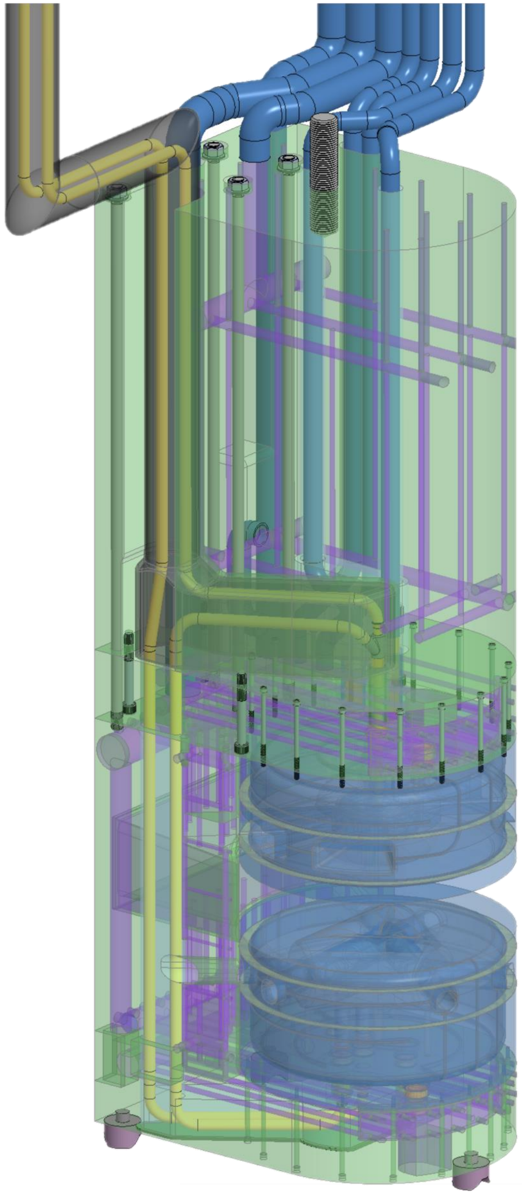
Moderator Reflector Assembly Overview

Jim Janney
MRA Lead Engineer

March 26, 2024

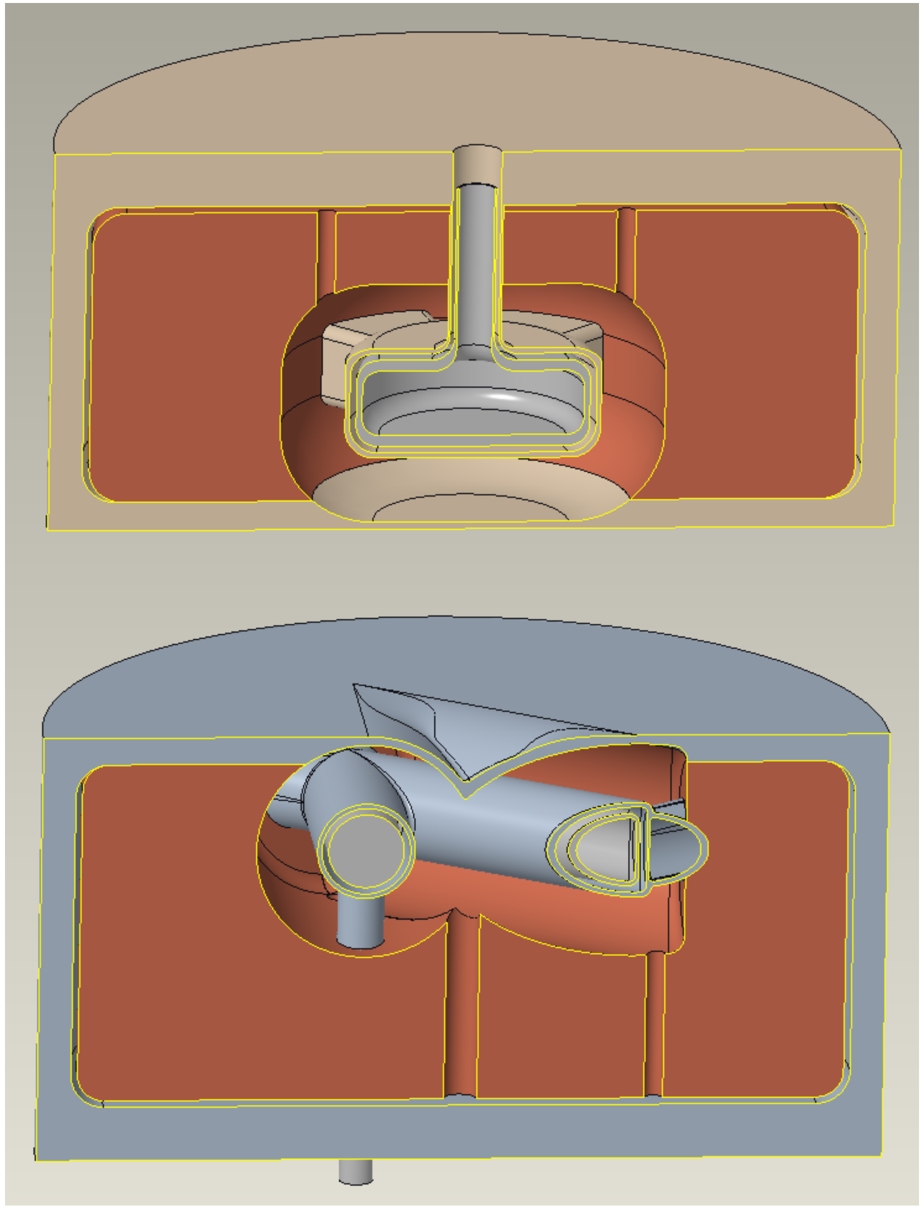
Outline

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



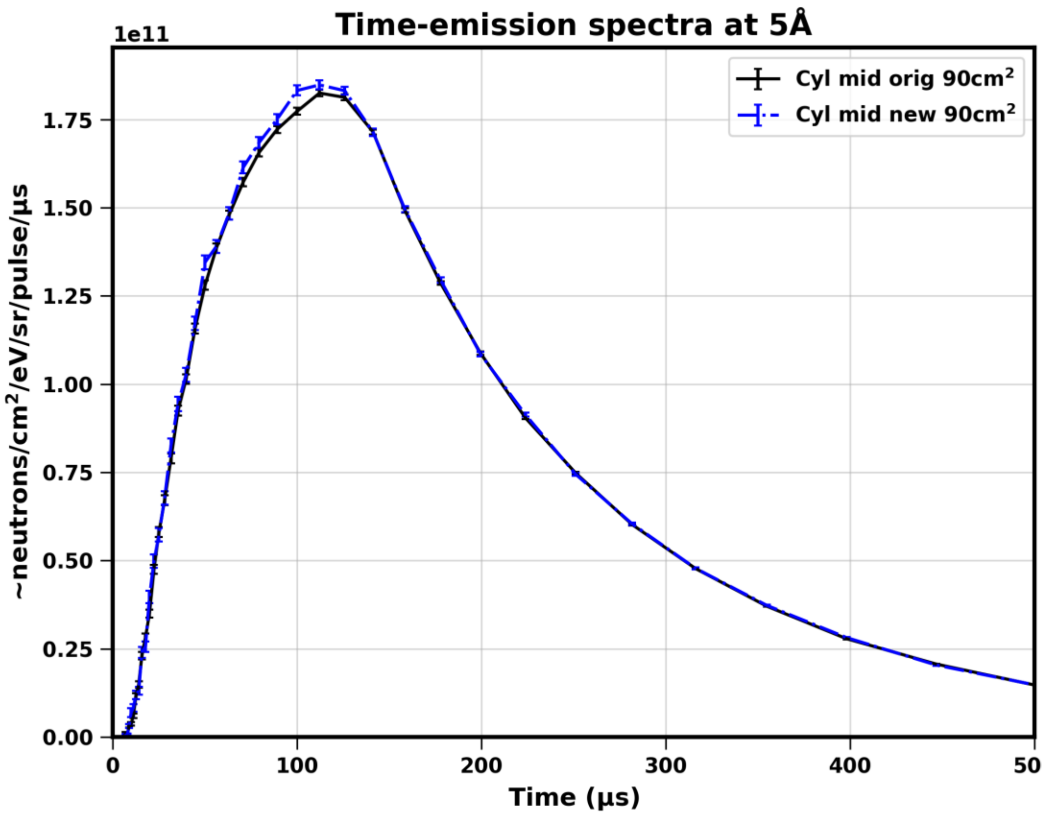
From MRA Optimization to Preliminary Design

