BDF target complex design

1st Beam Dump Facility (BDF) Targetry Systems Advisory Committee (TSAC)
4-6 March 2025 - CERN

Jean-Louis GRENARD - Gemma HUMPHREYS – CERN - SY-STI-TCD

with the contribution of all the members of HI-ECN3 WP4

Target Complex design - goal

- **Set the scene of the target complex**
  - ➢ Overall arrangement of the target station and integration in the underground cavern
  - ➢ Shielding configuration
  - ➢ Vacuum vessel, associated trolley mechanism
  - ➢ Proximity shielding design and constraints
- **Present the maintenance operations that are required**
- **Target systems failure scenarios and recovery**
- **Proposed Irradiation stations**
- **Will introduce more detail talks (Radiation protection, shielding, handling, robotics, safety, cooling, ventilation)**

What do we call Target Complex?

The target area

- Target station which contains the target
- The target beam instrumentation
- Associated shielding
- The space to perform target maintenance activities (inspections, replacement, repair…)
- Remote handling equipment (crane, spreaders, mobile robots)
- Confinement(s)

The target complex service building

- Air handling units
- Cooling stations
- Controls systems
- The space to perform target and associated utilities maintenance activities (inspections, replacement, repair…)
- The space to perform post irradiation examination and preparation for target (and other activated components) for final disposal

How we will introduce the target complex

08:30 → 09:05 **BDF target complex design**
Orateur: Jean-Louis Grenard (CERN)

09:15 → 09:35 **Facility lifecycle & target surface building**
Orateur: Jean-Louis Grenard (CERN)

09:45 → 10:10 **Radiation protection considerations for the target complex**
Orateur: Claudia Ahdida

10:20 → 10:40 **Coffee break**

10:40 → 11:00 **Target Systems handling**
Orateur: Roberto Rinaldesi (CERN)

11:05 → 11:20 **Target station shielding - Requirements, Design and Sustainability**
Orateur: Francois Butin (CERN)

11:25 → 11:40 **Overview of currently envisaged robotic tasks for Target Systems**
Orateur: Sergio Di Giovannantonio (CERN)

11:50 → 12:10 **Facility safety requirements and constraints**
Orateur: Melania Averna (CERN)

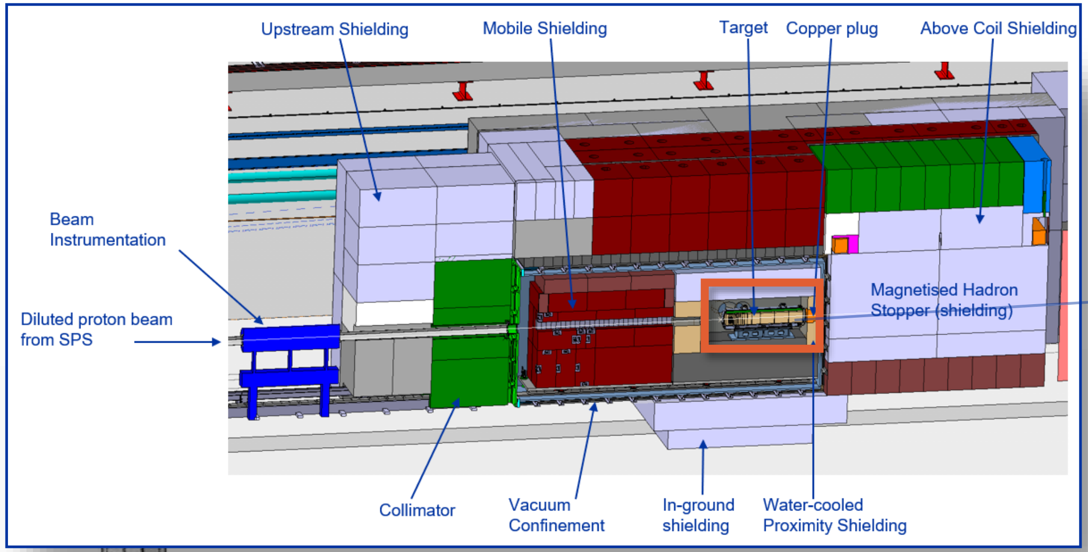
13:35 → 13:55 **Target Systems ventilation system integration**
Orateur: Nikola Zaric

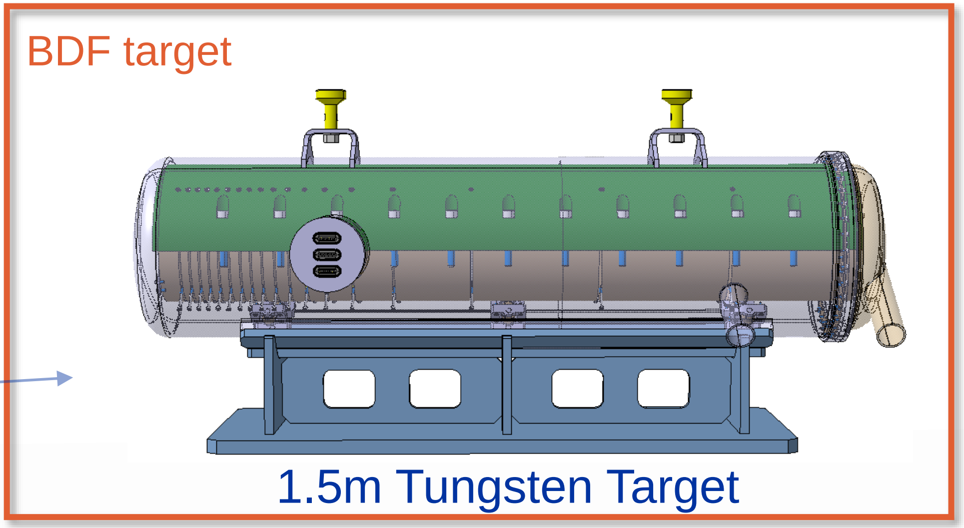
14:05 → 14:20 **Opportunities for service cell implementation for waste packaging & autopsy**
Orateur: Gerald Dumont (CERN)

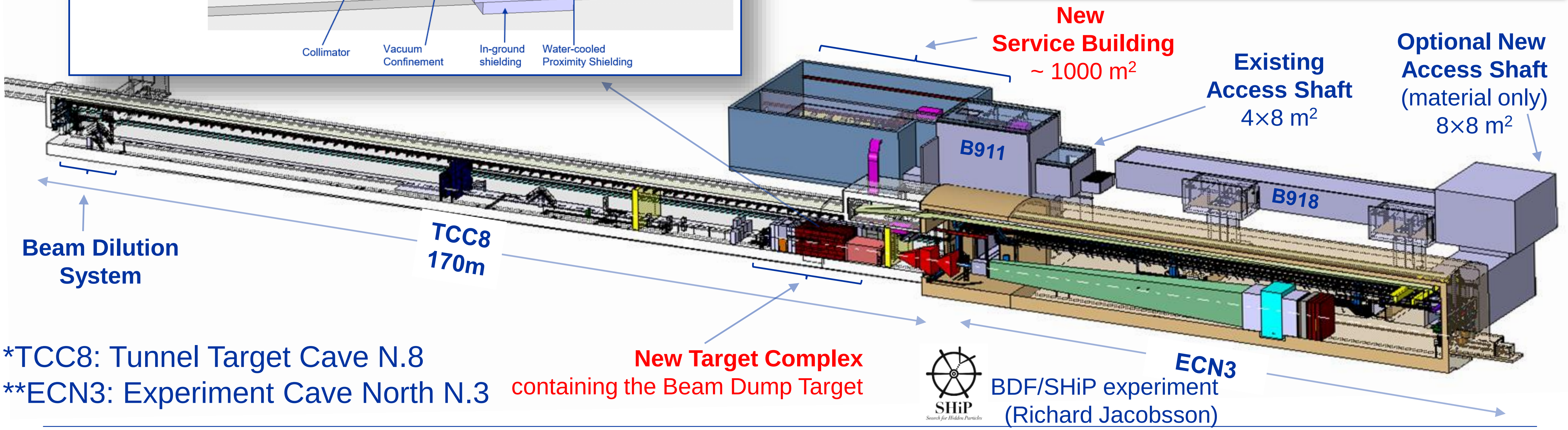
14:25 → 14:35 **BDF Target Complex WP planning**
Orateur: Jean-Louis Grenard (CERN)

14:40 → 15:10 **Q/A time**

BDF/SHiP Target Complex



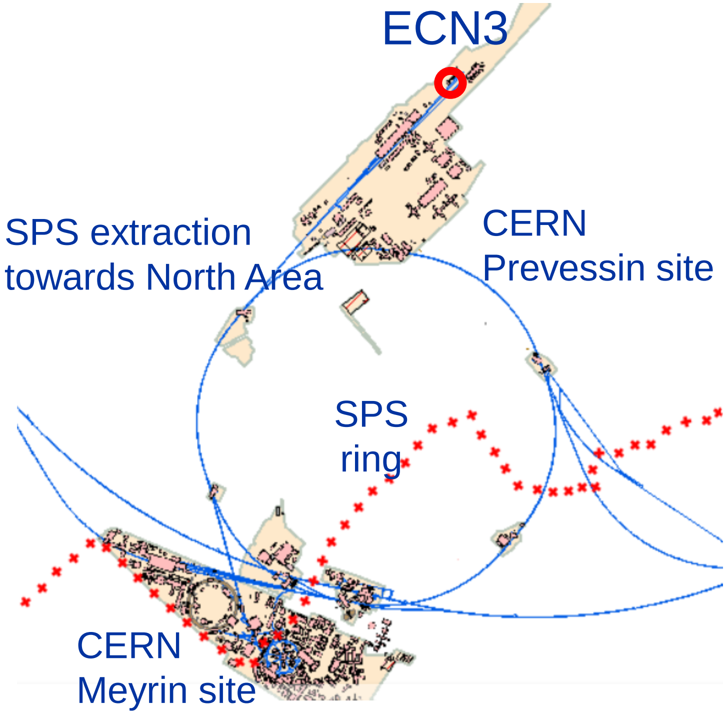




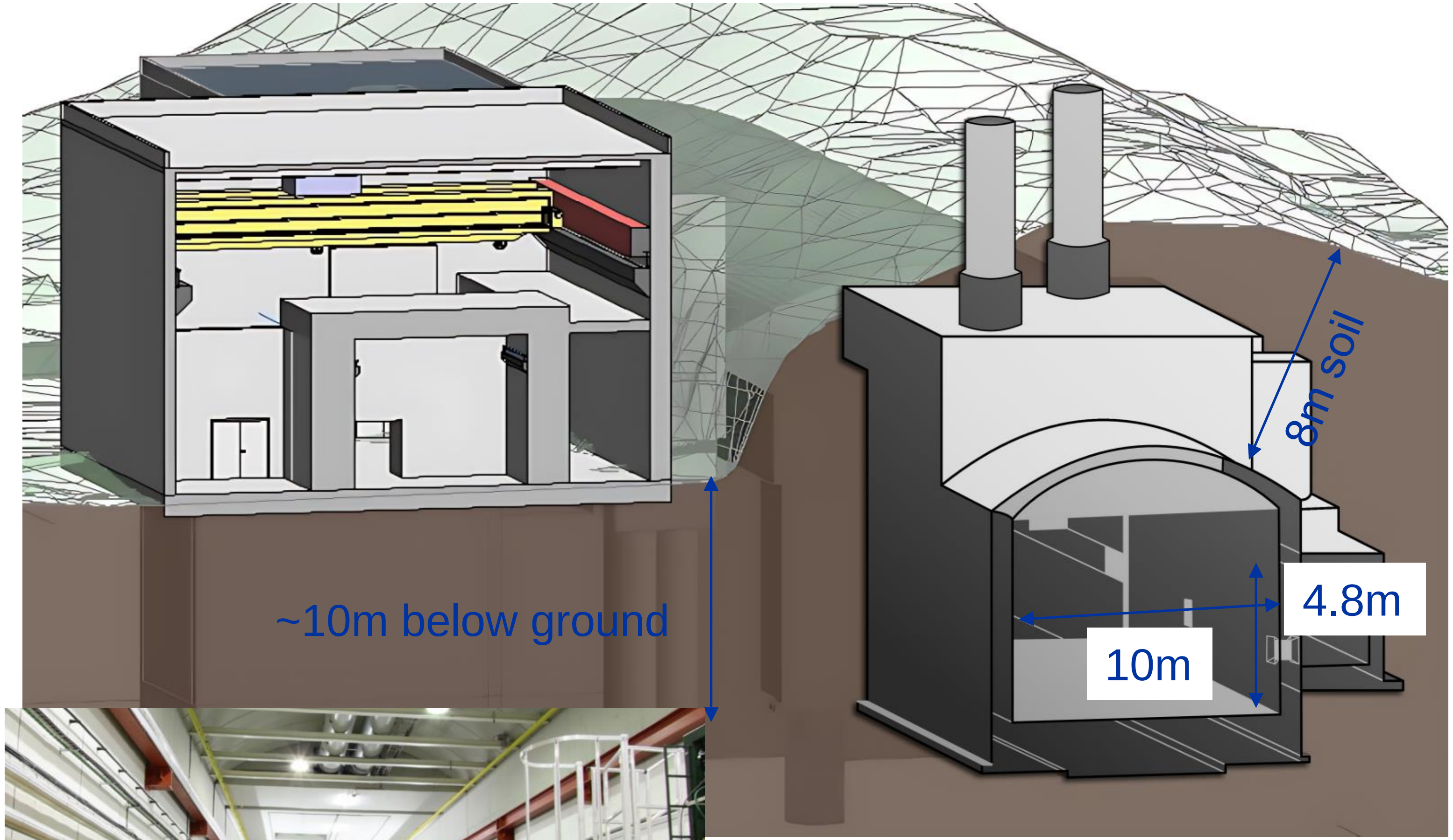
*TCC8: Tunnel Target Cave N.8

**ECN3: Experiment Cave North N.3

The TCC8 area benefits and constraints

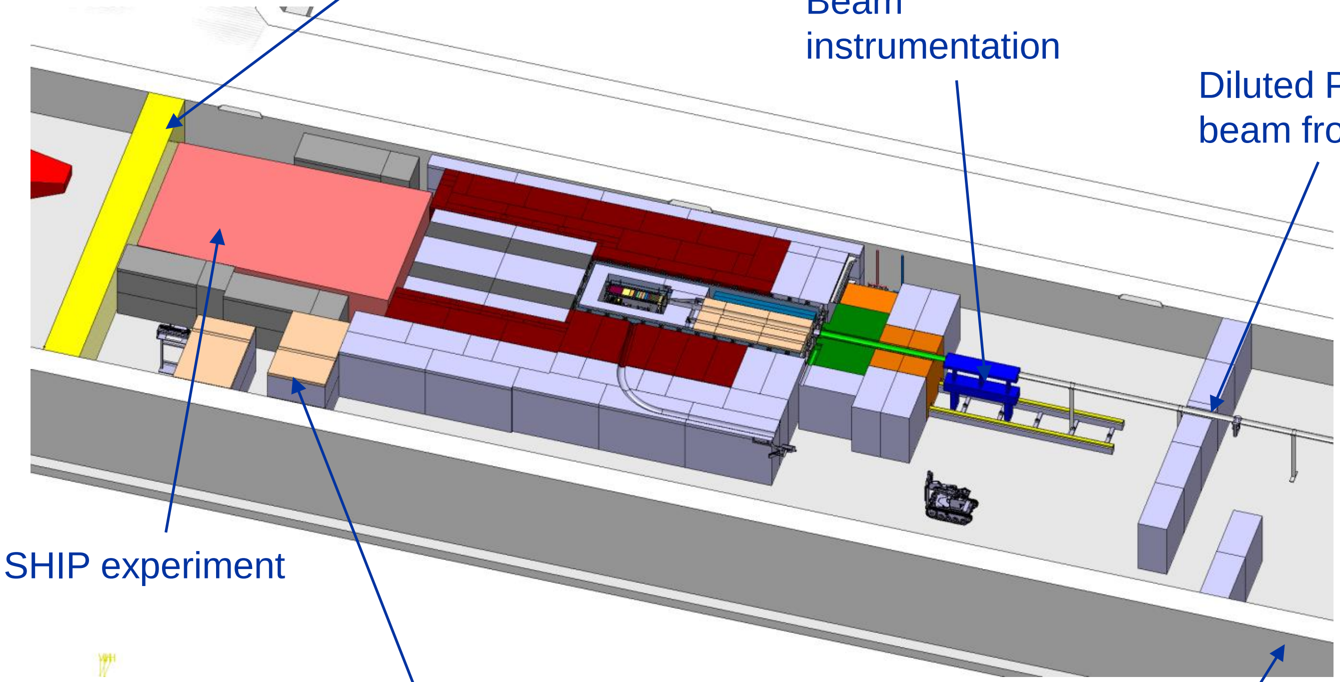


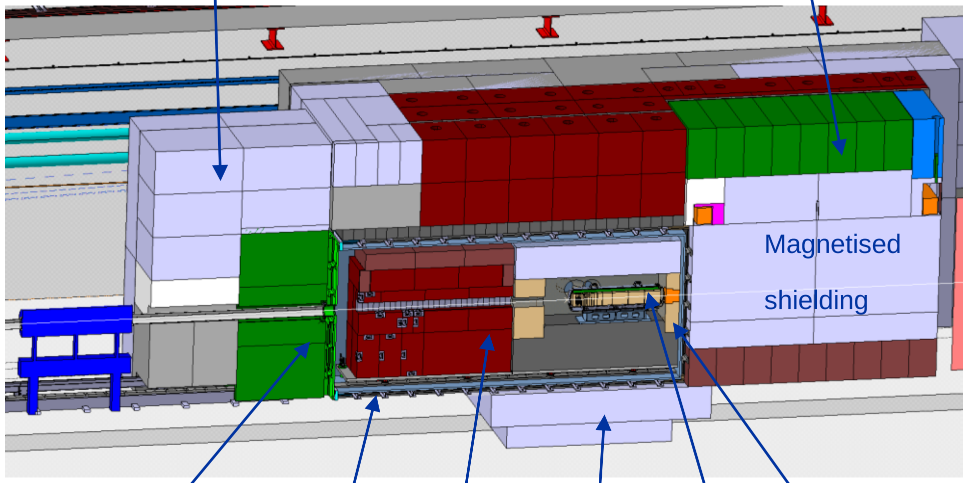
- Target station located in an underground cavern
- Pure vertical handling not an option due to the limited cavern size and shielding requirements
- No direct access to the target station from service building

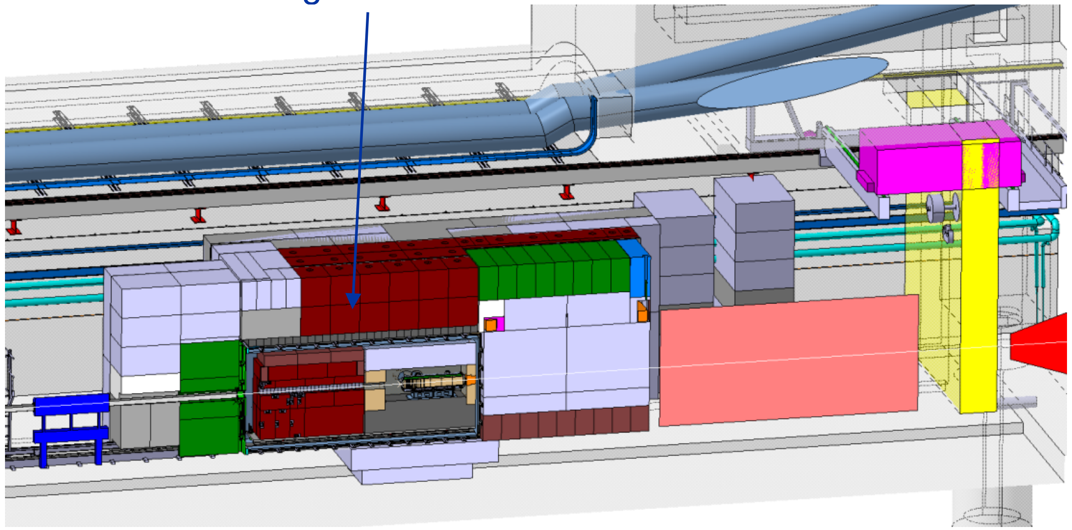


TCC8 cross section (length 170m)

