August 11,2026| Oak Ridge, TN

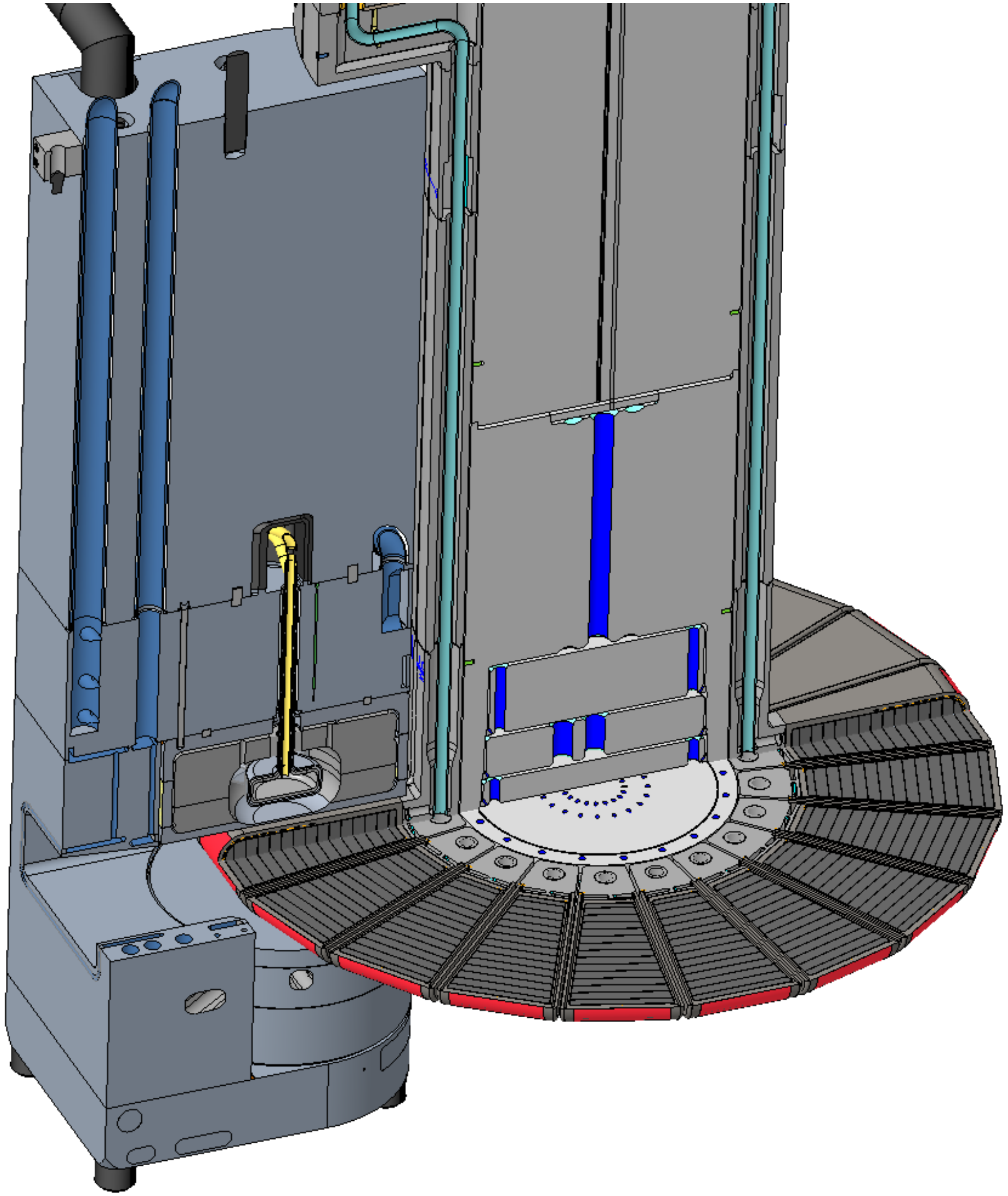
MRA Design

Jim Janney

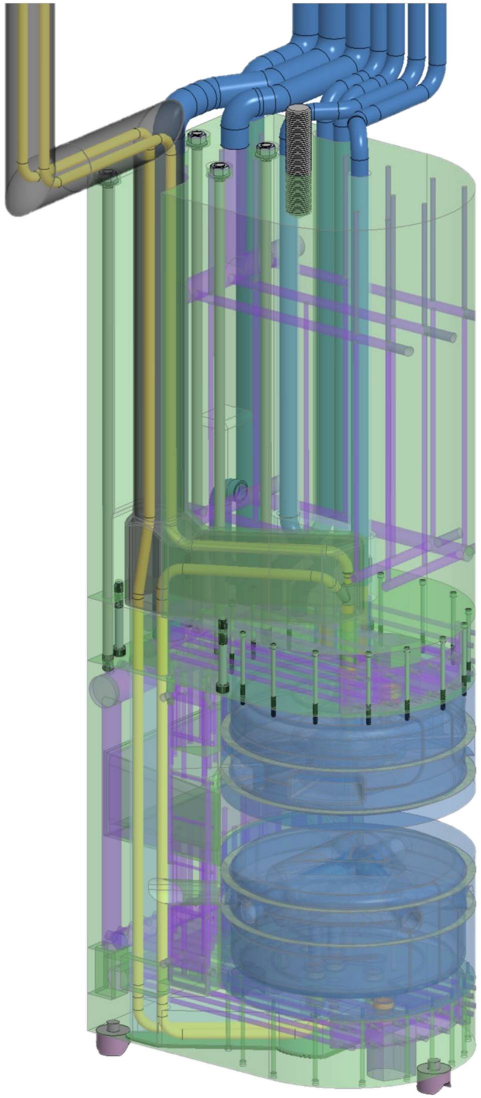
MRA Lead Engineer

Outline

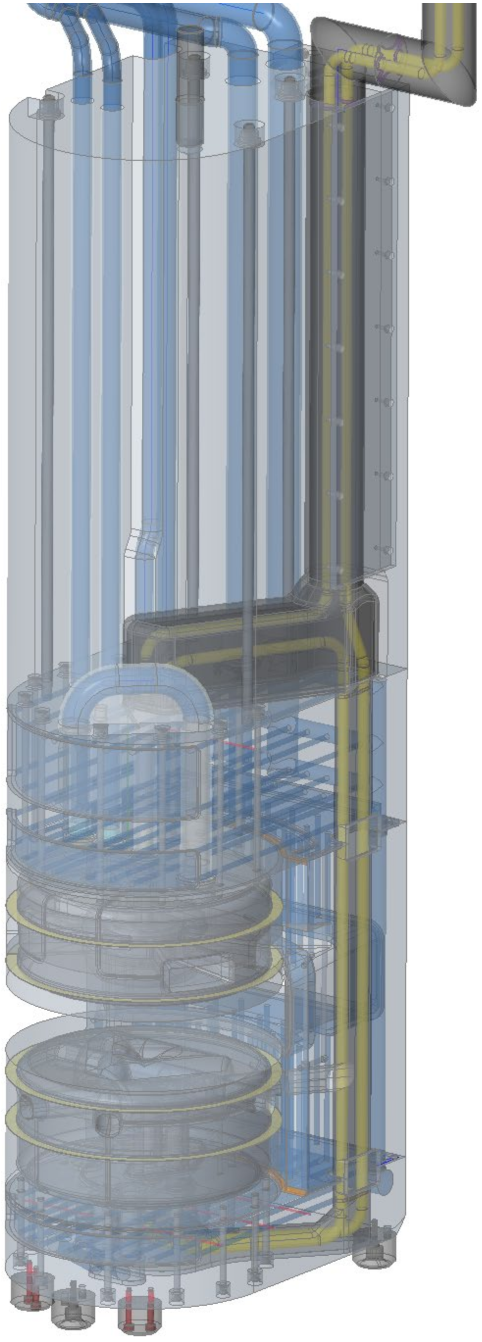
- Changes from Preliminary Design
- From Optimization to Engineering Design
- Hydrogen Vessels
- Reflector Vessels
- Backbone
- Hydrogen Transfer Lines
- MRA Misalignment



Changes from Preliminary Design



- Beamline arrangement updated
- Update based on final optimization
- Shielding height increased
- Backbone height increased with switch to carbon steel shield block
- Updated pipe routing
  - Hydrogen and water piping switched sides
  - Extra jog is water piping
- Backbone cooling updated to minimize deflections
- Lots of updates for manufacturability



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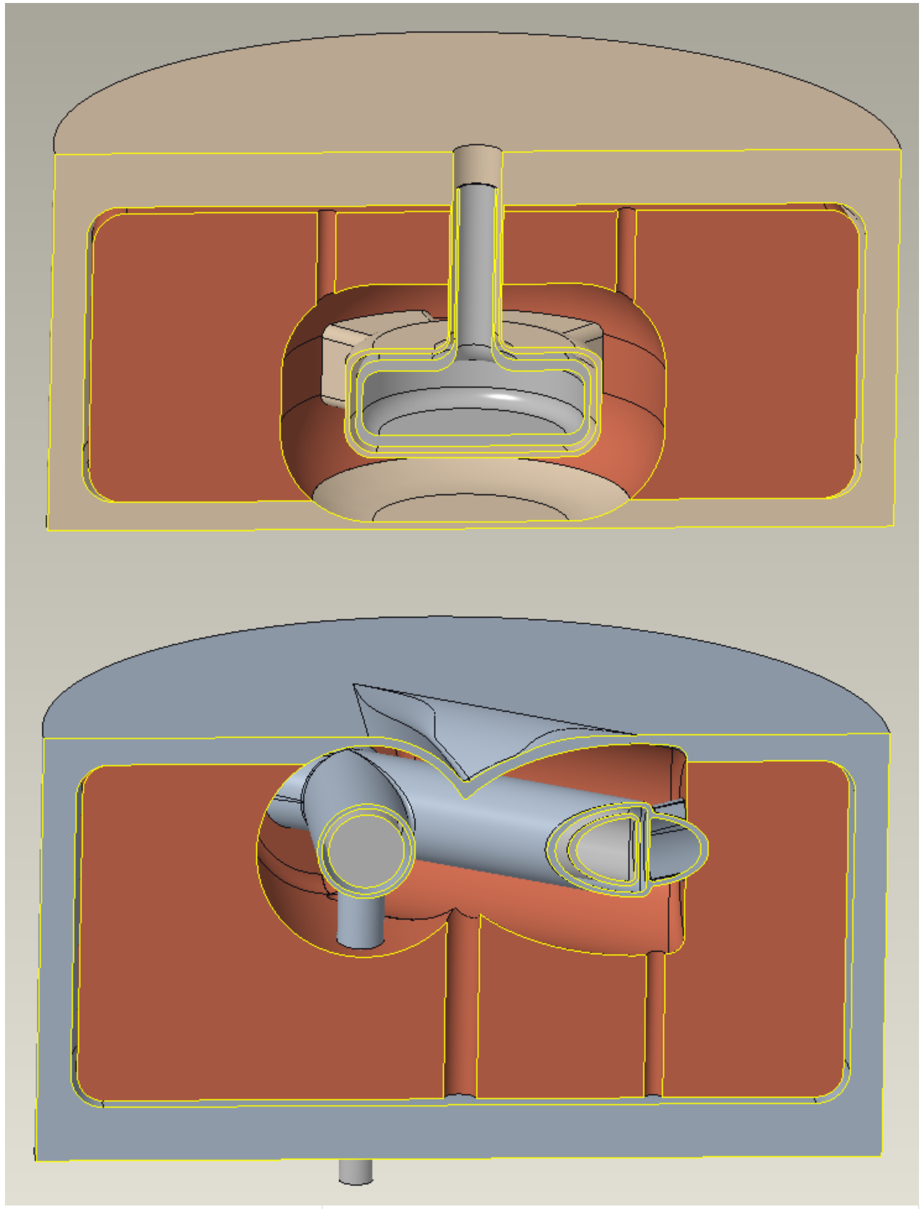
From MRA Optimization to Final Moderator Reflector Design

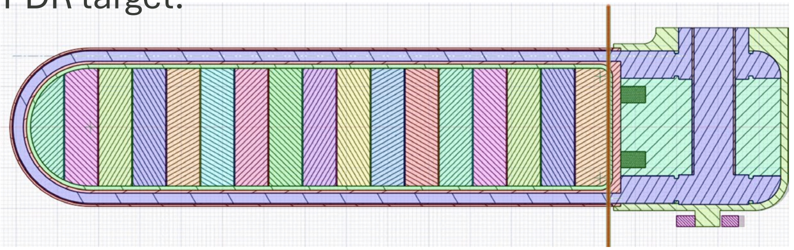
- Engineering design based on final optimization
  - No major changes from PDR optimized MRA
  - Subtle change to optimized tube reflector
    - Premoderator slight change with more DOF
- Designed for 18 beamports with 3 dual beamline ports planned – ST02, ST15, ST16
- Reflectometer beamport bumps added for ST02
- Wall thicknesses minimized based on analysis of internal pressure loading
  - Analysis during conceptual design showed that stresses from pressure loadings dominated thermal stresses



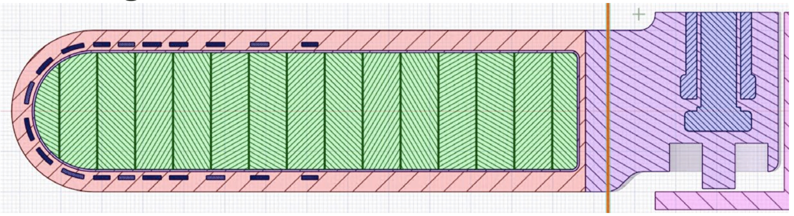
Neutronics Analysis of Final MRA Model

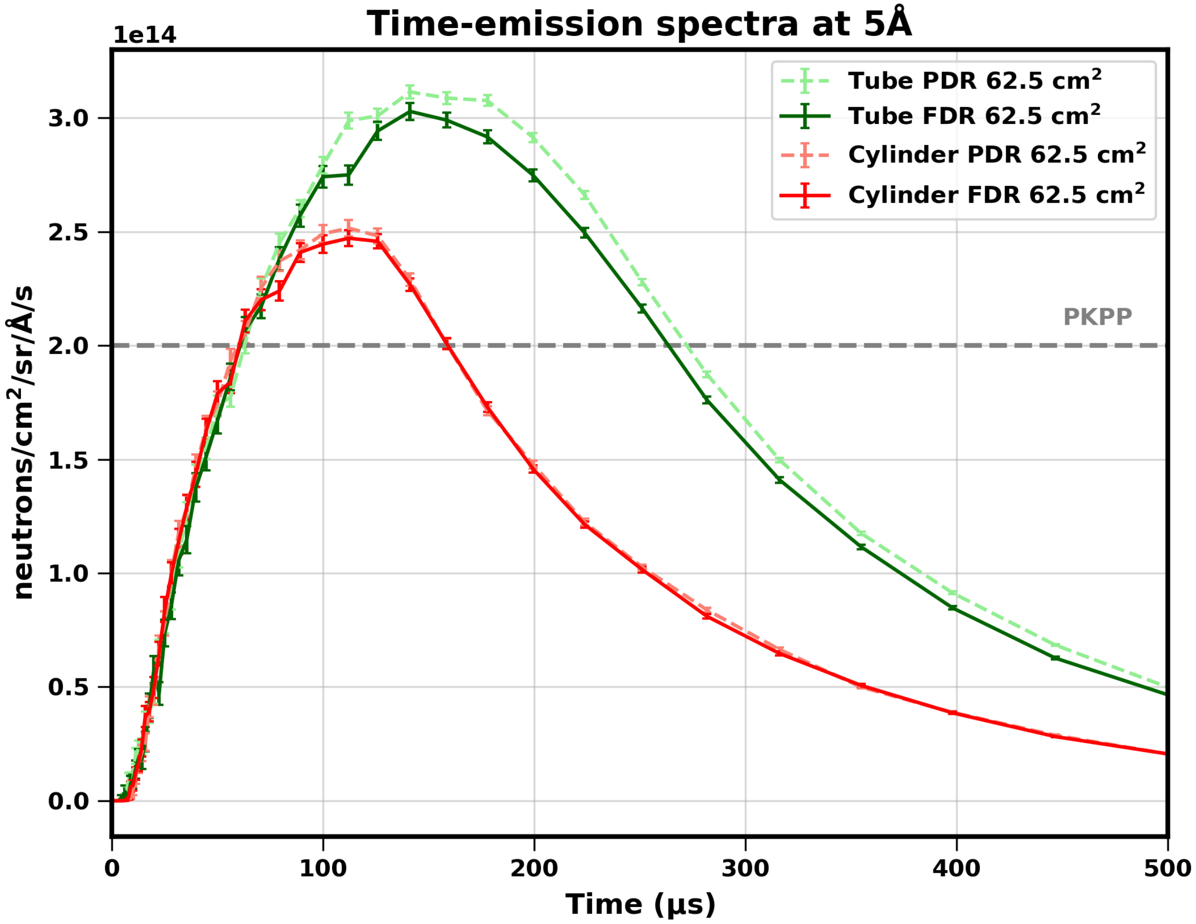
- Neutronic performance exceeds KPP with slight performance loss compared to preliminary MRA/Target design

