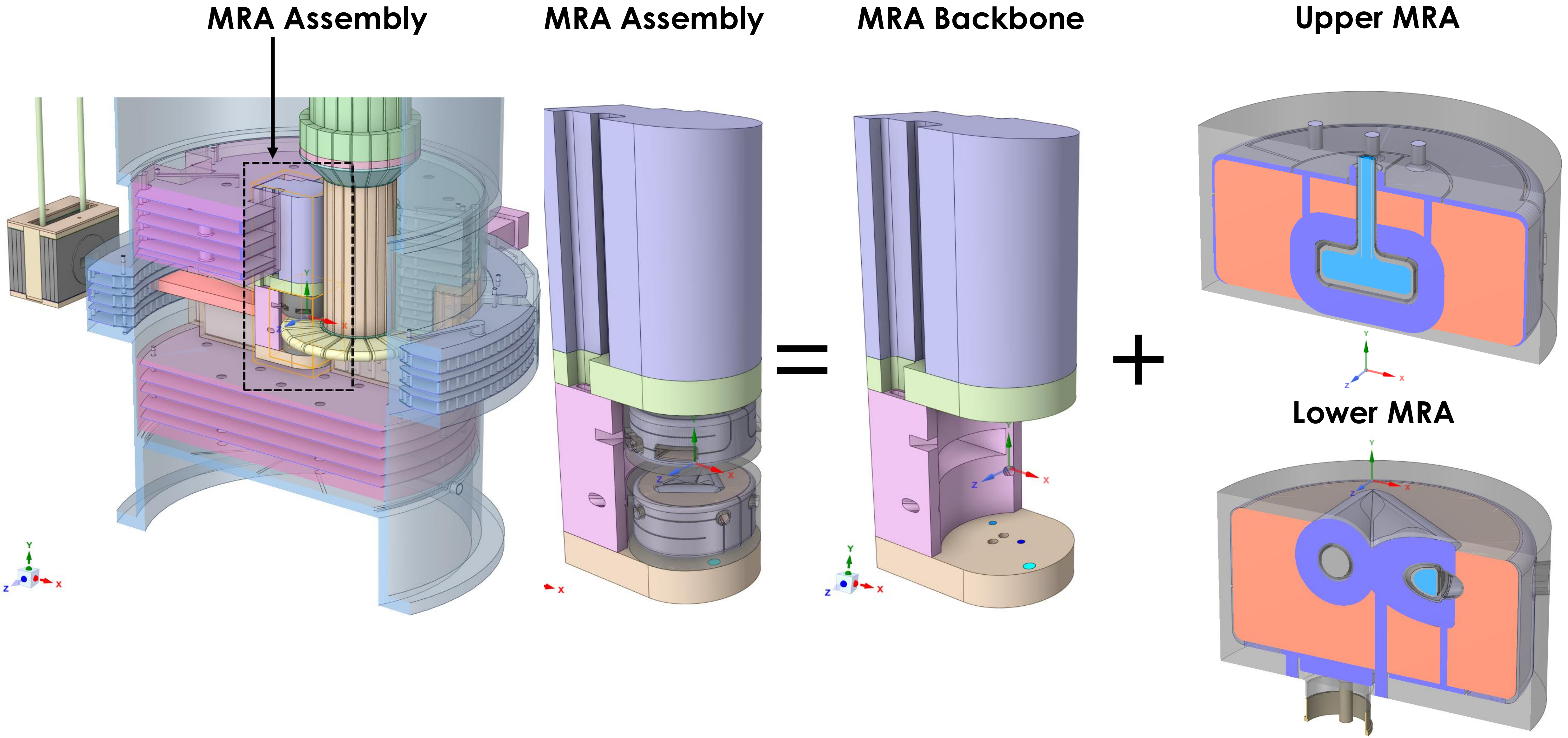
Preliminary STS MRA Thermal Hydraulic Analysis

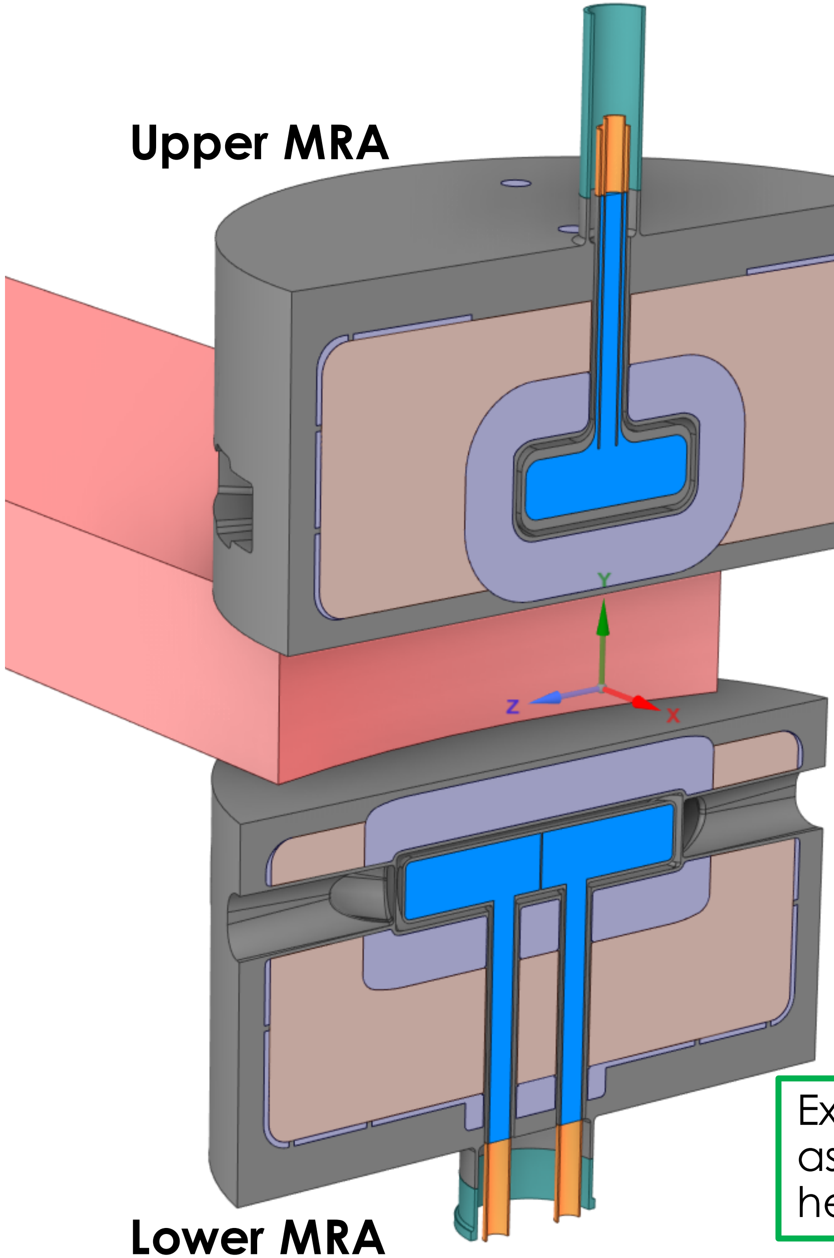
Min-Tsung Kao
Jim Janney
Ken Gawne
Bill Goosie
Lukas Zavorka

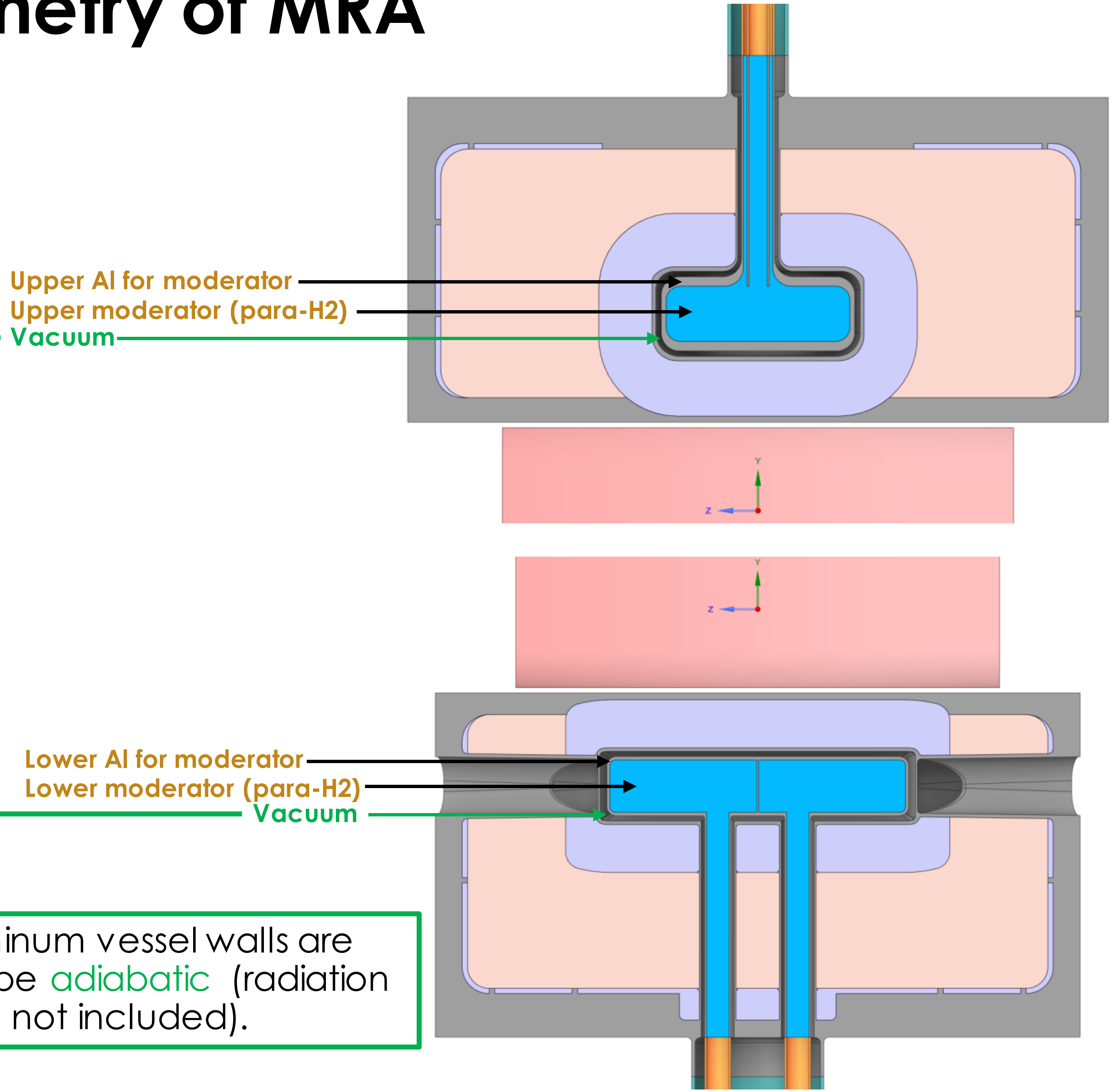
03/26/2024

Geometry



Geometry of MRA

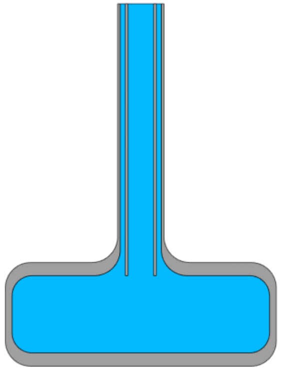


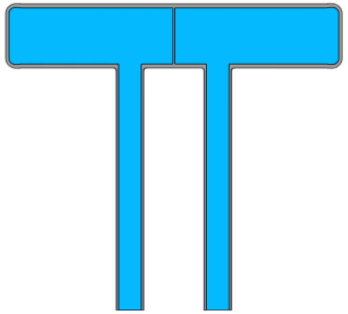


Exterior aluminum vessel walls are assumed to be adiabatic (radiation heat transfer not included).

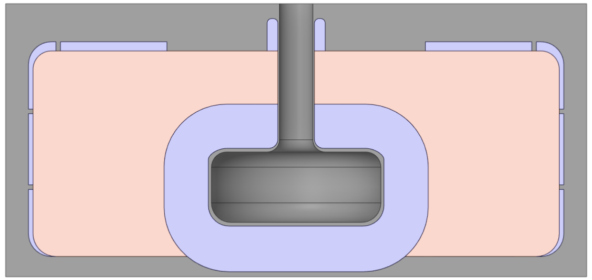
Outline

- CFD analysis for the upper (cylinder) and lower (tube) moderators

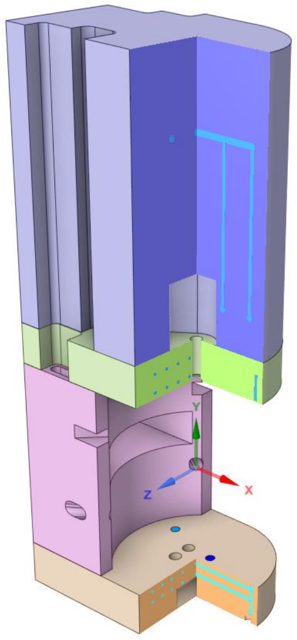




- CFD analysis for the upper reflector (similar to lower reflector)



- CFD analysis for the MRA backbone

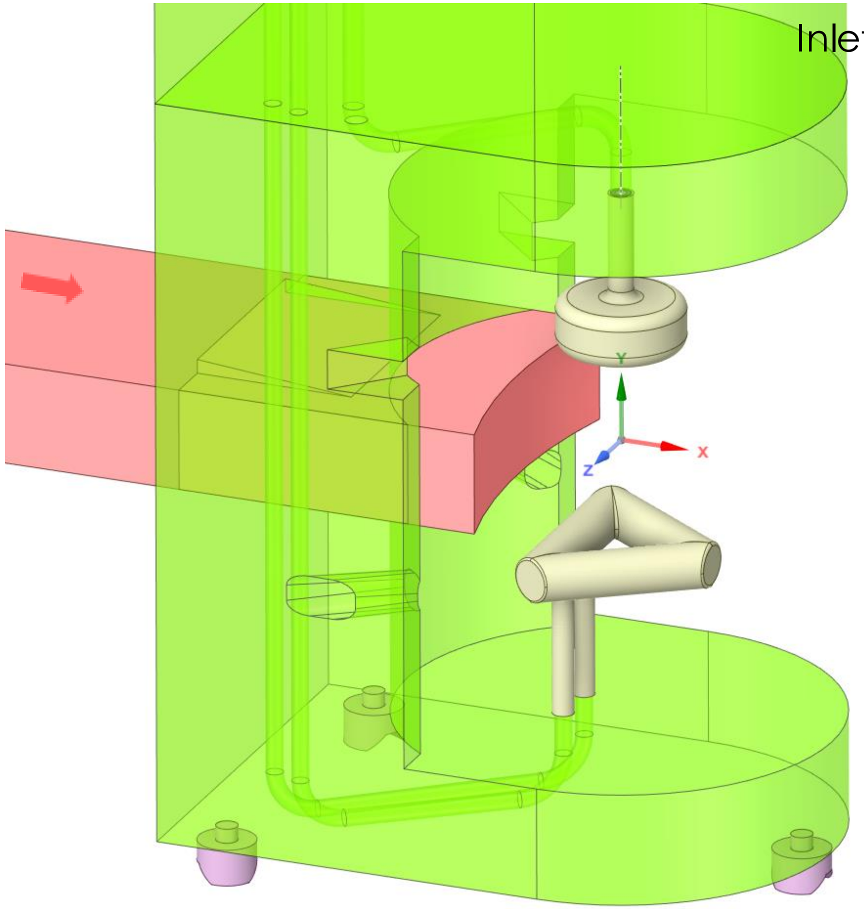


Part 1 : CFD analysis for Cylinder (upper) and Tube (Lower) Moderators

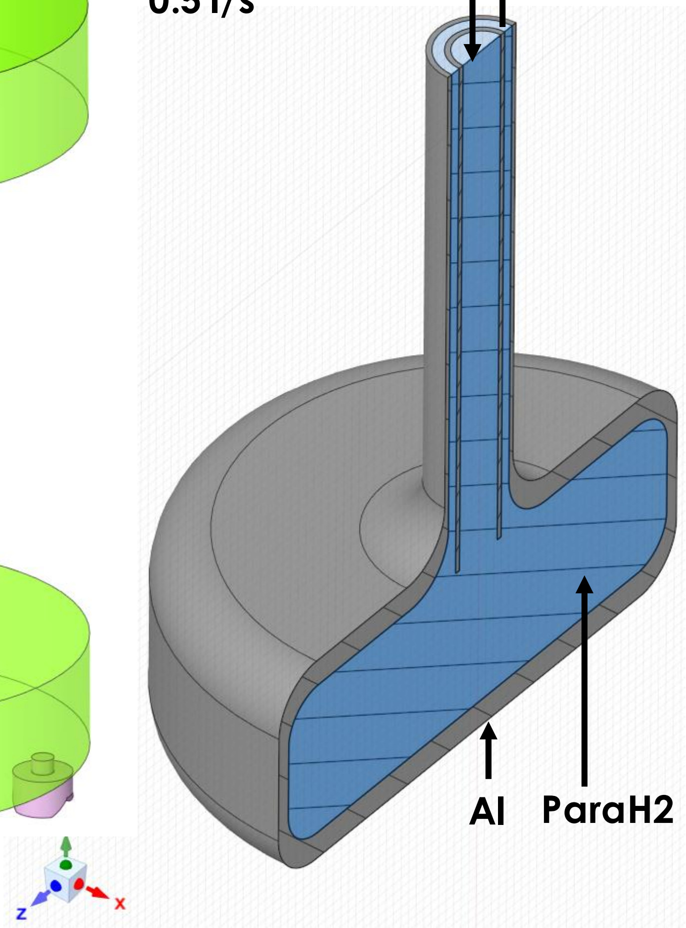
Requirements for the Moderators

- This thermal-hydraulic analyses were performed to demonstrate that the current cylinder and tube moderator designs can meet the following requirements.
- **Requirements**
  - Pressure drop < 0.05 bar
    - Low pressure drop allows flexibility for CMS design
  - Maximum hydrogen temperature < 32K
    - Hydrogen density starts to change quickly over 32K
  - Average hydrogen density > 72.9 kg/m^3
    - This density was assumed by neutronic calculations, but neutronics team thinks small deviations from this value will not cause significant loss of performance
  - Residence time > 0.2s, No regions of much longer residence time
    - Residence time >0.2s indicates the hydrogen will be in the moderator for greater than 3 beam pulses at 15 Hz which helps validate the steady state assumption

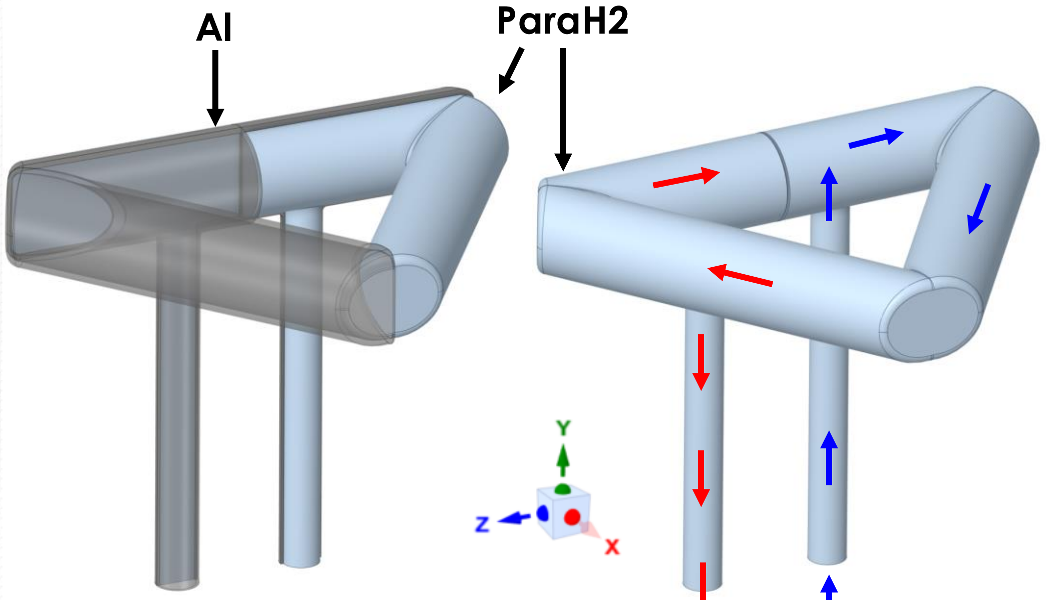
Cylinder and Tube Moderators



Cylinder Moderator

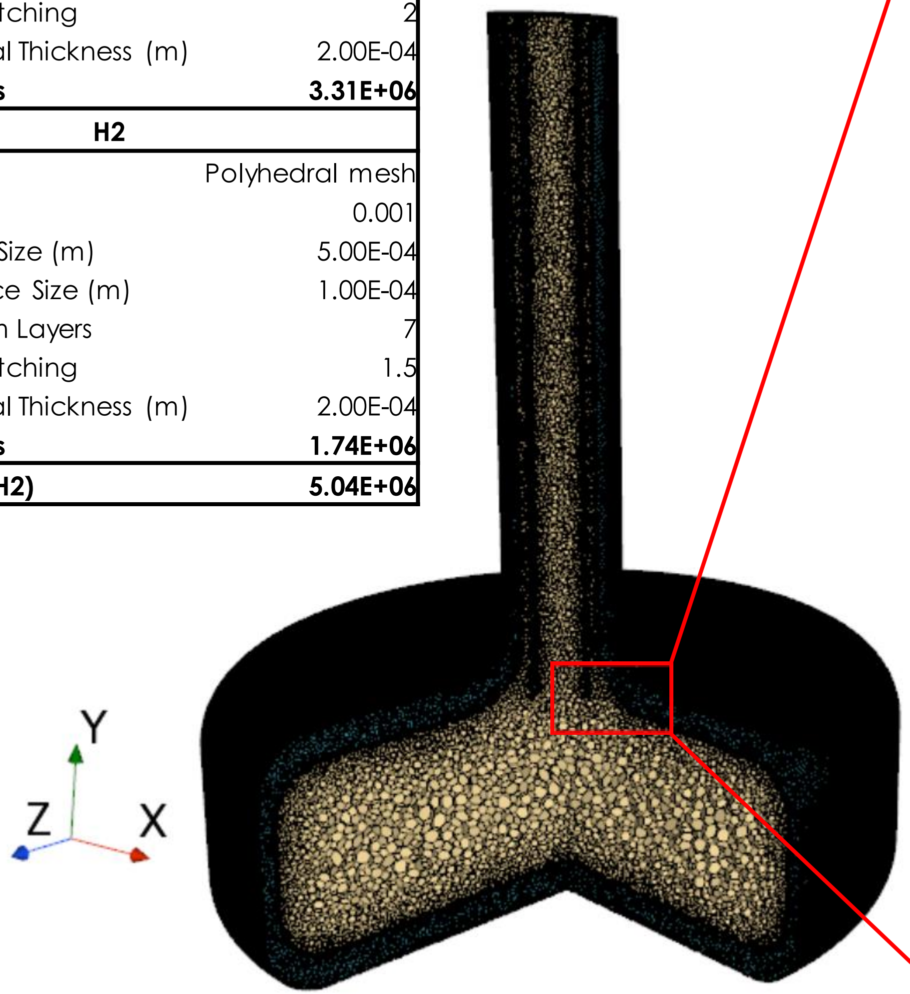


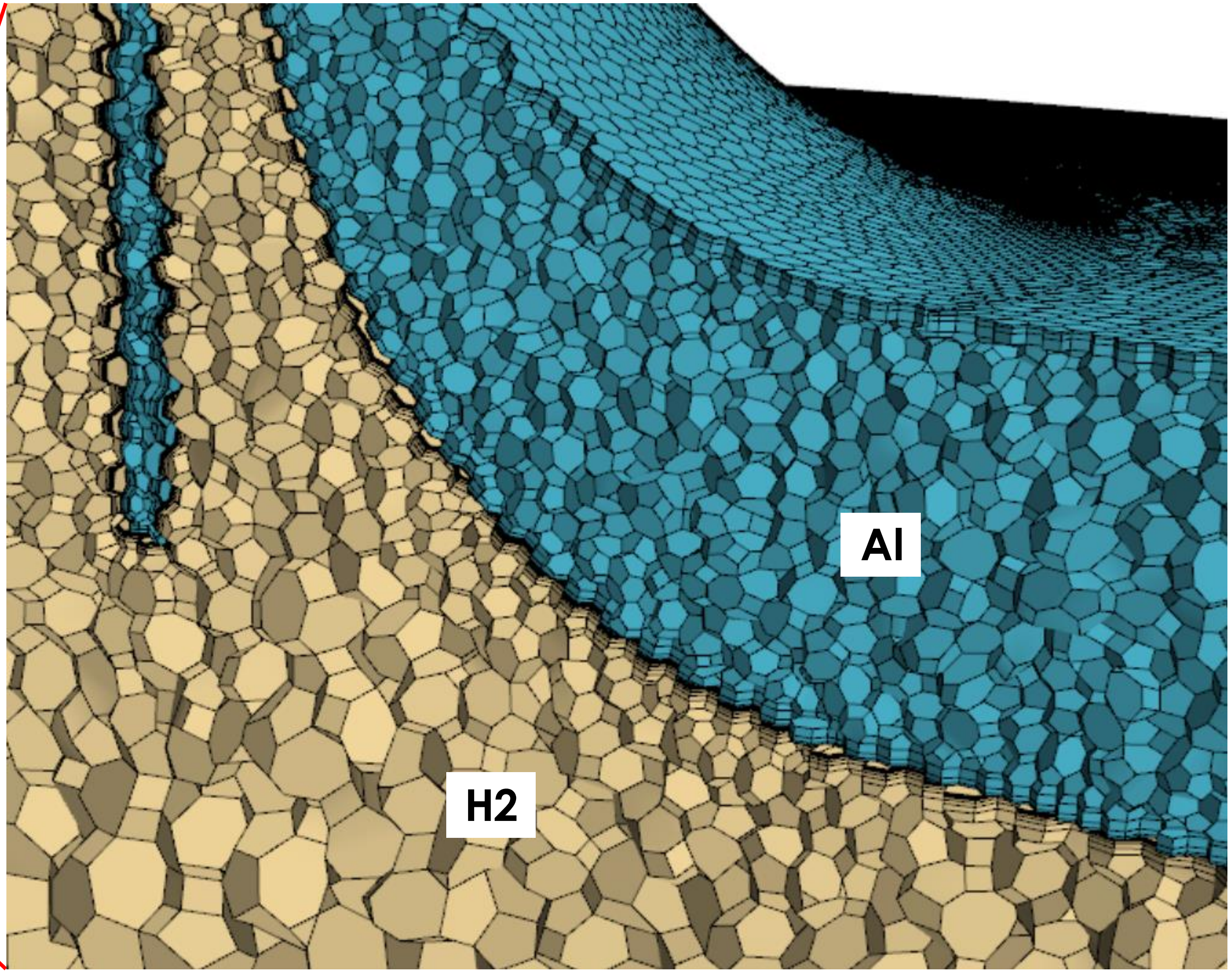
Tube Moderator



Steady State Heat Transfer Analysis for Cylinder Moderator, Mesh Configuration

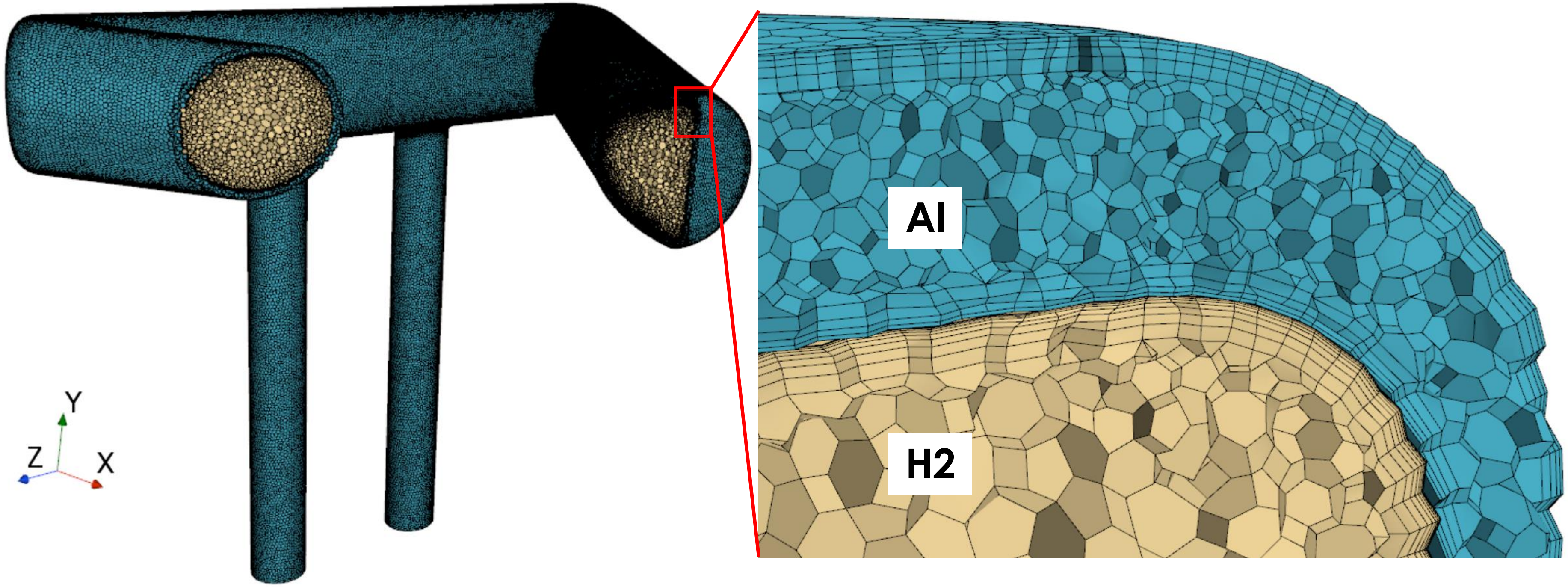
Cylinder Moderator	
Al	
Mesh Type	Polyhedral mesh
Base Size (m)	0.001
Target Surface Size (m)	3.60E-04
Minimum Surface Size (m)	1.00E-04
Number of Prism Layers	3
Prism Layer Stretching	2
Prism Layer Total Thickness (m)	2.00E-04
Number of Cells	**3.31E+06**
H2	
Mesh Type	Polyhedral mesh
Base Size (m)	0.001
Target Surface Size (m)	5.00E-04
Minimum Surface Size (m)	1.00E-04
Number of Prism Layers	7
Prism Layer Stretching	1.5
Prism Layer Total Thickness (m)	2.00E-04
Number of Cells	**1.74E+06**
Total Cells (Al+H2)	**5.04E+06**





Steady State Heat Transfer Analysis for Tube Moderator, Mesh Configuration

Tube Moderator	
Al	
Mesh Type	Polyhedral mesh
Base Size (m)	0.0025
Target Surface Size (m)	9.00E-04
Minimum Surface Size (m)	2.50E-04
Number of Prism Layers	4
Prism Layer Stretching	1.5
Prism Layer Total Thickness (m)	2.50E-04
Number of Cells	**9.87E+05**
H2	
Mesh Type	Polyhedral mesh
Base Size (m)	0.0025
Target Surface Size (m)	9.00E-04
Minimum Surface Size (m)	2.50E-04
Number of Prism Layers	8
Prism Layer Stretching	1.5
Prism Layer Total Thickness (m)	3.50E-04
Number of Cells	**9.12E+05**
Total Cells (Al+H2)	**1.90E+06**



Thermal Properties

Material	Thermal Conductivity, k (W/m-K)	Density, ρ (kg/m^3)	Specific Heat, Cp (J/kg-K)
Al (T = 20K)	28.43	2800	8.85
Para-H2	Table(T)	Polynomial in T	Table(T)

Thermal properties of Para-H2 can be found on https://webbook.nist.gov/chemistry/fluid/

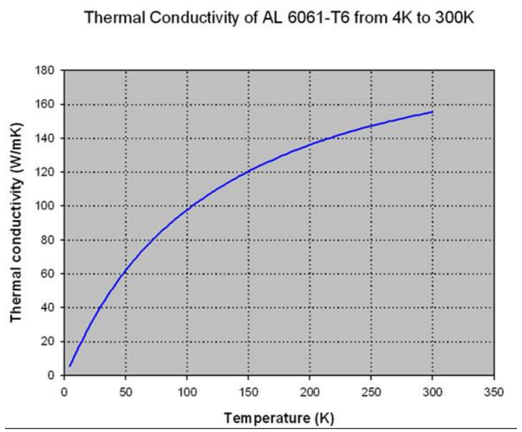
Thermal properties of Al6061-T6 can be found on https://trc.nist.gov/cryogenics/materials/6061%20Aluminum/6061_T6Aluminum_rev.htm

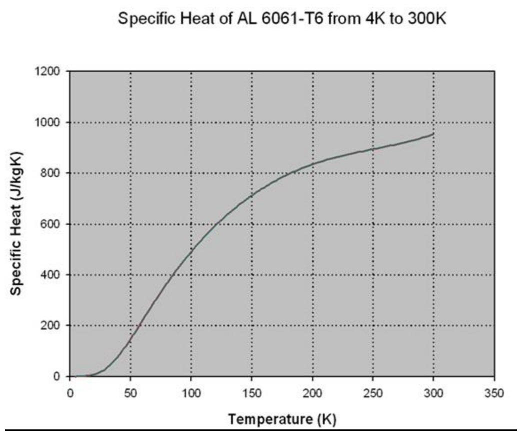
$$\rho_{H_2}(T) = a + bT + cT^2 + dT^3$$

$$k_{Al}(T) = 10^{a+b(log_{10} T)} + c(log_{10} T)^2 + d(log_{10} T)^3 + e(log_{10} T)^4 + f(log_{10} T)^5 + g(log_{10} T)^6 + h(log_{10} T)^7 + i(log_{10} T)^8$$

$$Cp_{Al}(T) = 10^{a+b(log_{10} T)} + c(log_{10} T)^2 + d(log_{10} T)^3 + e(log_{10} T)^4 + f(log_{10} T)^5 + g(log_{10} T)^6 + h(log_{10} T)^7 + i(log_{10} T)^8$$

Coefficient	ρ_{H_2} (kg/m3)	k_{Al} (W/m-K)	Cp_{Al} (J/kg-K)
a	138.907	0.07918	46.6467
b	-8.23187	1.0957	-314.292
c	0.370104	-0.07277	866.662
d	-0.00621765	0.08084	-1298.3
e		0.02803	1162.27
f		-0.09464	-637.795
g		0.04179	210.351
h		-0.00571	-38.3094
i		0	2.96344





Thermal properties of Al6061-T6 can be found on https://trc.nist.gov/cryogenics/materials/6061%20 Aluminum/6061_T6Aluminum_rev.htm

Thermal Properties of Para-H2 @1.45 MPa (14.5 bar)

https://webbook.nist.gov/cgi/fluid.cgi?Action=Load&ID=B5000001&Type=IsoBar&Digits=5&P=1.45&THigh=40&TLow=15&TInc=1&RefState=DEF&TUnit=K&PUnit=MPa&DUnit=kg%2Fm3&HUnit=kJ%2Fkg&WUnit=m%2Fs&VisUnit=Pa*s&STUnit=N%2Fm

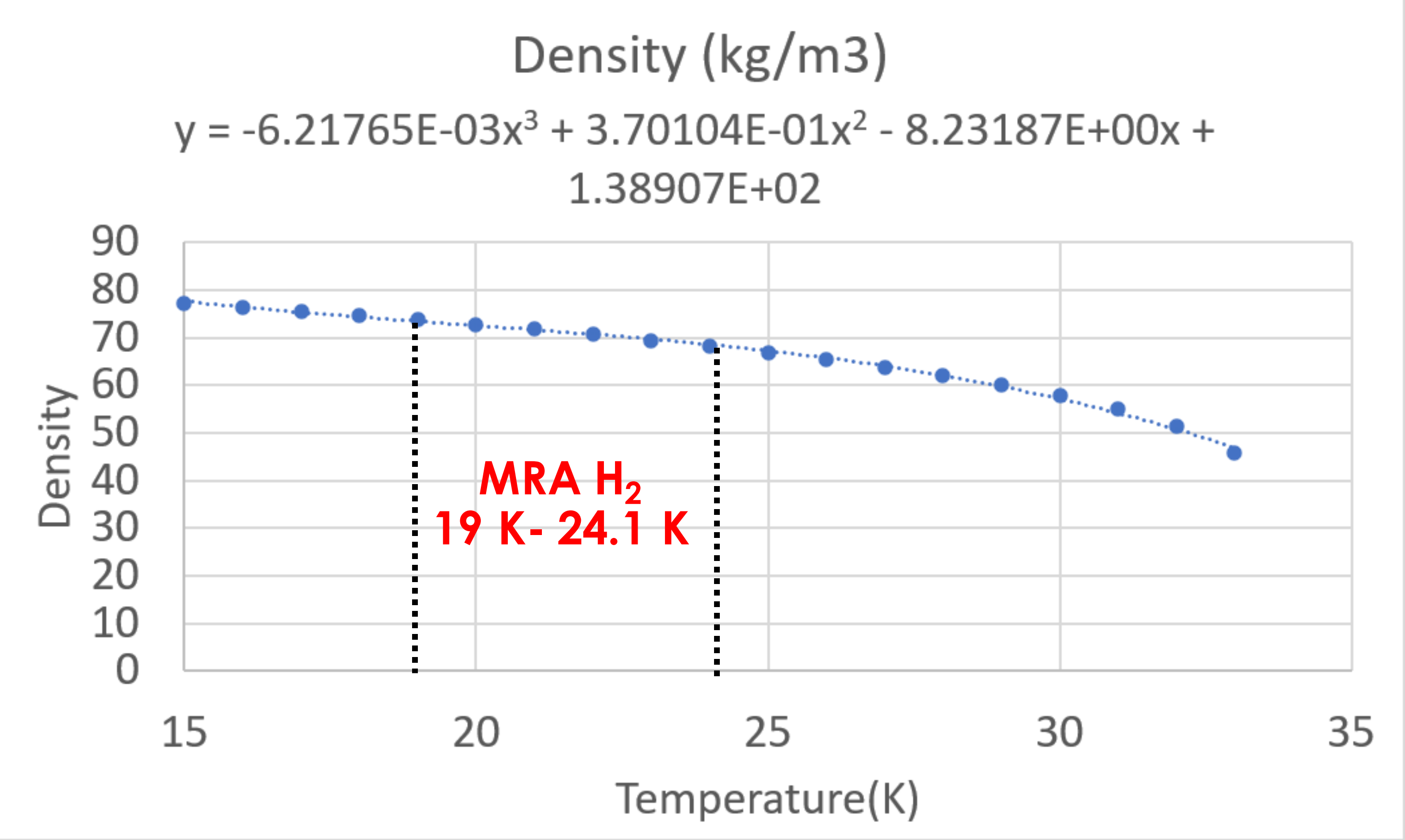
NIST **Density** **Specific Heat** **Thermal Conductivity**

