. 15

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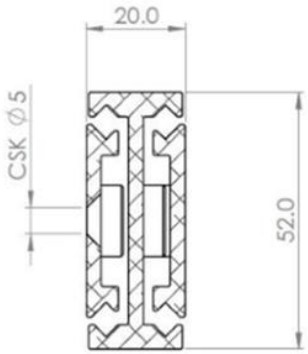
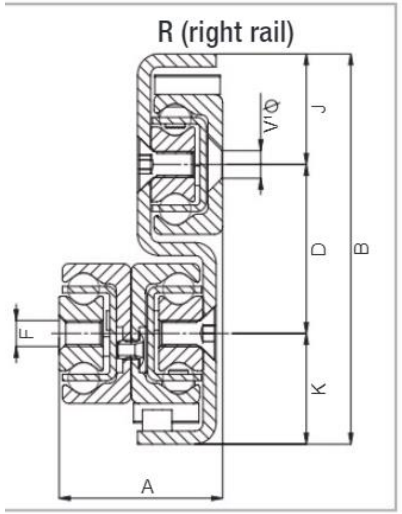
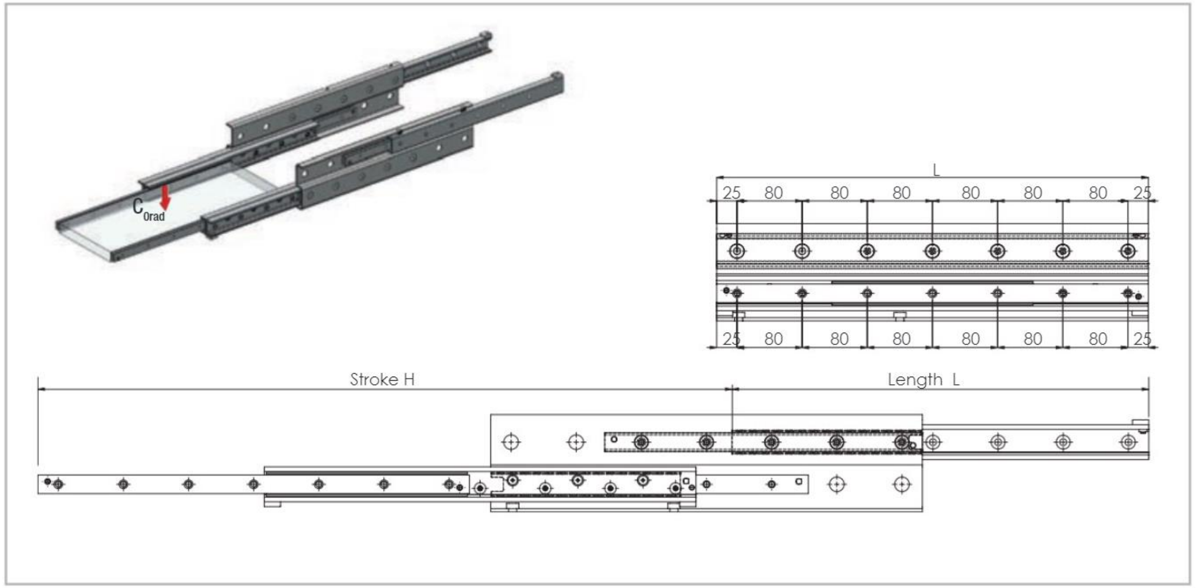


Input Optics Box – Bottom Rail Selection

Rail Cross Section and Specification Drawing

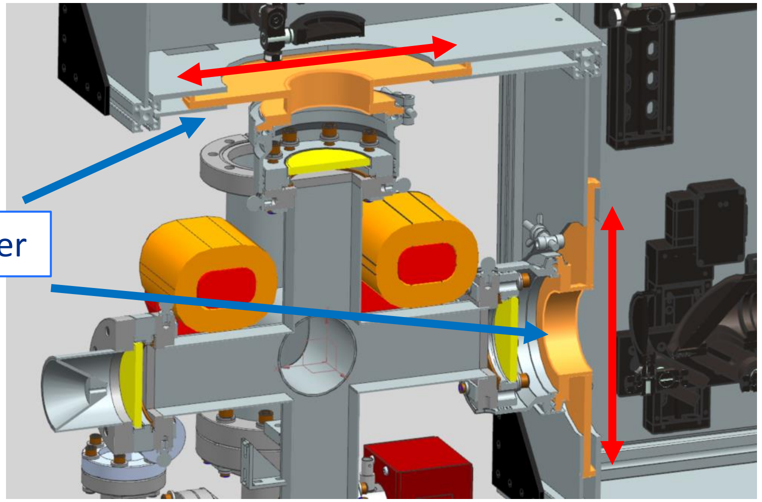
- Bottom rail added for stability
- Same manufacturer as top rail (Rollon)
- Rail Specs:
  - Rail Extension: 150% of its length (822 mm)
  - Material: Zinc-plated Steel
  - Load Capacity (pair): 147 kg
  - Unlubricated option?: Yes