PDR target:



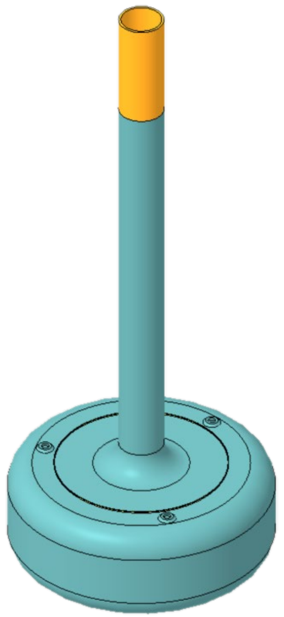
FDR target: 2 mm taller, 6% less W

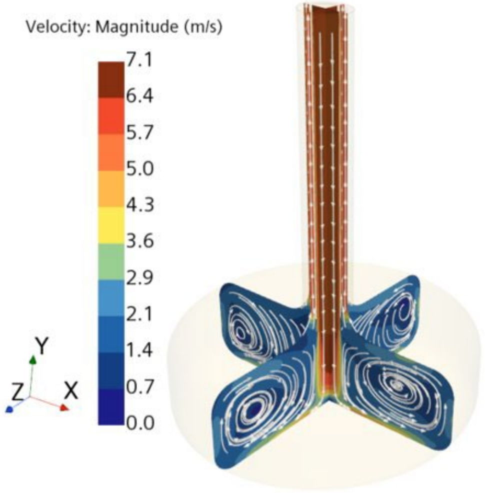




Upper Cylinder Hydrogen Vessel Details

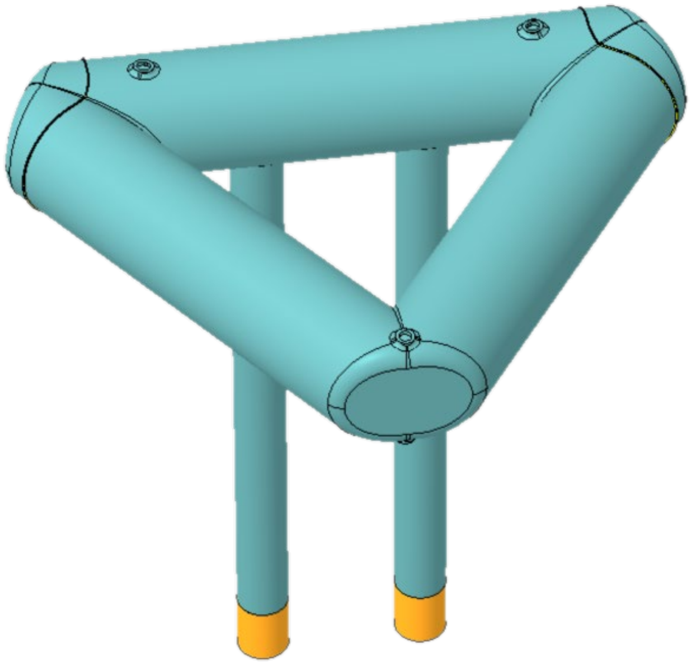
- Al6061-T6 chosen for material based on neutron transparency, cryogenic strength/ductility and HFIR/SNS experience
- Inlet stinger provides jet to cool bottom of the vessel – flow then travels to annular return along the vessel walls
- Held in place by 6 Titanium pins
  - Must precisely locate hydrogen vessel while minimizing heat transfer and allowing contraction from 300 K to 20 K
  - Vacuum vessel boss slots aligned with center of vessel so vessel center does not move with contraction
  - Ti-15-3-3-3 chosen to minimize thermal conductivity

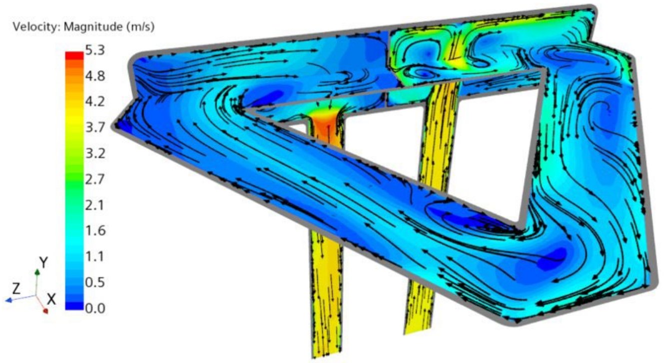




Lower Tube Hydrogen Vessel Details

- Al6061-T6 chosen for material based on neutron transparency, cryogenic strength/ductility and HFIR/SNS experience
- Hydrogen enters in 1 inlet tube, traverses around triangle, and exits out other tube
  - Baffle between inlet and return forces hydrogen around triangle
- Held in place by 6 titanium pins
  - Must precisely locate hydrogen vessel while minimizing heat transfer and allowing contraction from 300 K to 20 K
  - Vacuum vessel boss slots aligned with center of vessel so vessel center does not move with contraction
  - Ti-15-3-3-3 chosen to minimize thermal conductivity



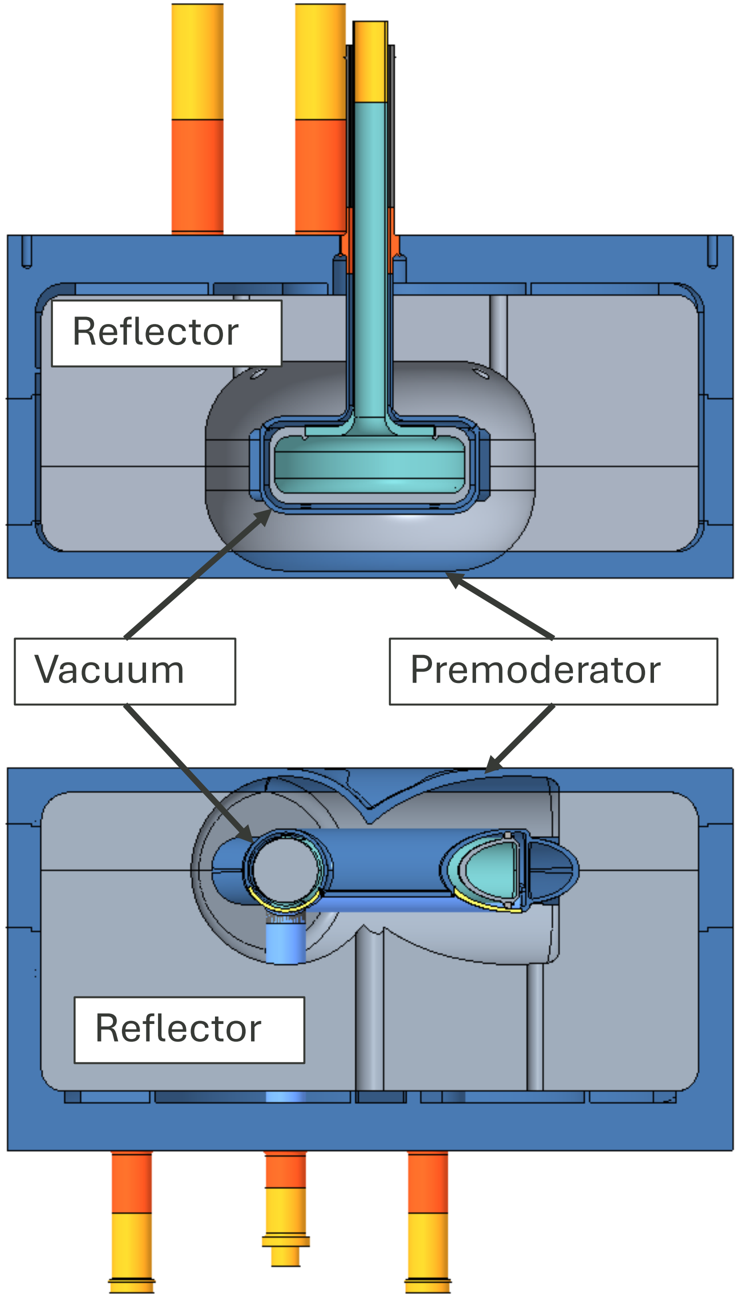


Hydrogen Vessel Safety Requirements

- The hydrogen system is a high energy system per SBMS Categorize Pressure System
  - Treated as gas system as we operate over the 1 atm hydrogen boiling point
- Credited HAR function – "Moderator and Hydrogen transfer line designed to meet design basis seismic loads."
- NFPA 2 Requirement – "Containers employed for the storage or use of [LH2] shall be designed, fabricated, tested, marked (i.e., stamped), and maintained in accordance with … the ASME Boiler and Pressure Vessel Code, or regulations of other administering agencies."
- MRA Requirement – "The MRA hydrogen vessels shall be designed to the intent of the 2023 ASME BPVC. Applied seismic loads shall be derived from the NPH BOD."
- Fabrication, Examination, and Testing will be guided by SBMS Equivalent Protection Exhibit
  - No additional equivalency document is currently planned

Reflector Vessel Overview

- Al6061-T6 chosen for material based on neutron transparency, radiation damage resistance and HFIR/SNS experience
- Vacuum vessel integrated into reflector vessel
  - Beamtubes connect from vacuum vessel to reflector vessel shell to provide neutron flight paths
  - Vacuum vessel lid connects to reflector vessel lid
- No helium layer – vacuum layer surrounded immediately by light water
- Premoderator zone formed by reflector vessel wall and beryllium reflector filled with light water
- Beryllium reflector cooled by premoderator water and light water on outside surfaces except for target side



Why Do Facilities Include a Helium Layer?

- Many existing neutron source facilities (HFIR, NIST, ISIS, SNS) feature tertiary helium layers around the vacuum layers of their hydrogen system
- The helium layer enables quick detection of small leaks from outside the insulating vacuum layer
  - Helium is the only inert species which does not freeze at 20 K
- Without helium layer, small leaks will freeze onto the cold surfaces of the hydrogen boundary, eluding detection for a longer amount of time

Relevant Historical Events

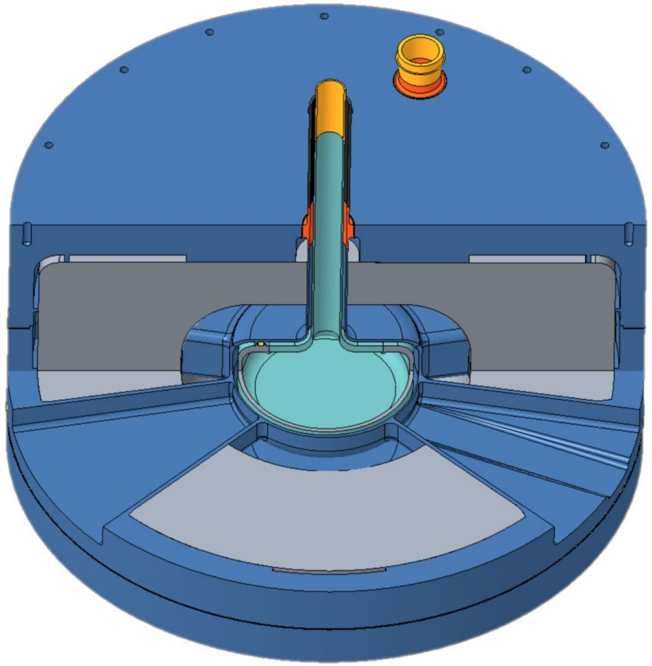
- Only 2 recorded accidents from freezing of substances onto cryogenic surfaces
- 2 ozone explosions from air condensation on cryogenic lines
  - Vacuum line rupture caused air ingress into He system vacuum at ORNL graphite reactor. Subsequent explosion upon warm up of the system.
  - Rover nuclear rocket engine hydrogen lines condensed air which subsequently exploded after irradiation causing a hydrogen fire
- Majority of ozone events involve oxygen contamination in liquid nitrogen systems
  - Oxygen present from initial nitrogen or from air inleaks forms ozone under irradiation
  - Ozone can concentrate as a solid in the liquid nitrogen
  - Concentrated ozone can then explode
  - First observed at ORNL at the graphite reactor in mid 1950s

Justification for No Helium Layer

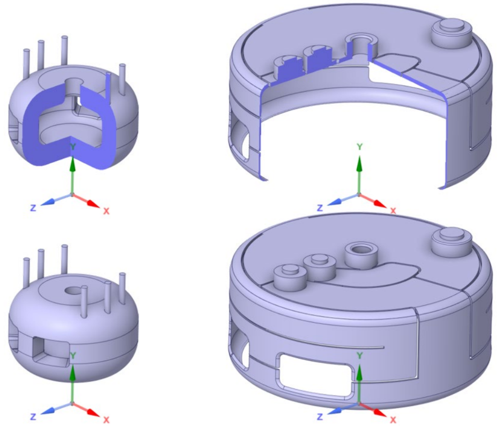
- Core Vessel prevents air leaks near the neutron source
- Water within the reflector vessels is the potential leaking species within the MRA resulting in ice accumulation
- Potential problems from water leaks – blockage of hydrogen venting through the vacuum space and energetic recombination of radiolysis products
- Small 1-3 mm vacuum gaps within the reflector vessel result in large heat leaks for small ice bridges
  - 14.5 mm diameter ice bridge results in ~400 W heat leak
  - Heat leak will cause hydrogen venting before vacuum gap is significantly blocked
- Maximum potential energy release from recombination of radiolysis products is 330 J/g (up to 240 J/g observed experimentally)
  - Enough energy to melt 10% of the ice
  - No damage will result in unconfined vacuum space

Upper Reflector Vessel

- Premoderator and reflector cooling flow paths have separate inlets, but common return
  - Locations chosen balance functionality within vessel and ease of fabrication outside vessel
- From plenum above reflector, 3 premoderator inlet channels and 3 premoderator return channels cause sweeping water flow under vacuum vessel in premoderator zone
- Reflector cooled from outside with symmetric, alternating circumferential flow
- Premoderator and reflector cooling join on top of the reflector vessel and exit to the backbone together



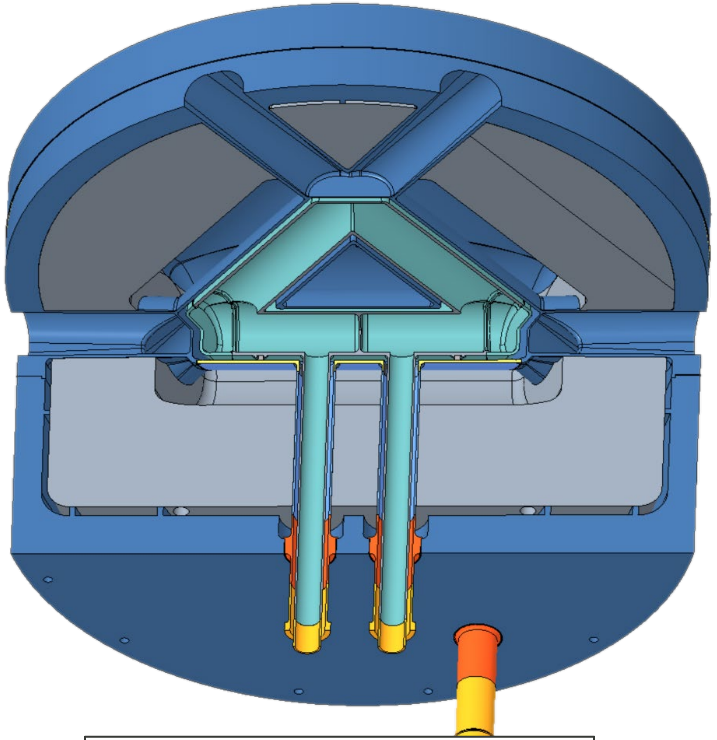
Upper Reflector Vessel



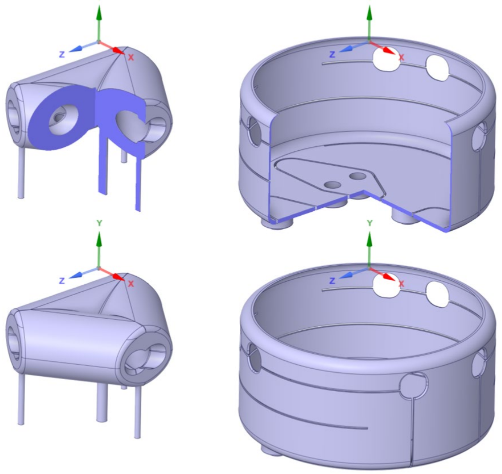
Premoderator and Reflector Flow Paths

Lower Reflector Vessel

- Premoderator and reflector cooling flow paths have separate inlets, but 2 common returns
  - Locations chosen balance functionality within vessel and ease of fabrication outside vessel
  - 2 returns allows integration with backbone design
- Central premoderator supply causes a water jet through the trianglular tube structure and 3 returns over extraction ports cause flow in these areas
- Reflector cooled from outside with symmetric, alternating circumferential flow
- Premoderator and reflector cooling join on the bottom of the reflector vessel and exit to the backbone in 2 common returns