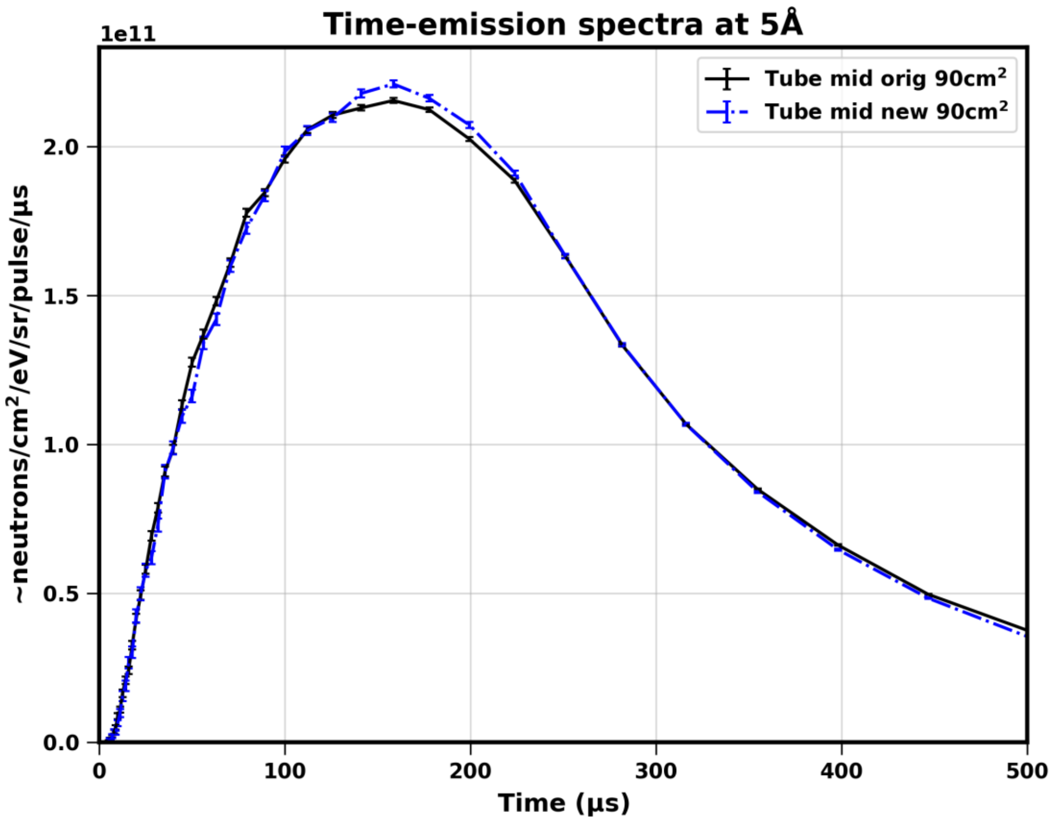
- Engineering design based on chosen configuration from preliminary optimization
  - Tube reflector diameter shrunk by 10 mm from optimum to match cylinder reflector
- Designed for 22 beamlines
- QIKR beamport bump added
- Wall thicknesses minimized based on analysis of internal pressure loading
  - Analysis during conceptual design showed that stresses from pressure loadings dominated thermal stresses



Neutronics Analysis of Preliminary MRA Model

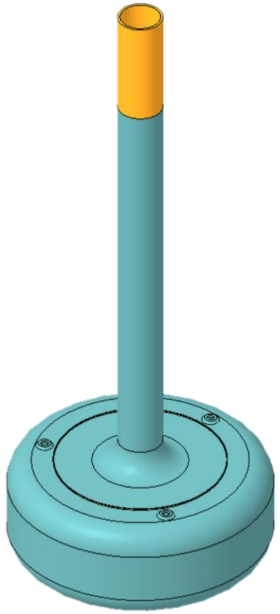
- Neutronic performance check shows minor improvement in performance for both moderators vs. original optimization

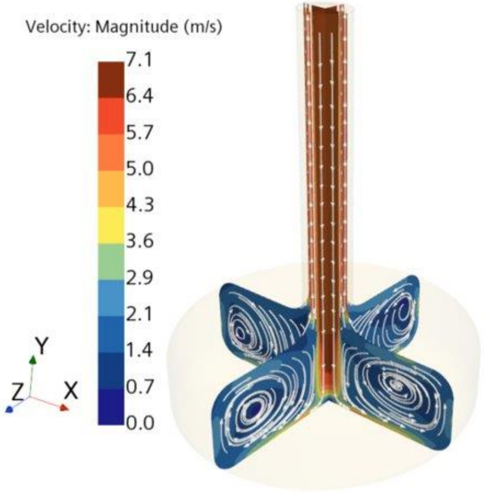




Upper Cylinder Hydrogen Vessel Details

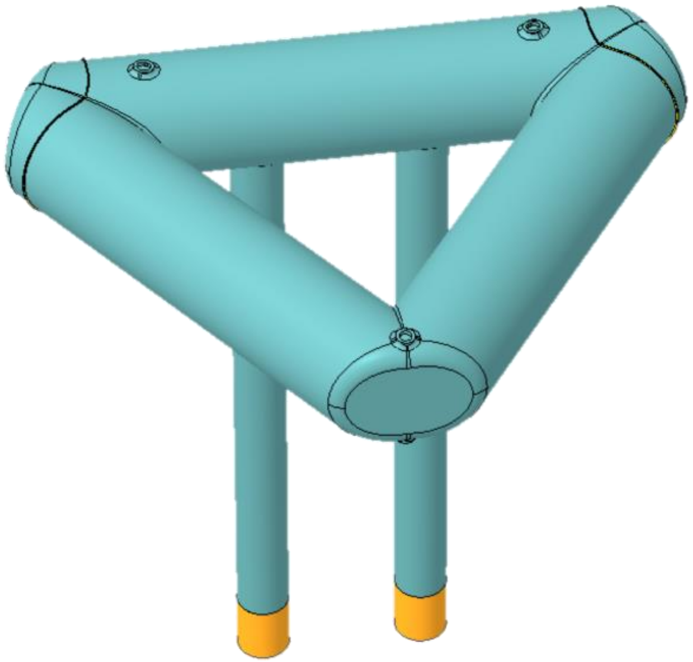
- Al6061-T6 chosen for material based on neutron transparency, cryogenic strength/ductility and HFIR/SNS experience
- Inlet stinger provides jet to cool bottom of the vessel – flow then travels to annular return along the vessel walls
- Held in place by 6 titanium pins
  - Must precisely locate hydrogen vessel while minimizing heat transfer and allowing contraction from 300 K to 20 K
- Note – Inlet temperature for thermal hydraulic analysis is outdated

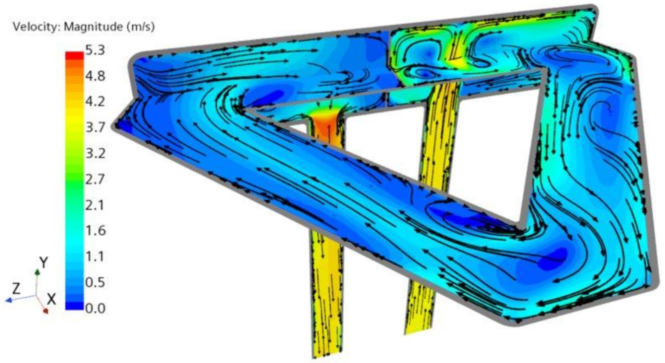




Lower Tube Hydrogen Vessel Details

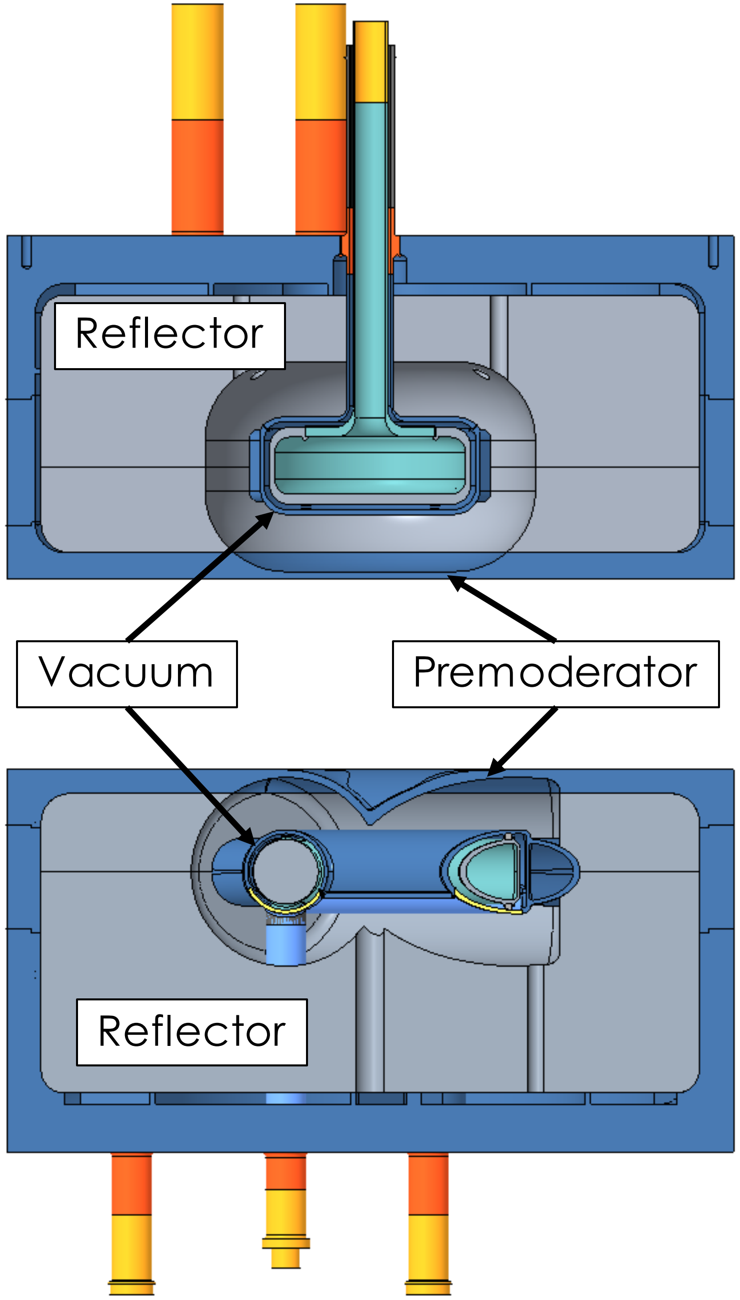
- Al6061-T6 chosen for material based on neutron transparency, cryogenic strength/ductility and HFIR/SNS experience
- Vacuum vessel integrated into reflector vessel
- Held in place by 6 titanium pins
  - Must precisely locate hydrogen vessel while minimizing heat transfer and allowing contraction from 300 K to 20 K
- Note – Inlet temperature for thermal hydraulic analysis is outdated





