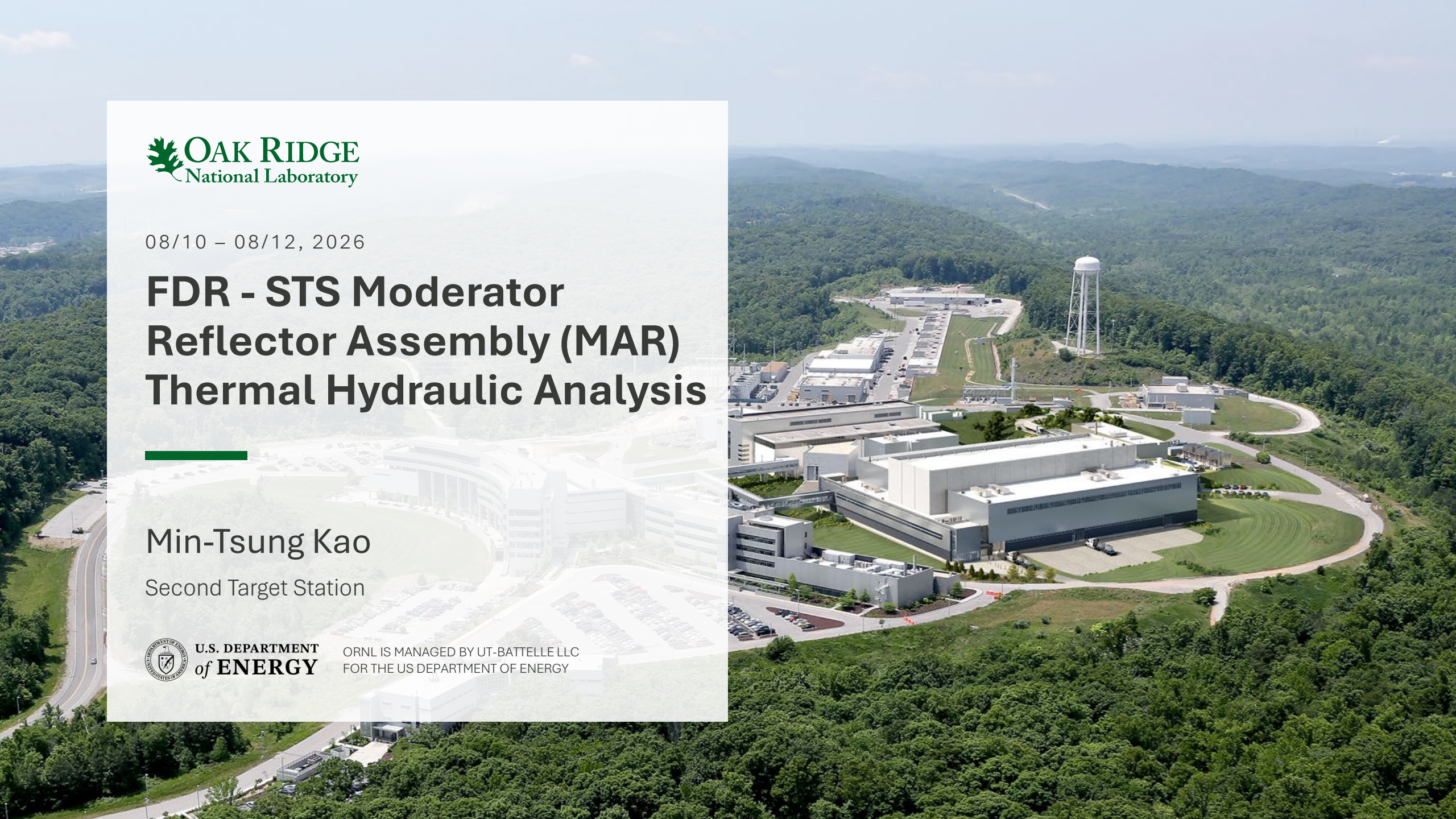


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08/10 – 08/12, 2026

FDR - STS Moderator Reflector Assembly (MAR) Thermal Hydraulic Analysis

Min-Tsung Kao

Second Target Station

U.S. DEPARTMENT of ENERGY

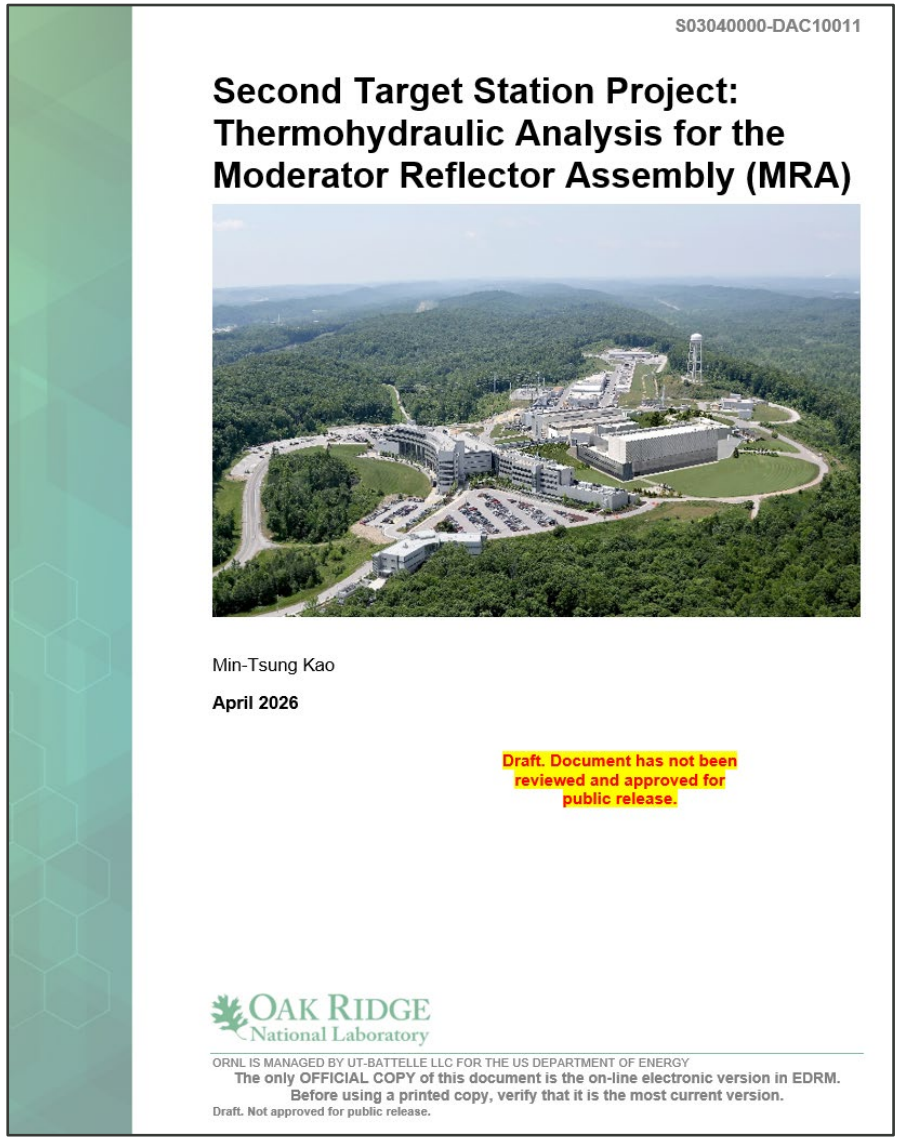
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FOR THE US DEPARTMENT OF ENERGY

- **Charge Question 2:**
  Has the design been shown to meet the requirements?

- **Charge question 3:**
  Do DACs and other supporting documentation adequately support the final design?

- **Question 5:**
  Is the design sufficiently mature to proceed with finalizing the procurement package?

Related Documents



S03040000-DAC10011

Second Target Station Project: Thermohydraulic Analysis for the Moderator Reflector Assembly (MRA)

Min-Tsung Kao

April 2026

Draft. Document has not been reviewed and approved for public release.