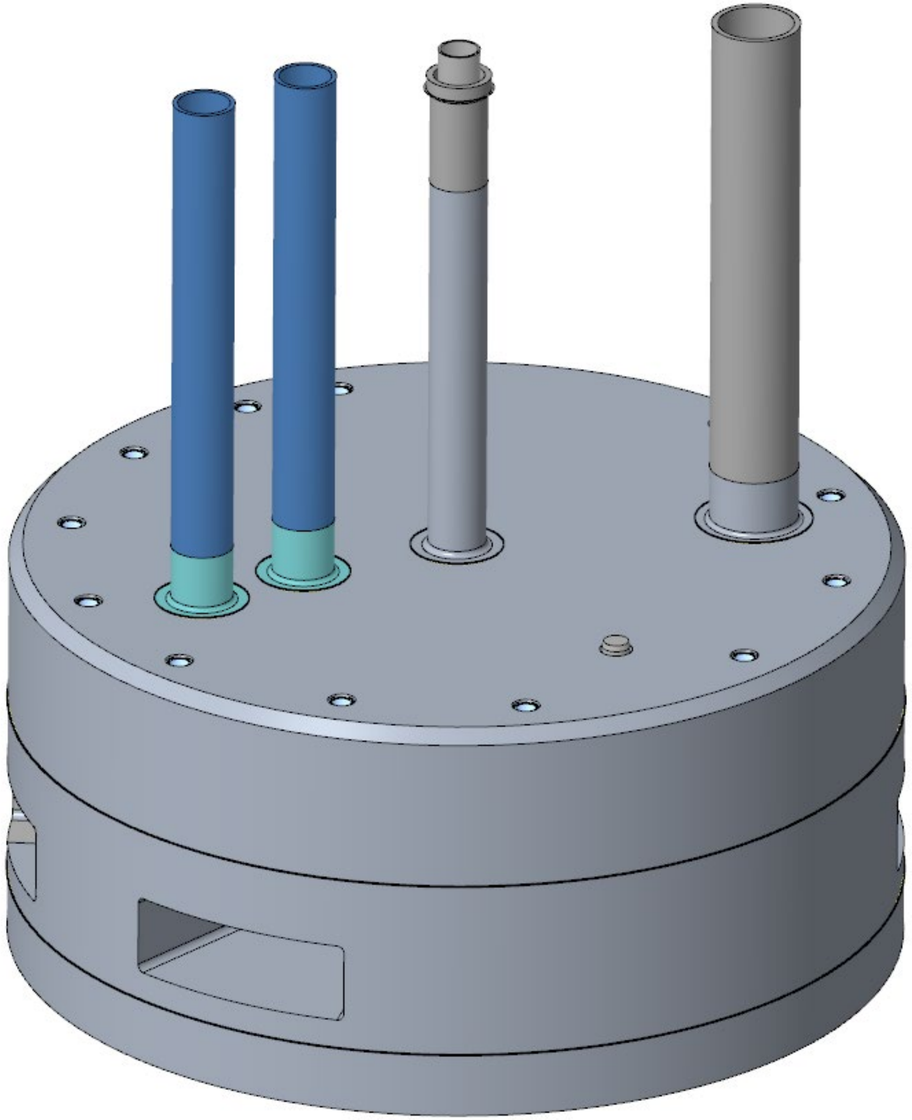
Lower Reflector Vessel



Premoderator and Reflector Flow Paths

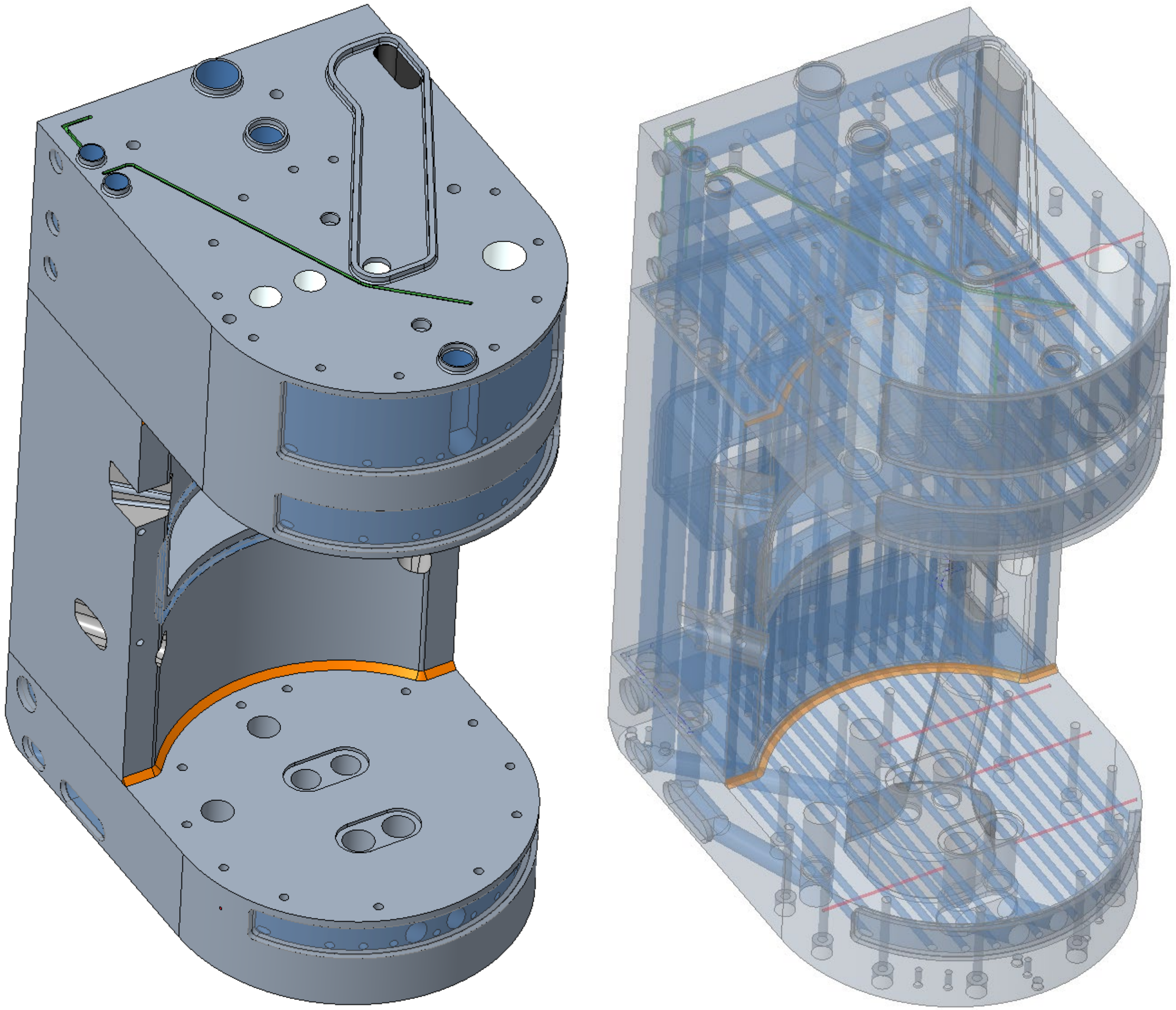
Reflector Vessel Utility Tubes

- All reflector vessel utility tubes include aluminum to stainless steel friction welds to interface to 316L backbone and piping
- All friction welds are close to reflector vessel to minimize heat input from subsequent welding
  - Upper vacuum tube is exception where aluminum extends a significant distance to minimize temperatures
- Some will pass through the backbone for subsequent pipe welding and some are welded to backbone



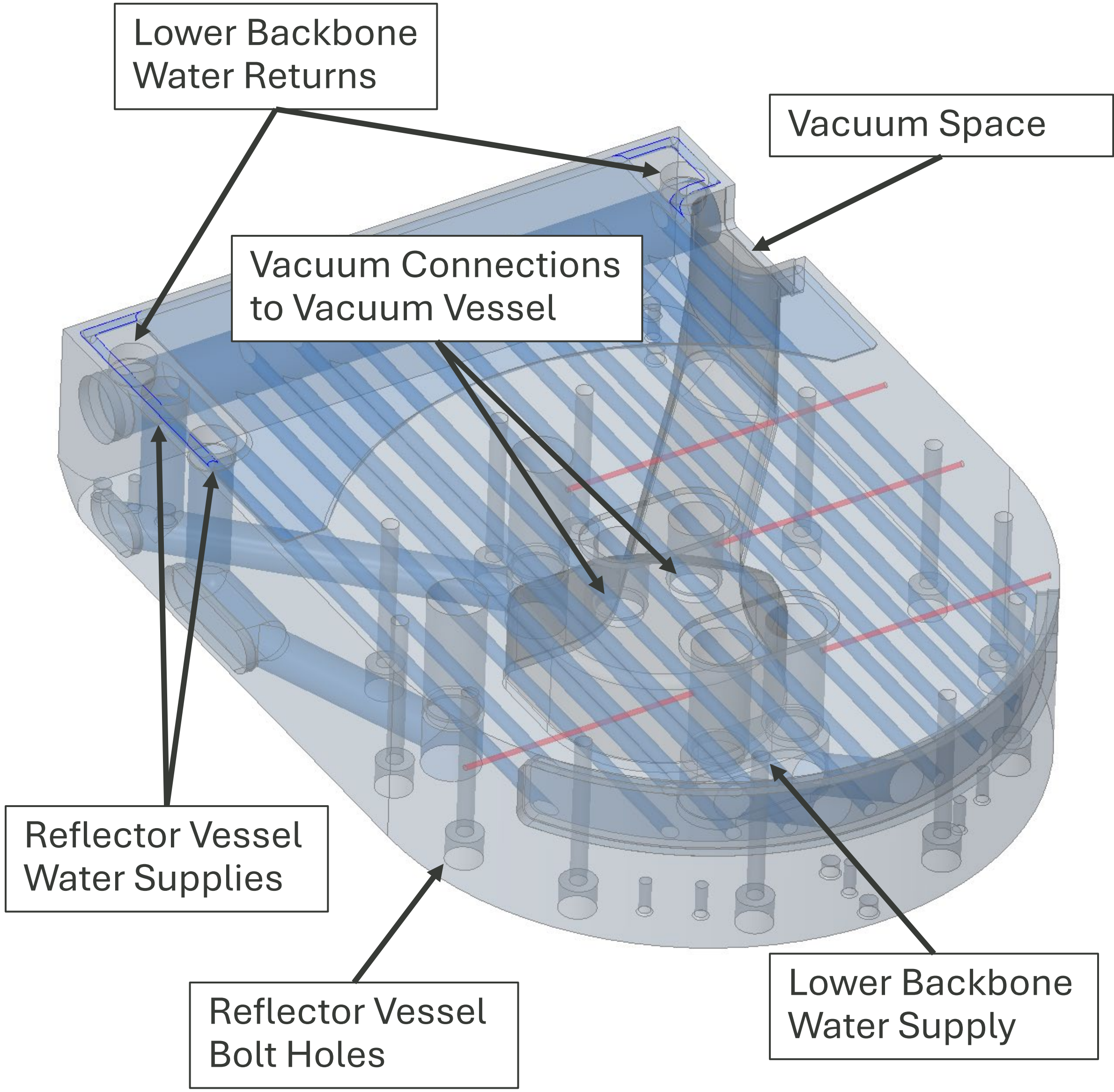
MRA Backbone

- 316L material for radiation damage and corrosion resistance
- Precisely positions both hydrogen vessels relative to the MRA alignment interface
  - Minimizes moderator deflection relative to alignment interface
- Allows routing of utilities to lower reflector around proton beam port
- Provides insulating vacuum boundary for hydrogen lines to hydrogen vessels
- Provides shielding



Lower Backbone

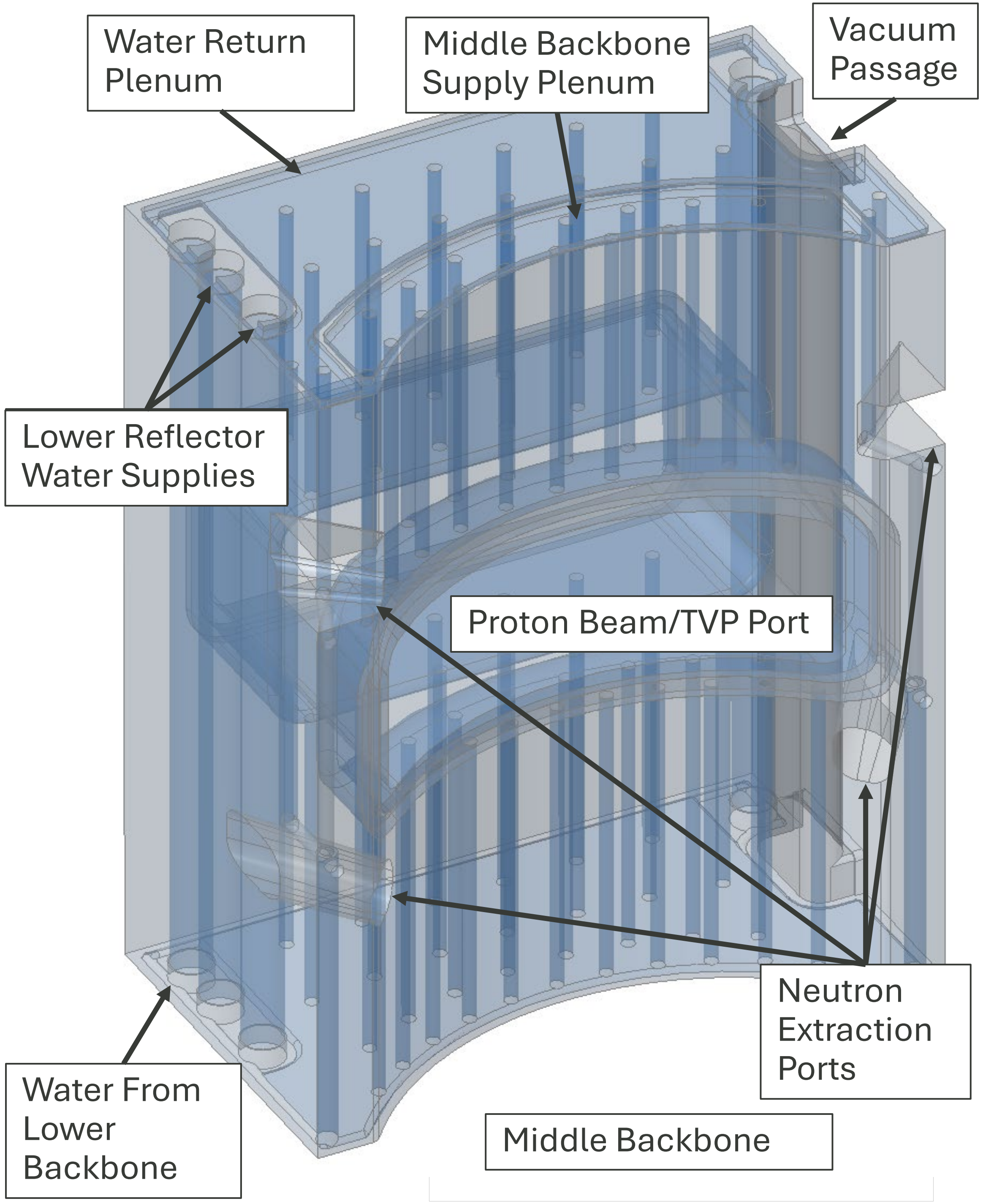
- Water from lower reflector vessel exits used to supply lower backbone cooling channels
- Cooling provided by 18 deep holes
  - Subsequently closed with plenum cover
- Vacuum space recessed into backbone with flush cover
  - Provides protection for hydrogen lines
- Lower reflector vessel water supplies routed in bored passages
- 6 connections from the lower reflector vessel must be sealed by EB welding



