# Optical Transport Line – Vacuum and Mechanical Systems

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PIP-II Beam Instrumentation Laser Wire
Final Design Review

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A Partnership of:
- US/DOE
- India/DAE
- Italy/INFN
- UK/UKRI-STFC
- France/CEA, CNRS/IN2P3
- Poland/WUST

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# Optical Transport Line – Overview

- The Optical Transport Line (OTL) is a portion of the Laserwire Beam Profile Monitor system.
- The main goal of the OTL is to safely provide a clean path for the free-space laser to travel. The OTL will house components that begin steering the laser towards the beamline for profile measurement.
- The OTL begins at the Laser Hut on the upstream end and ends 200 meters downstream at the end of the PIP-II Linac.
- The approximately 200 meters of aligned beam tube allows the laser to travel to the 13 Mirror Box locations.
- The Mirror Boxes contain pick-off mirrors and other optical diagnostic components that steer and measure the laser path.

# Overview cont…

- The pick-off mirrors are driven in and out of the laser path by mechanical linear stages. They turn the laser path 90° downward at locations that have Laser Optics Boxes. These are the locations where beam profile will be measured.
- The scope of the OTL is from the upstream Laser Hut to the furthest downstream Mirror Box, and from the ceiling where the Mirror Boxes are mounted down to the transition to the Optics Boxes below.
- The entirety of the OTL is under rough vacuum.
- The system contains a vacuum safety switch for protection from the laser.

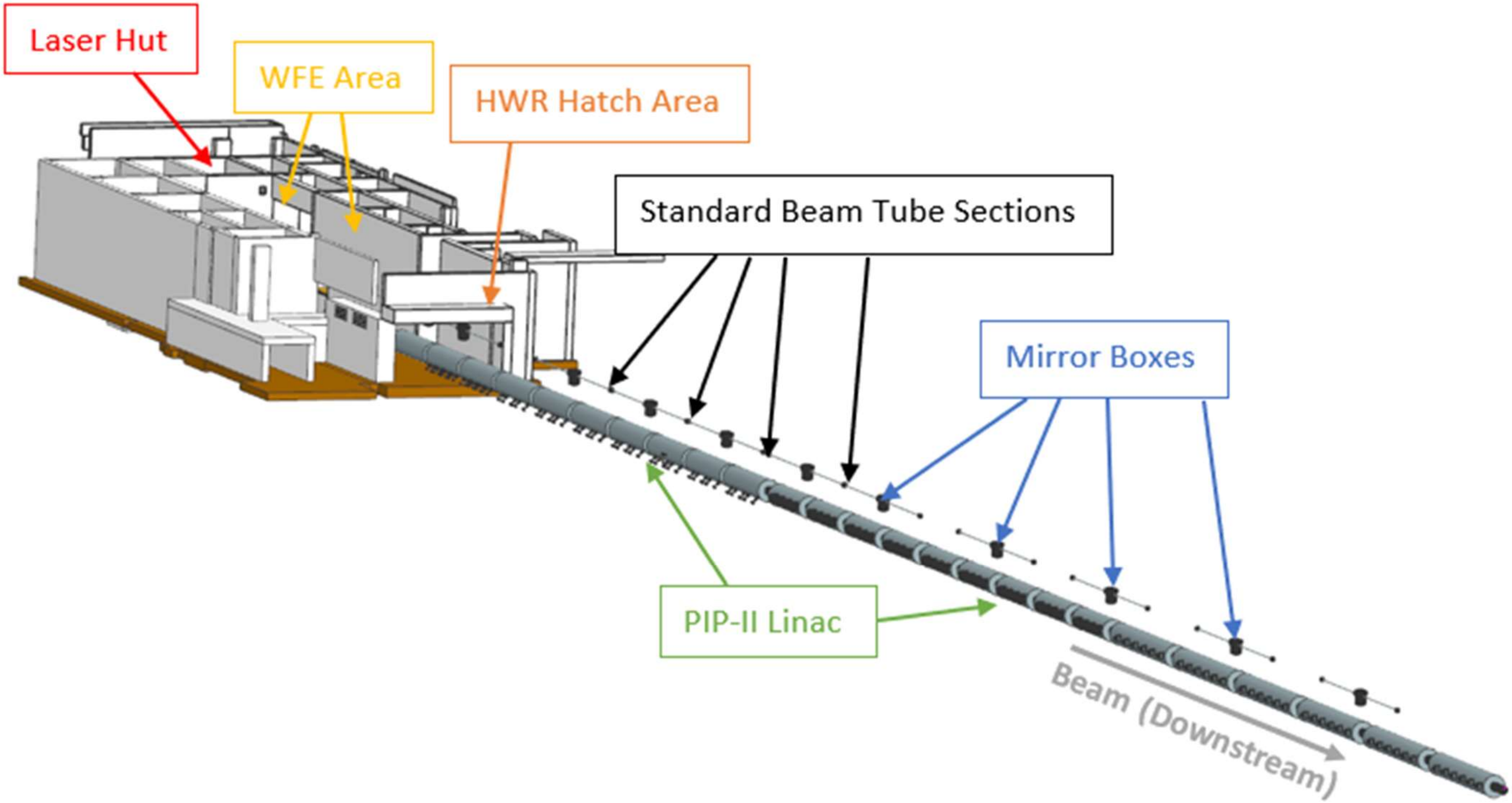
# Additional Instrumentation Locations

- The original request for the OTL included 13 mirror boxes.
- Materials and labor estimates have included this number.
- The initial design laid out 12 locations for mirror boxes along the PIP-II Linac.
- The final location has been decided for the 13$^{th}$ mirror box at the end of the Linac.
- Existing mirror box design is sufficient for the 13$^{th}$ mirror box. As the CF model evolves, potential interferences are expected to populate in that general area, we must keep an eye on the last location of the mirror box
- There will be a future 14$^{th}$ box installed upstream of the shield wall in the WFE. This box will act as a "feedback box" to correct the laser alignment as it continues down the 200m OTL.
- No ceiling in WFE, something similar to the HWR Hatch Hanger would potentially be utilized to hang this additional box.

# General Requirements

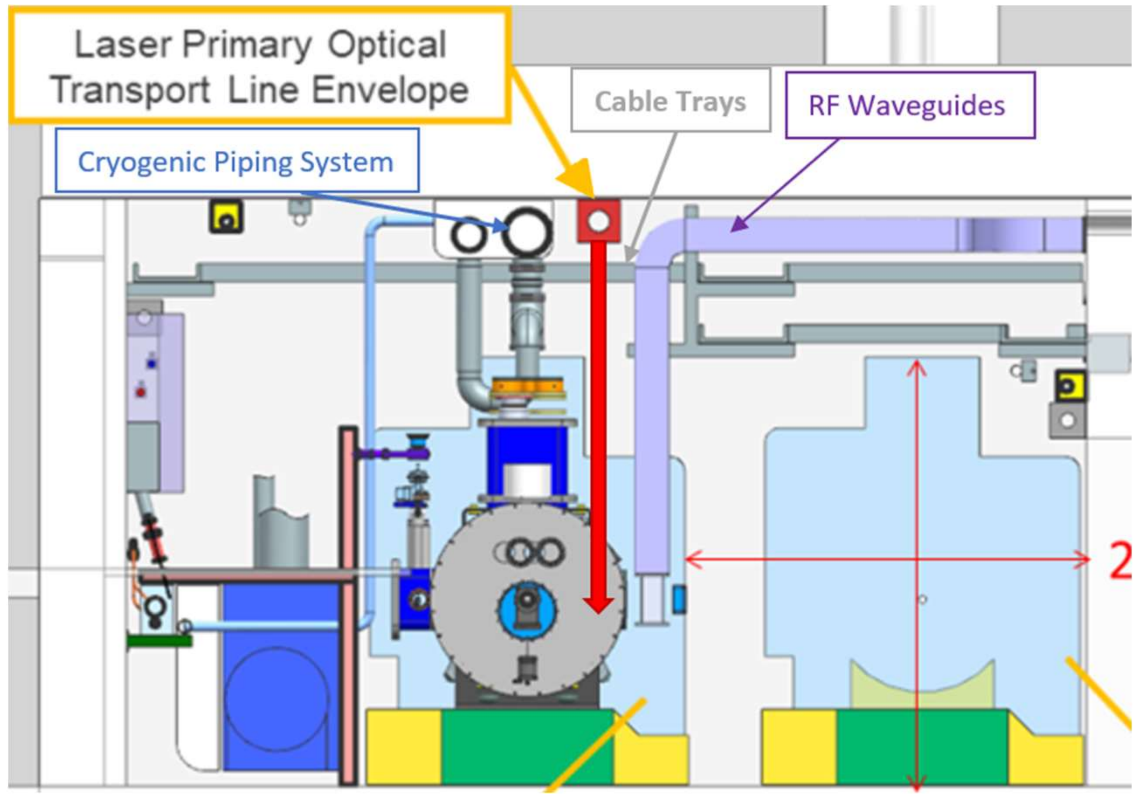
- 90mm (3.54”) aperture size requirement for entire length (longitudinally).
- Approximately 200m (650’) in total length.
- 12” x 12” envelope for installation at the ceiling in the PIP-II tunnel.
- 13 mirror boxes – initial size 18” W x 24” H x 12” D
- 13 mirror boxes + 1 feedback box – new size 21” W x 21” H x 12” D
- Removeable lid with access to install, inspect, and replace mirror components.
- Span the gap at the HWR hatch (no ceiling to mount to).
- Span the WFE area (no ceiling to mount to).
- Integrate the upstream end of the beamline into the Laser Hut.
- Design for total range of adjustability of all components to ±1” in all directions (xyz). Fine adjustment required. Maintain optically straight beam tube within 5mm.
- System vacuum requirement of <250 mTorr.
- No visibility of laser beam allowed.