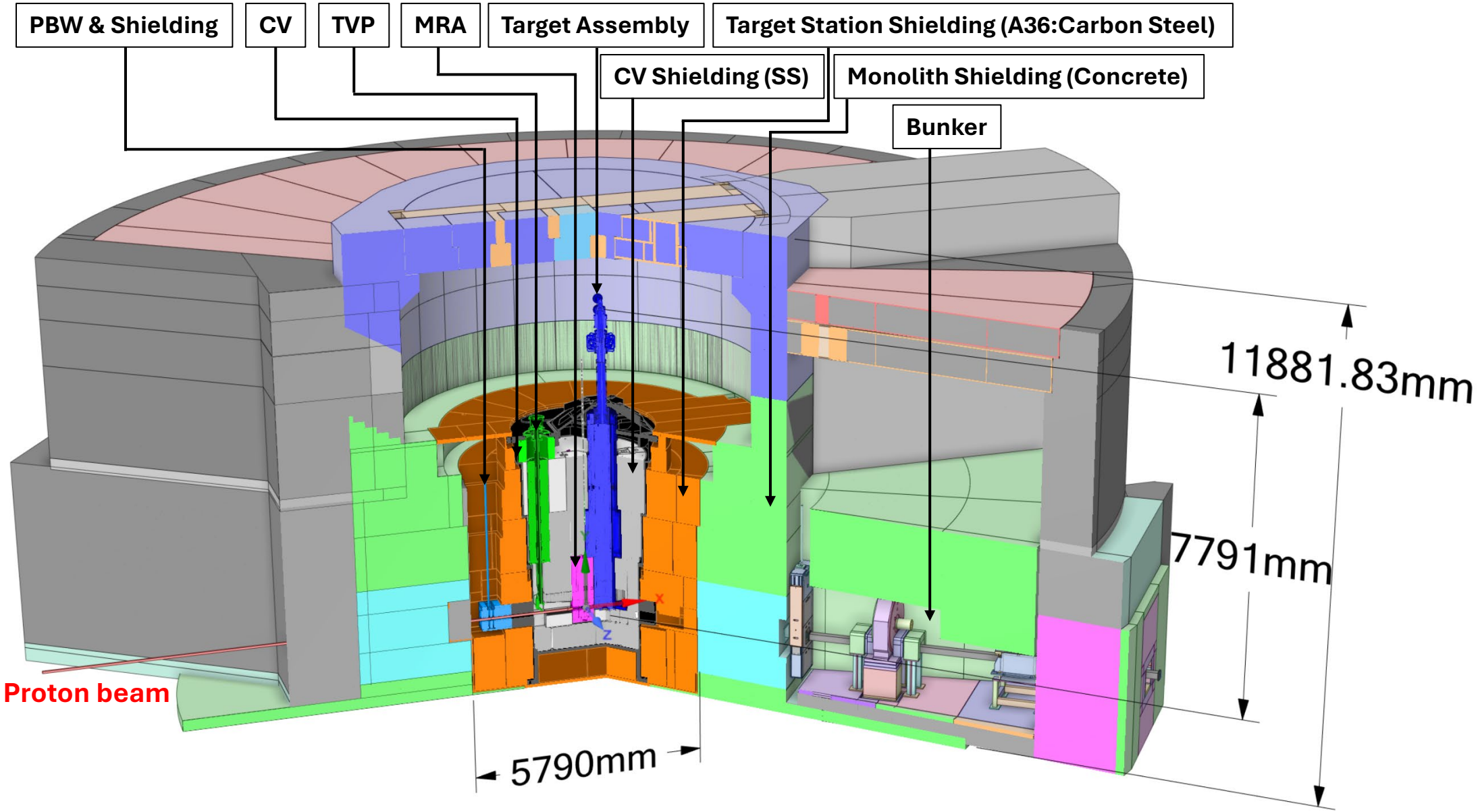
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