Lower Backbone

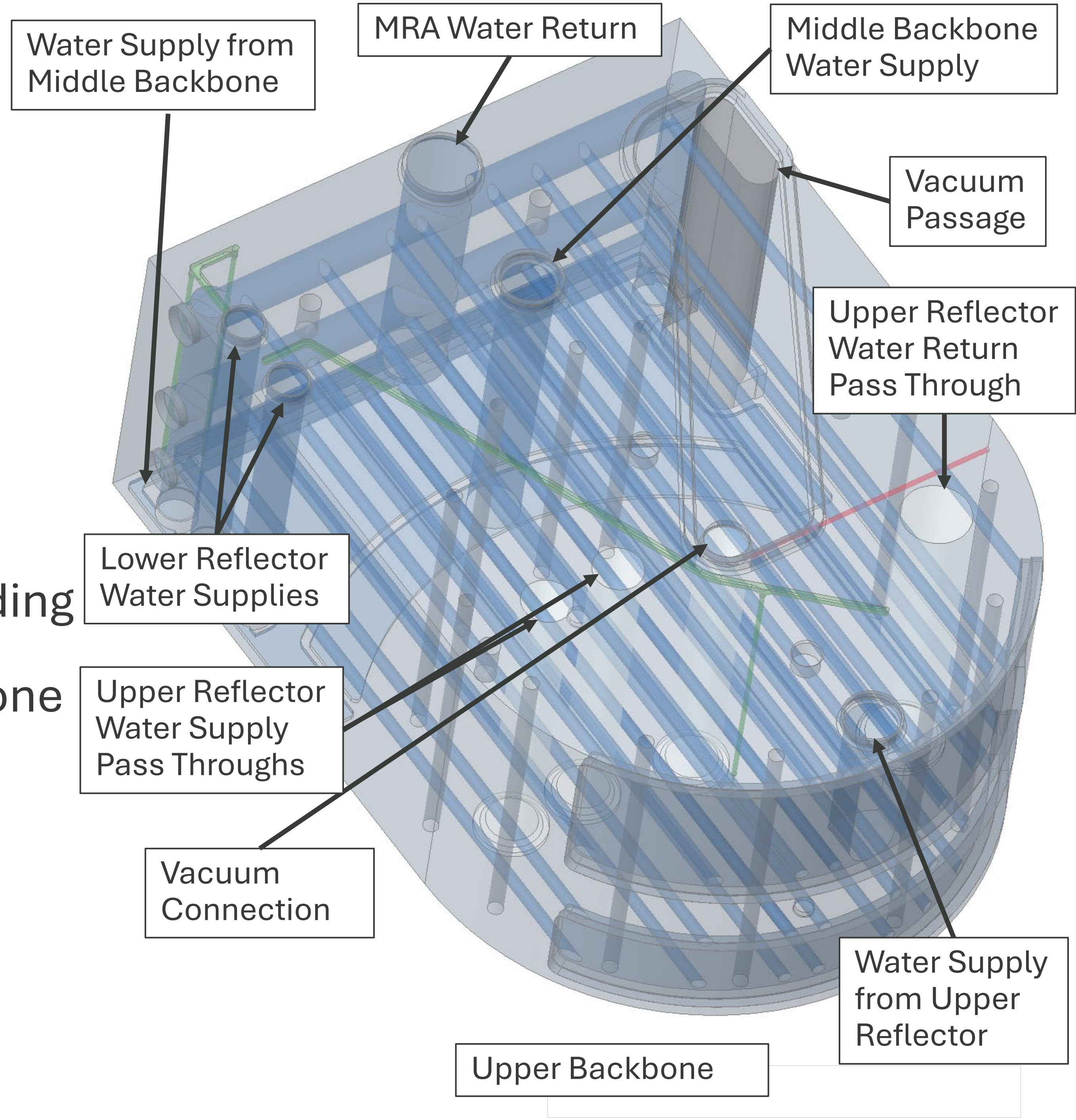
Middle Backbone

- Proton beam/ TVP port allows passage of proton beam and TVP view of target
- Ports to allow neutron beam extraction
- Separate backbone cooling supply used to cool middle backbone
  - Cooling provided by 39 deep drilled holes
  - Cooling distributed to produce uniform temperatures under 700 kW heating
- All lower reflector utilities routed around Proton Beam Port
- All lower and middle backbone water returns combined



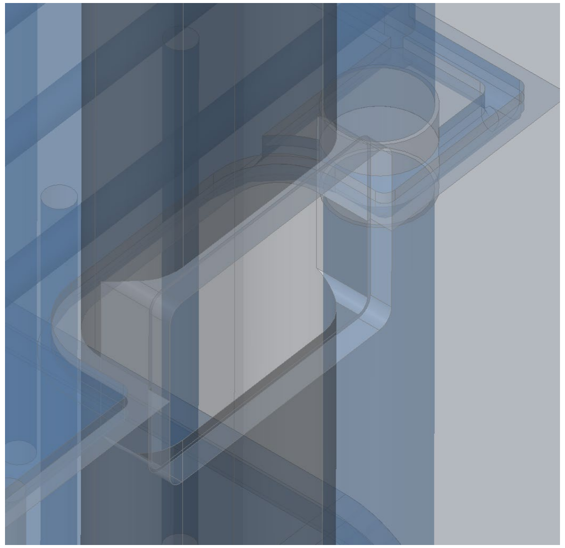
Upper Backbone

- Water from upper reflector vessel exit used to cool upper backbone
- Cooling provided by 32 deep holes
  - Subsequently plenum covers EB welded closed
- Vacuum connection from the upper vacuum vessel must be sealed by welding
- Vacuum space sealed to top of backbone
  - Protection provided by shield block
- Upper reflector water supplies routed through backbone but not connected

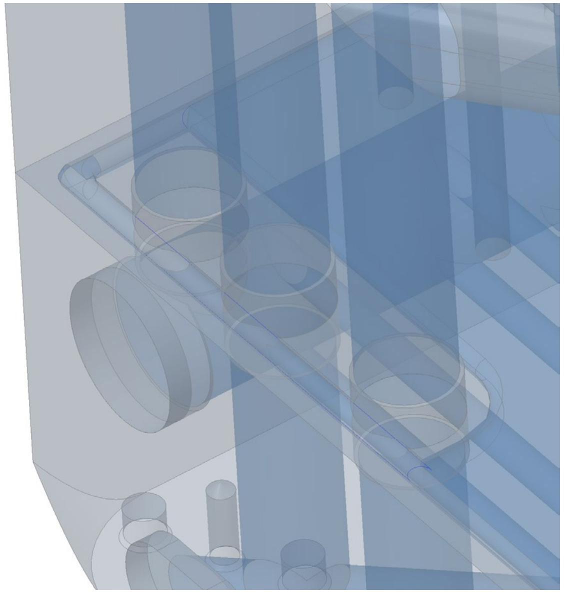


Backbone Weldment

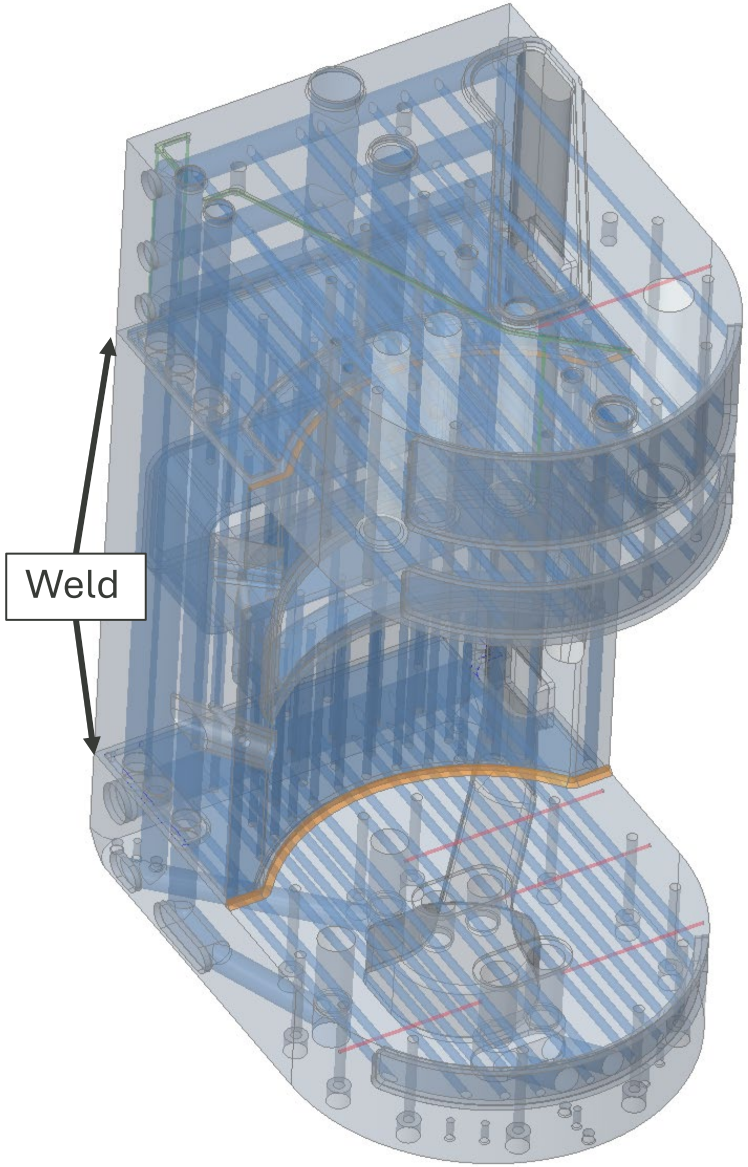
- Lower, Middle, and Upper Backbone welded together to provide support for upper and lower reflector vessels
  - Fillet weld reinforcement machined to improve fatigue resistance
- Plenums for middle backbone cooling holes are closed with these same welds
  - Sleeves reduce leakage from other water channels
- Recesses and cover plates allow welding behind and subsequent sealing of vacuum passages



Vacuum Cover Detail



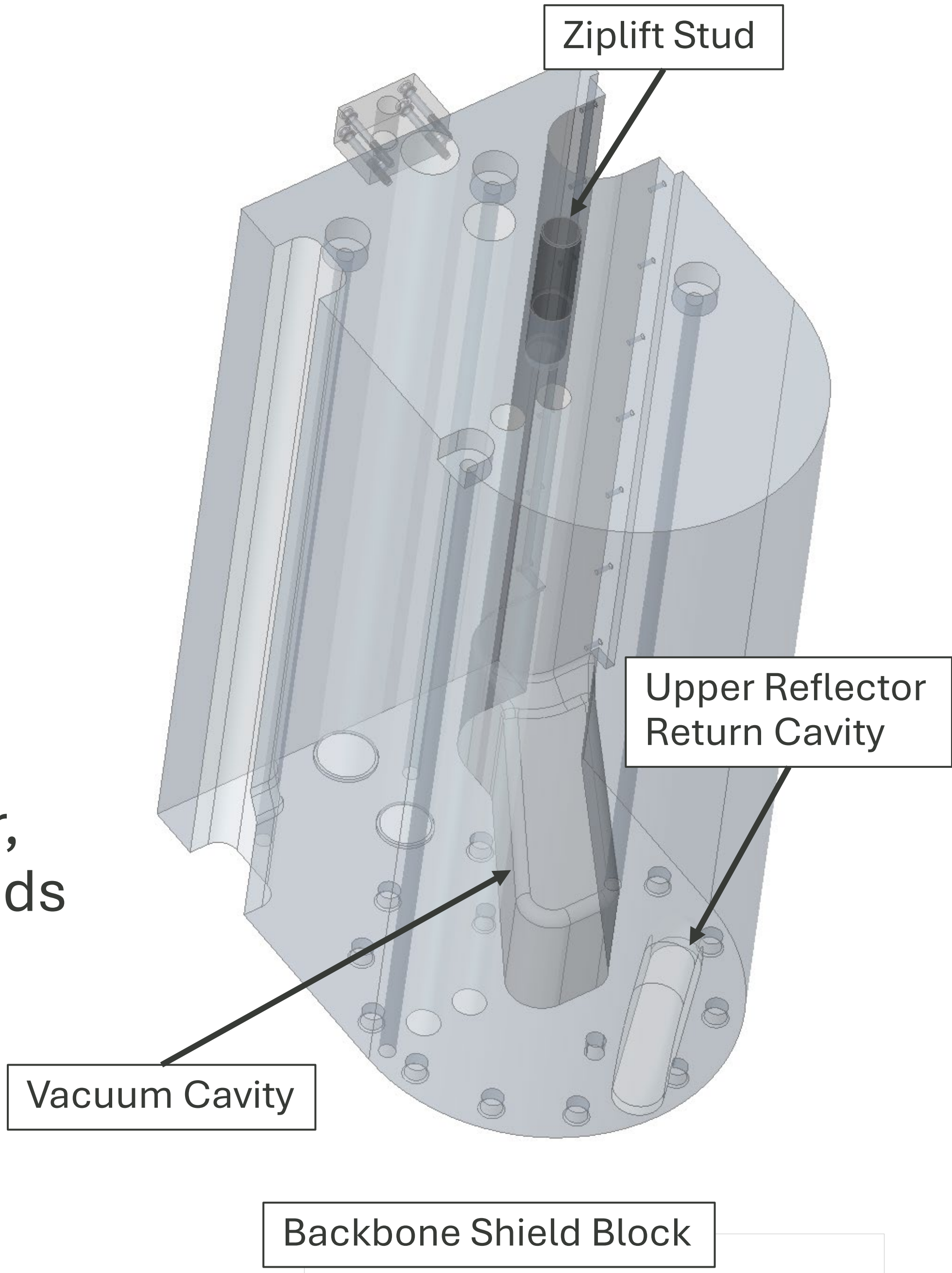
Sleeve Detail



Backbone Weldment

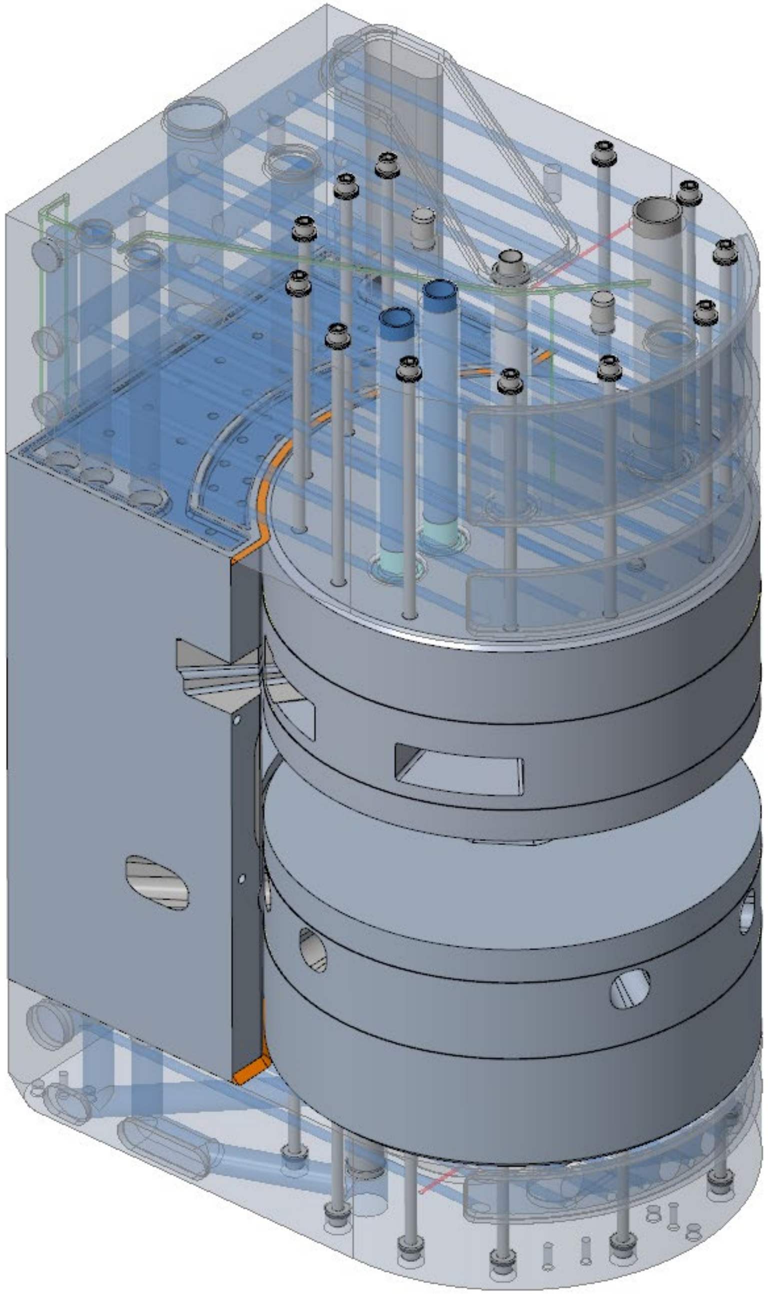
MRA Shield Block

- Not involved in moderator alignment
- Made from A36 Steel
  - Higher thermal conductivity allows contact cooling from upper backbone block below
  - Less activation than equivalent 316L block
- Extends 1.29 m above proton beam center
  - Extended 0.29 m from preliminary design
- Cavities to provide clearance to upper vacuum cover, Upper Reflector outlet, and Upper Reflector bolt heads
- Passages/chases for all MRA utilities
- Lifting stud for remote handling interface