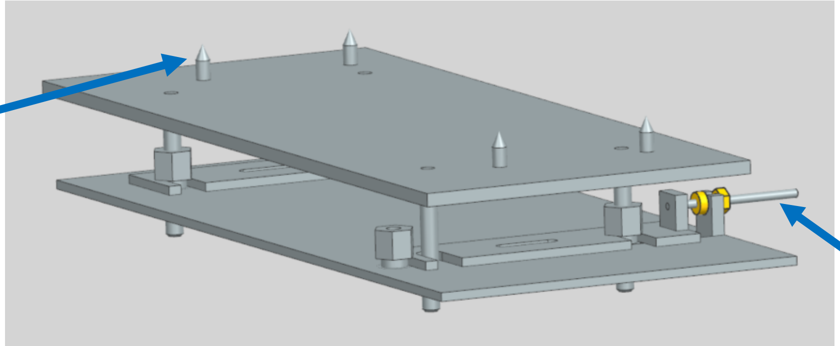




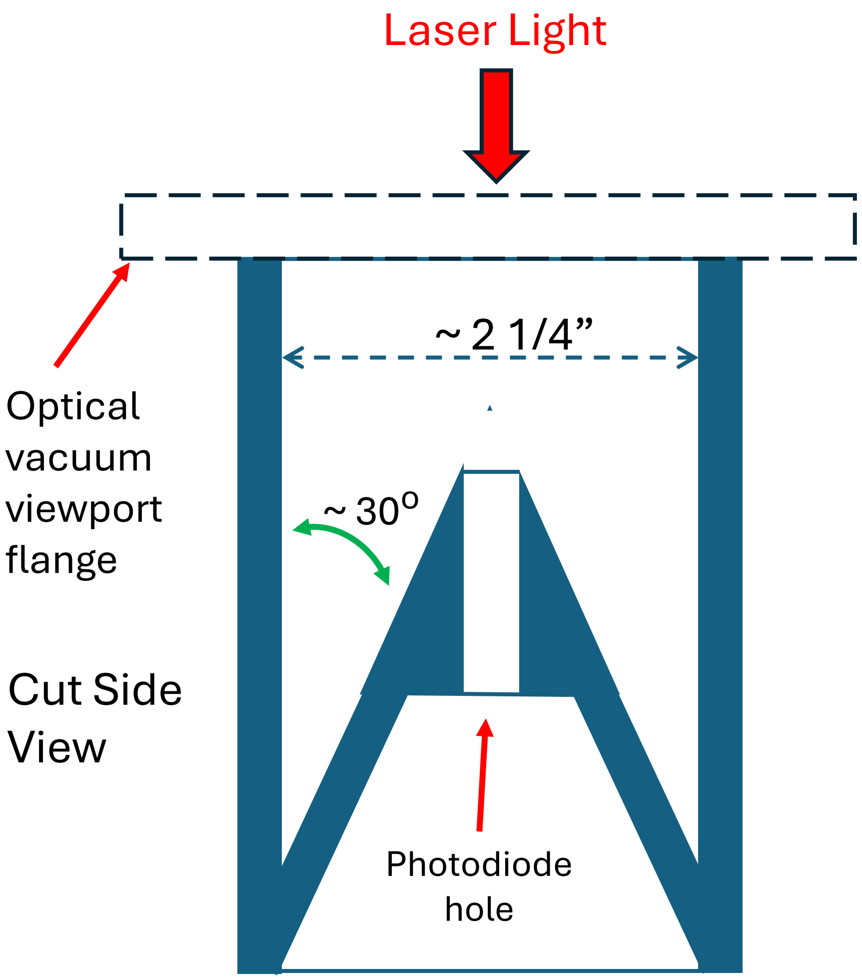
Input Optics Box – Alignment and Installation Features

- Sliding shutter design for vacuum flange connection
  - Allows for horizontal or vertical adjustment of the lens tubes over flanges when installing optics box
- Breadboard positioning switch/pin
  - Secures breadboard into a fixed position when inside optics box
- Alignment base plate
  - Interface between optics box and warm unit stand
  - Provides simple alignment and installation of box with optical transport line

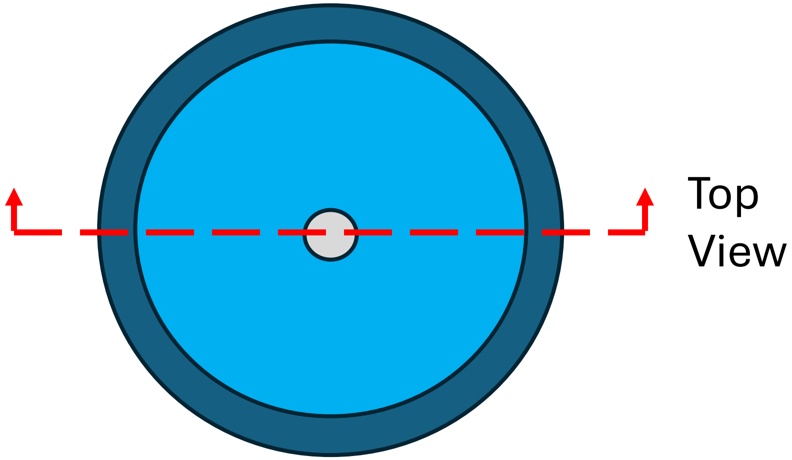


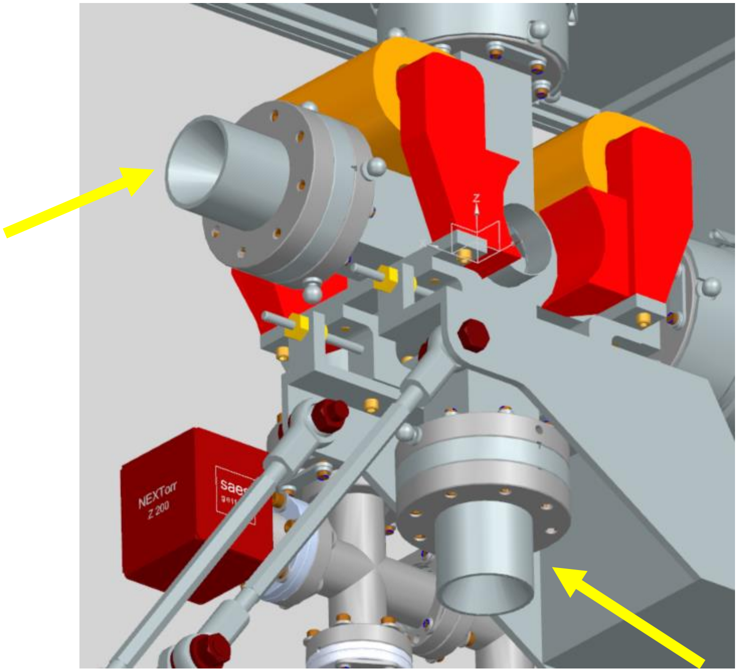


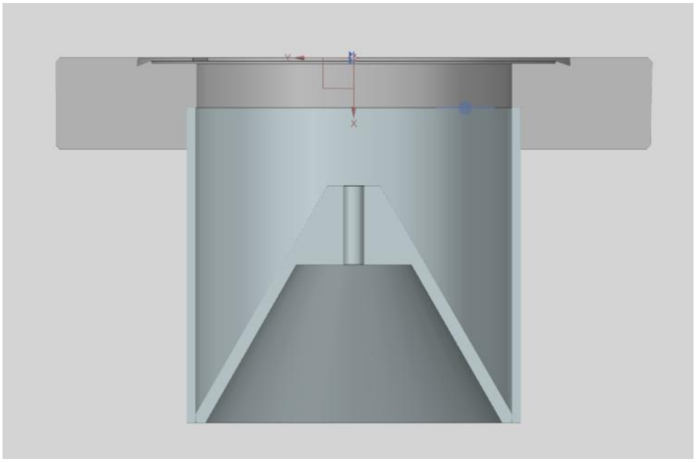
Output Dump Box – (part of last 10% of the design)



- Initial design input provided by V. Scarpine
- Dumps much simpler than output box from PIP2IT
- Will include photodiode to detect the presence of light
- Material: Black anodized aluminum (like input optics box)
- Final dimensions close to complete







Structural and Thermal Analysis Validation and Requirements

- Mechanical Validation Analyses criteria
  - Structural
    - Natural frequencies above 10 Hz and away from 60 Hz per study documented in ED0002931
    - Robustness with respect to yielding of material
  - Thermal
    - Mitigate possible high temperatures caused by power on magnets, especially on optical viewports
  - Optical Viewport laser energy deposition
    - Evaluate thermal effect of laser pulse energy deposition
      - Vendor recommends keeping temperature ramp below 2-3 deg C per minute https://www.lesker.com/viewports/viewports-cf-flanged-quartz-fused-silica.cfm?highlight=VPZL-450DU
      - Evaluate risk of thermo-mechanical stresses due to thermal gradients

ED0002931 - VIBRATION CONTROL BEST PRACTICES FOR PXIE:

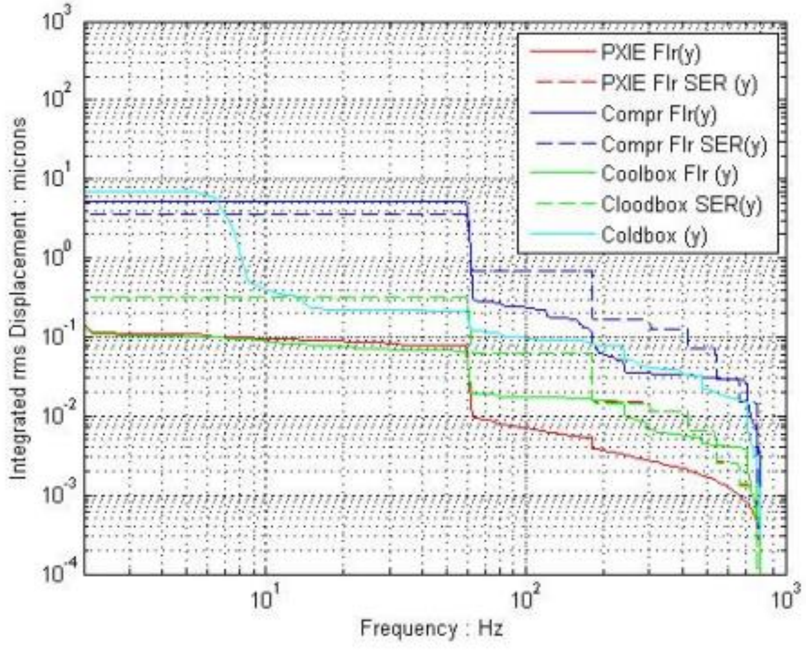


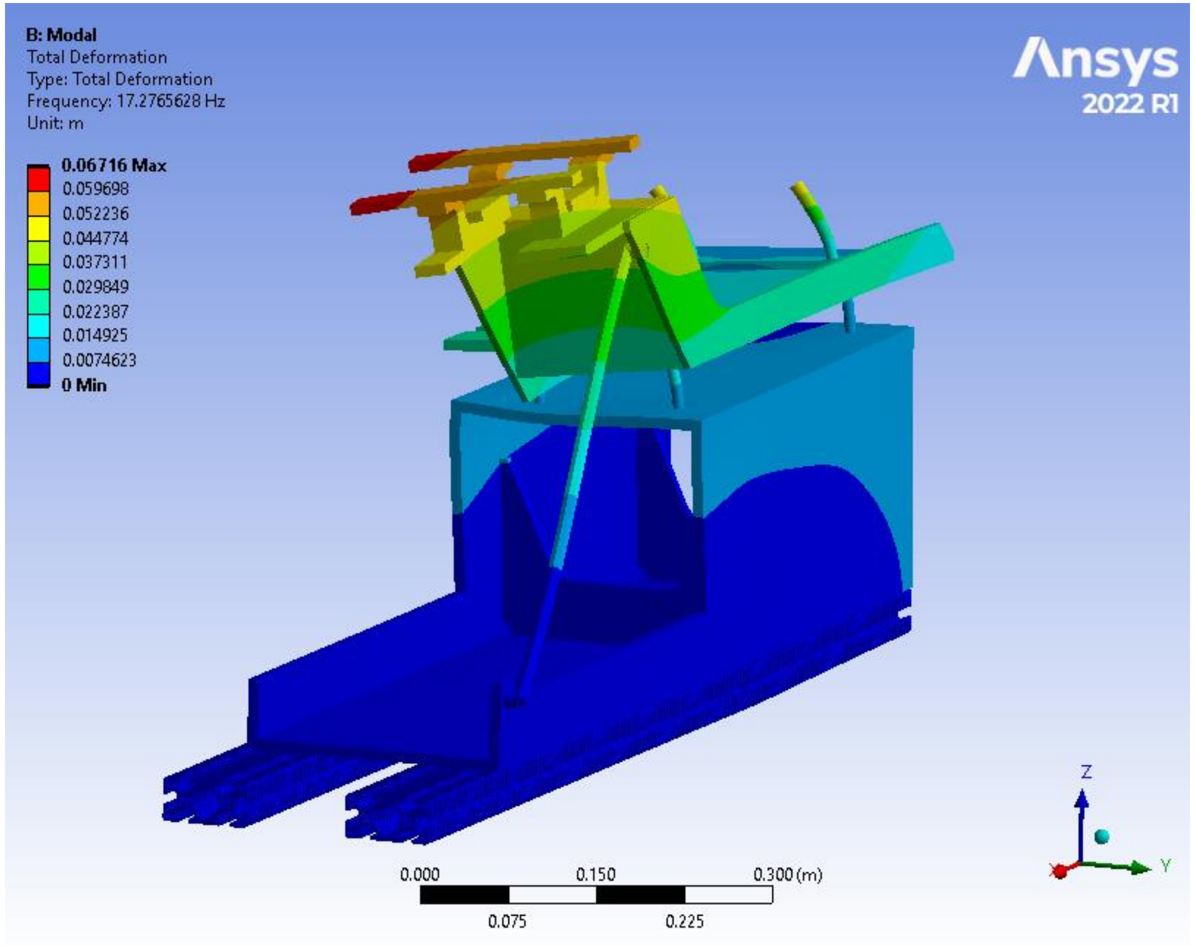
Figure 1: CMTF Integrated Vertical Displacement

Natural Frequencies – Stand

- Model and analysis assumptions
  - Stand fixed at mounting location on warm unit structure
  - Components mounted on stand were modeled as point masses
    - Box: 90kg
    - Chamber and attached components: 21 kg
    - Magnets: 22 kg
- Results
  - First mode is **17.3 Hz**, meeting > 10Hz requirement.
  - **No natural frequencies near 60 Hz**, the nearest modes are at 32.8 Hz and 93.4 Hz
  - All other modes are not of concern per ED0002931:

Mode	Frequency [Hz]
1.	17.2765628
2.	21.5647356
3.	23.5336209
4.	32.7570161
5.	93.3990076
6.	112.657462