Temperature (K)	Pressure (MPa)	Density (kg/m3)	Volume (m3/kg)	Internal Energy (kJ/kg)	Enthalpy (kJ/kg)	Entropy (J/g*K)	Cv (J/g*K)	Cp (J/g*K)	Sound Spd. (m/s)	Joule-Thomson (K/MPa)	Viscosity (Pa*s)	Therm. Cond. (W/m*K)	Phase
15.000	1.4500	77.241	0.012946	-48.154	-29.382	-2.6918	5.2775	7.0899	1277.6	-1.5529	2.4601e-05	0.092173	liquid
16.000	1.4500	76.451	0.013080	-41.113	-22.146	-2.2249	5.3273	7.3893	1261.2	-1.4699	2.2056e-05	0.095267	liquid
17.000	1.4500	75.618	0.013224	-33.762	-14.587	-1.7667	5.3864	7.7374	1244.7	-1.3801	1.9938e-05	0.097931	liquid
18.000	1.4500	74.738	0.013380	-26.058	-6.6569	-1.3136	5.4585	8.1293	1226.8	-1.2869	1.8140e-05	0.10016	liquid
19.000	1.4500	73.806	0.013549	-17.961	1.6851	-0.86267	5.5415	8.5610	1206.8	-1.1922	1.6595e-05	0.10197	liquid
20.000	1.4500	72.820	0.013733	-9.4346	10.478	-0.41178	5.6311	9.0301	1184.5	-1.0969	1.5250e-05	0.10334	liquid
21.000	1.4500	71.775	0.013932	-0.44422	19.758	0.040913	5.7227	9.5370	1160.1	-1.0008	1.4069e-05	0.10430	liquid
22.000	1.4500	70.665	0.014151	9.0459	29.565	0.49705	5.8123	10.085	1133.5	-0.90325	1.3020e-05	0.10484	liquid
23.000	1.4500	69.483	0.014392	19.076	39.944	0.95832	5.8974	10.682	1104.9	-0.80288	1.2081e-05	0.10498	liquid
24.000	1.4500	68.220	0.014659	29.695	50.950	1.4266	5.9763	11.340	1073.9	-0.69779	1.1232e-05	0.10471	liquid
25.000	1.4500	66.862	0.014956	40.964	62.651	1.9042	6.0484	12.078	1040.6	-0.58545	1.0454e-05	0.10405	liquid
26.000	1.4500	65.393	0.015292	52.968	75.141	2.3939	6.1136	12.925	1004.5	-0.46250	9.7355e-06	0.10301	liquid
27.000	1.4500	63.789	0.015677	65.820	88.551	2.8999	6.1729	13.926	965.25	-0.32430	9.0613e-06	0.10164	liquid
28.000	1.4500	62.015	0.016125	79.687	103.07	3.4277	6.2284	15.155	921.99	-0.16406	8.4190e-06	0.099862	liquid
29.000	1.4500	60.021	0.016661	94.820	118.98	3.9859	6.2833	16.742	873.63	0.028890	7.7952e-06	0.097672	liquid
30.000	1.4500	57.719	0.017325	111.63	136.76	4.5883	6.3446	18.948	818.36	0.27297	7.1732e-06	0.095018	liquid
31.000	1.4500	54.952	0.018198	130.89	157.27	5.2609	6.4264	22.384	752.91	0.60440	6.5284e-06	0.091797	liquid
32.000	1.4500	51.357	0.019472	154.29	182.52	6.0618	6.5662	28.974	670.52	1.1108	5.8131e-06	0.087785	liquid
33.000	1.4500	45.670	0.021896	187.70	219.45	7.1966	6.9155	50.428	552.16	2.1104	4.8772e-06	0.082744	upercritical
34.000	1.4500	26.227	0.038129	290.76	346.04	10.961	8.2878	154.04	393.52	5.7891	2.7995e-06	0.072017	upercritical
35.000	1.4500	18.615	0.053721	344.62	422.52	13.185	7.5856	45.216	417.49	6.7857	2.3764e-06	0.050051	upercritical
36.000	1.4500	16.043	0.062333	368.49	458.87	14.210	7.1967	30.303	436.27	6.7671	2.3032e-06	0.045324	upercritical
37.000	1.4500	14.475	0.069086	385.70	485.87	14.950	6.9661	24.392	451.59	6.5915	2.2854e-06	0.043362	upercritical
38.000	1.4500	13.346	0.074928	399.88	508.52	15.554	6.8168	21.189	464.92	6.3739	2.2889e-06	0.042386	upercritical
39.000	1.4500	12.466	0.080217	412.32	528.64	16.077	6.7152	19.171	476.92	6.1480	2.3033e-06	0.041886	upercritical
40.000	1.4500	11.747	0.085129	423.64	547.07	16.544	6.6434	17.781	487.97	5.9262	2.3239e-06	0.041658	upercritical

Thermal Properties of Para-H_2 @1.45 MPa (14.5 bar)

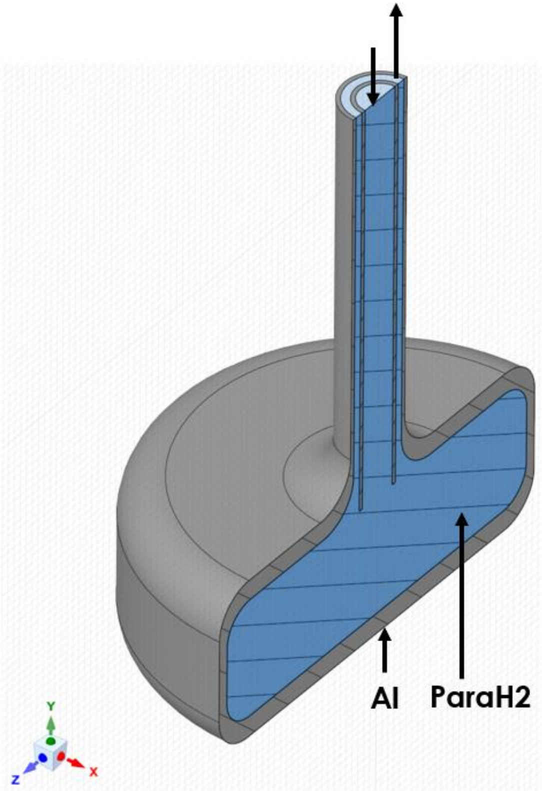
https://webbook.nist.gov/cgi/fluid.cgi?Action=Load&ID=B5000001&Type=IsoBar&Digits=5&P=1.45&THigh=40&TLow=15&TInc=1&RefState=DEF&TUnit=K&PUnit=MPa&DUnit=kg%2Fm3&HUnit=kJ%2Fkg&WUnit=m%2Fs&VisUnit=Pa*s&STUnit=N%2Fm

	A	B	C	D	F	I
1		original data	Polynomial		1.38907E+02	138.907
2	Temperature (K)	Density (kg/m3)		error(%)	-8.23187E+00	-8.23187
3	15	77.241	77.72	-0.48	3.70104E-01	0.370104
4	16	76.451	76.48	-0.03	-6.21765E-03	-0.00621765
5	17	75.618	75.38	0.24		
6	18	74.738	74.39	0.35		
7	19	73.806	73.46	0.34		
8	20	72.82	72.57	0.25		
9	21	71.775	71.67	0.10		
10	22	70.665	70.73	-0.07		
11	23	69.483	69.71	-0.23		
12	24	68.22	68.57	-0.35		
13	25	66.862	67.27	-0.41		
14	26	65.393	65.79	-0.39		
15	27	63.789	64.07	-0.28		
16	28	62.015	62.09	-0.07		
17	29	60.021	59.80	0.22		
18	30	57.719	57.17	0.55		
19	31	54.952	54.16	0.79		
20	32	51.357	50.73	0.62		
21	33	45.67	46.85	-1.18		
22						
23		Cylinder	Tube			
24	m_dot(l/s)	0.5	0.5			
25	m_dot(m^3/s)	0.0005	0.0005			
26	m_dot(kg/s)	0.0369	0.0369			
27						



Inlet mass flow rate

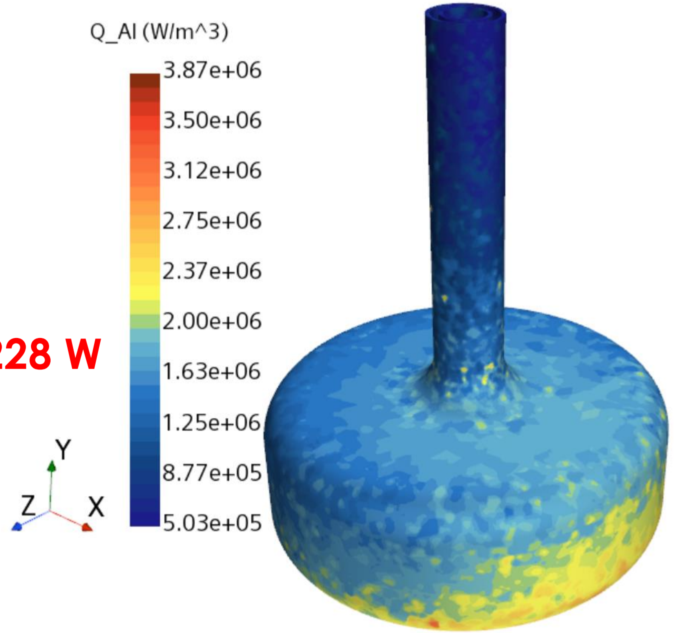
Results of Upper (Cylinder) H_2 Moderator

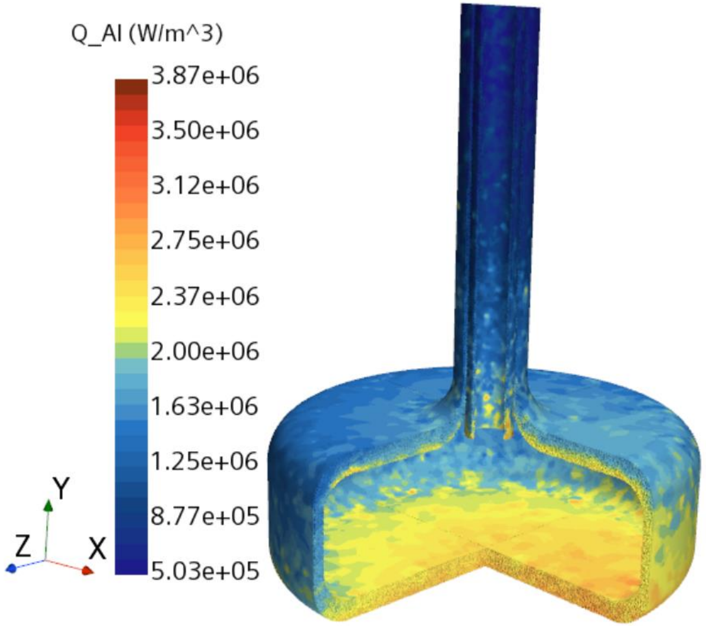


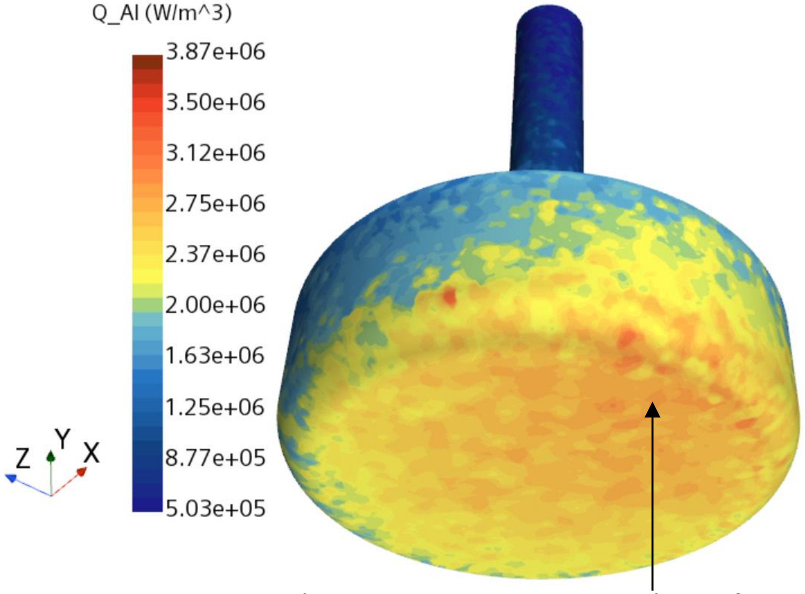
Steady State Heat Transfer Analysis for Cylinder Moderator, Heat Source

Q of Al

Q_Al = 228 W



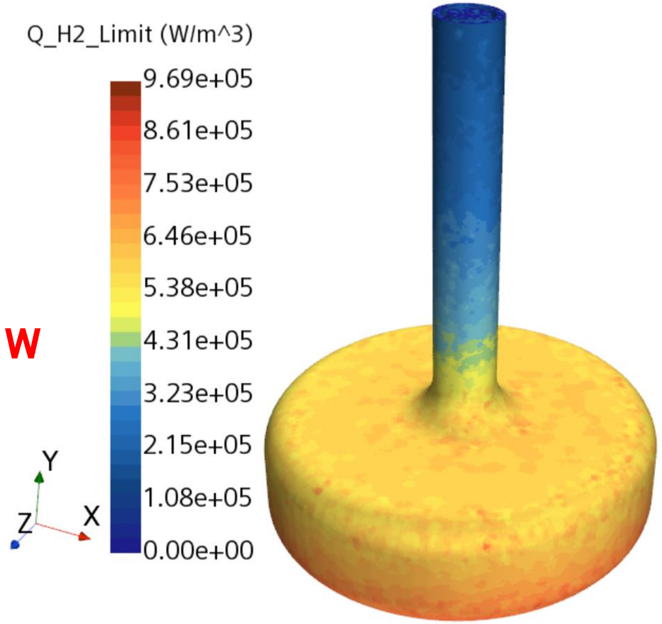


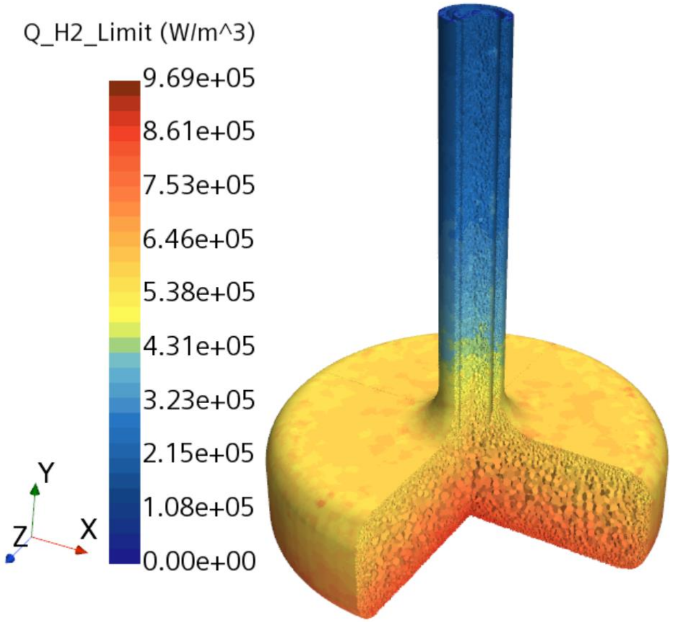


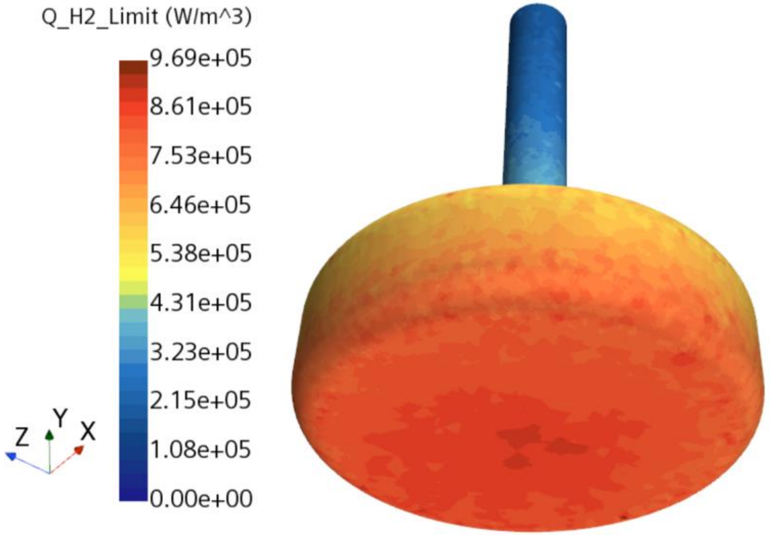
Heating peaks on the rear side of Al (+x, downstream of proton beam).
From **slow** and **thermal neutrons** generated in the **rear** portion of **W target**.

Q of H_2

Q_H_2 = 162 W





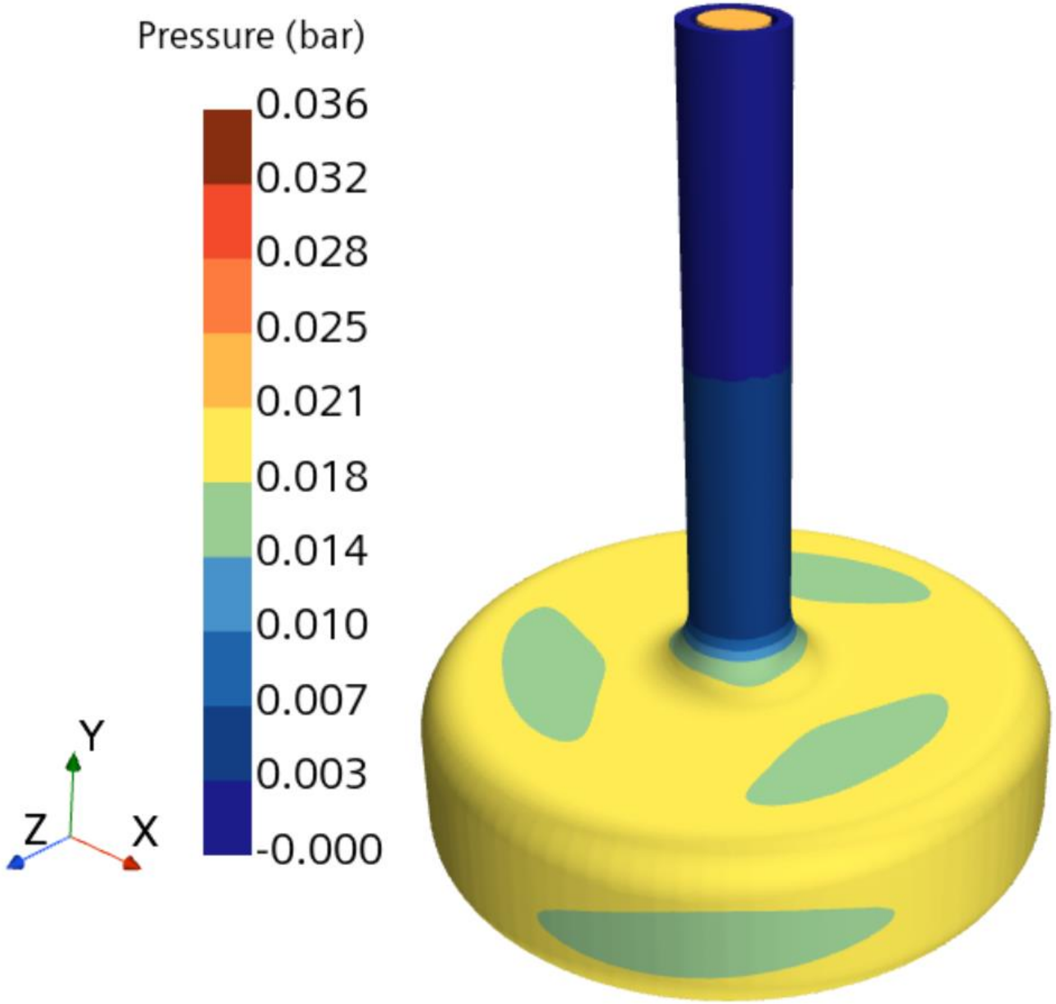


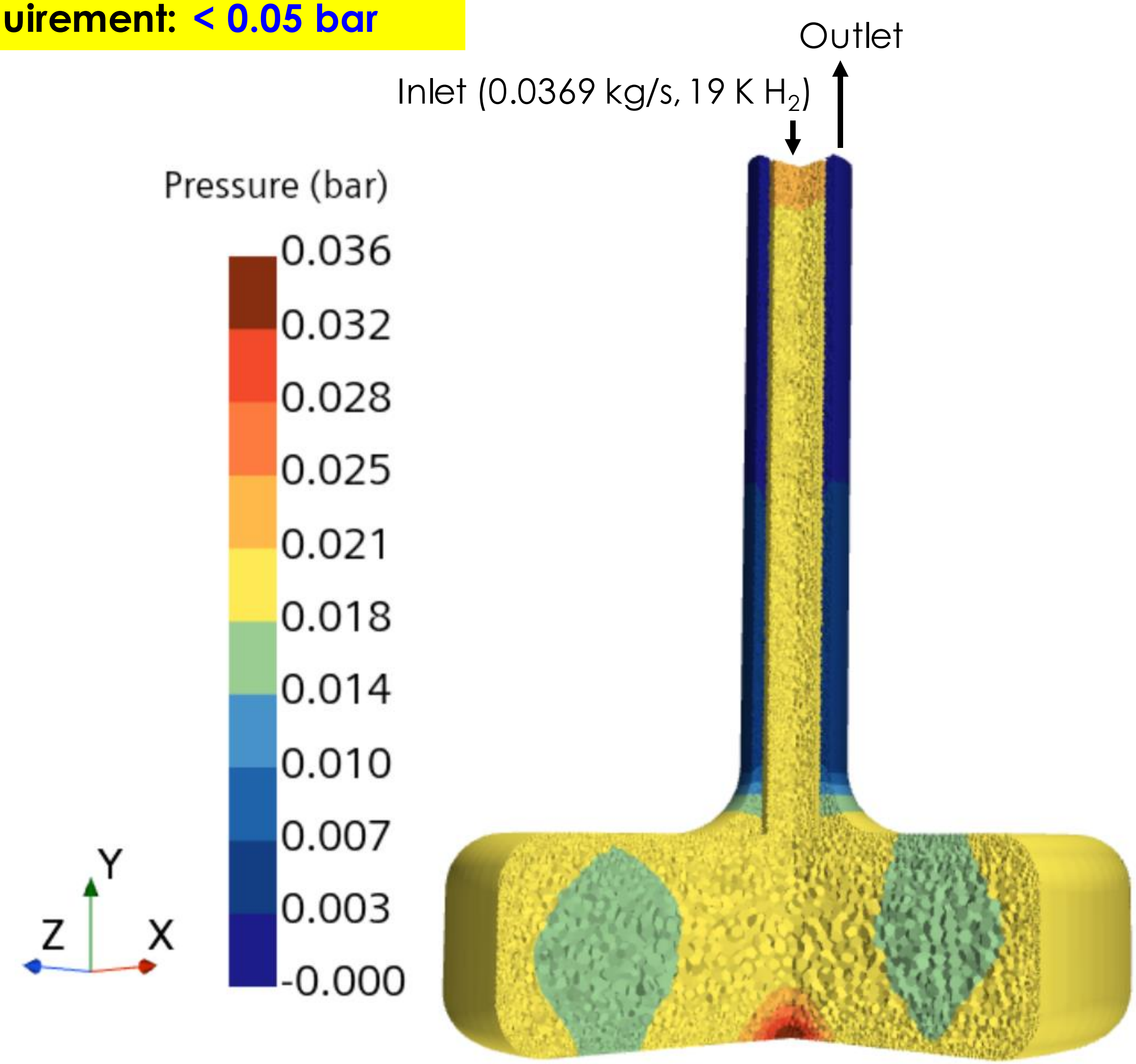
Uniform heating for H_2

Steady State Heat Transfer Analysis for Cylinder Moderator, Pressure

$\Delta P_{inlet-outlet} = 0.023 \text{ bar } (= 2.3 \text{ kPa} = 0.33\ psi = 0.023\ atm)$

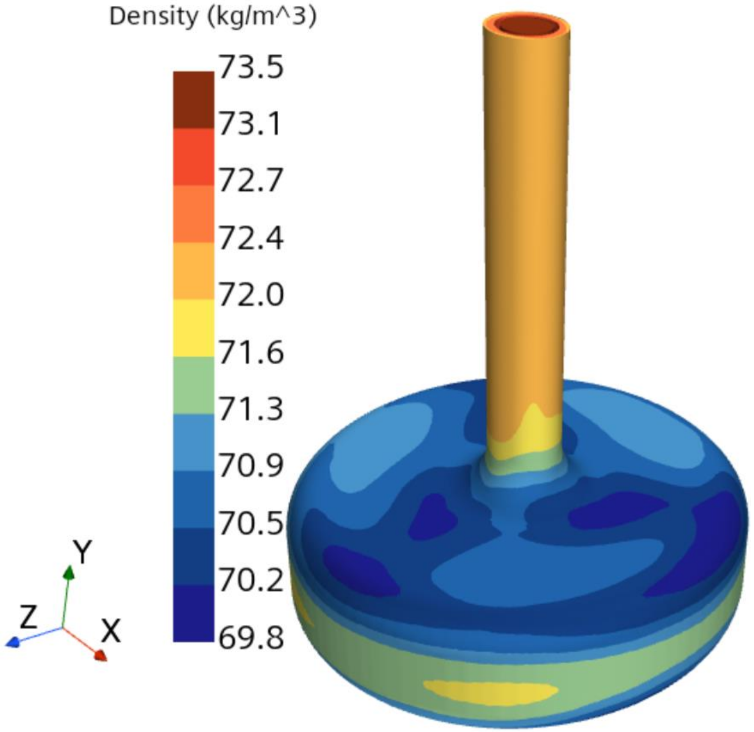
Requirement: < 0.05 bar

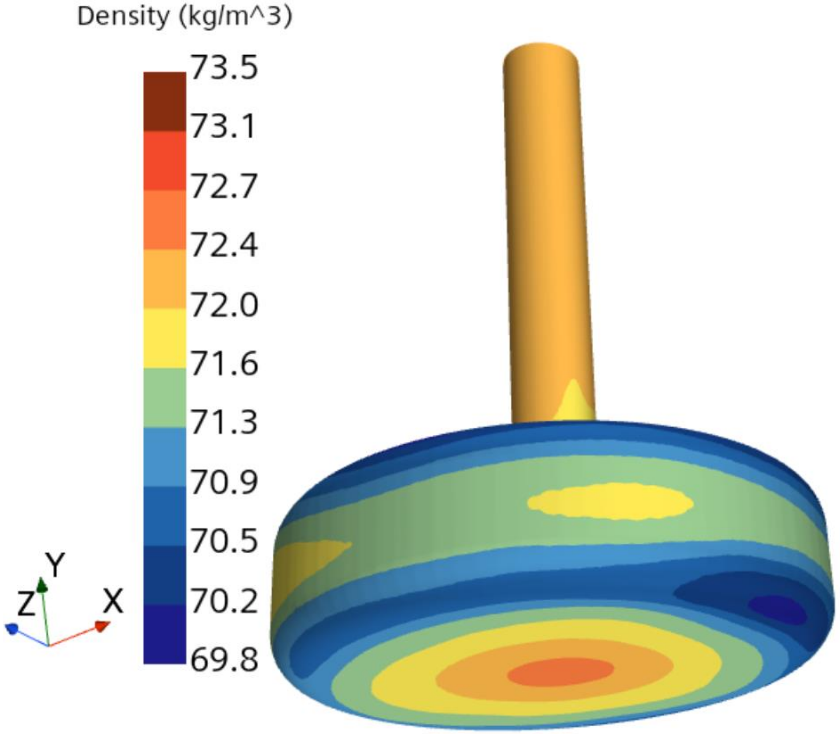


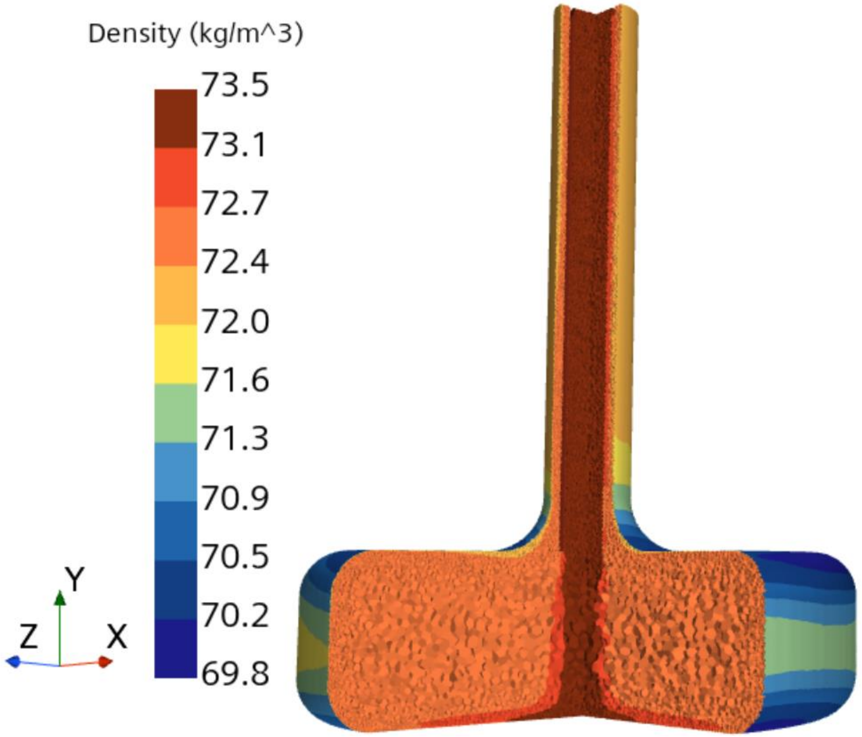


Steady State Heat Transfer Analysis for Cylinder Moderator, Density of H_2

Requirement: > 72.9 kg/m^3



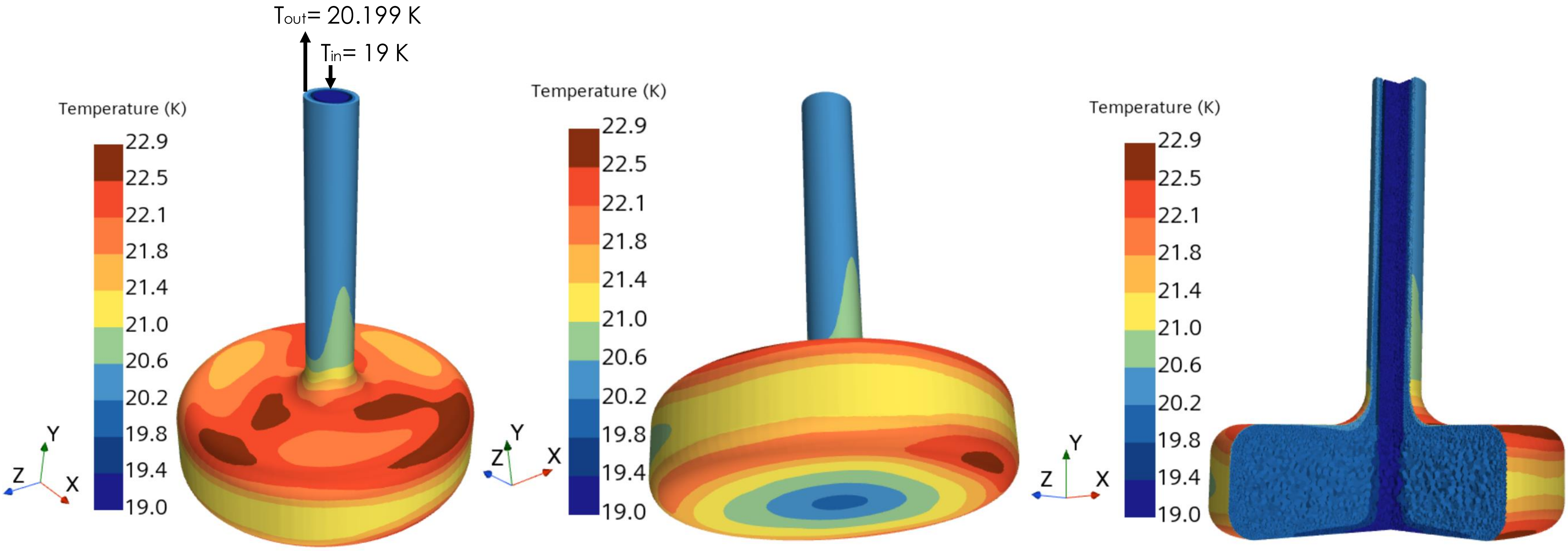




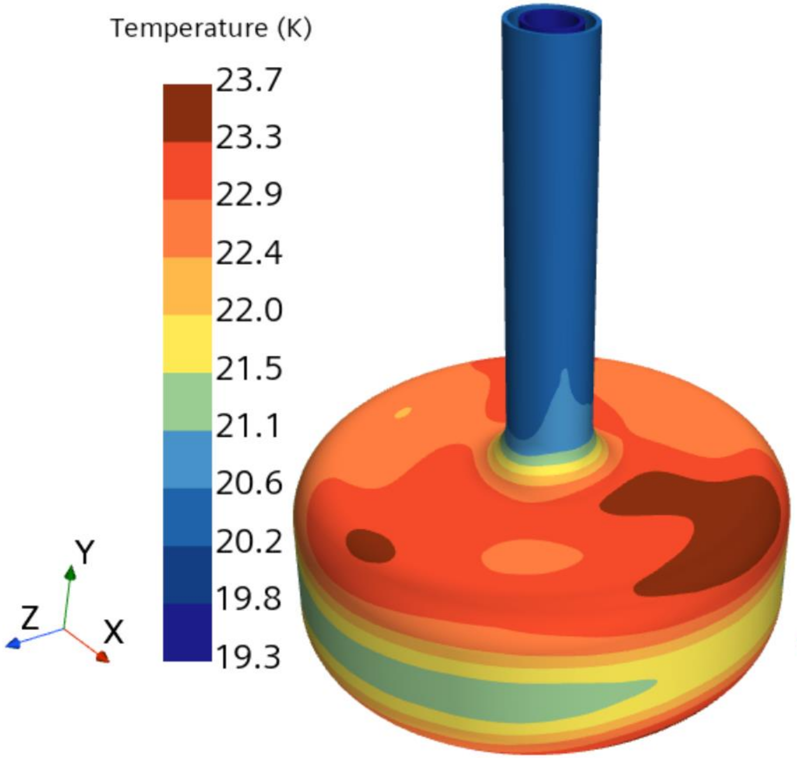
Cylinder (upper) Moderator	
H_2 Density at 19 K (kg/m^3)	73.806
Average H_2 Density (kg/m^3)	72.569
Variation (%)	1.68

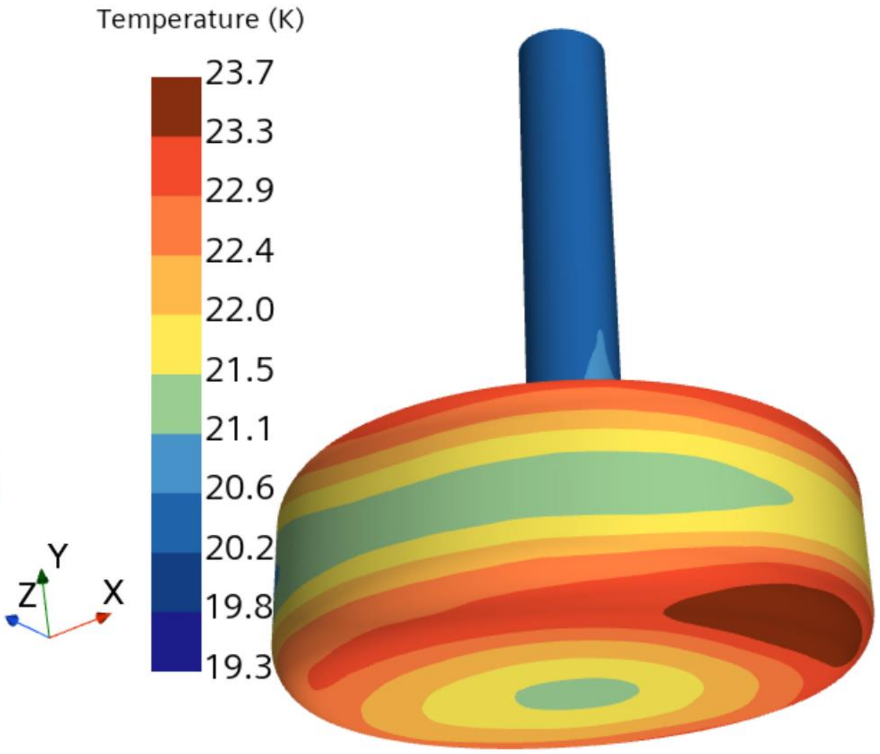
Steady State Heat Transfer Analysis for Cylinder Moderator, Temperature of H_2