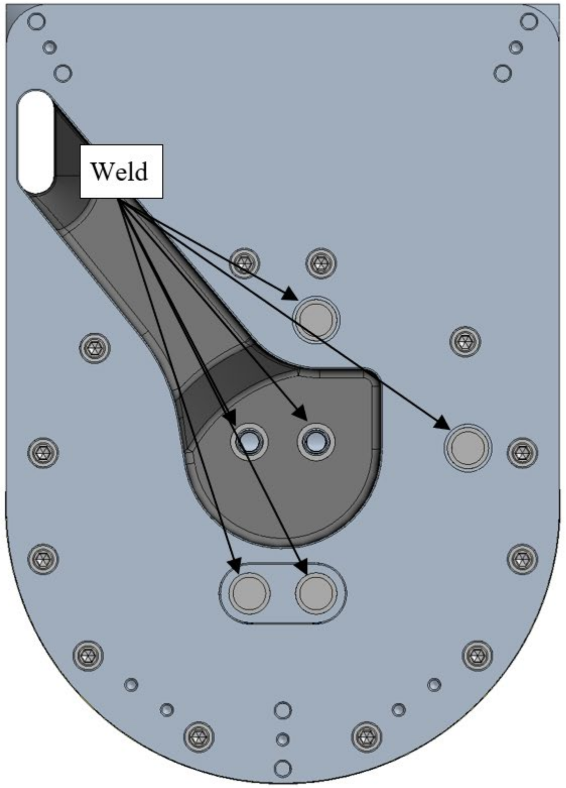
Reflector Vessel Assembly Fasteners

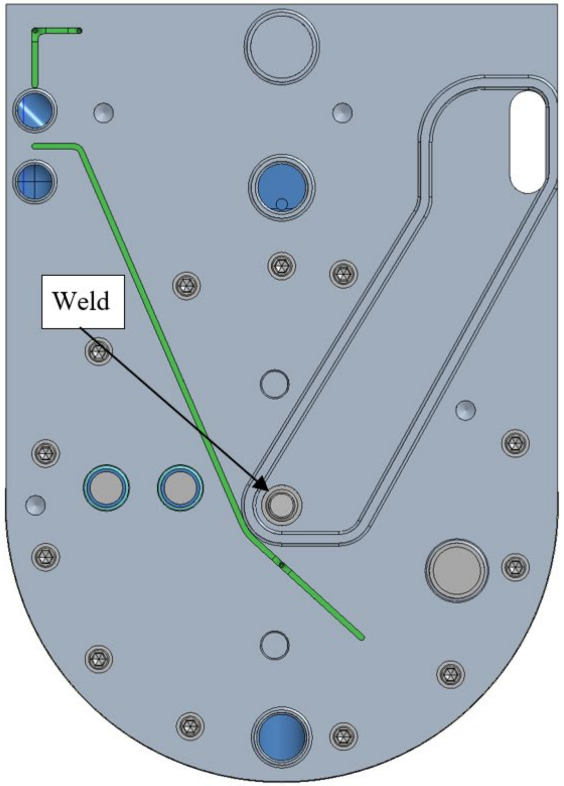
- Provide structural connection between reflector vessels and backbone
- Each Reflector Vessel fastened to backbone using 12 3/8”-16 SS316 SHCS
- Design preload of 4 kN per screw
  - Specified to approximately equal the pressure force on the reflector vessel cap so that no separation occurs from pressure loading
  - Ensures utility connections see minimal loading
- Preload applied by flattening Belleville washers
  - Also maintains preload under differential thermal expansion



Reflector Vessel Assembly Utility Welds

- All lower reflector utilities (2 vacuum, 4 water tubes) weld to backbone
  - 6 mm deep EB welds
- Upper reflector vacuum tube seals to backbone
  - 6 mm deep EB weld
  - All water utilities pass through backbone
- Upper reflector vessel uses dowel pins for alignment while lower reflector vessel does not due to the 6 connections



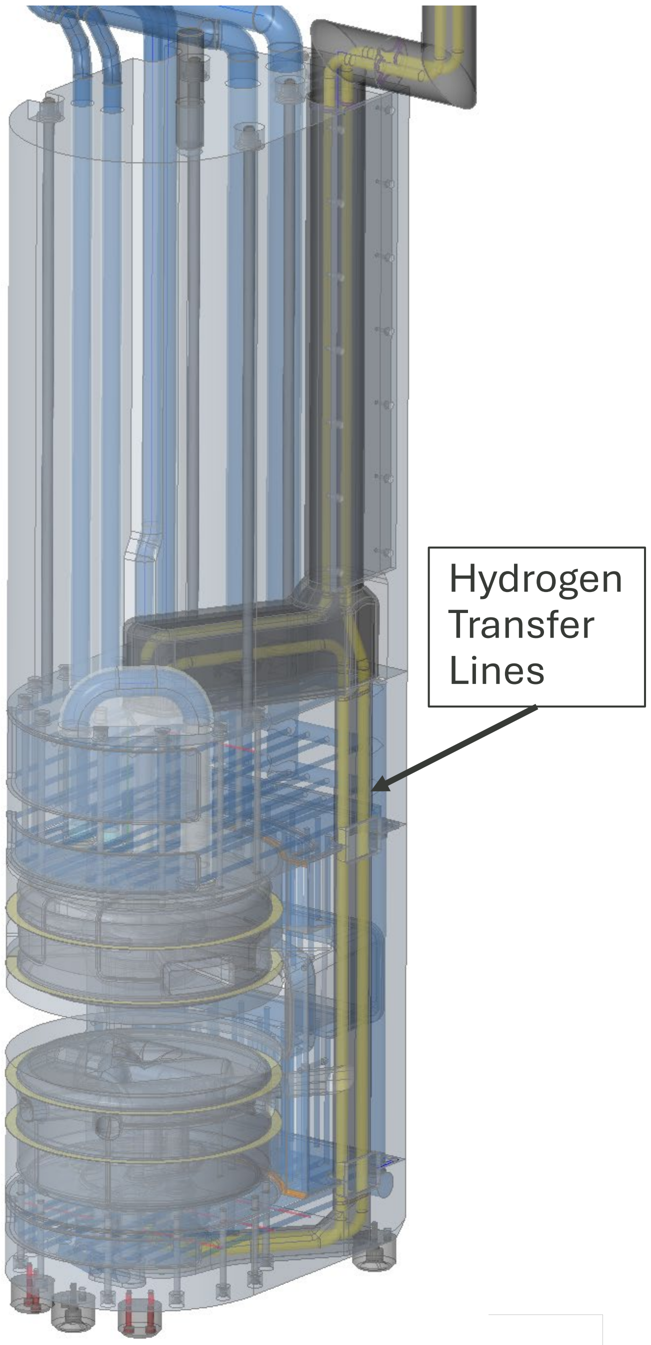


MRA Shield Block Assembly Fasteners

- Provide structural connection from MRA shield block to backbone
- Fastened using 4 5/8”-13 SS 316 Threaded Rods
- Design preload of 9 kN per rod
  - Specified so that each rod provides enough preload to prevent separation of shield block and backbone during lifting
  - Ensures utility connections see minimal loading
- Preload applied by flattening Belleville washers
  - Also maintains preload under differential thermal expansion

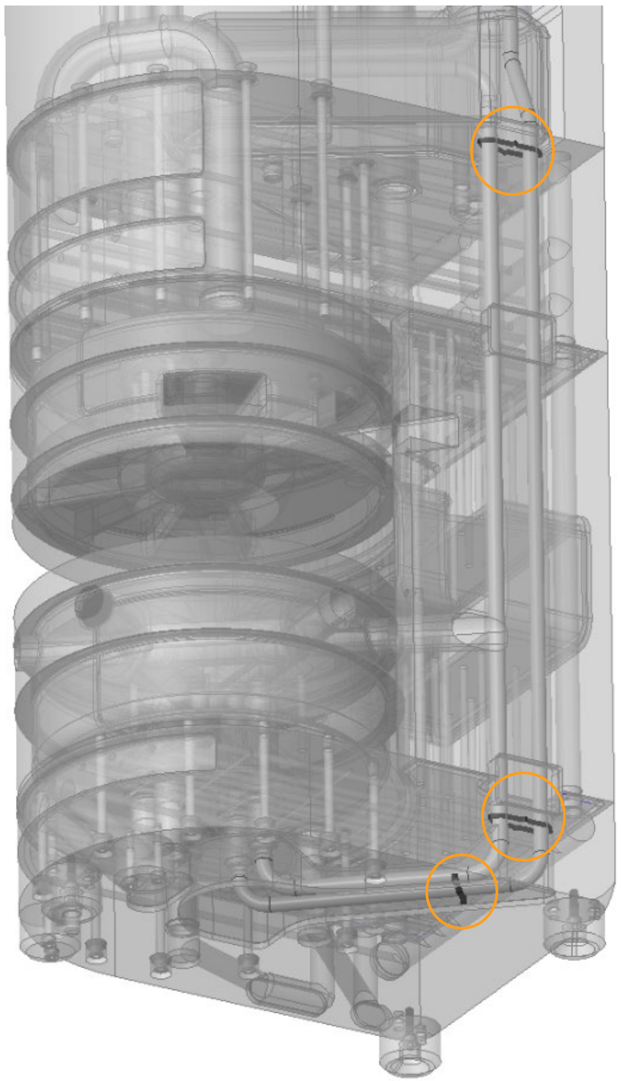
Hydrogen Transfer Lines

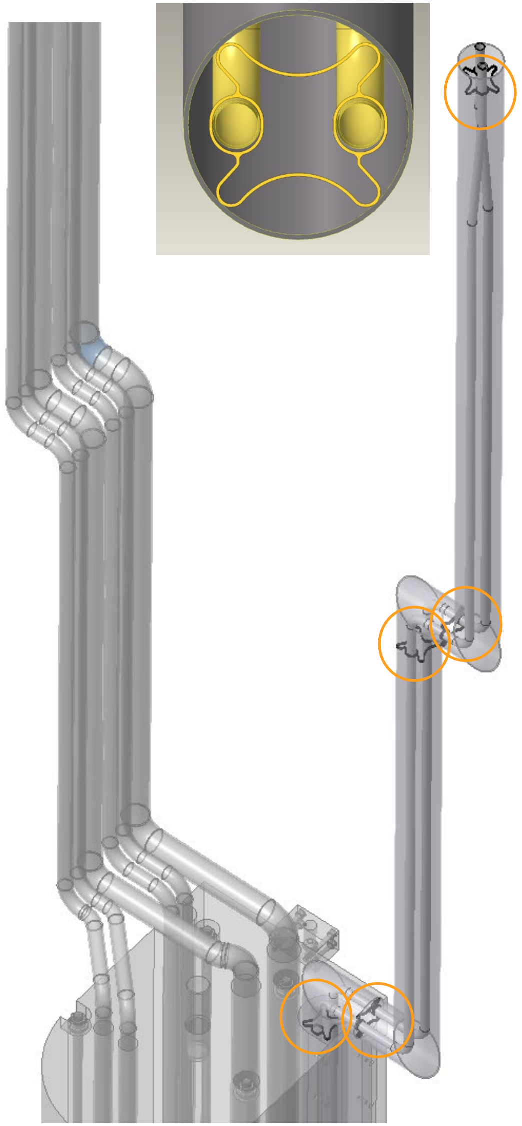
- Hydrogen supplied to moderators in series from single transfer line based on single CMS loop
  - Upper moderator then lower moderator in series
- Invar hydrogen tubes to minimize thermal contraction
- 316L vacuum boundary
- Separate supply and return lines in a single vacuum jacket
  - Less pressure drop per volume of return hydrogen than concentric
  - Easier fabrication process than concentric lines
  - Extra space for contraction since moderators are nearly fixed
- All welded hydrogen lines and surrounding vacuum layer
- Protected in backbone or in chases



Hydrogen Transfer Line Spacers

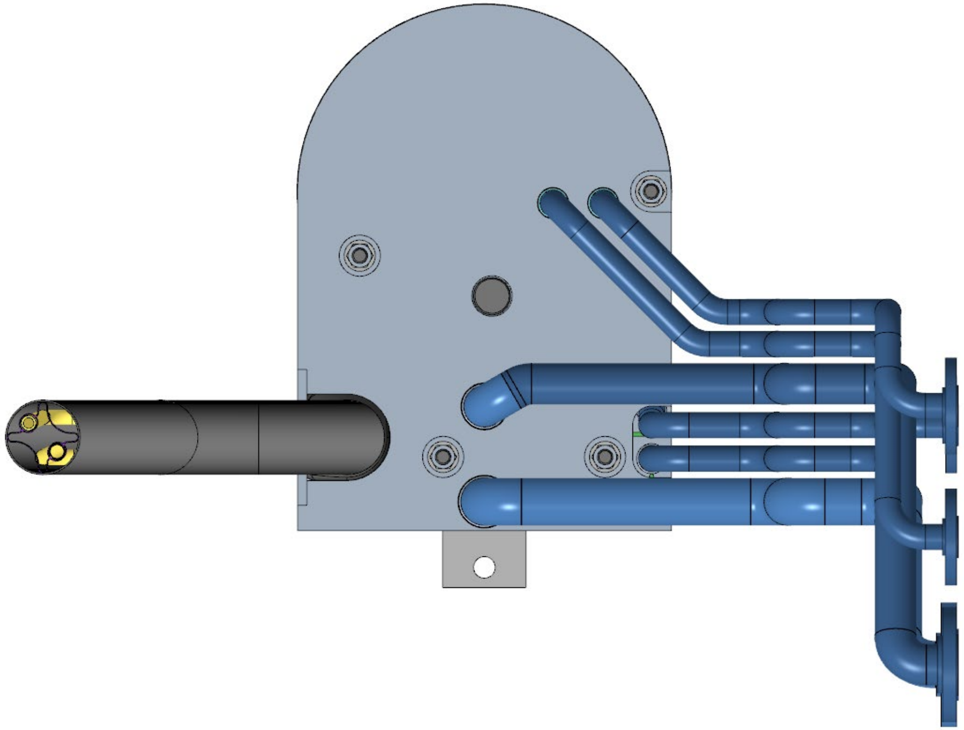
- Hydrogen tubes must be supported within vacuum spaces to prevent thermal shorts from 20K to ambient
- Spacers must minimize thermal loads and provide support without over constraining hydrogen tubes
- Spacers made from Ti-15-3-3-3 to minimize thermal conductivity with small cross sections to not be too stiff or prevent venting of potential hydrogen leaks