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
- No helium layer – vacuum layer surrounded immediately by light water
- Premoderator zone formed by reflector vessel wall and beryllium reflector
- Beryllium reflector cooled by premoderator water and 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

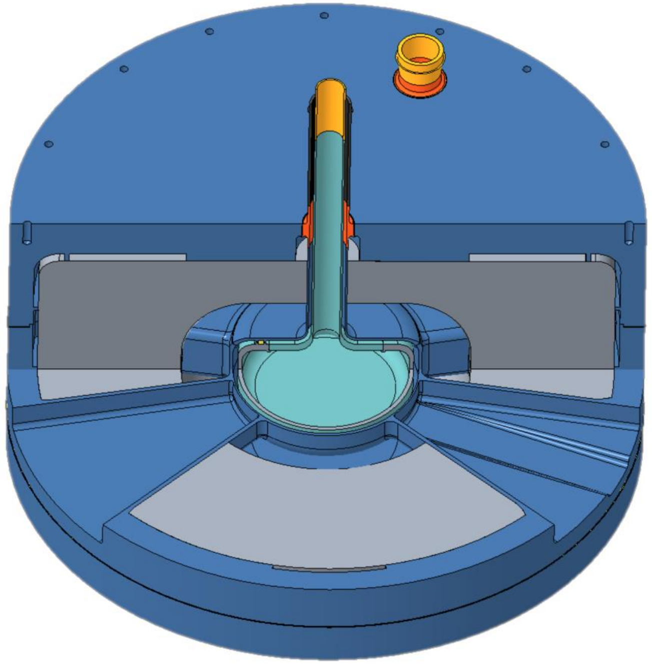
- Only 2 recorded accidents from freezing of substances onto cryogenic surfaces
- 2 ozone explosions from air condensation on cryogenic lines
  - Vacuum line rupture caused air ingress into He system vacuum at ORNL graphite reactor. Subsequent explosion upon warm up of the system.
  - Rover nuclear rocket 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

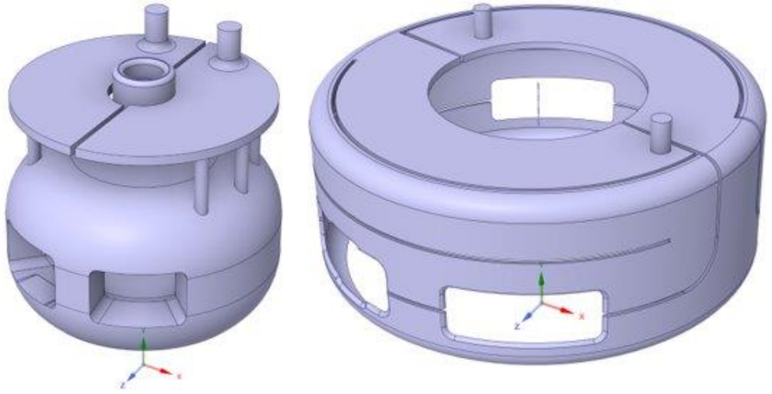
- Core Vessel prevents air leaks near the neutron source
- Water within the reflector vessels is the potential leaking species within the MRA resulting in ice accumulation
- Potential problems from water leaks – blockage of hydrogen venting through the vacuum space and energetic recombination of radiolysis 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

- 3 premoderator supplies and 3 premoderator returns 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
- Preliminary thermal hydraulic analysis model used separate exits
  - No significant change in results expected



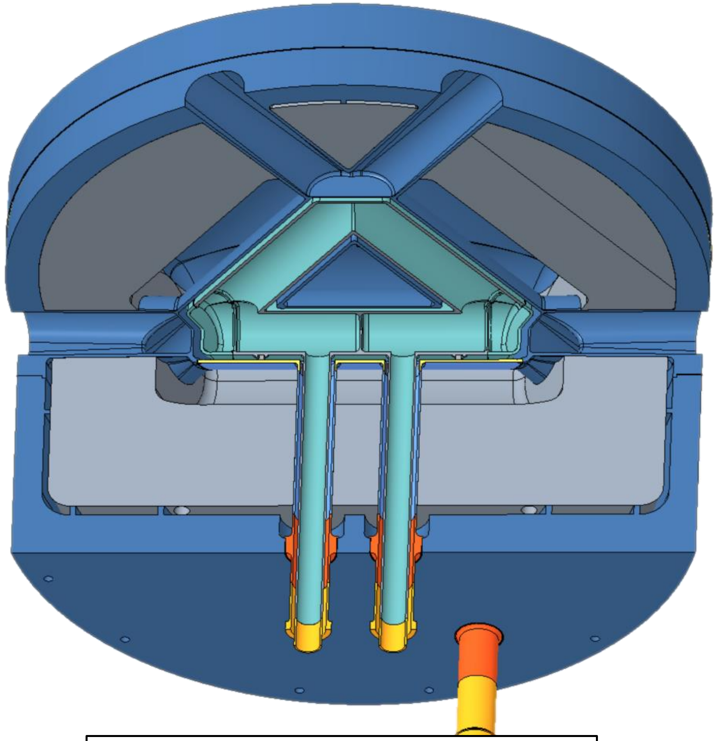
Upper Reflector Vessel

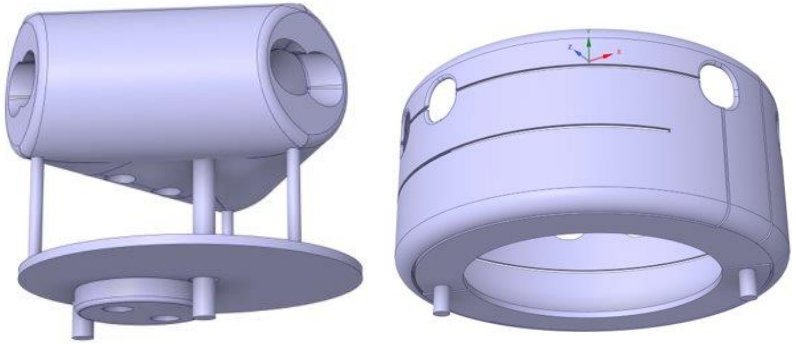


Premoderator and Reflector Flow Paths

Lower Reflector Vessel

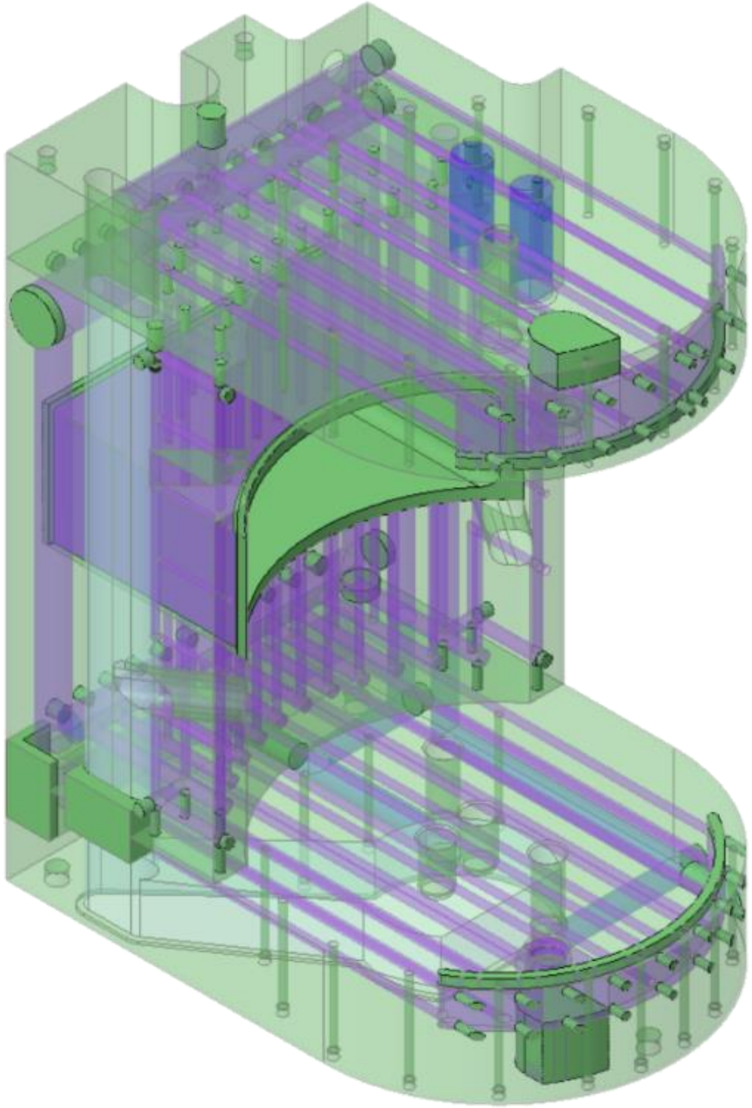
- Central premoderator supply causes a water jet through the trianglular tube structure and 3 returns over extraction ports cause flow in these areas
- Reflector cooled from outside with symmetric, alternating circumferential flow
- Premoderator and reflector cooling join on top of the reflector vessel and exit to the backbone together
- Preliminary thermal hydraulic analysis model used separate exits
  - No significant change in results expected