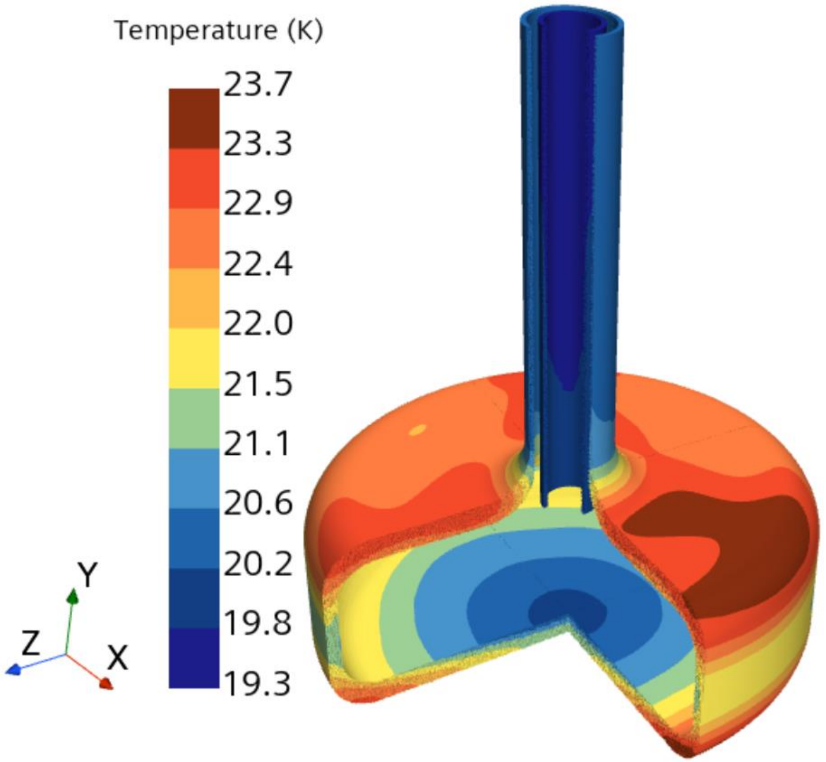
Requirement: < 32K



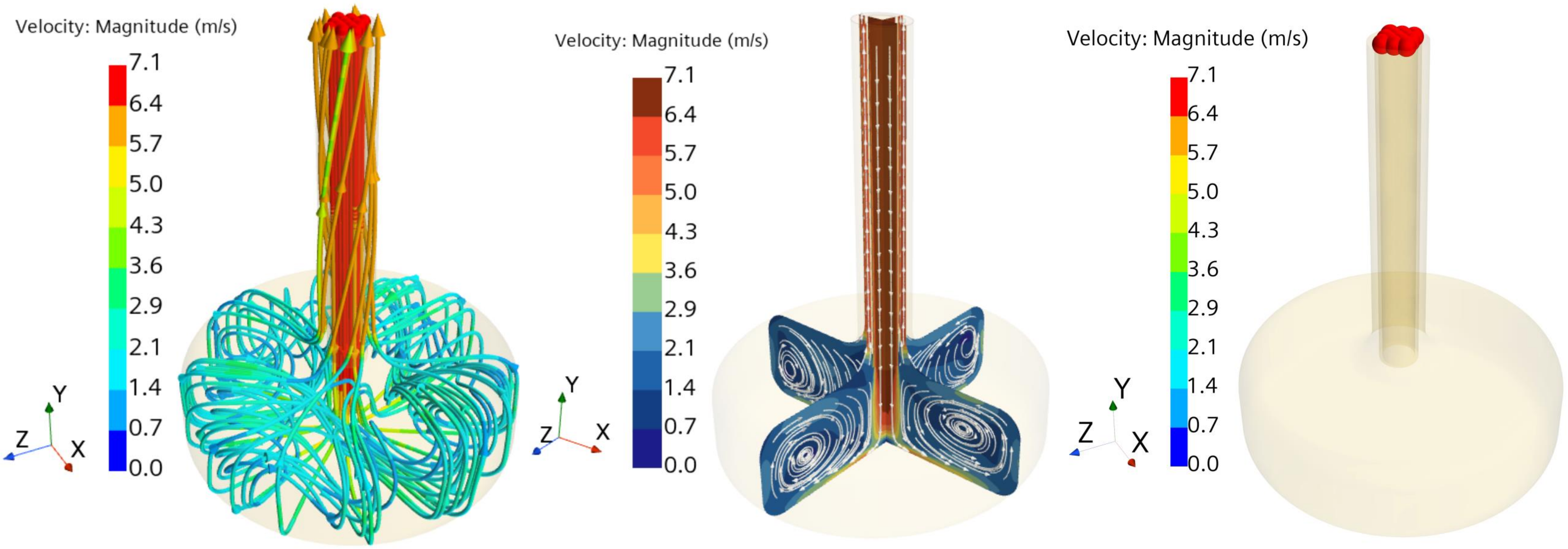
Steady State Heat Transfer Analysis for Cylinder Moderator, Temperature of Al





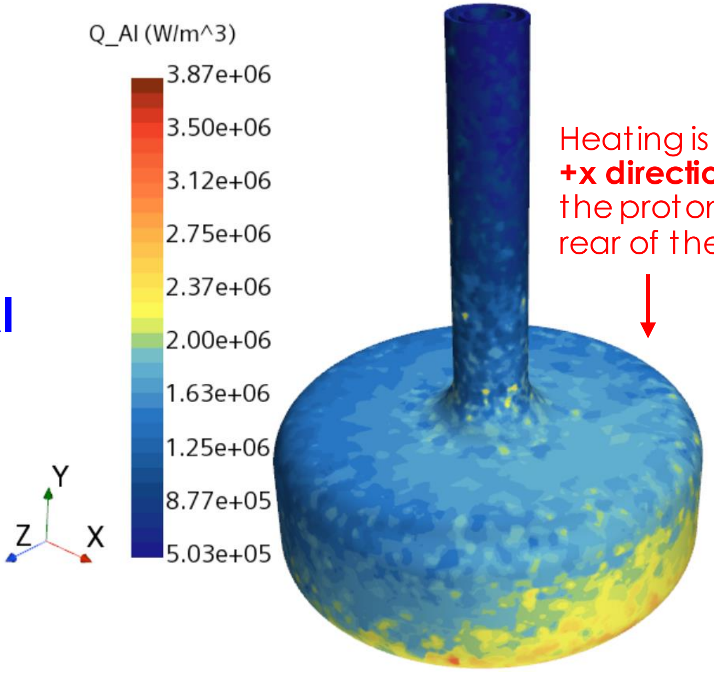


Steady State Heat Transfer Analysis for Cylinder Moderator, Streamlines



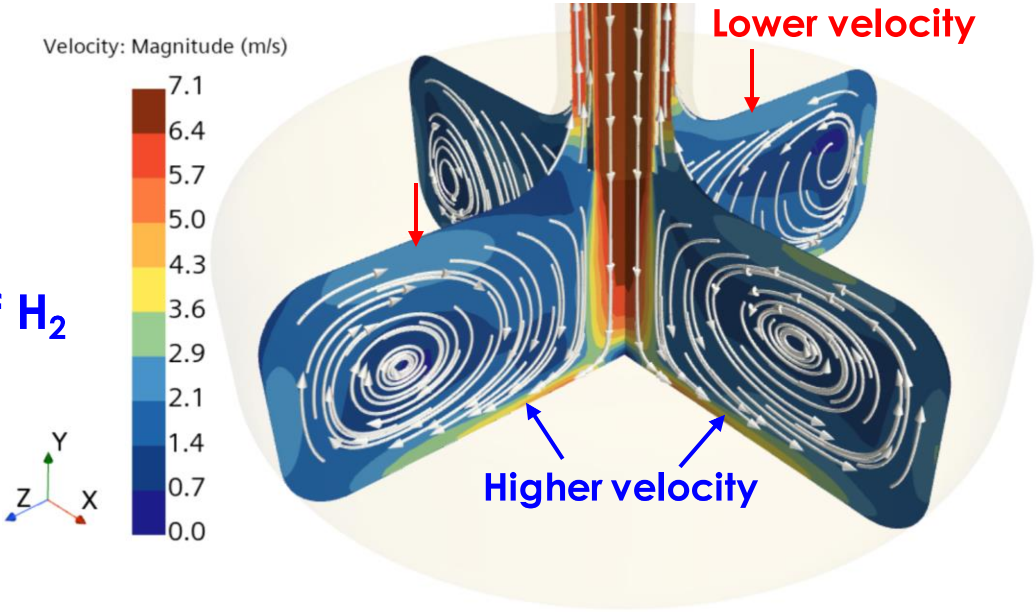
Steady State Heat Transfer Analysis for Cylinder Moderator

Q of Al



Heating is **higher** in **+x direction** (along the proton beam, rear of the target)

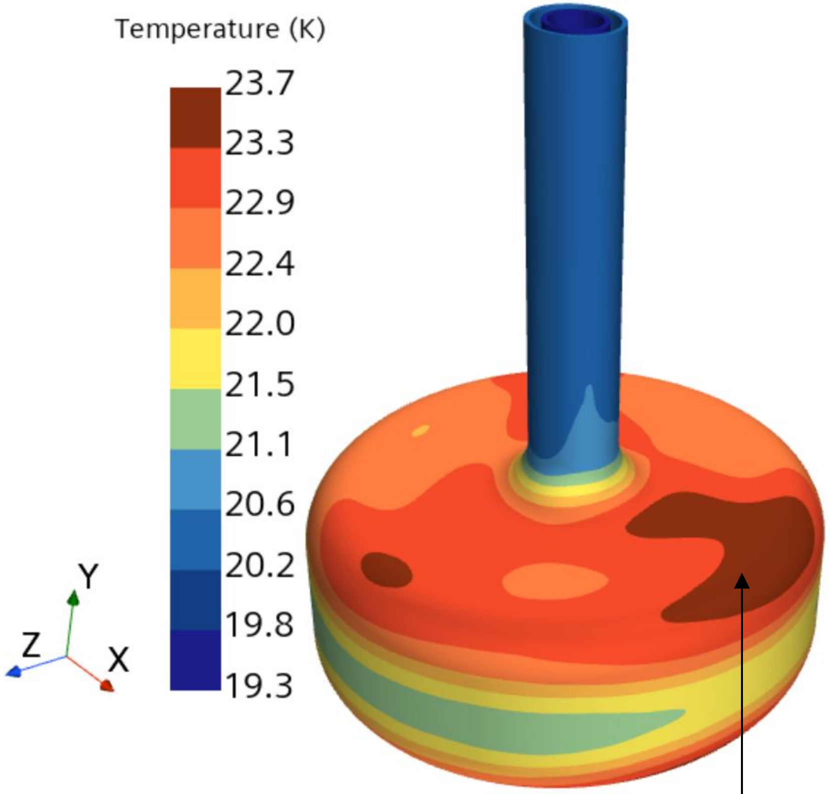
Velocity of H_2



Lower velocity

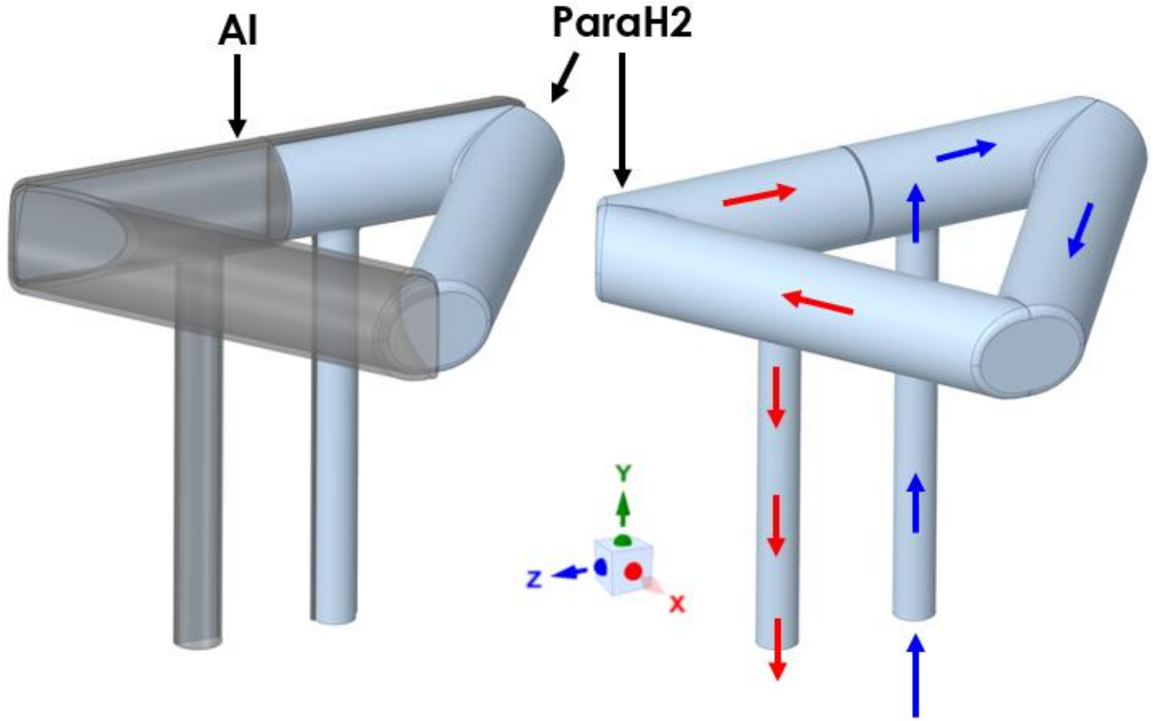
Higher velocity

Temperature of Al



Peak Al temperature occurs at the **top surface** in **+x direction.**

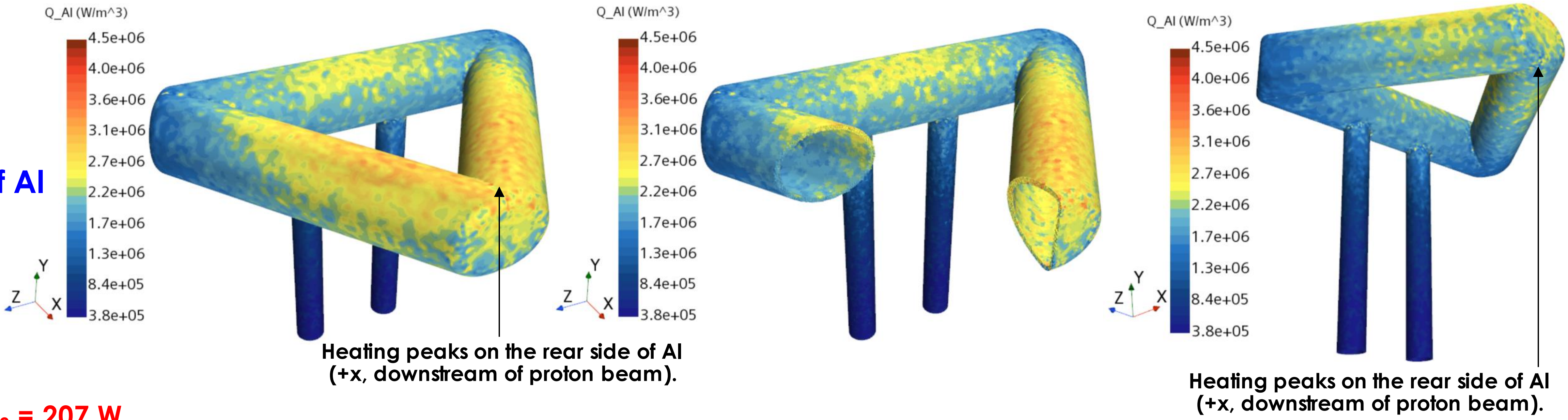
Results of Lower (Tube) H_2 Moderator



Steady State Heat Transfer Analysis for Tube Moderator, Heat Source

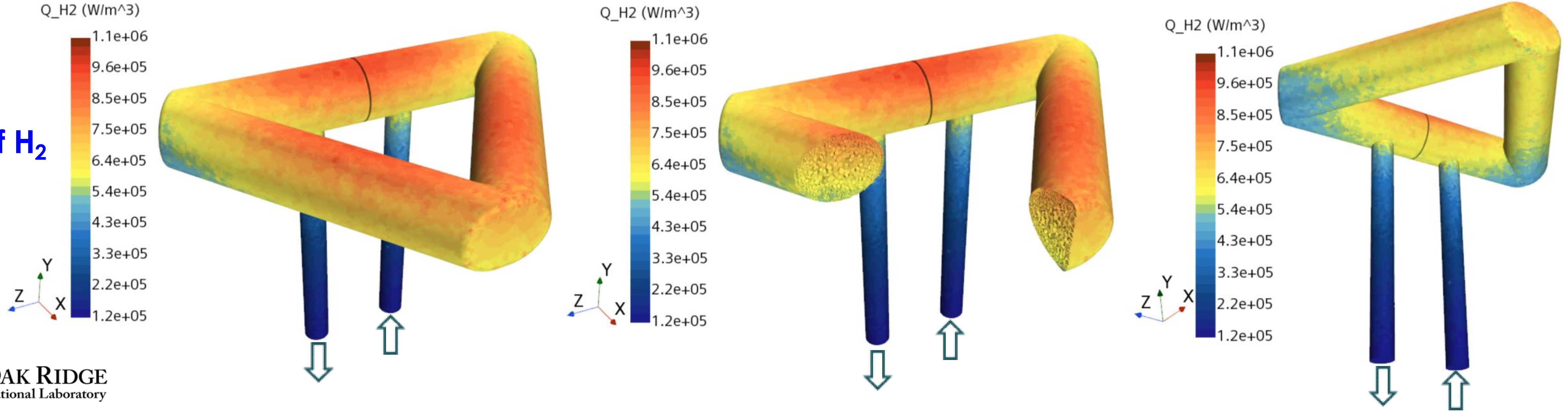
Q_Al = 186 W

Q of Al



Q_H_2 = 207 W

Q of H_2

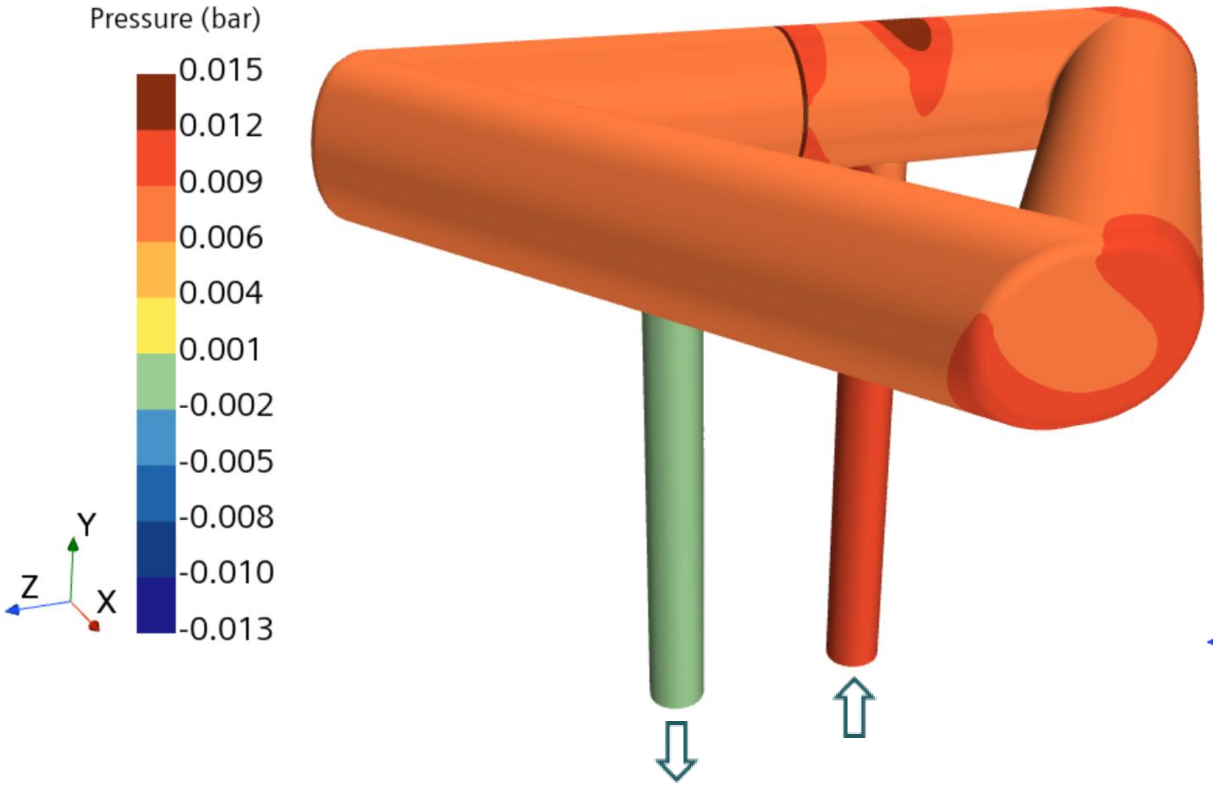


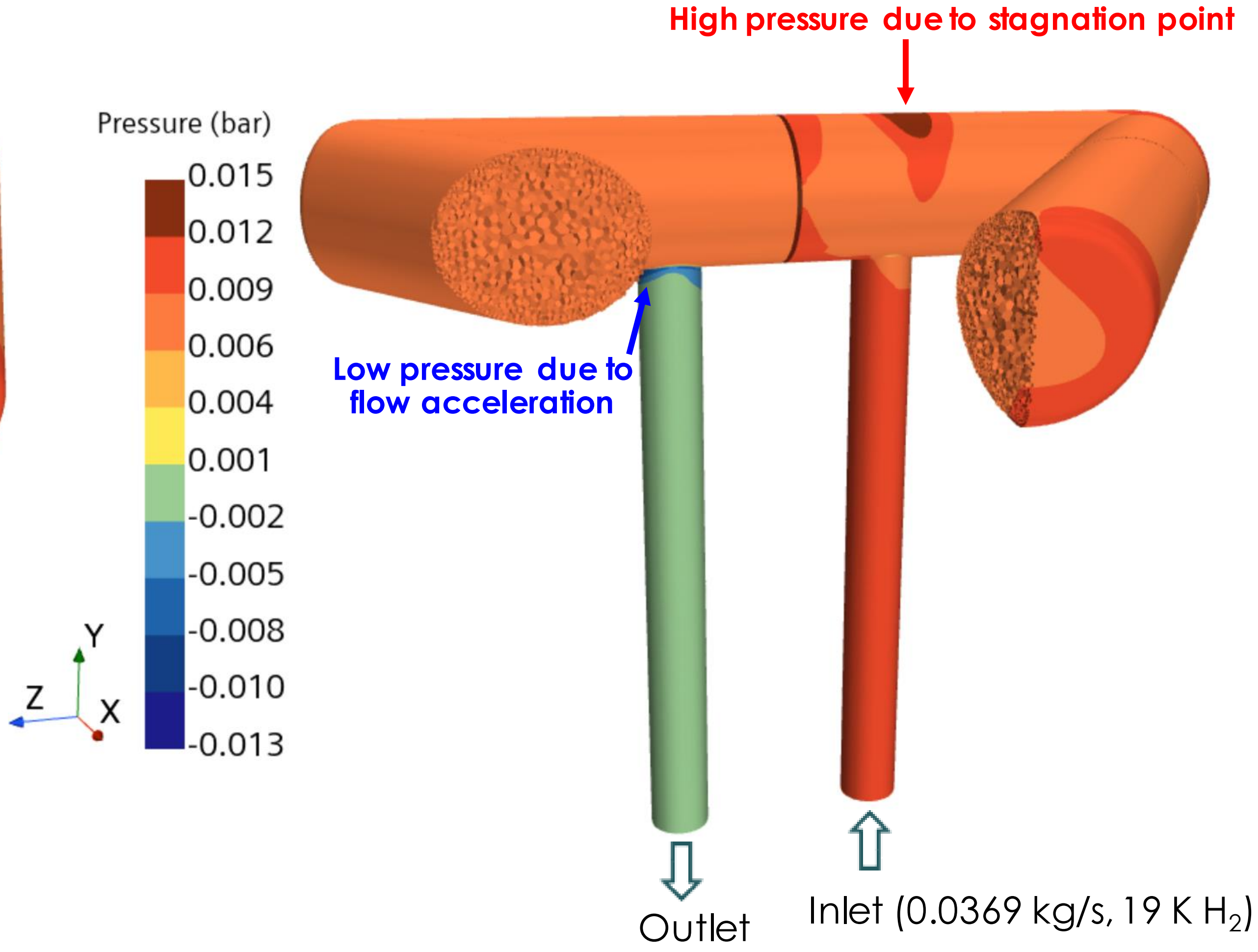
OAK RIDGE National Laboratory

Steady State Heat Transfer Analysis for Tube Moderator, Pressure

$\Delta P_{inlet-outlet} = 0.0106 \text{ bar } (= 1.06 \text{ kPa} = 0.15\ psi = 0.0105\ atm)$

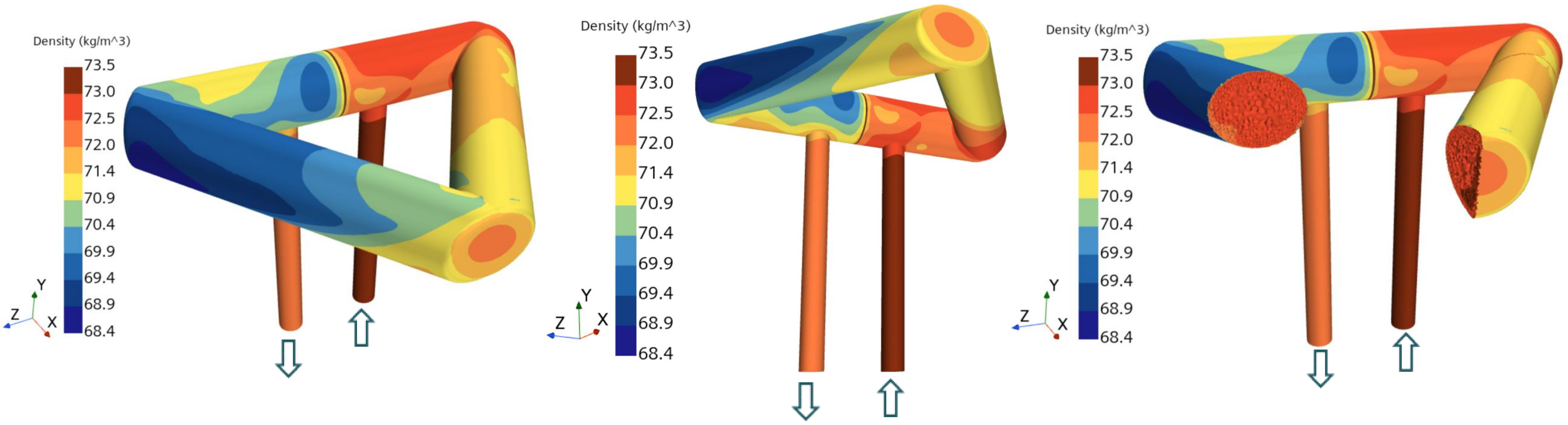
Requirement: < 0.05 bar





Steady State Heat Transfer Analysis for Tube Moderator, Density of H_2

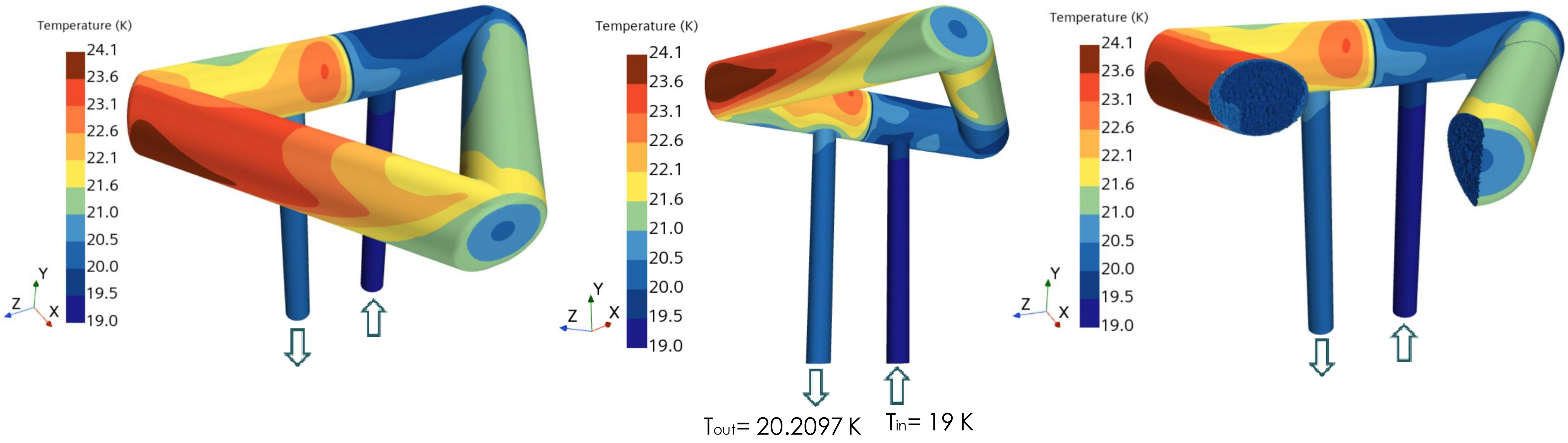
Requirement: > 72.9 kg/m³



Tube (lower) Moderator	
H_2 Density at 19 K (kg/m^3)	73.806
Average H_2 Density (kg/m^3)	72.832
Variation (%)	1.32

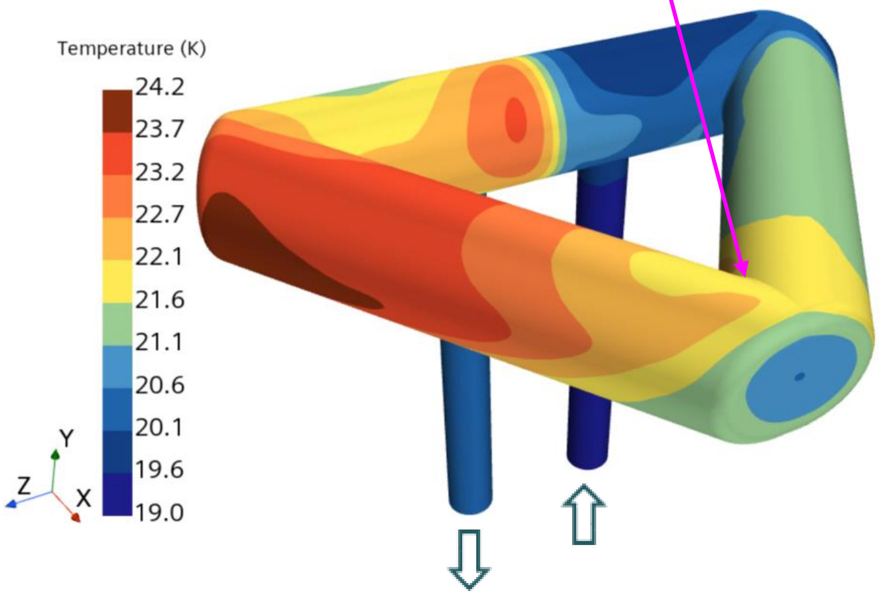
Steady State Heat Transfer Analysis for Tube Moderator, Temperature of H_2

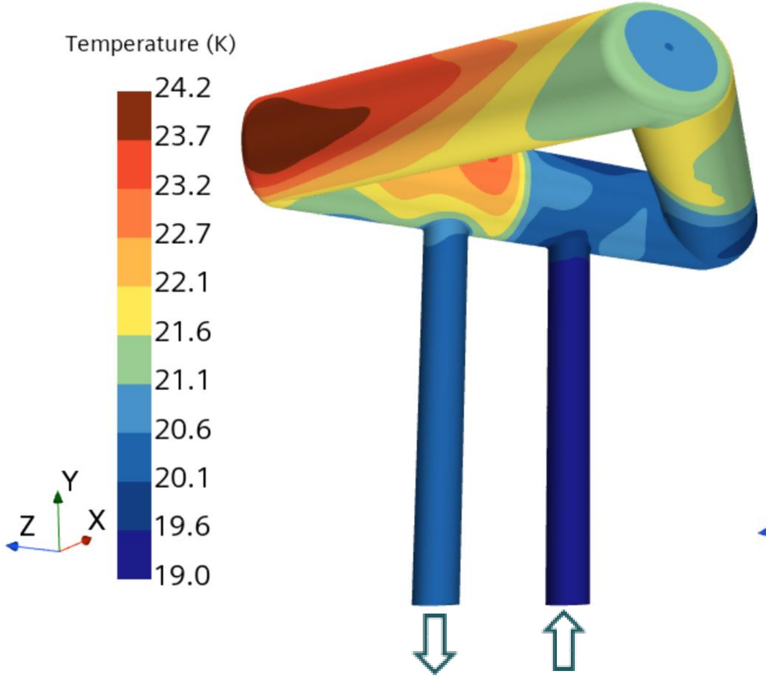
Requirement: < 32K

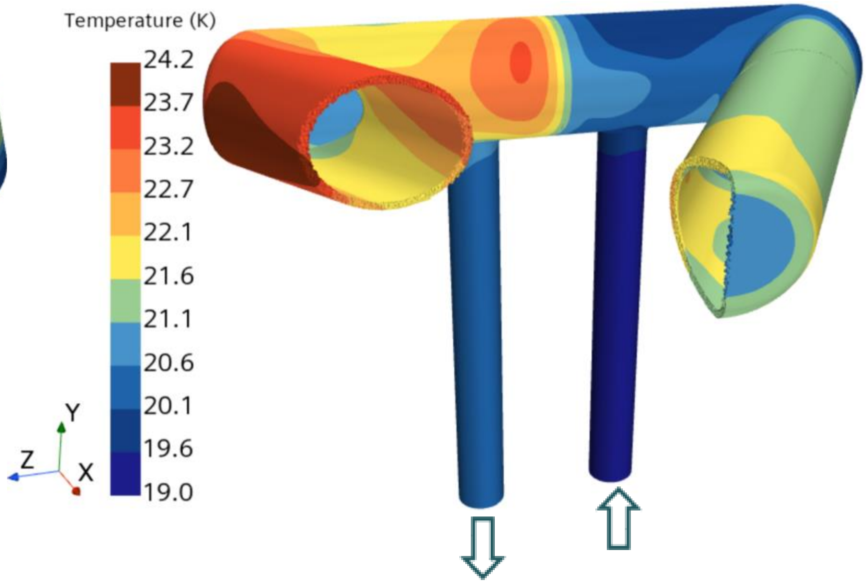


Steady State Heat Transfer Analysis for Tube Moderator, Temperature of Al

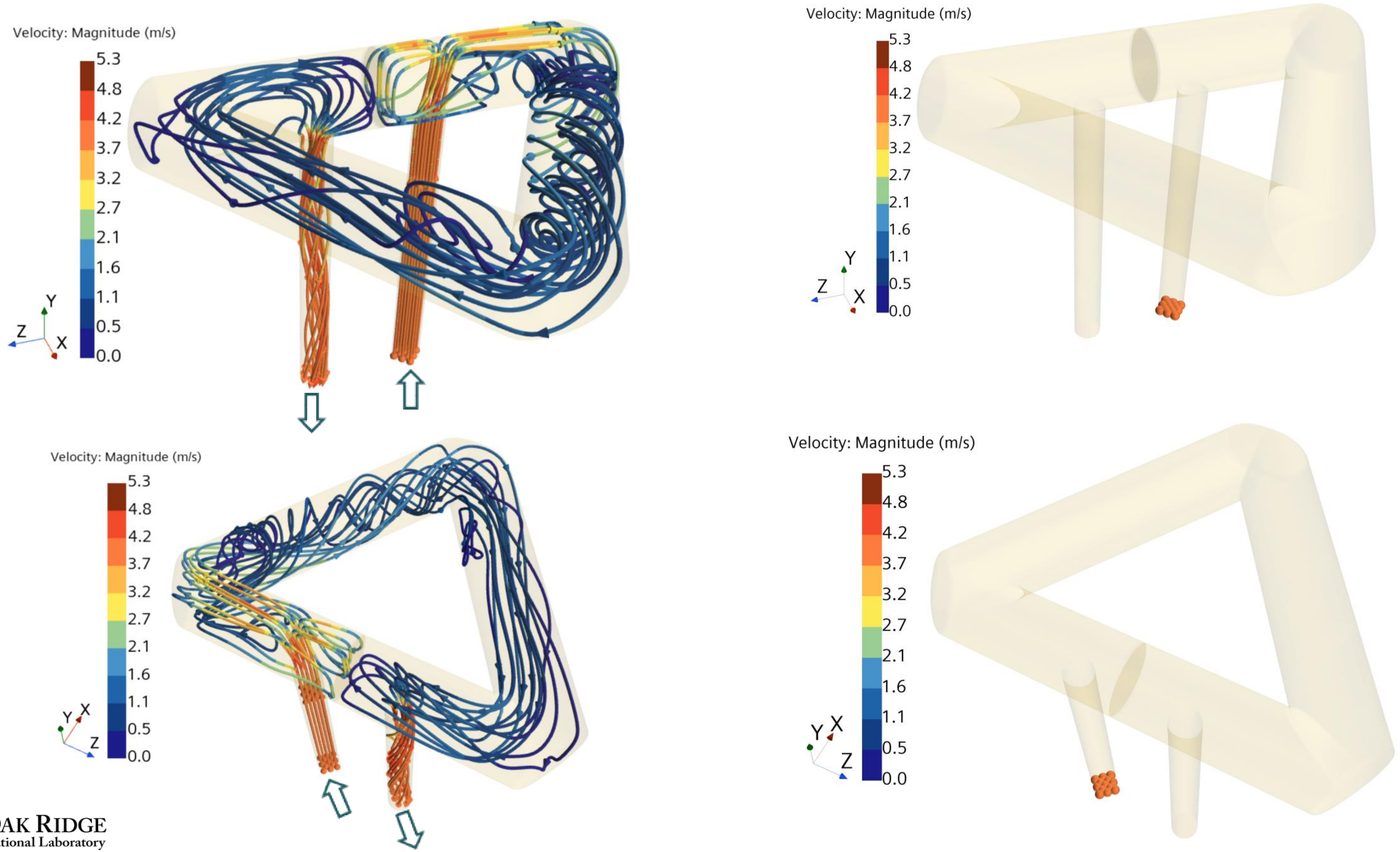
Peak heating location is not where the peak temperature occurs.