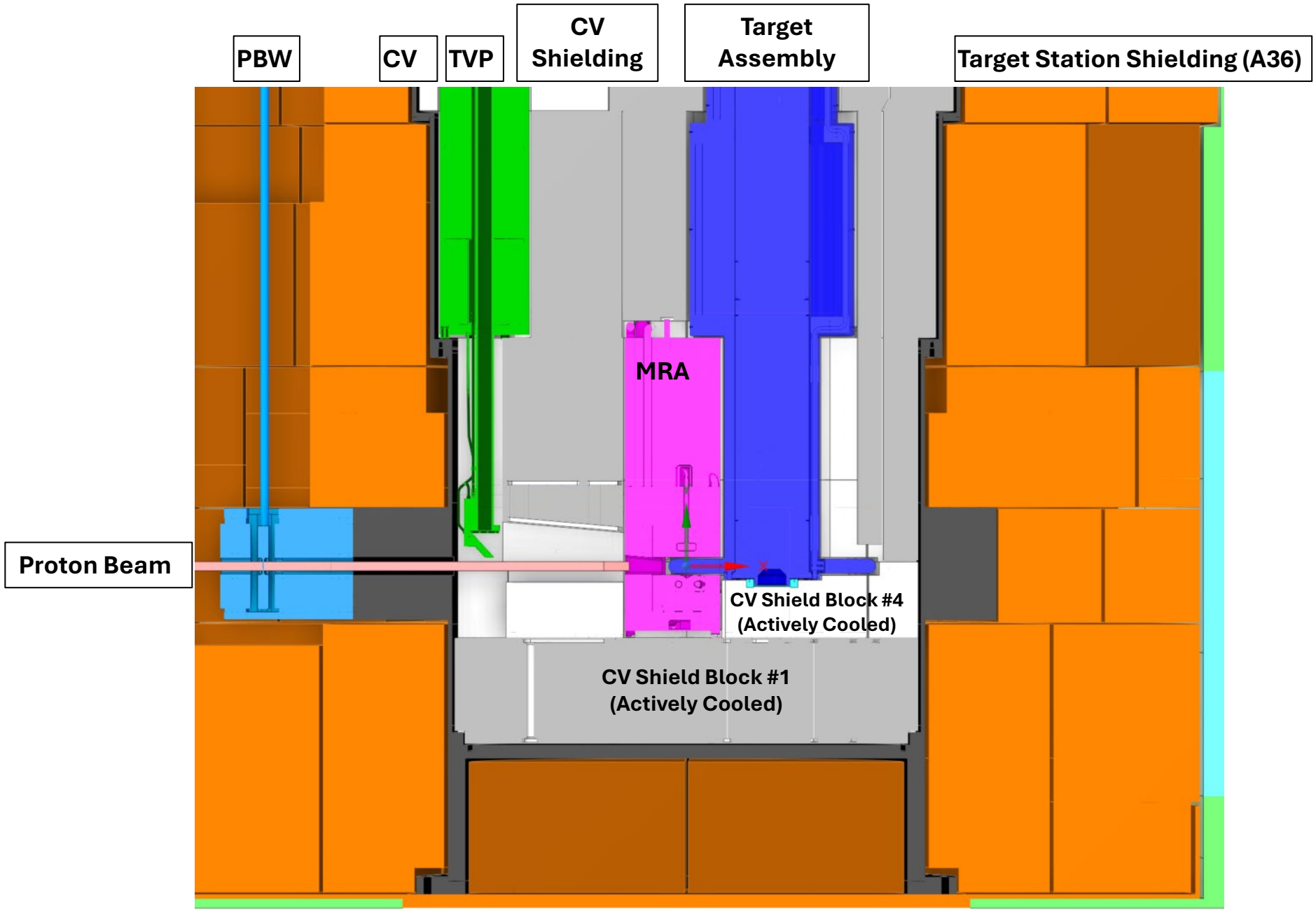
Outline