First mode at 17.3 Hz

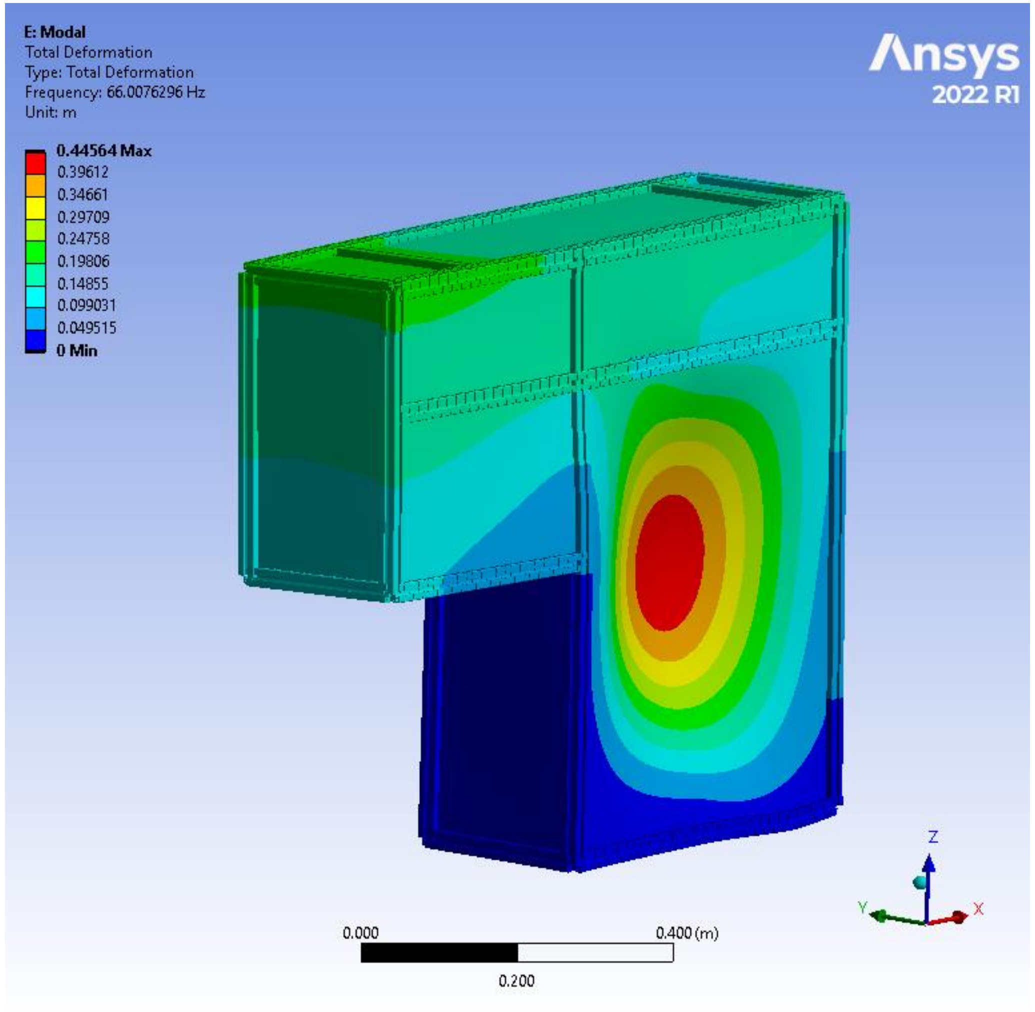


Natural Frequencies – Optical Boxes

- Model and analysis assumptions
  - All panels attached structurally to 25mm frame
  - Box fixed at bottom plate
  - Rails and board components modeled with a 39 kg point mass attached to mounting 25mm frame
- Results
  - First mode is **66 Hz**, meeting > 10Hz requirement and away from 60 Hz
  - All other modes are not of concern per ED0002931:

Mode	☑ Frequency [Hz]
1.	66.0076296
2.	73.341009
3.	135.646615
4.	155.672254
5.	158.047152
6.	185.134822

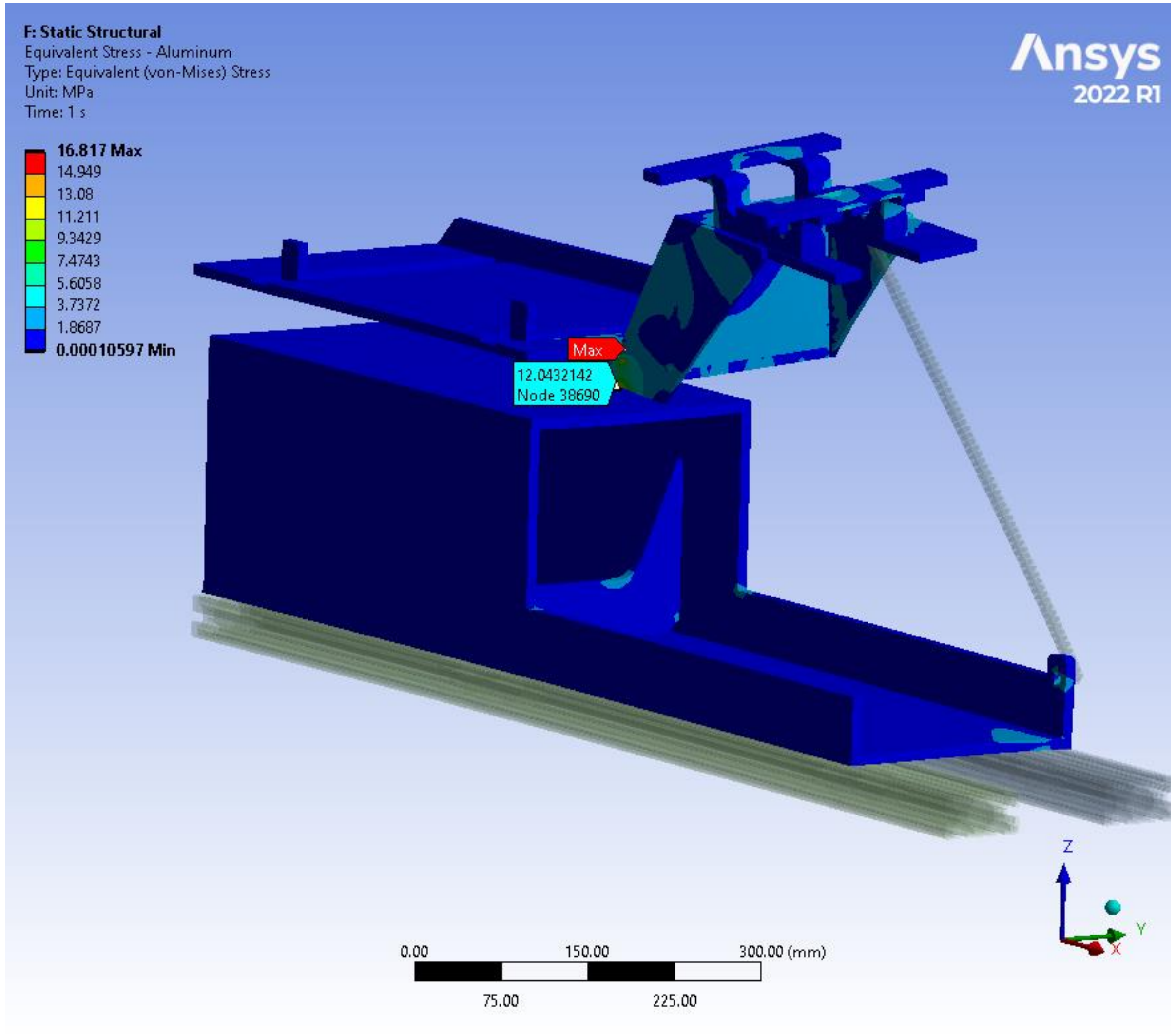
First mode at 66 Hz



Structural Analysis – Stress on Stand

- Model and analysis assumptions
  - Stand fixed at mounting location on warm unit structure
  - Components mounted on stand were modeled as point masses
    - Box: 90kg
    - Chamber and attached components: 21 kg
    - Magnets: 22 kg
- Results
  - 16.8 MPa maximum stress on Al 6061 components = **factor of safety of 16** for yield strength of 276 MPa
  - Due to artificial stress singularity in model for 3/8in rods, hand calculations will be performed for validation