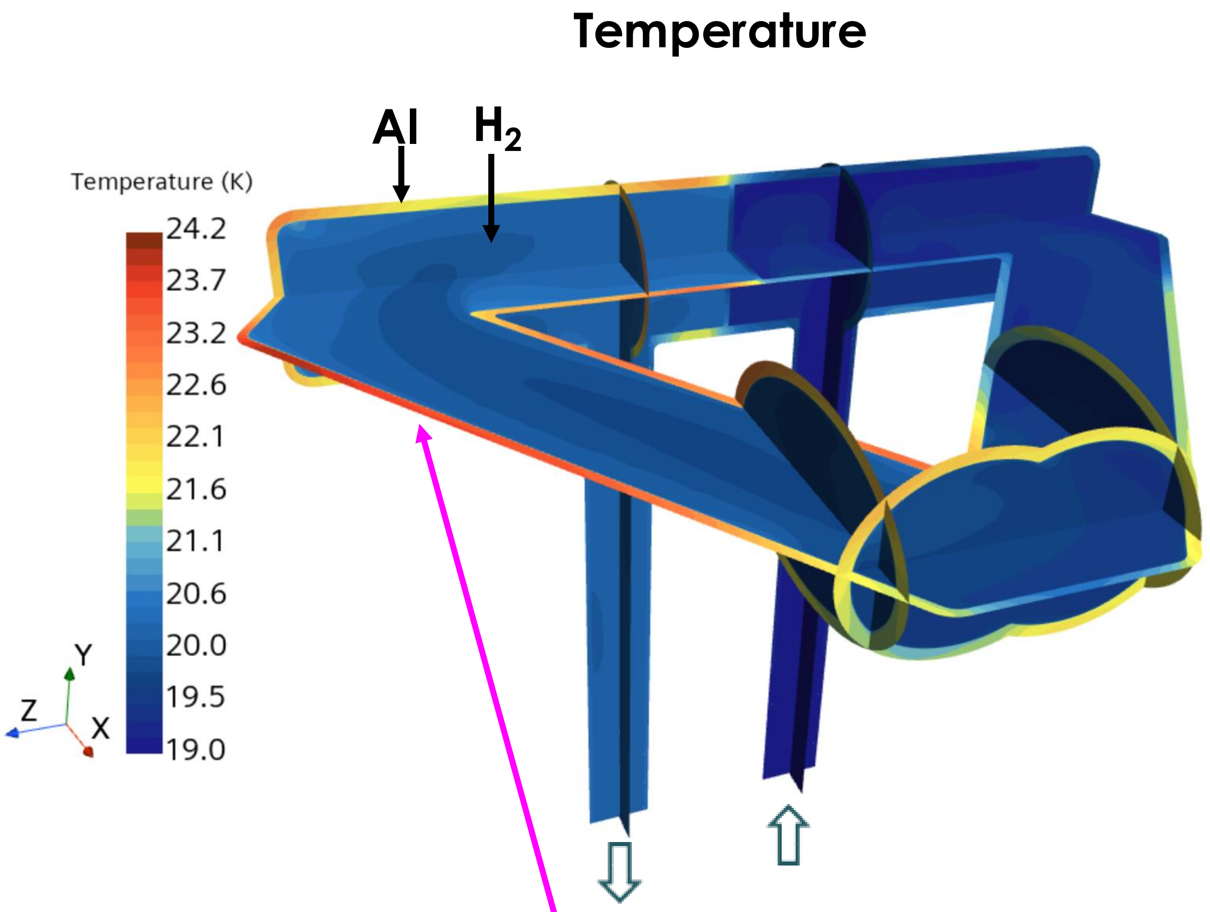


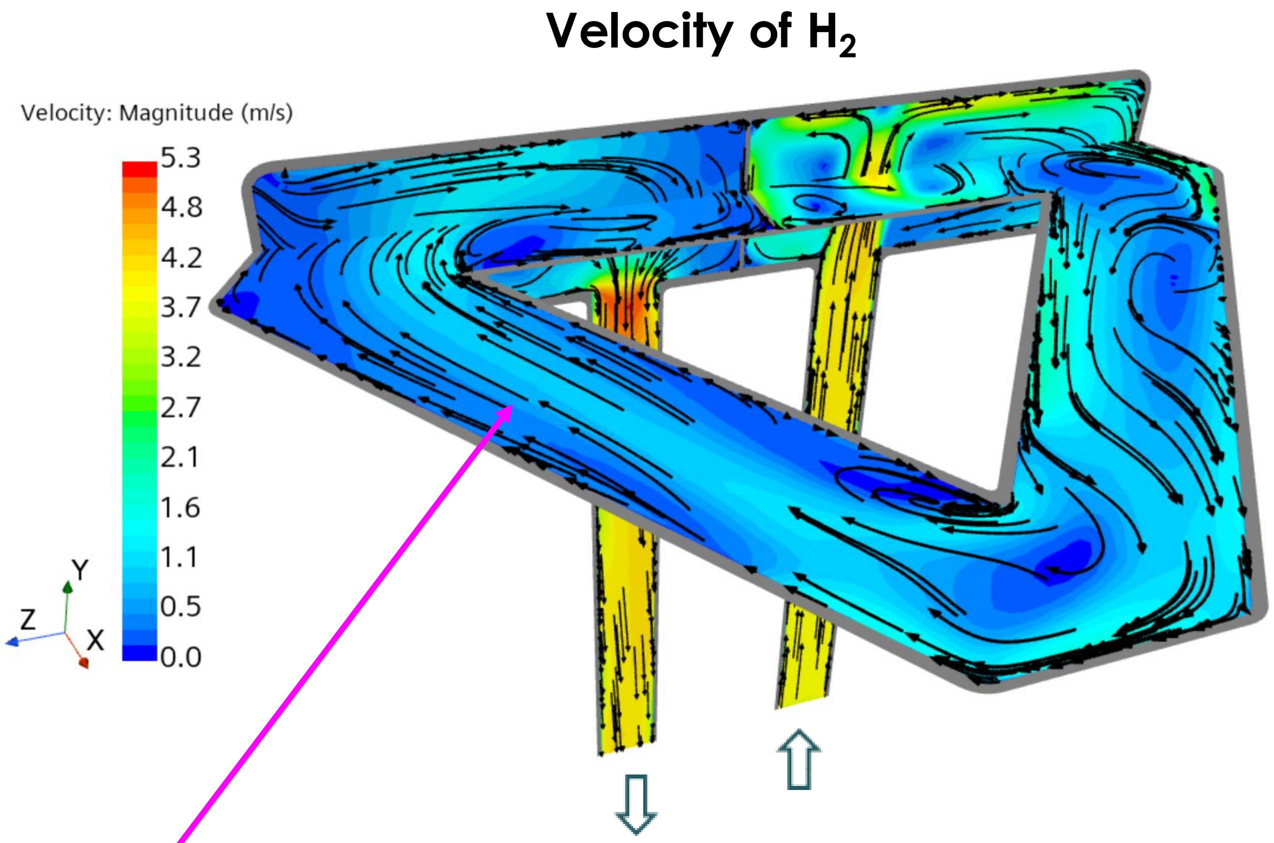
Steady State Heat Transfer Analysis for Tube Moderator, Streamlines



OAK RIDGE
National Laboratory

Steady State Heat Transfer Analysis for Tube Moderator, Temperature & Velocity

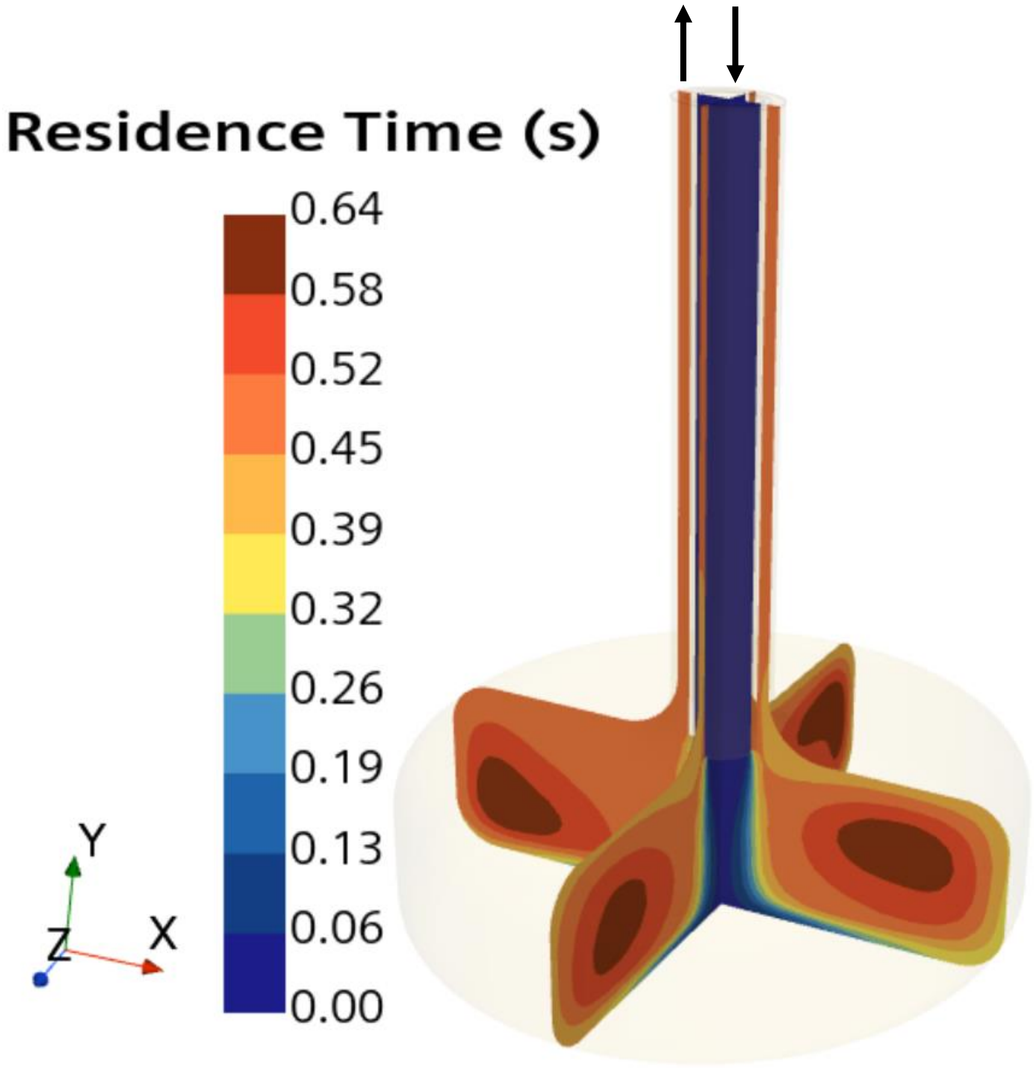




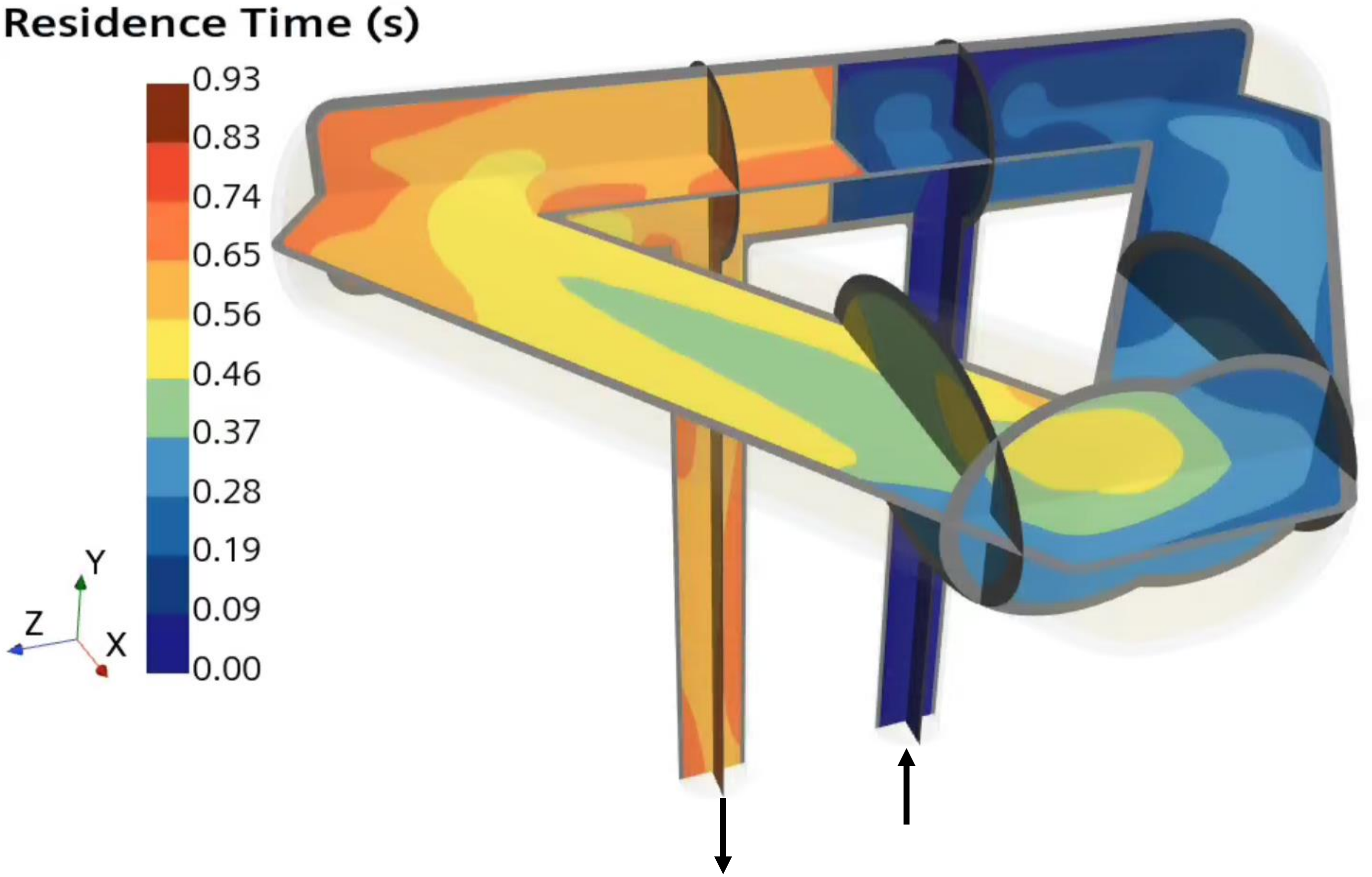
The H_2 mainstream is away from the Al wall and thus Al temperature is higher along this tube.

Steady State Heat Transfer Analysis, Residence Time

Cylinder Moderator



Tube Moderator



OAK RIDGE National Laboratory

Comparison between Requirements and CFD Results

	Requirement	CFD Result	
		Cylinder Moderator	Tube Moderator
Pressure drop (bar)	< 0.05	0.023	0.0106
Maximum hydrogen temperature (K)	< 32	22.9	24.1
Average hydrogen density (kg/m^3)	> 72.9	72.569	72.832
Residence time (s)	> 0.2	0.64	0.93

- Except for average hydrogen density, all requirements are met with at least a factor of 2 margin
  - High confidence that margins are greater than uncertainties

Summary

- Most requirements are met except for the average hydrogen density (72.9 kg/m^3).
  - All other requirements are met with at least a factor of 2 margin
- Neutronics will evaluate sensitivity to hydrogen density and will update hydrogen density requirement
- Final moderator analysis will include additional details
  - Moderator inlet temperatures updated based on single loop in series CMS design
  - Inclusion of moderator weld backer geometry
  - Inclusion of cylinder moderator transition to concentric flow geometry

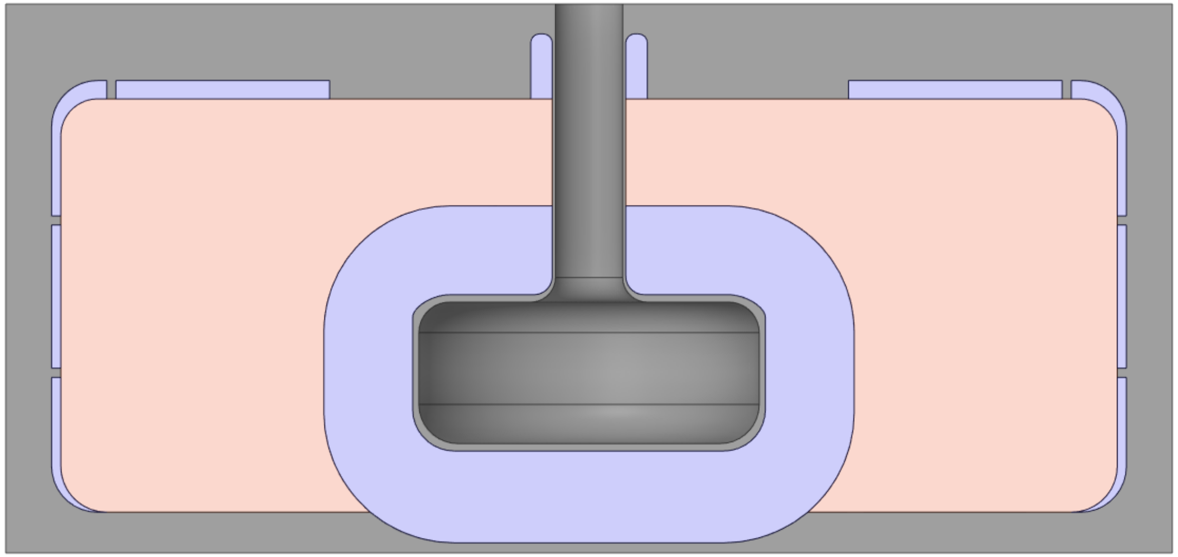
2% of 700 kW

Q = 15 kW

2% of 700 kW

Q = 16 kW

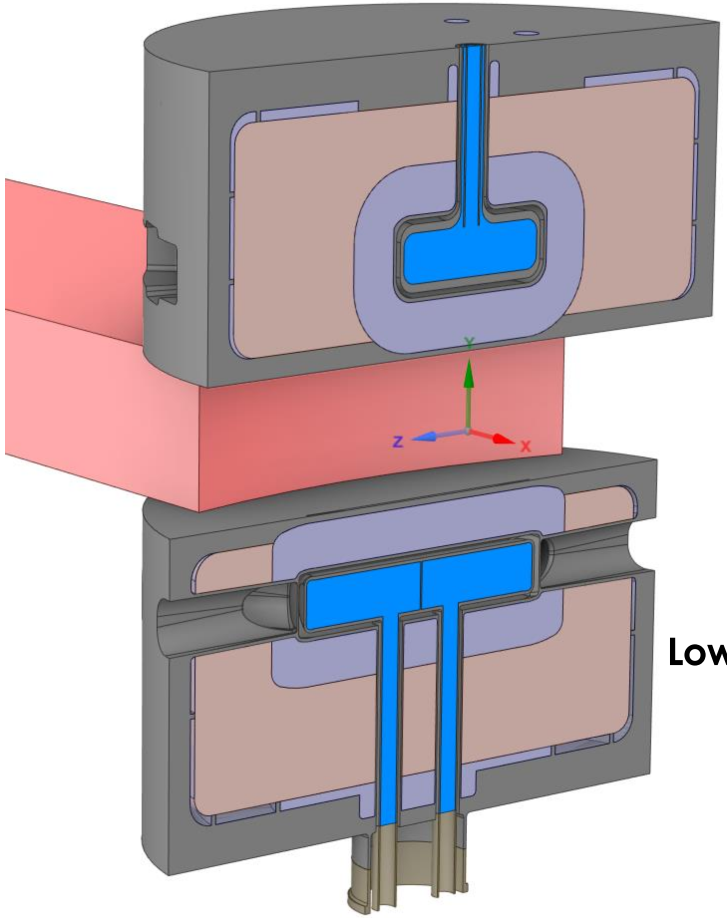
Part 2 : CFD analysis for the upper reflector (similar to lower reflector)

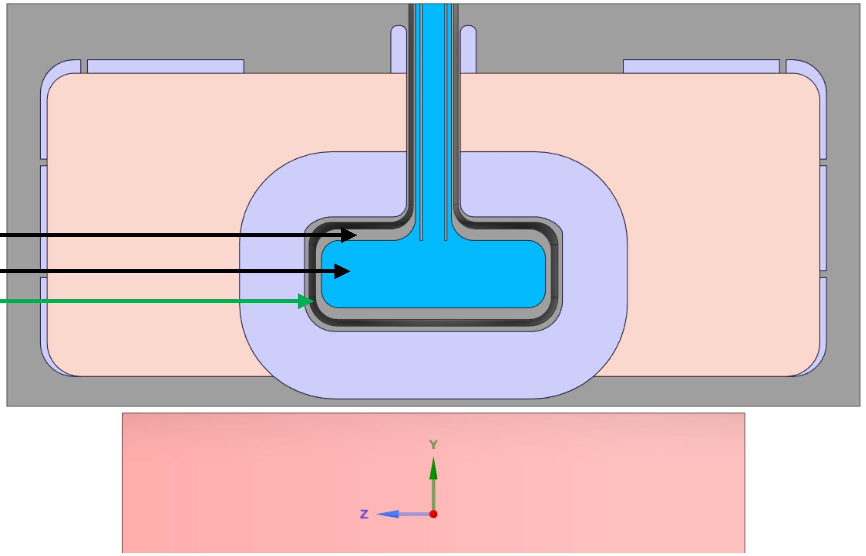


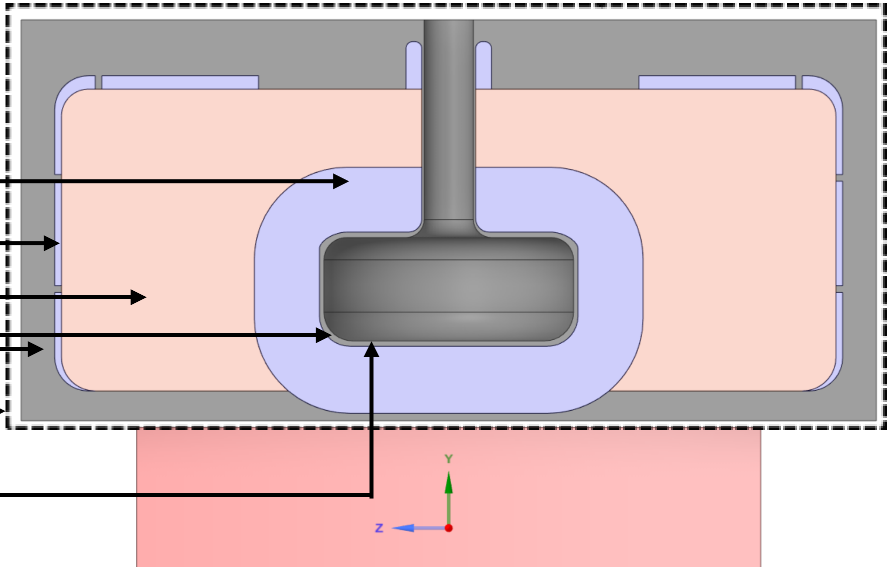
Requirements for MRA Reflectors

- This thermal-hydraulic analyses were performed to demonstrate that the current MRA design (without moderators, which were done in separate analyses and the results were also documented in a separate presentation) can meet the following requirements.
- **Requirements**
  - Pressure drop < 15 psi
    - Low pressure drop allows flexibility for CMS design
  - Maximum water temperature < 100°C
    - No water boiling
  - Maximum Aluminum temperature < 100°C
  - Maximum Beryllium temperature < 100°C

Geometry of Upper MRA

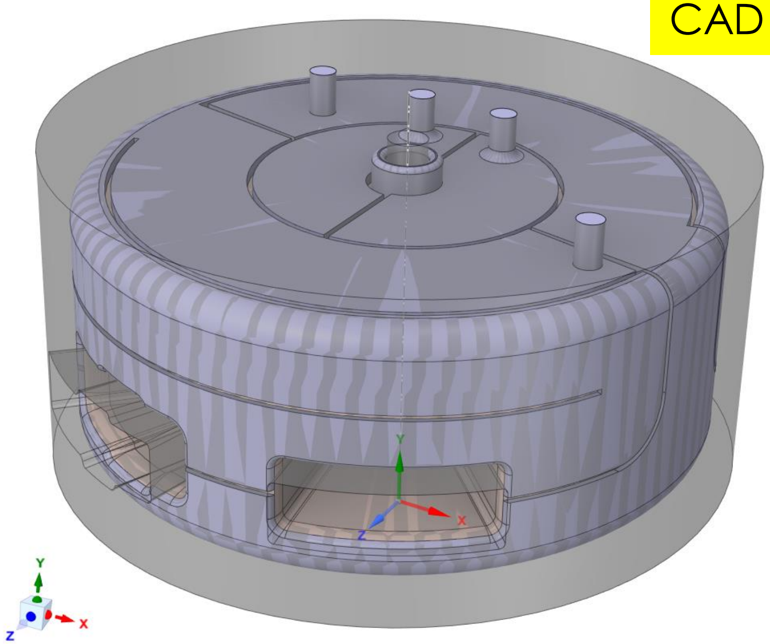


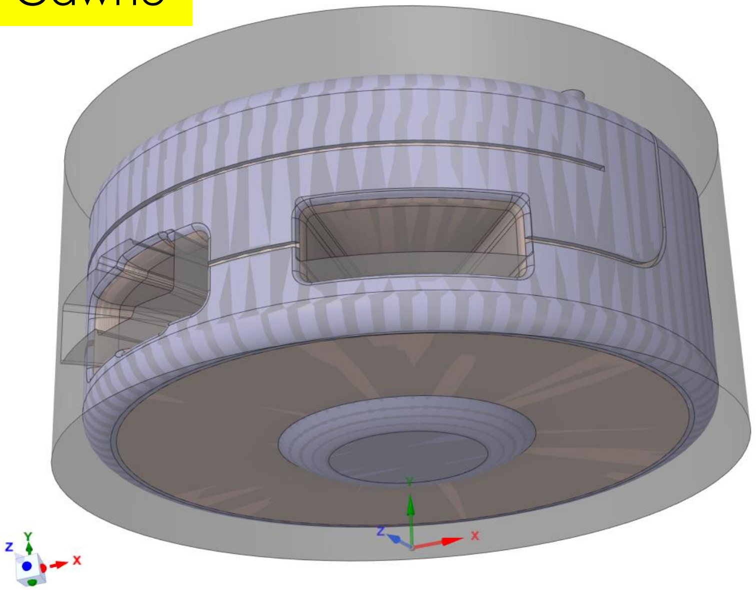




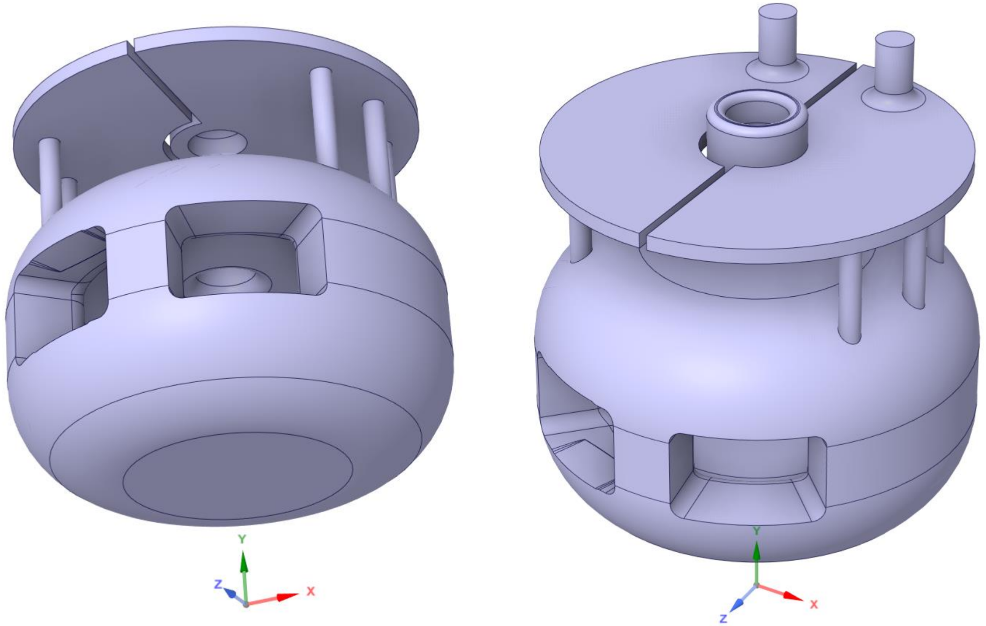
Steady State Heat Transfer Analysis for Upper MRA, Geometry

CAD model from Ken Gawne

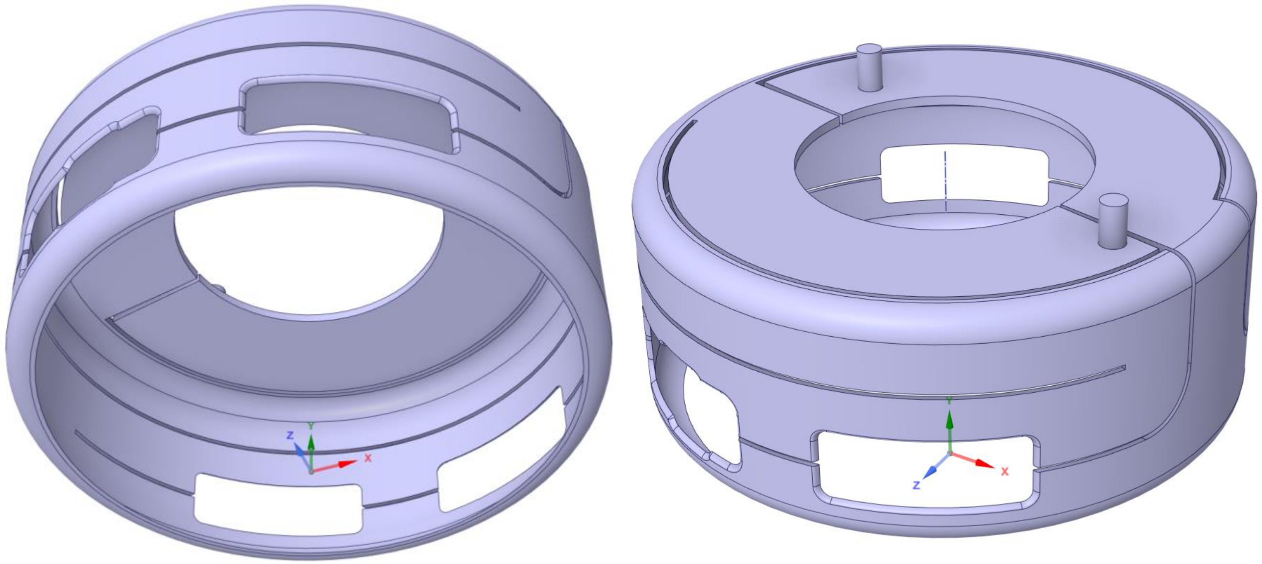




Upper PreModerator (H_2O)

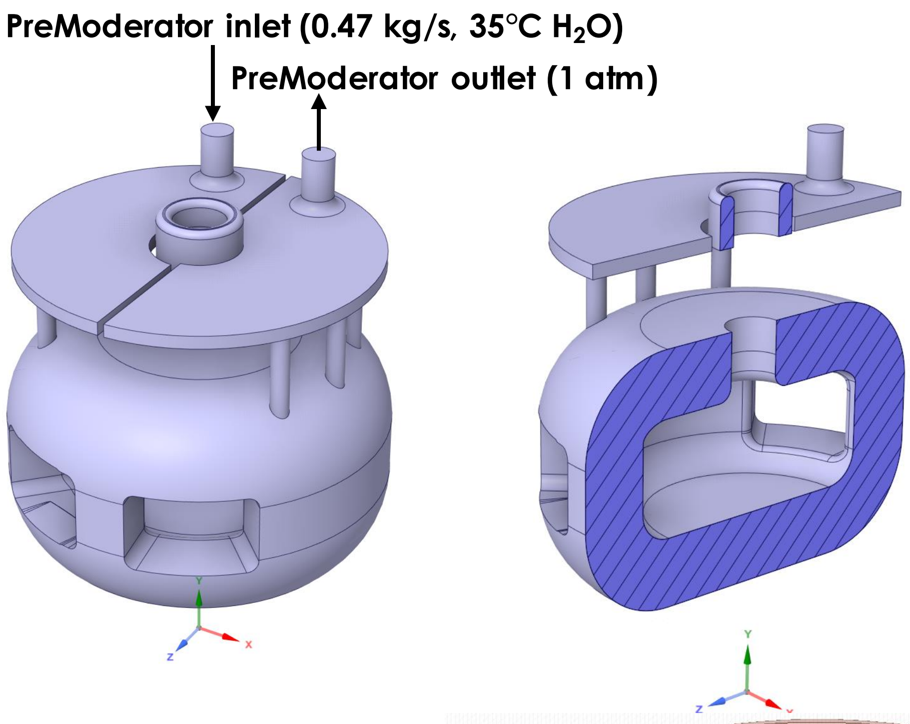


Upper Reflector (H_2O)

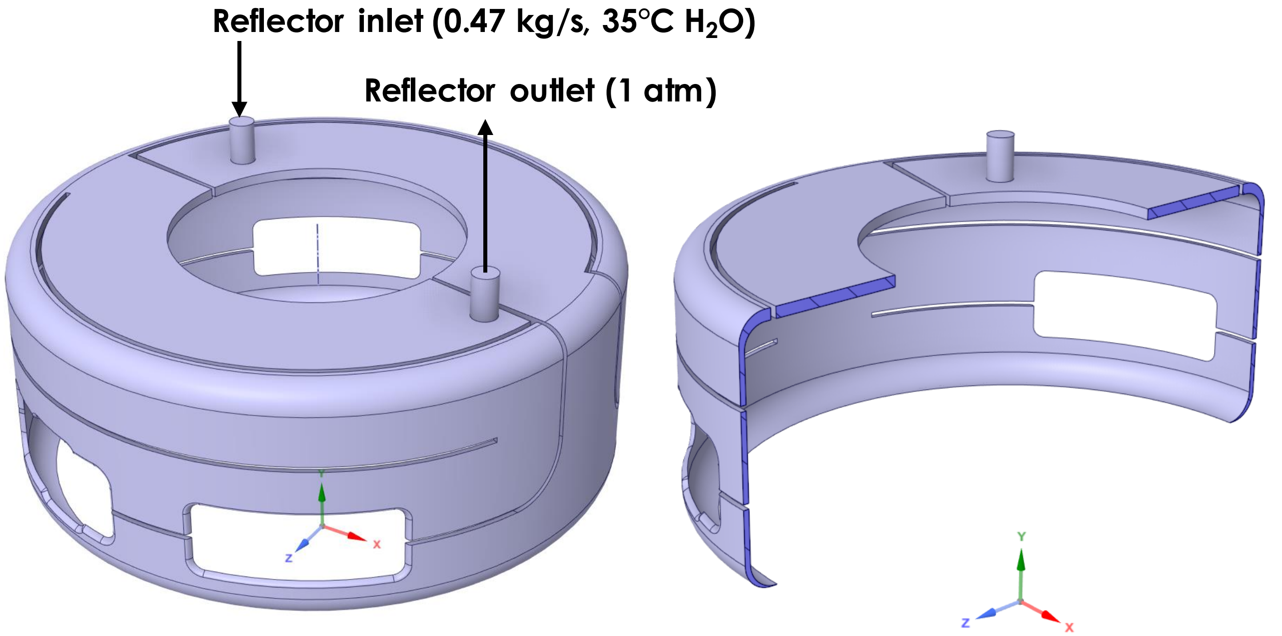


Steady State Heat Transfer Analysis for Upper MRA, Geometry

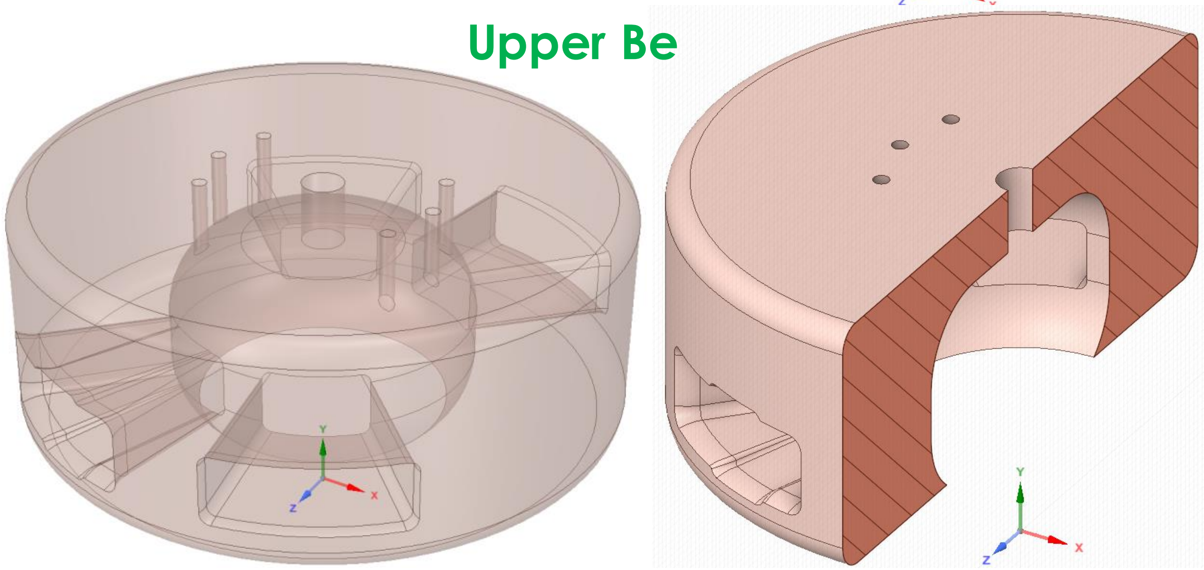
Upper PreModerator (H_2O)