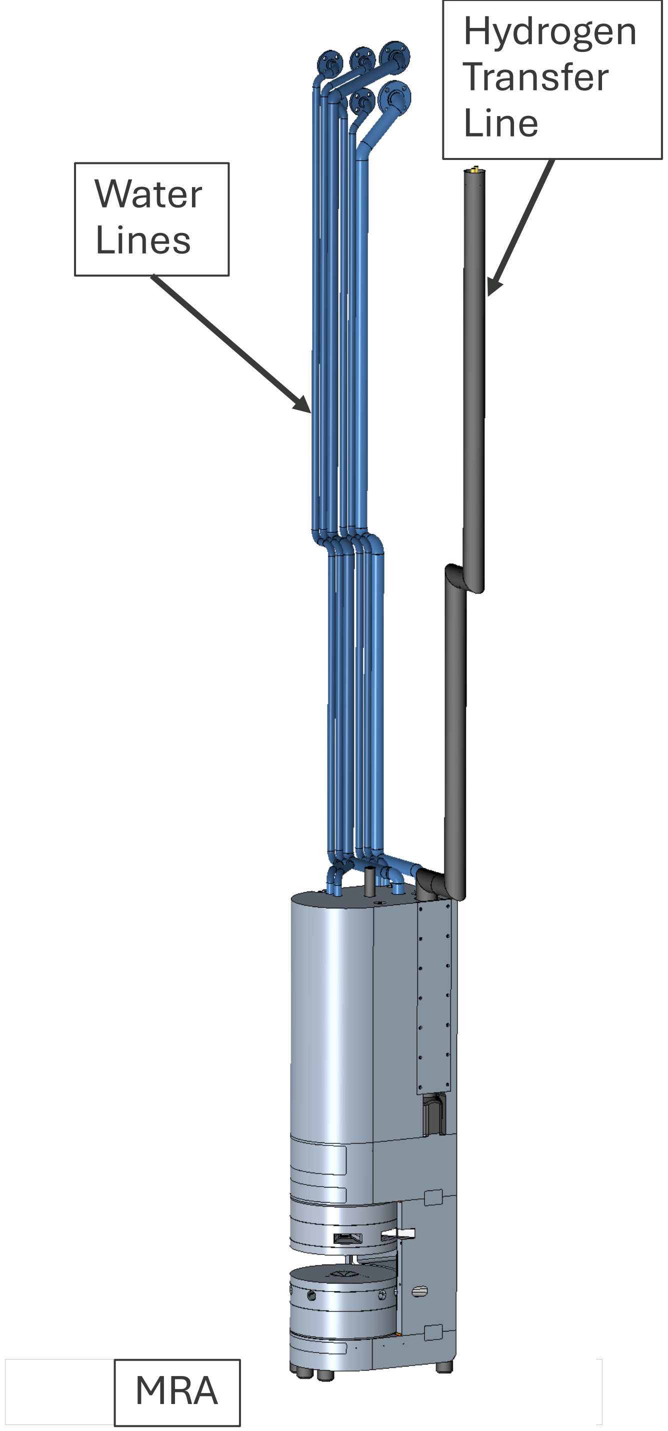




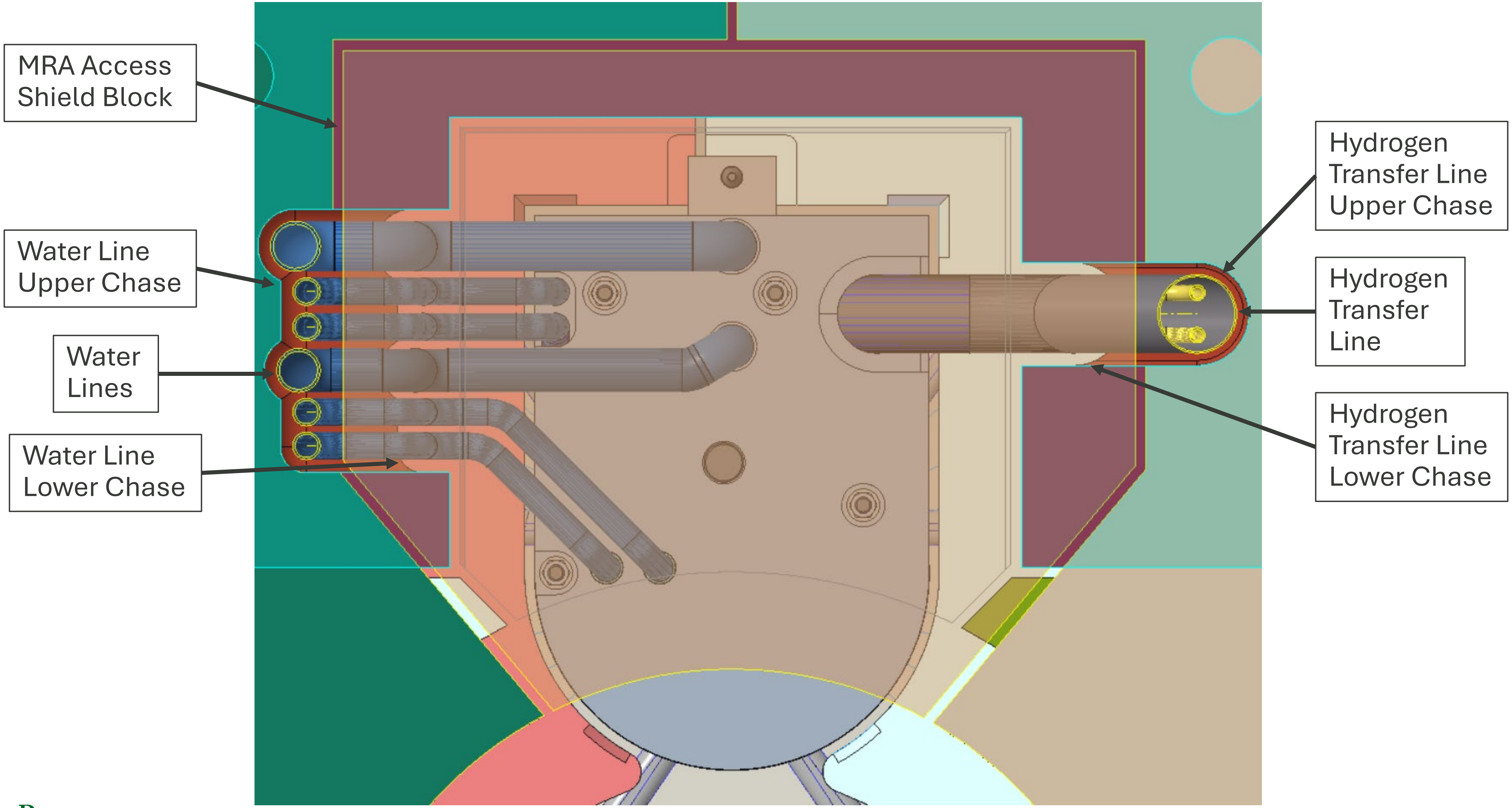
Pipe Routing above Shield Block

- Hydrogen transfer line has double jog to reducing streaming
- Water piping has double jog to reduce streaming
  - Arrangement allows for hydraulic cutter access above shield block
- Piping steps out to allow installation of Core Vessel shield blocks above the MRA



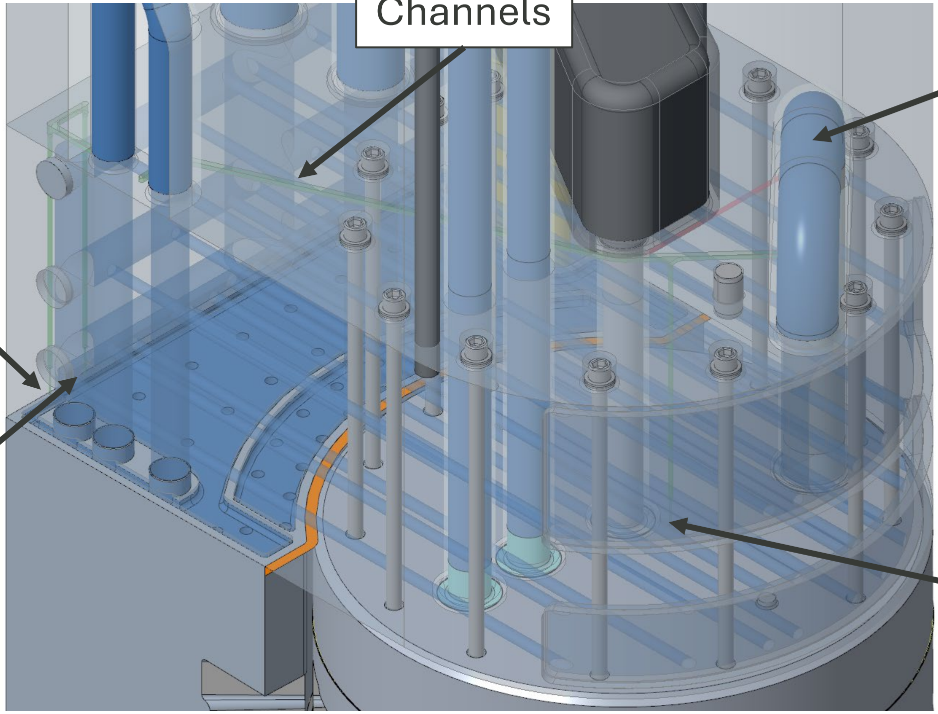


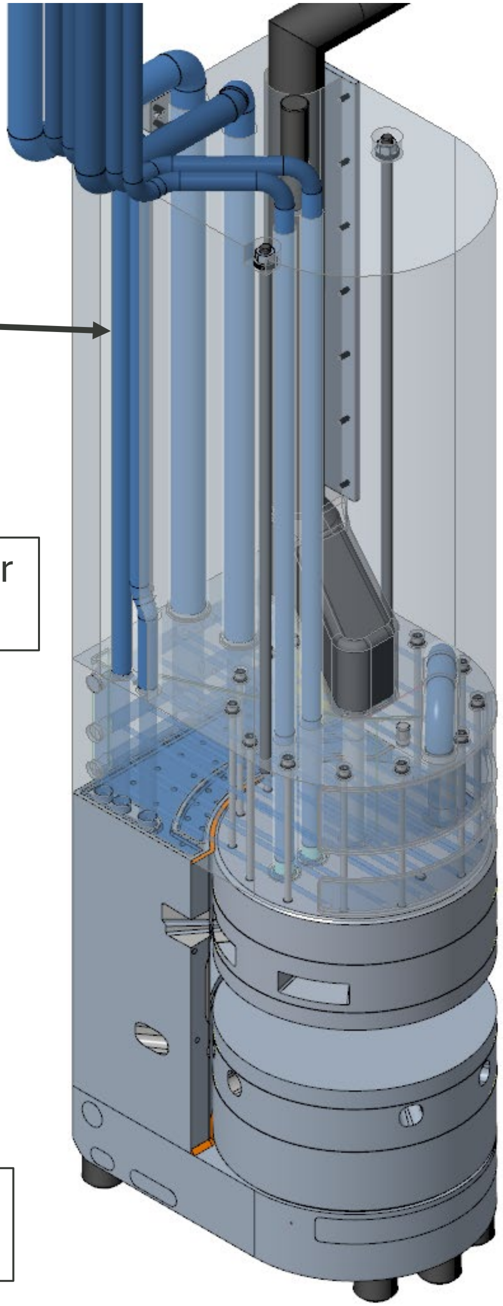
Core Vessel Shielding MRA Piping Chases



Thermocouple Design

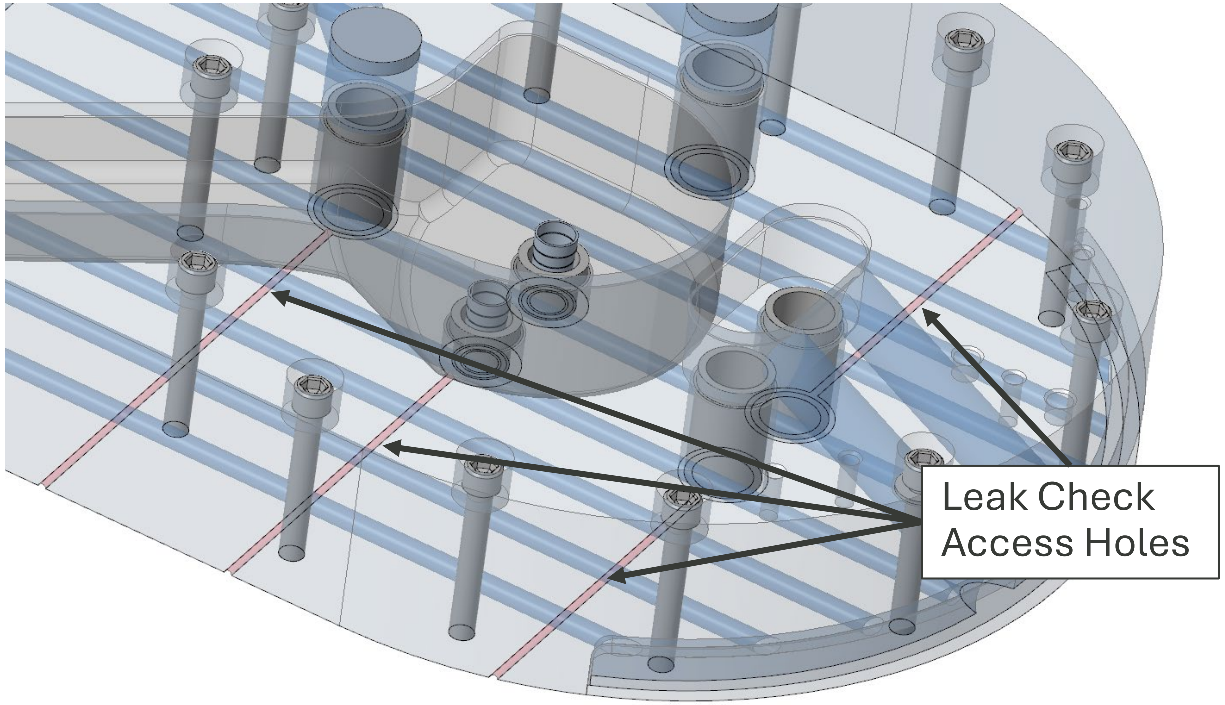
- Thermocouples for information only
  - Omega BLMI-304-K-116U-120
- All located in or above upper backbone
  - No risk of target or beamline interference

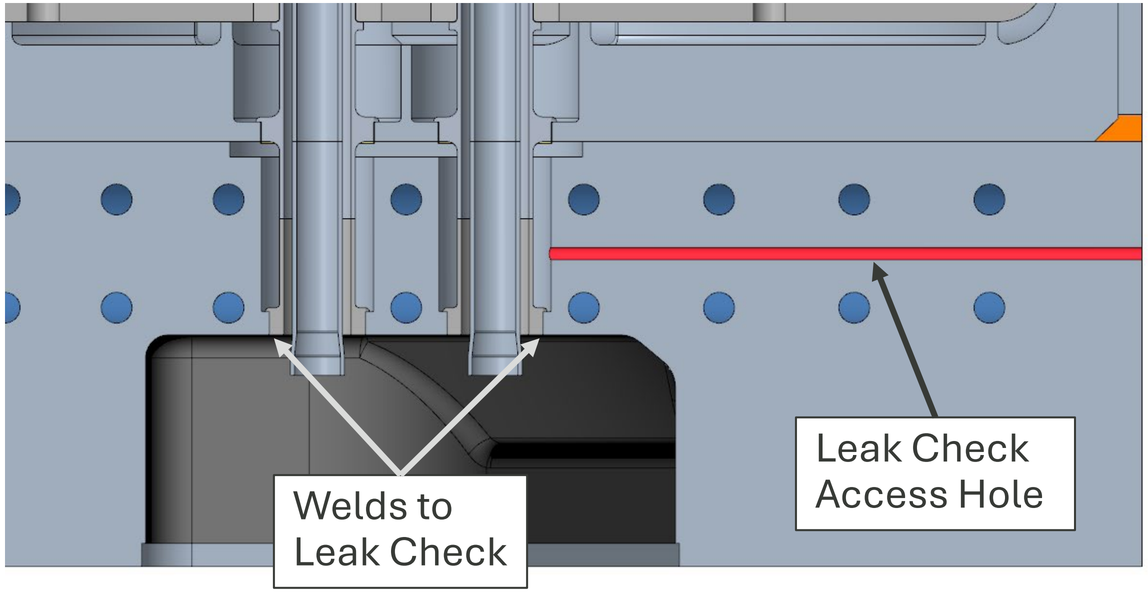




Leak Check Access Holes

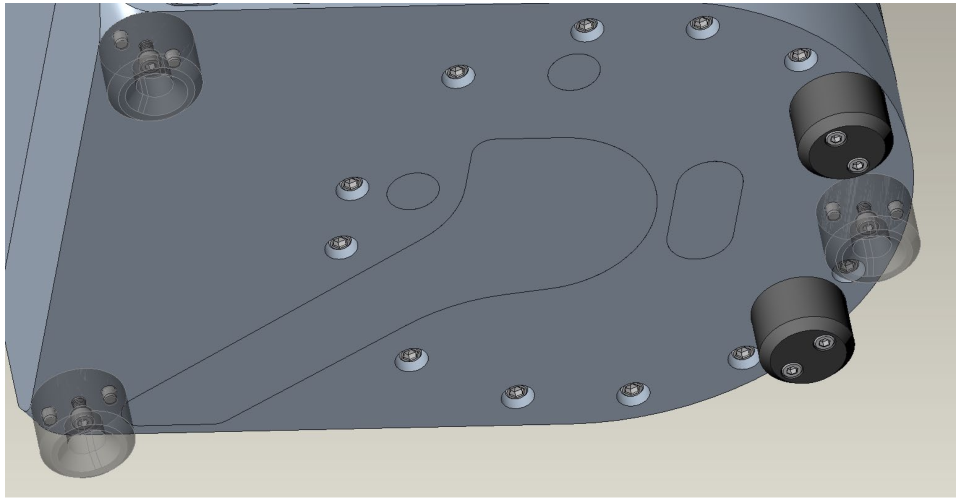
- Reflector to backbone welded connections need access for leak checking
- Small access holes added for spraying helium to the outside of these welds