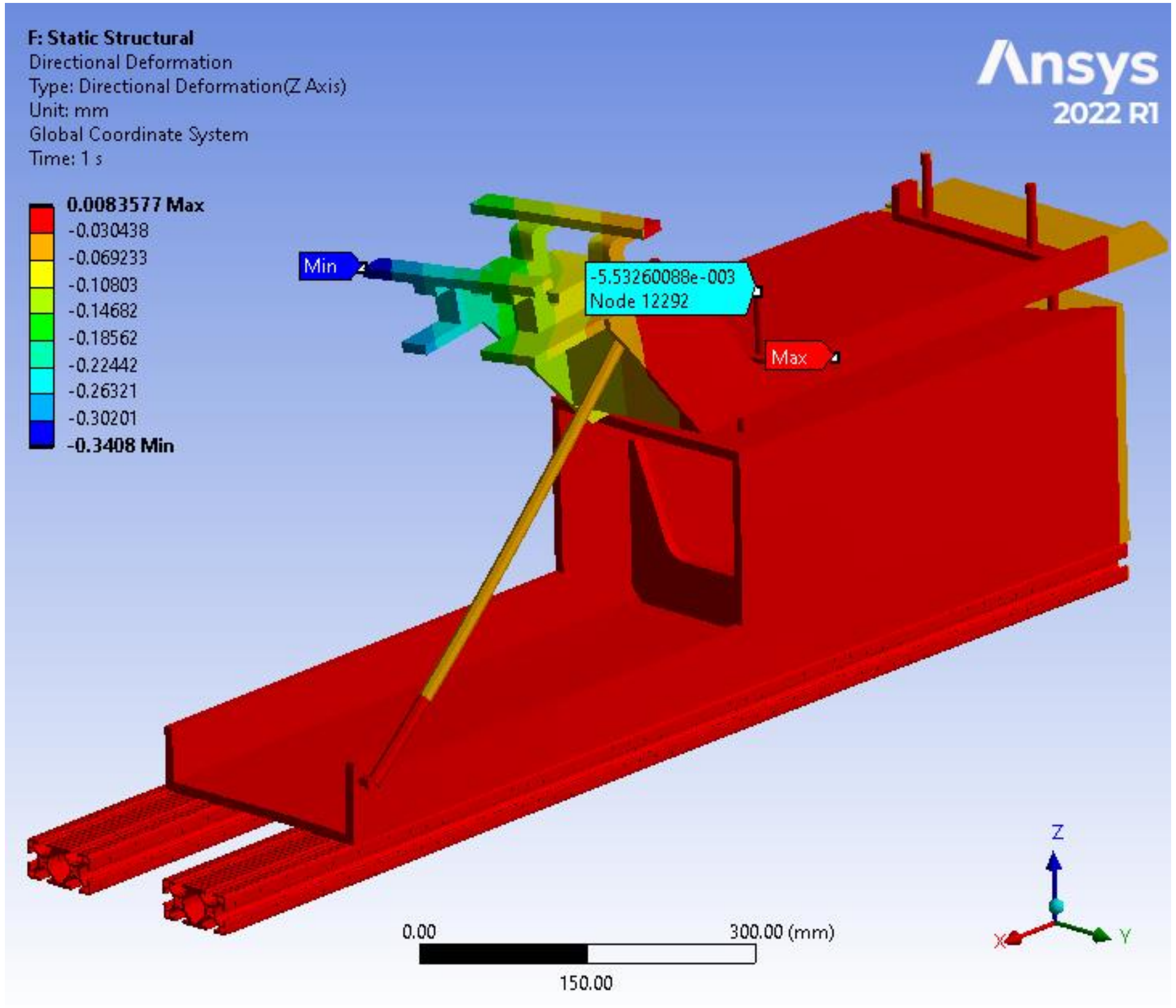
Von-mises stress results, 100X deformation scale



Structural Analysis – Deflections on Stand

- Model and analysis assumptions
  - Same assumptions as stress analysis of stand
- Results
  - Maximum deflection due to gravity of **0.34mm is not a concern** as alignment of vacuum chamber will rectify any deflection due to deformation
  - Deflection at optical boxes base is negligible in the 0.01mm to 0.03mm range