Lower Reflector Vessel


Premoderator and Reflector Flow Paths

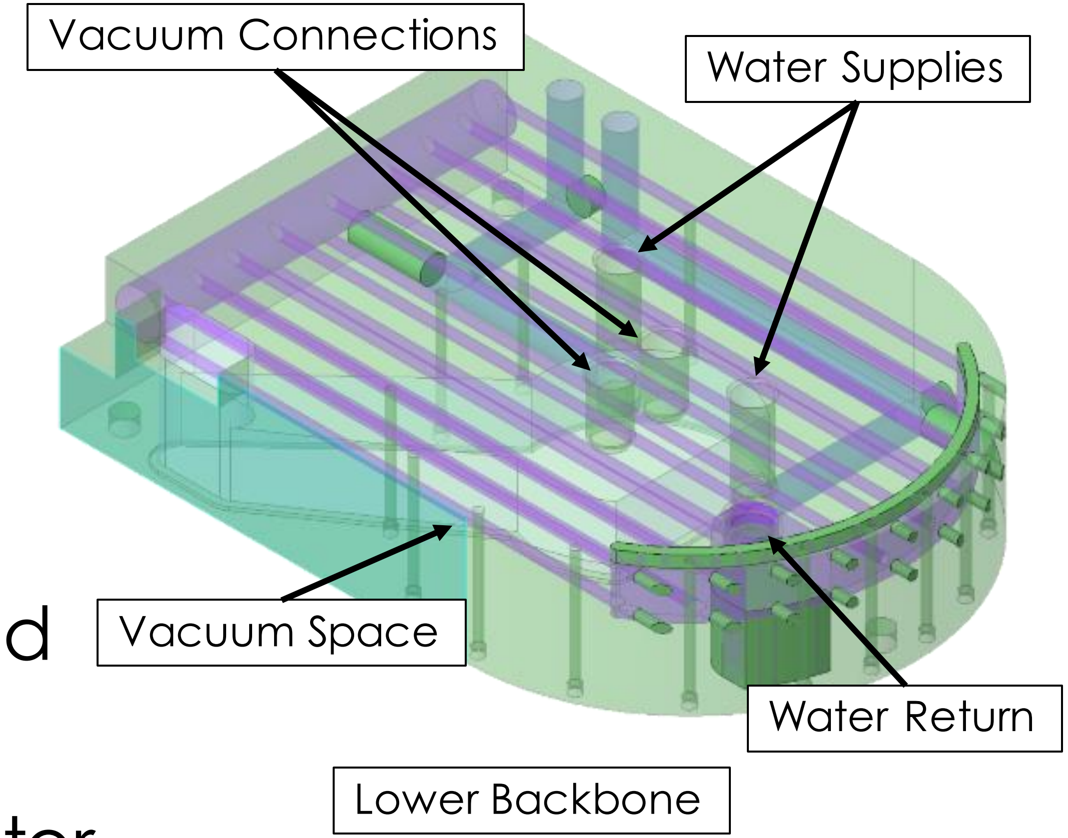
Backbone Design Goals

- Precisely position both hydrogen vessels relative to the mounting interface
- Minimize moderator deflection relative to mounting interface
- Allow routing of utilities to lower reflector around proton beam port
- Protect hydrogen lines from suroundings
- Manufacturability
- Provide shielding



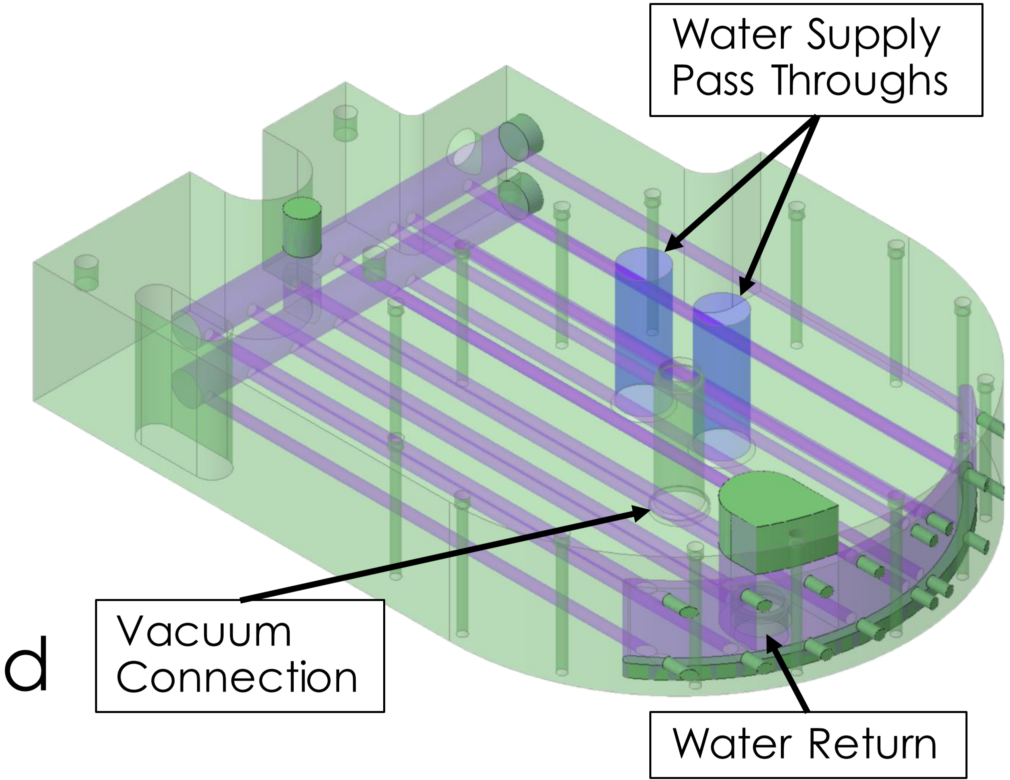
Lower Backbone

- Water from lower reflector vessel exit used to cool lower backbone
- Cooling provided by 18 deep holes
  - Subsequently plug welded closed
- Vacuum space recessed into backbone with flush cover
  - Provides protection for hydrogen lines
- Lower reflector water supplies routed in bored passages
- 5 connections from the lower reflector vessel must be sealed by welding



Upper Backbone

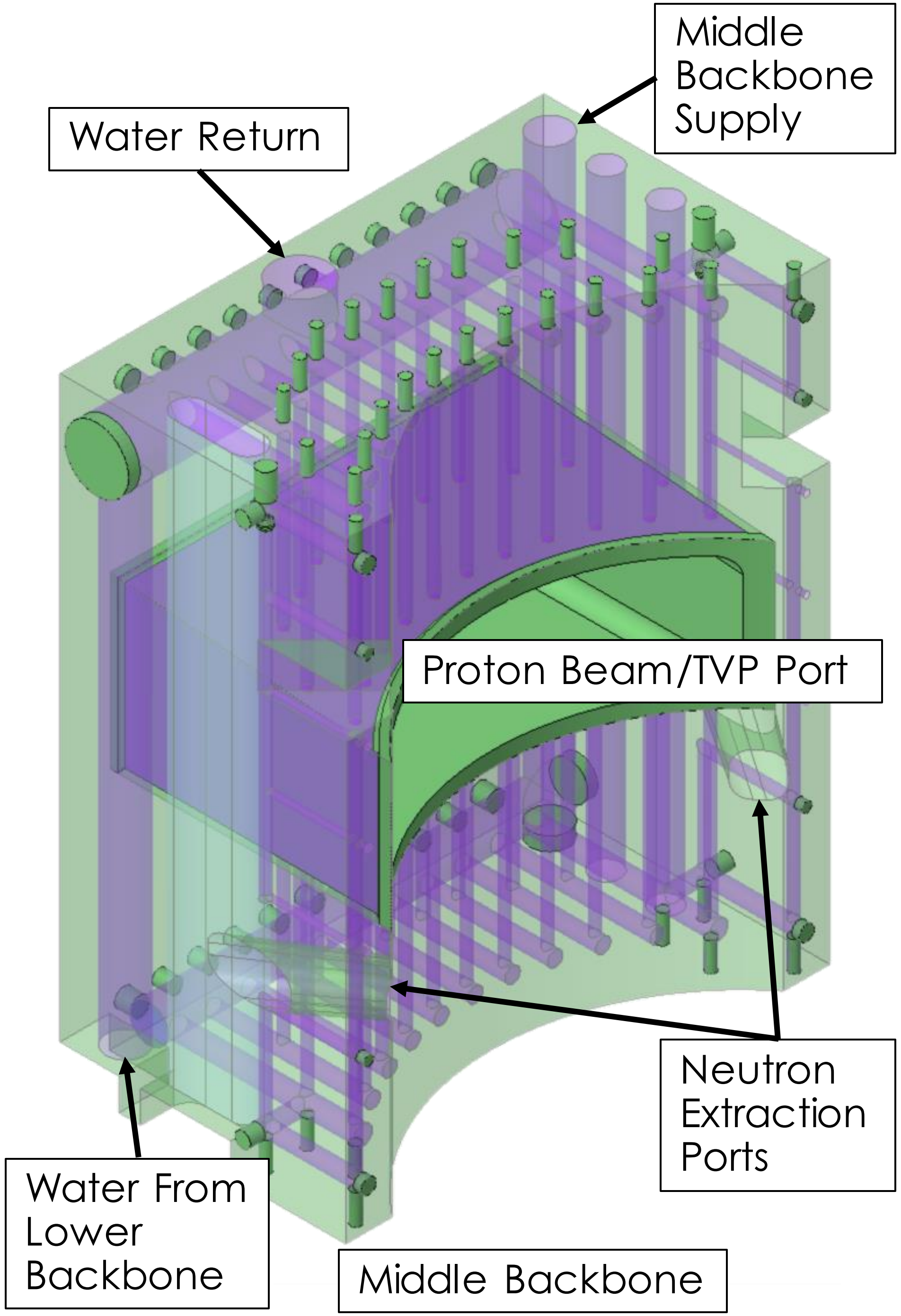
- Water from upper reflector vessel exit used to cool upper backbone
- Cooling provided by 16 deep holes
  - Subsequently plug welded closed
- Vacuum space sealed to top of backbone
  - Protection provided by shield block
- Upper reflector water supplies routed through backbone but not connected
- 2 connections from the upper reflector vessel must be sealed by welding