# OTL and Mirror Boxes above Linac



# Cross-Sectional View of Tunnel

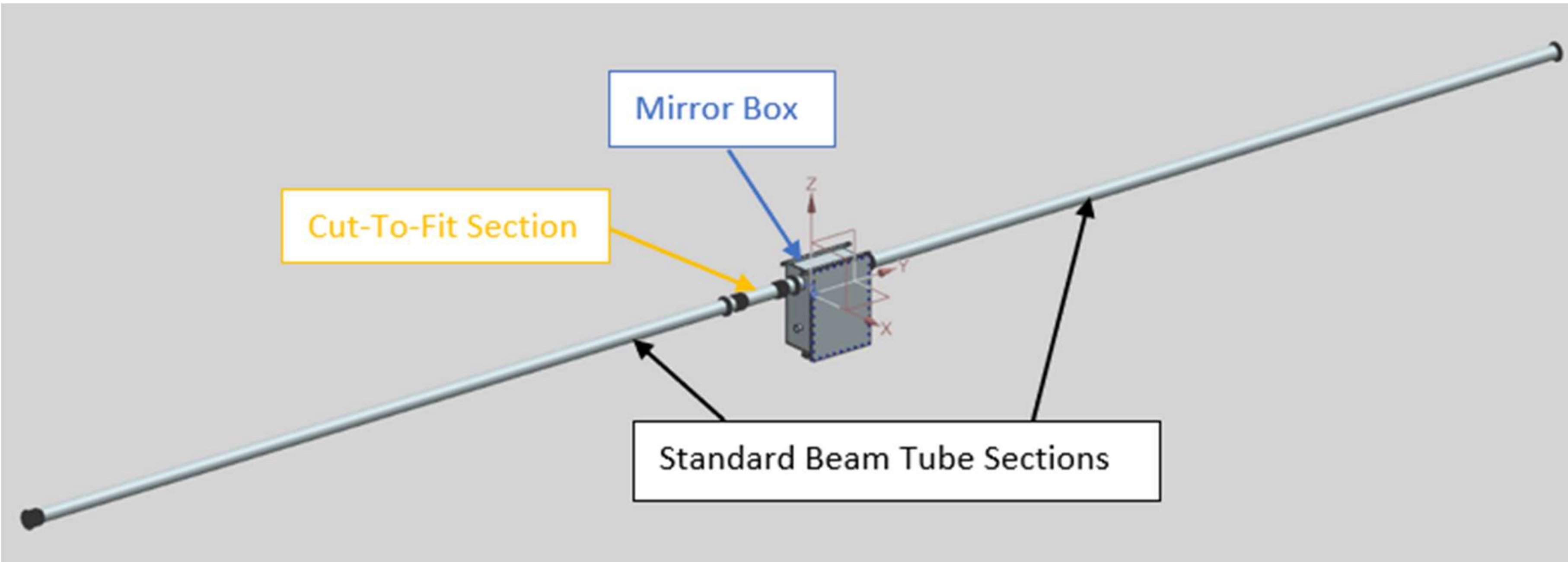
- 12" x 12" envelope for optical transport line.
- Shares physical space with cryogenic piping header.
- Shares physical space with cable trays.
- Shares physical space with RF Waveguides.
- Interface with CF to make connections at the ceiling.
- Interface with Laser Optics Boxes to connect laser path to the beam line (see red arrow).
- Access for installation and service of transport line is from the main aisle (right).



# Base Components of the OTL

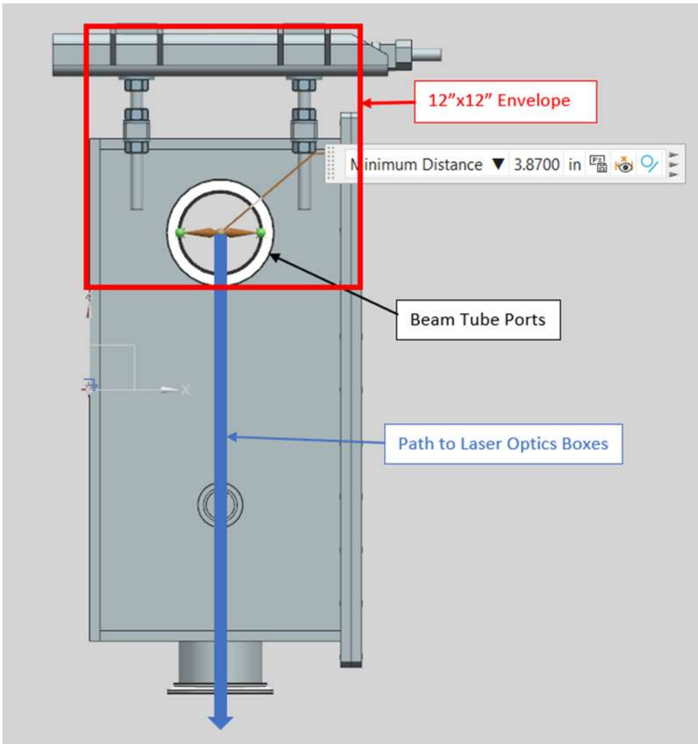
1. Standard Section (repeating components)
2. Mirror Box (Optical Junction Box)
3. Downpipe to Optics Boxes
4. Mirror Box Hangers
5. Beam Tube Hangers (Linac Area)

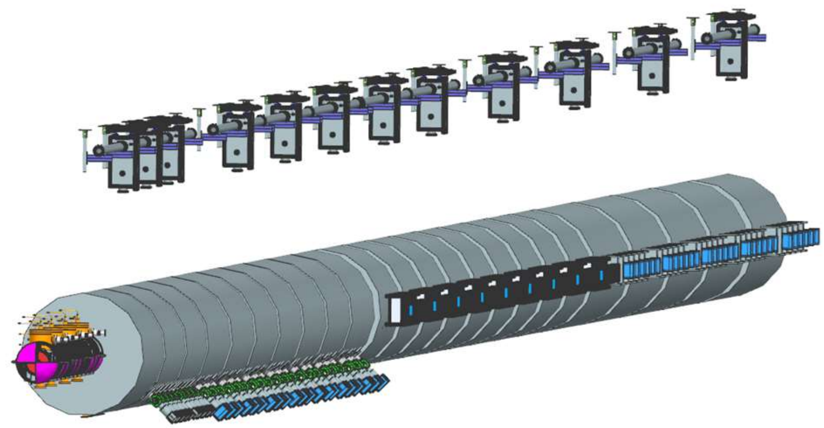
# Standard Section - Optical Transport Line Components




A standard section of the Optical Transport Line consists of a Mirror Box, some quantity of the standard 20’ long beam tube sections, and a cut-to-fit beam tube section.

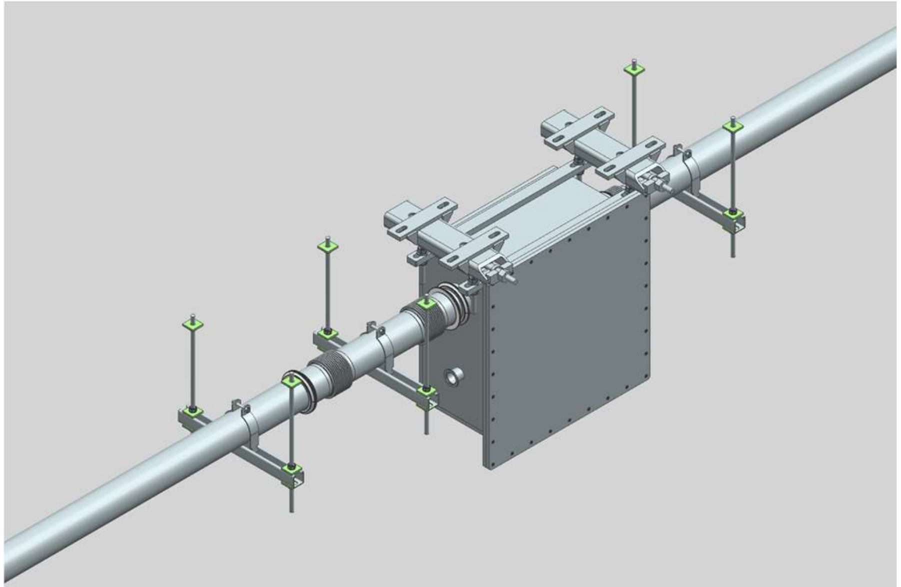
# Aperture and Length

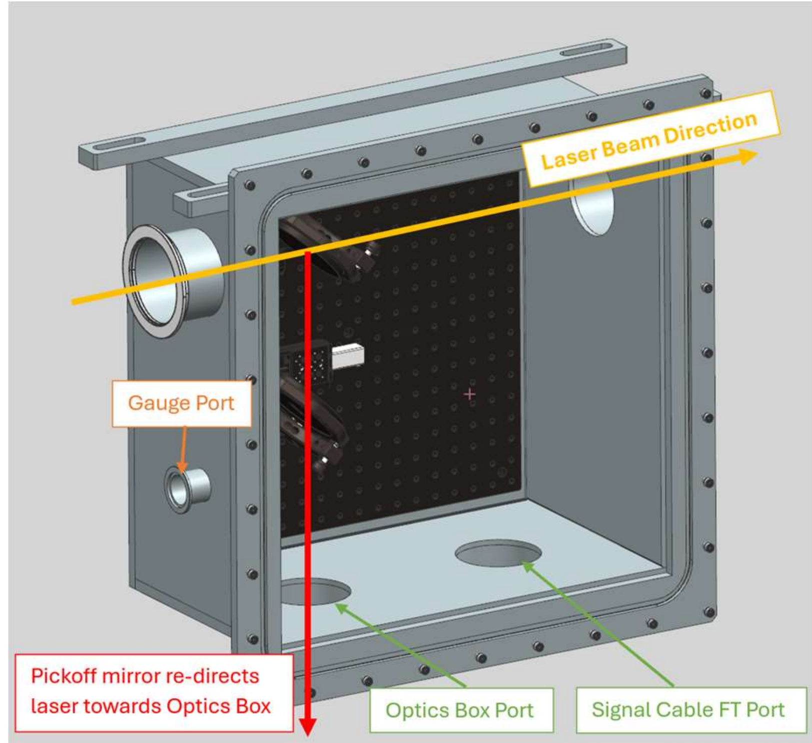


- 3.87" aperture is maintained along the entire laser line.
- Transport line is confined within the 12" x 12" envelope specified by PIP-II.
- Row view of 12 (13th out of view) Mirror Boxes above PIP-II Linac.
- Total of 200 meters from Laser Room to end of OTL.