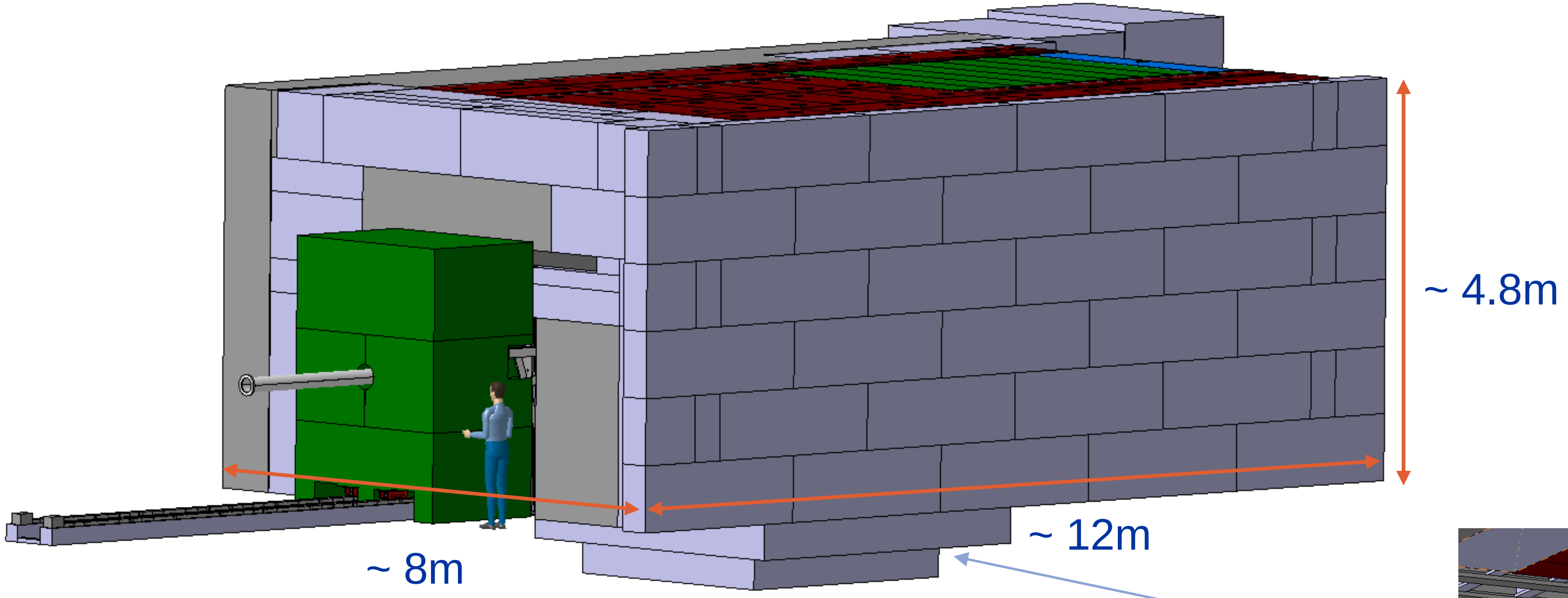
BDF Target complex integration

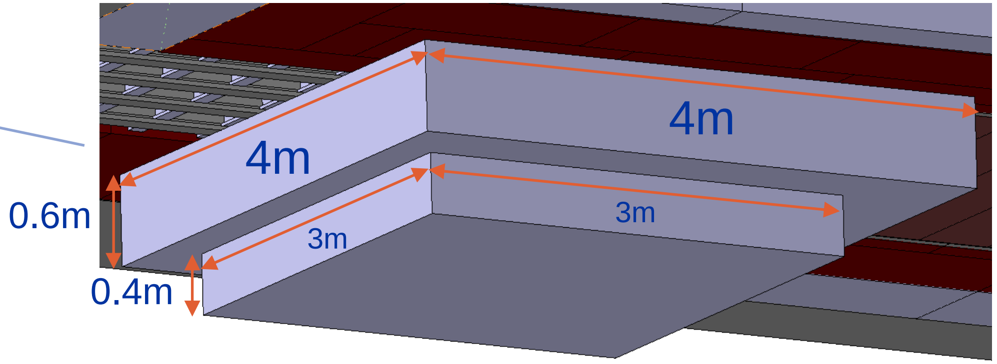






BDF Target complex integration - shielding



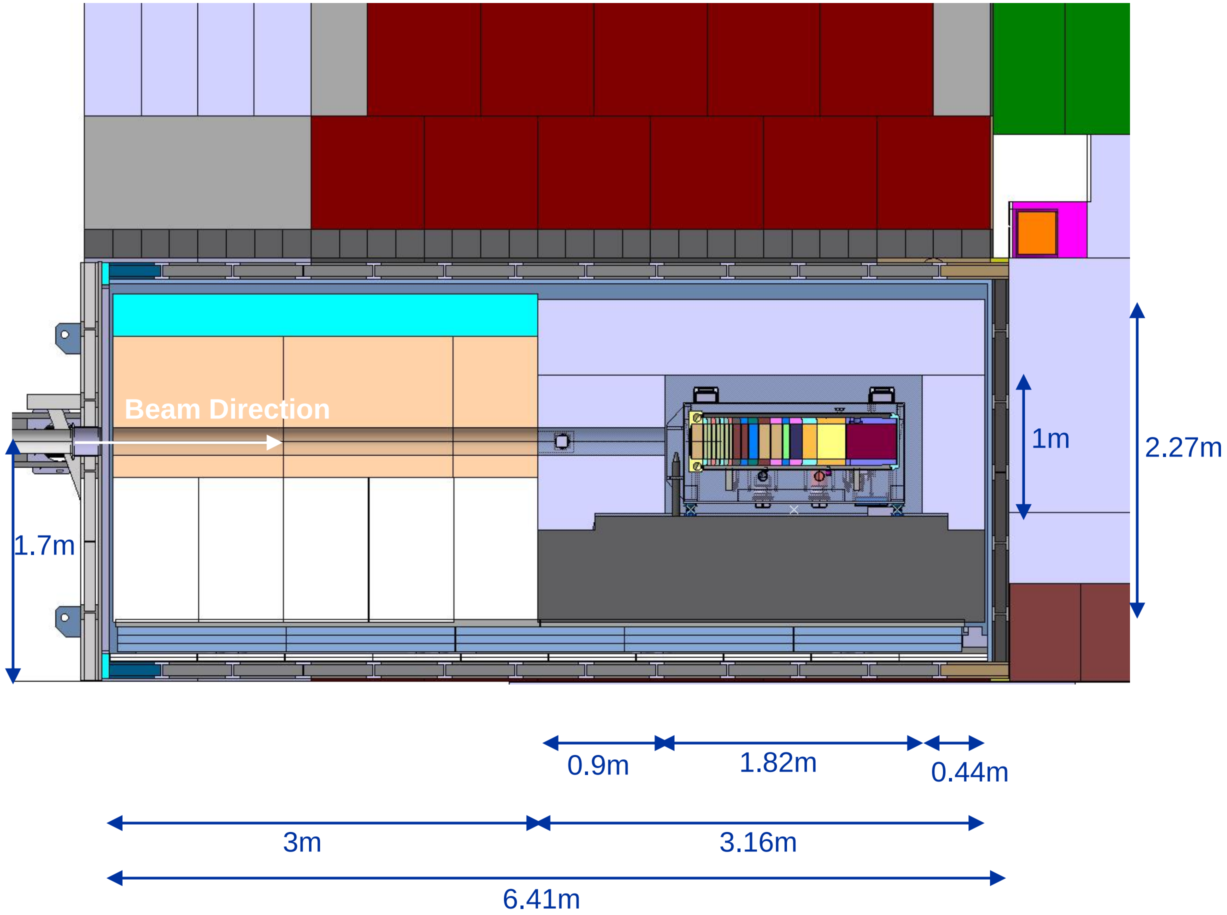


In-Ground Shielding
13.2 m³

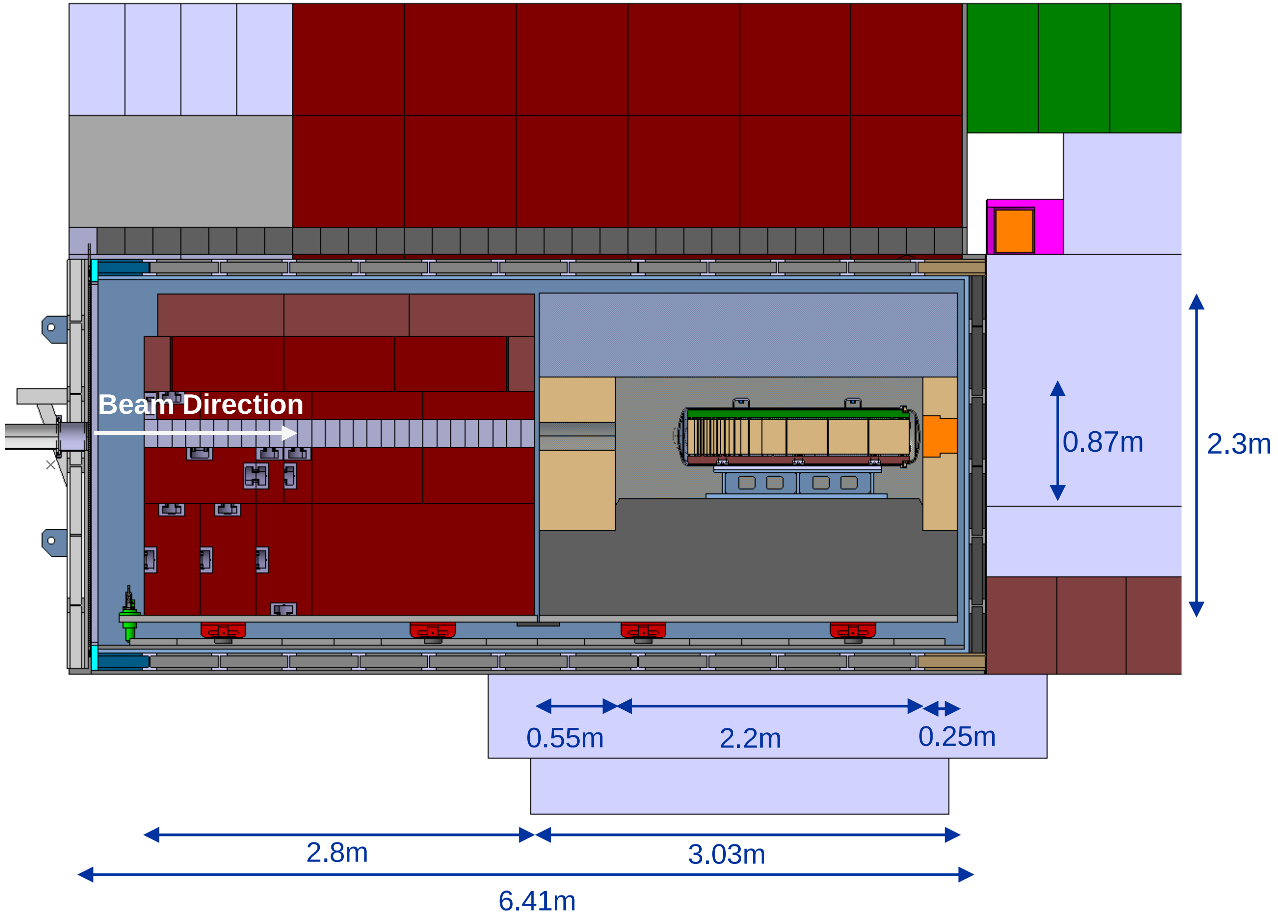
- ~ 180 m³ (~1400t) of cast iron + US1010
- ~ 360 m³ (~800t) of concrete / marble
- Shielding specificities discussed in F. Butin talk

W Helium Cooled vs CDS Design configuration

CDS Design Configuration:



W Helium Cooled Configuration:



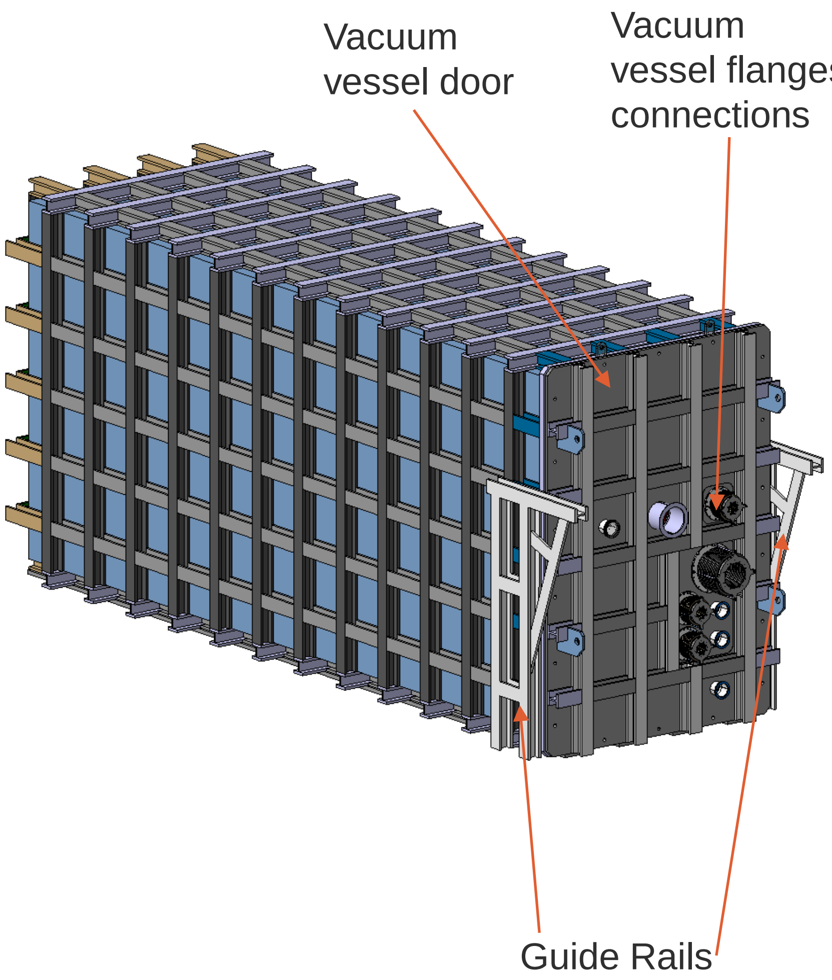
BDF Target complex integration – Vacuum Vessel

Primary Functions:

- Minimise activation of the surrounding air
- Maintain vacuum level of 10^{-3} mbars
- House the target, related proximity shielding and relevant cooling components
- Maintain target alignment with the beamline
- Keep beam line vacuum continuity

Auxiliary Functions:

- Contain a system to ease the removal of the target and shielding
- Provide structural integrity
- Integrate with the safety systems
- Allow for integration of coolant pipes into the vessel



External Dimensions (without guide rails):

- 6410 x 2050 x 2965mm

Internal Dimensions:

- 6210 x 1750 x 2665mm

Volumes:

- **Internal** = $28.96 m^3$
- **External** = $38.96 m^3$

Empty Weight:

- ~25000kg

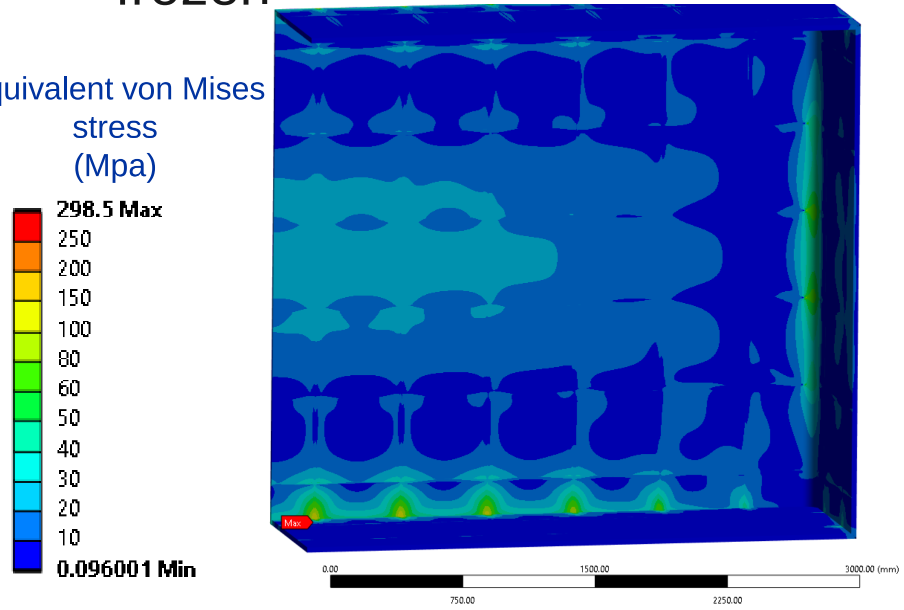
Foreseen Internal Load:

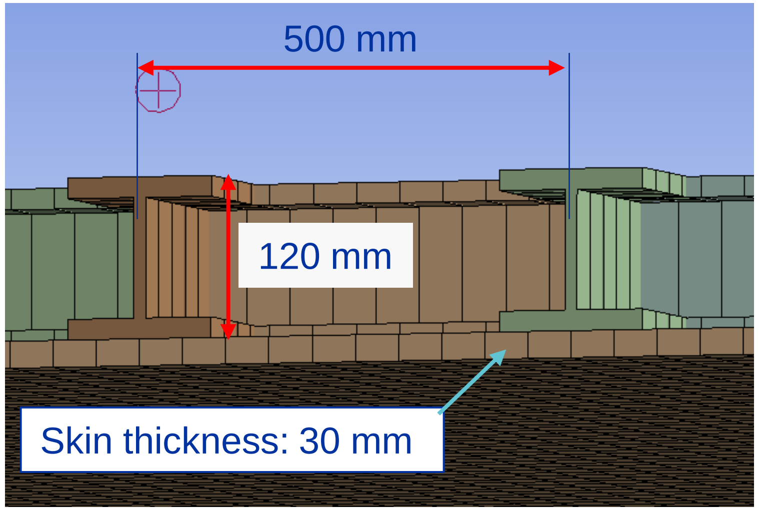
- ~142000kg

Vacuum Vessel Structure

- Current structural analysis performed with stainless steel skin and structural steel external frame
- Structural steel poses issues for SHiP due to magnetic properties in the vicinity of the hadron stopper
- Preliminary analysis performed on current structure, would need to perform again when new material is selected for structure and size frozen

Equivalent von Mises stress (Mpa)





Similar Stainless-Steel vessel designed by Cadinox for UKEA
3590 X 2610 X 4250mm

Vacuum Vessel Connections

Bellows and seals required:

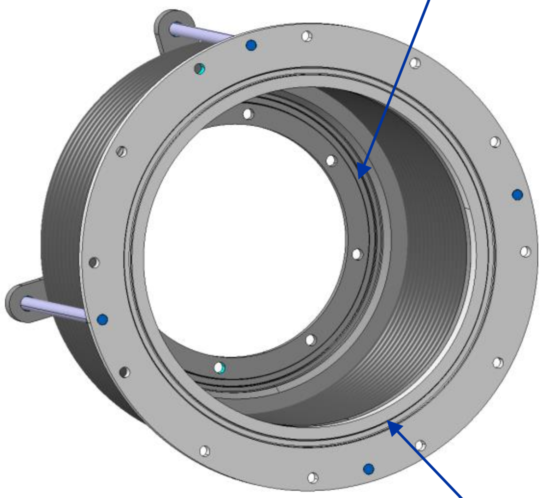
- All located on the vessel door

Functionality of feedthrough bellows:

- Compensate for misalignment
- Cope with thermal expansion
- Allow target removal

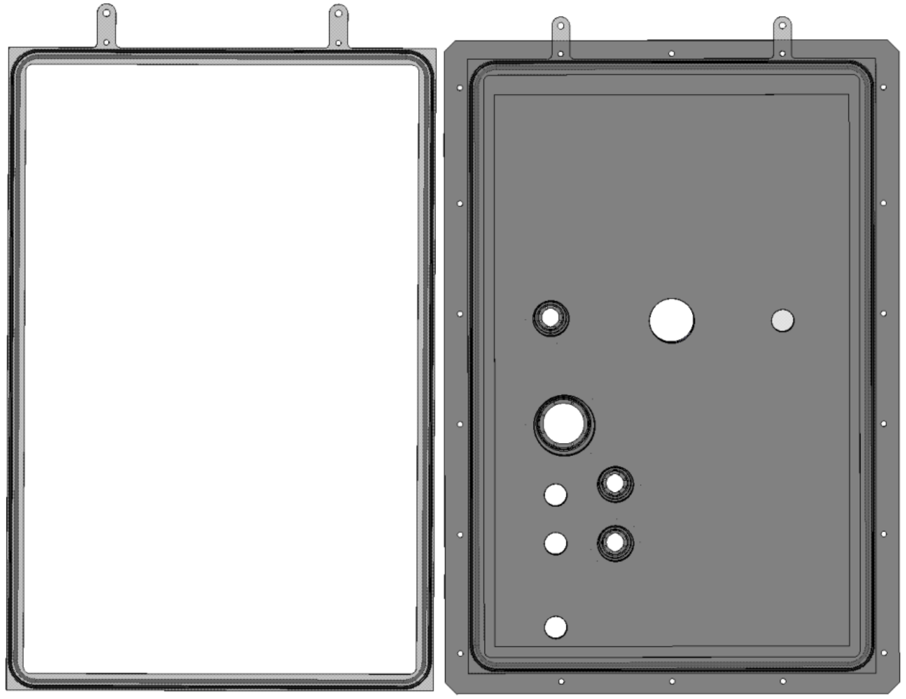
Further development for optimising the dismantling process (i.e. replacing multiple screws through use of a chain clamp)

153mmø EPDM seal

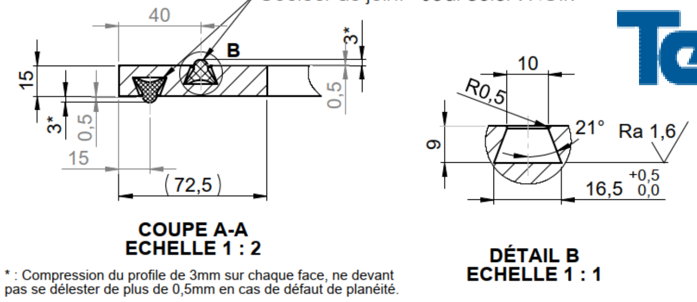


DN200 Bellow

220mmø EPDM seal



2 EPDM profiles mounted on a metal frame and installed onto vessel door (same principle as ISIS target station)

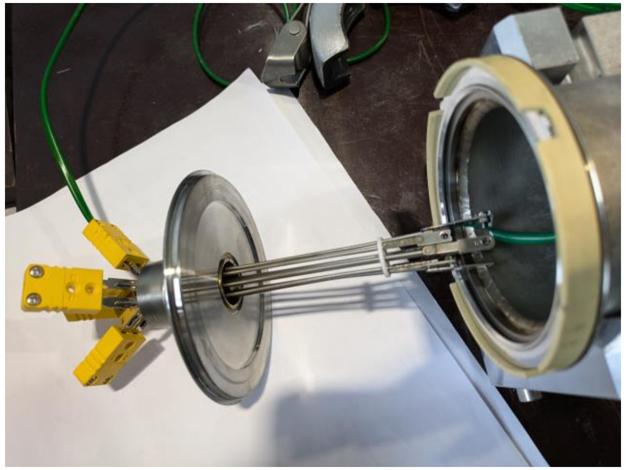


Technetics

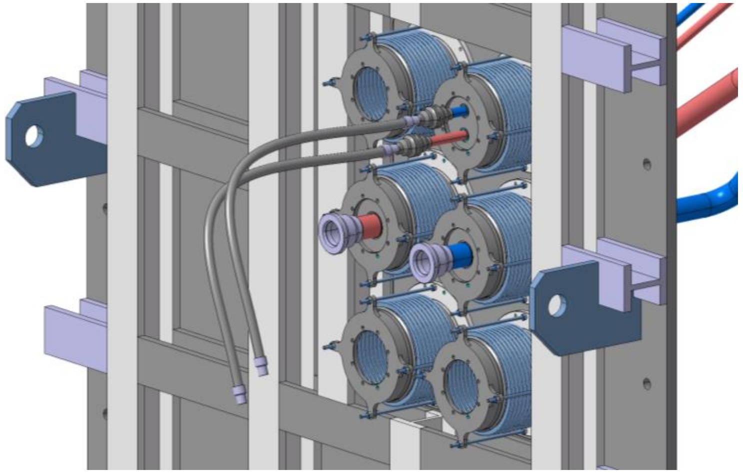
EPDM: Ethylene Propylene Diene Monomer

Remotely Operated Flanges Connections

- Current target coolant pipe layout doesn't allow for 2 flanged pipes (DN50) to fit next to each other for the target cooling
- Looking to reposition target cooling pipes so that there will be 1 pipe per remotely operated flange connection
- Total foreseen remote connection numbers: 2 for helium target cooling, 1 for water cooling of proximity shielding (integrated into the same flange connection)
- Also require a feedthrough for target and proximity shielding life monitoring (i.e. thermocouples)