Upper Backbone

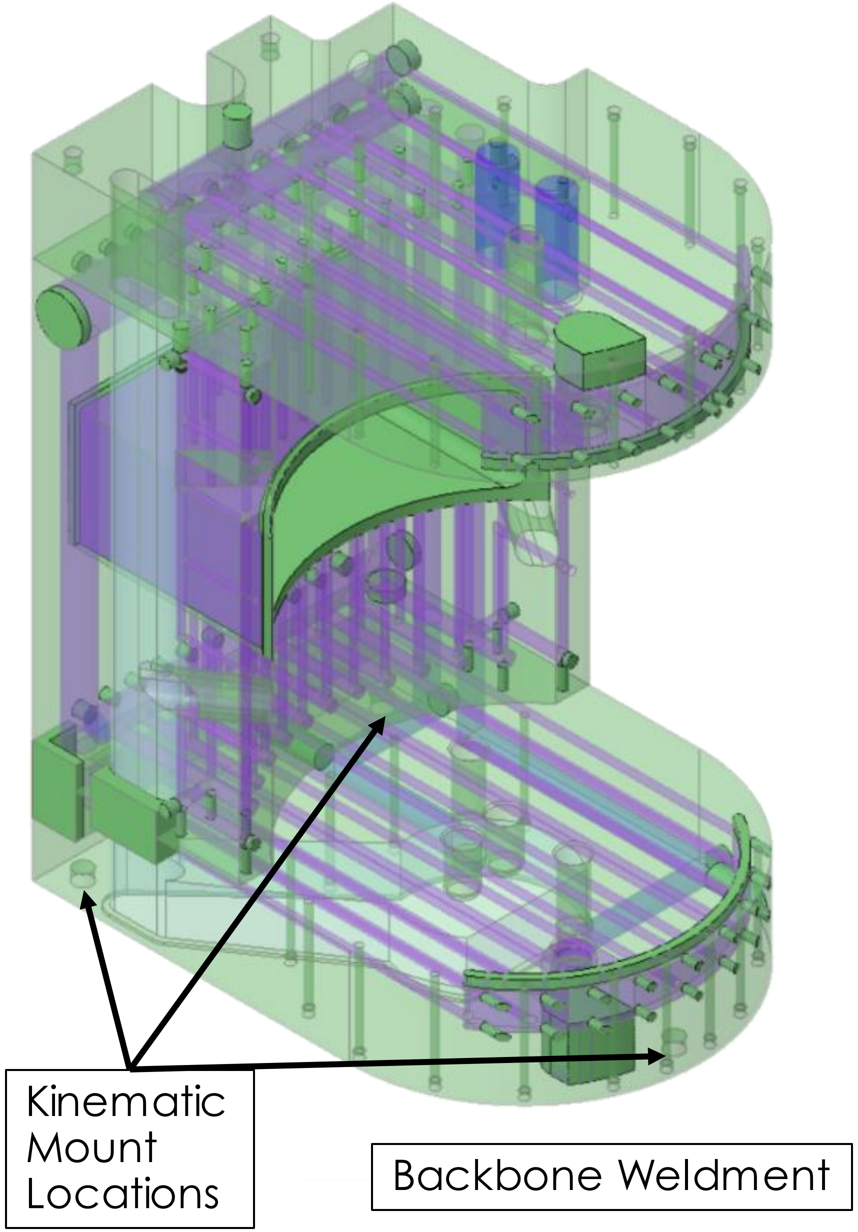
Middle Backbone

- 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 26 deep drilled holes
  - Cooling focused near proton beam port and reflector vessels
- All lower reflector utilities routed around Proton Beam Port
- All lower and middle backbone water returns combined



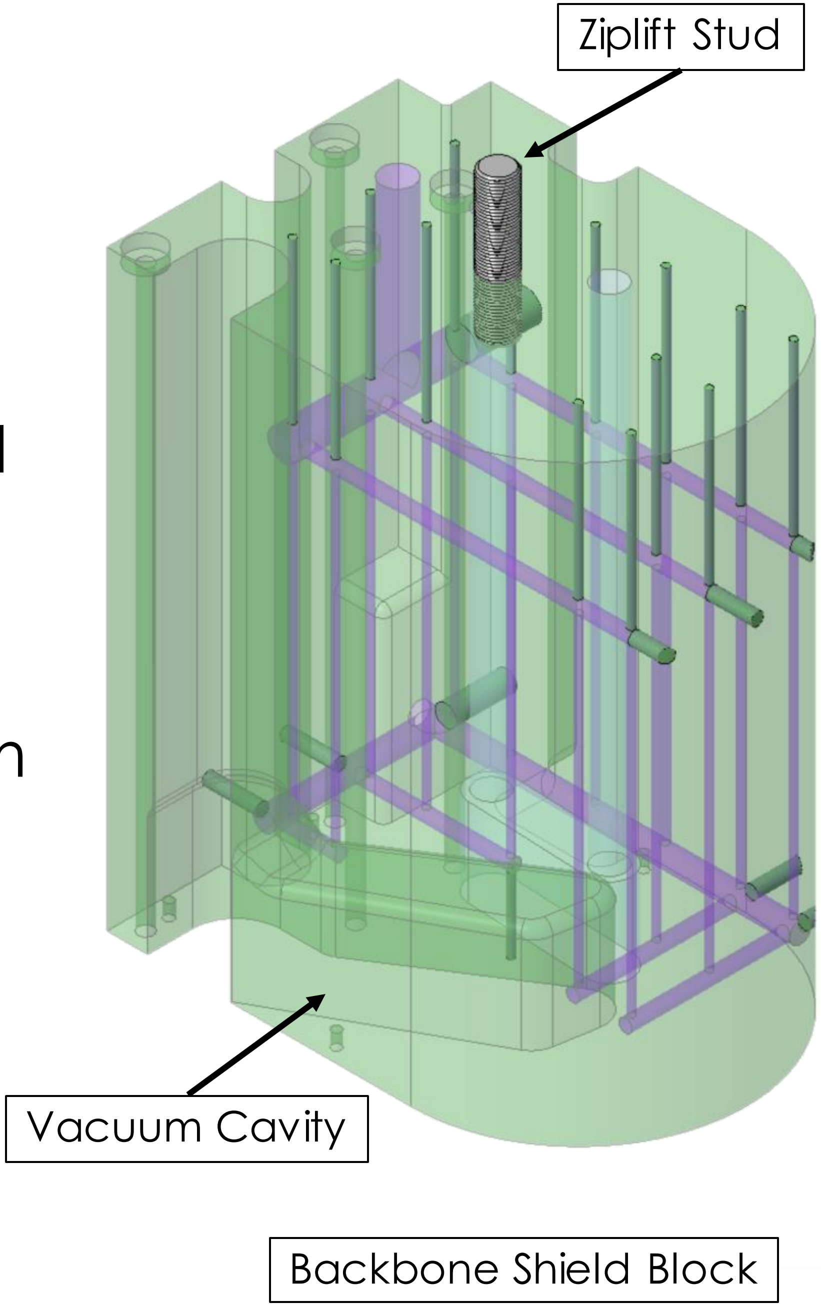
Backbone Weldment

- Lower, Middle, and Upper Backbone welded together to provide support for upper and lower reflector vessels
- Reflector vessels bolted to backbone at the outside of outer flat surfaces
- Kinematic mounts installed on lower backbone to allow for precise alignment of moderators



Backbone Shield Block

- Not involved in moderator alignment
- Extends 1 m above proton beam center
  - Height of required water cooled zone
- Water from upper backbone exit used to cool backbone shield block
- Cooling provided by 14 deep holes
- Cavity to provide clearance to upper vacuum cover
- Passages/chases for all MRA utilities
- Ziplift stud for remote handling interface
- Bolted to backbone weldment



Water Cooled Components Summary

Inlet	Flow (GPM)	Inlet T (C)	Total dP (psi)	Reflector dP (psi)	Backbone dP (psi)	Total Heat Load (W)	Reflector Heat Load (W)	Backbone Heat Load (W)	Total Water Heat Load (W)	Reflector Water Heat Load (W)	Backbone Water Heat Load (W)	Outlet	Flow (GPM)	Outlet T (C)	Notes - Scaling factor of 1.046 on all backbone loads to account that neutronic simulation was done with 95% SS, 5% h2o shielding
Upper Premoderator	7.5	35	5.70	2.53	3.17	11198	6648	4550	3001	2977	24	Upper	15	40.9	Also cools backbone upper shield block, upper block and jumper elbow while flowing through backbone loop 4
Upper Reflector	7.5	35	11.37	8.20	3.17	12681	8131	4550	415	391	24				Also cools backbone upper shield block, upper block and jumper elbow while flowing through backbone loop 4
Lower Premoderator	7.5	35	3.46	2.08	1.38	10770	7912	2858	4190	4159	31				Also cools backbone lower block while flowing through backbone loop 2 and loop 3 lower
Lower Reflector	7.5	35	9.22	7.70	1.52	10981	8128	2853	383	357	26	Lower	30	39.3	Also cools backbone lower block while flowing through backbone loop 1 and loop 3 lower
Backbone	15	35	1.64		1.64	12547		12547	135		135				Cools backbone middle block while flowing through loop 3 upper