- **Geometry**
- **Requirements**
- **CFD Analysis of the MRA Hydrogen Loop**
- **CFD Analysis of the MRA without the Hydrogen Loop**
- **Air Accumulation** in the **Lower Reflector Vessel**
    - Transient Analysis without Heat Transfer
    - Transient Analysis with Heat Transfer
- **Requirement Verification**
- **Conclusions**

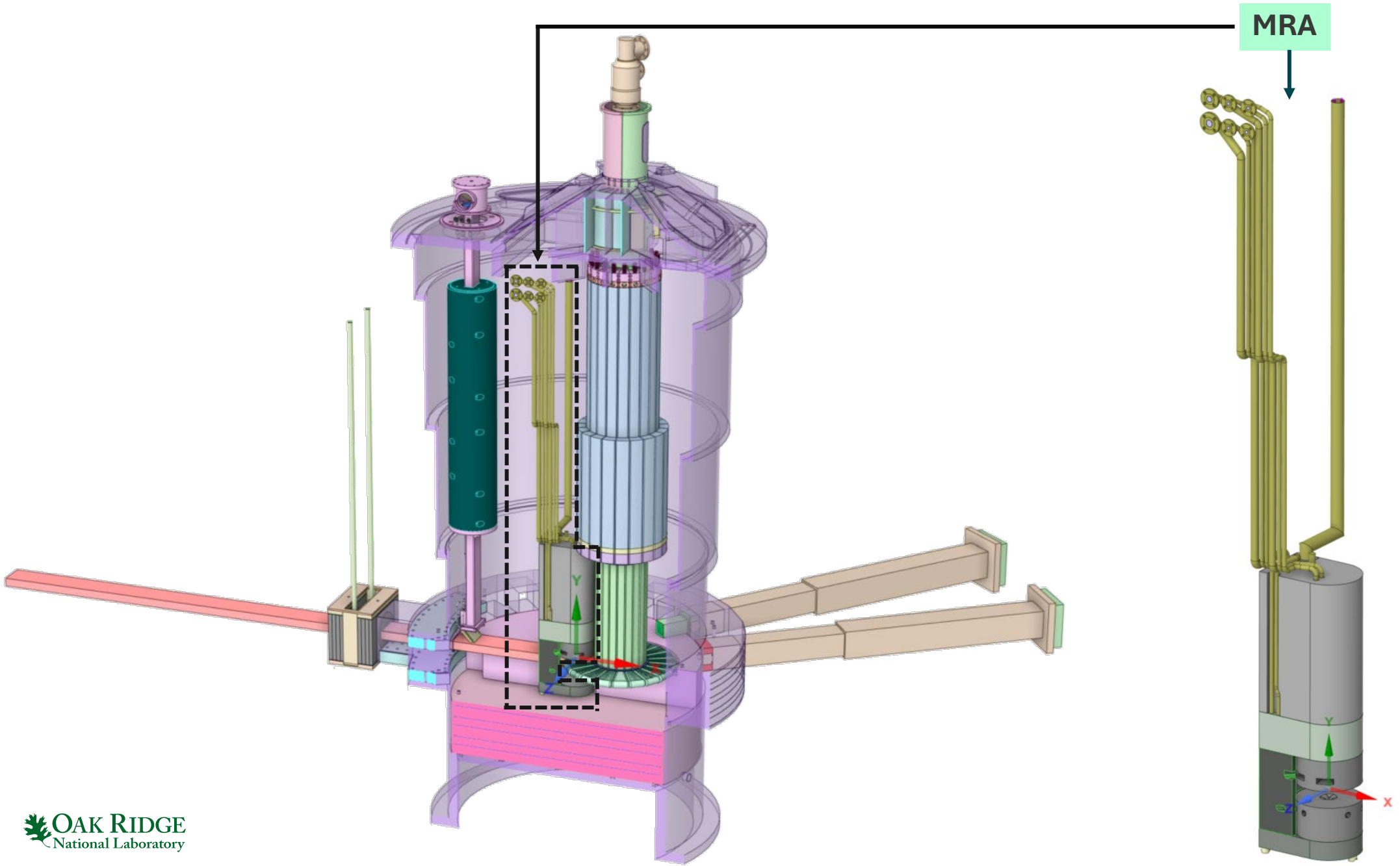
Relative location of the MRA in STS



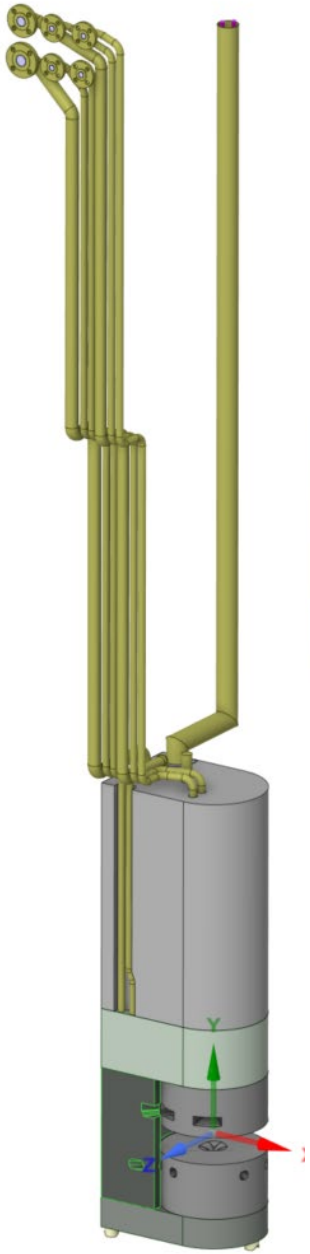
Proton Beam and MRA



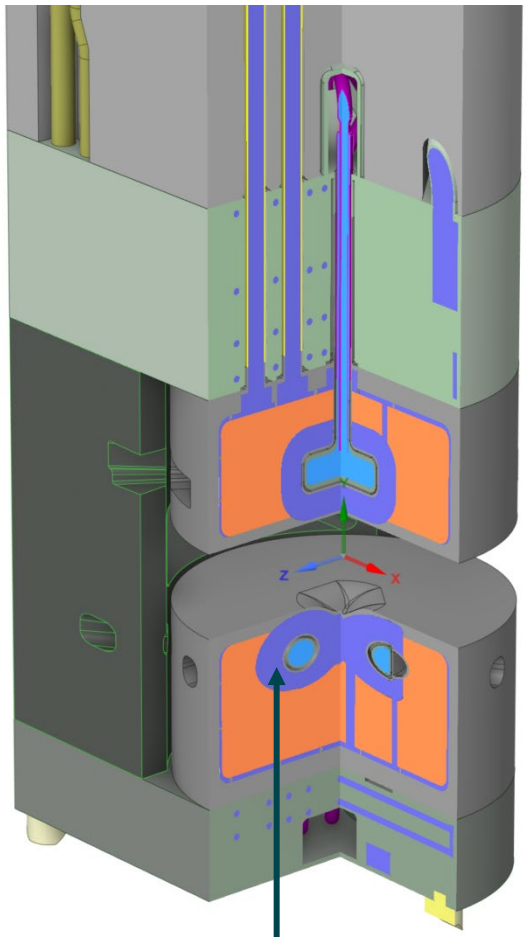
MRA, Geometry



MRA, Geometry

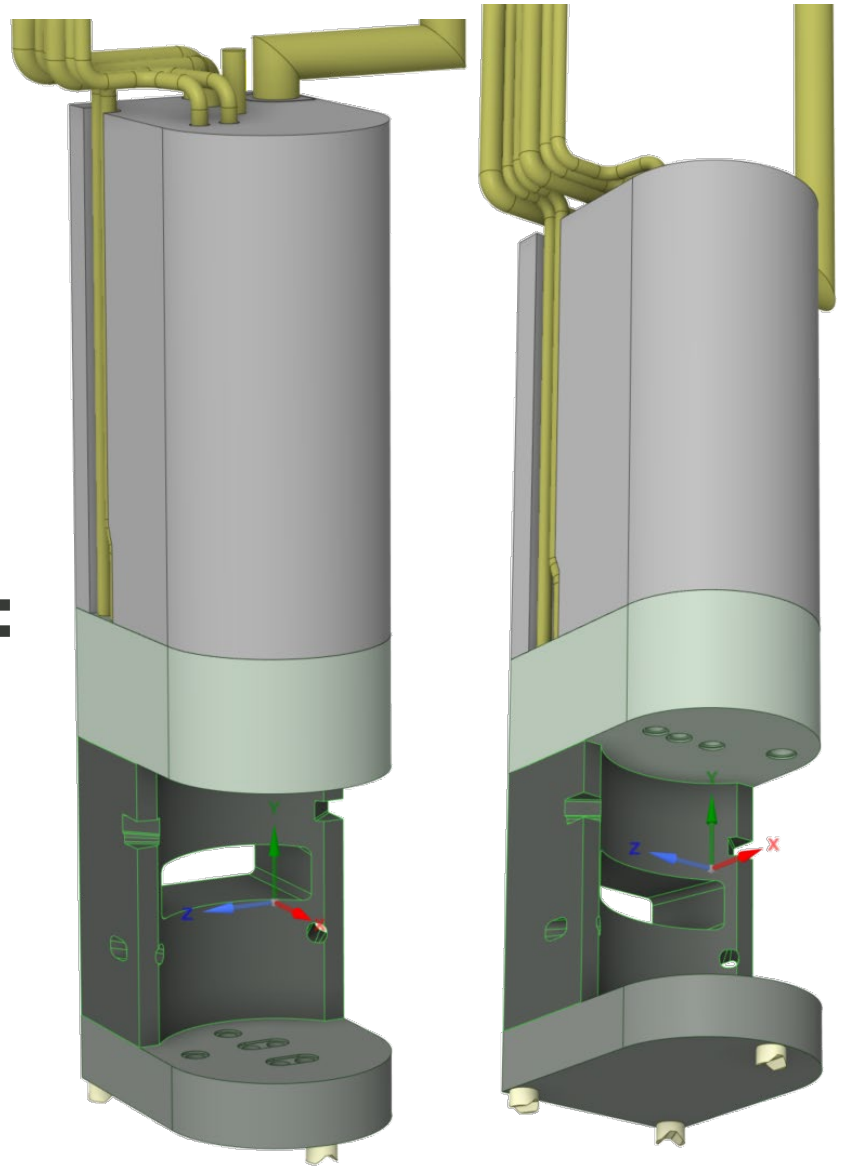