# Mirror Box Design



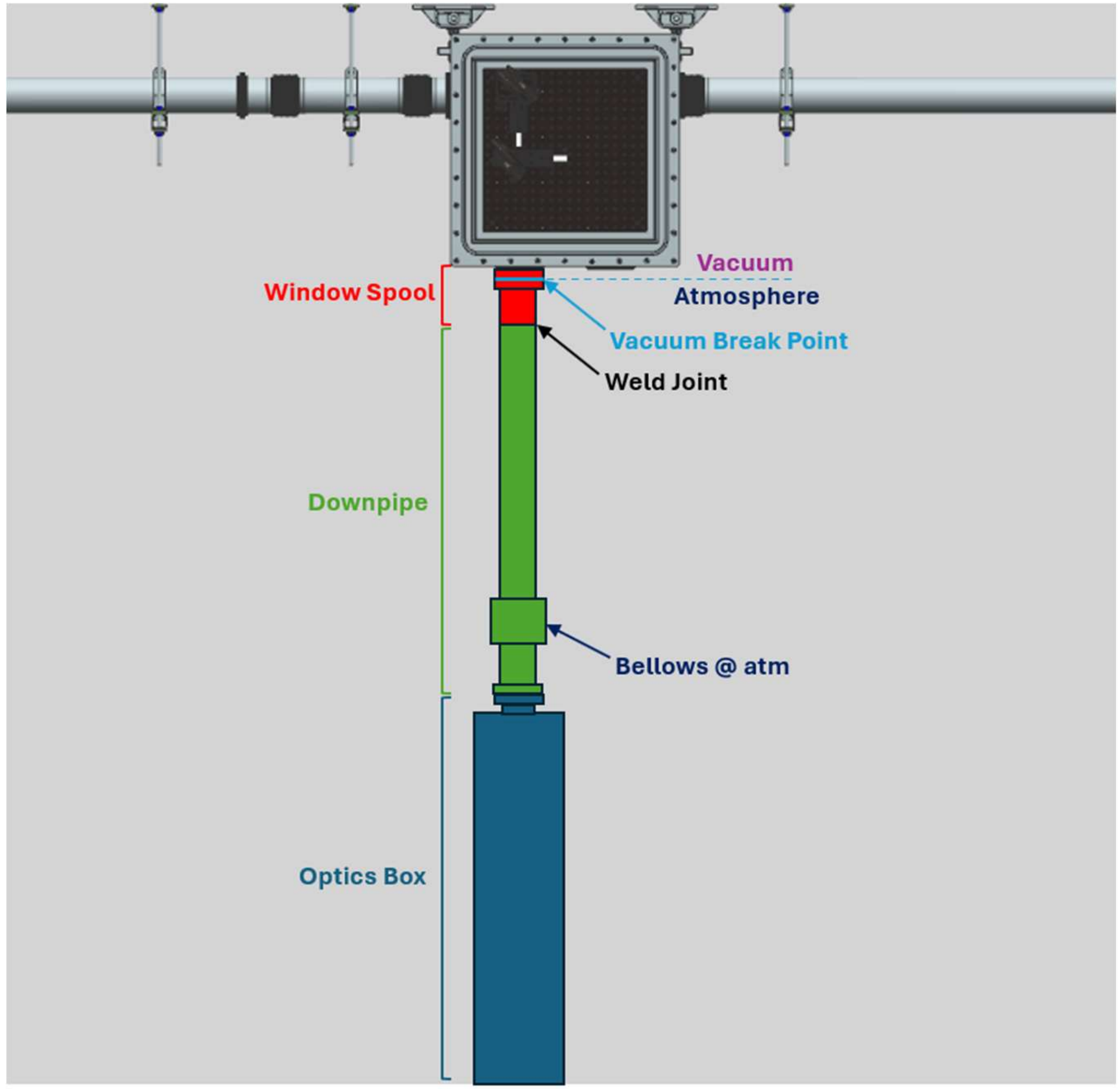



- Quantity 13 Mirror Boxes locations along OTL.
- All ½” stainless-steel plate design.
- Inside welded design (vacuum system).
- The removable lid is aluminum for weight reduction during installation and service.
- The final size of 21”x21”x12” allows ample room for linear stages and pickoff mirrors.
- The back plate is made of ¾” thick stainless-steel for mounting components (reduce deflection).

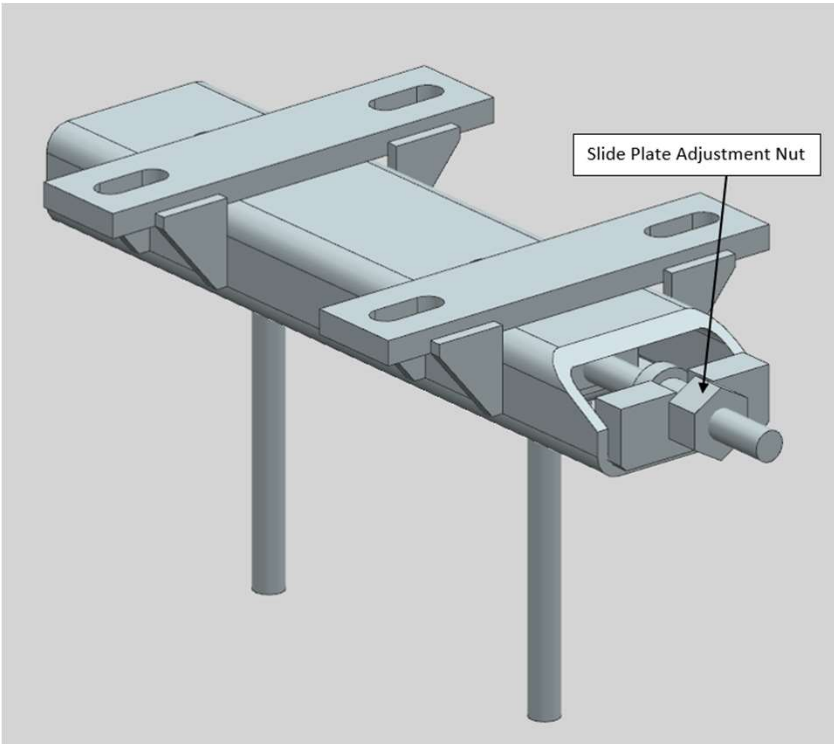
- Laser ports designed w/ NW100 vacuum flanges.
- Bottom ports are for laser transport to Laser Optics Boxes and signal cable feedthrough.
- KF-40 port for gauging location options.

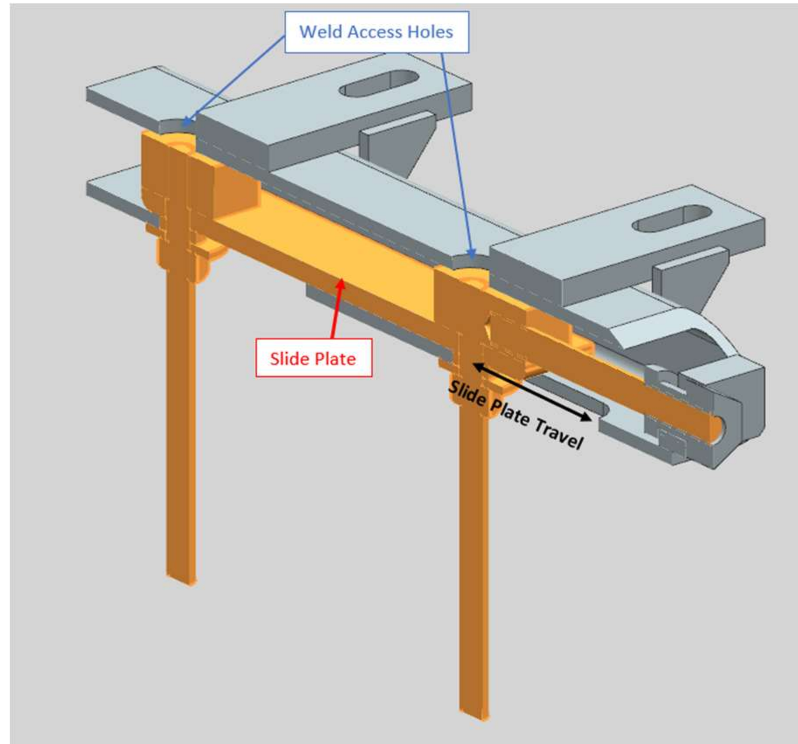
# Downpipe to Optics Boxes

- Downpipe needed for safe travel of laser path from Mirror Box down to Optics Box.
- Window Spool mounts directly to ISO-100 flange.
- Window acts as a vacuum break right at the Mirror Box.
- Additional pipe length is part of spool to accommodate welding far from sensitive window.
- Downpipe and bellows are at atmosphere and present no vacuum loading on supports.
- Downpipe easily mounts to Optics Box via another ISO-100 flange.
- Joints at atmosphere will need additional lockout accommodations to prevent opening.



# Mirror Box Hangers

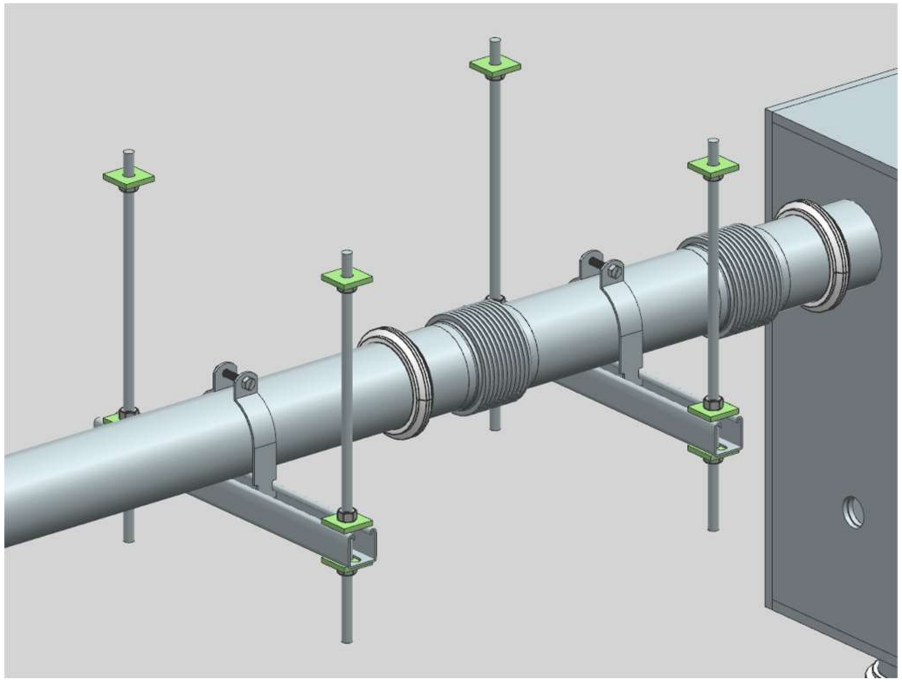


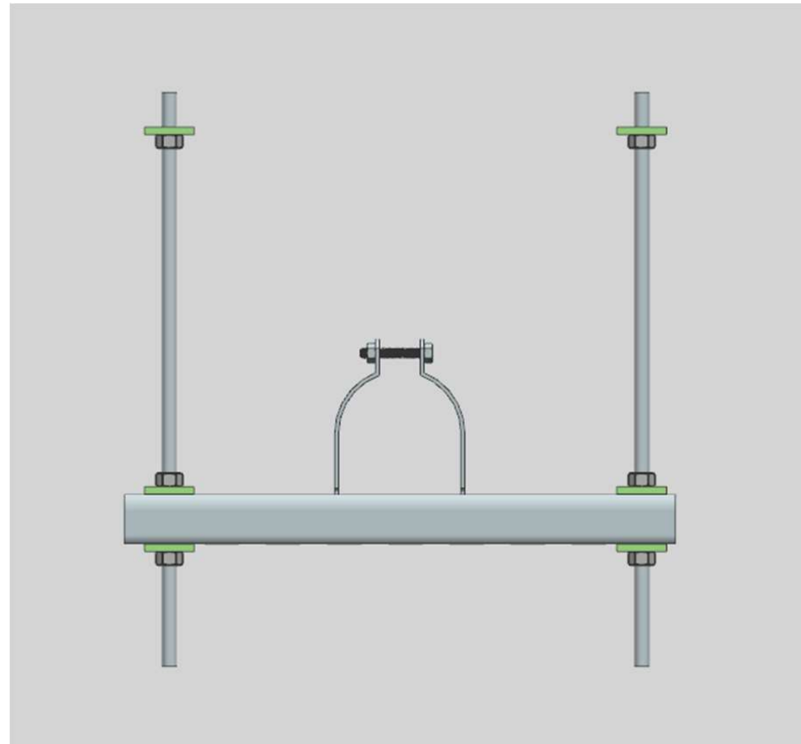




- Steel component construction.
- Slotted ceiling plates to adjust for installation obstructions (rebar).
- Also provides additional z-adjustment.
- Slide plate design with threaded rod hangers (x and y adjustment).