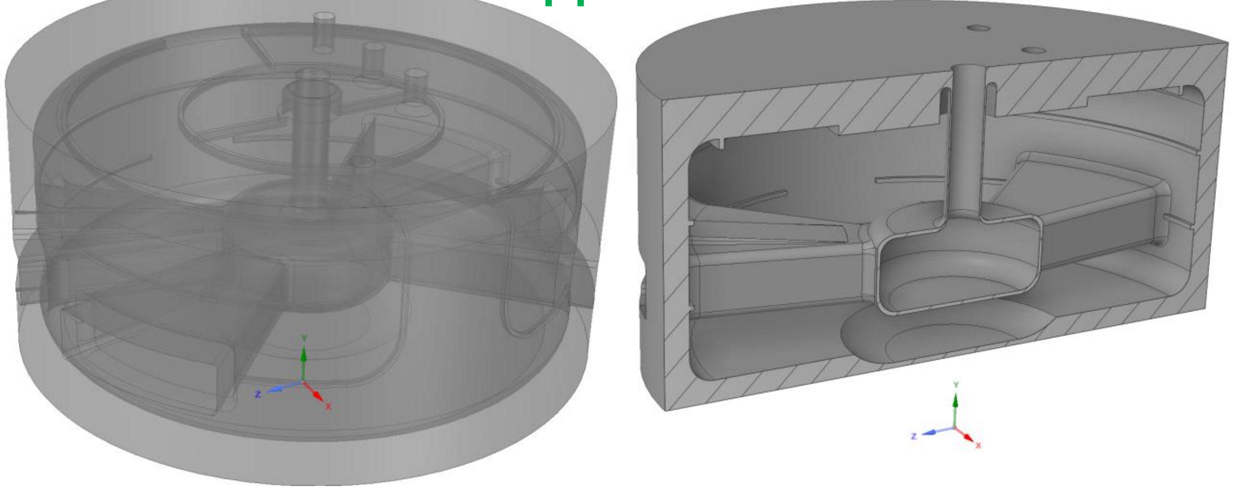
Upper Reflector (H_2O)



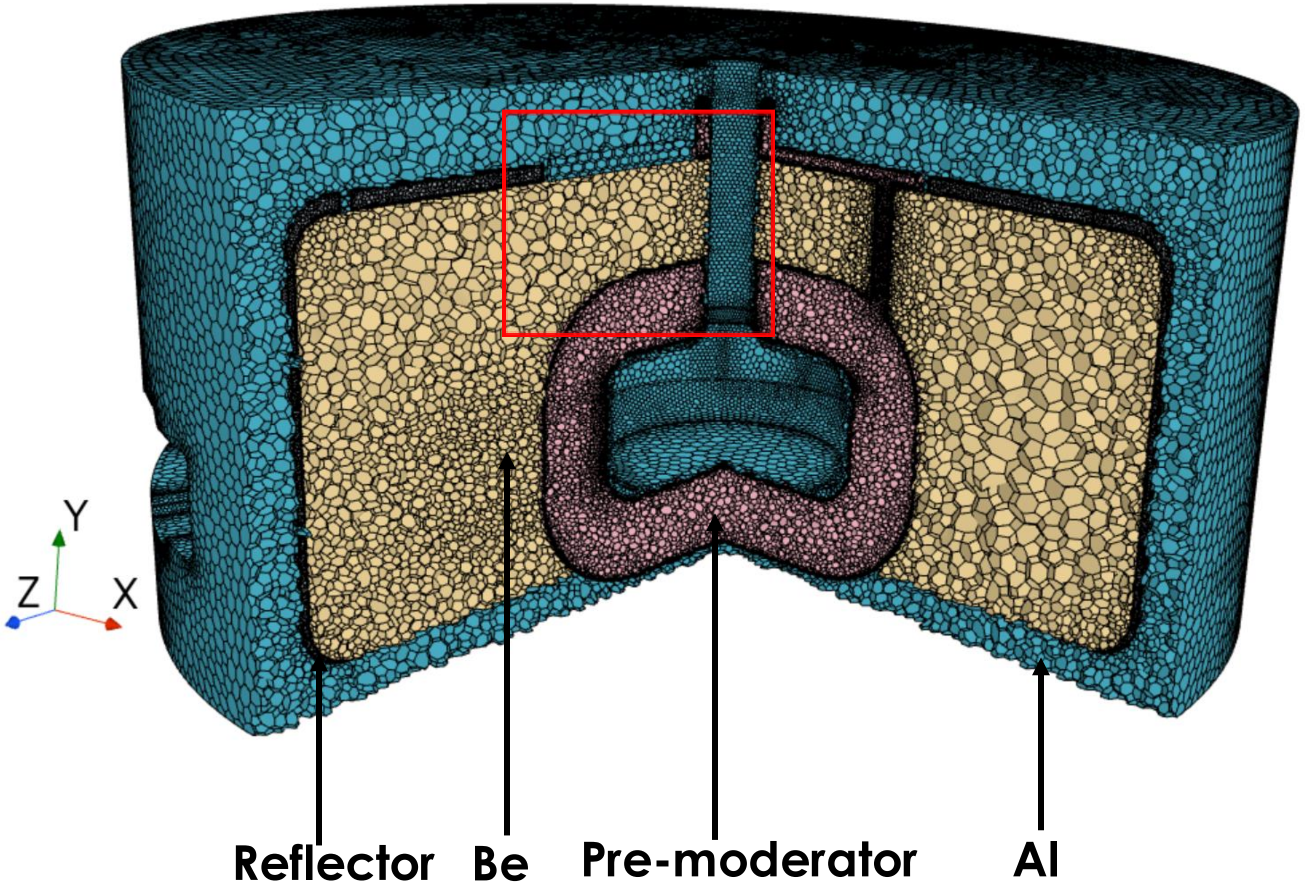
Upper Be

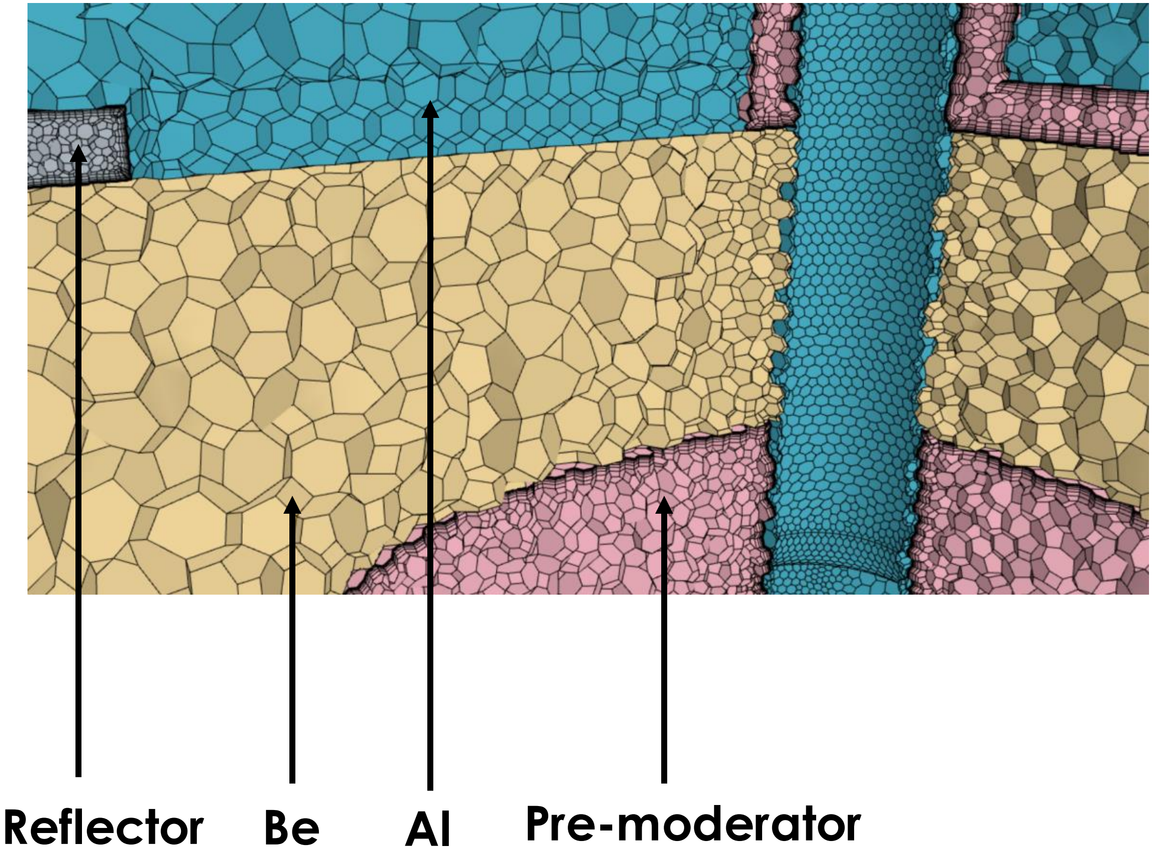


Upper Al



Steady State Heat Transfer Analysis for Upper MRA, Mesh Configuration





Steady State Heat Transfer Analysis for Upper MRA, Mesh Settings

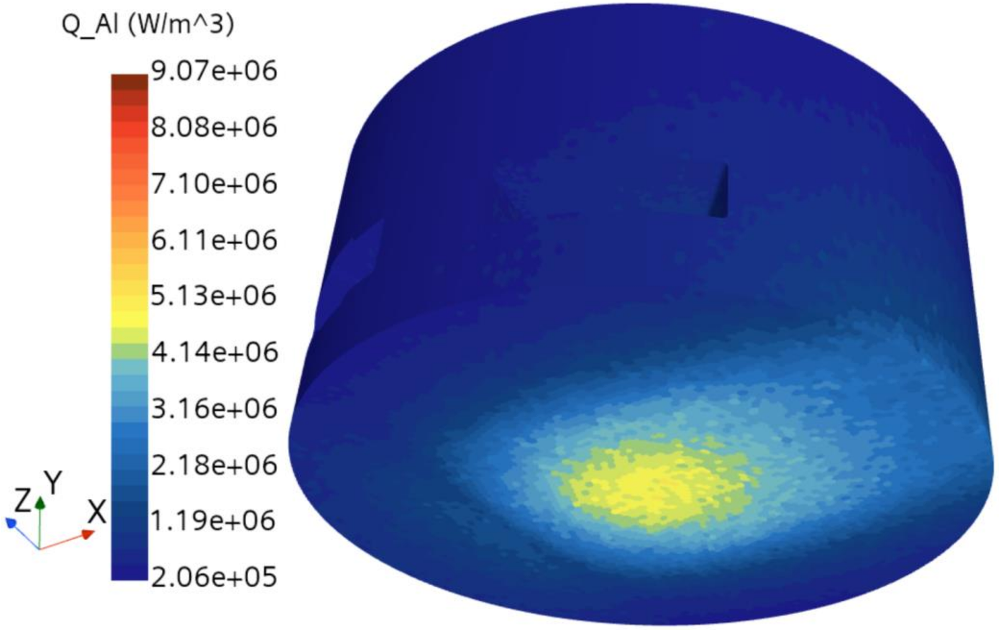
Upper MRA (Without Moderators)				
	Al	**Be**	**PreModerator (H2O)**	**Reflector (H2O)**
Mesh Type	Polyhedral mesh	Polyhedral mesh	Polyhedral mesh	Polyhedral mesh
Base Size (m)	1.00E-02	1.00E-02	4.00E-03	2.00E-03
Target Surface Size (m)	5.00E-03	5.00E-03	2.00E-03	1.00E-03
Minimum Surface Size (m)	1.00E-03	1.00E-03	4.00E-04	2.00E-04
Number of Prism Layers	0	0	8	8
Prism Layer Stretching	0	0	1.5	1.5
Prism Layer Total Thickness (m)	0	0	1.33E-03	7.00E-04
Number of Cells	**2.42E+05**	**1.77E+05**	**1.13E+06**	**5.18E+06**
Total Cells	**6.74E+06**			

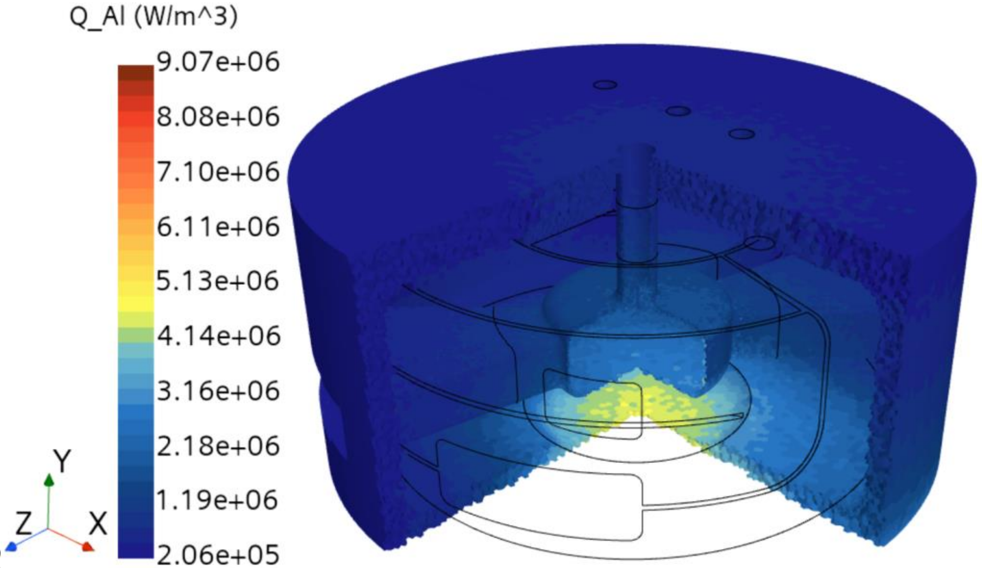
Thermal Properties

Material	Thermal Conductivity, k (W/m-K)	Density, ρ (kg/m^3)	Specific Heat, Cp (J/kg-K)	Viscosity (Pa-s)
Al	167	2800	880	N/A
Be	168	1850	1925	N/A
H2O (PreModerator & Reflector)	0.617	995	4173	7.98E-04

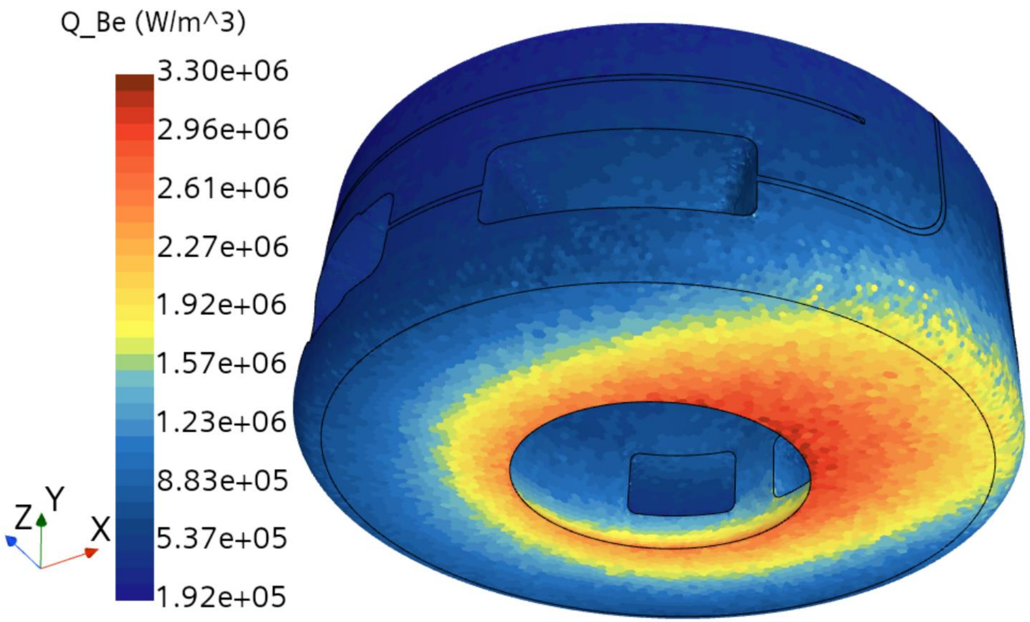
Steady State Heat Transfer Analysis for Upper MRA, Heat Source

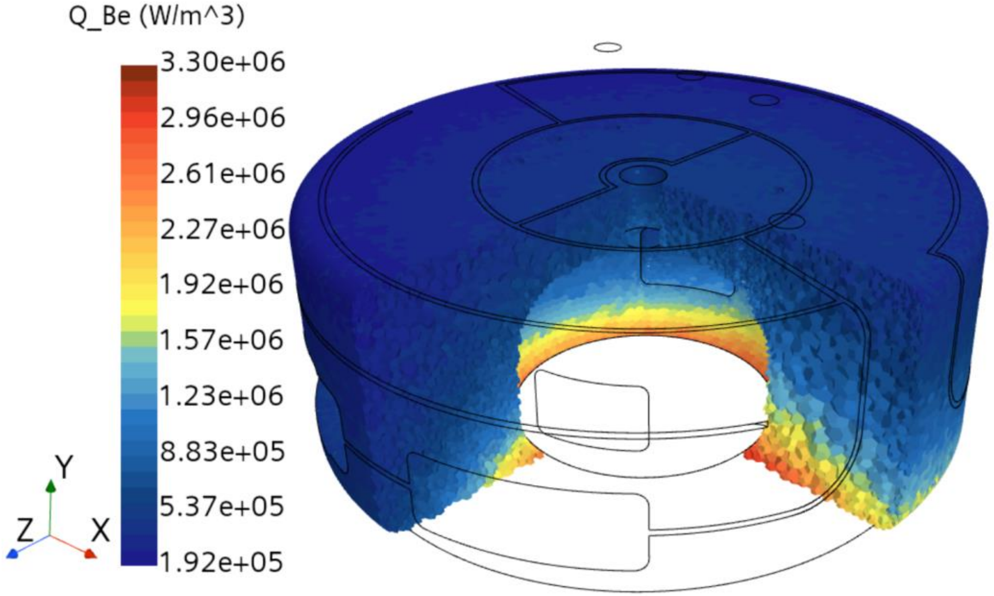
Q_Al = 4.99 kW





Q_Be = 6.42 kW

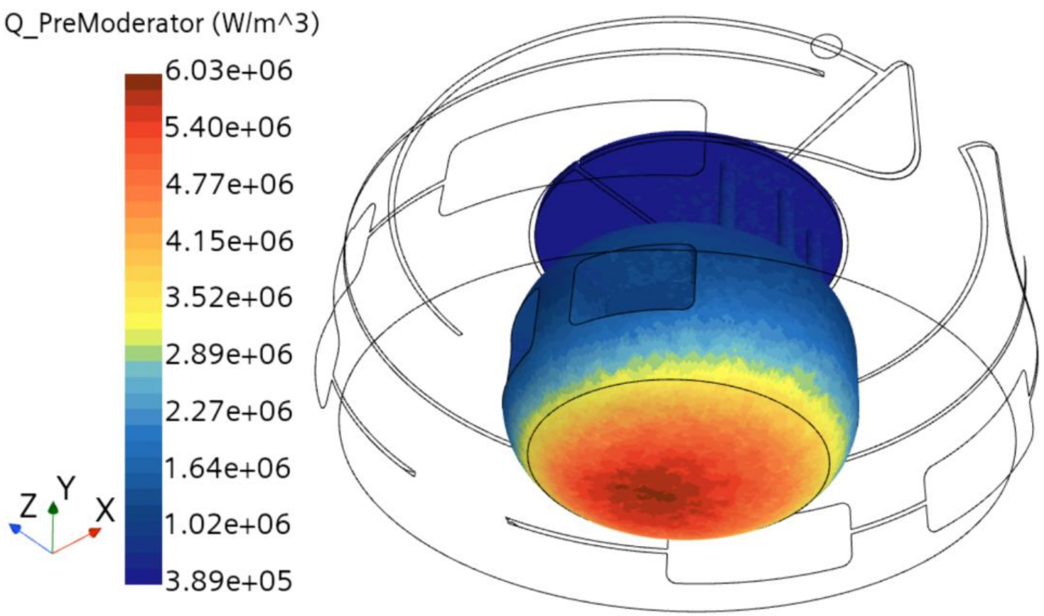


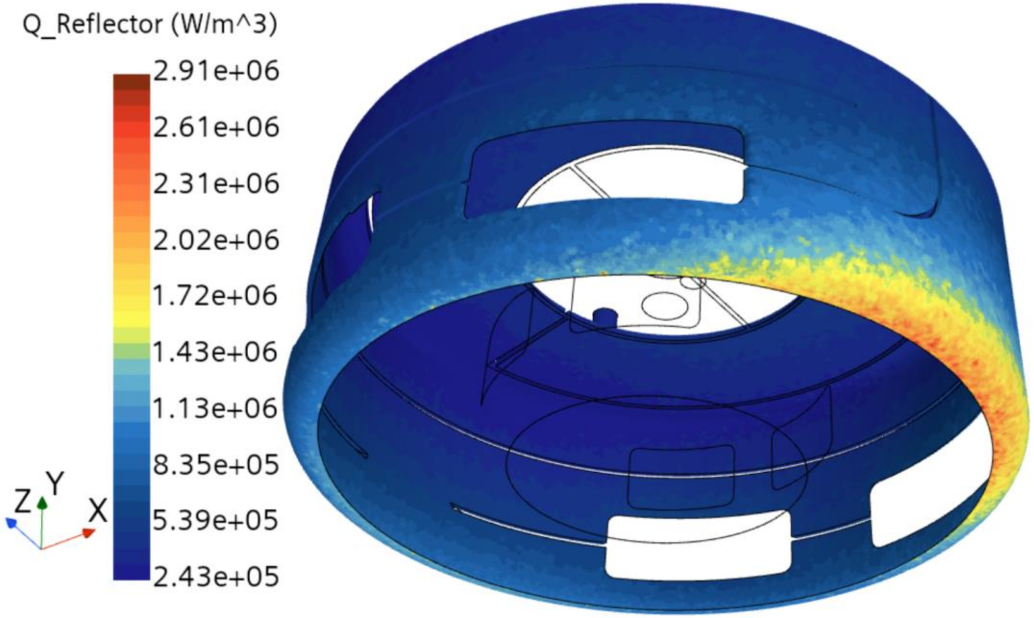


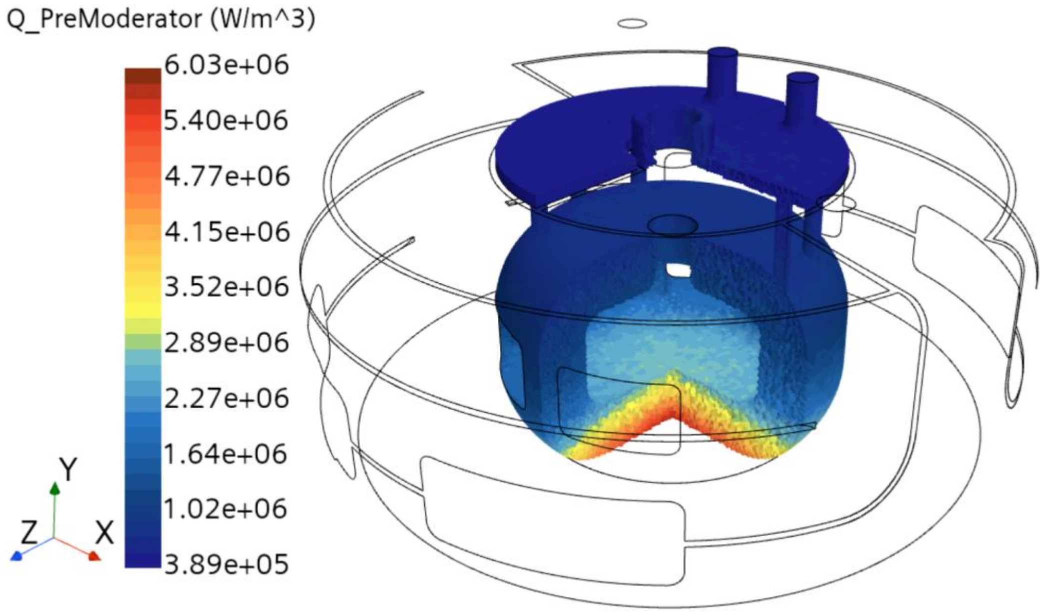
Steady State Heat Transfer Analysis for Upper MRA, Heat Source

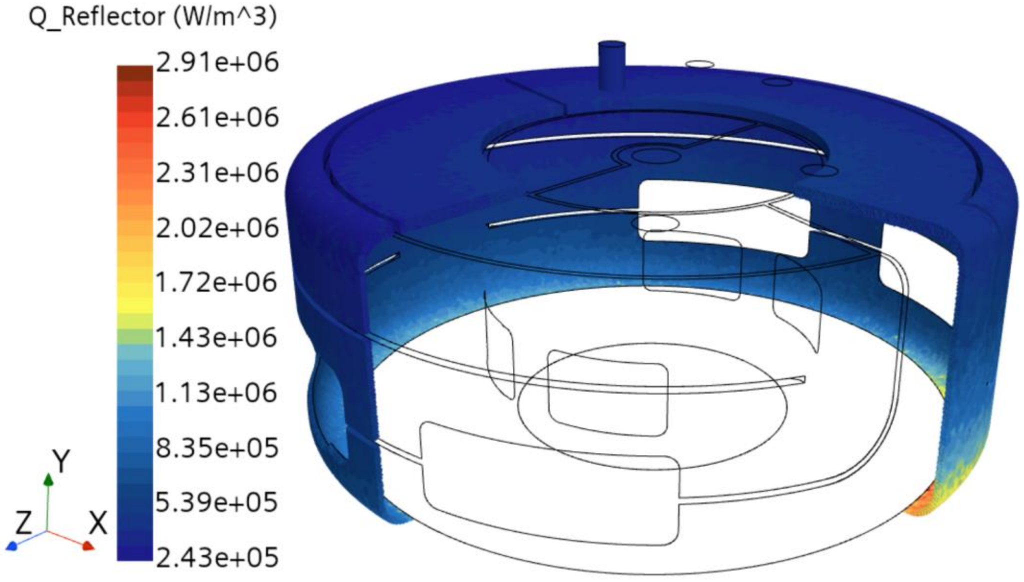
Q_PreModerator = 2.98 kW

Q_Reflector = 0.39 kW





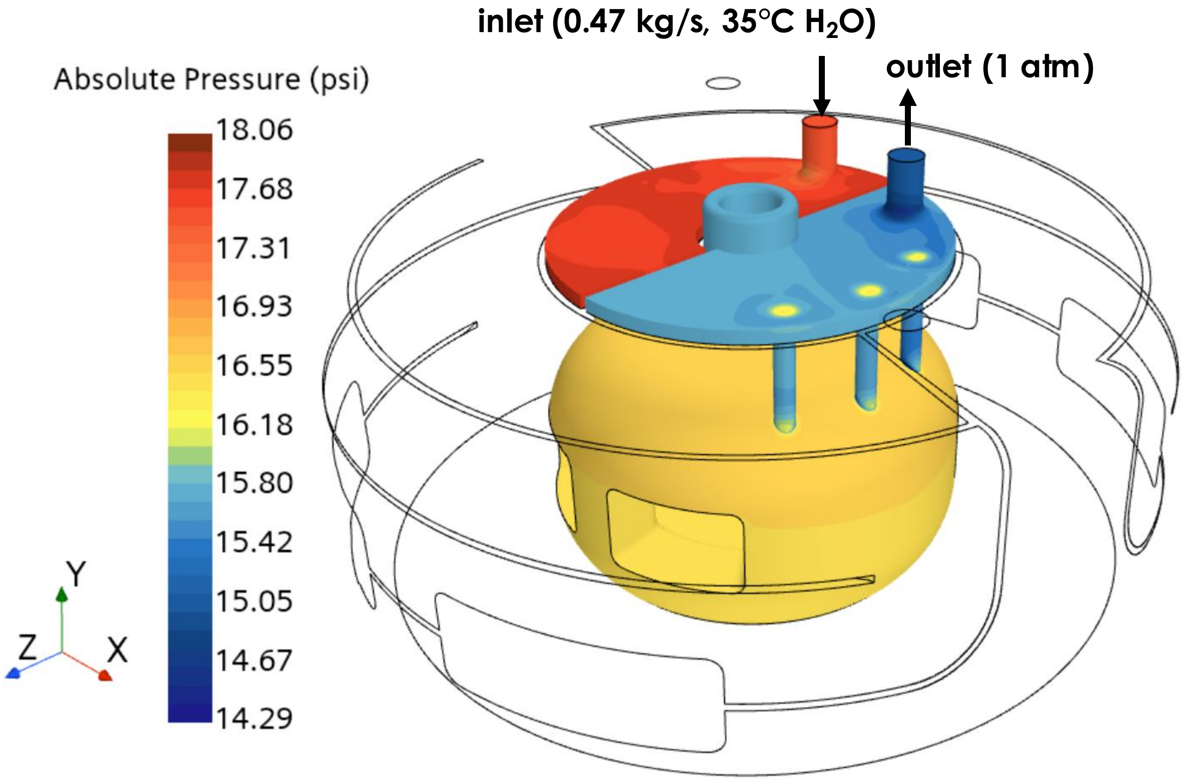


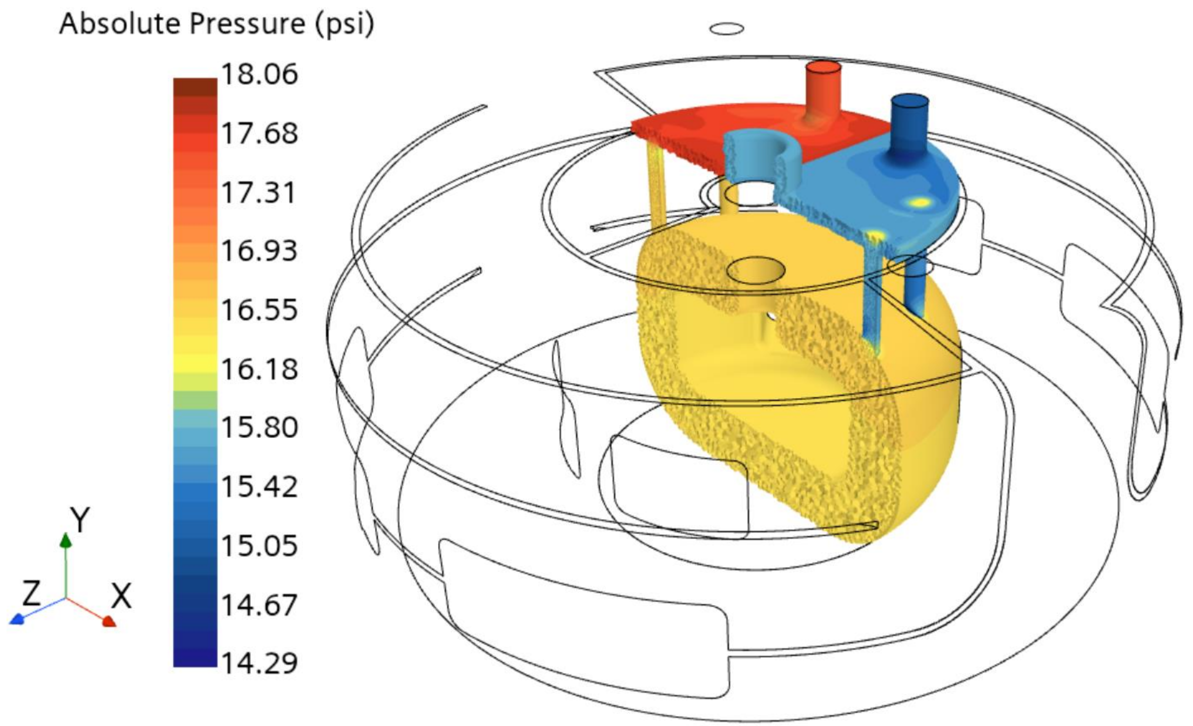


Steady State Heat Transfer Analysis for Upper PreModerator, Pressure

$$\Delta P_{inlet-outlet} = 0.17 \text{ bar } (= 17.4 \text{ kPa} = 2.53\ psi = 0.17\ atm)$$

Requirement: < 15 psi

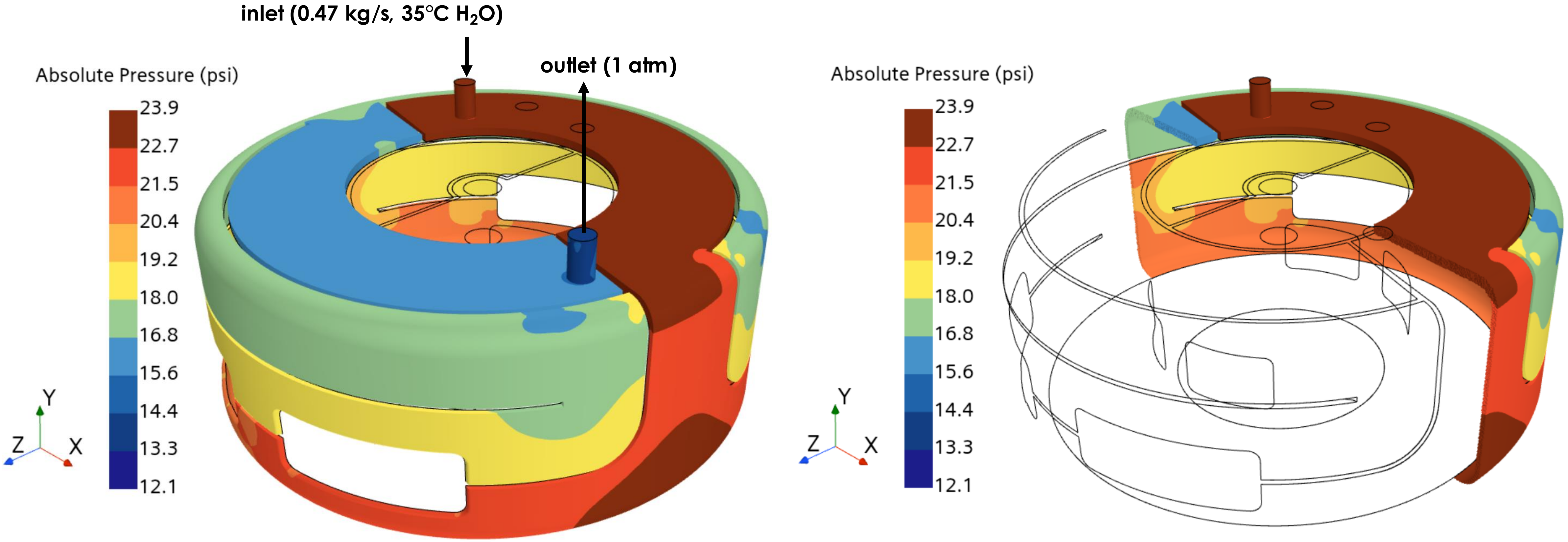




Steady State Heat Transfer Analysis for Upper Reflector, Pressure

$$\Delta P_{inlet-outlet} = 0.56 \text{ bar } (= 56.5 \text{ kPa} = 8.2\ psi\ = 0.56\ atm)$$

Requirement: < 15 psi

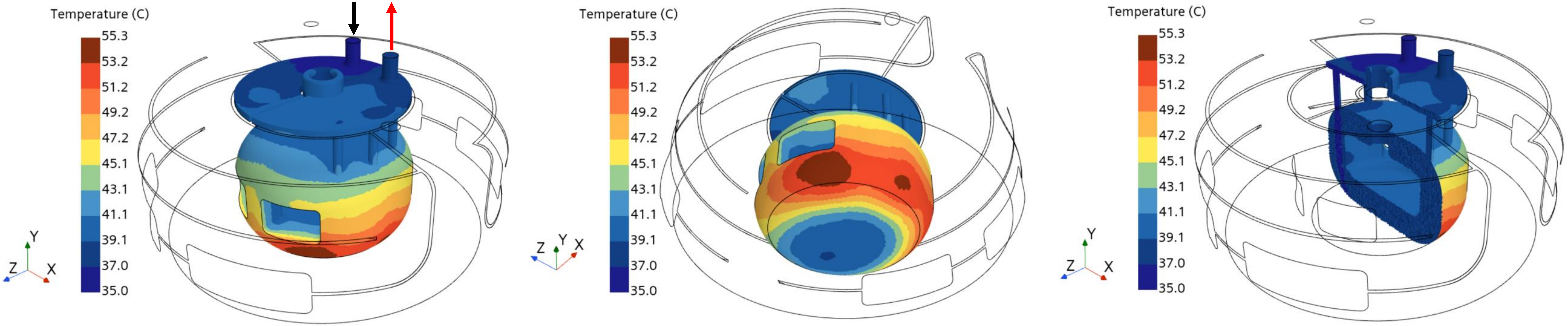


Steady State Heat Transfer Analysis for Upper PreModerator (H_2O), Temperature

Requirement: < 100°C

Peak Temperature of Upper PreModerator: 55.3°C

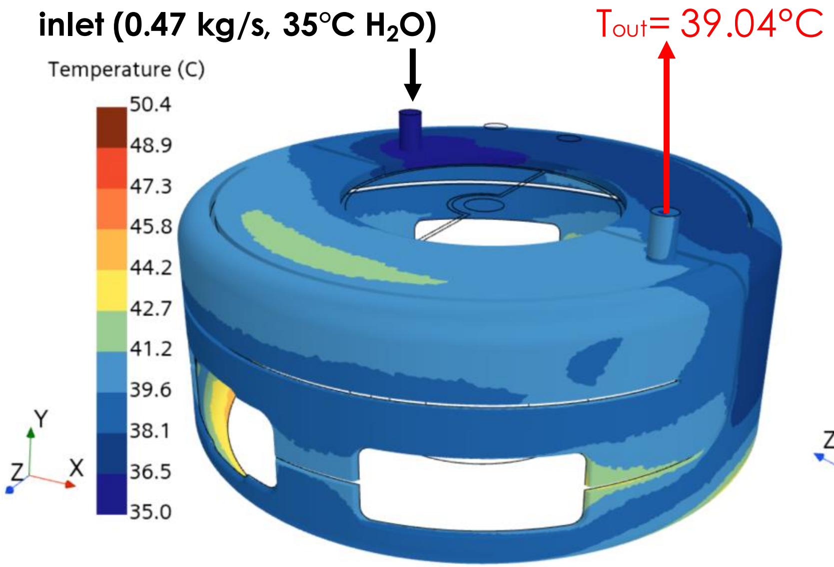
inlet (0.47 kg/s, 35°C H_2O) T_{out}= 38.30°C