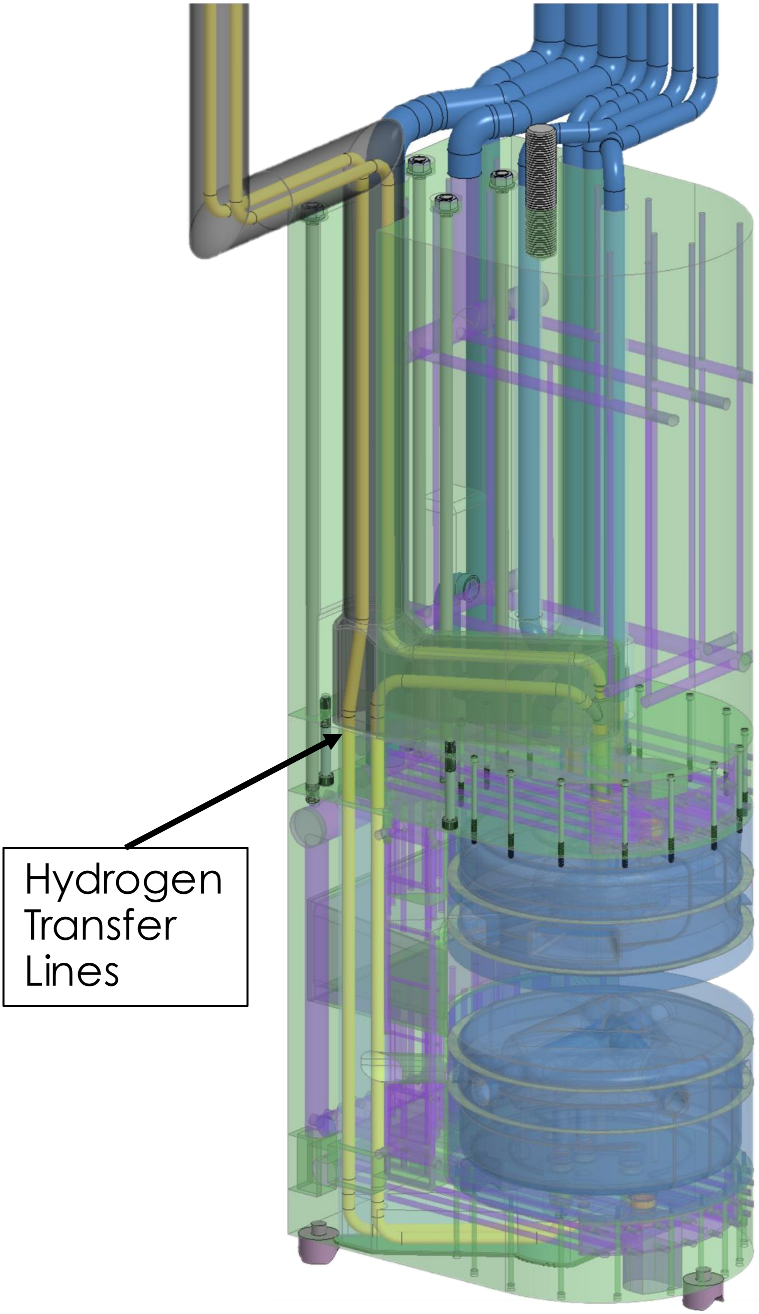
Heat Load Comparison

Component	CFD Heat Load (W)	Neutronics Heat Load (W)	Difference (%)
Upper Reflector Assembly	14779	14651	0.87
Lower Reflector Assembly	16040	15928	0.70
Backbone Assembly	27357	30098	9.10

- Combines results of Reflector and Backbone thermal hydraulic analyses
- Pressure drops and heat loads added to inform interface to process systems
- All water loops meet requirement of pressure drop less than 15 psi

Hydrogen Transfer Lines

- Hydrogen supplied to moderators in series from single transfer line based on changes to CMS
  - Upper moderator then lower moderator
- Invar used to minimize thermal contraction
- 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 Loop Summary

Component	Flow Rate (kg/s)	Tin(K)	Pin(bar)	L(m)	ID(m)	Bends	Heat Load(W)	Flow Speed (m/s)	Reynolds Number	dP/L (Pa/m)	dP/Bend (Pa)	Tout(K)	dP (Pa)	Pout(bar)	Mass (kg)
Inlet to Upper Moderator	0.037	18.34	14.08	4.06	0.014	4	5.00	3.26	192474	508.98	99.0	18.35	2464	14.06	0.041
Upper Moderator	0.037	18.35	14.06				411.12					19.66	2300	14.04	0.018
Upper Moderator to Lower Moderator	0.037	19.66	14.04	1.28	0.014	4	5.00	3.32	215119	517.77	100.7	19.67	1066	14.02	0.018
Lower Moderator	0.037	19.67	14.02				446.67					20.98	1060	14.01	0.024
Lower Moderator to CMS	0.037	20.98	14.01	4.78	0.014	4	5.00	3.38	239265	527.60	102.6	21.00	2932	13.98	0.055

- Moderator thermal hydraulic analysis boundary conditions will be updated during final design to reflect current CMS design
- Moderator heat loads in this table include neutronic heat loads for transfer lines – will be divided properly during final design
- Pressure drop of hydrogen tube sections calculated using Darcy-Weisbach Equation and equivalent length for 90° bends

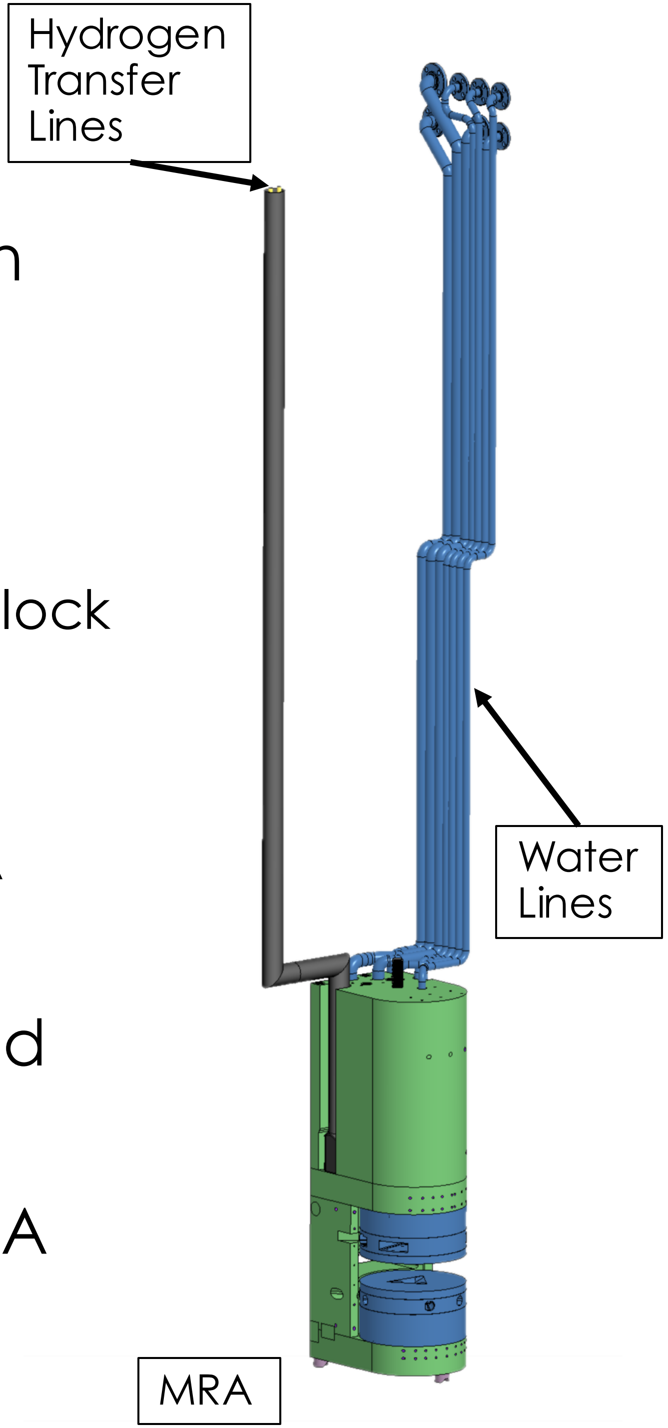
Heat Load Comparison

Component	CFD Heat Load (W)	Neutronics Heat Load (W)	Difference (%)
Cylinder Moderator	392.27	390.44	0.468
Tube Moderator	394.08	393.04	0.494

- Combines results of moderator thermal hydraulic analyses and updated CMS design
- MRA hydrogen pressure drop of 0.098 bar meets requirement of less than 0.1 bar