- Access holes at the top give ability to tack weld threaded rod for safety.
- Will design a drilling template for ease of drilling Hilti locations in ceiling.

# Beam Tube Hangers

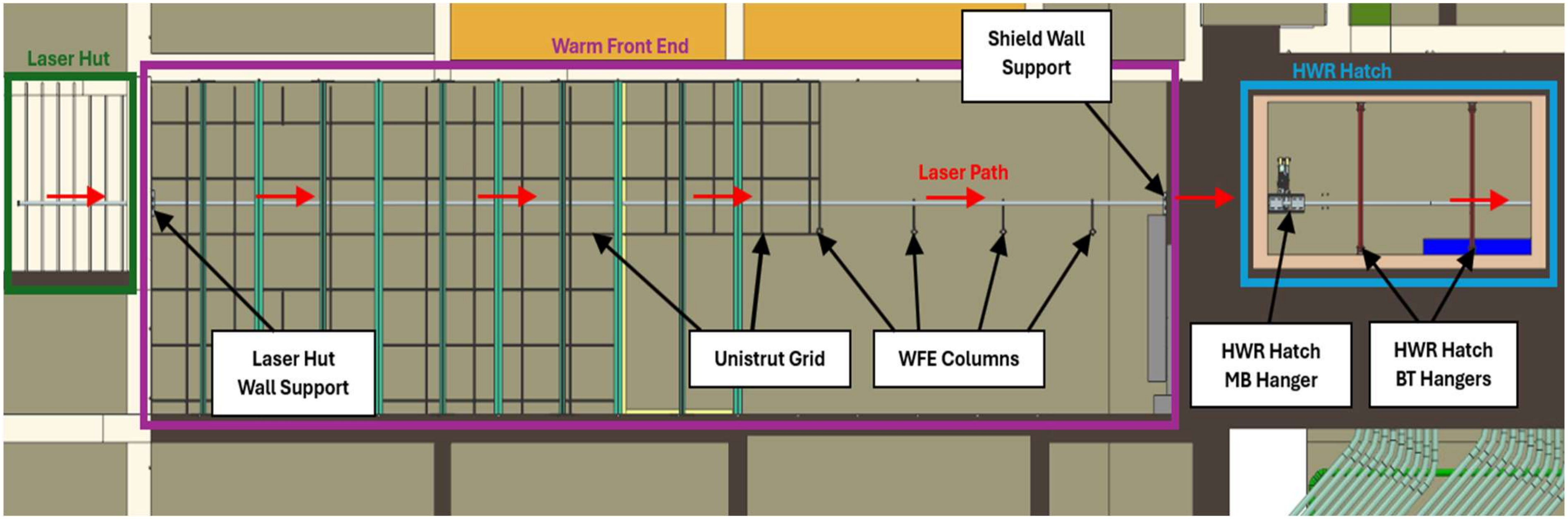




- Beam tube hangers designed using common Unistrut parts.
- Design provides a wide range of alignment with sufficient adjustment.
- Designed alignment tool – later described in alignment slides.

- Due to concrete anchor requirements in ceiling (FESHM7080), these will need to be mounted one of two ways: a) suspended from existing Unistrut embedment or b) suspended from additional hung sections of Unistrut (spanning from embedment to embedment).

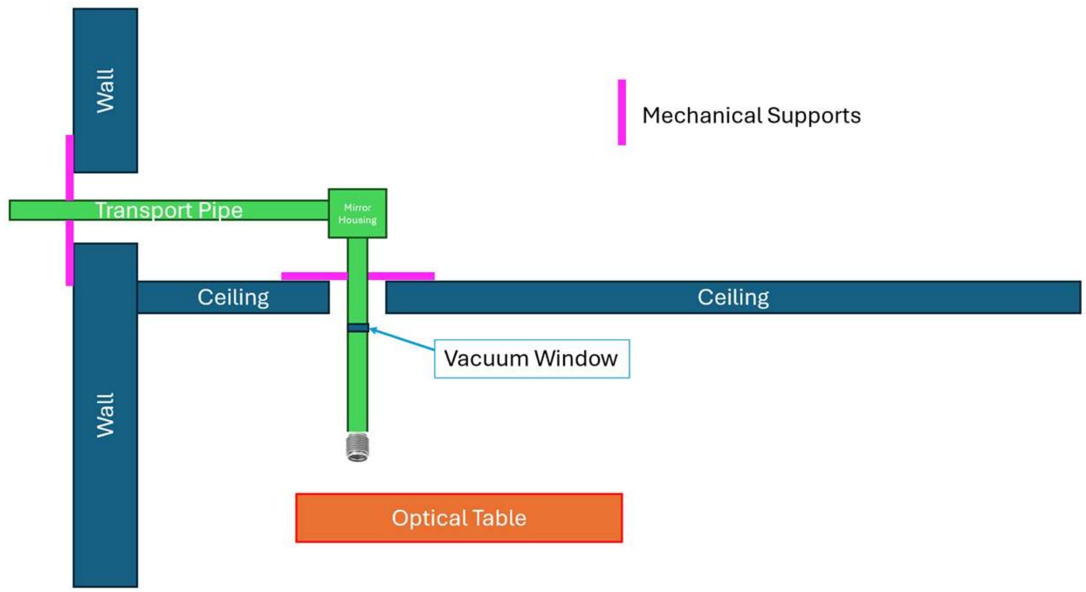
# Area Specific Components (US to DS)




1. Laser Hut (mezzanine)
2. Laser Hut Wall Opening
3. WFE Area
4. Shield Wall Opening
5. HWR Hatch Area
6. PIP-II Linac Area

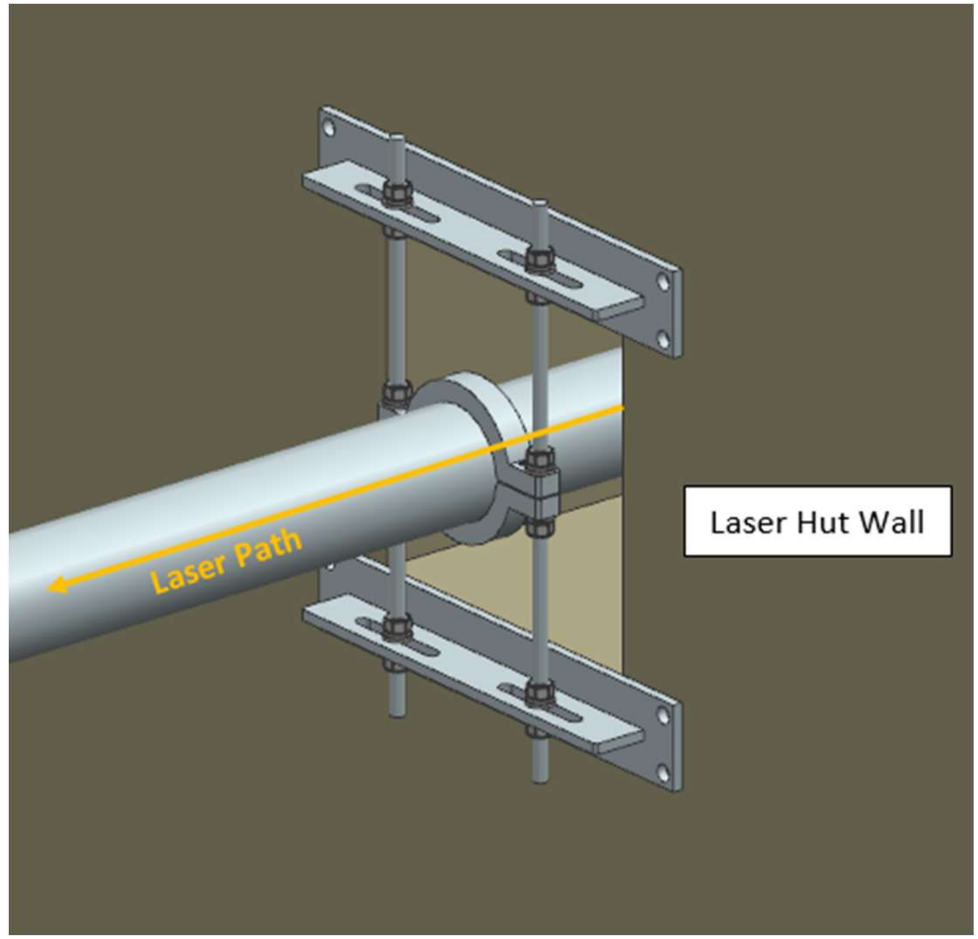
# Laser Hut Right-Angle Mirror Box

- Need for a right-angle mirror box above the laser hut to turn the laser path downstream as it leaves the laser table vertically.
- Simple box design, cubic with conflat ports, removable side panel access, and mounting standoffs for small a optics board.
- Bellows is out of vacuum space to eliminate vertical vacuum force.
- Laser Hut wall support takes up horizontal vacuum force. No vacuum load is present in Laser Hut Area.