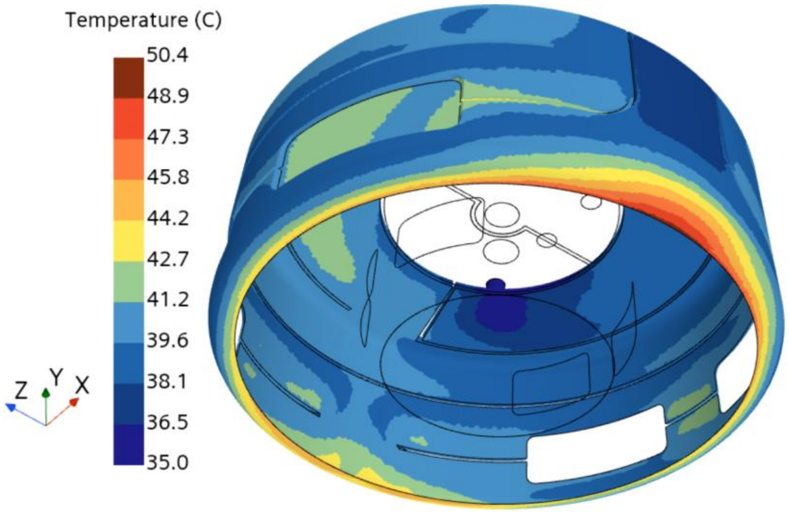


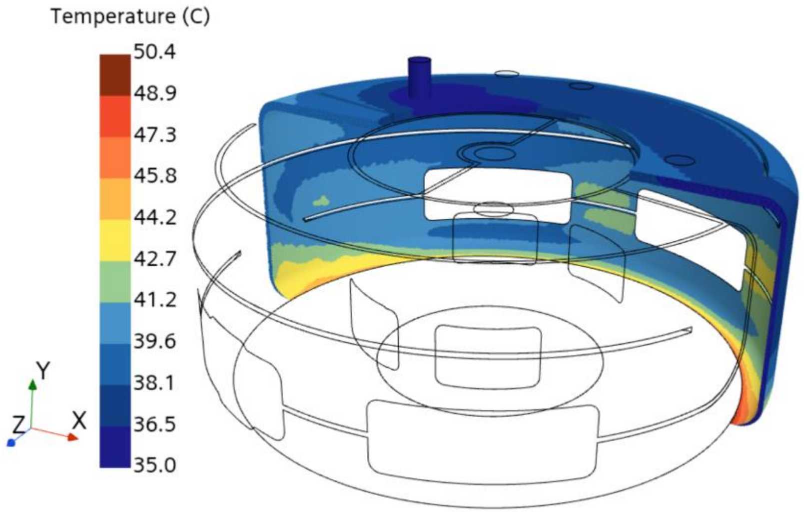
Steady State Heat Transfer Analysis for Upper Reflector(H_2O), Temperature

Requirement: < 100°C

Peak Temperature of Upper Reflector: 50.4°C



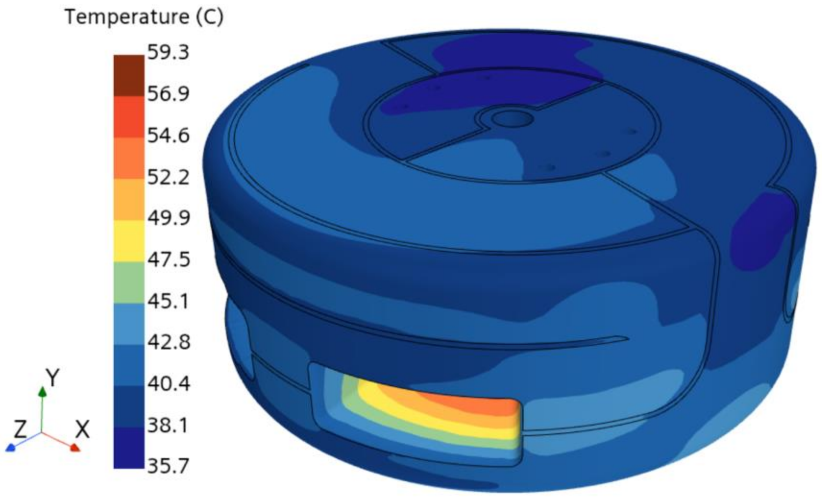


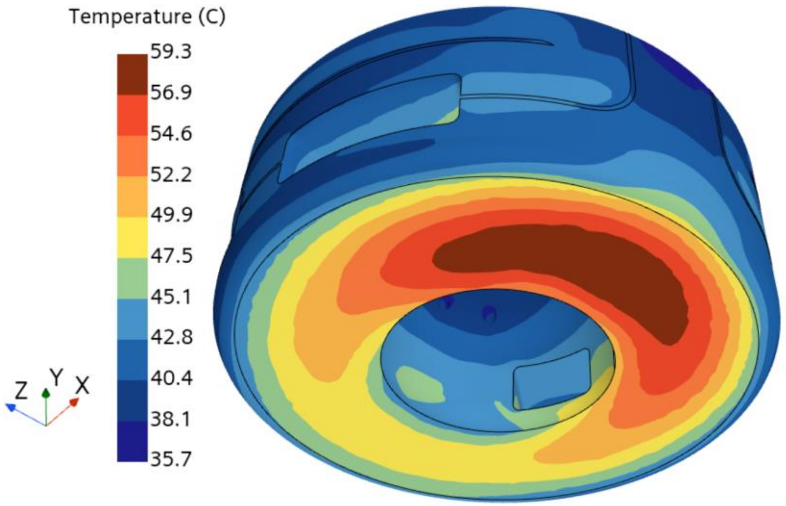


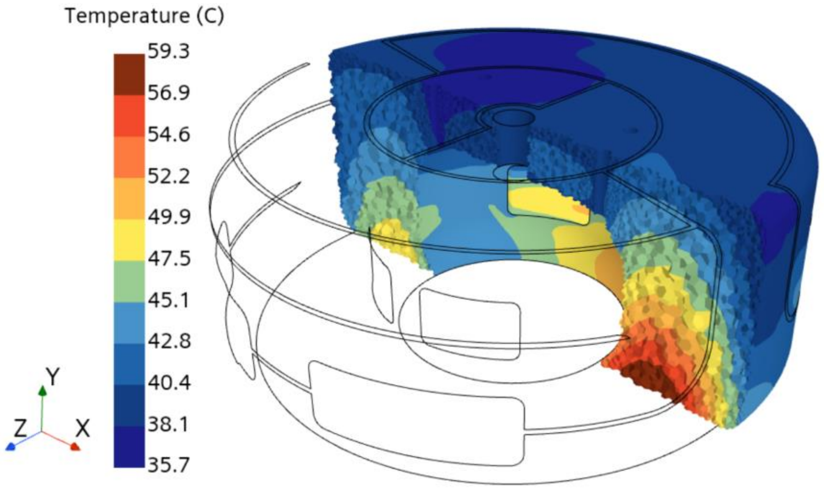
Steady State Heat Transfer Analysis for Upper Be, Temperature

Requirement: < 100°C

Peak Temperature of Upper Be: 59.3°C



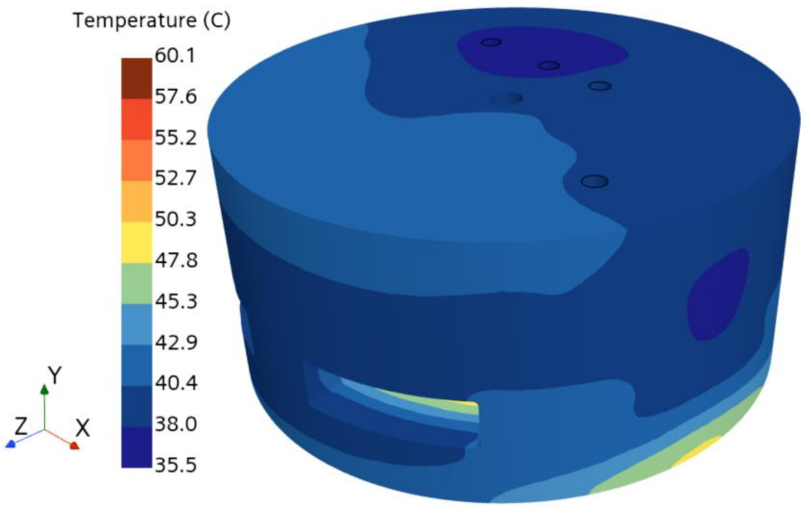


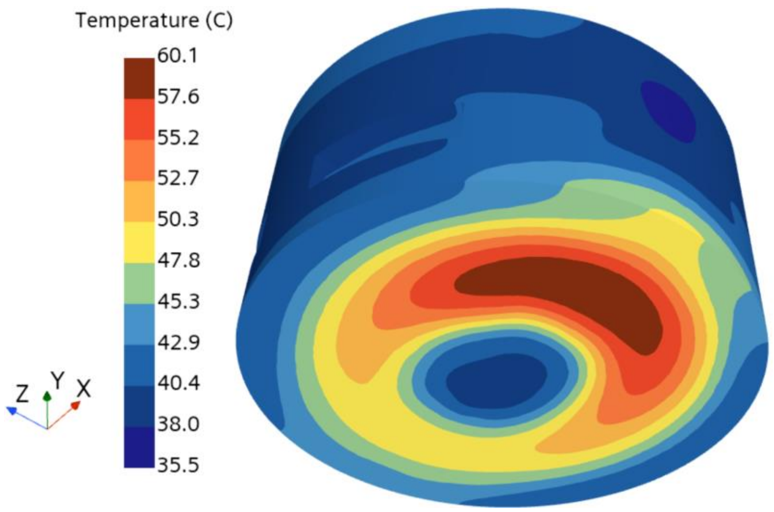


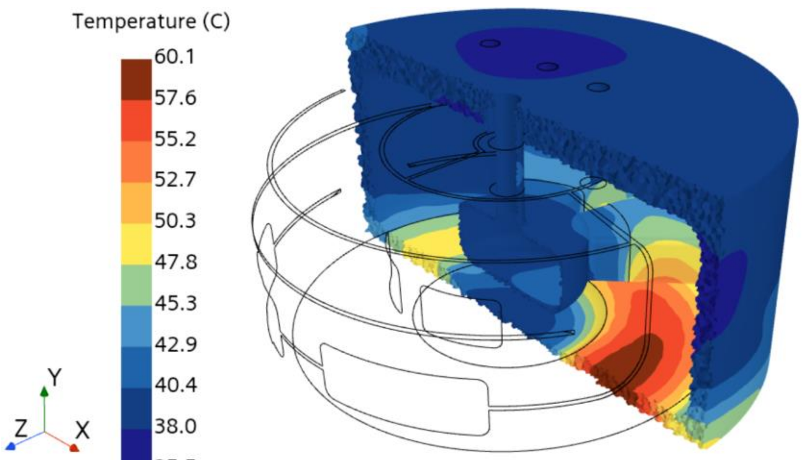
Steady State Heat Transfer Analysis for Upper Al, Temperature

Requirement: < 100°C

Peak Temperature of Upper Al: 60.1°C

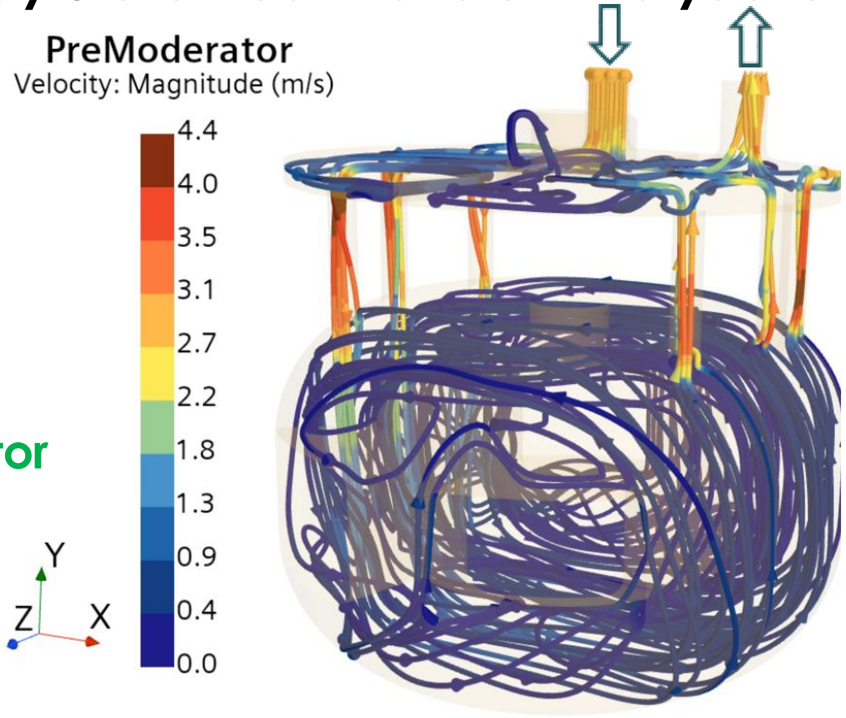




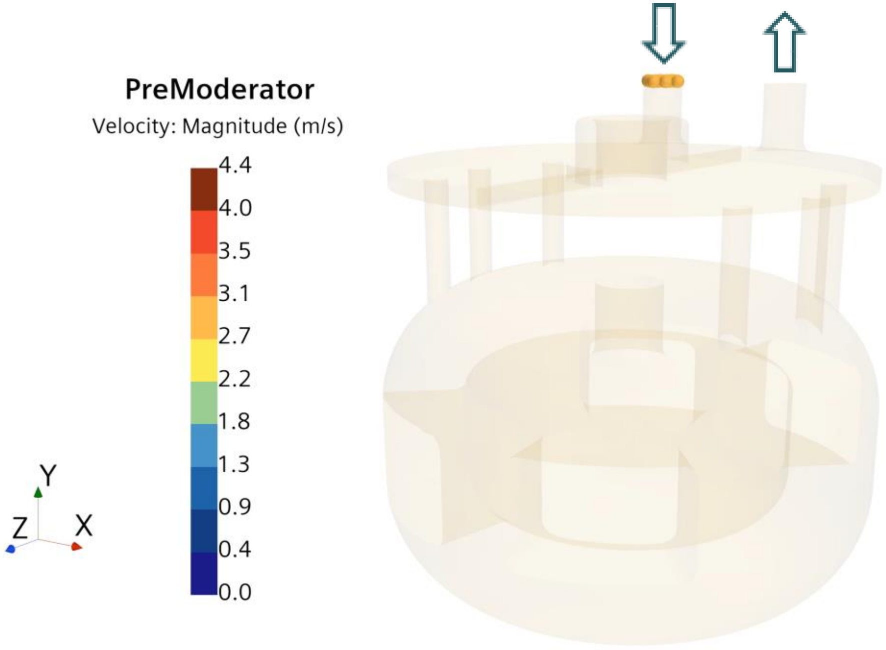


Steady State Heat Transfer Analysis for Tube Moderator, Streamlines

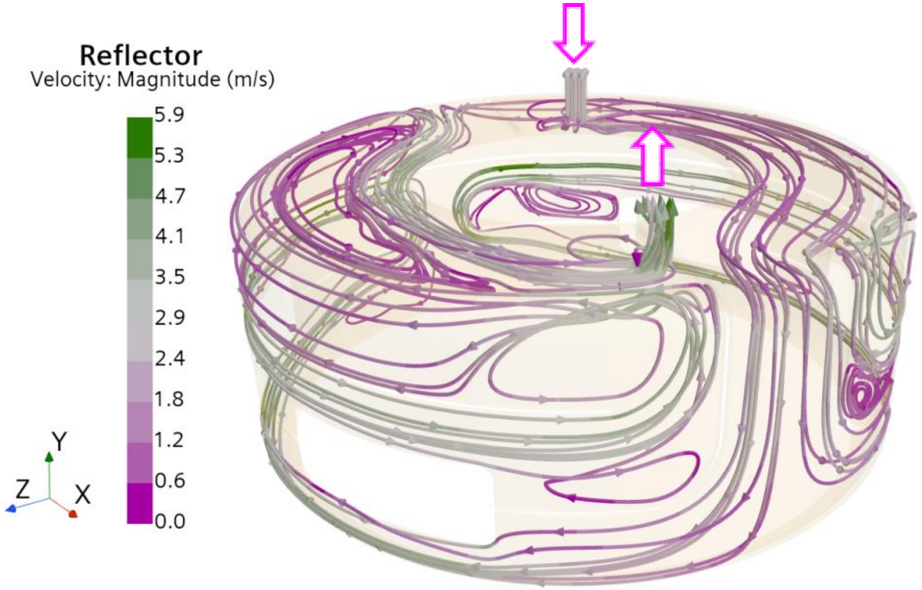
Upper PreModerator

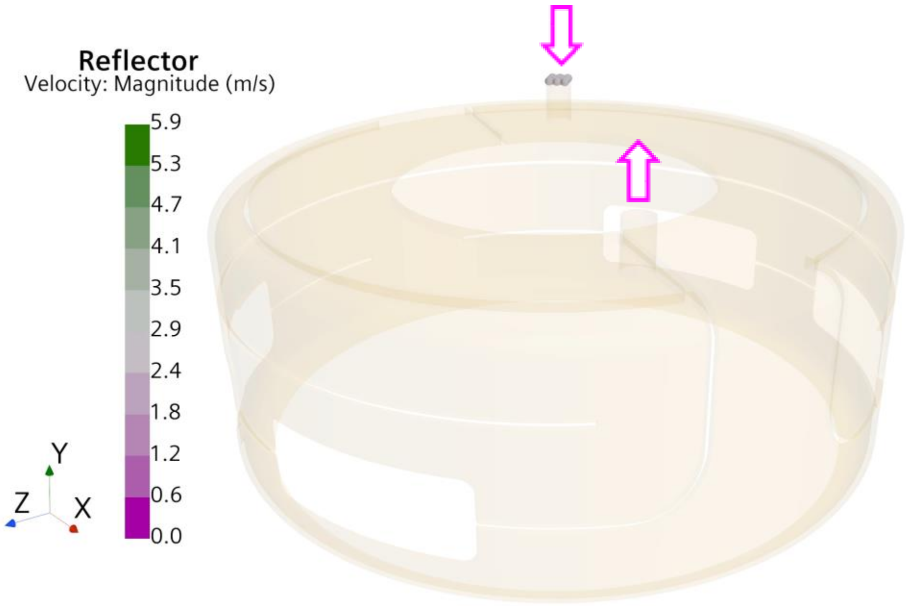


Animation

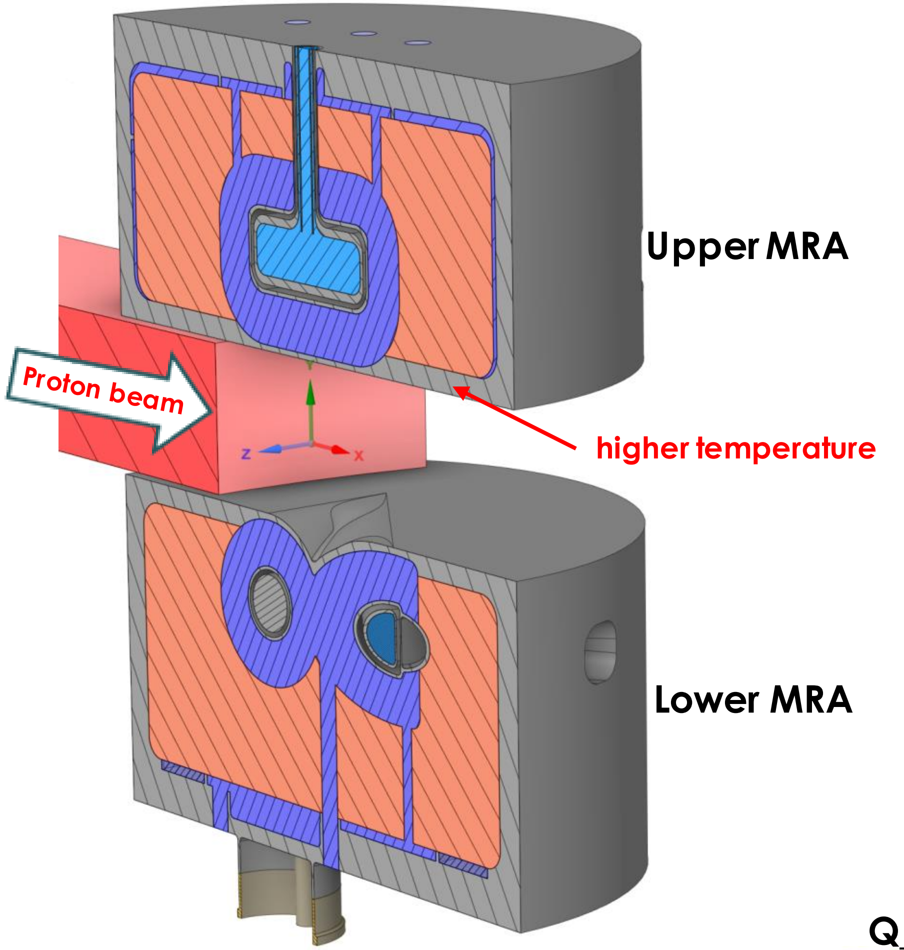


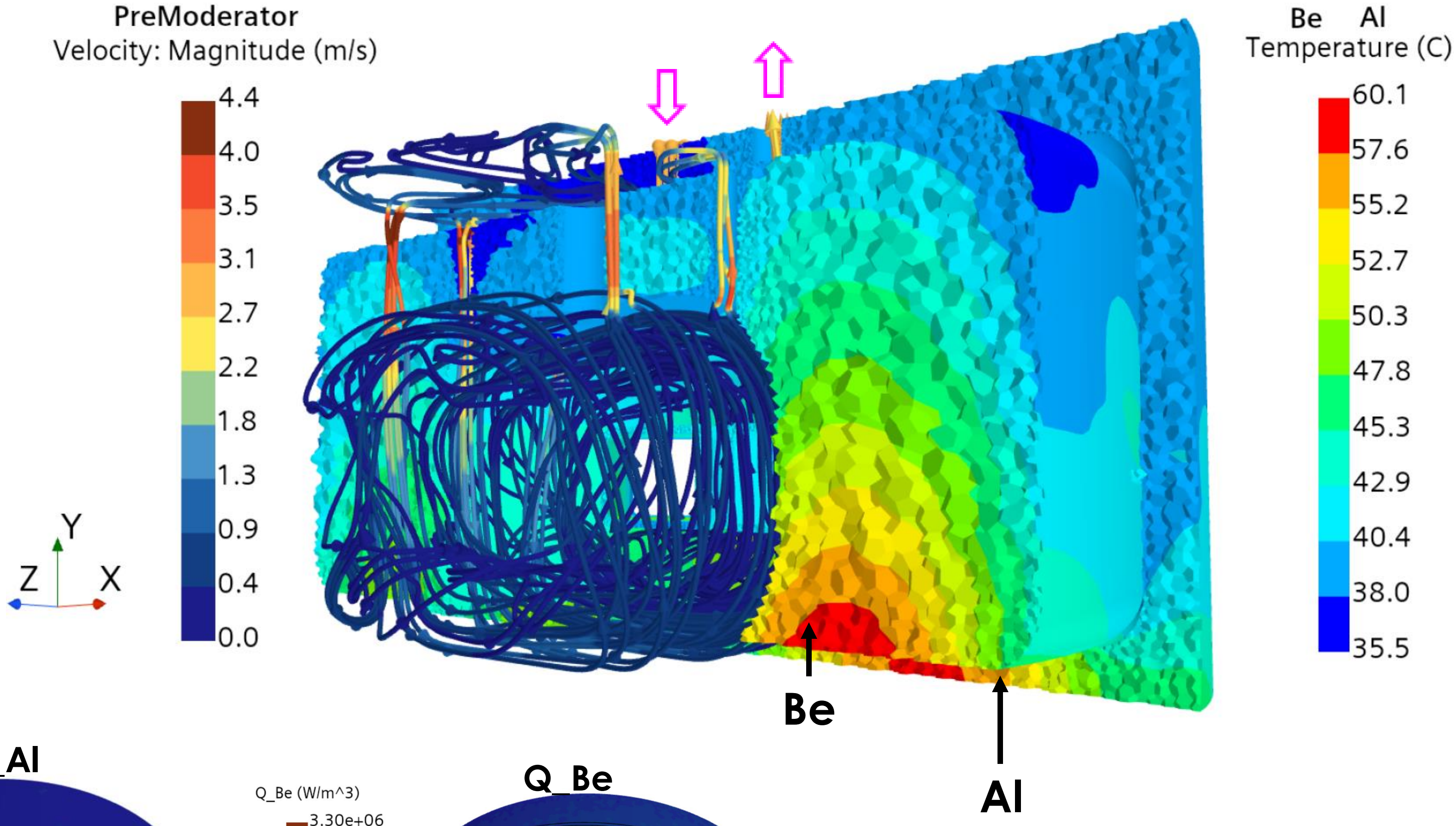
Upper Reflector

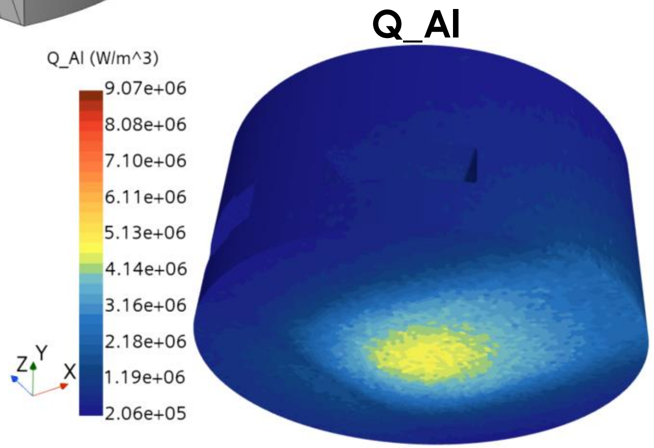


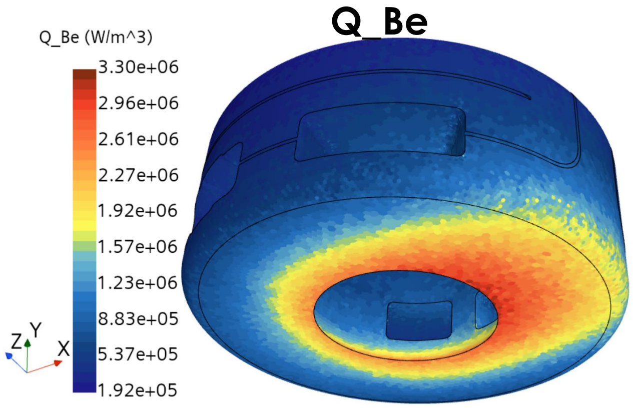


Steady State Heat Transfer Analysis for Upper MRA, Velocity & Temperature









Comparison between Requirements and CFD Results

Upper MRA (without Moderator)

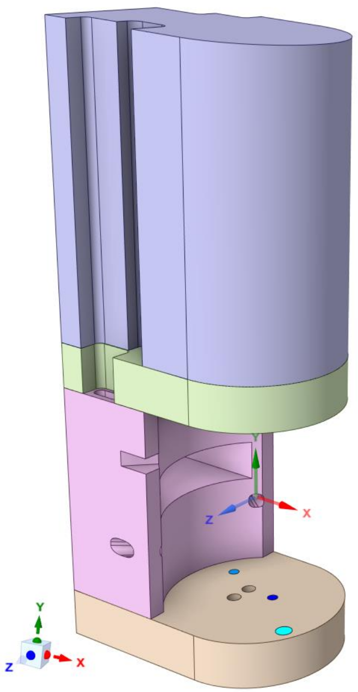
	Requirement	CFD Result	
Maximum Aluminum Temperature (°C)	< 100	60.1	
Maximum Beryllium Temperature (°C)	< 100	59.3	
		PreModerator	**Reflector**
Pressure Drop (psi)	< 15	2.53	8.2
Maximum Water Temperature (°C)	< 100	55.3	50.4

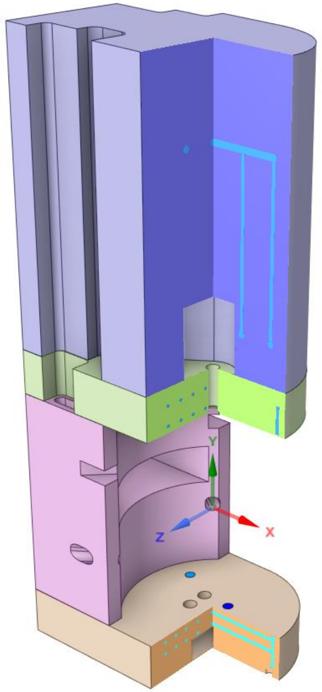
- All requirements are met with at least a factor of 1.83 margin
  - High confidence that margin to requirements is significantly higher than uncertainties

Summary

- The locations of the inlet and outlet for the reflector were adjusted several times to reduce the pressure drop from 22 psi to 8 psi. The main idea is to reduce the vortex near the outlet since the pressure within the vortex region is very low and thus the pressure would be increased.
- All requirements are met with high margins
- Items to be included in final analysis
  - Update inlet/outlet geometry based on final backbone design
    - Preliminary backbone inlet/outlets are moved slightly from locations used in this analysis
  - Update inlet temperature to match final process systems inlet temperature – current estimate is 32.3 C
  - Include weld backer geometry for the reflector vessel welds

Part 3 : CFD analysis for the MRA backbone



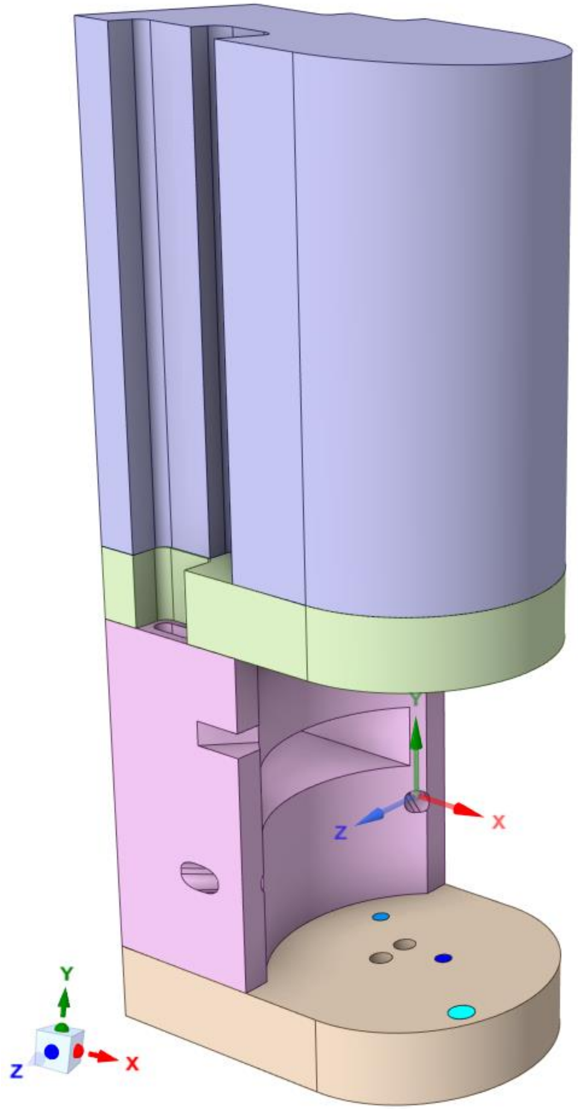


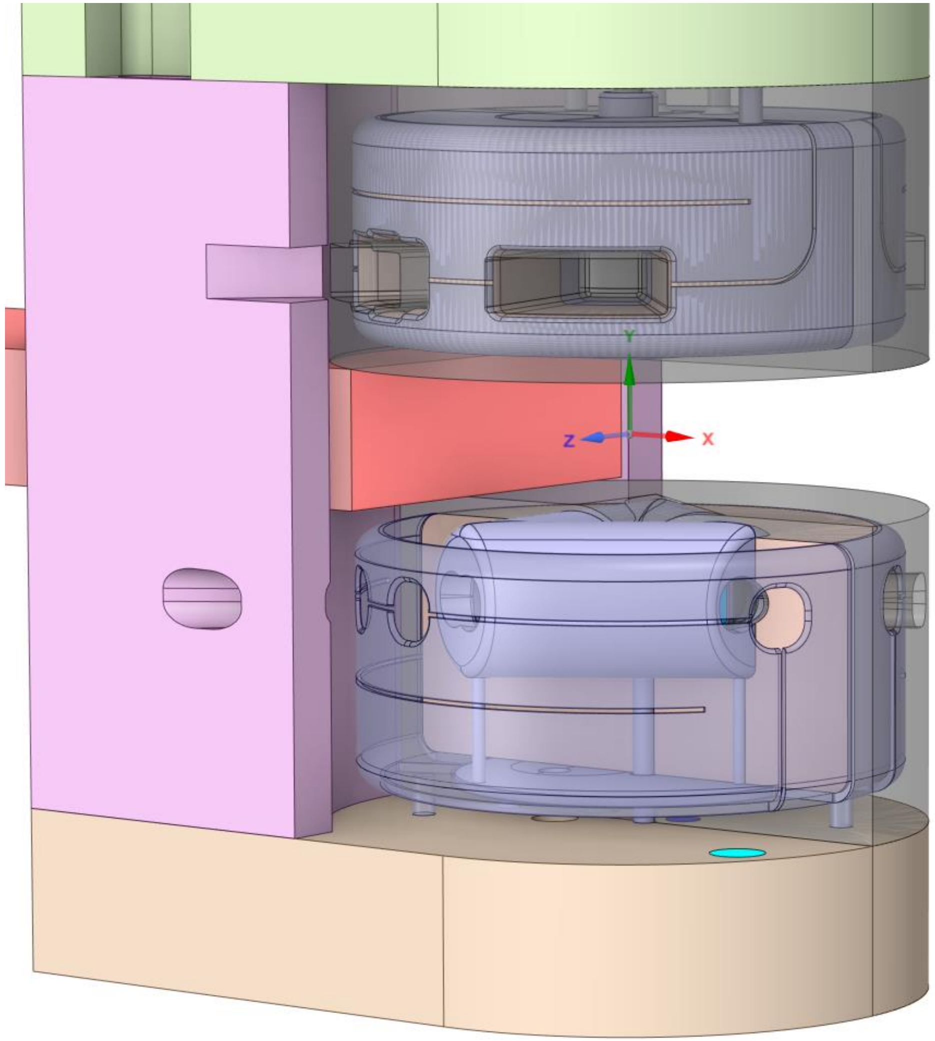
Requirements for MRA Backbone

- This thermal-hydraulic analyses were performed to demonstrate that the current MRA backbone design can meet the following requirements.
- **Requirements**
  - Maximum water temperature < 100°C
    - No water boiling
  - Maximum stainless-steel temperature < 200°C
  - Pressure drop < 0.5 psi
    - For the cooling loops 1 & 2
  - Pressure drop < 4.0 psi
    - For the cooling loops 3 & 4
- **Goal** : minimize stainless steel temperatures in order to minimize thermal displacements

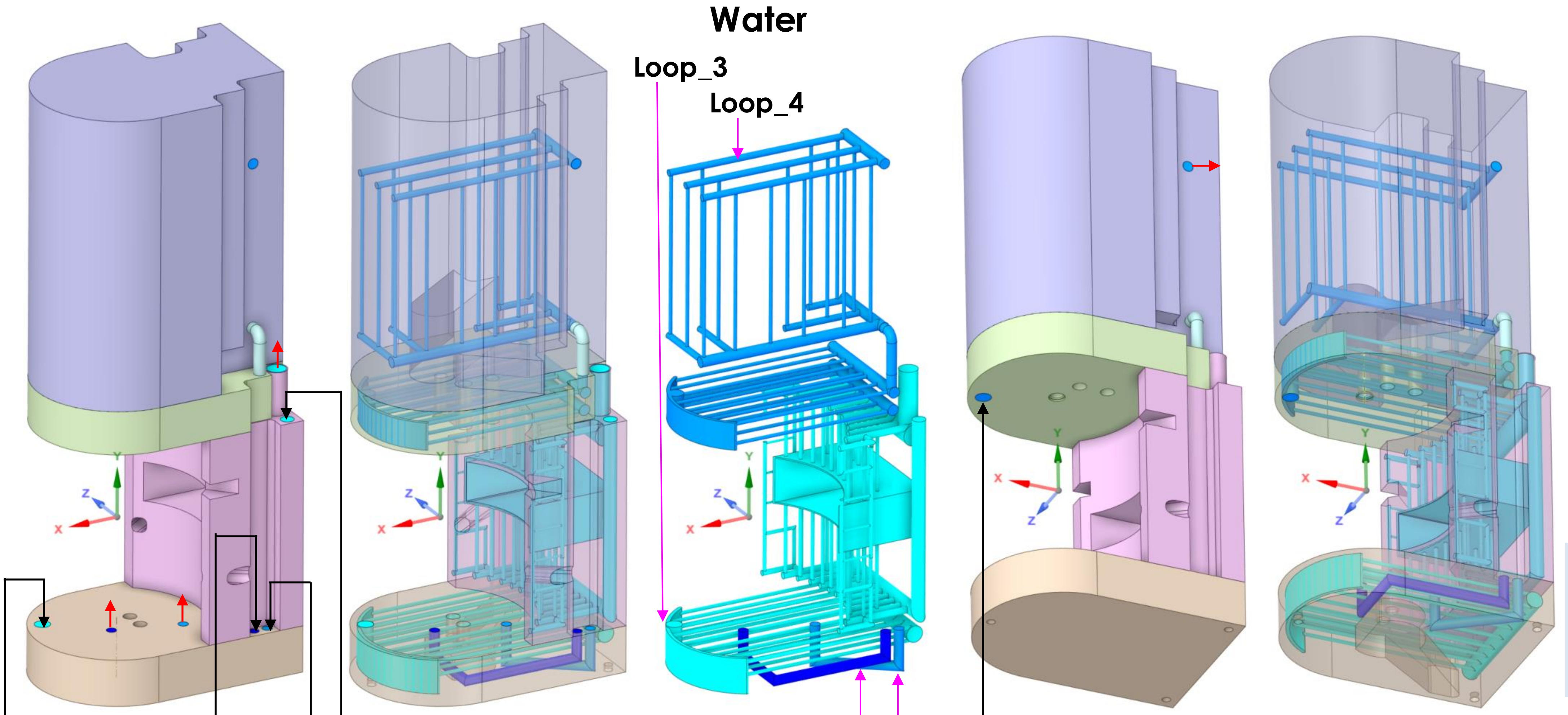
Geometry

MRA Backbone





MRA Full Backbone Geometry



Loop_3_1 & Loop_4: outlet temperatures from reflector vessel analyses

0.47 kg/s (7.5 GPM) , 35.0°C (**Loop_1: Lower Reflector Inlet**)