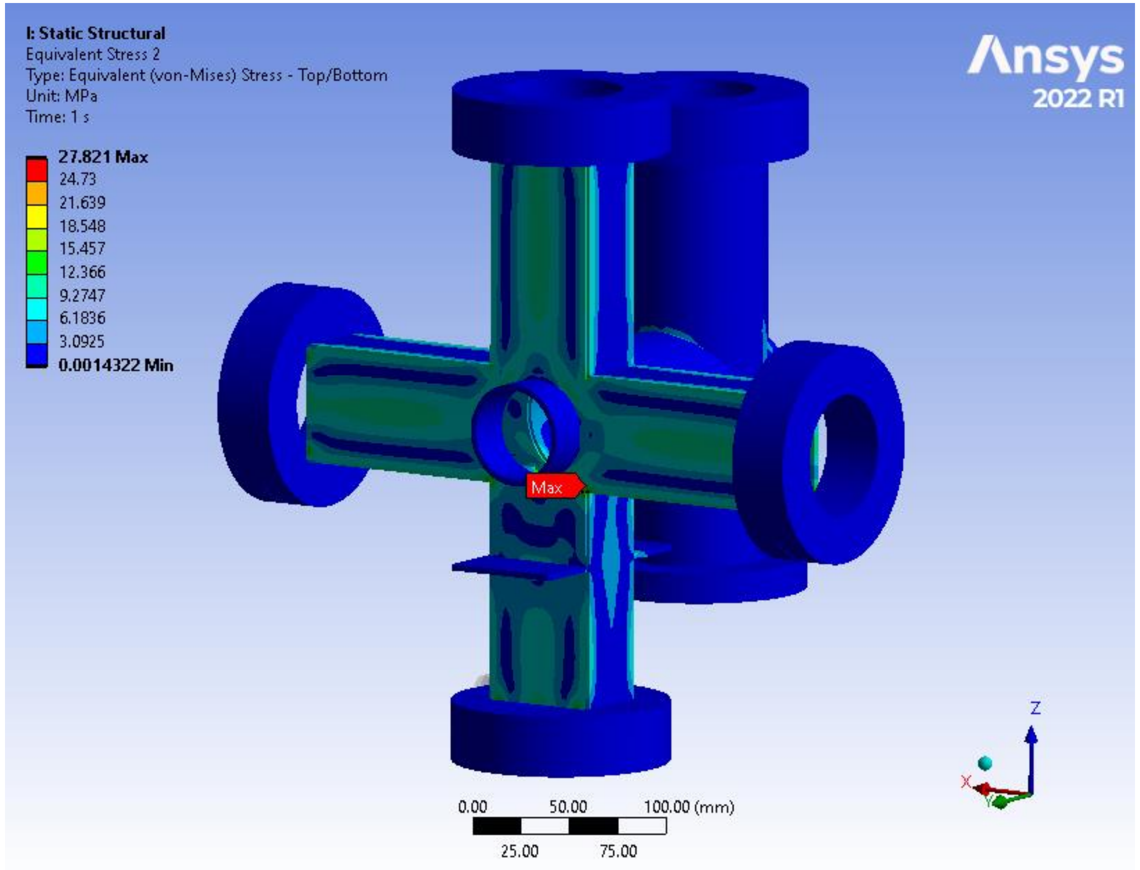
Deformation, 100X deformation scale



Structural Analysis – Stress from Vacuum Loads

- Model and analysis assumptions
  - 1/8in thick material
  - 101,325 Pa atmospheric pressure applied on outer faces
- Results
  - 27.8 MPa maximum stress on 1/8in thick 316L components = **factor of safety of 6.11** for yield strength of 170 MPa

Von-mises stress results, 100X deformation scale

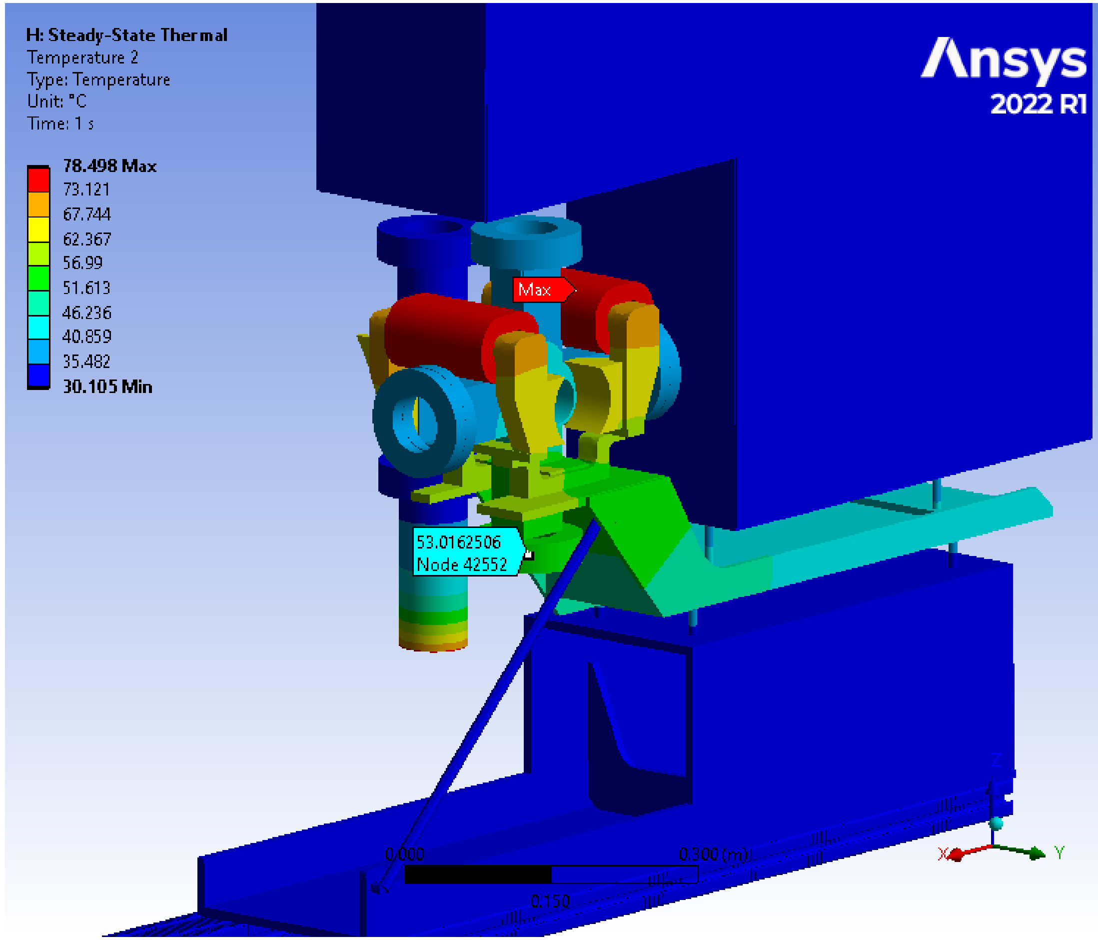


Thermal Analysis – Steady-State

- Model and analysis assumptions
  - 22.8W heat generation at the magnet coils for laser wire unit at the highest beam energy
  - 10 W from vacuum pump and gauges added as heat flow
  - 7 W/m^2K convection to 30 deg C ambient air
  - Steady-state, equilibrium analysis
- Results
  - 78.5 deg C maximum temperature at the magnet coils
  - 53 deg C maximum temperature at vacuum window

Laser Wire Unit	Magnet Power, W
1	0.0403
2	0.1907
3	0.3564
4	1.1992
5	2.1245
6	3.1604
7	4.0204
8	5.7973
9	9.2314
10	12.4972
11	16.6865
12	22.8295