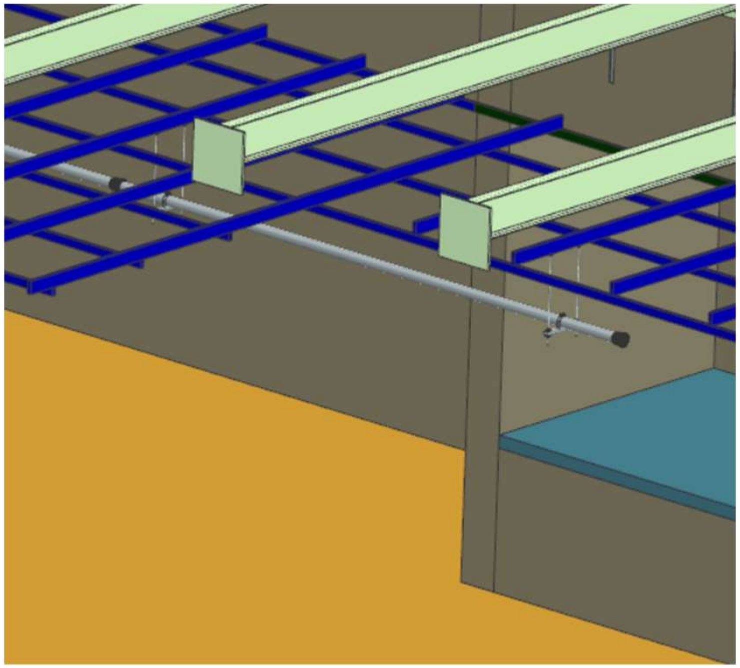


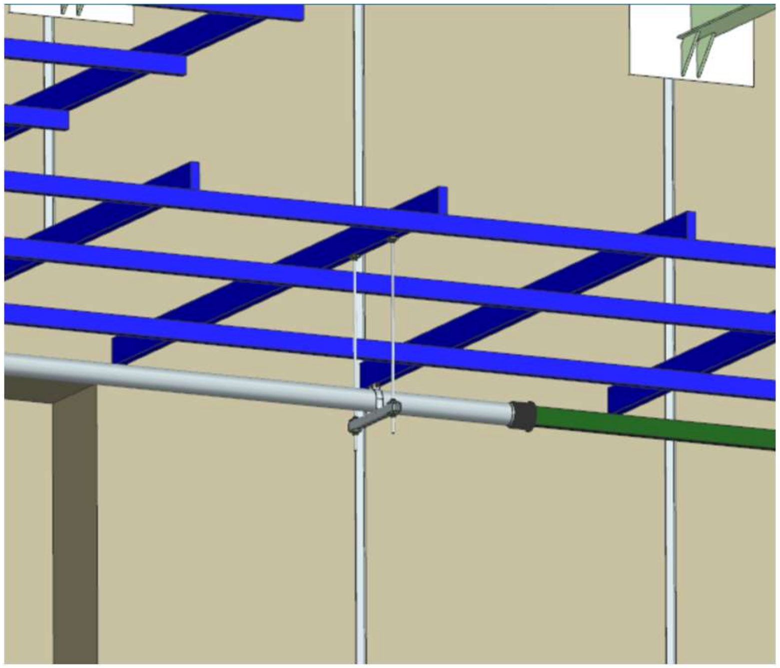
# Laser Hut/Shield Wall Support

- Vacuum loads are expected at the upstream and downstream ends of the Optical Transport Line.
- The Laser Hut wall is concrete and provides a good location to tie into.
- The Laser Hut Wall Support is mounted to the outside Laser Hut wall and provides support at the upstream end of the OTL.
- The design contains sufficient alignment considerations in x, y, and z directions.
- Clamping forces to resist slip are explained in later slides.



# WFE Supports – Unistrut Lattice/Grid



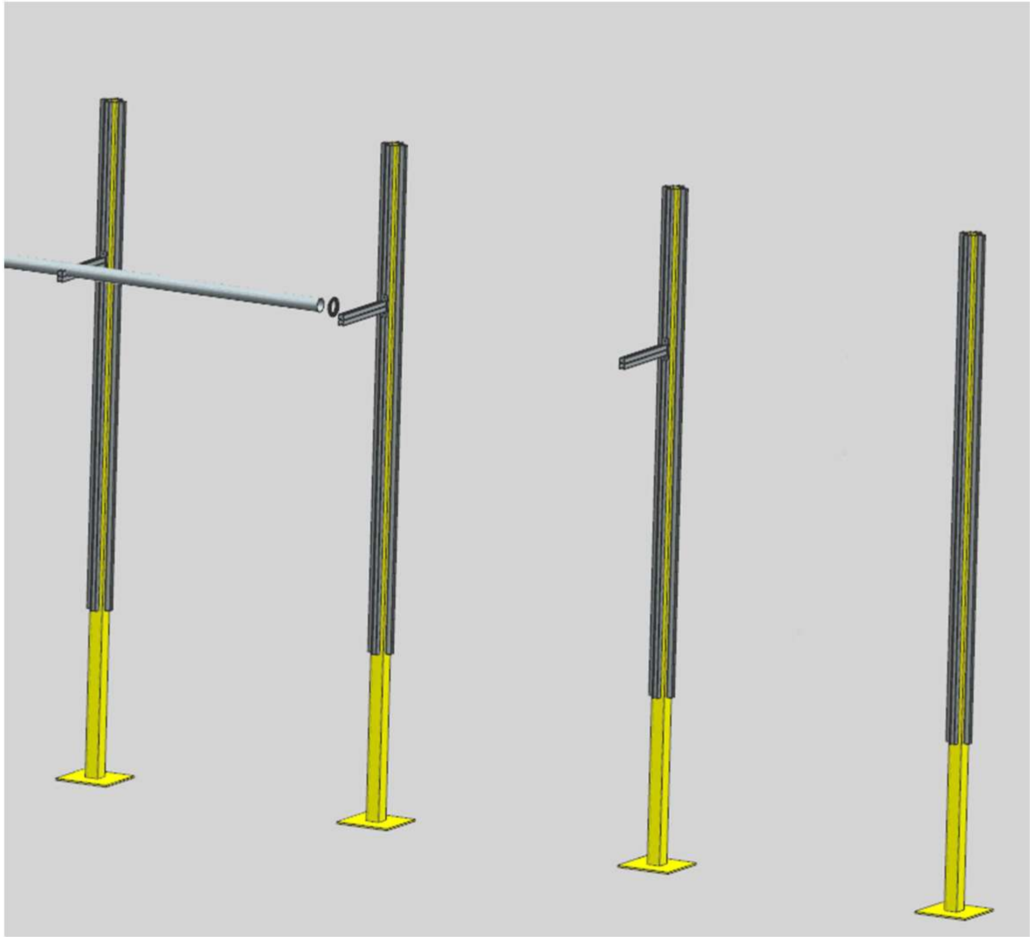


- Beam tube suspended from the Unistrut grid in the WFE are hung by an altered version of the tunnel beam tube hangers.
- No sustained vacuum forces will be present between the laser hut wall and shield wall.
- Beam tube alignment tool is still used for the hanging and alignment of these hangers.

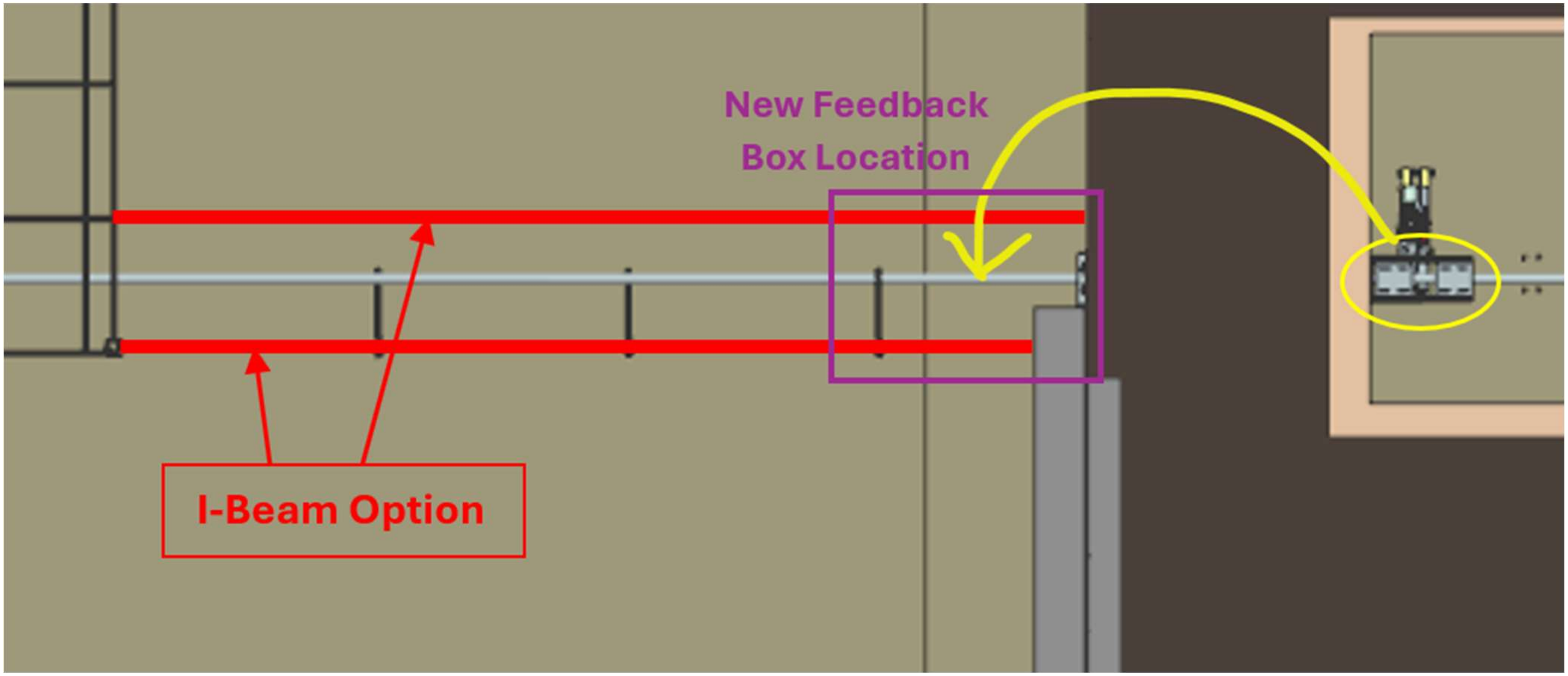
- The solution for hanging components in this area is relatively new.
- Small design changes are still expected in order to alleviate sustained alignment and vibration concerns.
- A base plate and Unistrut extension stand will be implemented to shorten the length of threaded rods, but still use existing design and alignment tool.

# WFE Supports – Span from Grid to Shield Wall

- Span has no Unistrut grid or ceiling to support from.
- This small section is currently supported by 4 Unistrut columns mounted to the floor, with Unistrut arms cantilevered out to hold beam tube.
- No sustained horizontal loads are present in the region between the Laser Hut and Shield Wall.
- Crane operation is still viable for access to WFE components between the columns and East wall.
- Similarly, this design is still in flux. Running parallel I-beams above the beamline is another option that frees up floor space. This option has been discussed with PIP-II installation team and drafting is currently working on this design.