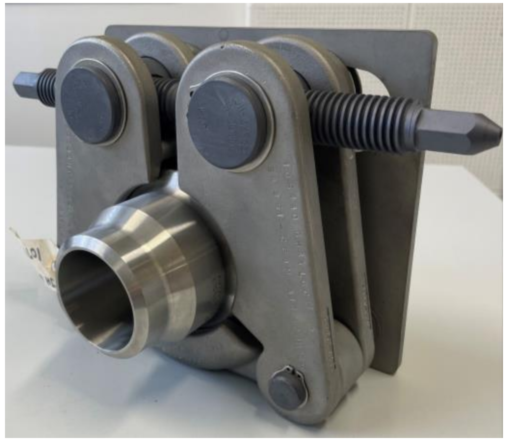


Typical vacuum thermocouples feedthrough



Pipe Configuration

Integrated dose: 1-5 kGy/year in this area
Residual dose: ~500-800μSv/h compatible with human intervention

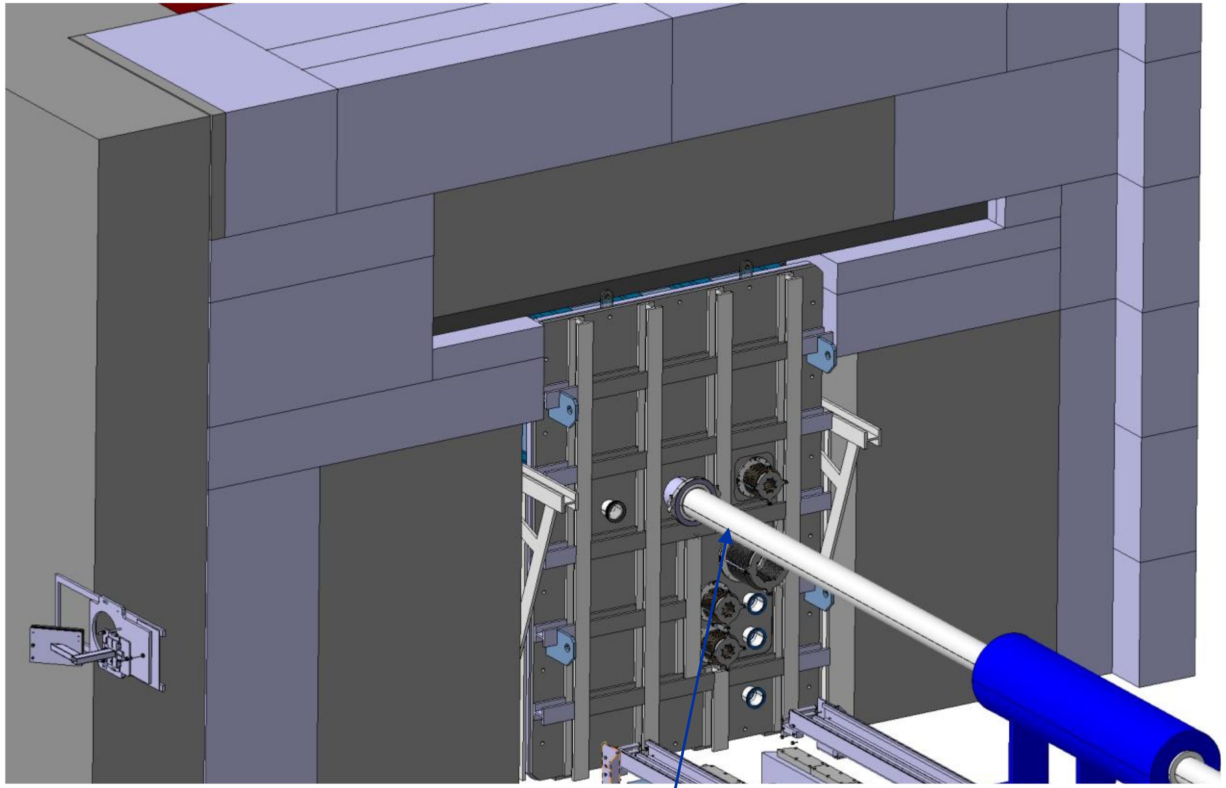


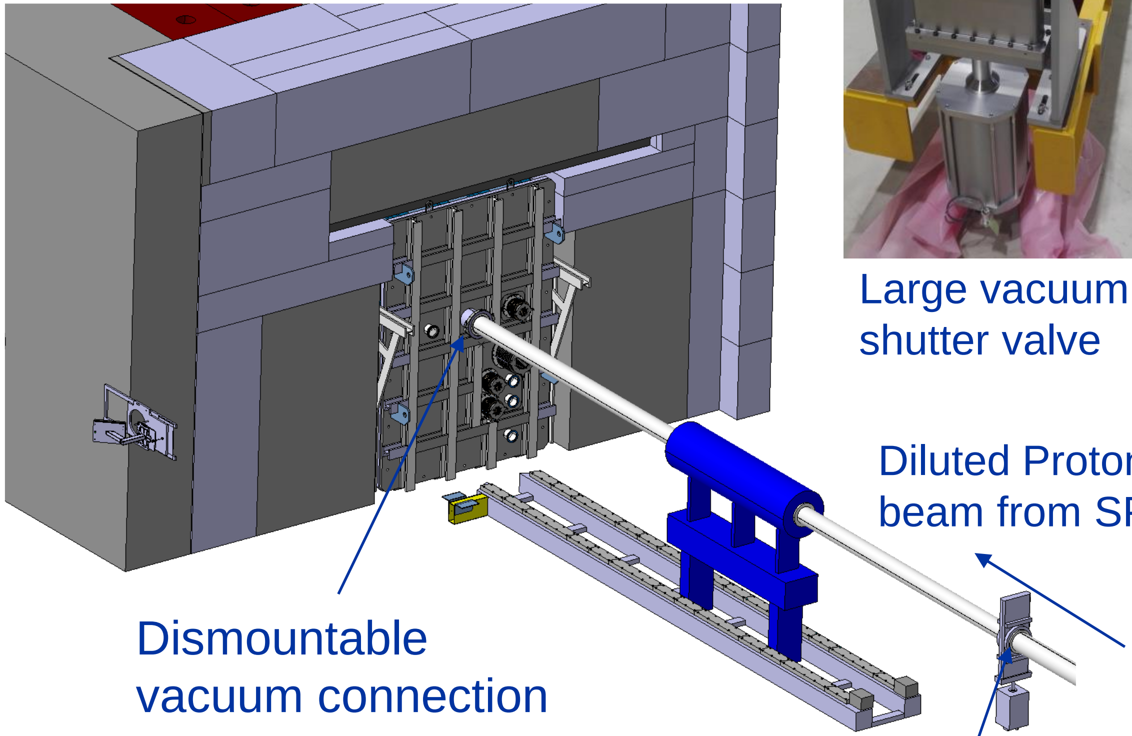
Remote flange connection to be implemented (possible manipulation with robotic solution in S. Di Giovannantonio talk)

Connection of Vacuum Vessel with Beam Line

Direct connection between beam line and vacuum vessel (probably a bellow is required)

Large vacuum shutter valve





Diluted Proton beam from SPS

Dismountable vacuum connection

Vacuum chamber diameter ~200mm

* Vessel door shielding not shown to allow for image clarity

Shutter Valve

Proton Beam Window (PBW)

- **Study of the proton beam window (PBW) is very preliminary. Full study in the pipeline. Some early considerations/checks:**

Requirements

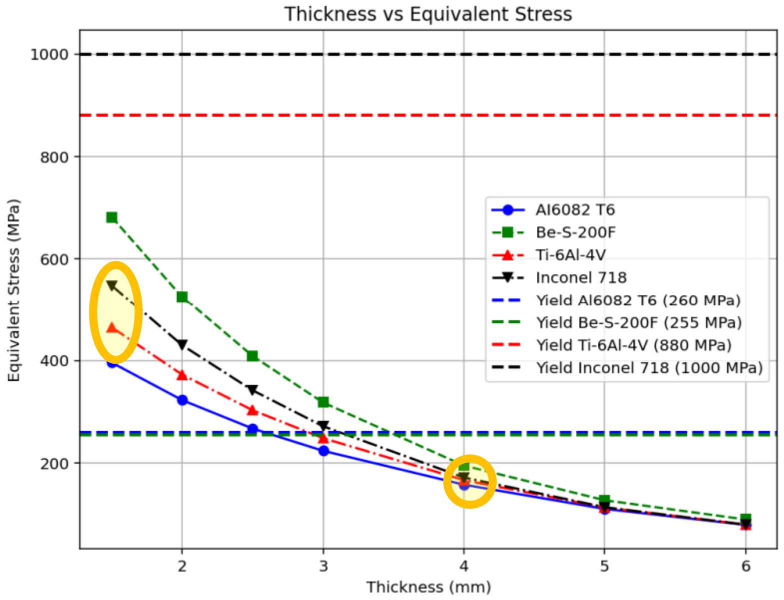
- Separates beamline vacuum (1 to 9 e-3 mbar) from vacuum vessel vacuum (~1e-3 mbar) – not a strong requirement
- Confines (safety) in case of leaks in target station
- **As close as possible:** to the target to avoid creating background (considered < 5m)
- **As thin as possible:** to avoid heating, creating background and having significant radiation damage
- **But…as far as possible:** to the target for ease of maintenance and reduce window size (and thus thickness to cop with pressure)

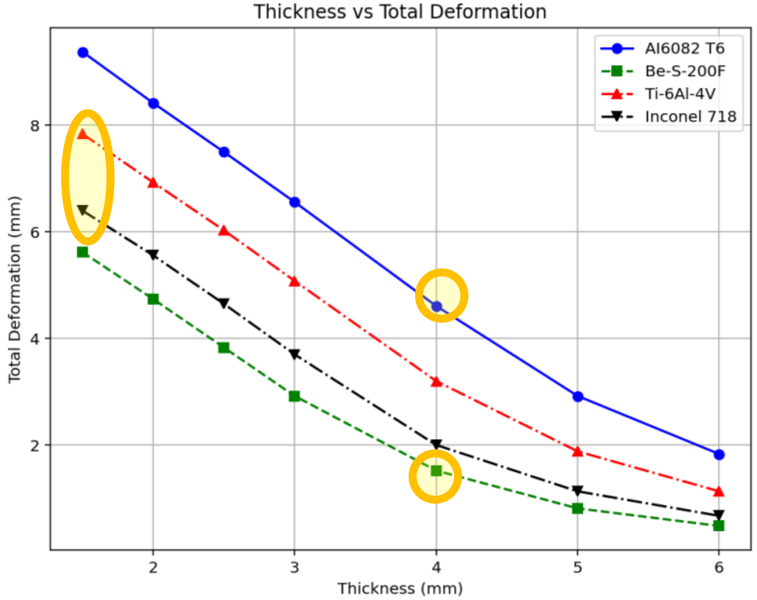
Early structural checks (<u>no beam impact considered yet</u>).

- In operation vacuum differential is not a problem. But once venting is done on one side:
  - Ti and Inconel (best for radiation damage) are best candidates to reduce thickness (~1mm).
  - Be and Al are good candidates due to low density but require higher thicknesses (>3-4 mm).
- Venting may be done on each side separately, so shape optimization is limited. Solution could be mixed window setup (e.g. CfC stiffener + very thin Ti window + CfC stiffener).

Reflection

- **Line will be equipped with shutter valve. What is the risk/benefit of also having a PBW? Shall we pursue a windowless system?**



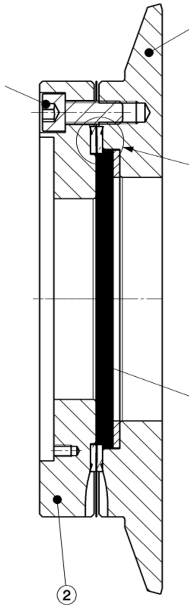


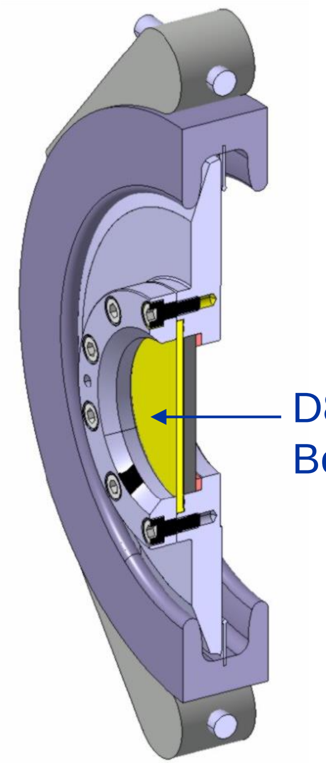
Assuming D480 mm

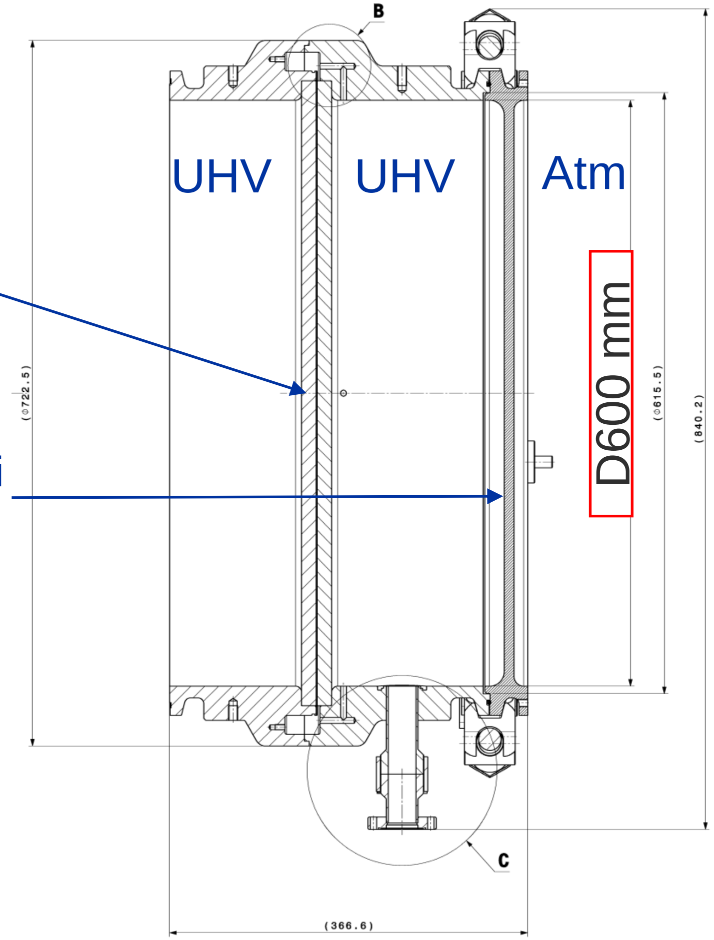
Proton Beam Window (PBW)

Typical examples of beam window

- LHC-TDE UHV window
- HiRadMat Dump window







Vacuum Vessel Potential Weak Points and Mitigations

Potential Weak Points	Mitigations
Vessel Door Seal	Every time door is opened, the seal will be replaced
Internal coolant pipe misalignment with connection to upstream coolant pipes	Installation of bellows and a remotely operated flange connection system
Seals within the bellow connections	Every time door is opened, the seals will be replaced
Shielding pool under vessel will become one of the lowest points in experiment and susceptible to flooding in extreme circumstances	Implement a drainage system into base of pool
All connections through vessel e.g. cooling pipes, thermocouples, vacuum pipe, etc	Placing these as far from the target as possible and all passing through 1 door which can be replaced and opened as and when needed

Vacuum Vessel FFMEA

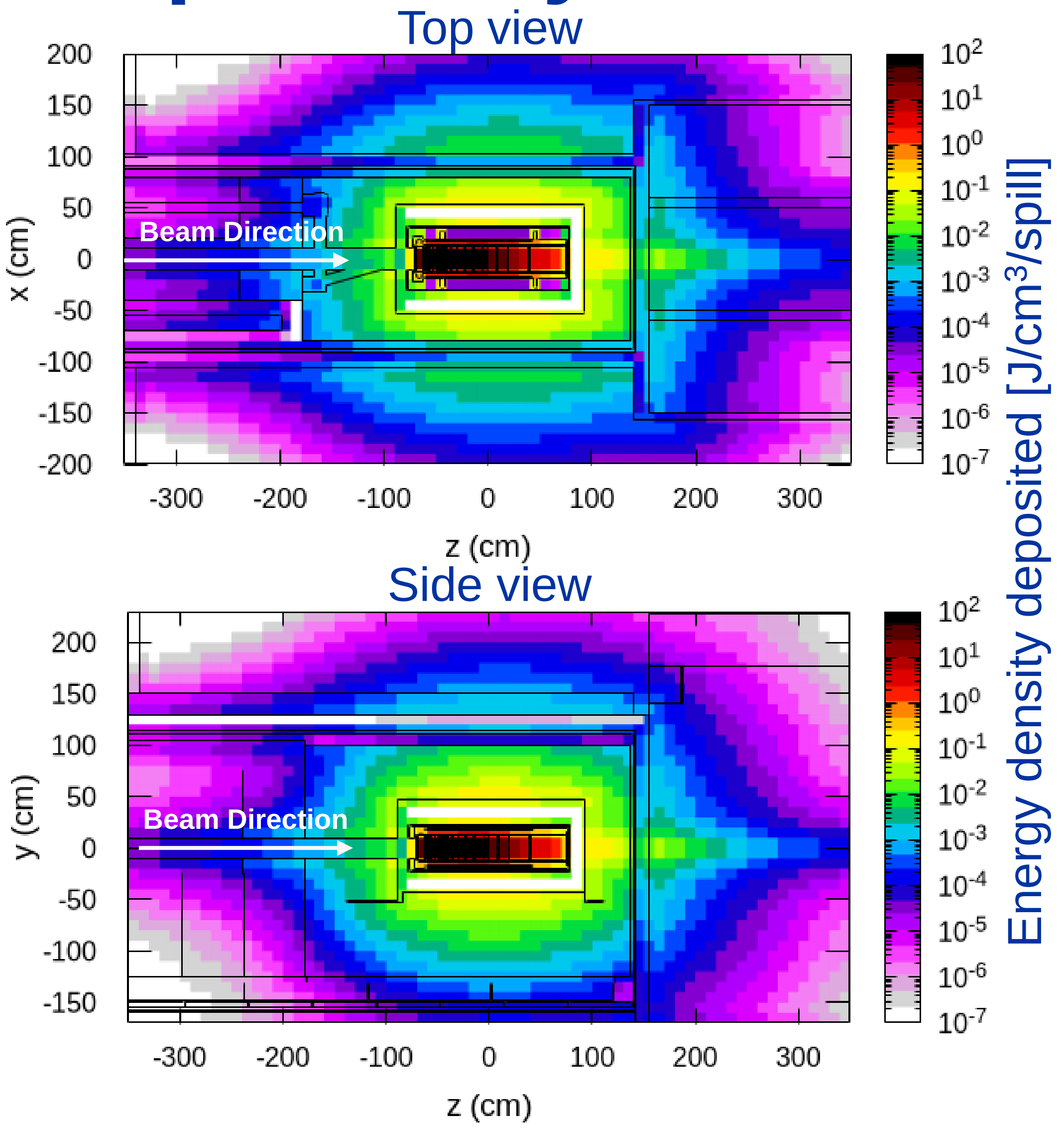
Functional Failure Modes and Effects Analysis (FFMEA)

Process of identifying possible failure modes in the functions of the vacuum vessel, causes, effects and prioritise order for mitigation

- **Completed defining a list of requirements:**
  - Functional Requirements
  - Performance Requirements
  - Implementation Requirements
  - System Requirements
- **Next step is to detail:**
  - Upstream and downstream influences
  - Failure modes and causes
  - Assign score based on likelihood, severity, effect, detection
- **Current Conclusions:**
  - Many failure modes stem from material degradation → material selection and preventive maintenance key aspect to address
  - Thorough planning needs to be conducted for how to maintain target alignment over time and during the installation process
  - All active components should be installed on an accessible/dismountable part → the justification for having all connections on the vacuum vessel door

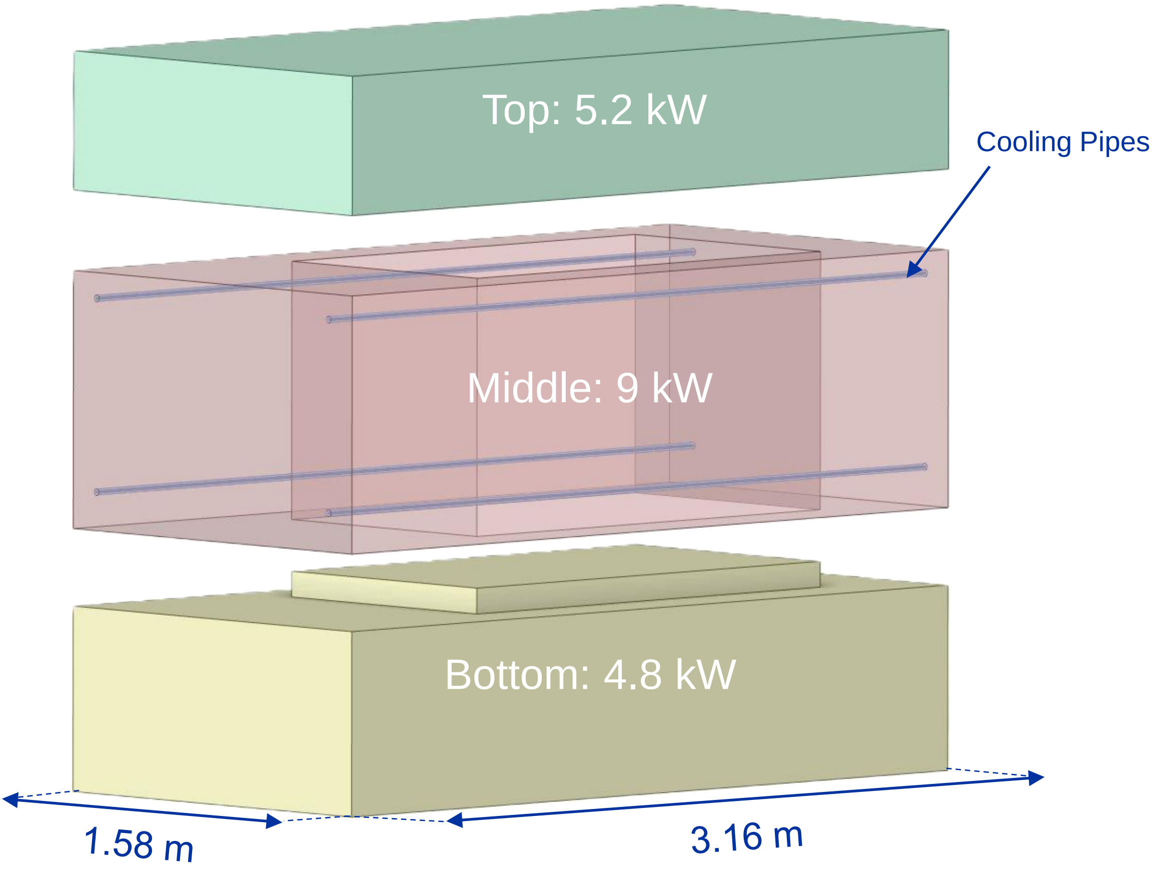
BDF Target complex integration – proximity shielding