0.47 kg/s (7.5 GPM) , 35.0°C (**Loop_2: Lower Premoderator Inlet**)

0.94 kg/s (15 GPM) , 39.2°C (**Loop_3_1: Lower Reflector/Premoderator Combined Outlet**)

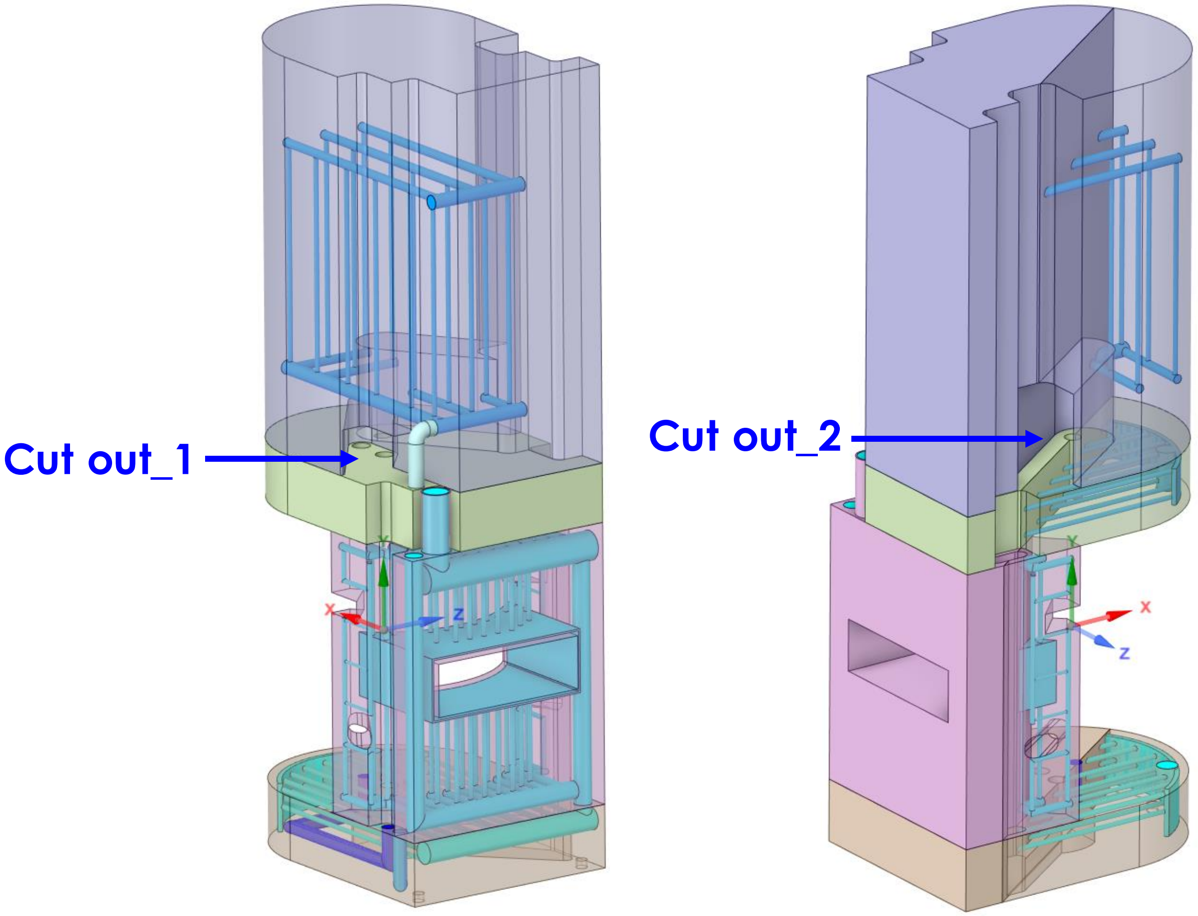
0.94 kg/s (15 GPM) , 35.0°C (**Loop_3_2: Middle Backbone Inlet**)

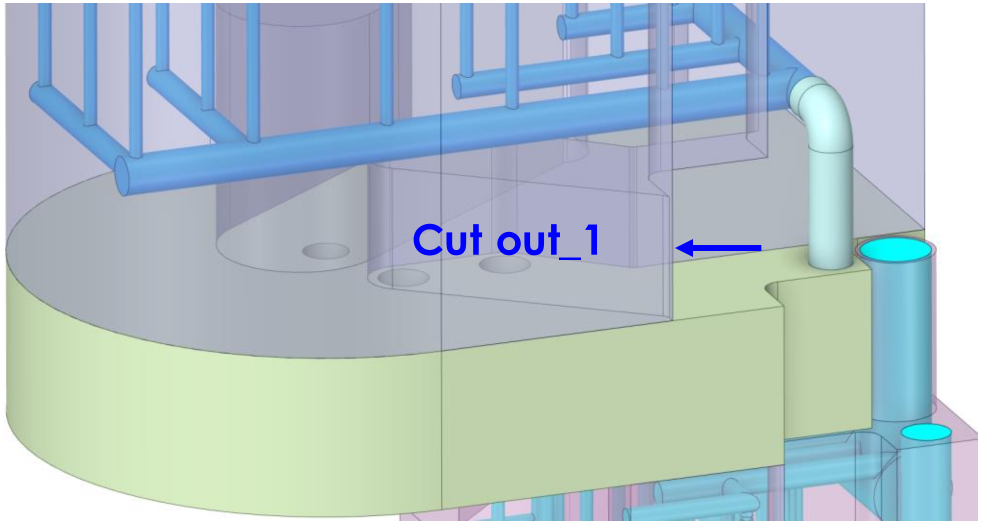
0.94 kg/s (15 GPM) , 38.7°C (**Loop_4: Upper Reflector/Premoderator Combined Outlet**)

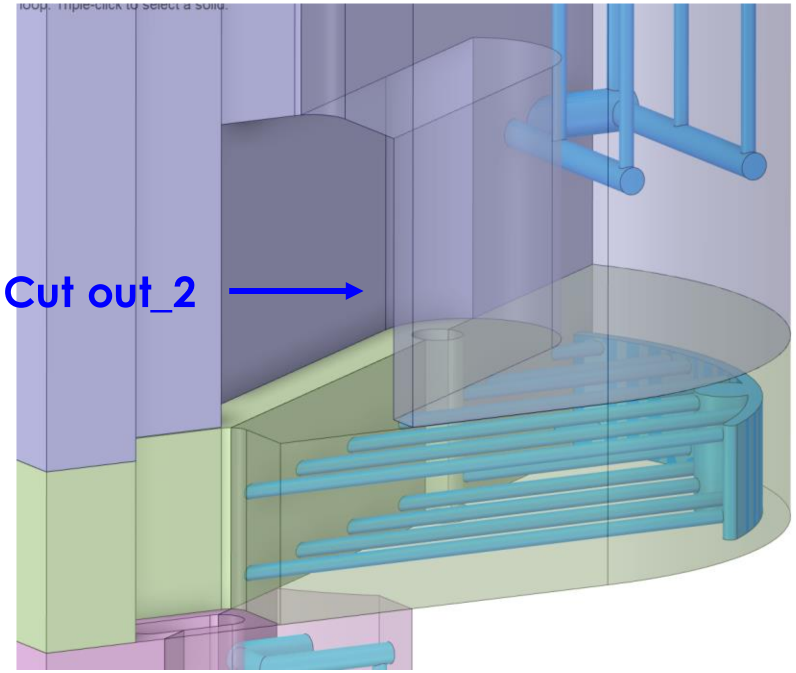
MRA Full Backbone Geometry, Pipe Cut Outs

Higher temperature is expected around the **Pipe cut outs** (difficult to route cooling passages)

Pipe Cut Outs:
slots with clearance for routing piping to the component

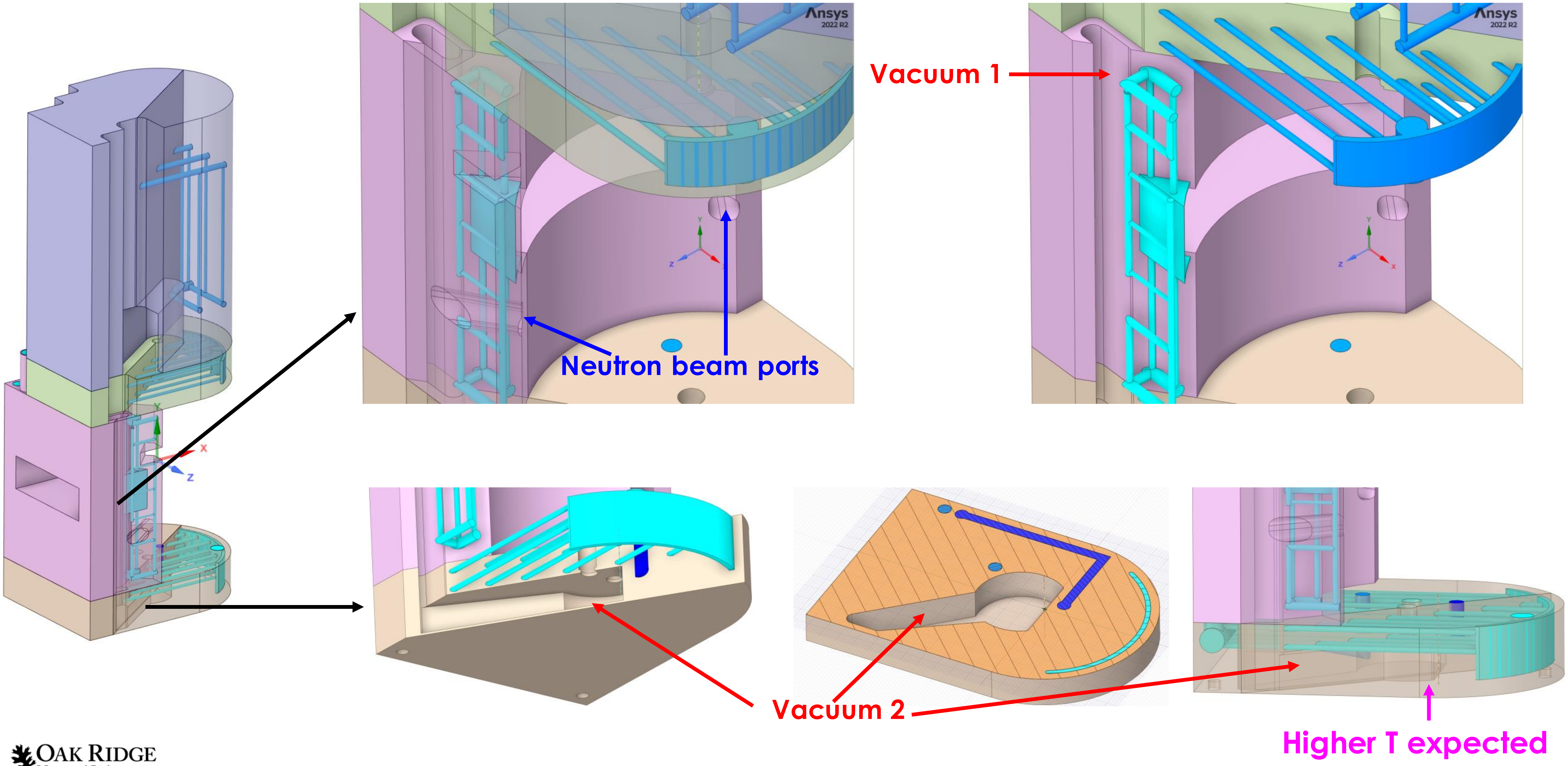






MRA Full Backbone Geometry, Vacuum Regions

Higher temperature is expected around the vacuum regions (difficult to route cooling passages)

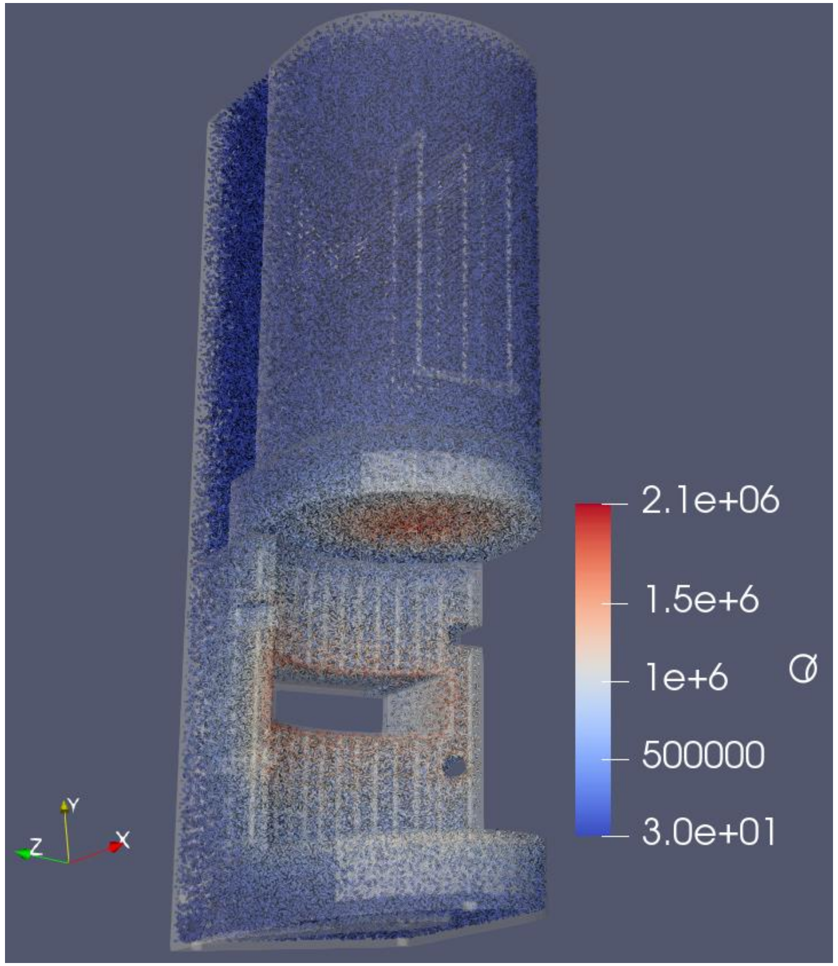


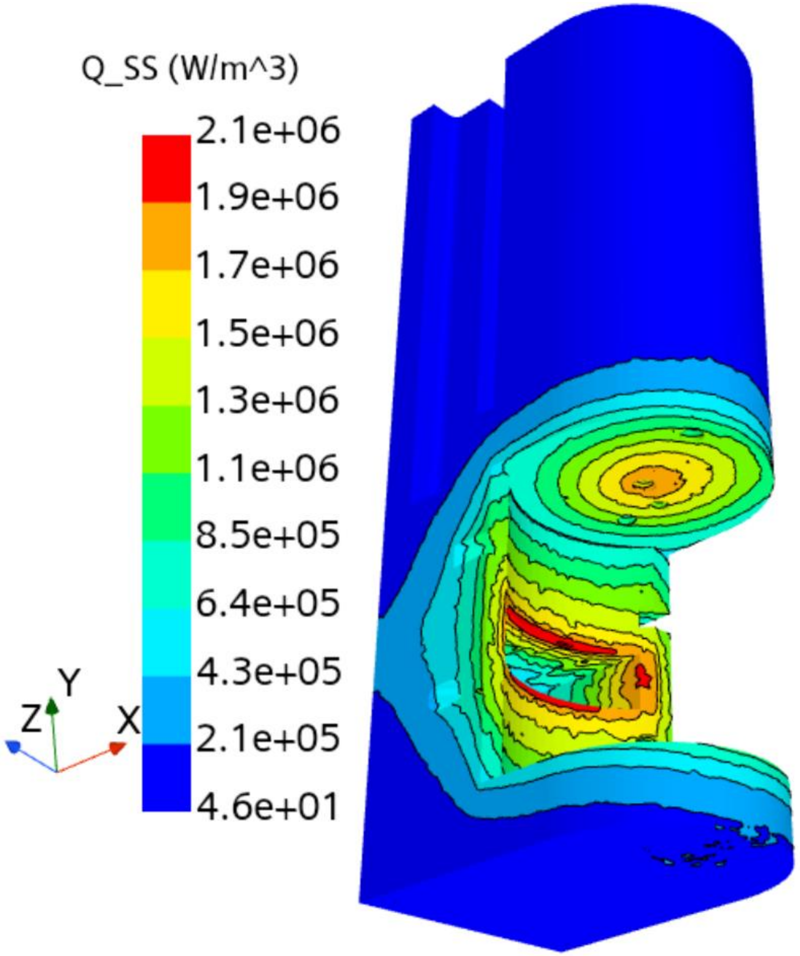
MRA Full Backbone Heat Source

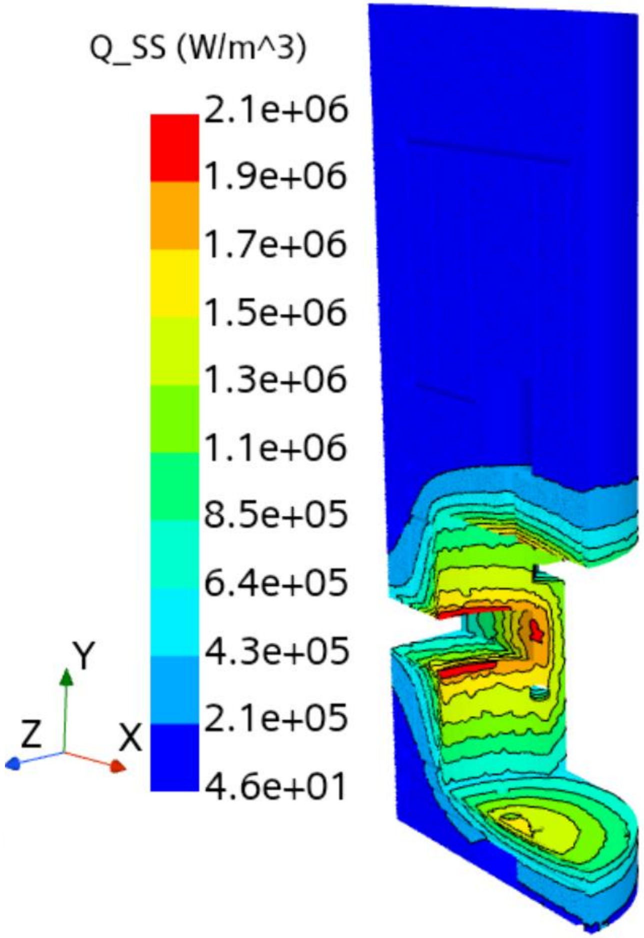
3.7% of 700 kW

$QSS = 26{,}054\ W$

energy deposition from Lukas

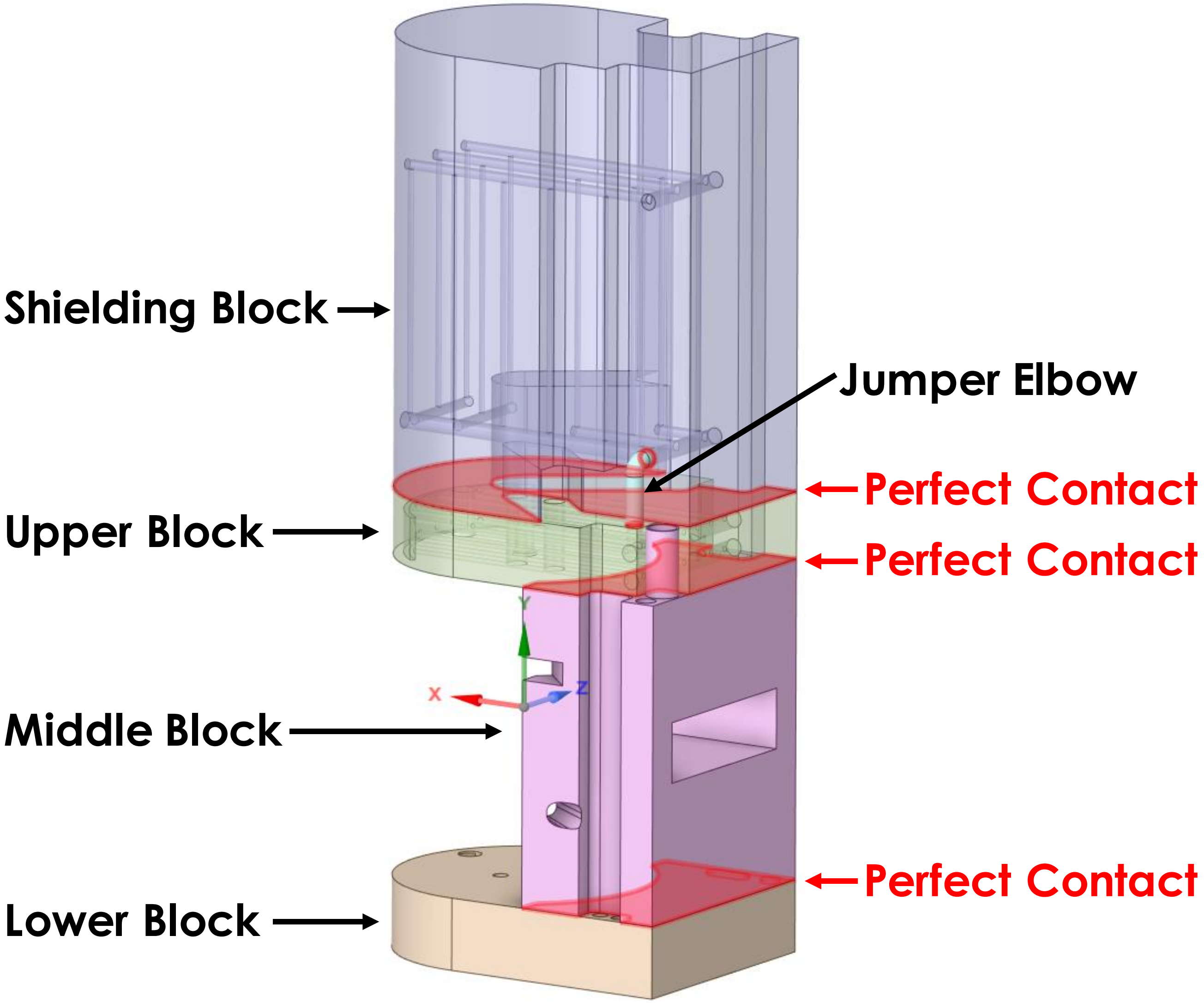






Oak Ridge National Laboratory

MRA Full Backbone Heat Source (Solid)

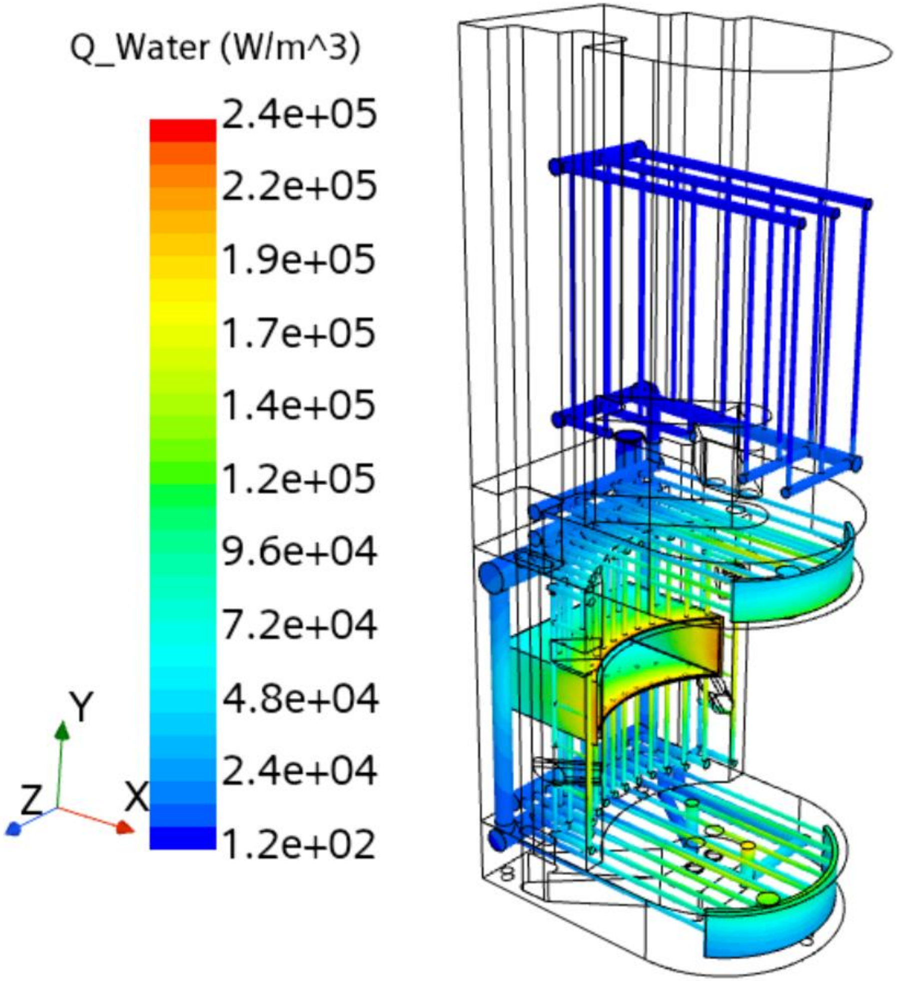


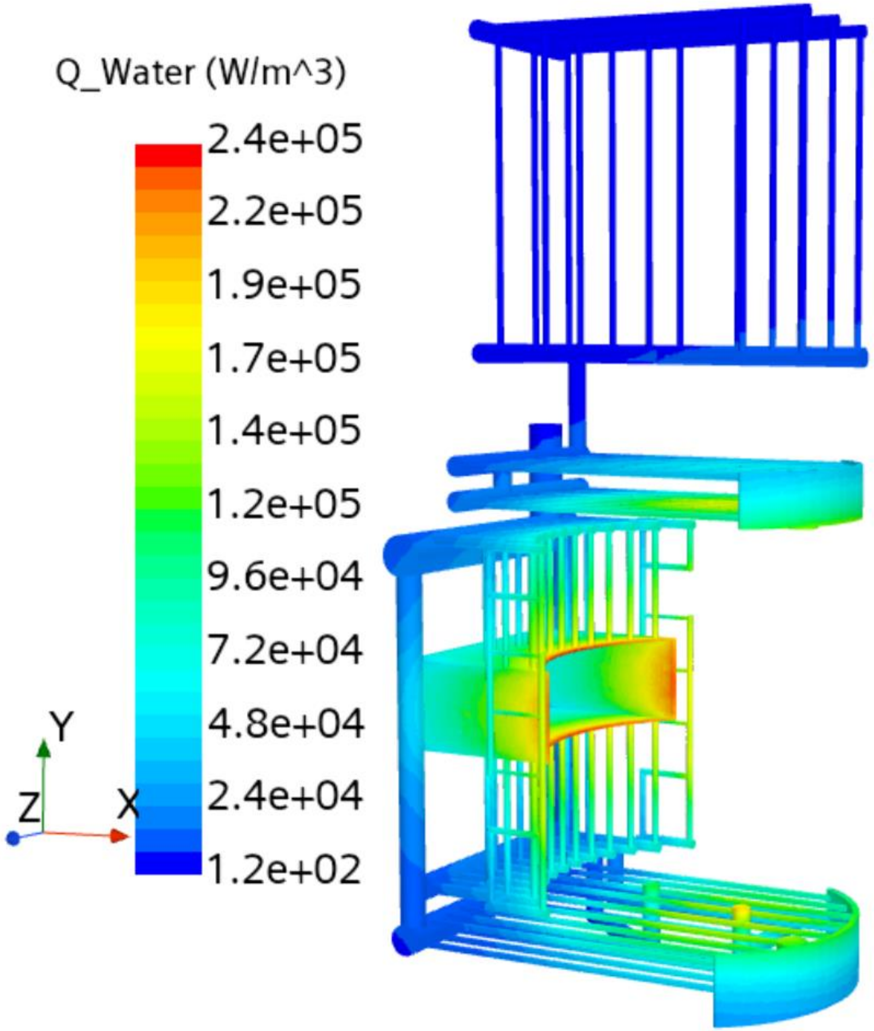
Part	Heat (W)
Shielding Block	2.157842e+03
Upper Block	6.494906e+03
Middle Block	1.199489e+04
Lower Block	5.405235e+03
Jumper Elbow	7.509197e-01

Heat Source in Water

Q_Water approximation: $Q_{water} = QSS * \frac{\rho_{water}}{\rho_{SS}} = QSS * \frac{997.561}{7969}$

Q_{water} = 229.57W





SS316 Material Properties from Ansys

SS316 Material Properties From Ansys

Stainless steel, 316, annealed
Data compiled by Ansys Granta, incorporating various sources including JAHM and MagWeb.

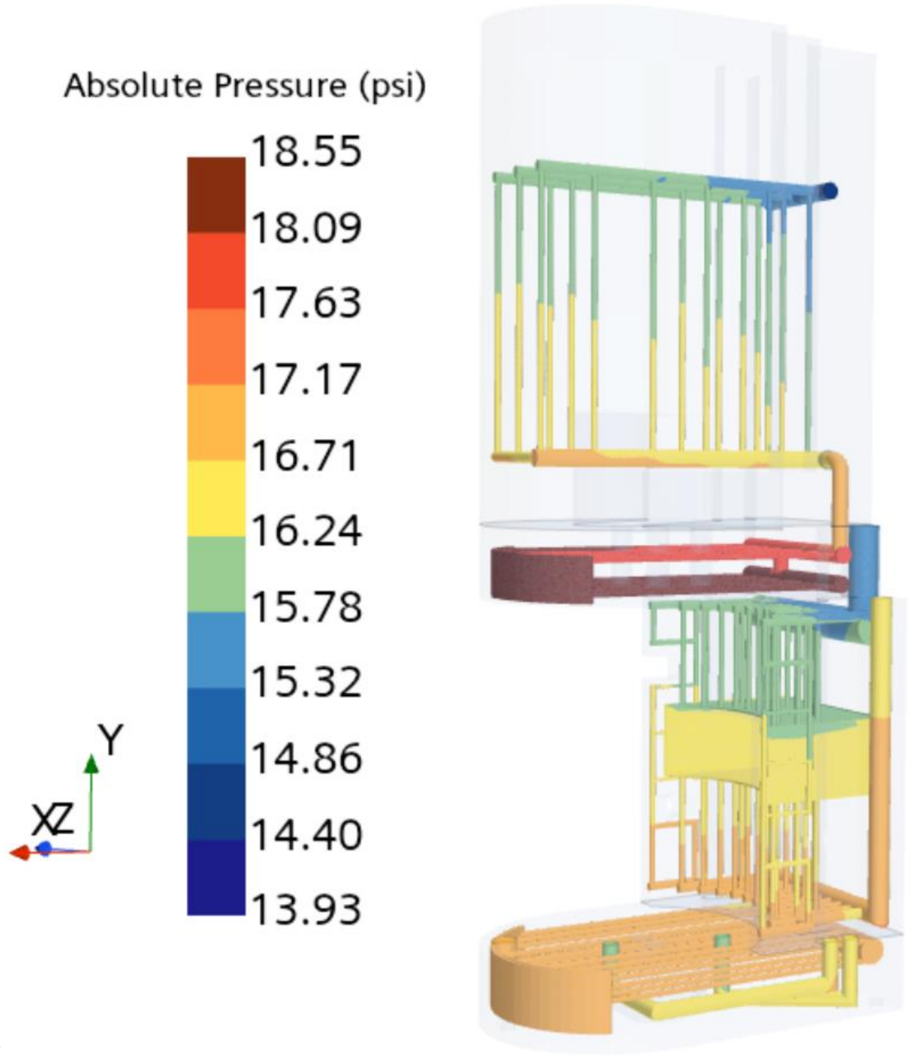
Density (kg/m^3)	7969
Coefficient of Thermal Expansion (1/K)	1.61E-05
Specific Heat (J/kg-K)	486.1
Thermal Conductivity (W/m-K)	14.58
Young's Modulus (Pa)	1.95E+11
Poisson's Ratio	0.27
Bulk Modulus (MPa)	1.413E5
Shear Modulus (MPa)	76772
Tensile Ultimate Strength (MPa)	565.1
Tensile Yield Strength (MPa)	252.1

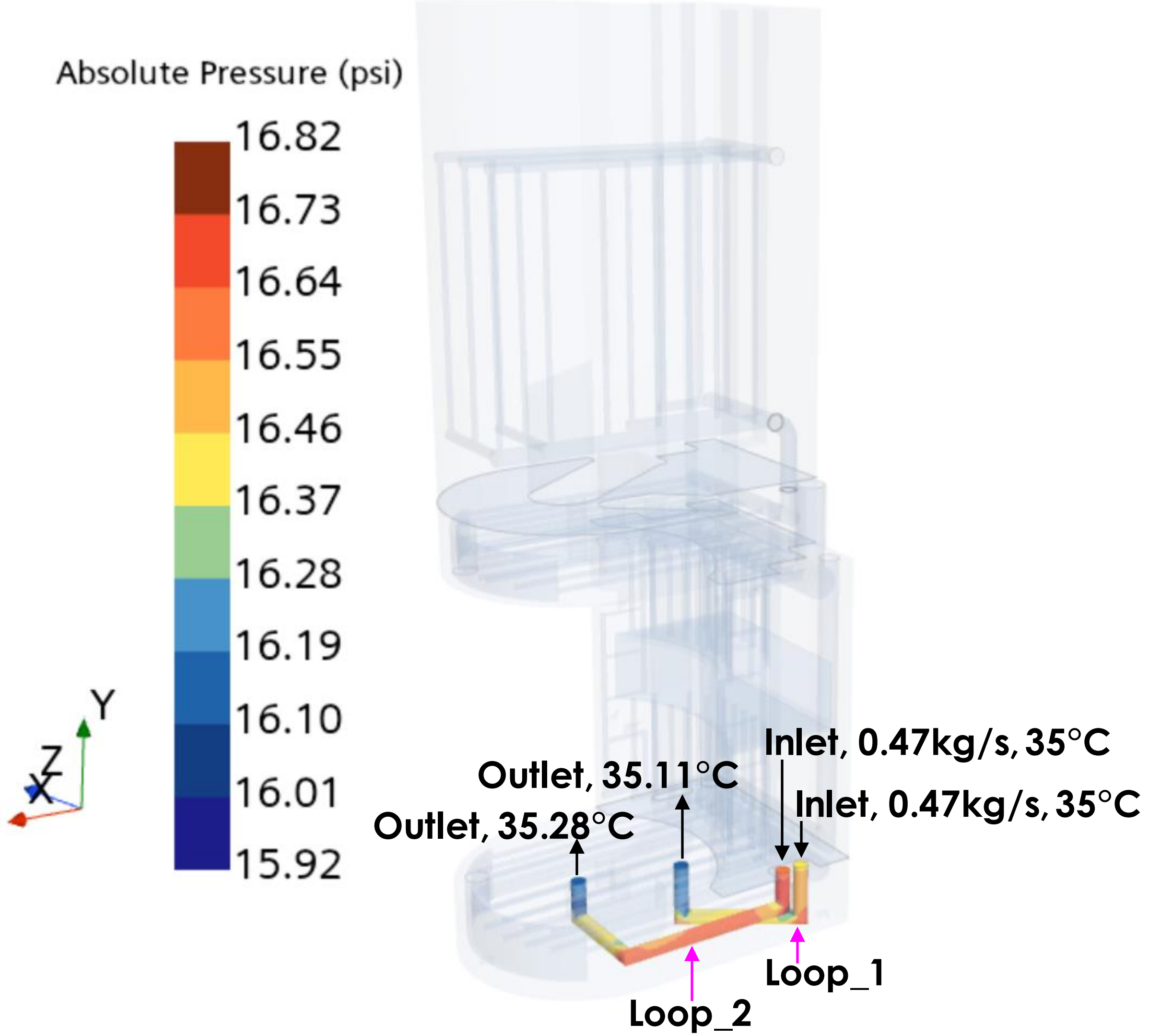
MRA Full Backbone, Water Pressure

Requirement for 7.5 GPM circuit : < 0.5 psi

$$\Delta P_{inlet-outlet} = 0.255\ psi\ (Loop\_1\ , 7.5GPM)$$
$$\Delta P_{inlet-outlet} = 0.404\ psi\ (Loop\_2\ , 7.5GPM)$$