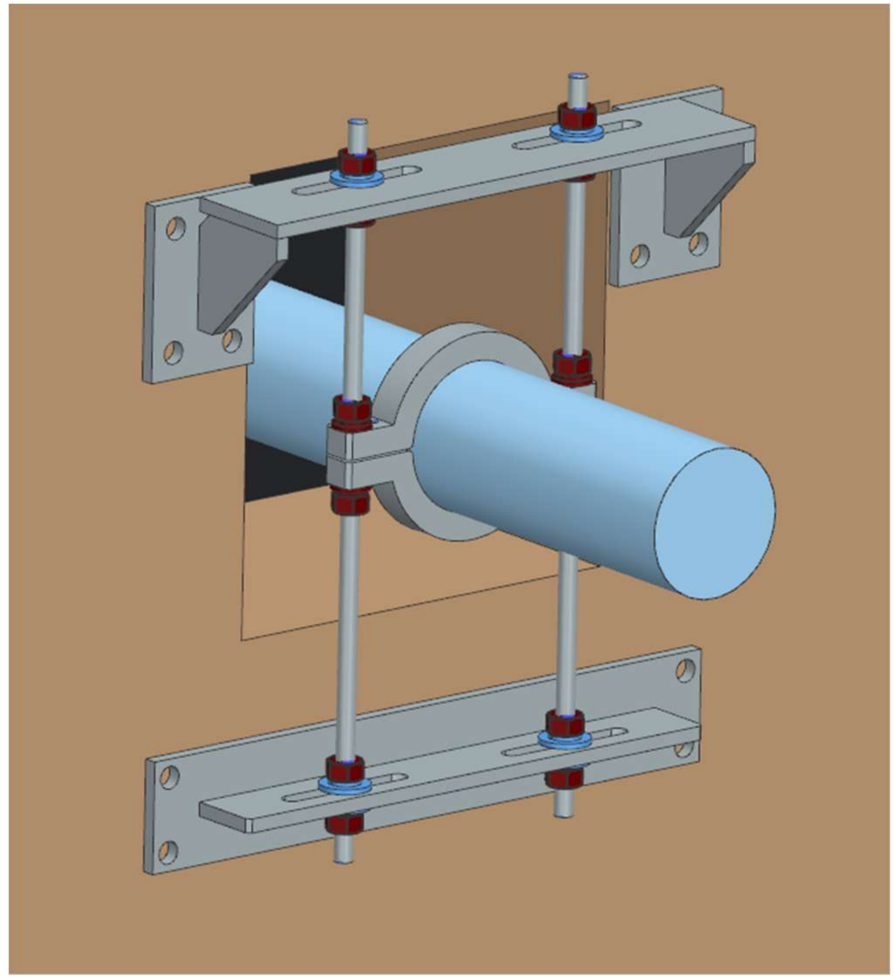
# Feedback Box ($14^{th}$ Mirror Box)



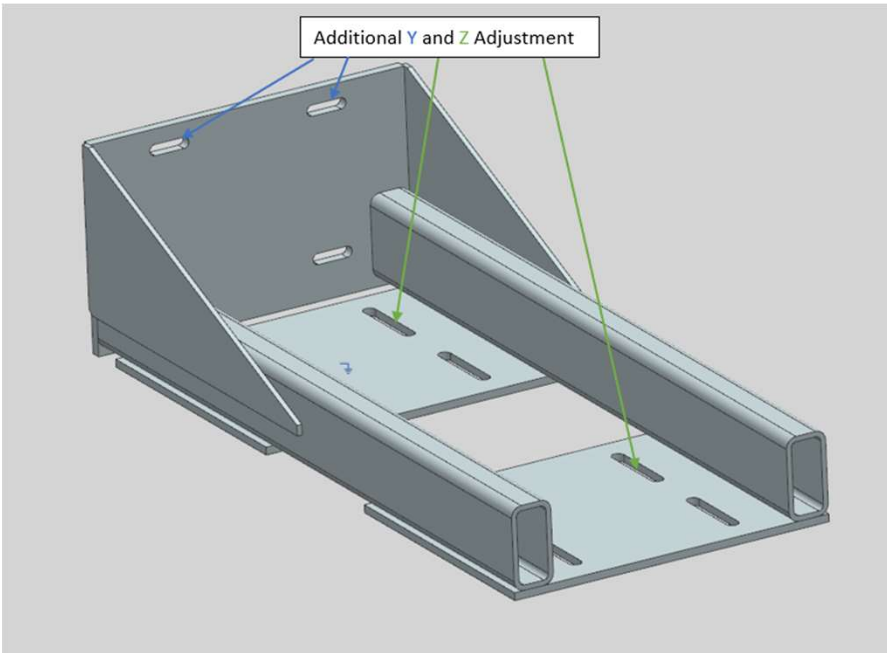

- New Feedback Box used to correct laser early in its travel.
- Located before shield wall in WFE. No ceiling coverage.
- Will utilize existing mirror box design, and possibly HWR Hatch Hanger design (discussed in upcoming slides)
- Downstream end of WFE could need an I-Beam re-design to allow for easier hanging of this new Feedback Box.

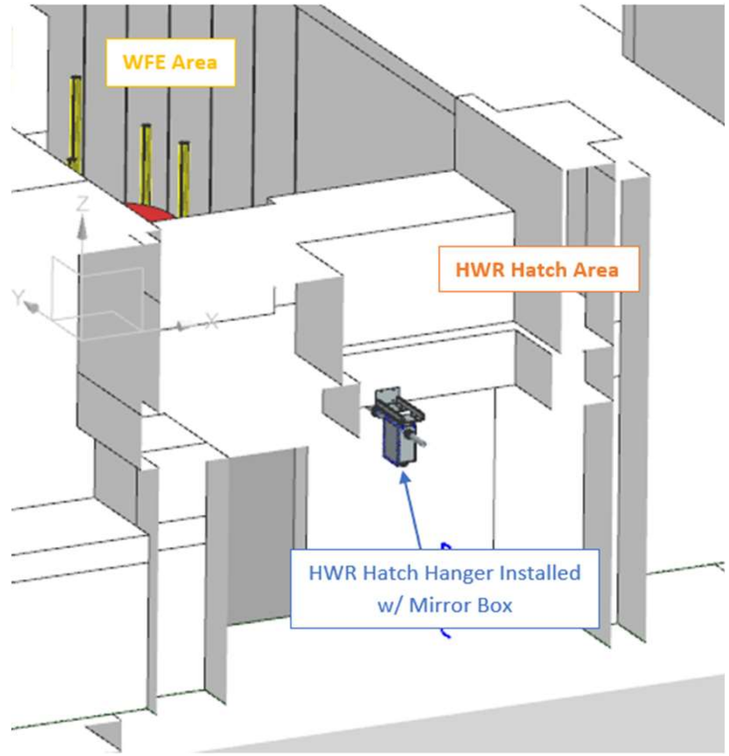
# Shield Wall Support

- Shield wall support was needed for stability of the beam tube (competition with other items in wall opening, take up any vacuum forces for WFE area)
- New design (from drafter Will Derylo) is more adaptable to relieve stress in extra long threaded rods.
- New design will be implemented at the Laser Hut wall opening.
- Vacuum force versus friction force (clamping force) are discussed in later slides.



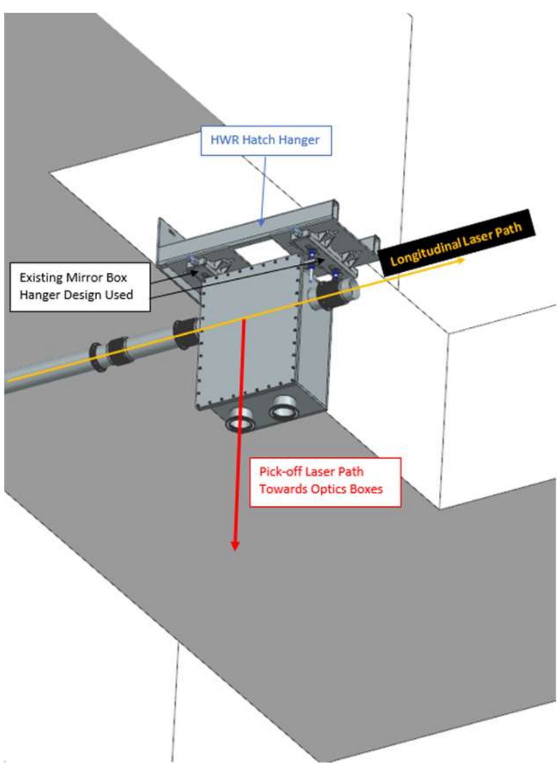
# HWR Hatch Hanger

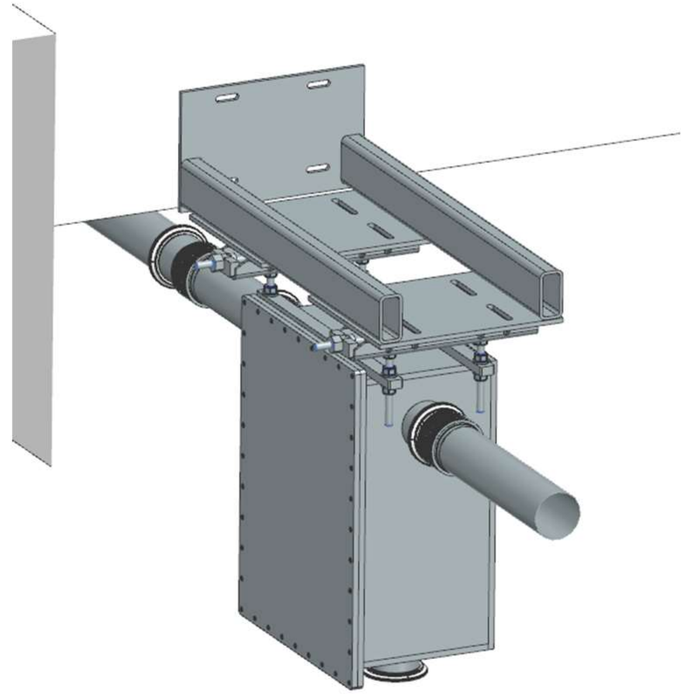



- Requirements dictated that components inside the footprint of HWR hatch would require additional methods of installation.
- HWR Hatch Hanger resolves the need for a Mirror Box that is positioned under the HWR hatch with no ceiling to mount to.
- The design is a steel box tube cantilever structure.
- Design iterations to follow as analysis begins for FDR (deflection, vibration, etc.)
- Hatch Hanger plates designed to accept existing Mirror Box Hanger bolt pattern.