- **Requires active cooling due to significant energy deposition**
- **Power to extract from the shielding blocks:**
  - **~20kW**
- **Must allow for easy removal of the target**



Proximity shielding - Cooling Circuit location

Approximation of energy deposited into each block with ANSYS imported from FLUKA:

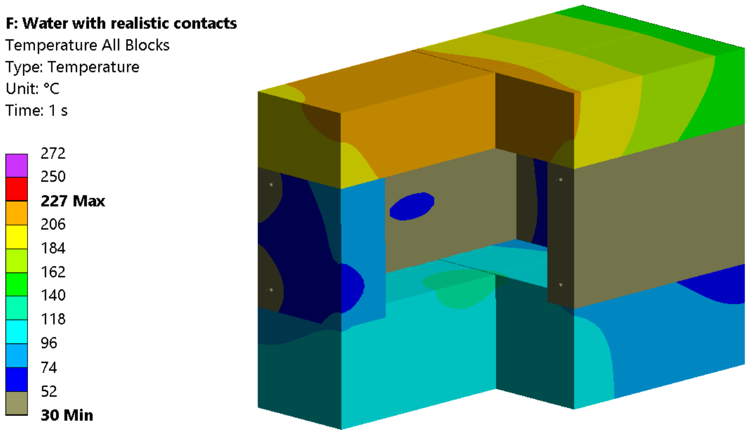
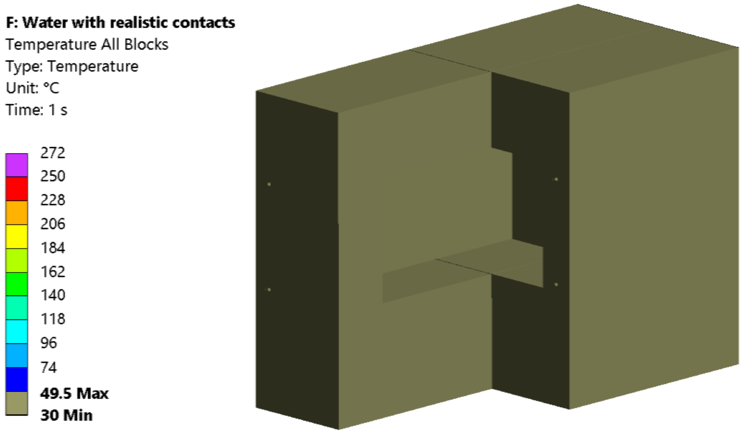


*TCC: Thermal Contact Conductance

Top Shielding	
Advantages	**Disadvantages**
• Simpler to implement into cooling system	• Cooling connections must be undone to access the target • Low contact pressure for TCC*
Middle Shielding	
Advantages	**Disadvantages**
• Target can be removed without disconnecting cooling • In contact with the top and bottom shielding • Receives around 50% of the total absorbed energy	• More features disrupting piping • Higher activation of the water
Bottom Shielding	
Advantages	**Disadvantages**
• Target can be removed without disconnecting cooling • Large amount of contact pressure with the middle shielding • Simpler to implement cooling circuit	• No direct contact with top shielding

Cooling location evaluation

Middle Block Coolant Medium Comparison

All cast-iron		All copper
	Worst-case* water ←→	
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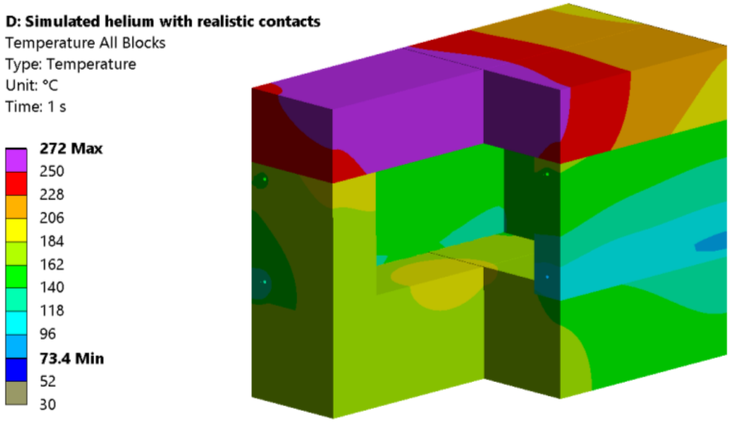
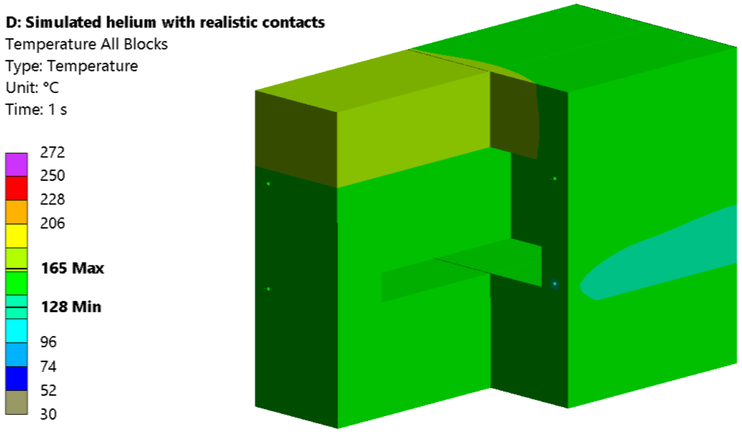
	Best-case* helium ←→	

*TCC

Preliminary findings for material and coolant

Shielding material	All copper		All cast-iron	
Coolant medium	Helium*	Water	Helium*	Water
Thermal conduction between blocks	Best-case	Worst-case	Best-case	Worst-case
Temperatures				
Min [°C]	128.4	30	73.4	30
Max [°C]	164.5	48	271.9	158.1
Avg [°C]	150.4	31.3	153.3	54.6
ΔT [°C]	36.1	18	198.5	128.1

*Helium mass flow rate: 30 g/s which is already quite demanding ~10% of the cooling power for the target

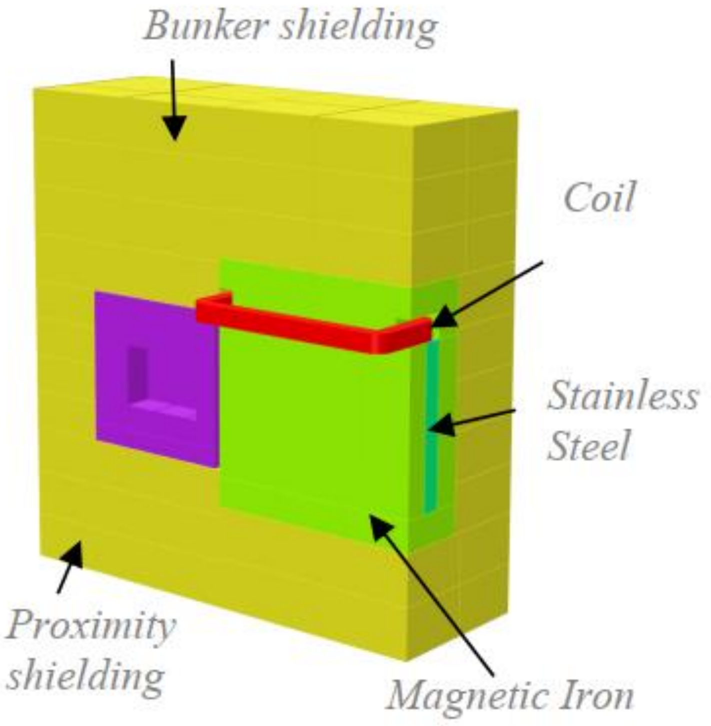
Proximity shielding baseline

- **Water cooling**
  - Lower complexity
  - Lower cost
  - Easier and more standard implementation for the cooling station
  - Potential water leaks would have to be managed in the vacuum vessel (detection, drainage, material selection, coating)
    - Vacuum vessel will become retention vessel
    - All in-vessel components should be corrosion resistant (everything made of Stainless steel, copper…)

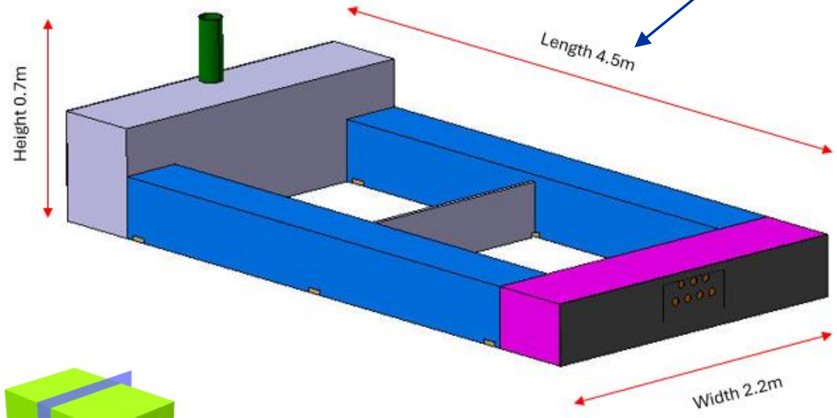
- **Copper alloy - (Cu-OFE, Cu-ETP or similar)**
  - Better thermal conductance
  - Water cooled copper = low temperatures for entire shielding
    - Less concern for thermal stresses and possibly creep

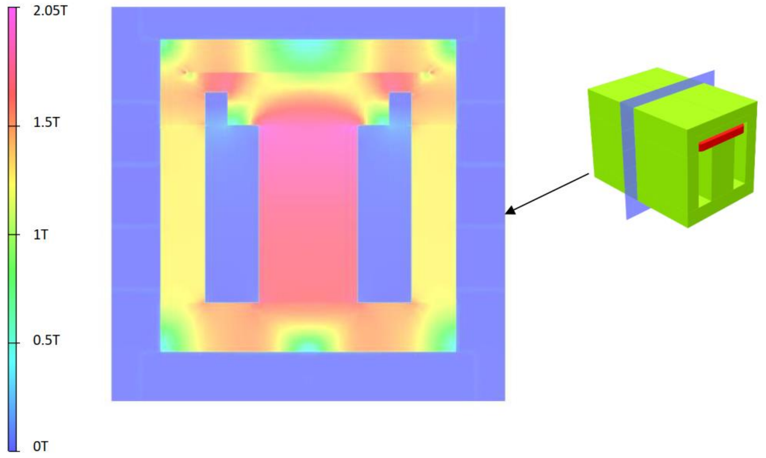
Detail engineering design to start following preliminary thermomechanical assessment

The Magnetized Hadron Stopper Shielding
A fraction of the experiment embedded in the target station



Overall Length being optimized
Tentatively will go down to 2.5m





Should stay bellow 30t

Why we would like to maintain our system!

Normal maintenance operations (yearly basis):

- **In vessel system inspection**
- **Removal of Irradiation module**

System replacement:

- **Target replacement in case of failure or reaching end of life (every ~5 years)**
- **Proximity shielding exchange in case of failure**

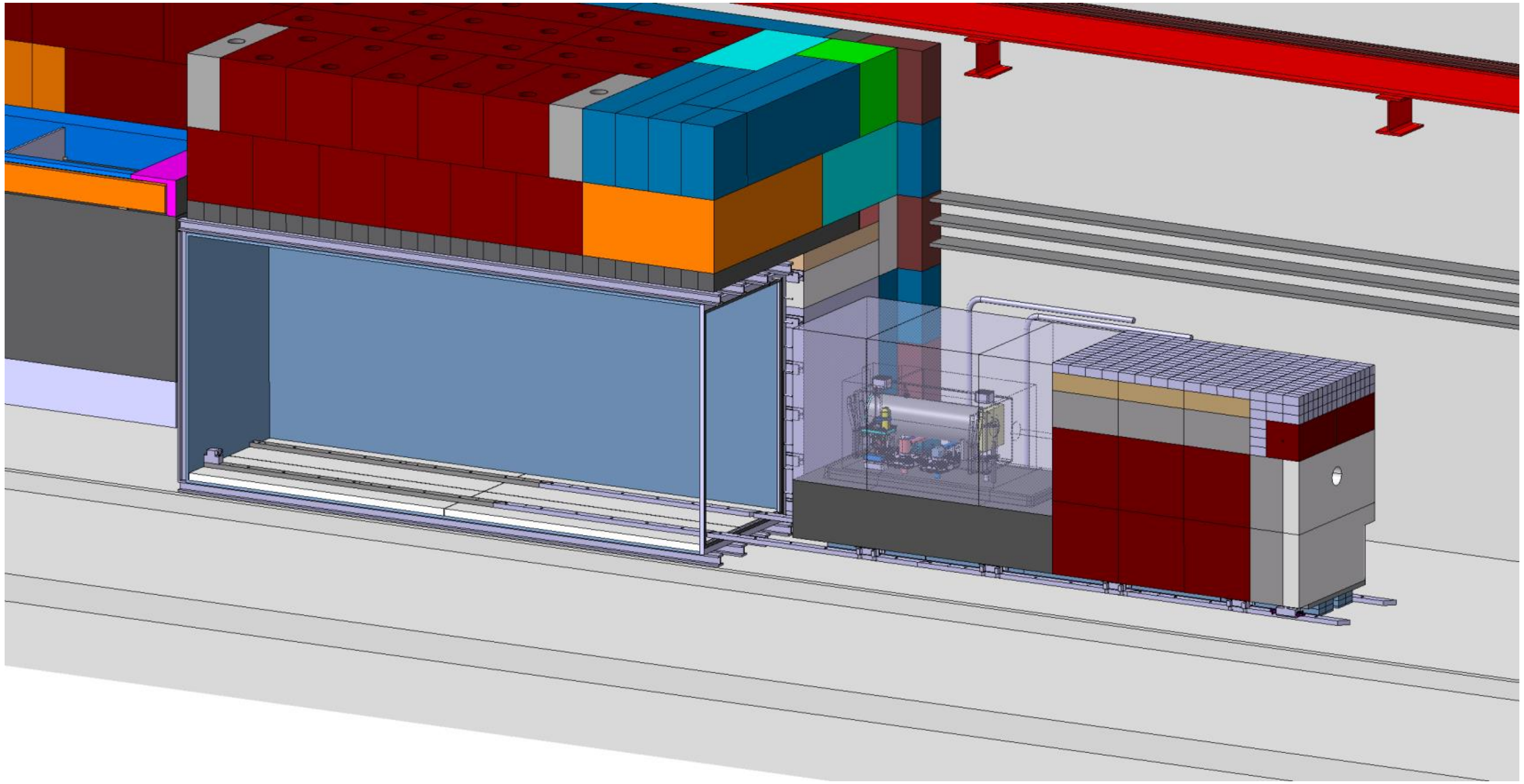
    Systems shall be designed to be replaceable within a winter stop (~20 weeks)

System reconfiguration/dismantling

BDF Target complex integration extraction

Trolley need to roll out to access in vessel components (target, proximity shielding and possible irradiation module*)

- Vacuum vessel need to be open
- Utilities need to be disconnected
- Trolley need to be extracted (142t)



* Irradiation module introduced later

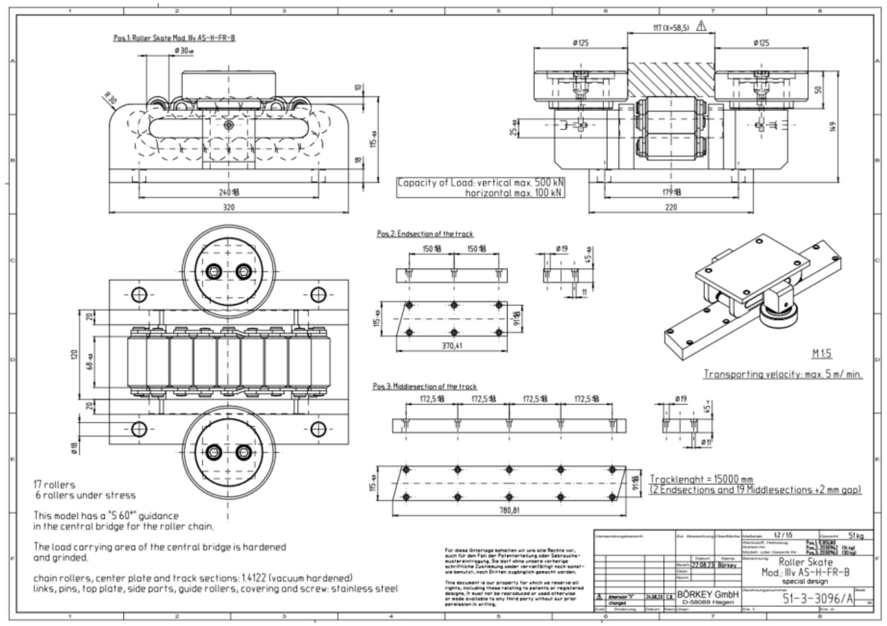
BDF Target complex integration extraction trolley

- Full stainless steel chain action rollers
  - ‘’Egyptian’’ system
  - No rolling element such as bearing
- Designed by specialized company:
  - Number of rollers and configuration (8 rollers foreseen)
  - Prototype stainless steel rollers and rails already at CERN for a test campaign (material selection assessment, test, ageing under harsh environment)
- **Typical applications:**
  - Bridge sliding supports (salty environment)

Other solutions discarded:

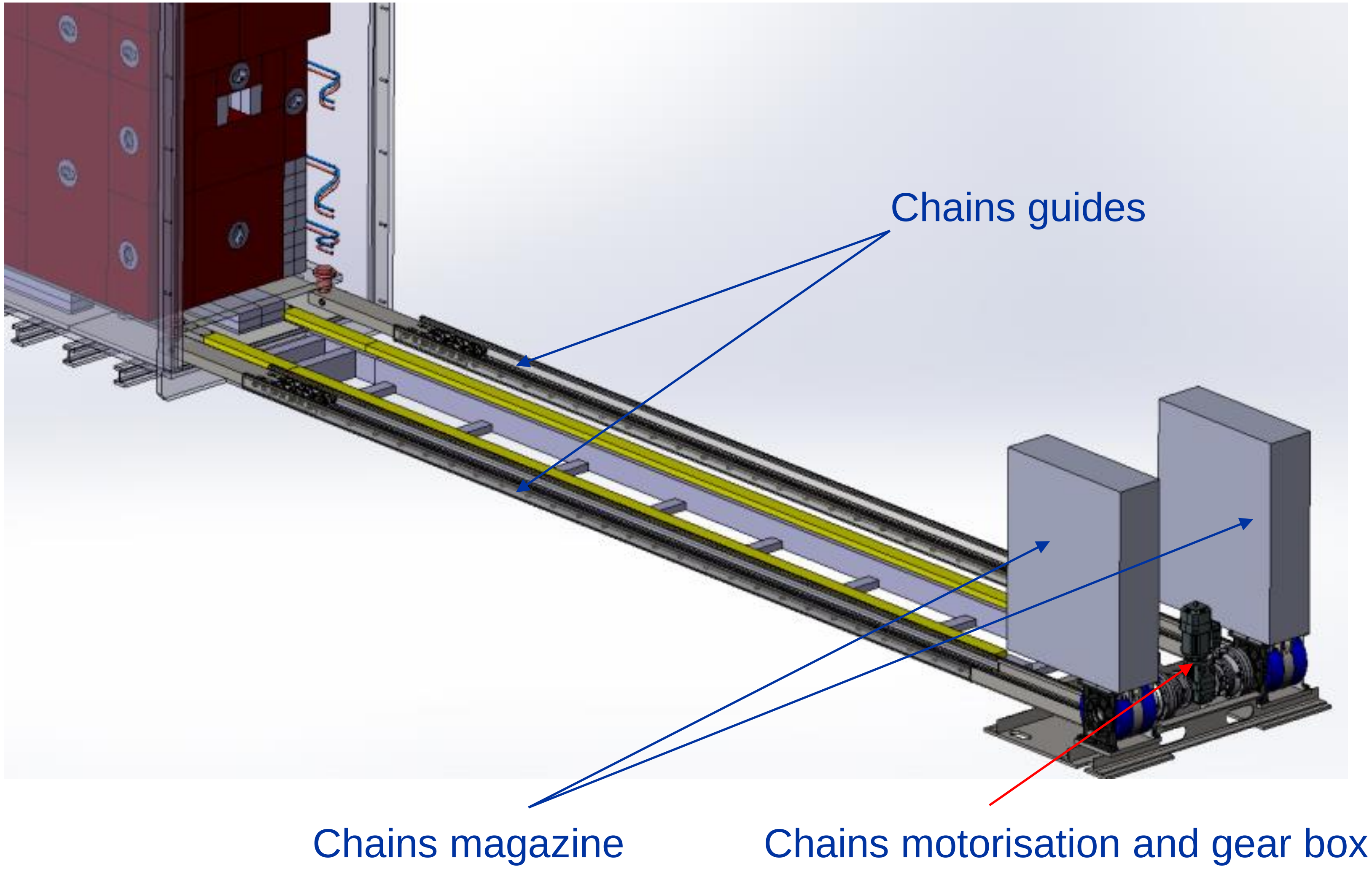
Wheels → precise rolling elements

On purposed air pads → complex system to operate (floor flatness and tightness)