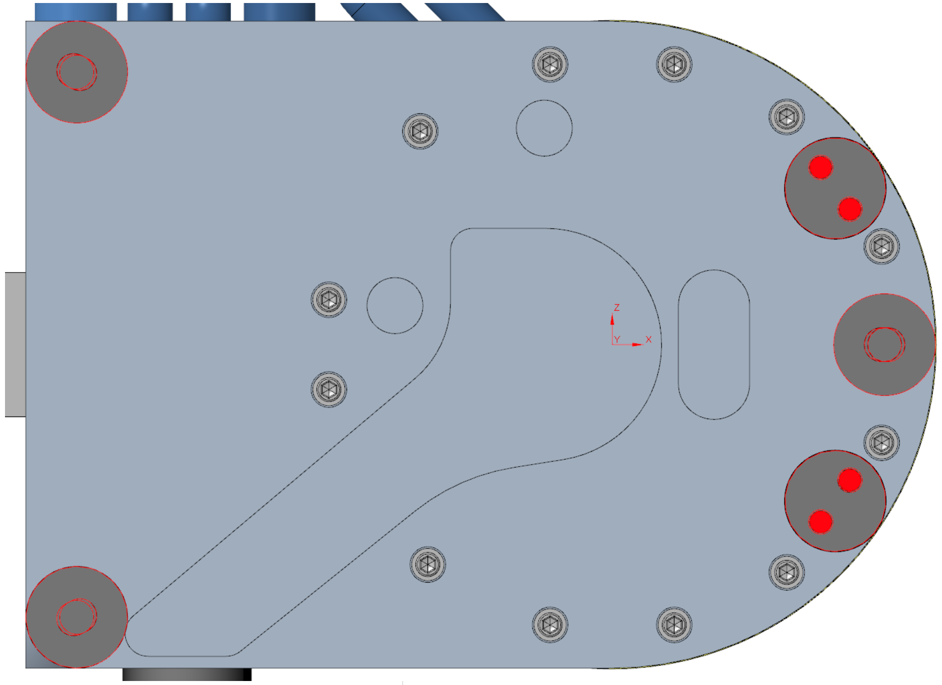




MRA Alignment Blocks

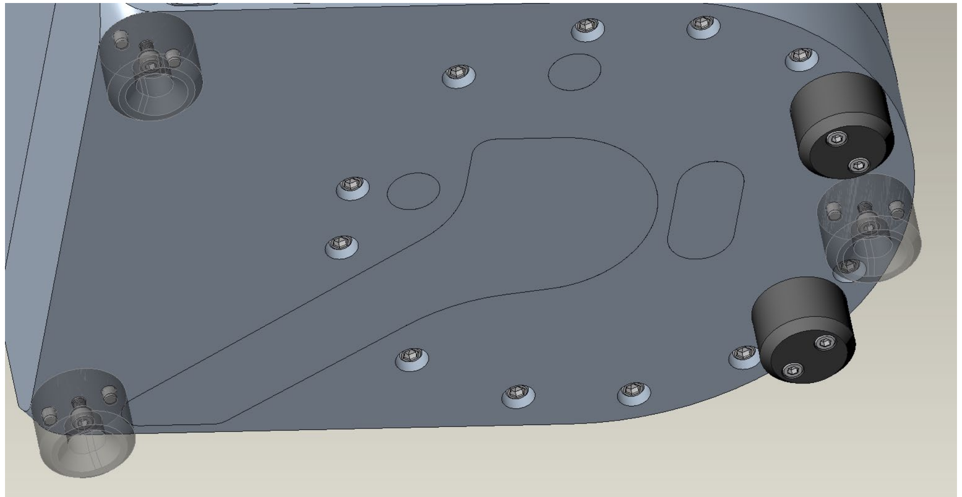
- 3 slotted alignment blocks interface to pins in CV shielding
  - Aligned to moderator centers to minimize moderator movement
- Flats on bottom of block interface to flat of CV Shielding
- Each block restrains 2 DOF
  - 6 total DOF restrained but not fully kinematic due to pin to slot gaps
- Alignment blocks on first MRA will be custom machined to align MRA to STS global coordinate system based on CV alignment pin survey
- Alignment blocks fixed with dowel pins

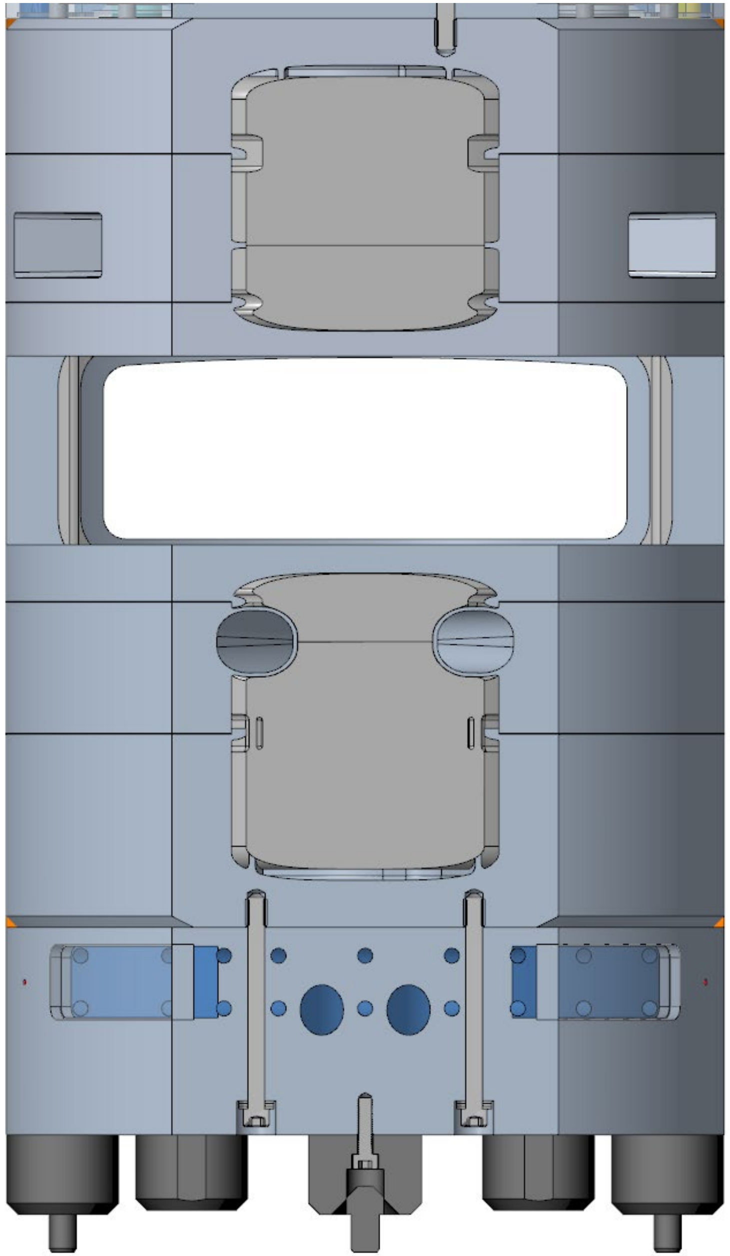




MRA Alignment Blocks are Self Guiding

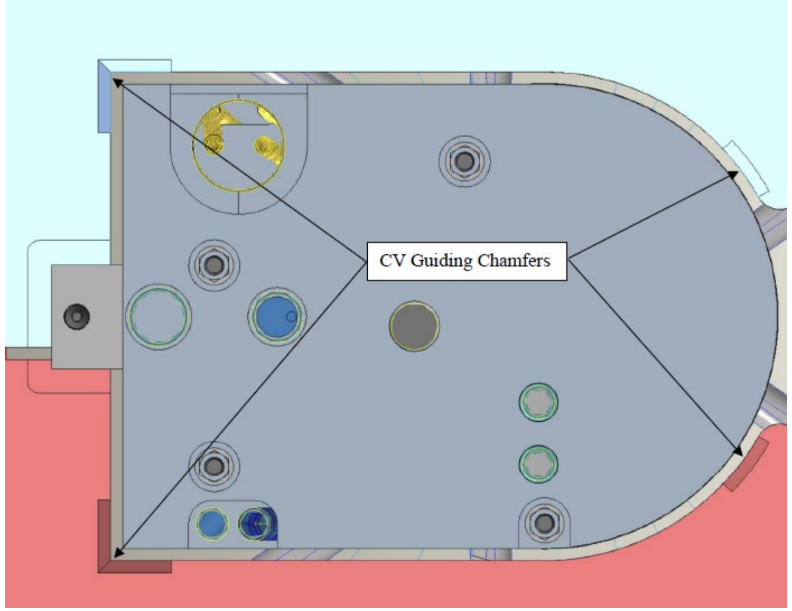
- MRA Alignment Blocks and mating pins include self guiding ramps
  - Designed so that self guiding should occur from any orientation within Core Vessel MRA Cavity
- Self guide from minimum of 14 mm of offset
- Nominal MRA cavity clearance is 10 mm

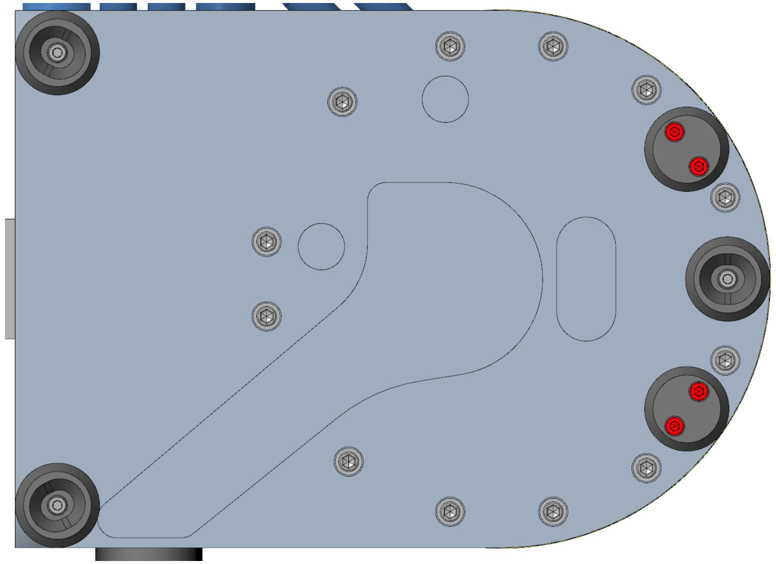




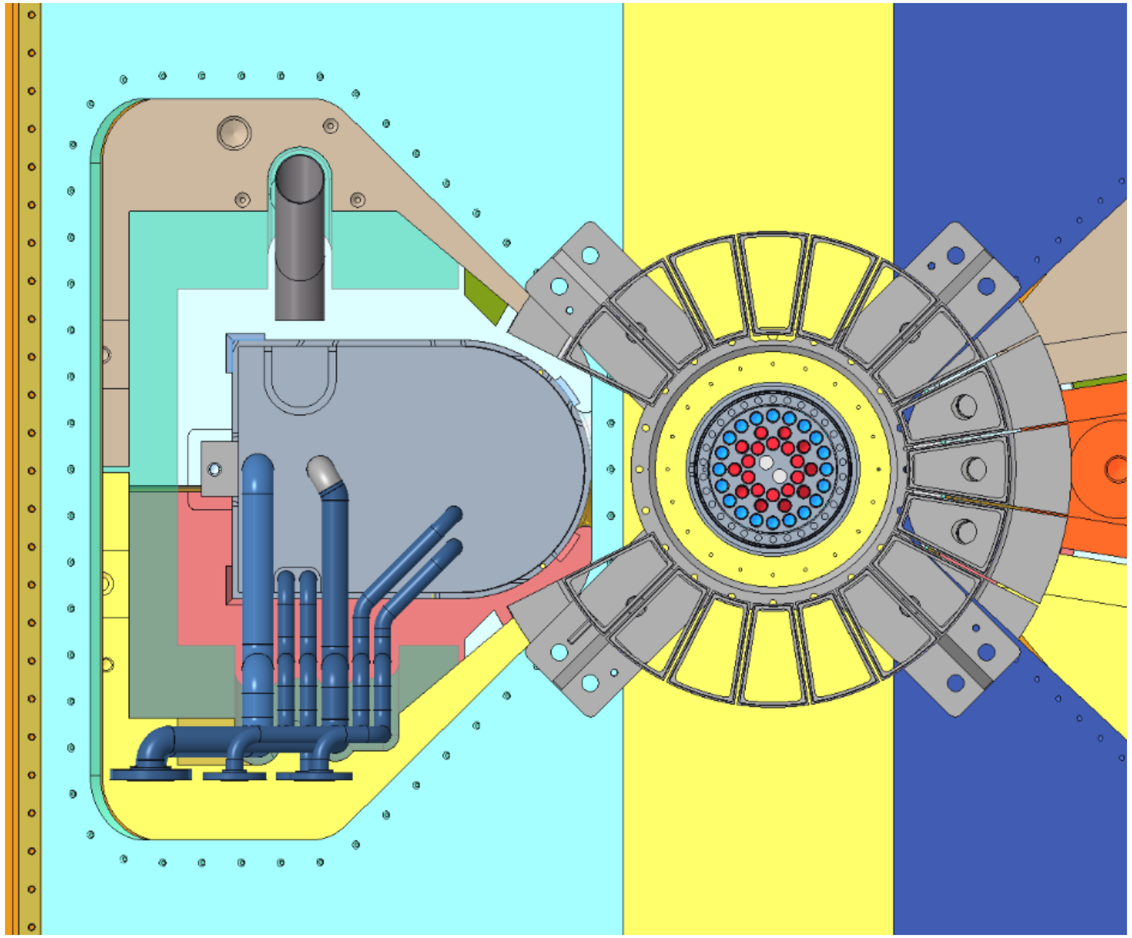
MRA Guiding Blocks

- MRA Alignment Blocks include outside ramps for guiding MRA off Core Vessel shielding
  - Core Vessel Shielding also includes mating ramps
- Target side Alignment Block does not have any adjacent shielding to be guided from
- MRA Guiding Blocks interface to nearest available Core Vessel Shielding
  - Coarse alignment function only – no impact to final alignment
  - Shorter than Alignment Blocks to prevent interference