# HWR Hatch Hanger cont…

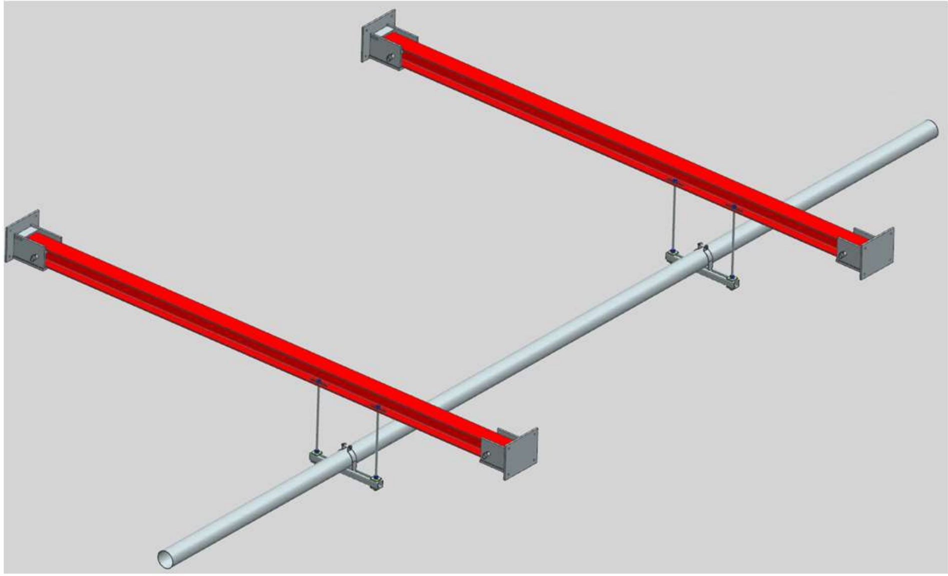


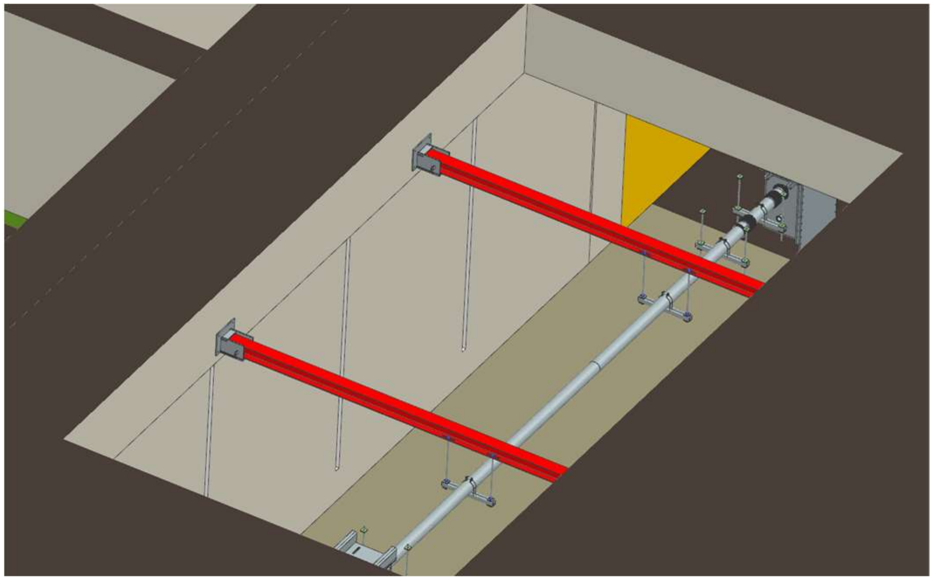



- Ground view – HWR Hatch Hanger essentially imitates an extension of the ceiling.
- Note: Images shown here missing additional gussets.

- Aerial Isometric View
- The Mirror Box and HWR Hatch Hanger can be removed for HWR hatch use.

# HWR Hatch Beam Tube Hanger

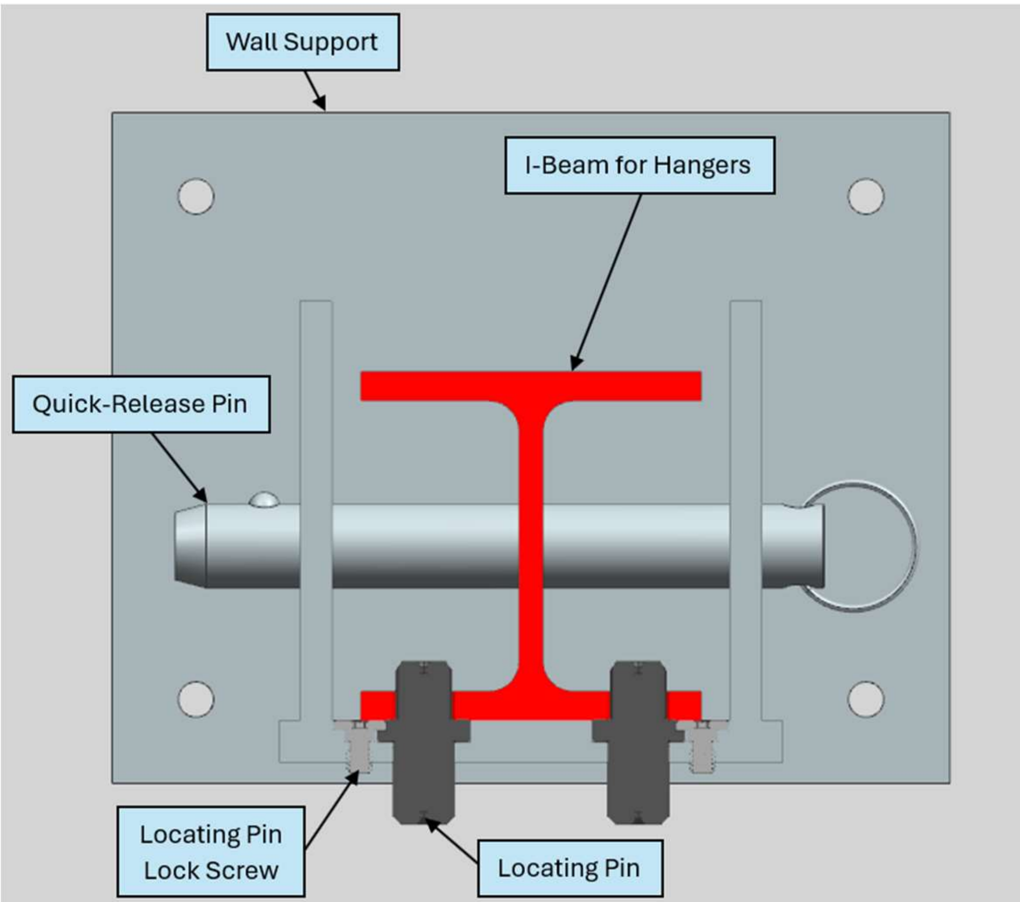


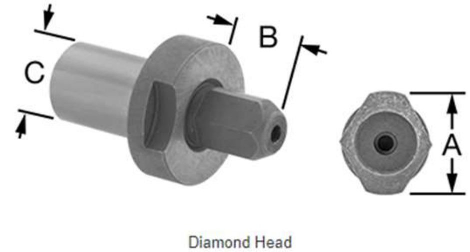


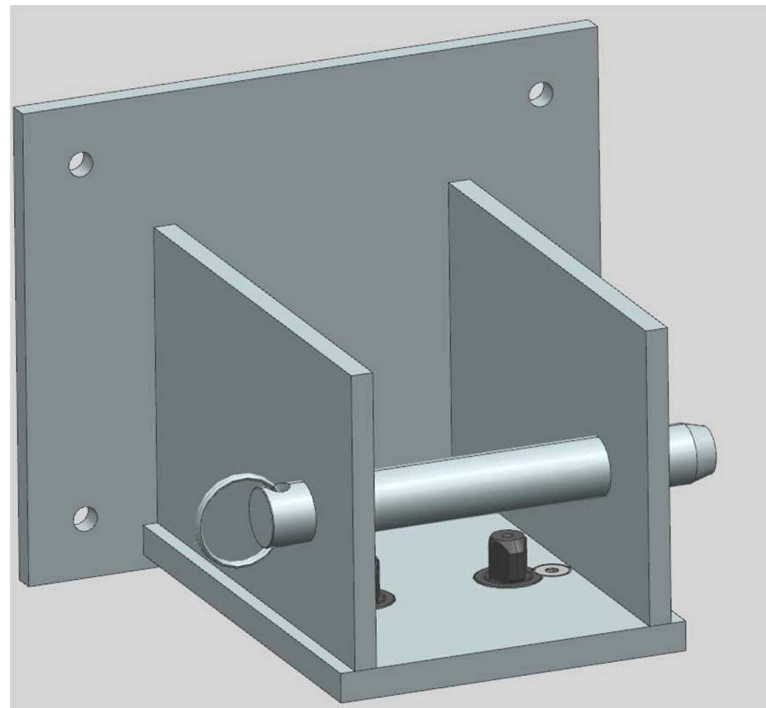
- Support was needed for hanging of beam tube in the HWR Hatch span.
- Bottom flange of I-Beam mimics the height of the PIP-II Linac ceiling
- Removable and replaceable with limited access to East wall.

- Locating pin and quick-release pin design allows for installation from the West aisle.
- East end has toleranced holes for accuracy of placement/replacement.
- West end of support is slotted in x-direction for both the locating pins and quick release pins.

# HWR Hatch Beam Tube Hanger



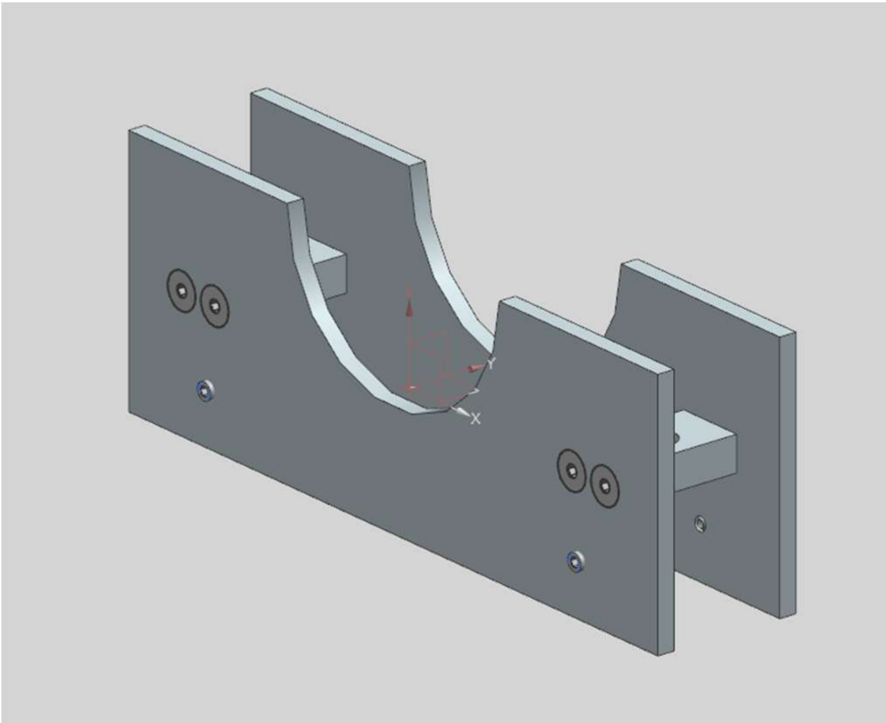



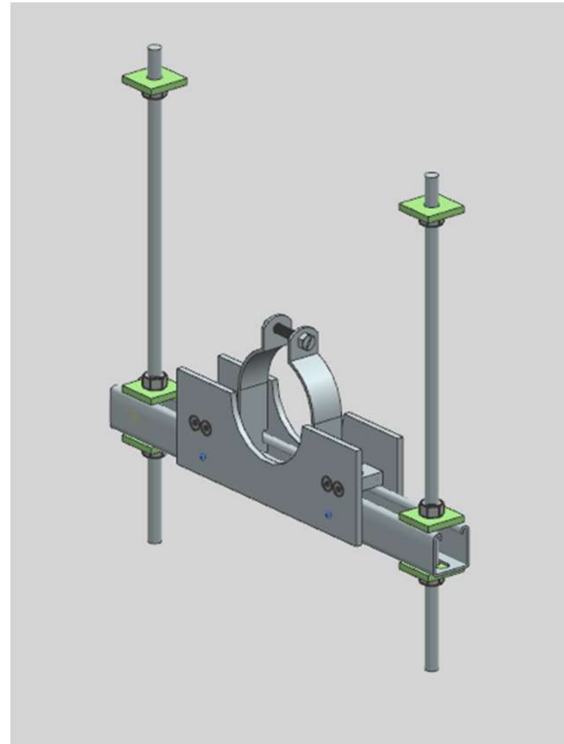



# Device Adjustment

- Mirror Boxes, Beam Tube Hangers, and Laser Hut Wall Support will have alignment in x, y, and z directions.
- Total alignment adjustment will be ±1” in all directions.
- Fine alignment adjustments will be required.
- Preliminary installation and alignment procedures are being worked on.
- Randy Thurman-Keup has a more detailed explanation of the installation order, and alignment procedure.