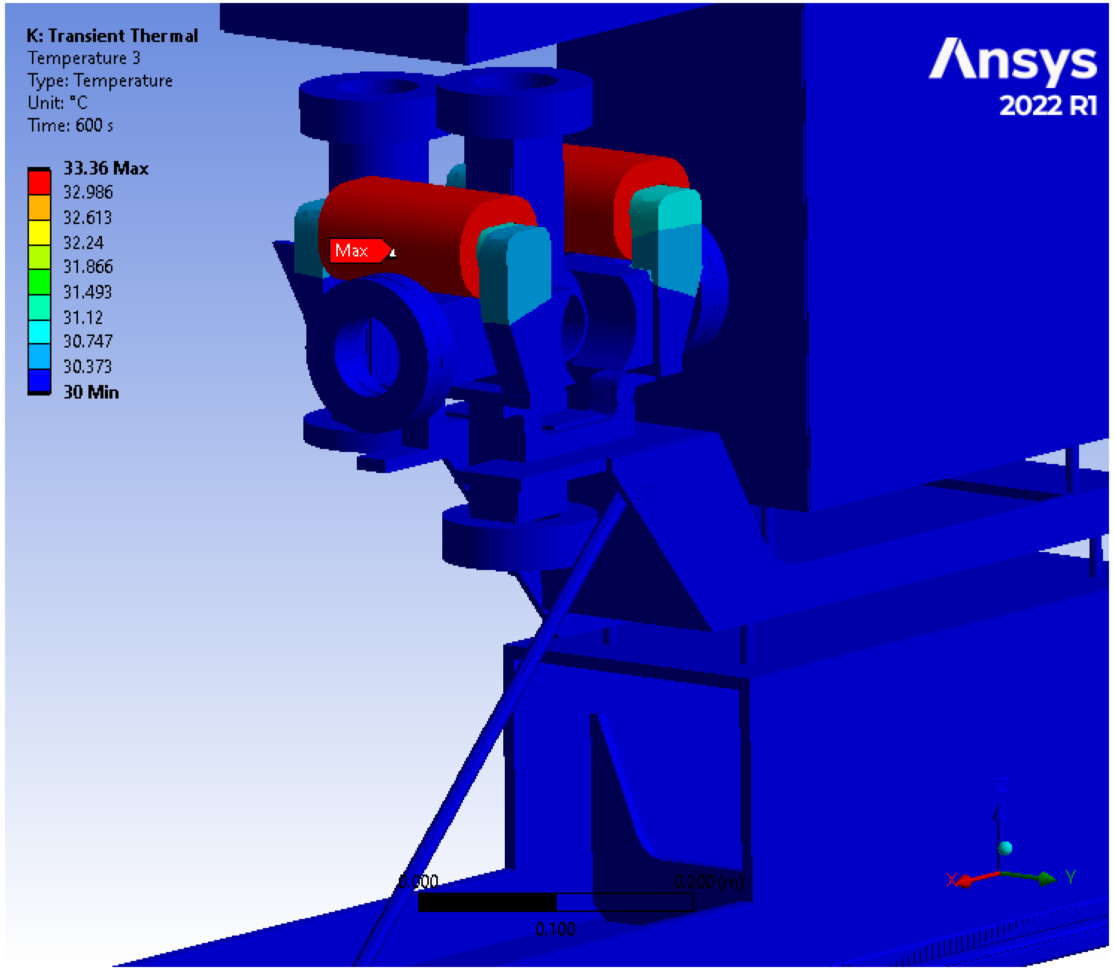
Temperature results:



Thermal Analysis – Transient

- Model and analysis assumptions
  - 22.8W heat generation at the magnet coils for laser wire unit at the highest beam energy
  - 10 W from vacuum pump and gauges added as heat flow
  - 7 W/m^2K convection to 30 deg C ambient air
  - Transient-thermal analysis, 30 deg C initial temperature, first 10 minutes after powering up magnets
- Results
  - **~0.5 deg C per minute** temperature rise at the magnet coils
  - Viewports temperature increase lag behind coils, and temperature increase per minute is expected to be lower

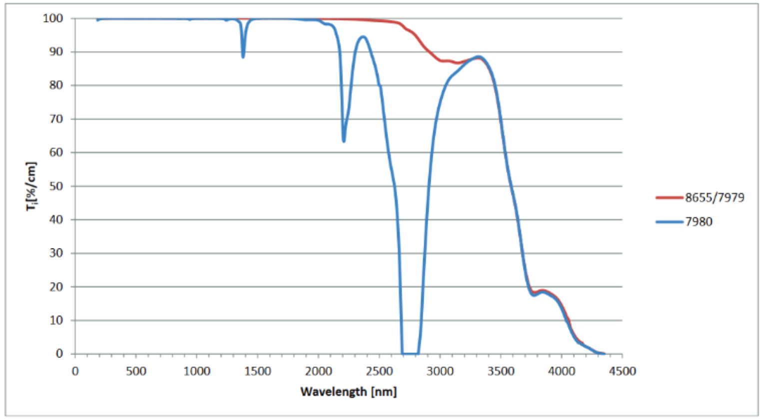
Temperature results after 10 minutes:



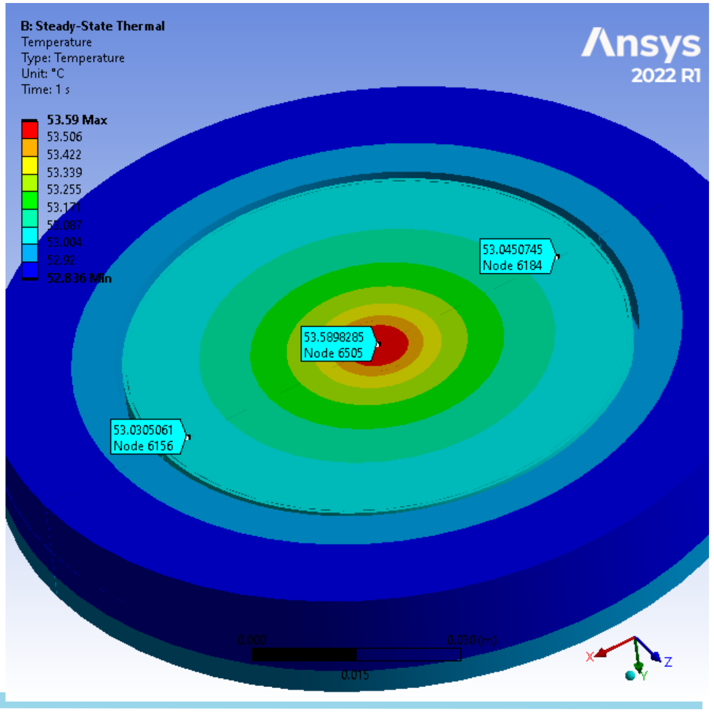
Steady-State Thermal Analysis – Optical Viewport

- Model and analysis assumptions
  - **50 mJ laser power on 1 cm^2 for each 10-microsecond pulse** = 1 W average power over time
  - 99% transmittance at laser wavelength = 1% of laser power is deposited into fused silica glass as heat
  - Steady-state analysis, 53 deg C (for highest power magnets) constant temperature at flange contact with chamber, 7 W/m^2K convection to 30 deg C air
- Results
  - Steady-state thermal analysis of window shows a **<1 deg C temperature gradient** on the glass, thermo-mechanical stresses caused by laser energy deposition are minimal

Broad Spectrum Internal Transmittance



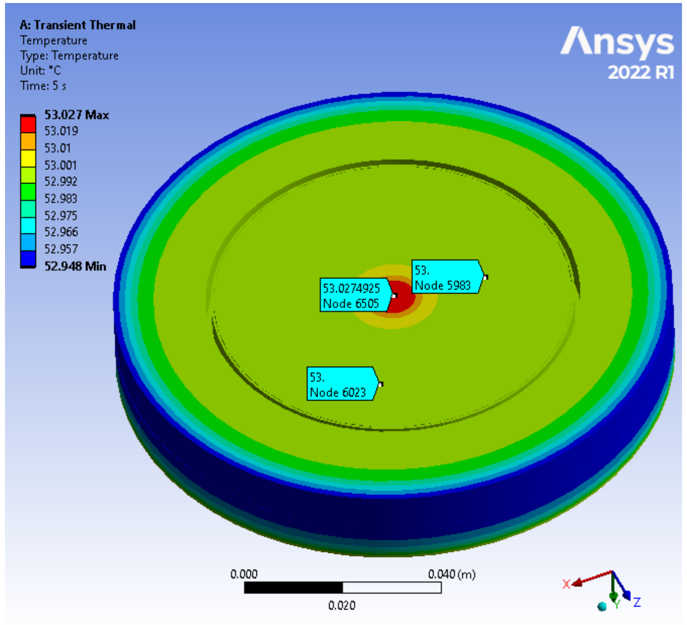
Temperature results:



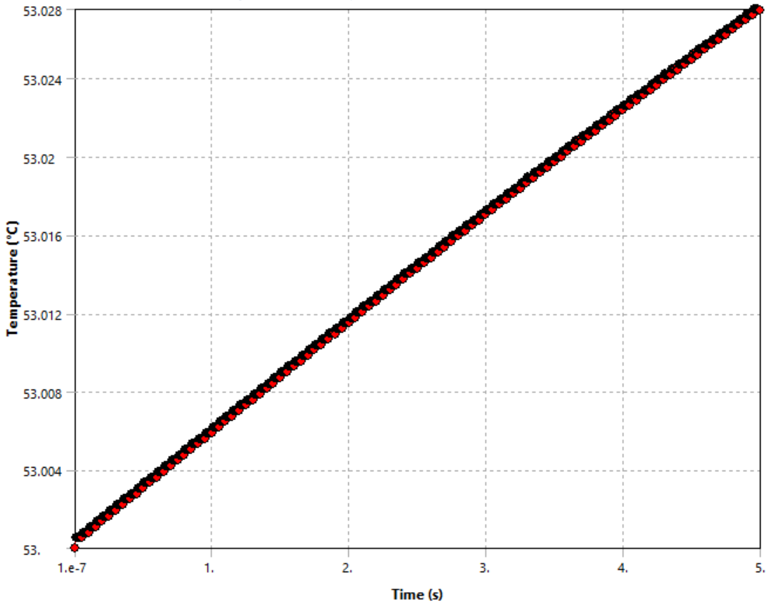
Transient Thermal Analysis – Optical Viewport

- Model and analysis assumptions
  - **50 mJ laser power on 1 cm^2 for each 10-microsecond pulse** = 5000 W instantaneous power at each pulse, followed by cooling time between pulses
  - 99% transmittance at laser wavelength = 1% of laser power is deposited into fused silica glass as heat
  - Transient-thermal analysis, 53 deg C initial temperature, 53 deg C (for highest power magnets) constant temperature at flange contact with chamber, 7 W/m^2K convection to 30 deg C air
- Results
  - Transient thermal analysis shows that for each pulse, temperature increase is **~0.00028 deg C. At 5 seconds**, temperature **gradient is ~0.028 deg C**

Temperature results after 5 seconds:

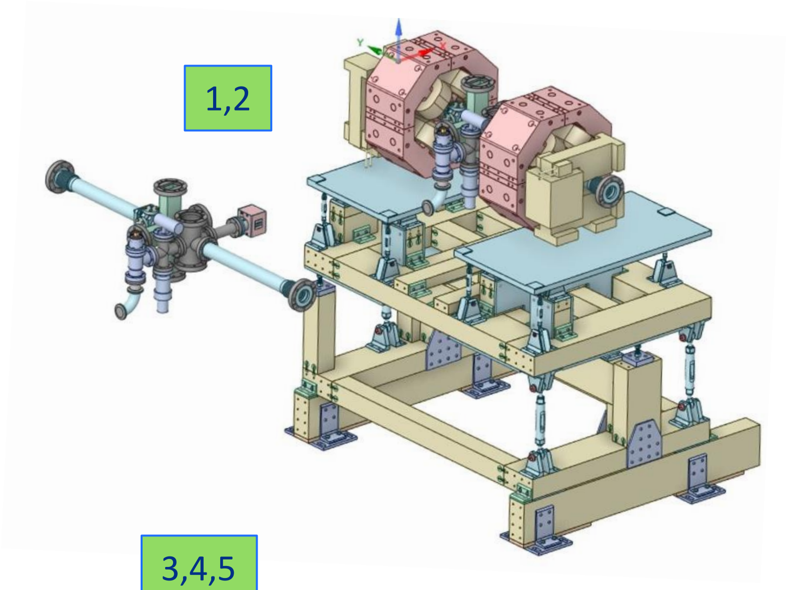


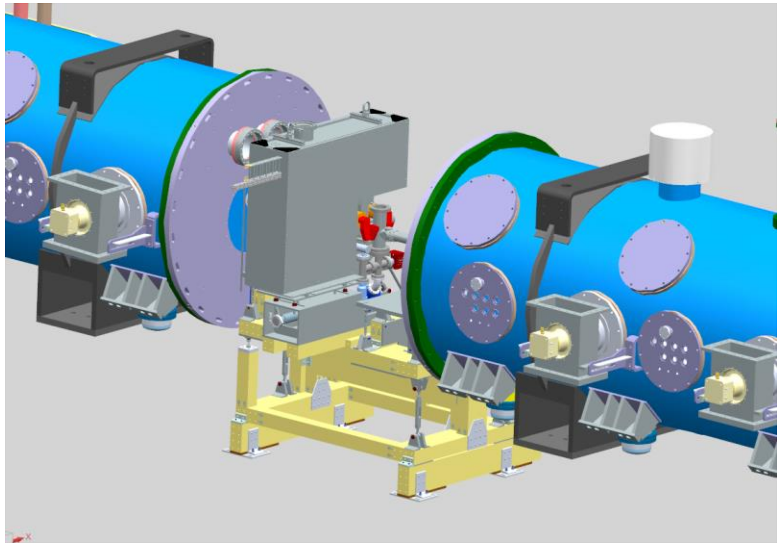
0.28 deg C temp increase after 5 seconds:



Installation Procedure

1. Vacuum chamber is integrated with warm units vacuum assembly and installed with laser wire stand on warm unit structure along with warm quad magnets
2. Laser wire magnets are installed
3. Warm units including vacuum, beam instrumentation, magnets, and structures are installed between cryomodules and vacuum connections are made
4. Laser wire vacuum chamber is aligned by alignment group
5. Optical boxes base plate is aligned with laser alignment jig
6. Optical boxes are installed and fastened in place, with light-tight interfaces with vacuum chamber laser ports





Remaining 10% of Final Design and Path Forward

- Complete remaining 10% of the design
  - Finalize the design of the faraday cup and laser dumps
  - Complete engineering drawings
- Continue working with PIP-II Vacuum Systems to integrate vacuum chamber in warm unit vacuum assembly, including joints with adjacent bellows and BPMs
- Fabricate the first unit
  - Verify assembly and installation processes
  - Install assembly in warm unit structure and verify ergonomics for installation
  - Verify structural and thermal modeling assumptions and correlate analyses as appropriate
  - Make any updates to design for full production laser wire system

Summary

- Operational PIP2IT system was built and commissioned. It validated many of the mechanical components that are used in the PIP-II system
- Structural analyses show that the system is robust with respect to vibration and yielding of material. Thermal results are correlated with physical testing results and show relatively high magnet coil temperature for conditions and assumptions analyzed, and low thermal gradient at the optical viewport glass
- Remaining 10% of design is progressing
- First laser wire unit will be built to verify fit, ergonomics, and installation and maintenance procedures

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