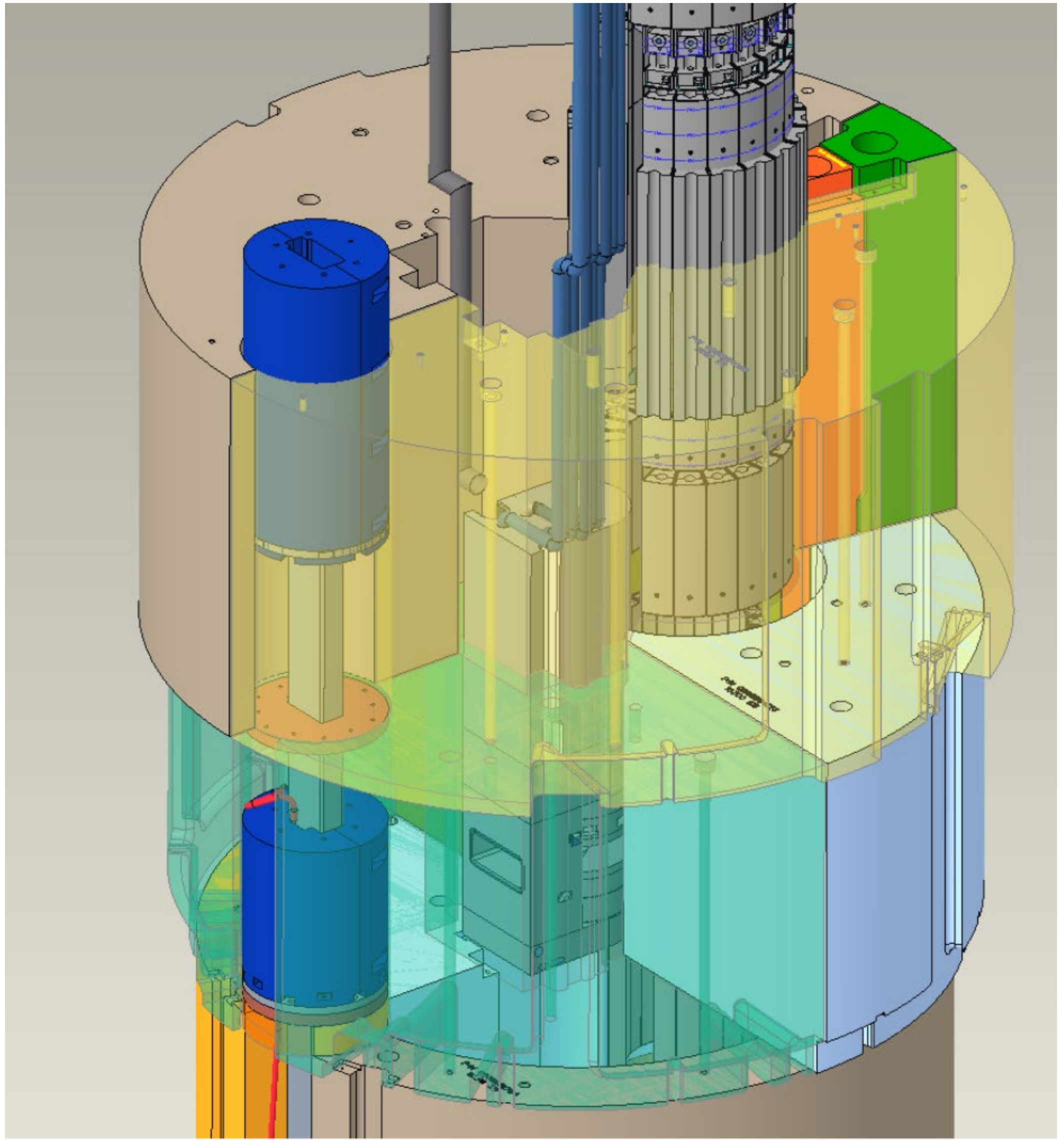




MRA Design for Installation



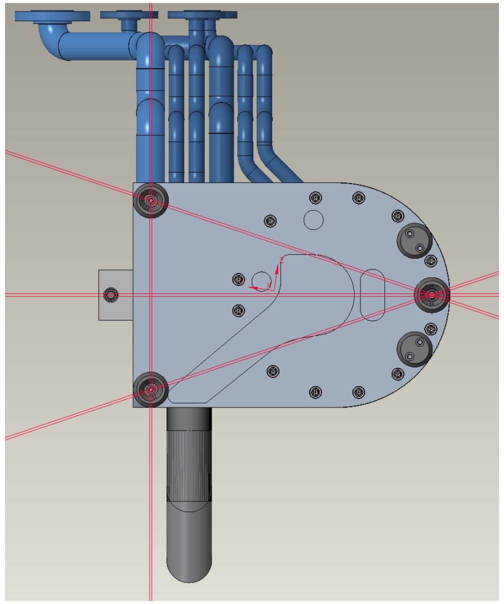
MRA Designed for Vertical Installation/Removal with 3 Target Segments Removed

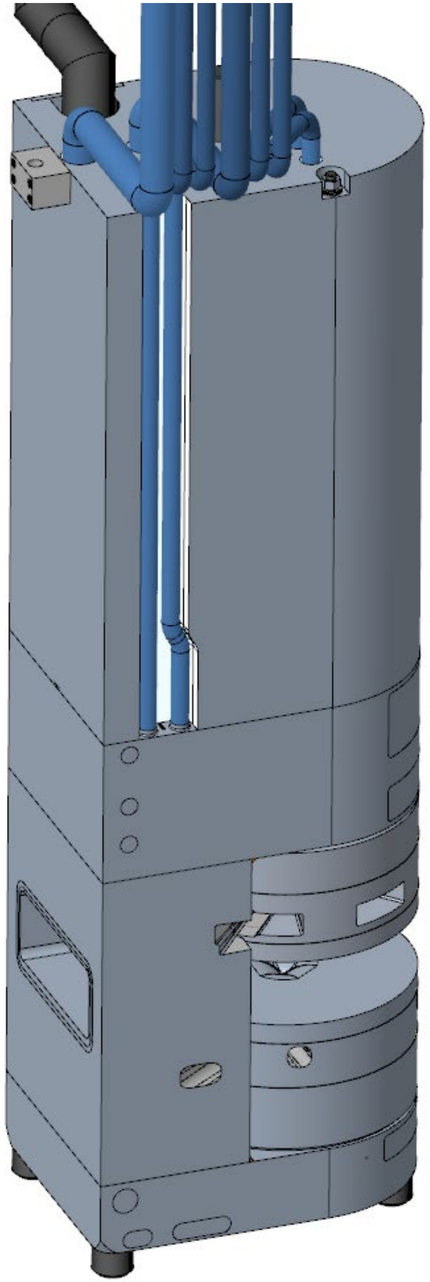


MRA Engages into MRA Shielding Cavity prior to Piping Entering into Piping Chases

MRA Seismic Design

- MRA is top heavy with small base of support
  - Additional shielding height made this worse
- Radiological conditions do not allow hands on access to MRA for installing traditional restraints
- Seismic block added to MRA shield block to restrain MRA tipping without loading piping
  - Seismic block is designed to only interact with seismic pin in an event and not during normal operation
  - 1 mm of clearance to allow for tolerances and thermal deflections with influencing alignment

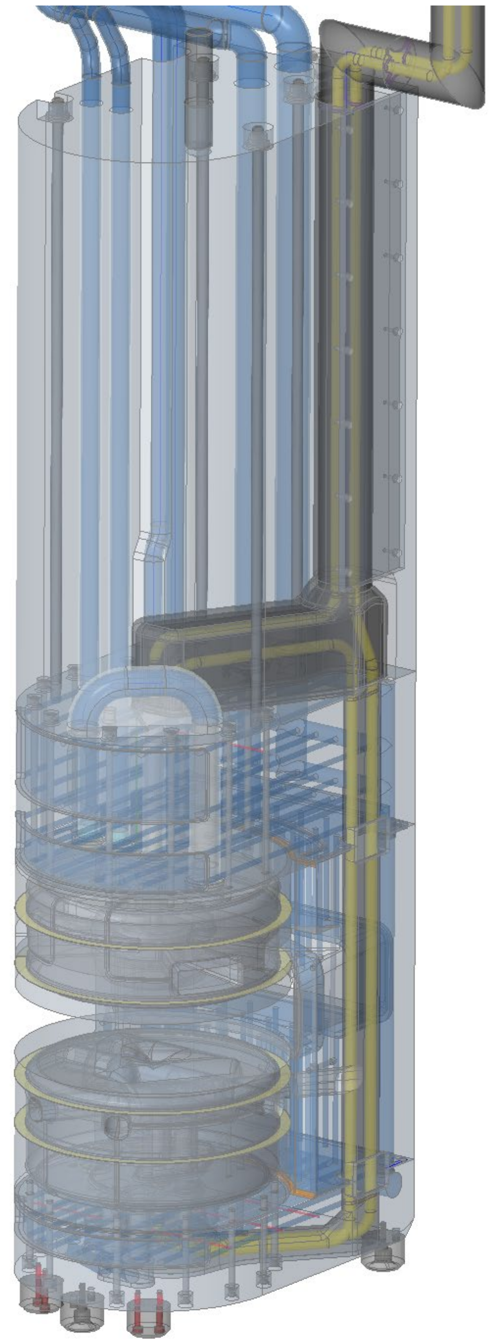




MRA Fastener Analysis

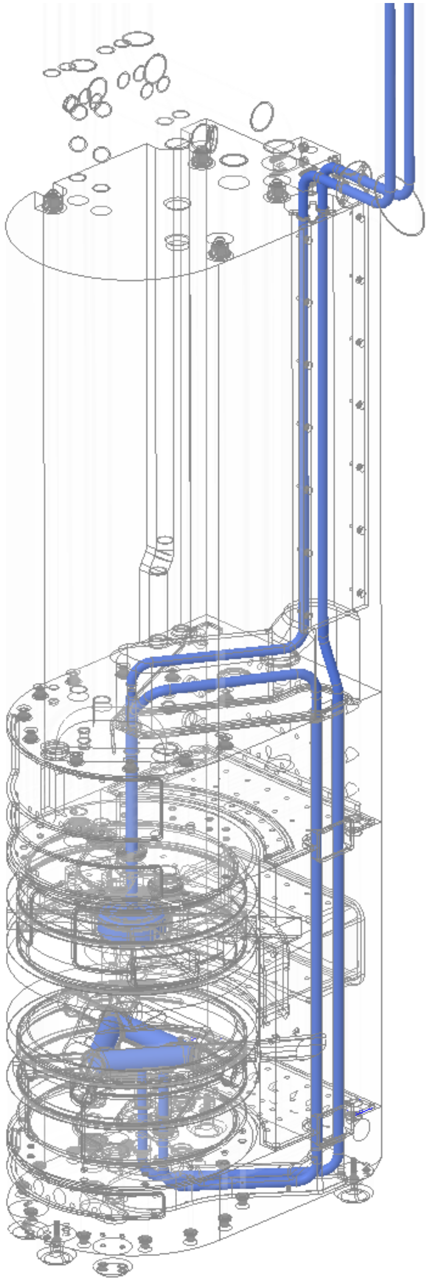
- Preload, Lifting, Seismic, and Pressure loads considered
- Design for at least a safety factor of 3 to yield
  - Prevent permanent deformation that could impact alignment
- Threaded fasteners evaluated for axial and thread failure
- Pins evaluated for shear failure

	Load Case Factor of Safety to Yield			
Fastener	Preload	Lifting	Seismic	Pressure
Remote Handling Stud		10.1		
Shield Block Threaded Rods	3.08	13.9	3.95	
Shield Block Alignment Pins			8.99	
Reflector Vessel Screws	3.11	410	154	3.07
Alignment Block Pins			3.32	
Seismic Block Pins			3.59	
Seismic Block Screws			38.5	
Hydrogen Vessel Pins			1020	



MRA Static Heat Loads to Hydrogen Boundary

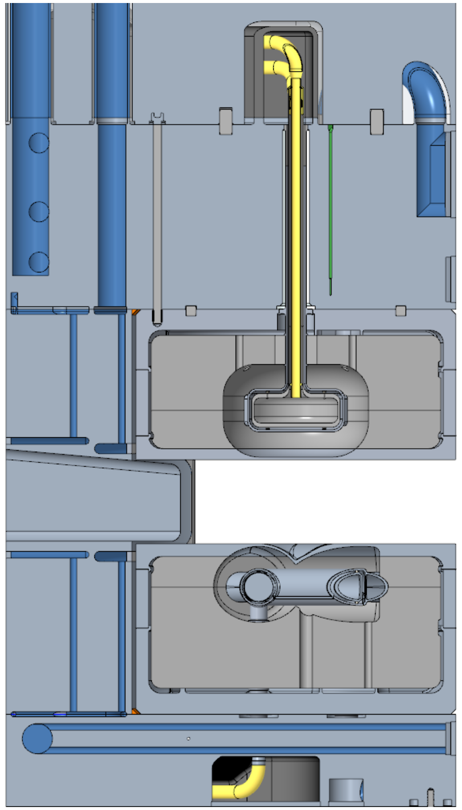
- Calculated heat transfer through conduction and radiation
  - Convection negligible due to vacuum insulation
  - Vacuum boundary surface temperatures conservatively estimated from MRA thermal hydraulic analysis for beam on conditions
  - Assumed perfect thermal contact for conductivity calculations
  - Emissivity values were conservative for polished surfaces



Component	Beam On			Beam Off		
	Q_{rad} (W)	Q_{cond} (W)	Q (W)	Q_{rad} (W)	Q_{cond} (W)	Q (W)
Upper Reflector	2.70	14.44	17.14	2.03	13.74	16.47
Lower Reflector	2.69	14.44	17.13	2.42	13.74	16.85
Upper Backbone	7.24	2.76	10.00	4.89	2.33	7.22
Middle Backbone	5.42	0.00	5.42	3.16	0.00	3.16
Lower Backbone	4.97	5.52	10.49	2.64	4.66	7.30
MRA Transfer Line	29.73	5.83	35.56	19.72	5.83	25.55
Total	52.75	42.99	95.74	34.86	40.30	75.16

MRA Loss of Cooling Analysis

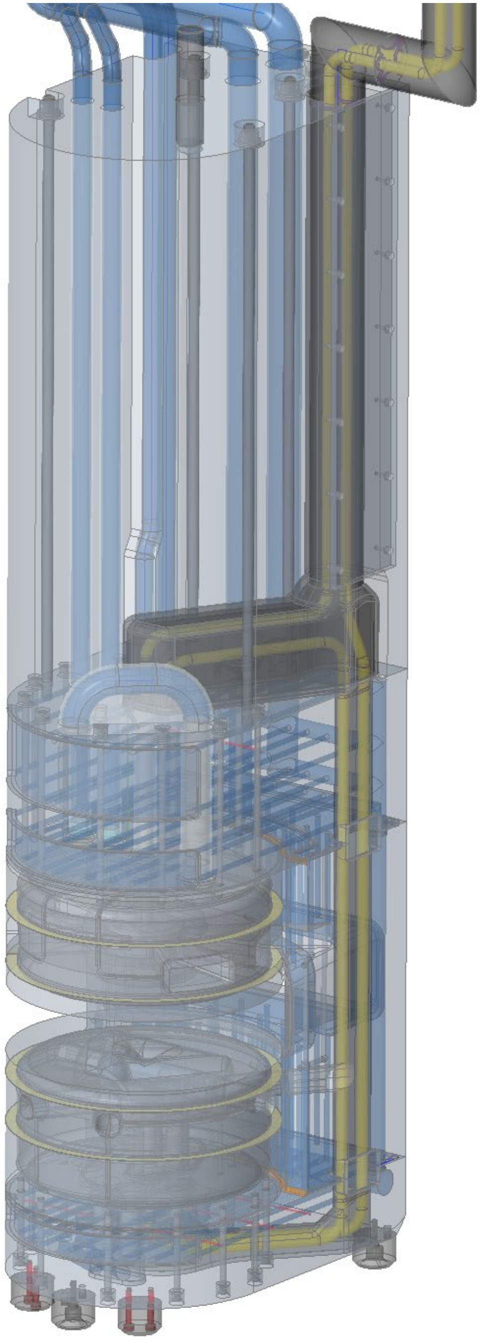
- ESS Moderator Plug failure demonstrated risk of freezing water from MRA loss of water cooling while maintaining hydrogen flow
- Potential estimated for STS MRA with 1-D calculations
  - Assumed beam off starting conditions and constant heat transfer rate
  - Assumed no heat transfer between MRA elements or to surroundings
  - Estimated time to reach 0°C and initiate water freezing
- Minimum 34 hours gives time for troubleshooting and venting H_2



	Material	Mass (kg)	c_p (J/kg-K)	$\Delta H_{32\text{-}0}$(J)	q (W)	$t_{32\text{-}0}$ (hr)
Upper Reflector	Aluminum	18.32	896	5.29E+05		
	Beryllium	17.19	1950	1.08E+06		
	Water	2.56	4112	3.39E+05		
	Total			1.95E+06	15.77	34.3
Lower Reflector	Aluminum	19.71	896	5.69E+05		
	Beryllium	21.08	1950	1.32E+06		
	Water	3.31	4112	4.39E+05		
	Total			2.33E+06	16.15	40.1
Backbone	Stainless	637.97	500	1.03E+07		
	Water	7.95	4112	1.05E+06		
	Total			1.13E+07	43.24	72.8

Summary

- MRA Final Design implemented without significant neutronic performance loss relative to Preliminary Design
- Backbone designed to locate and support reflector vessels with minimal thermal deflections
- Quasi kinematic mounts provide repeatable, precise moderator positioning
- The following analyses will show the details of how the design meets the MRA System Requirements



Thank You