# OTL Beam Tube Alignment Fixture





- OTL Alignment Tool will help center and keep beam tube in place during initial alignment.
- If beam tube needs removal or repair, alignment fixture will hold its position.

- Beam tube clamps are able to be installed with alignment fixture in position.
- Set screws for quick hold, holes for permanent Unistrut hold.

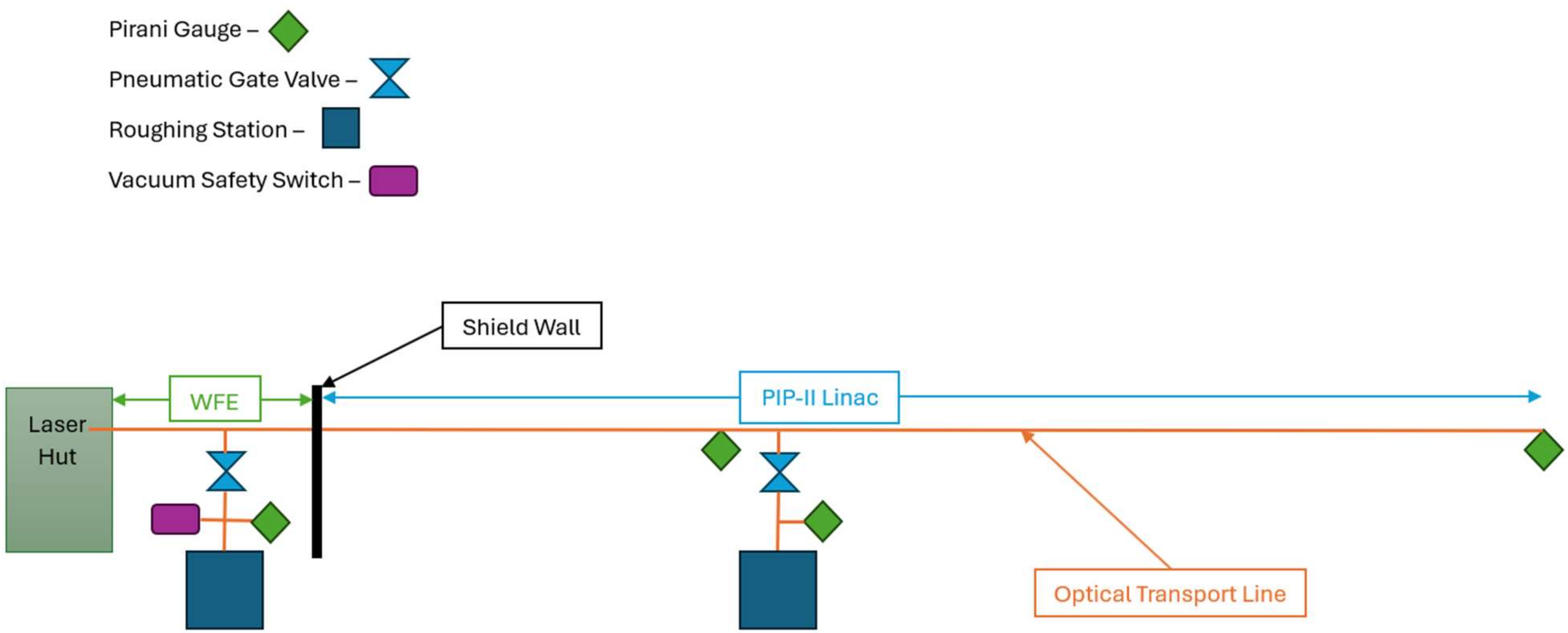
# Vacuum & Safety Interlock System

- The OTL is designed as a rough vacuum system with the goal of achieving <250 mTorr.
- The Mirror Boxes are 100% stainless steel welded construction with a total 6 vacuum ports/openings.
- 2 main beamline ports utilizing the NW100 SS vacuum flanges with o-rings and clamps.
- 2 bottom ports (1 pickoff port, 1 feedthrough port), both utilizing NW100 SS flanges.
- 1 side mounted KF40 SS vacuum port with o-ring and clamp. To be used for gauging, pump out, etc…
- 1 main access lid - ¾” aluminum plate, with bolted o-ring and o-ring groove design.
- Beam tube sections were detailed on slide 11.
- O-rings are to be specified as EPDM or material with comparable radiation resistance and vacuum properties.
- Estimated quantity of 80 o-rings, 50 bellows.

# Vacuum & Safety Interlock System cont…

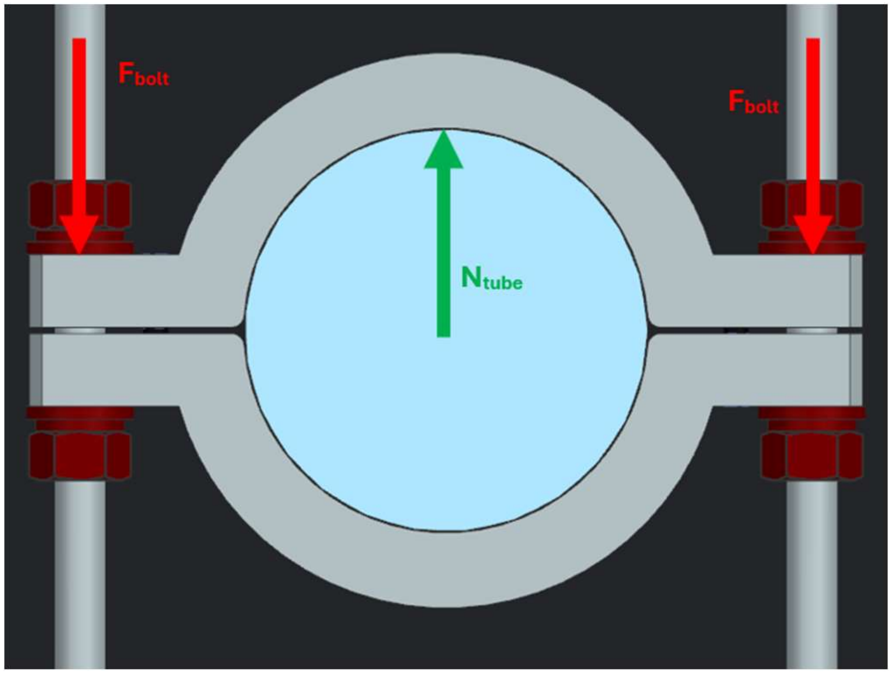
- All elements of vacuum system shall follow standard UHV practices, including pre-clean and ultrasonic cleaning of vacuum parts.
- Individual components and entire system shall be leak tight to a leak rate of 2.5x10^-10 Torr-L/s on a calibrated helium leak detector.
- The vacuum pumping will consist of rough vacuum pumps. Gauging consisting of quantity 4 Pirani gauges (rough vacuum) will be installed, one at each end of the line, one near the middle, and one on the inlet of the pump. Roughing valves will isolate the pumping from the system when needed.
- By making the laser transport line a vacuum system, we're able to utilize a vacuum safety interlock switch to cut power to the laser when vacuum is let up to atmosphere.
- The safety switch will be positioned such that it can be valved out and tested independent of the beamline.
- This will require that the roughing valve is a gate valve that can shut off the laser when closed, maintaining laser safety.

# Safety Interlock Switch & Vacuum Equip. Layout




- The vacuum safety interlock switch will be installed on the WFE side of the shield wall.
- Installed behind interlock configured electromechanical gate valve. Gate Valve Closed = Laser Power Off
- Smaller volume to vent to test safety interlock switch.
- Quicker recovery, no leak checking transport line with each test, easier access from WFE side of shield wall.

# Charge Specific – Friction Support Analysis




The friction of the clamshells is what prevents slipping of the beam tube through the support due to the vacuum force. $\therefore\ F_{friction} \geq F_{vacuum}$

| | |
|---|---|
| $r := 2.5\ in$ | Maximum outer radius of bellows |
| $A := \pi \cdot r^2 = 19.635\ in^2$ | Maximum application area of atm pressure |
| $P_{atm} := 14.7\ psi$ | Atmospheric pressure |
| $F_{vacuum} := P_{atm} \cdot A = 288.634\ lbf$ | Maximum vacuum force |
| $F_{friction} = \mu_s \cdot N_{tube}$ | Equation for friction between tube and clamp |

From schematic:

| | |
|---|---|
| $\Sigma F_y = N_{tube} - 2 \cdot F_{bolt}$ | Sum of the forces in the y-direction |
| $N_{tube} = 2 \cdot F_{bolt}$ | Equating normal force to the bolt clamping force |
| $\therefore\ F_{friction} = \mu_s \cdot 2 \cdot F_{bolt}$ | Solving for frictional force |
| $\mu_s := .5$ | Coefficient of friction (SS-to-SS) |
| $n_f := 2$ | Factor of safety |
| $F_{friction} \geq n_f \cdot F_{vacuum}$ | Apply factor of safety, $n_f$, to vacuum force |
| $\mu_s \cdot 2 \cdot F_{bolt} \geq n_f \cdot F_{vacuum}$ | Then solve for clamping force in each bolt, $F_{bolt}$ |
| $F_{bolt} := \dfrac{n_f \cdot F_{vacuum}}{\mu_s \cdot 2} = 577.268\ lbf$ | Clamping force required in each bolt to prevent slip |

Calculate torque necessary to achieve clamping force (Shigley's Ninth Edition):

| | |
|---|---|
| $K := .2$ | Torque Factor |
| $F := F_{bolt} = 577.268\ lbf$ | Required clamping force in each bolt |
| $D := 0.5\ in$ | Nominal bolt diameter |
| $T := F \cdot D \cdot K = 4.811\ ft \cdot lbf$ | Required torque to achieve necessary clamp force |

- The friction between the SS clamp and the SS pipe must exceed the longitudinal vacuum force.
- The expected vacuum force is ~289 lbf.
- Using a factor of safety of 1, the required clamping force must exceed ~577 lbf.

- The torque required to achieve this clamping force is < 5 ft-lbs.
- Hand-tightening of any ½” connection will easily exceed this torque value.
- Slip is not a concern at the laser hut and shield wall openings.

# Summary…

- The free-space laser option requires a low vacuum Optical Transport Line that is optically straight for its entire length.
- The structures that support the OTL address the requirements and allow sufficient alignment considerations.
- Unique locations in the tunnel and their challenges are realized and have been addressed (Laser Hut opening, WFE supports, Shield Wall opening, HWR Hatch, vacuum loads).
- Design changes moving towards fabrication and installation are small and inconsequential to completion.
- Laser safety has been considered and has a solution for all connections.
- The current design of the OTL shows it can meet the design requirements and is ready for fabrication.