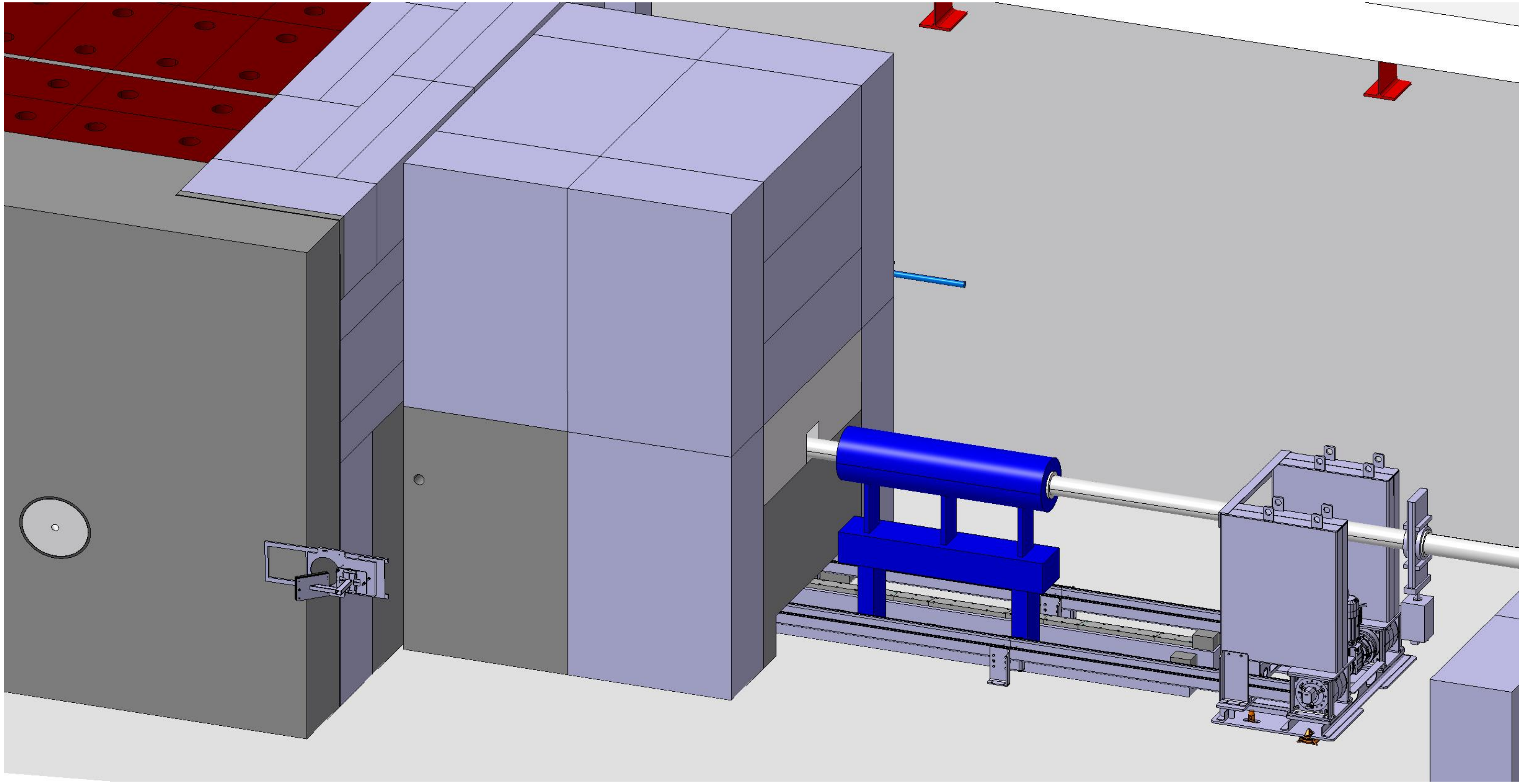
Push/pull chain mechanism

- Actuator installed on purpose
- Guides and docking station stays in place
- Remotely controlled
- Full stainless-steel chain
- Redundant chains
- Connection of the chains remotely compatible*
- Recovery from failure scenario remotely compatible*