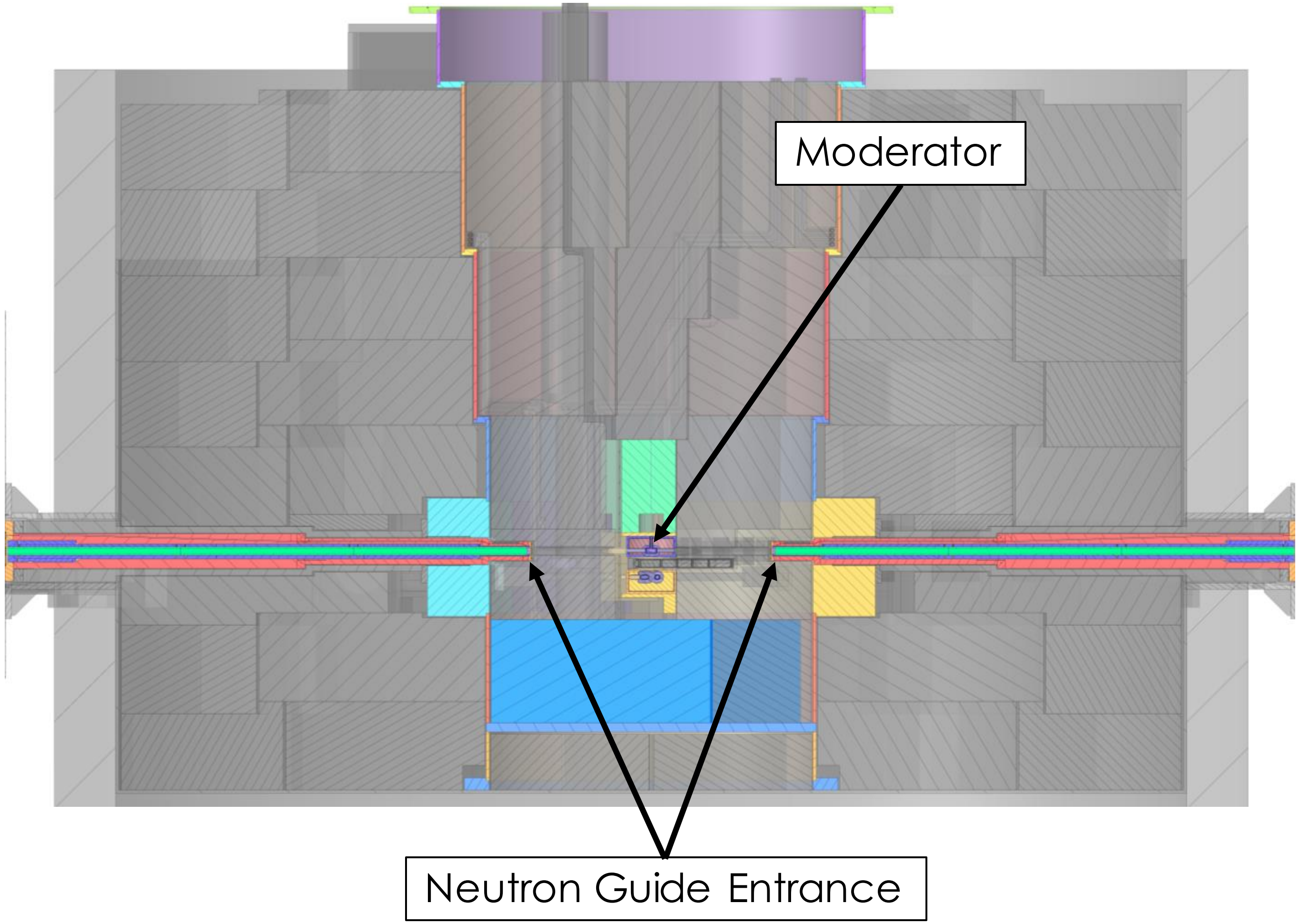
Pipe Routing above Shield Block

- Hydrogen transfer line has single jog to ease fabrication while reducing streaming
  - Dose rates do not meet requirements – will adjust routing
- Water piping has double jog to reduce streaming
  - Arrangement allows for hydraulic cutter access above shield block
  - Dose rates found to be too high for cutting operation with preliminary design – additional shielding will be required
- Core Vessel Shielding arranged to form chases for MRA piping
- Piping steps out to allow installation of Core Vessel shield blocks above the MRA
- Steps are small enough to allow installation through MRA port in the core vessel lid



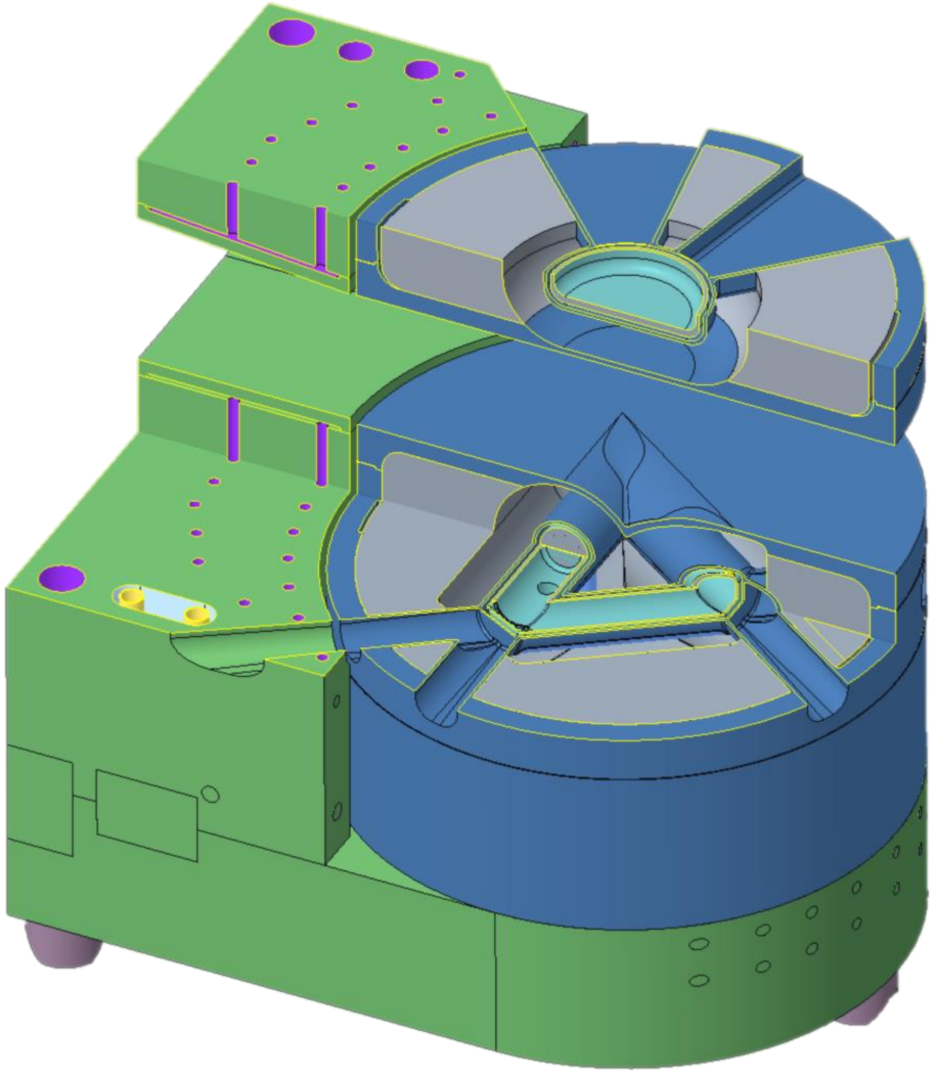
MRA to Neutron Guide Entrance Alignment

- Small moderators demand precise alignment between moderators and neutron guide entrances
- Need to define potential misalignment for each, in addition to the potential for deflections between there mounting interfaces
- Worst case alignments will be used to determine neutronic performance from worst case alignment

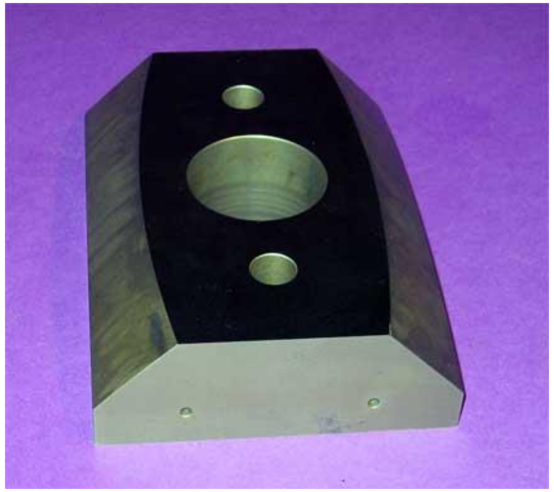


MRA Alignment

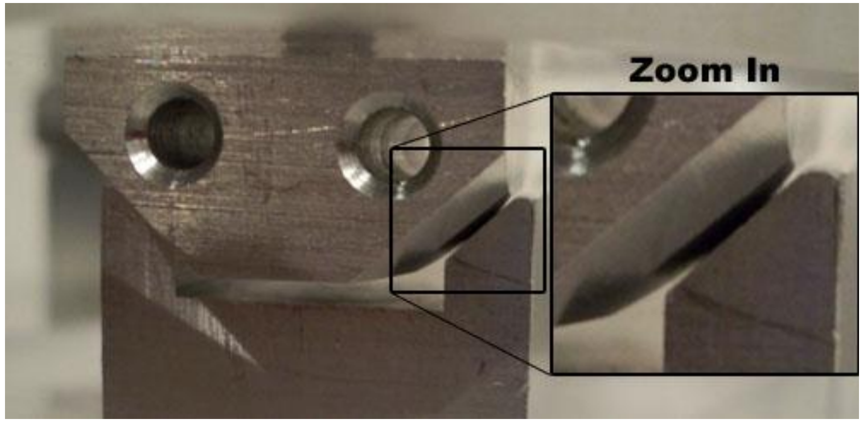
Component	Tolerance
Moderator Profile Tolerance	+/- 0.125 mm
Moderator Assembly Tolerance	+/- 0.5 mm
MRA Installation Repeatability	+/- 0.25 mm
S&A Inspection Accuracy	+/- 0.125 mm
Total	+/- 1 mm