Loops_1-4





MRA Full Backbone, Water Pressure

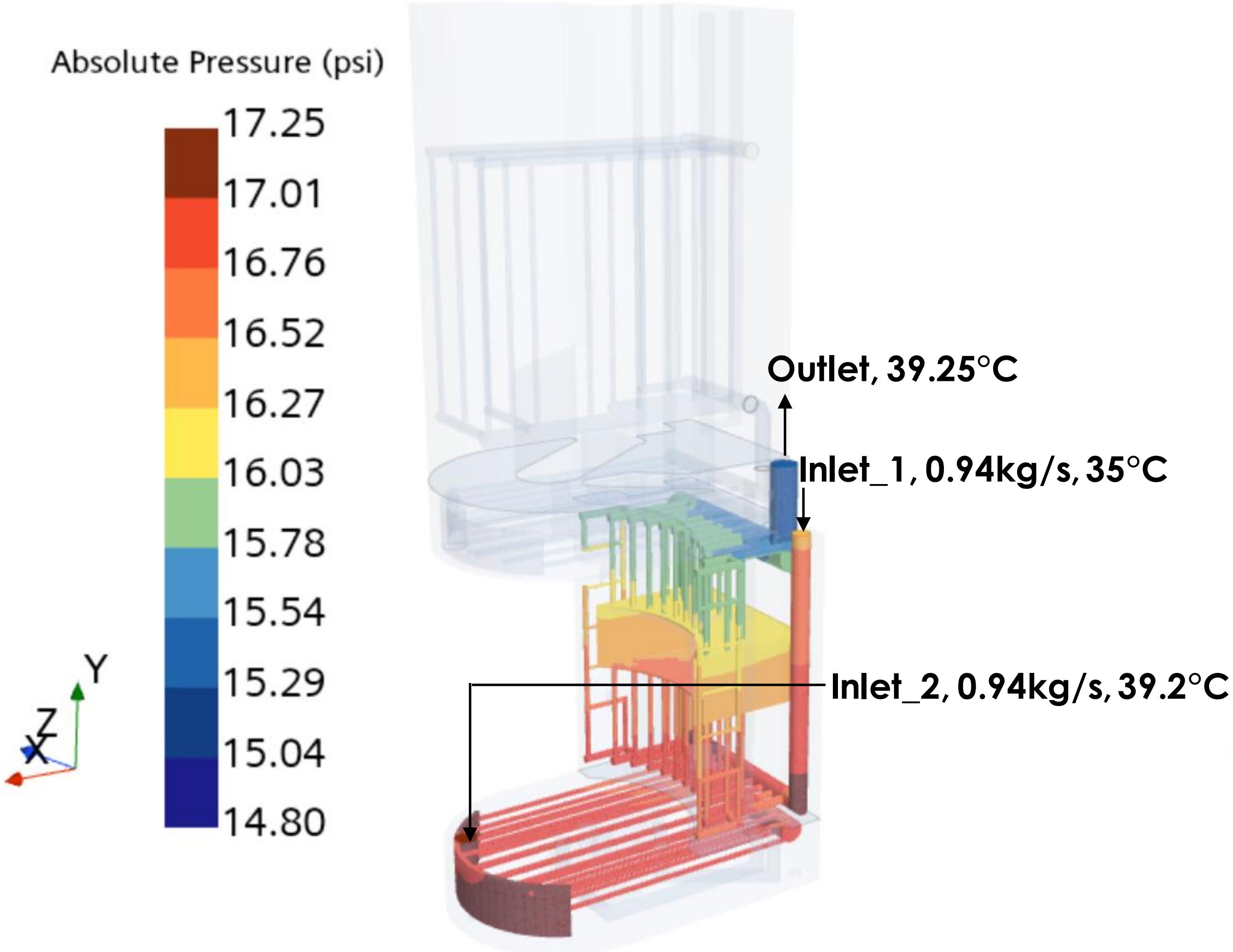
Requirement for 15 GPM circuit : < 4 psi

$\Delta P_{inlet-outlet} = 1.64\ psi$ (Loop_3_1, 15 GPM)

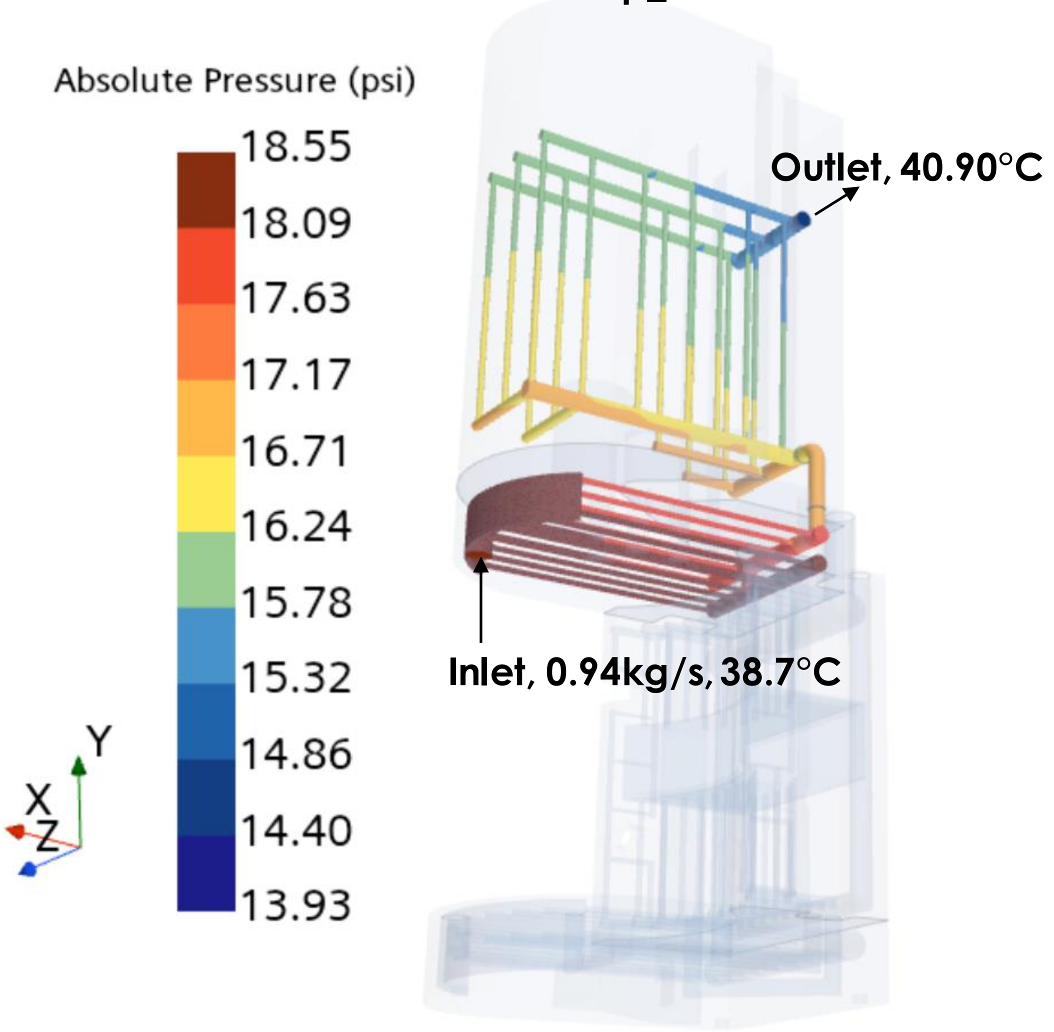
$\Delta P_{inlet-outlet} = 1.12\ psi$ (Loop_3_2, 15 GPM)

$\Delta P_{inlet-outlet} = 3.17\ psi$ (Loop_4, 15 GPM)

Loop_3



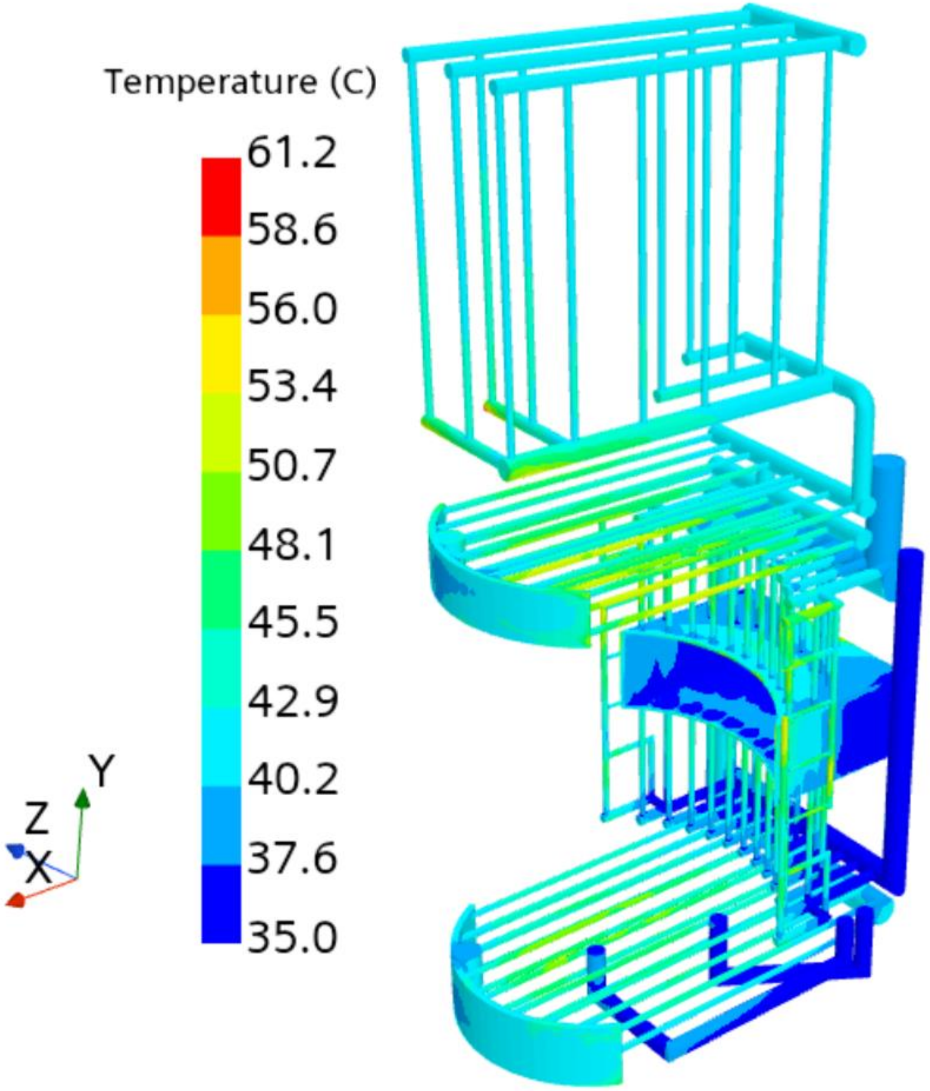
Loop_4

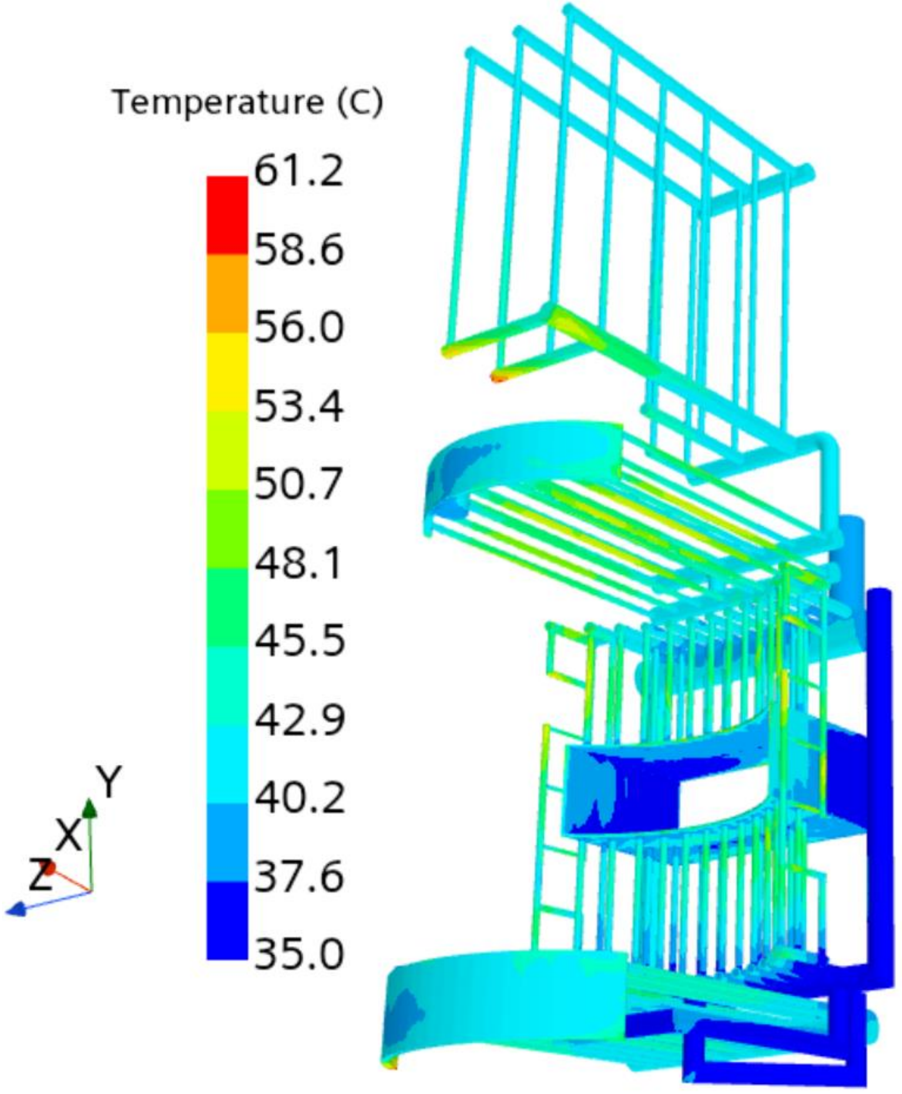


MRA Full Backbone, Water Temperature

Requirement: < 100°C

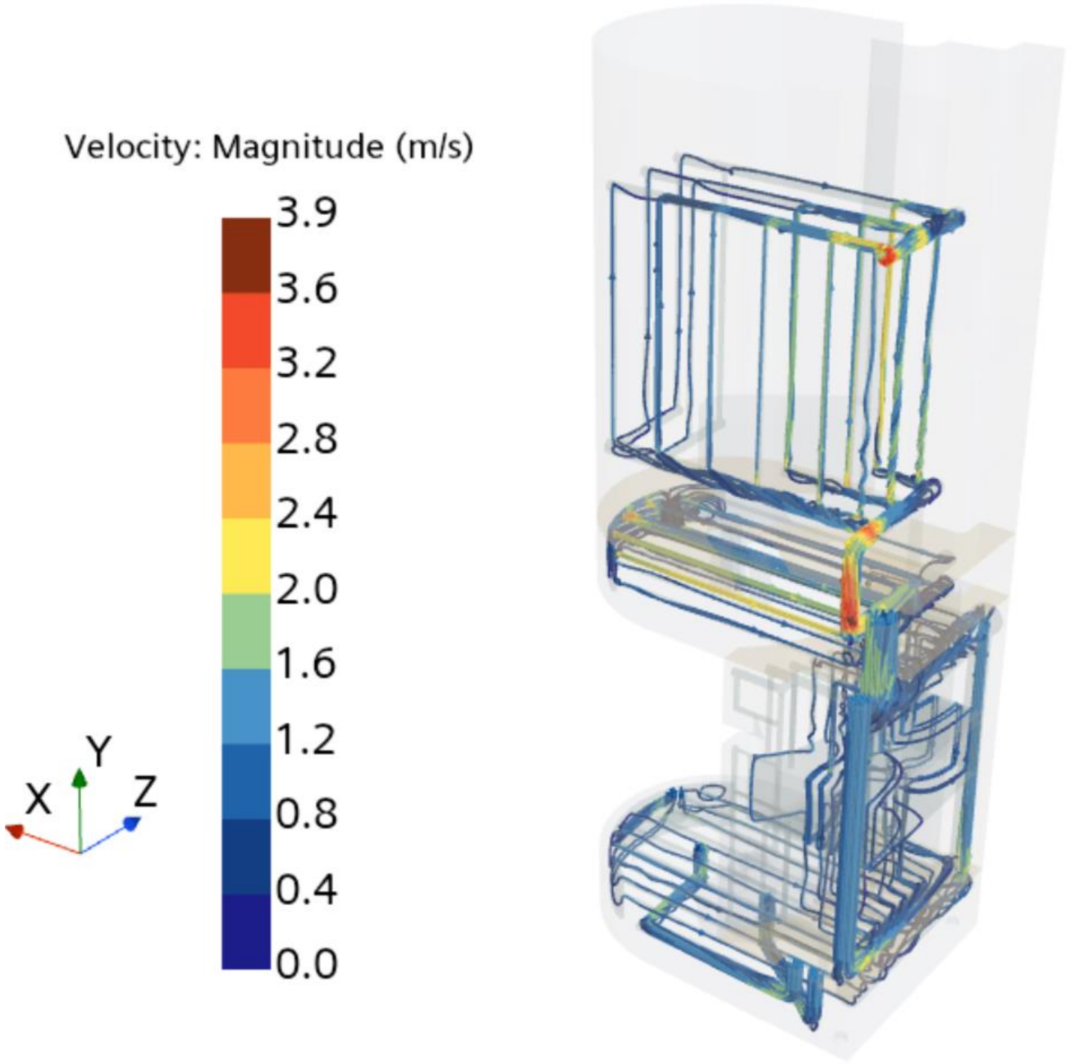
Peak : 61.2°C



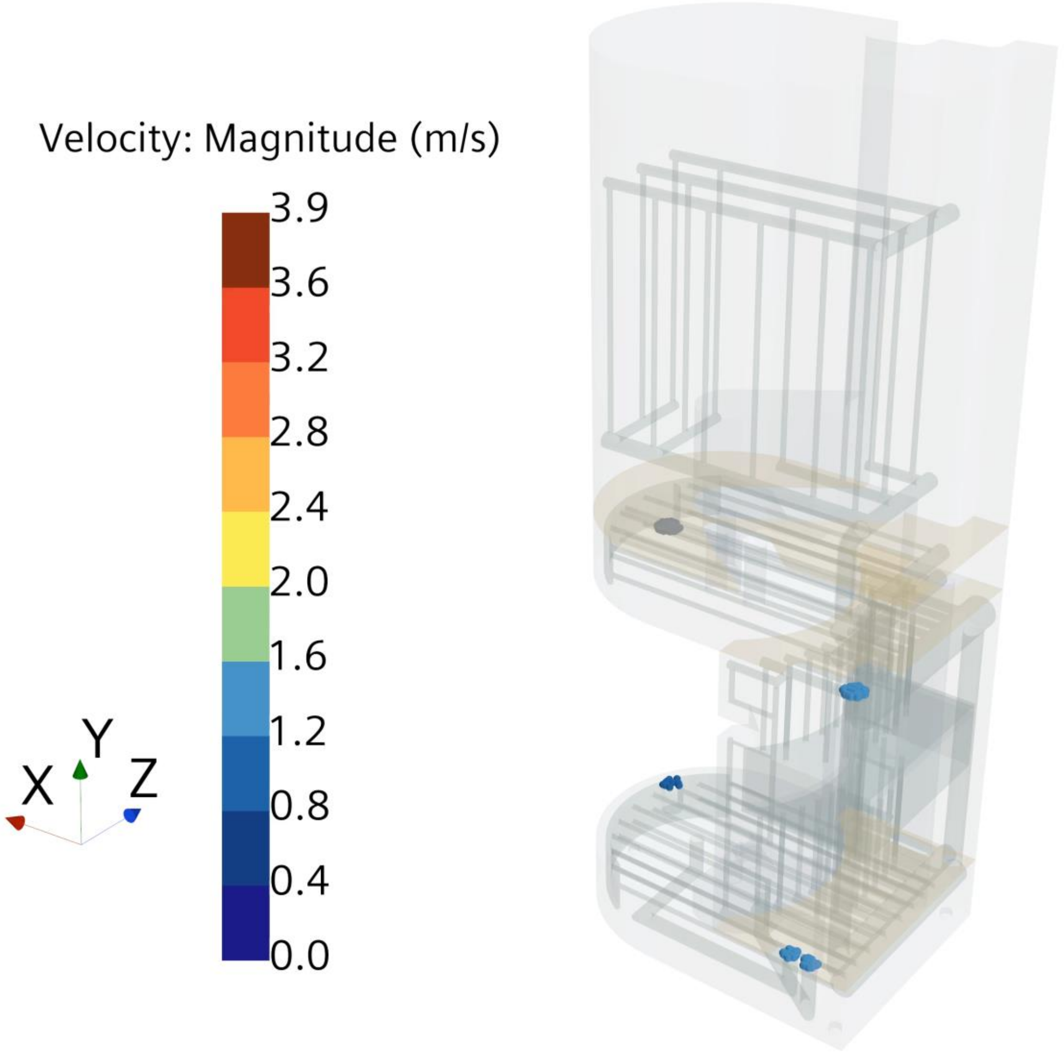


OAK RIDGE National Laboratory

MRA Full Backbone, Water Streamlines



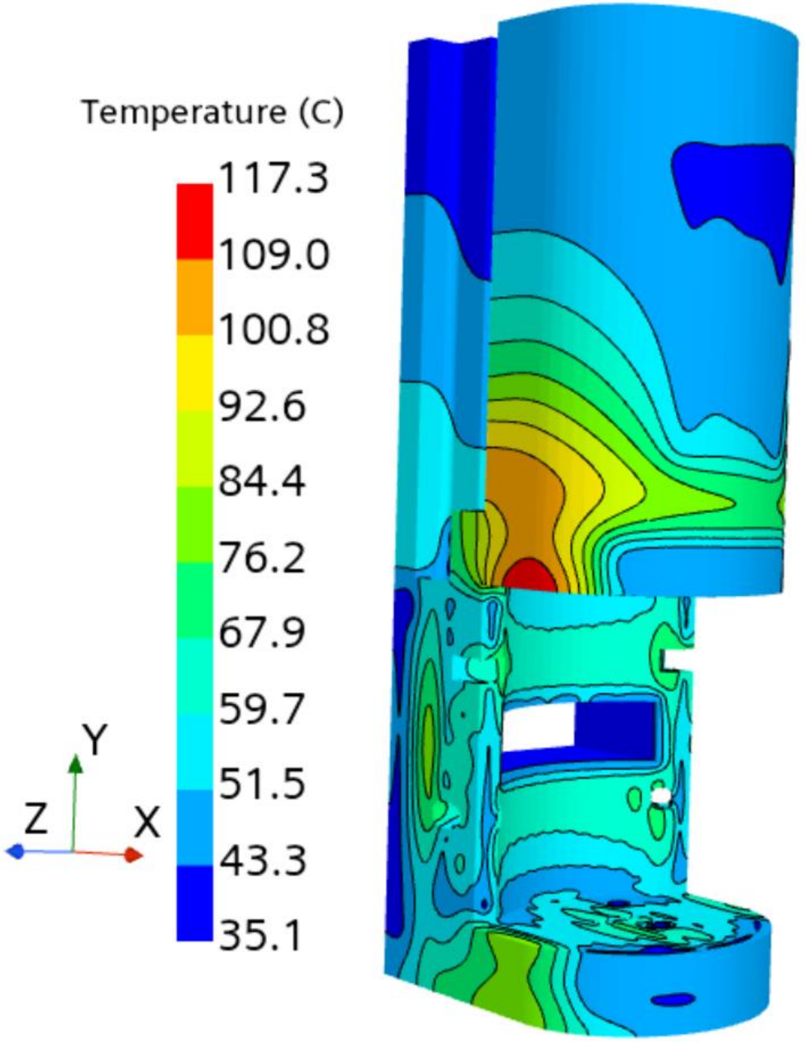
Streamline Animation

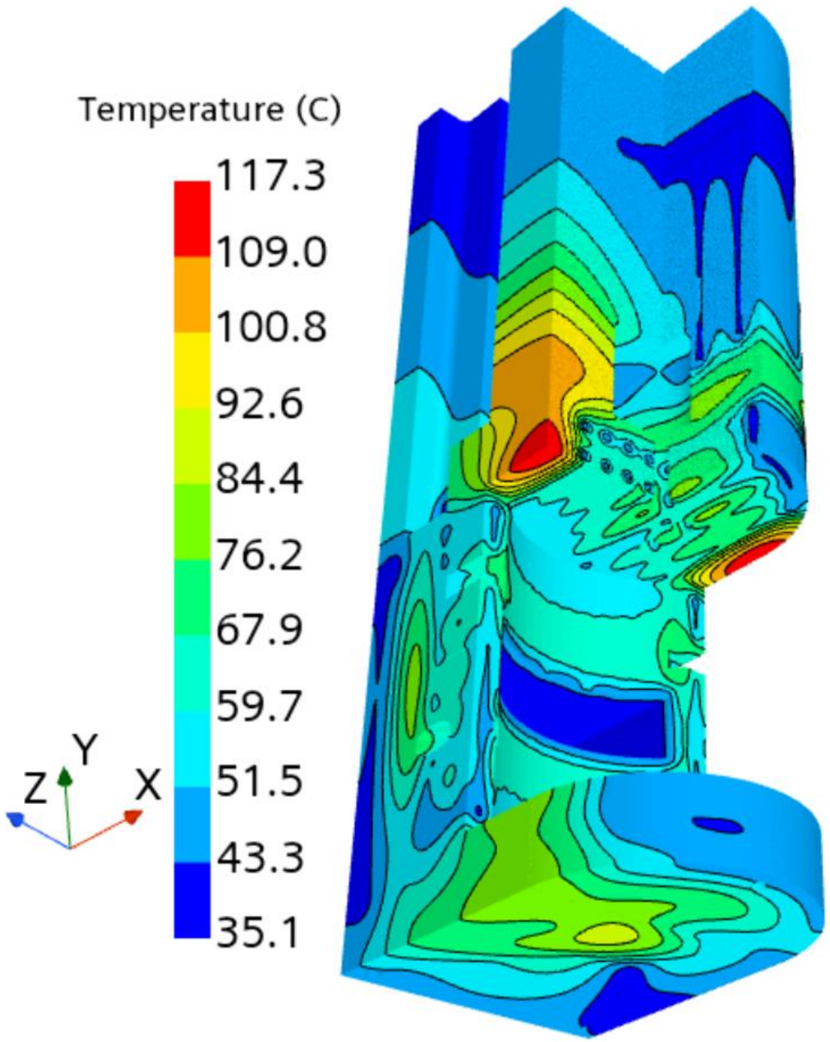


MRA Full Backbone, SS Temperature

Requirement: < 200°C

Peak : 117.3°C



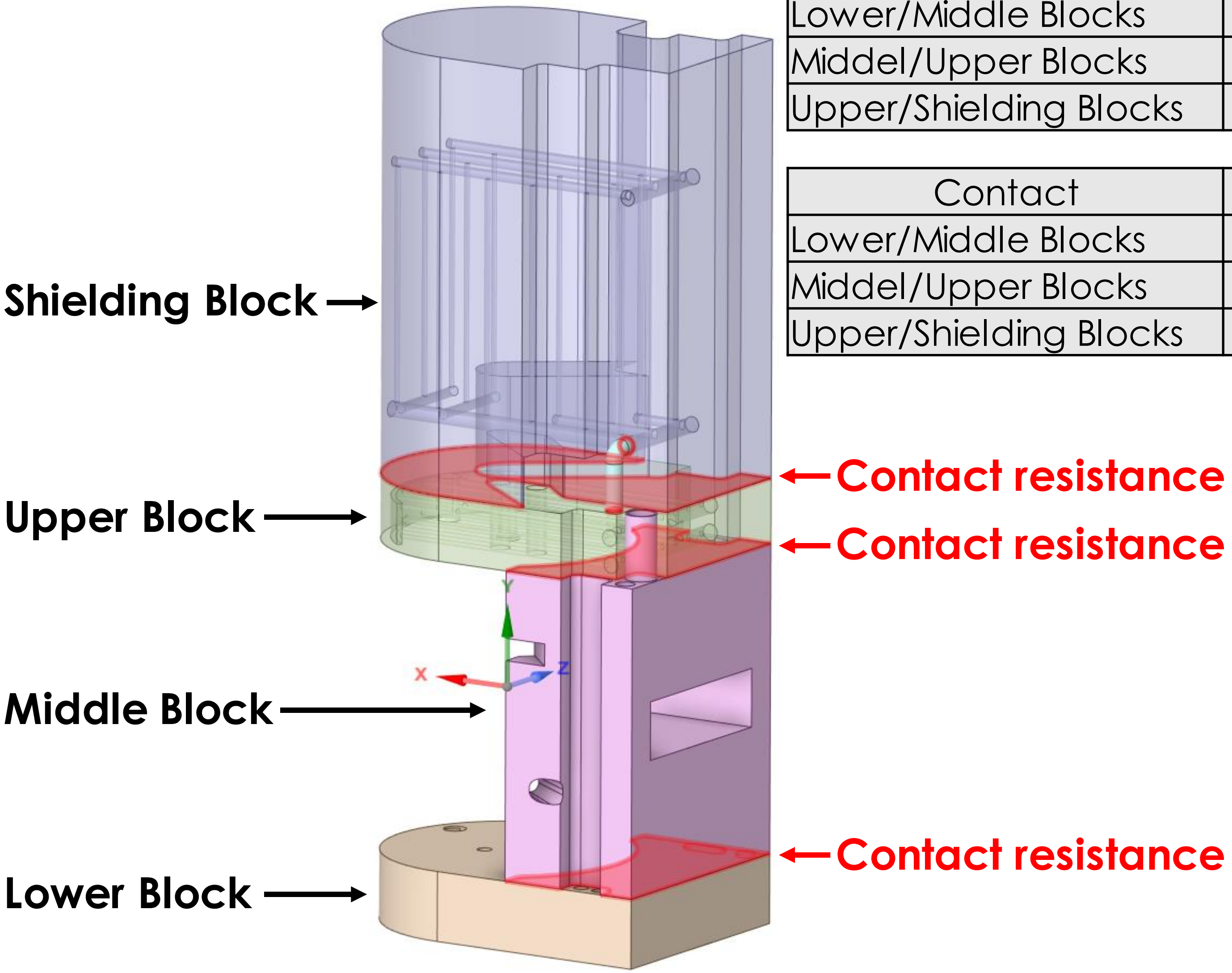


Thermal Contact Resistance of MRA Backbone

R = L/k

Contact	Gap Size, L (mm)	Helium, k (W/m-K)	R (m^2 -K/W)
Lower/Middle Blocks	0.1	0.154933	6.4544E-04
Middel/Upper Blocks	0.1	0.154933	6.4544E-04
Upper/Shielding Blocks	0.1	0.154933	6.4544E-04

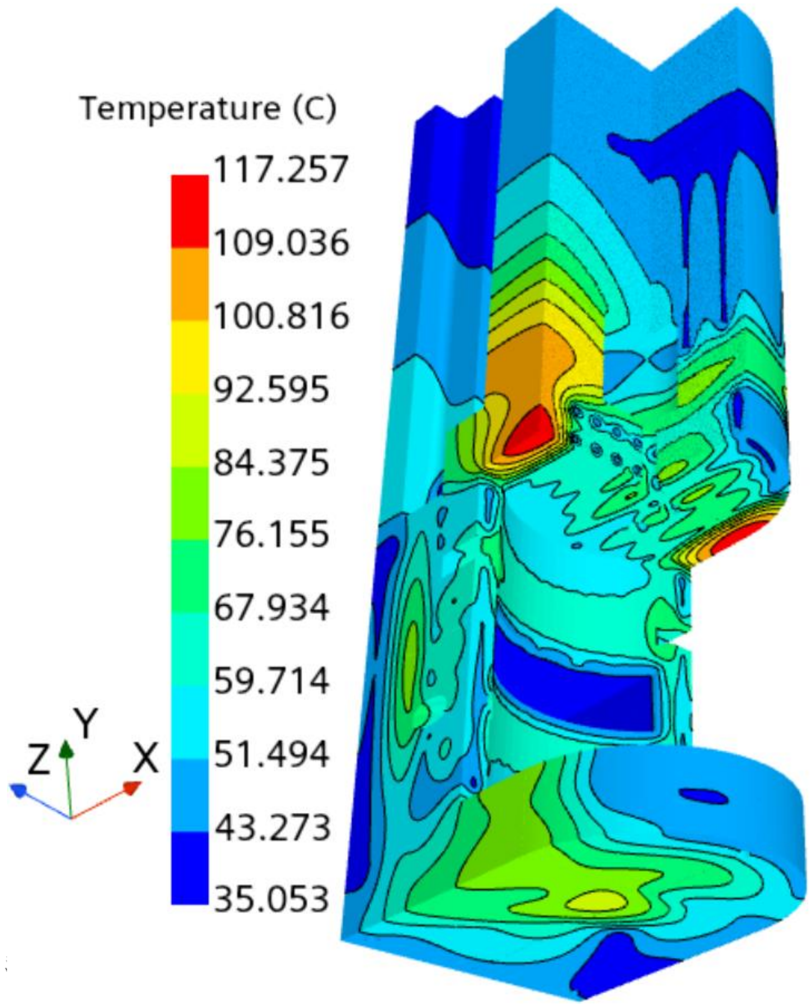
Contact	Gap Size, L (mm)	Helium, k (W/m-K)	R (m^2 -K/W)
Lower/Middle Blocks	1.0	0.154933	6.4544E-03
Middel/Upper Blocks	1.0	0.154933	6.4544E-03
Upper/Shielding Blocks	1.0	0.154933	6.4544E-03



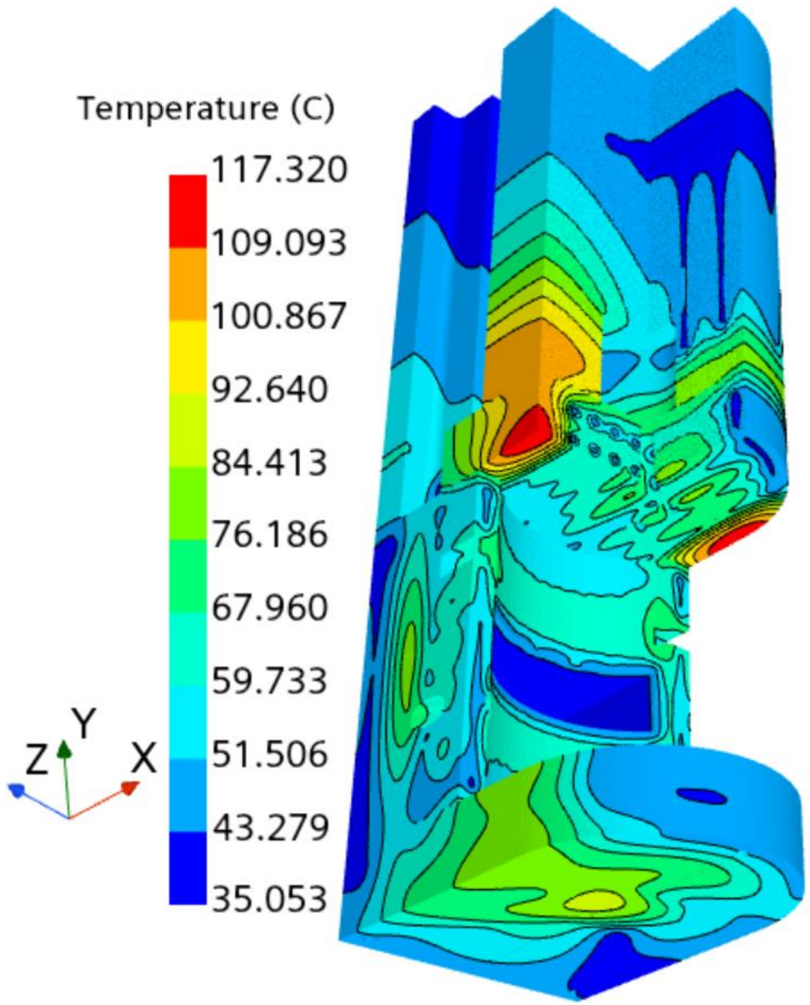
OAK RIDGE National Laboratory

MRA Full Backbone, SS Temperature Comparison

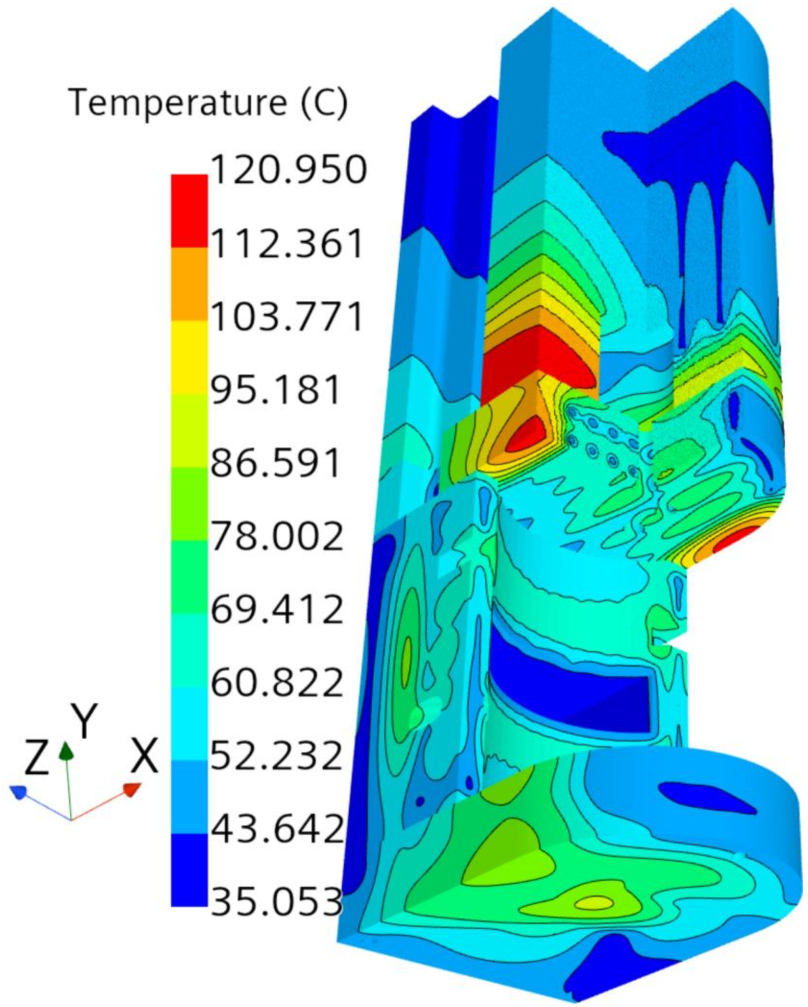
Perfect Contact



0.1 mm Helium Gap



1 mm Helium Gap



Comparison between Requirements and CFD Results

MRA Backbone

	Requirement	CFD Result
Maximum Water Temperature (°C)	< 100	61.2
Maximum Stainless-steel Temperature (°C)	< 200	117.3
Pressure Drop (psi) for Loop 1	< 0.5	0.255
Pressure Drop (psi) for Loop 2	< 0.5	0.404
Pressure Drop (psi) for Loop 3_1	< 4.0	1.64
Pressure Drop (psi) for Loop 3_2	< 4.0	1.12
Pressure Drop (psi) for Loop 4	< 4.0	3.17

Summary

- All requirements are met.
  - Water does not boil.
  - Stainless-steel temperature is less than 200°C
  - Pressure drops for loops 1 & 2 are less than 0.5 psi
  - Pressure drops for loops 3 & 4 are less than 4.0 psi.