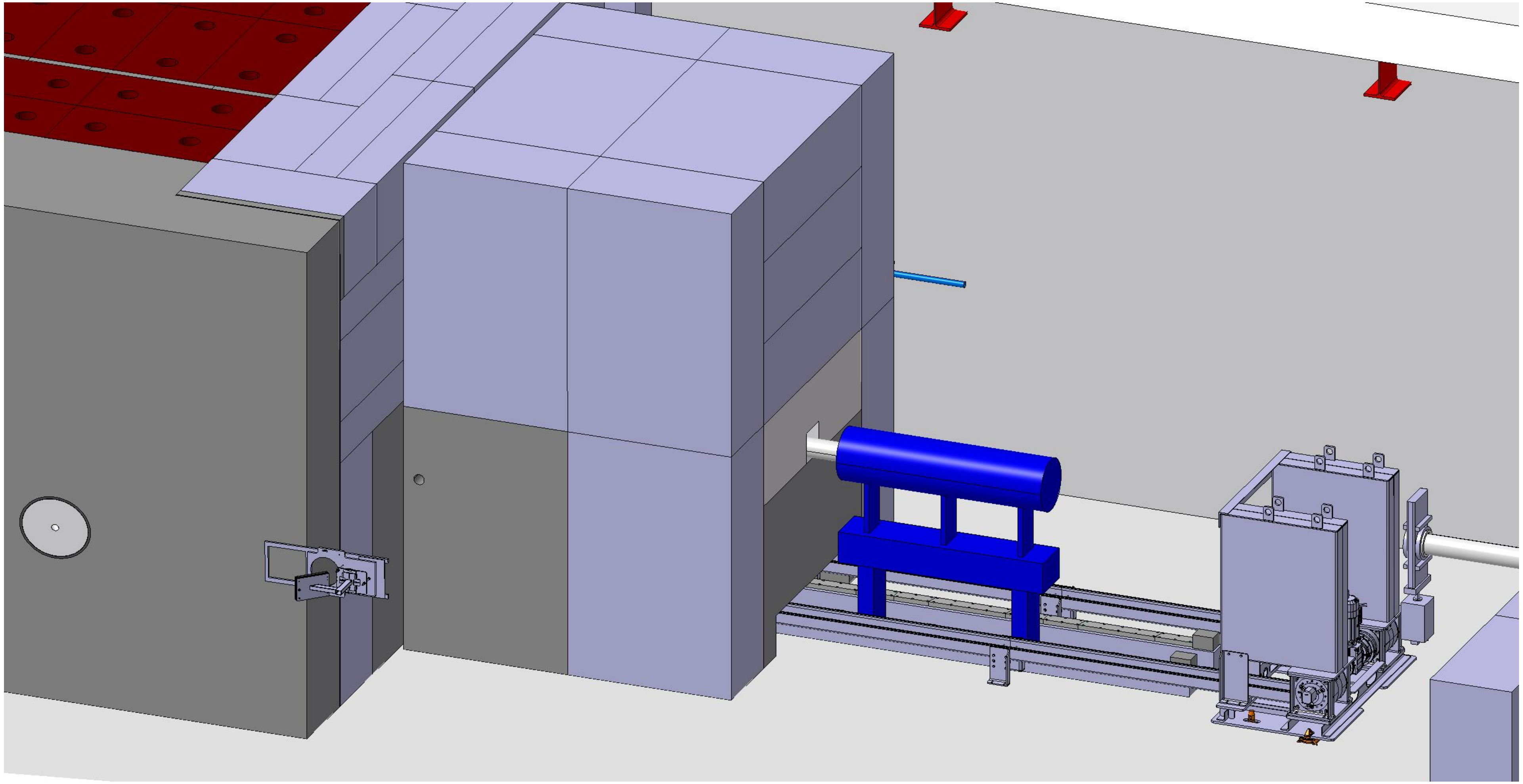


* Discussed in S. Di Giovannantonio talk

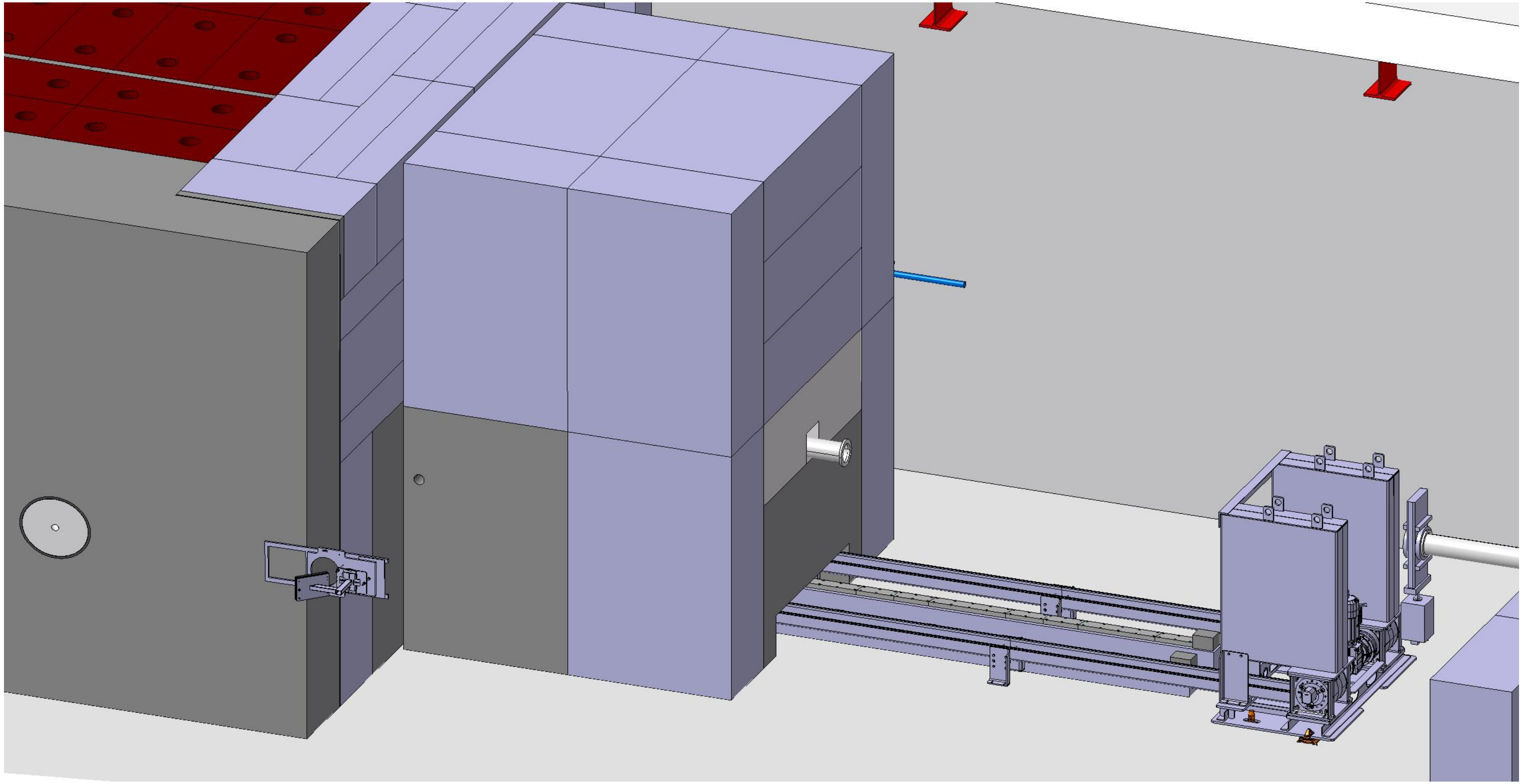
Target removal tentative sequence



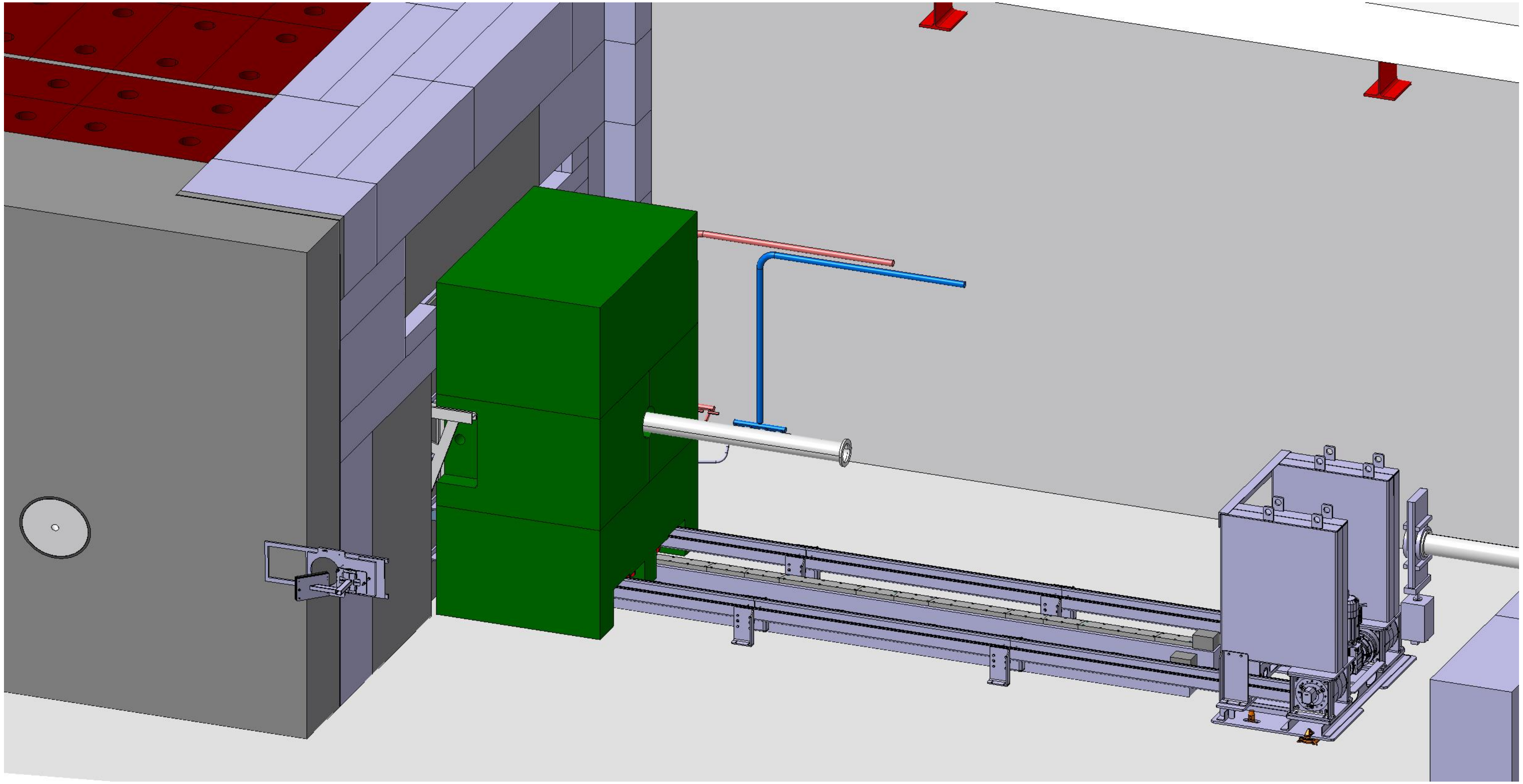
Beam line removal



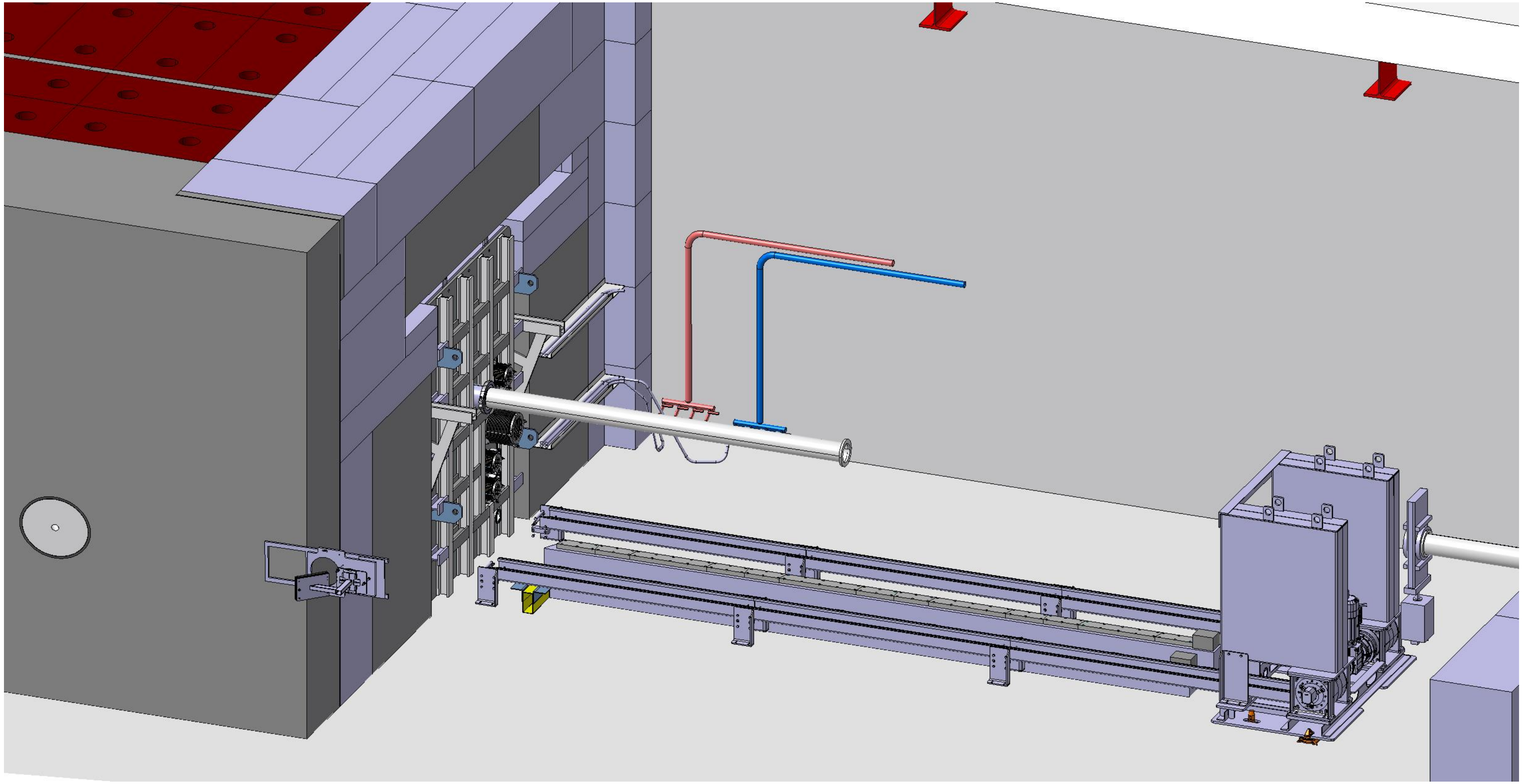
Beam instrumentation package removal



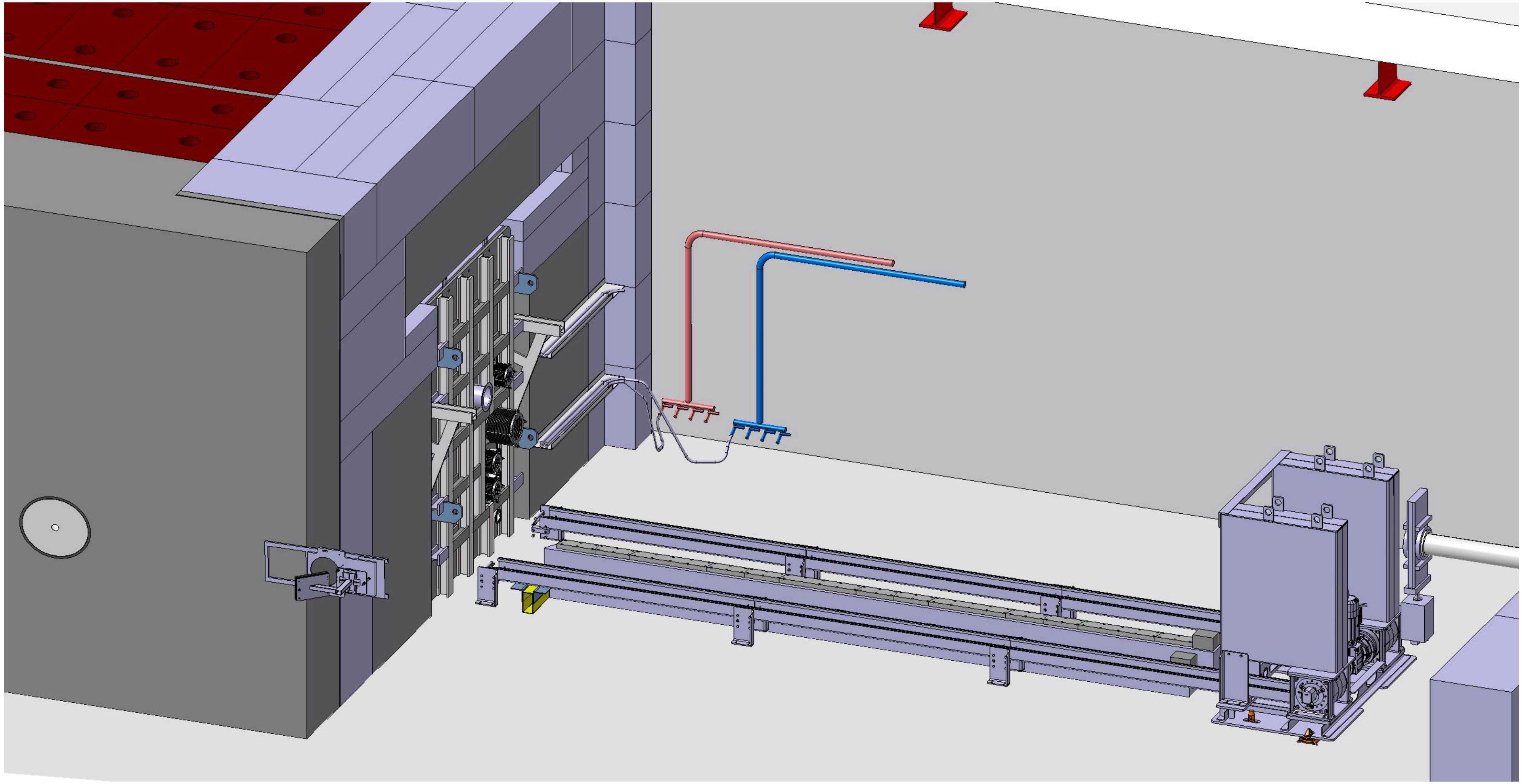
Collimator shielding removal



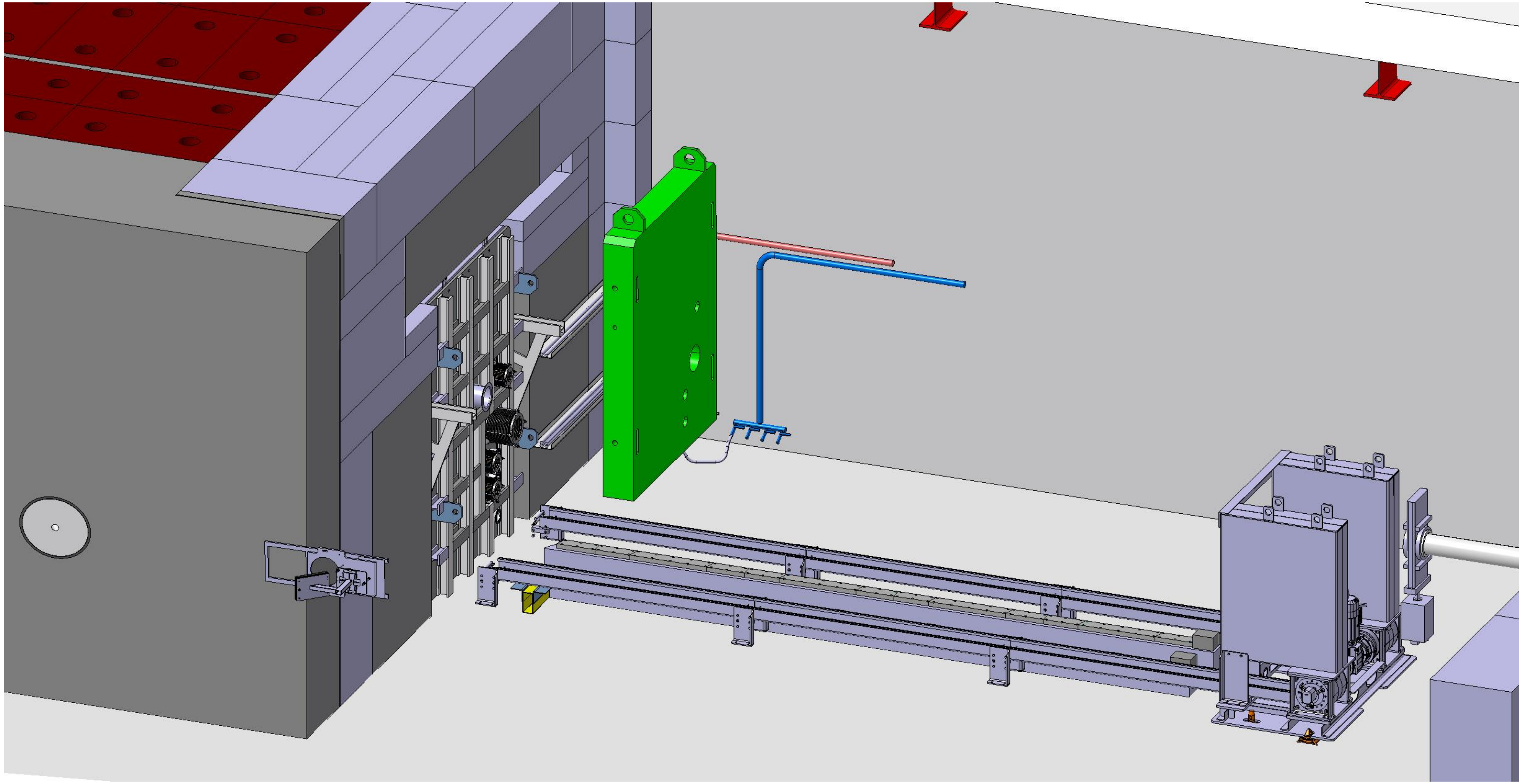
Collimator removal



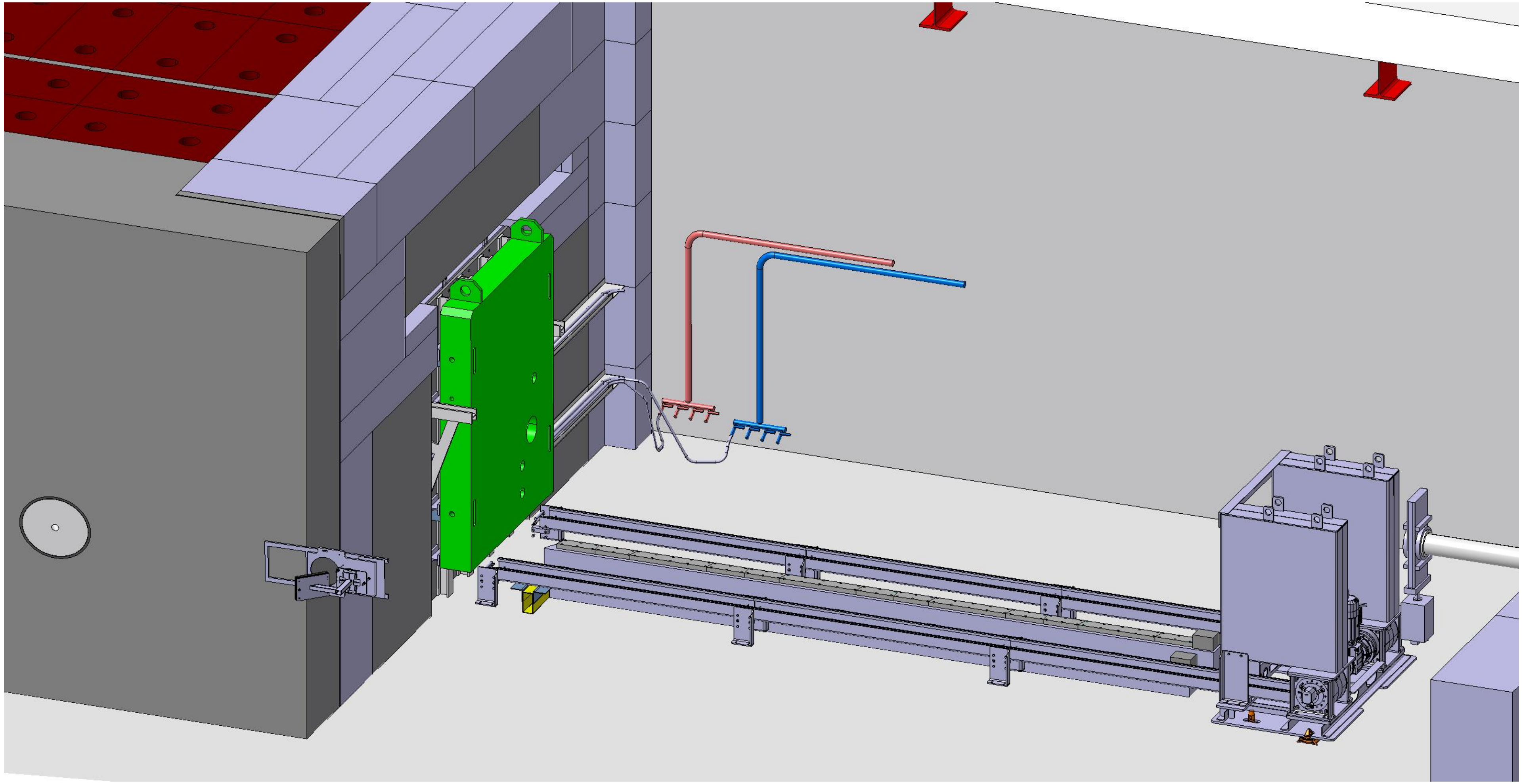
Beam Pipe Removal



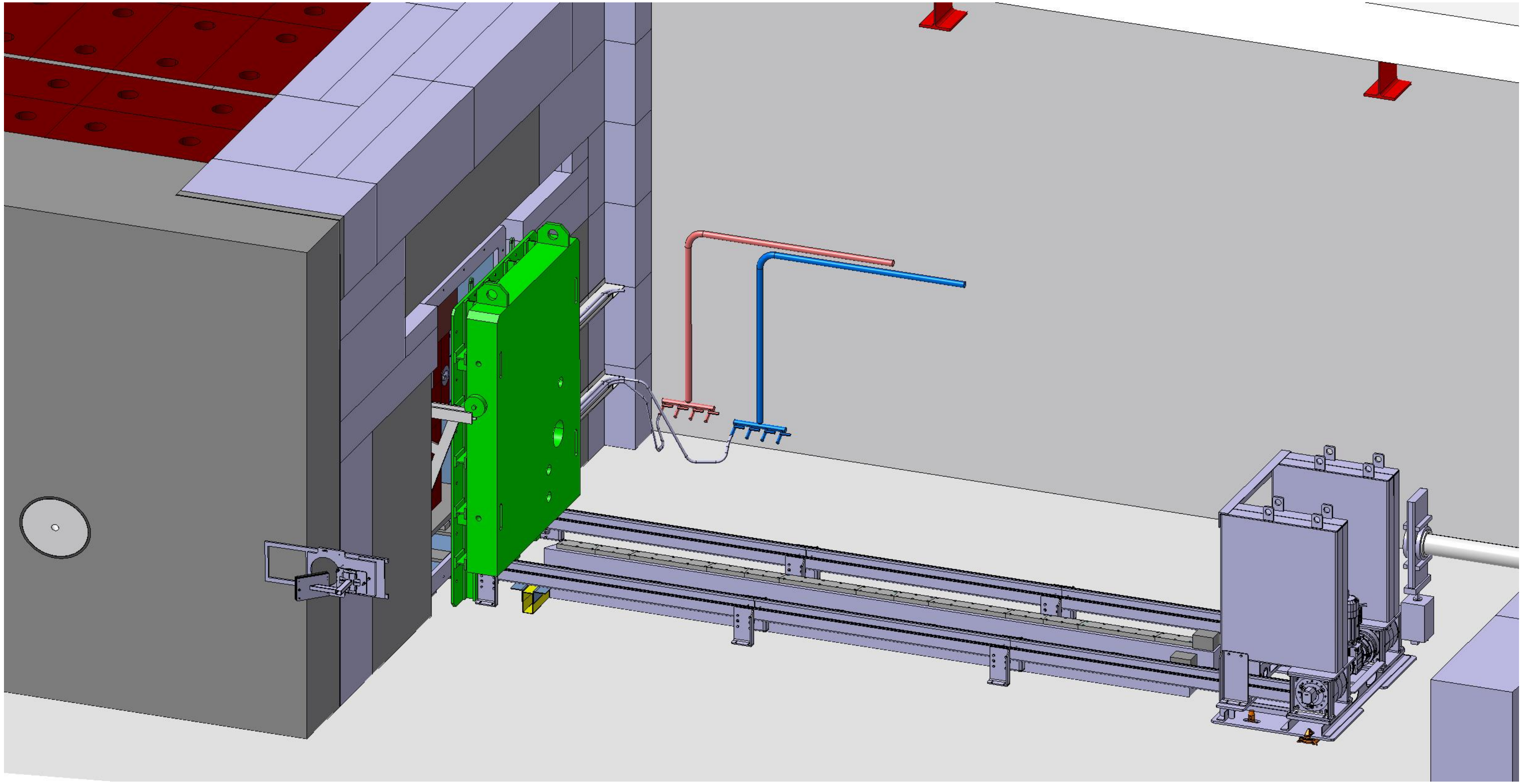
Vacuum vessel door lifting + shielding tool installation



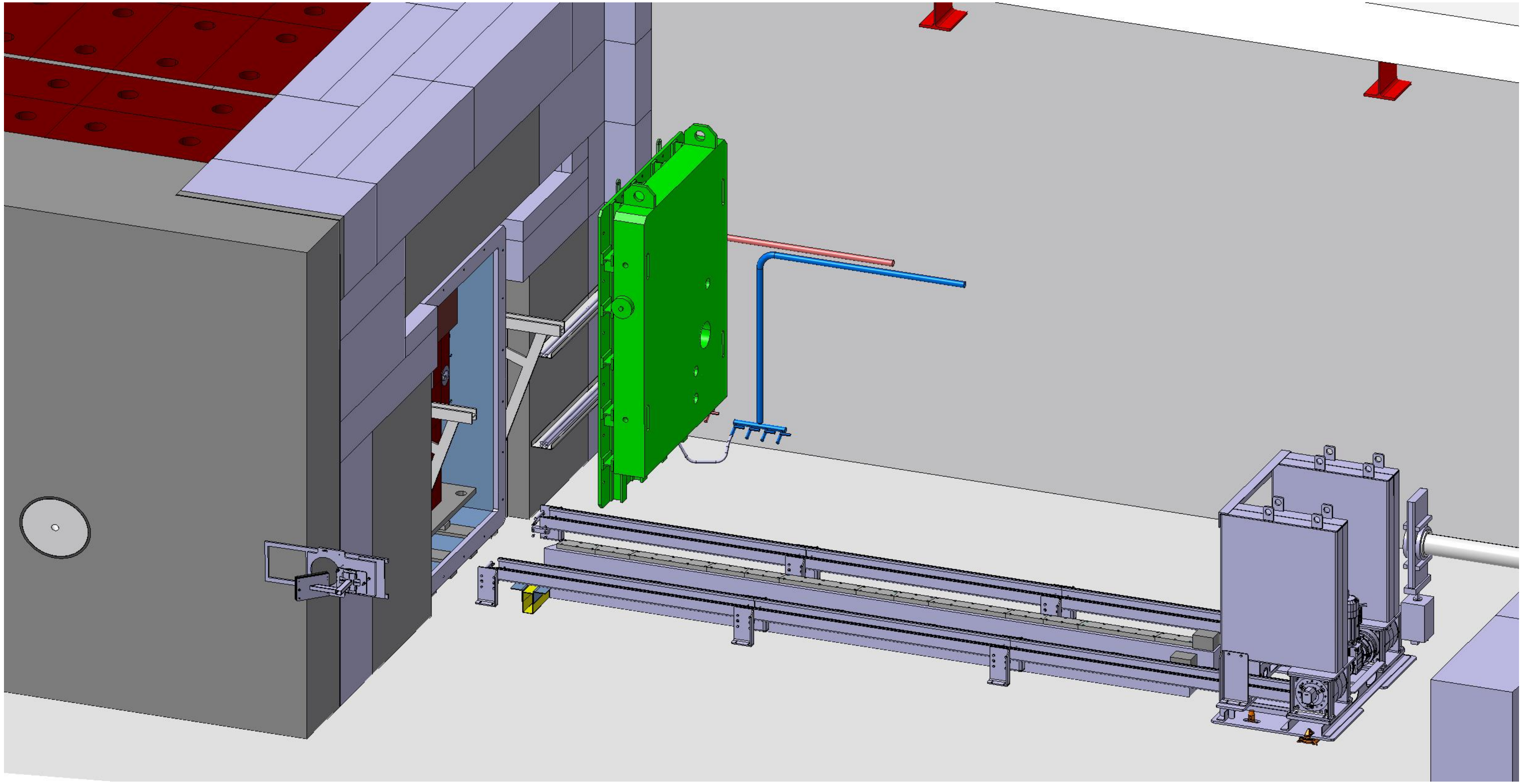
Disconnection of utilities and vacuum vessel door unbolting