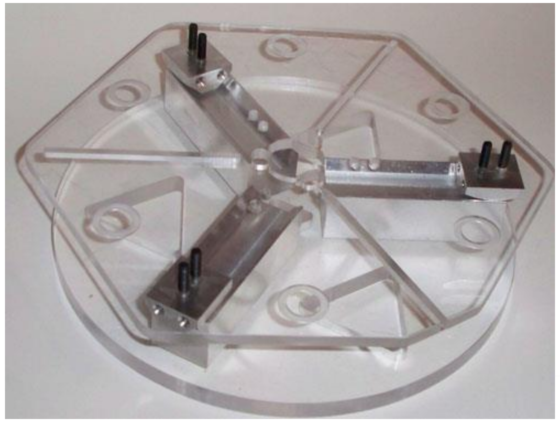
MRA Installation Repeatability



- Alignment scheme uses kinematic mount based on canoe spheres in vees for carrying heavy load
  - Based on vertical installation allowed by segmented target

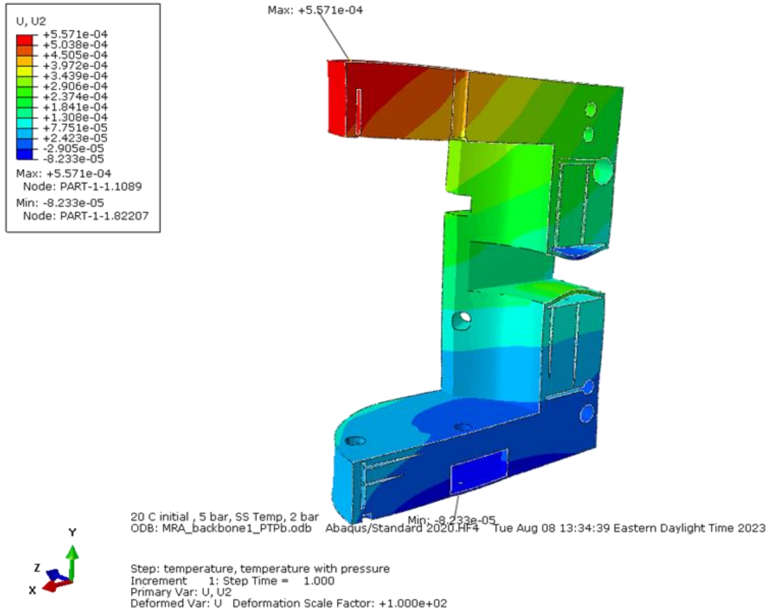


- Literature search suggests repeatability of +/- .125 mm for canoe spheres in vees
  - Extensively used at FRIB



Backbone and Shield Block Deflections

- Thermal distortion is largest contributor to guide landing to reflector differential movement
  - Pressure is only important for Shield Block 1
- Only vertical distortion is considered as other relative motions are less than 0.1 mm
- Differential movement for the upper reflector (0.46 mm) is slightly more than for the lower reflector (0.31 mm), but we will use 0.5 mm for both



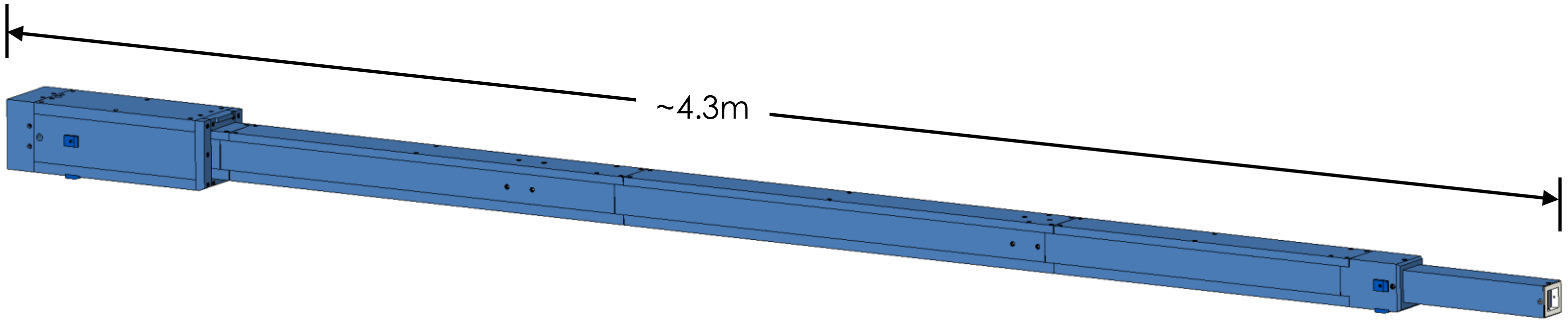
```
20 C initial , 5 bar, SS Temp, 2 bar
ODB: MRA_backbone1_PTPb.odb    Abaqus/Standard 2020.HF4    Tue Aug 08 13:34:39 Eastern Daylight Time 2023

Step: temperature, temperature with pressure
Increment      1: Step Time =    1.000
Primary Var: U, U2
Deformed Var: U   Deformation Scale Factor: +1.000e+02
```

Deflections	Upper	Lower	Notes
CV Guide Insert Landings	0.171	0.171	Thermal only - other deflections less than 1e-3 mm
Guide Entrance Total	0.171	0.171	
CV Shield Block Landing	0.107	0.107	Thermal only - other deflections less than 1e-3 mm
CV Shield Block 1	0.252	0.252	At MRA Mount Points
MRA Mount Total	0.359	0.359	
Backbone	0.395	0.009	Deflection of Reflector Mounting Interface
Reflector	-0.122	0.116	Defelection from Mounting to Moderator
MRA Total	0.273	0.125	
Moderator Relative to Guide	0.460	0.312	

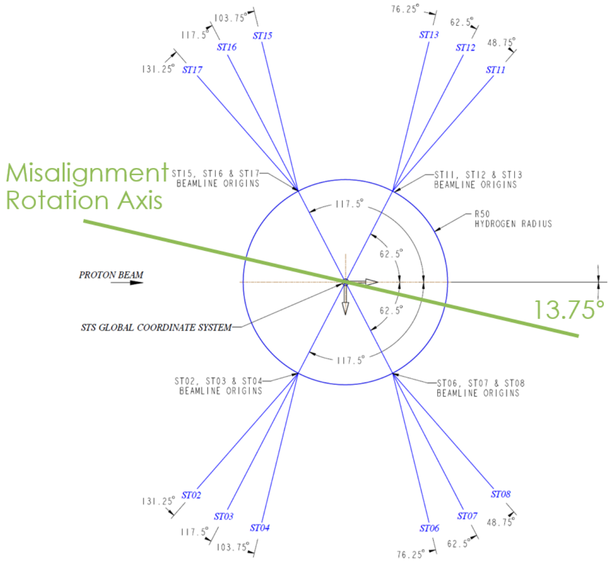
Guide Entrance Alignment

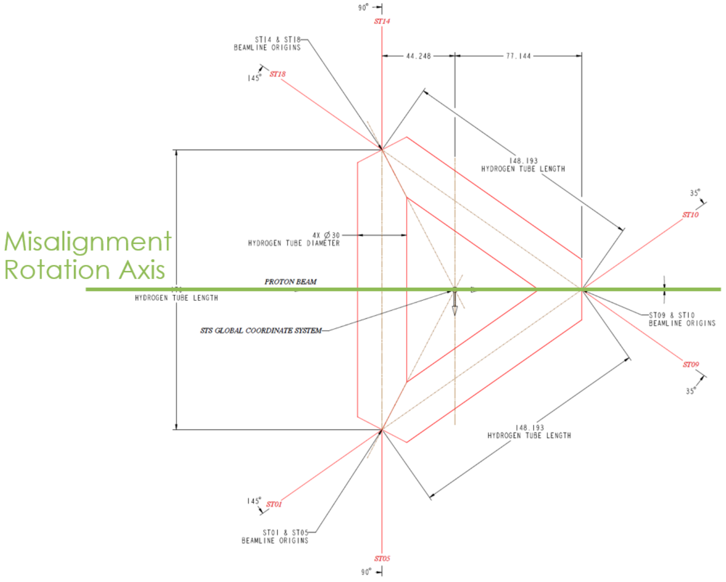
- Instrument systems claims a worst case guide entrance alignment of +/- 1 mm from nominal location
- Due to length of optic, rotation resulting from misalignment is assumed to be 0.
- We will assume a vertical misalignment of 1 mm to create a worst case misalignment with the other relative movements



MRA Alignment for Neutronics Analysis

- Cylinder reflector vessel rotated by 1.2° to give worst case alignment to ST13
- Tube reflector vessel rotated by 0.75° to give worst case alignment to ST05
- Backbone/Shield Block Deflections and Guide Entrance Tolerance are assumed to be in the same direction
  - Results in 1.5mm relative vertical offset
- Reflector vessels and moderators translated 1.5 mm vertically away from target, in addition to previously described rotations





Summary

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