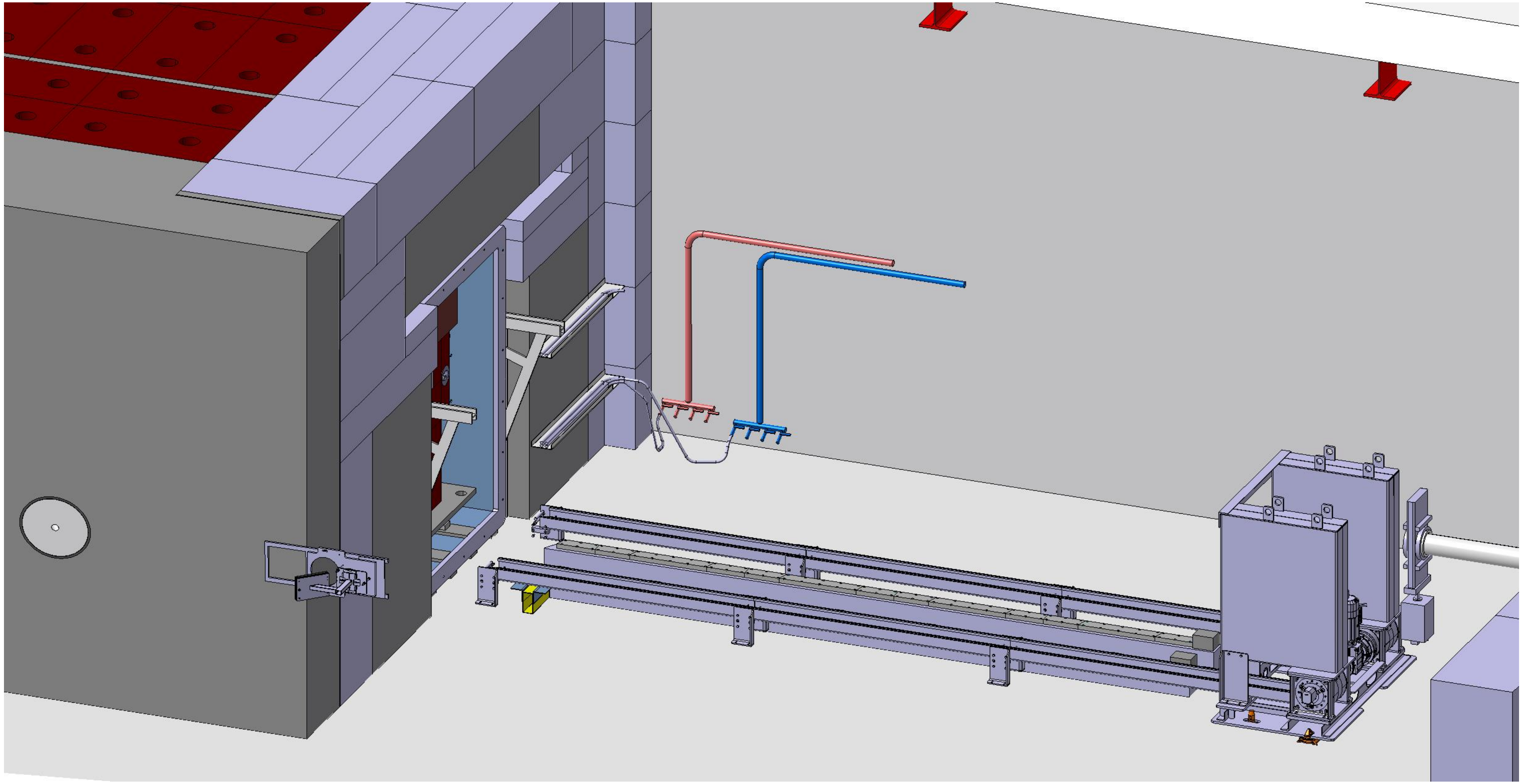
Vacuum vessel door removal 1/2



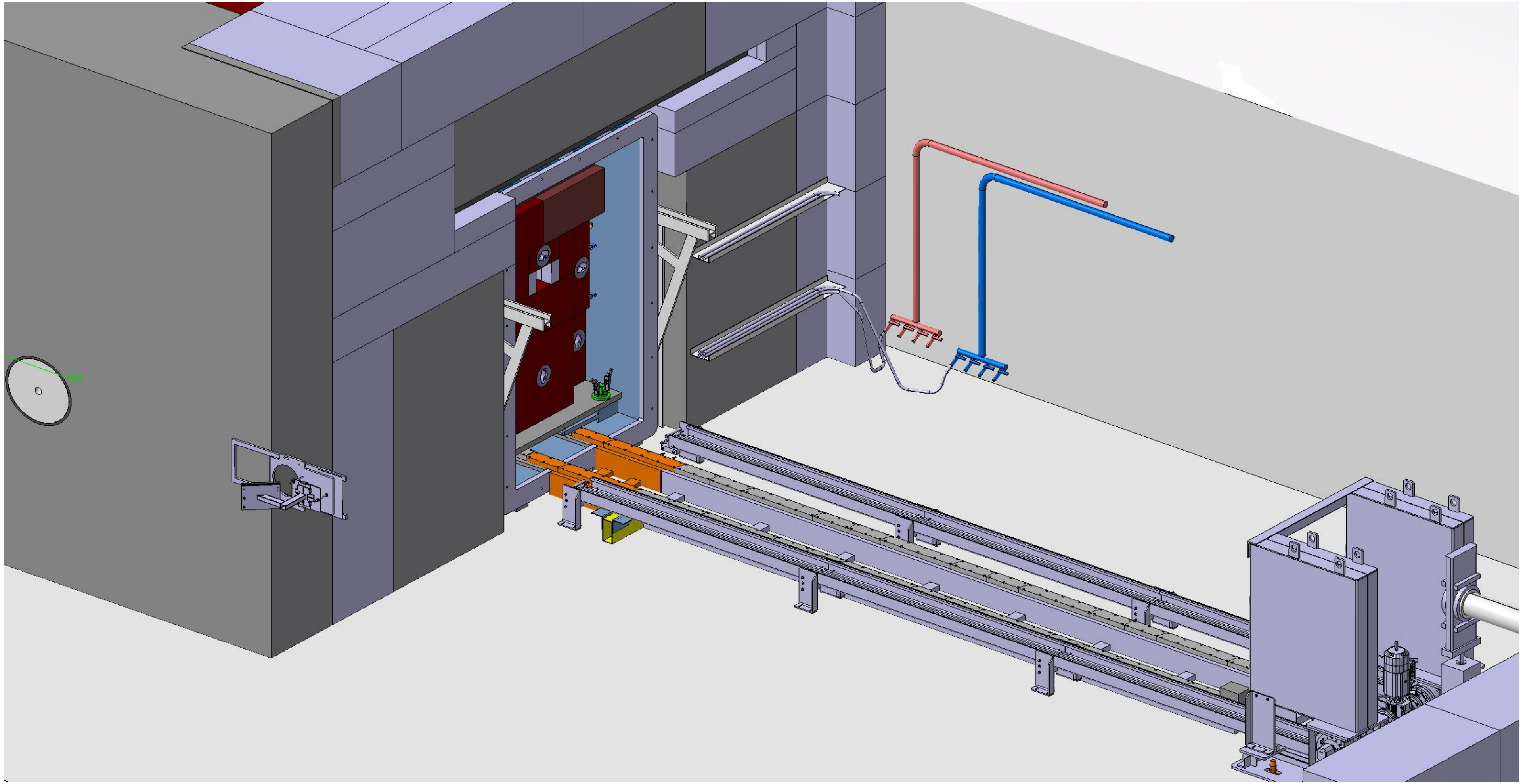
Vacuum vessel door removal 2/2



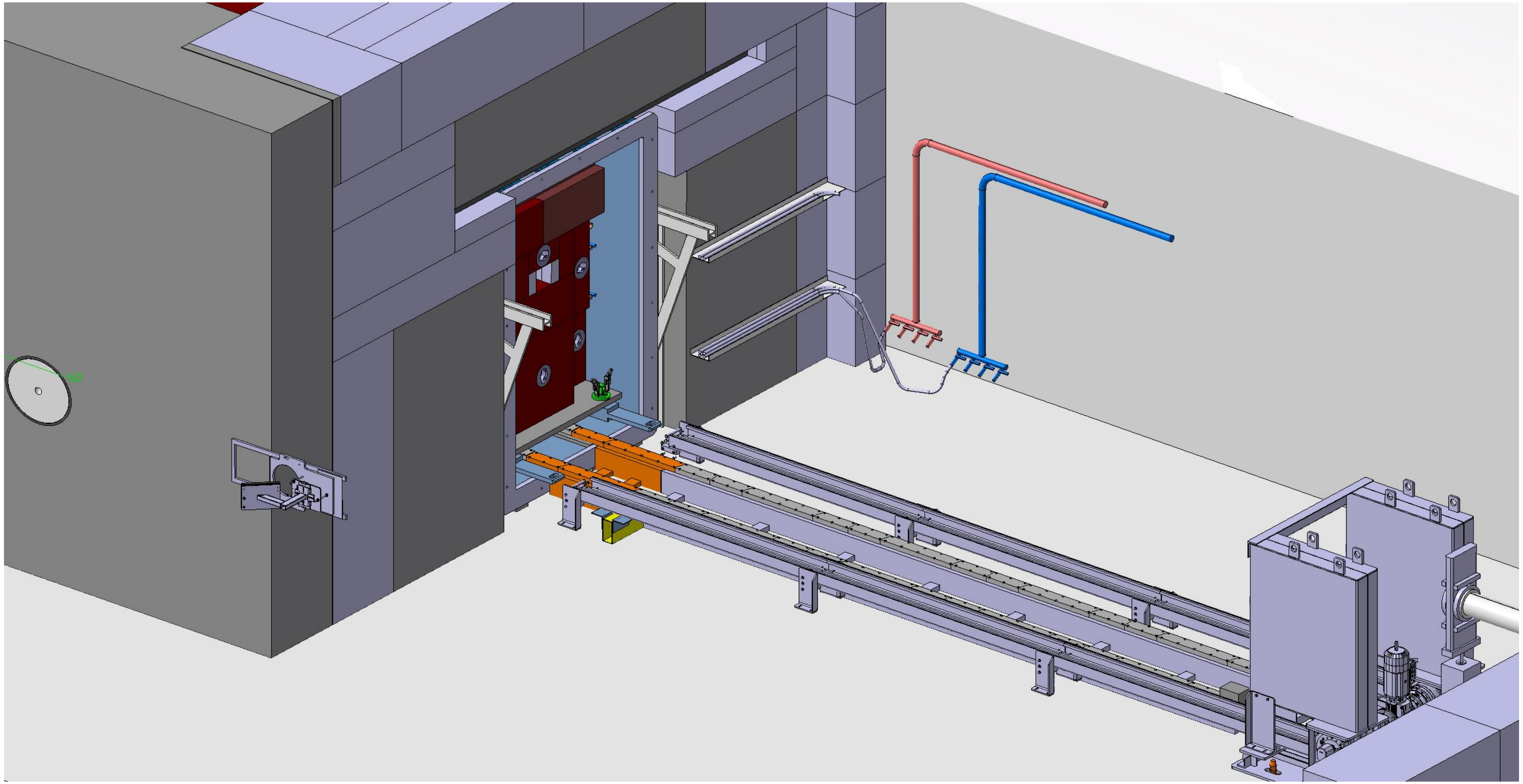
Vacuum vessel open



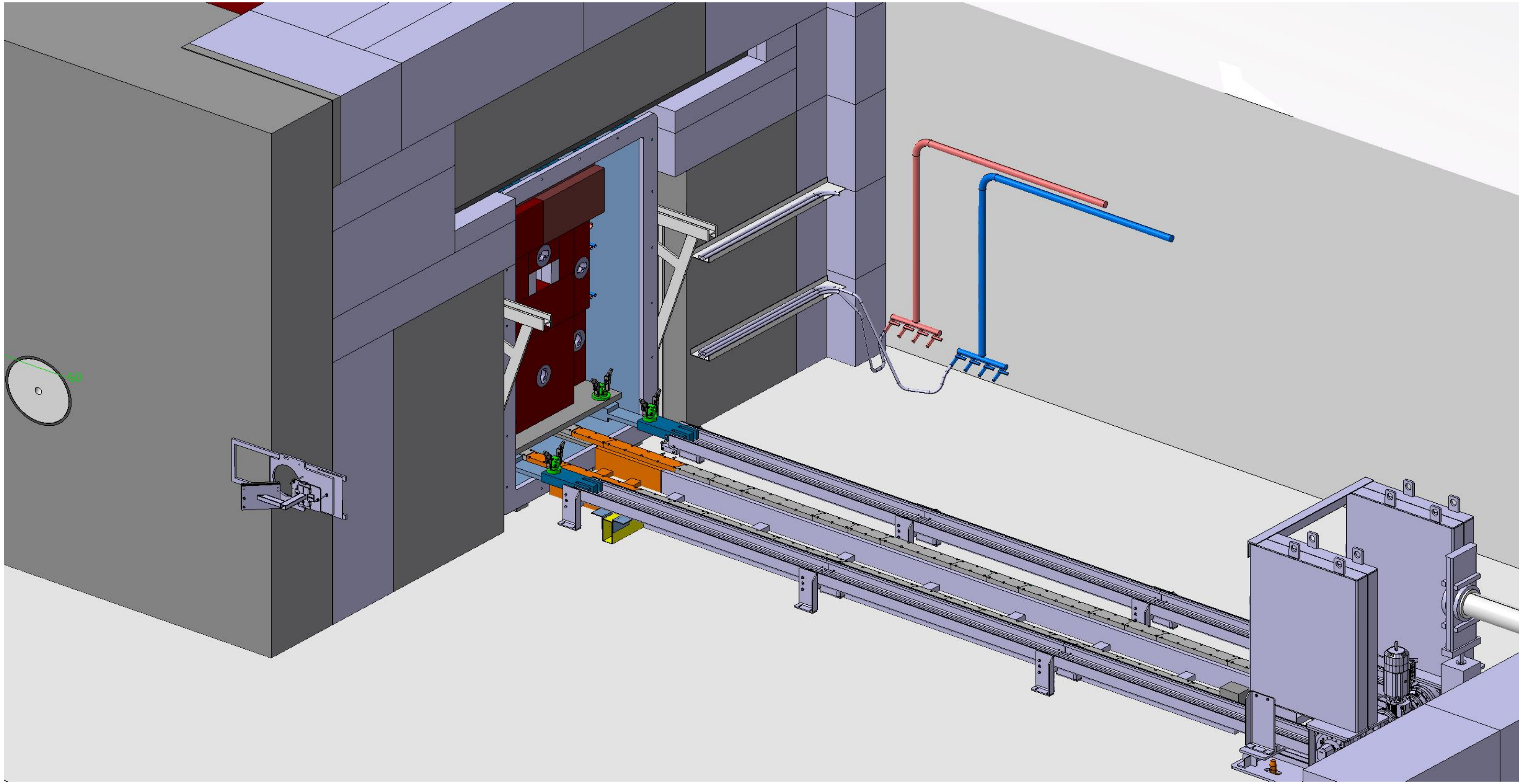
Transfer rail installation



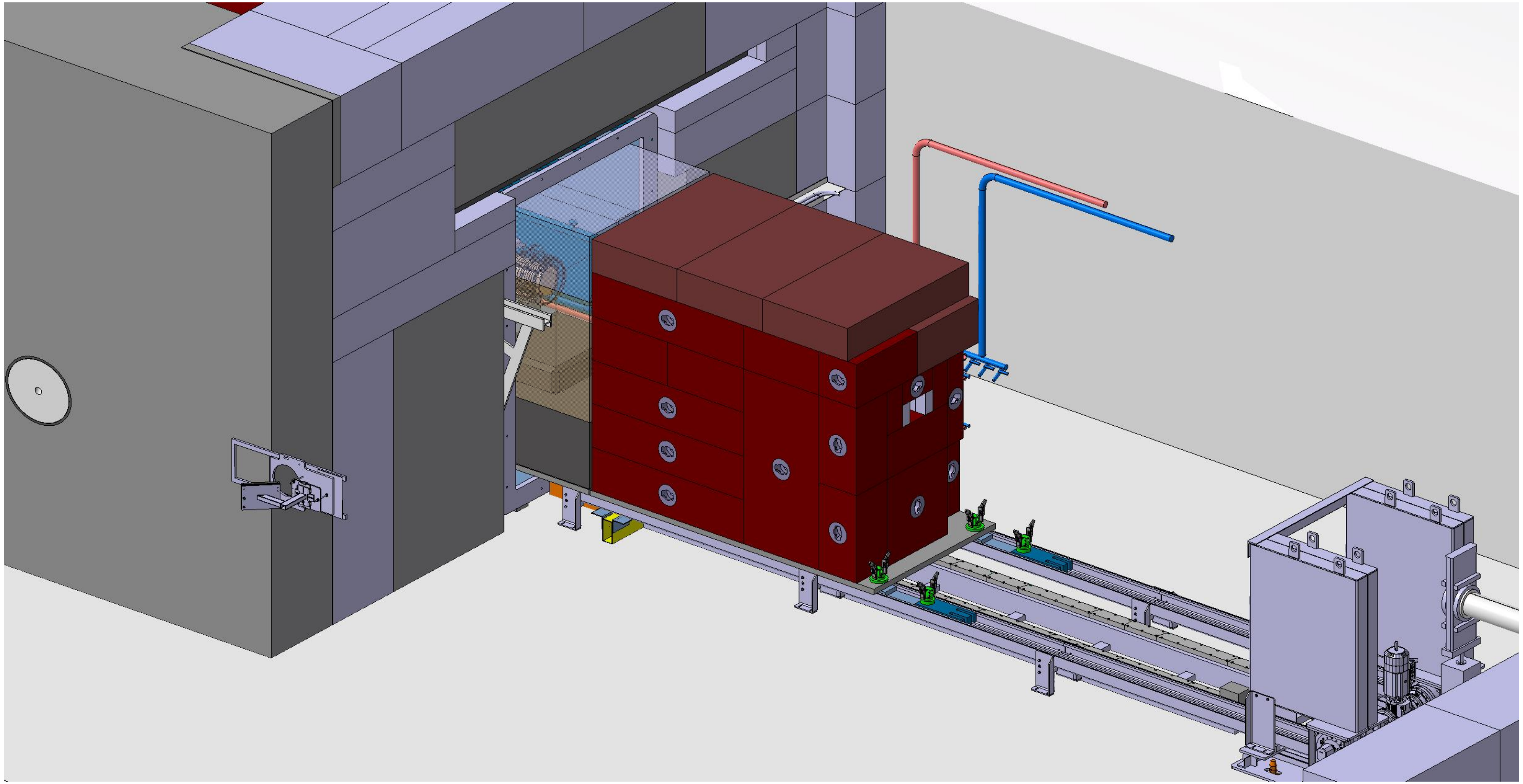
Push/pull chain mechanism connection 1/2



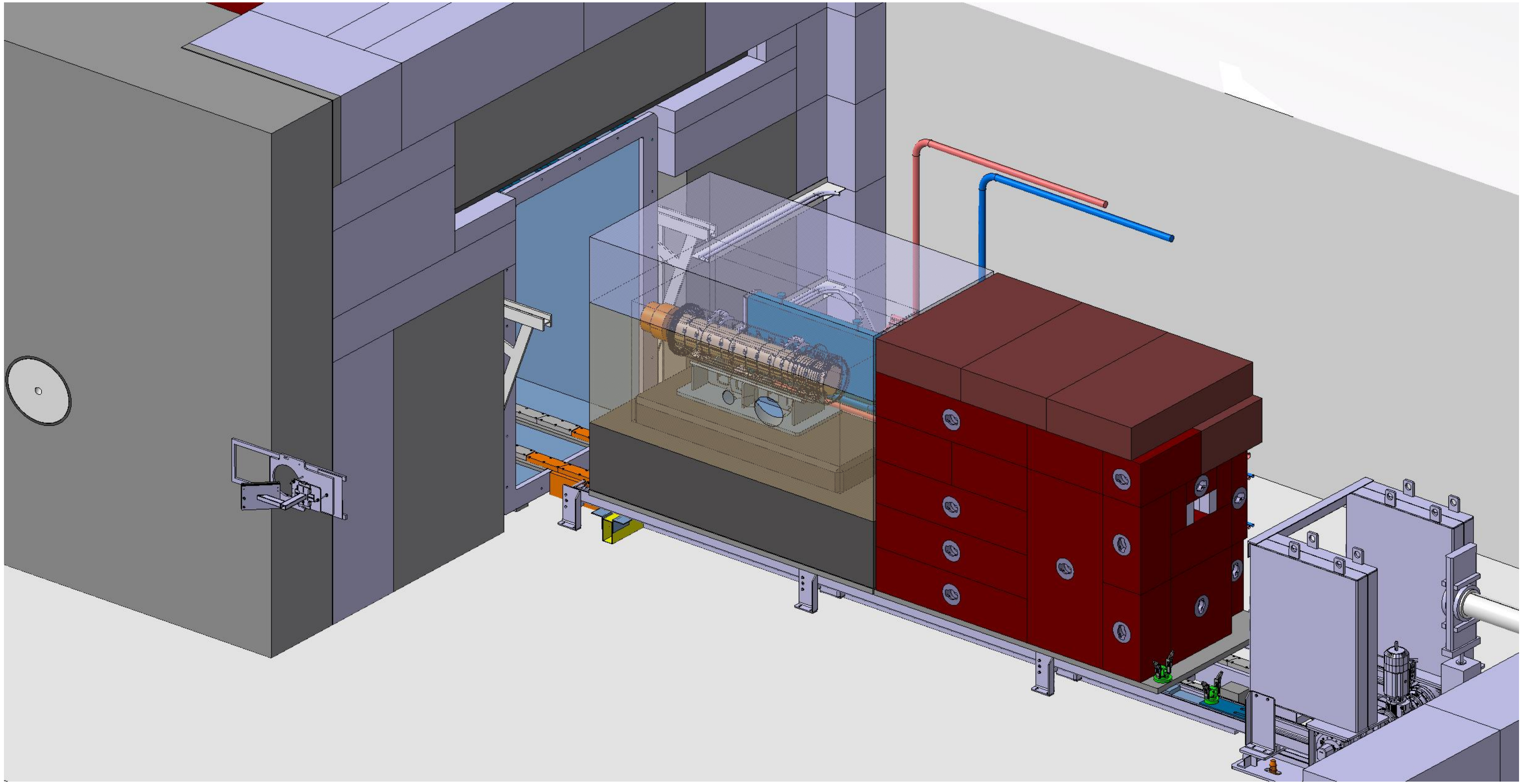
Push/pull chain mechanism connection 2/2



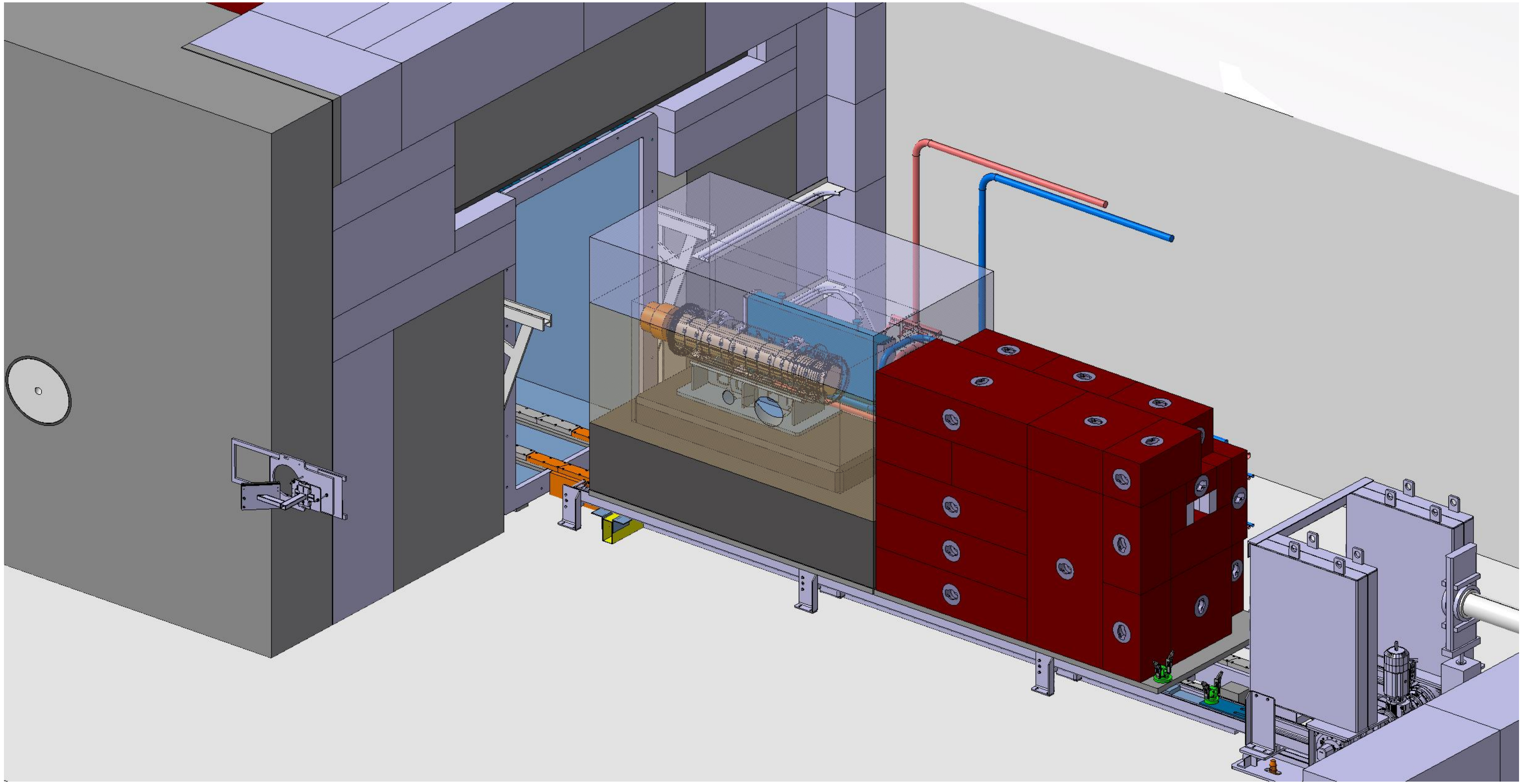
Trolley extraction 1/2



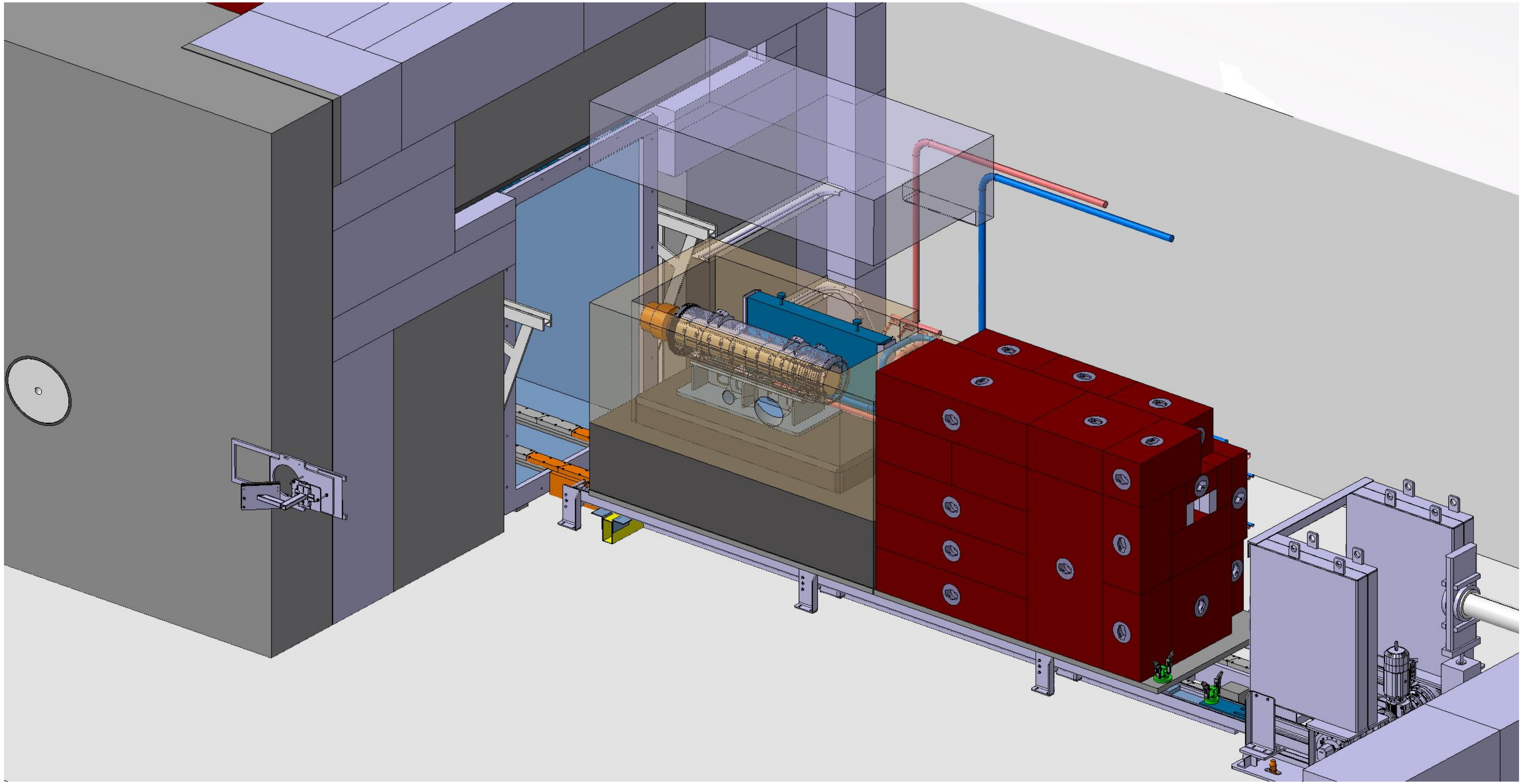
Trolley extraction 2/2



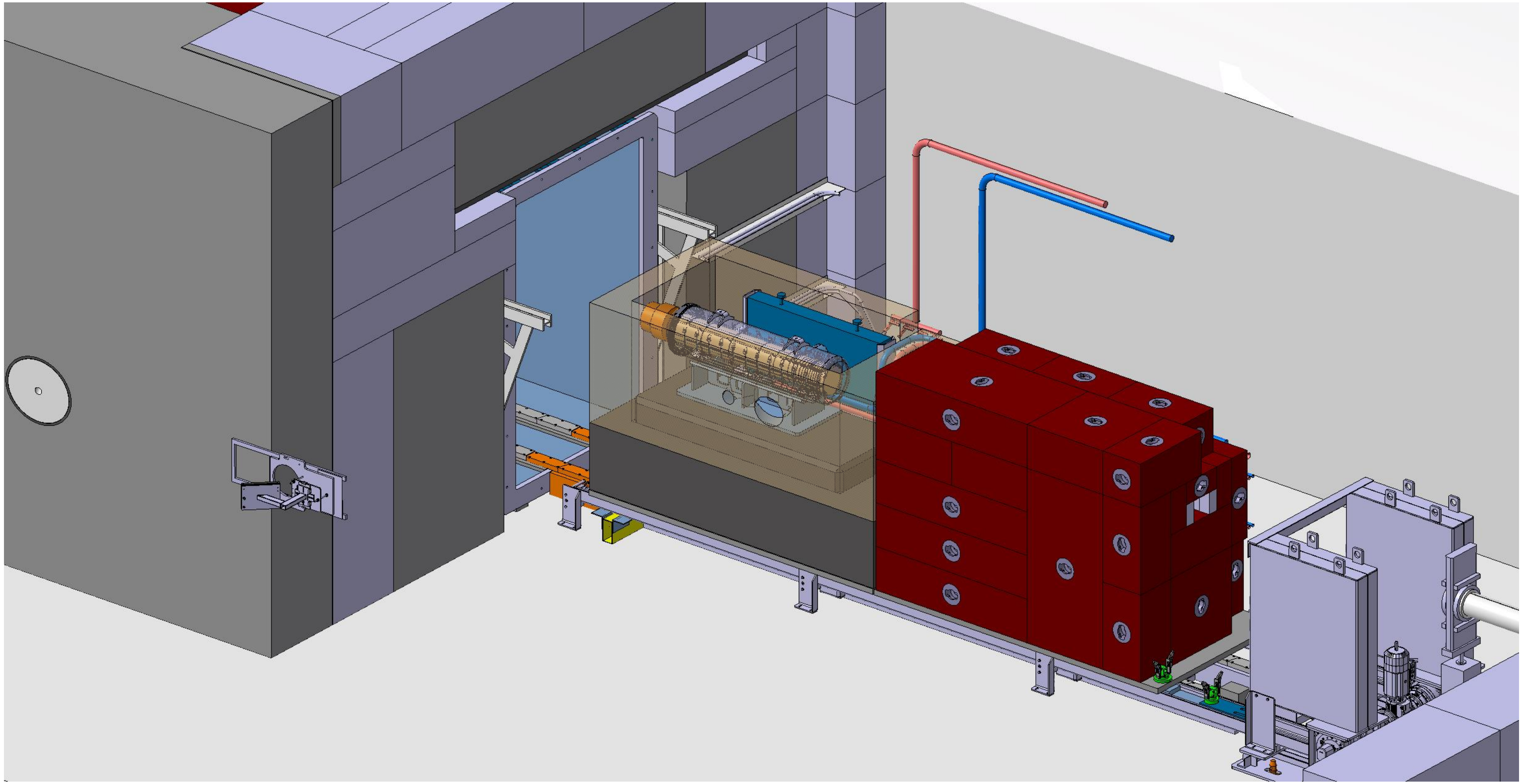
Upstream shielding partial removal



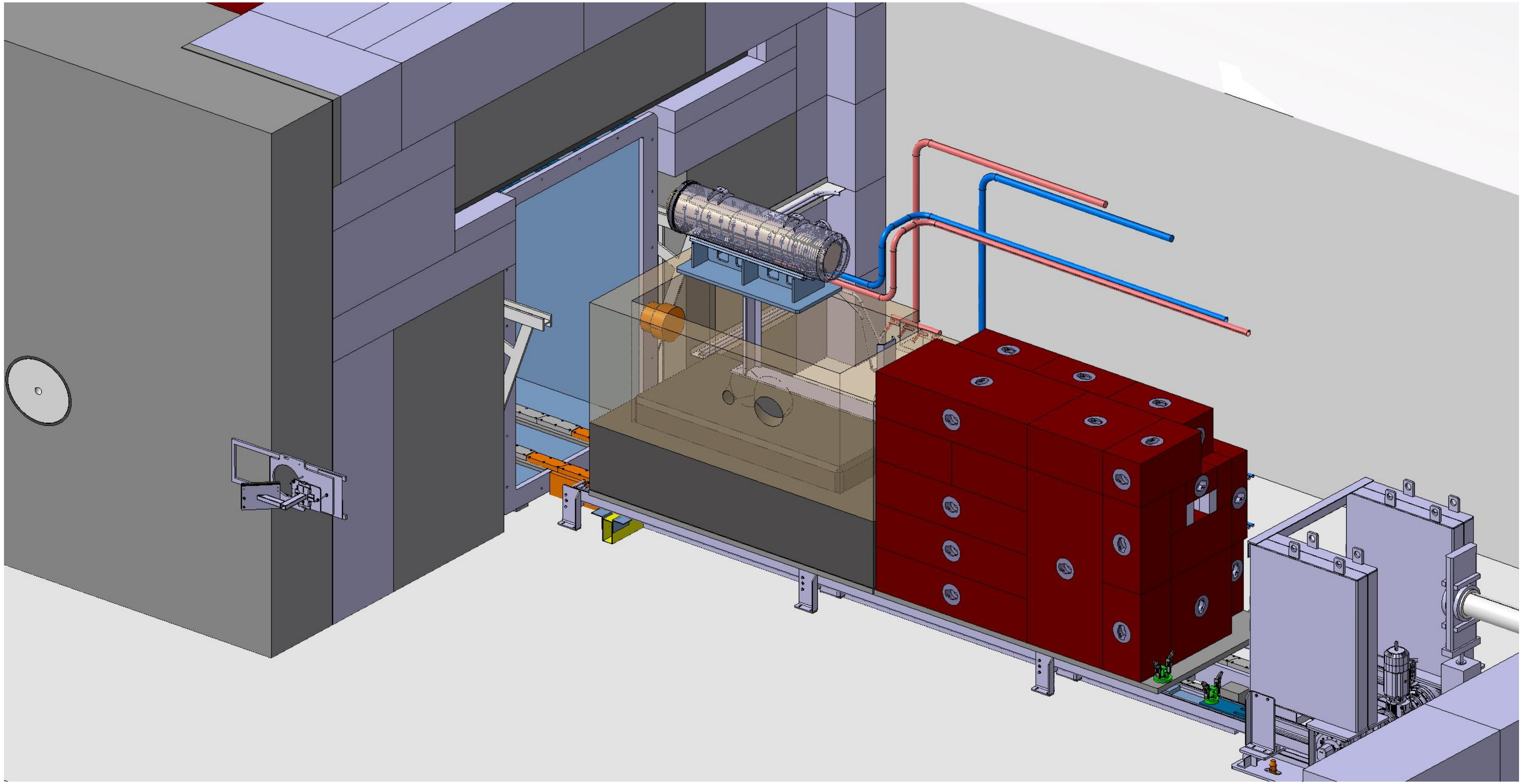
Proximity shielding upper lead removal



Proximity shielding upper lead removed

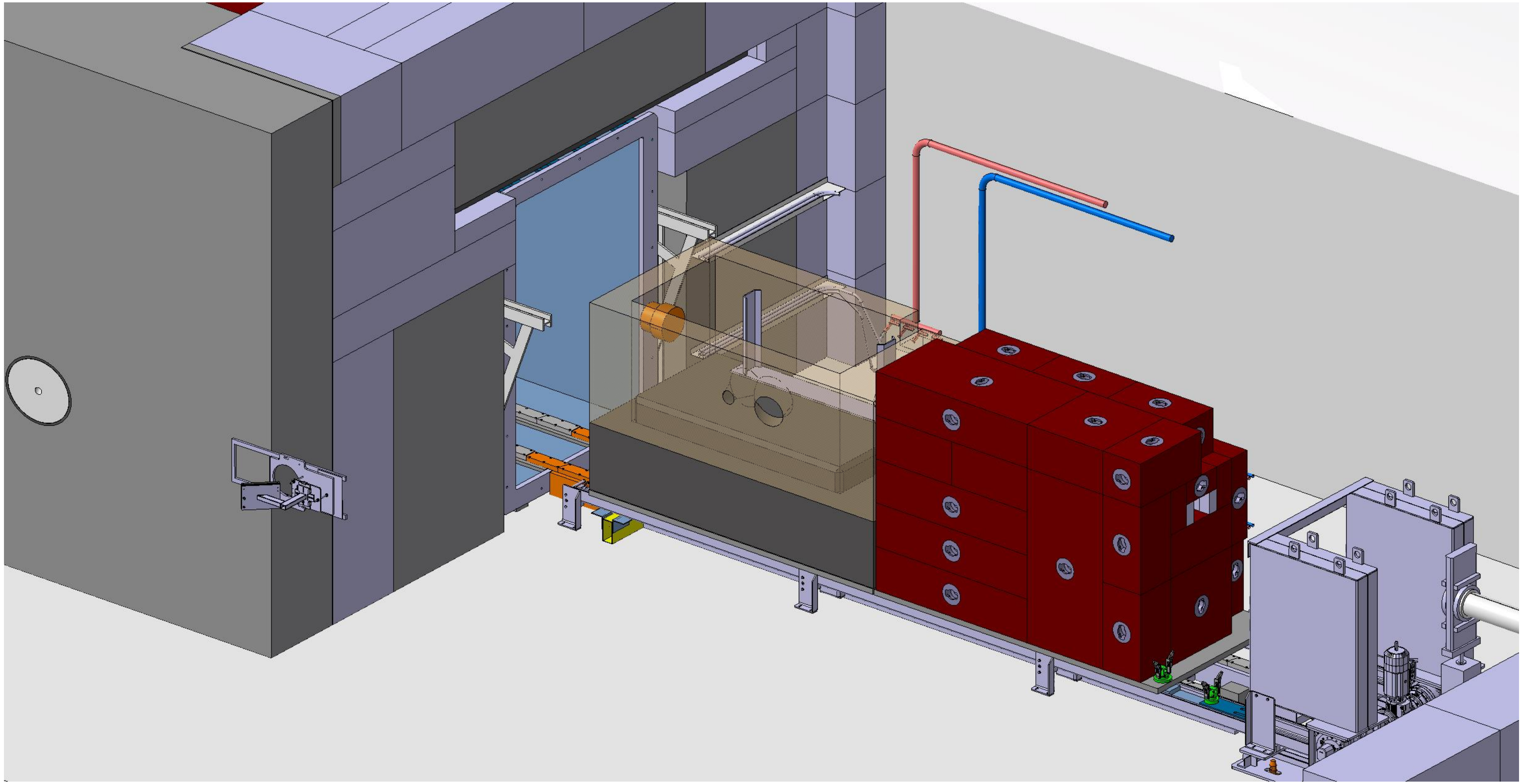


Target removal

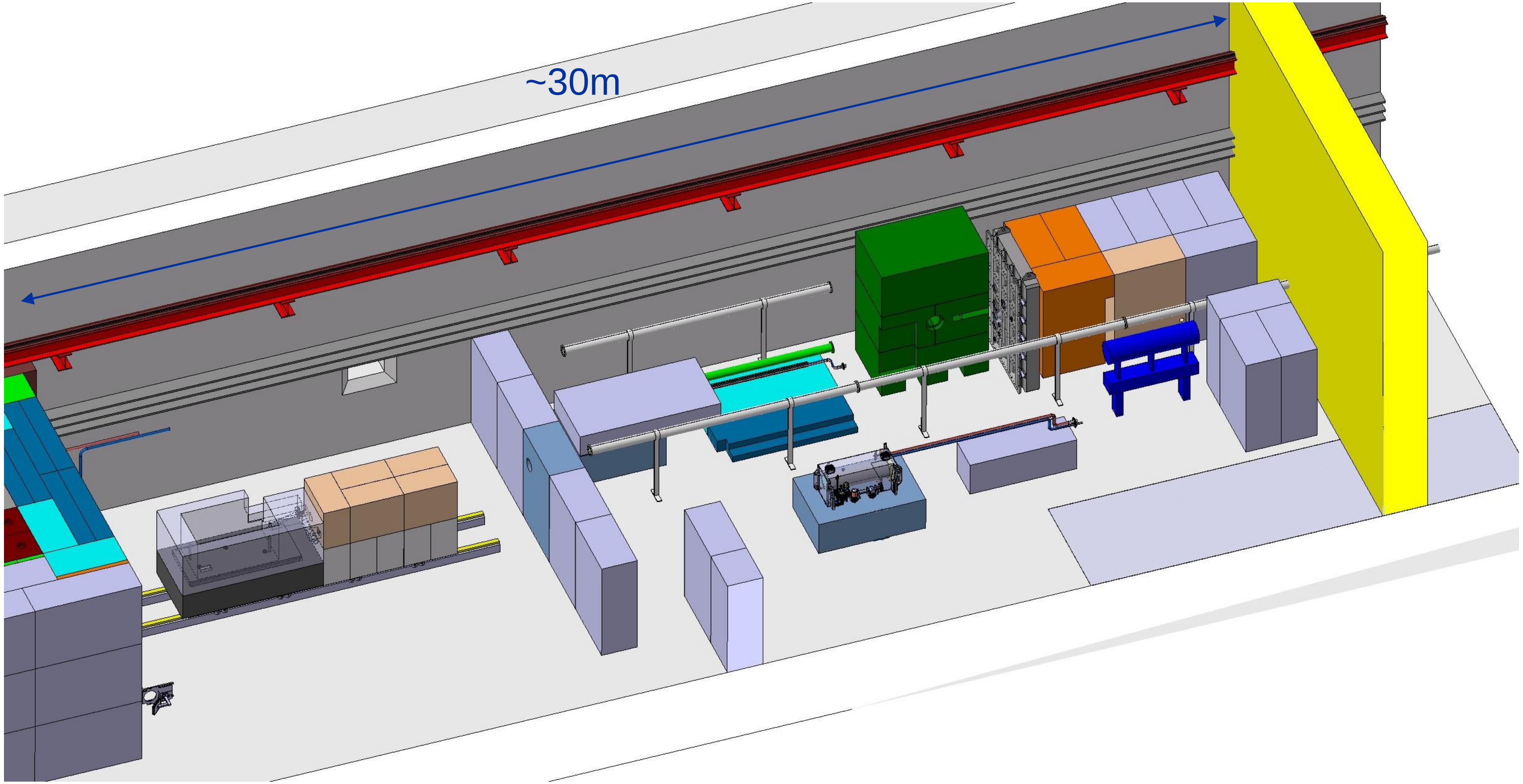


The following handling steps will be covered by C. Duran Gutierrez

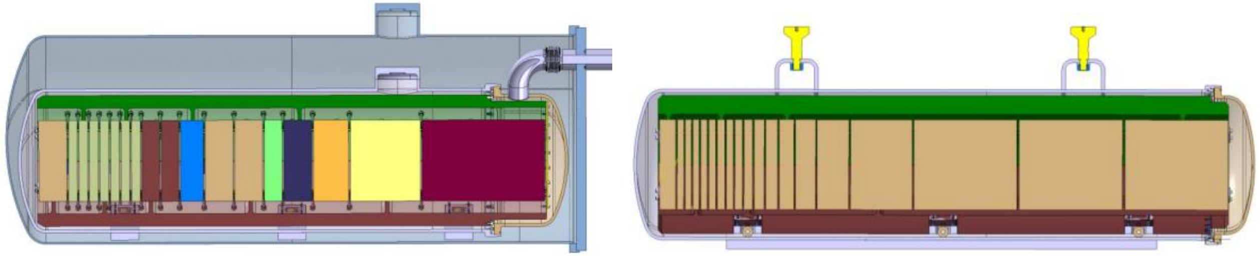
Target removed



Space requirement for target exchange



Final Target Selection and Impact on Target Station

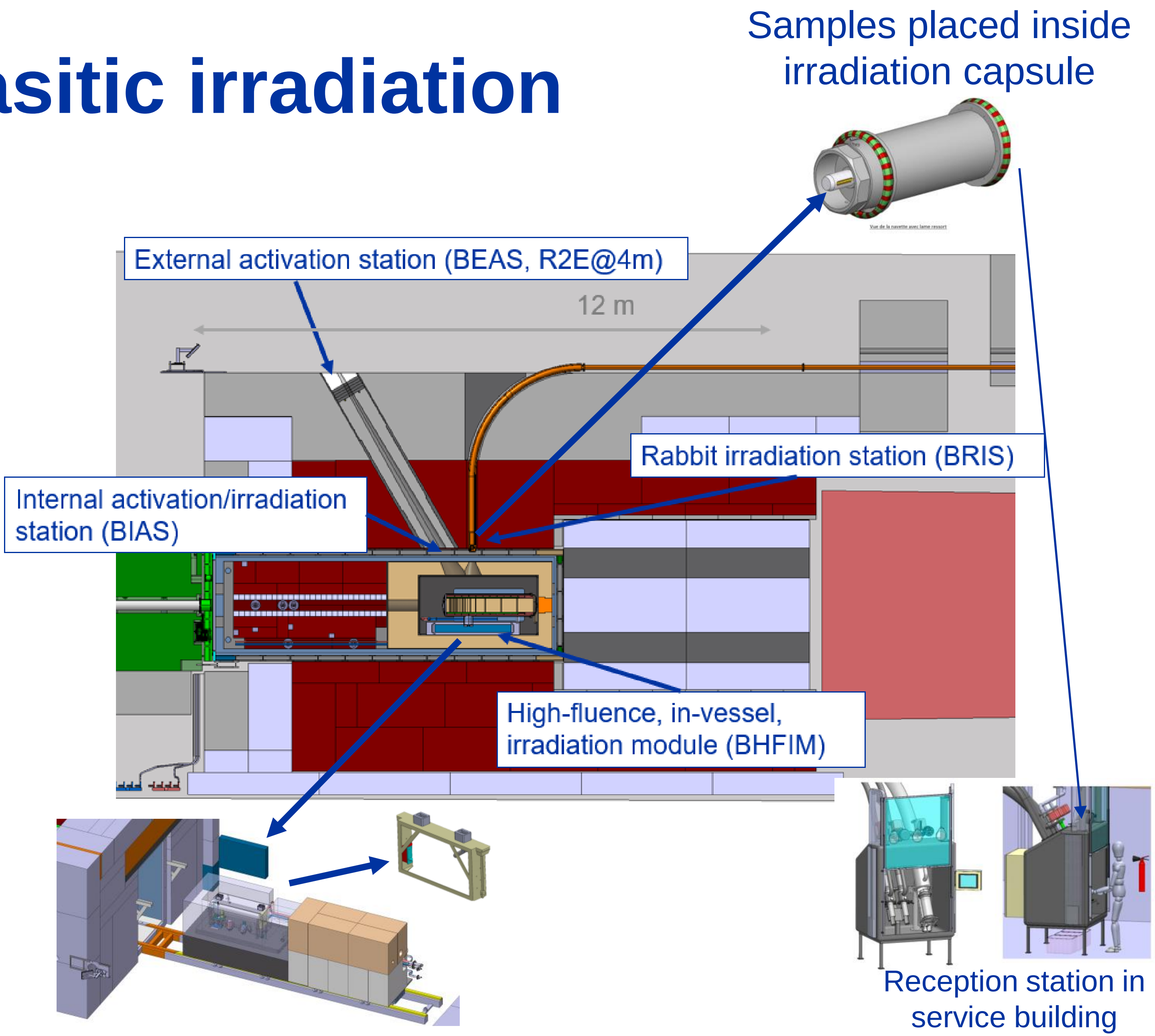


Key Parameters	CDS Design Target	1.5m Full W Target
Target Absorbing Block Dimension	1.36m x ⌀ 0.25m	1.5m x ⌀ 0.25m
Overall Tank Dimension	~1.5m x ⌀ 0.6m	~1.7m x ⌀ 0.42m
Weight	~2 tons	~2.3 tons
Number of Cooling Pipes	4 (2 water, 2 helium)	2, both helium
Cooling Medium	Inner vessel with circulated water	Circulated helium
Leak Detection Method	Outer vessel injected with static helium	No detection method

- **Weight** and **size** both in **similar ranges**
- Internal **layout** of **proximity shielding** will require **adaptation**
- **CDS design** would require an **additional** circuit for **He confinement** around the target – Consequently target would be **more challenging** to handle due to the increased number of pipes and door interfaces
- Full W target **cooled** by **helium**, reducing risk of **contaminated water** leak into vessel

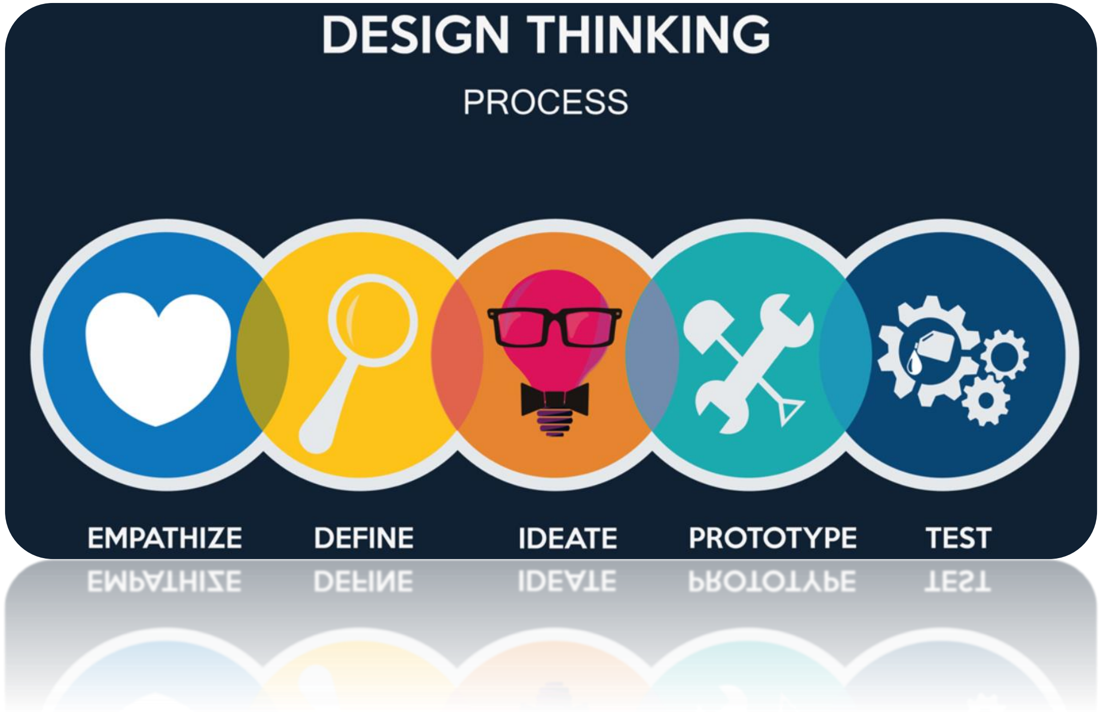
Opportunities for parasitic irradiation

- BDF/SHiP offers the unique opportunity to access **unprecedented radiation levels in mixed field** – allowed due to the specific feature of the experiment
- Priority is given to SHiP, so **irradiation opportunities will have to be parasitic** to the operation of the complex
- **<u>None</u> of the irradiation capabilities shown are part of the target station baseline, but are intended as realistic possibilities and are being proposed**



Concluding remarks

- **Design approach:**
  - Building and developing sets of technological bricks
  - Minimize interdependencies of systems (especially overlapping dependencies)
- **Minimize number of systems / connections in the harsh area**
- **Located connections on a maintainable system**
- **Using as much as we can return of experience**
- **Demonstrate robustness of solutions using various method**
  - Simulation
  - Prototyping



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