MRA

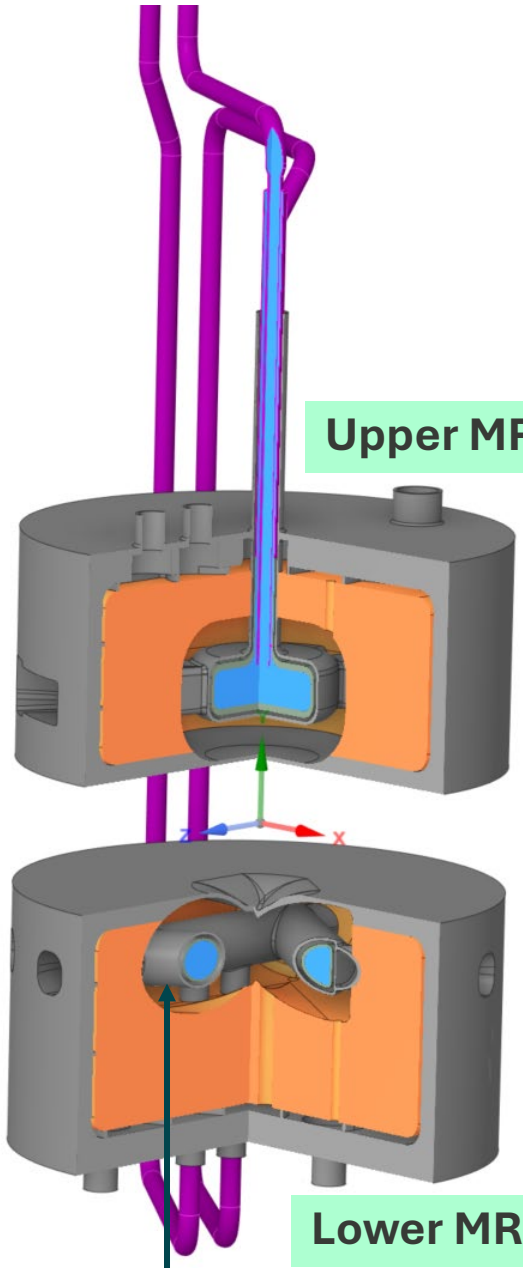


=

MRA Backbone + Shield Block



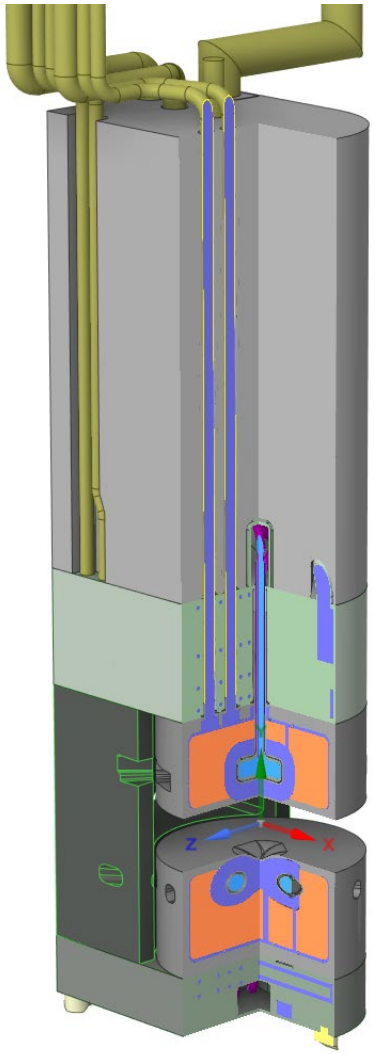
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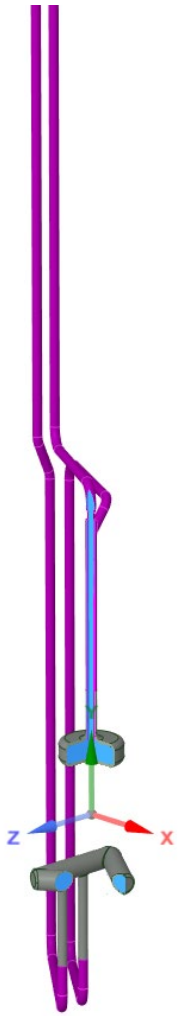
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MRA, Geometry

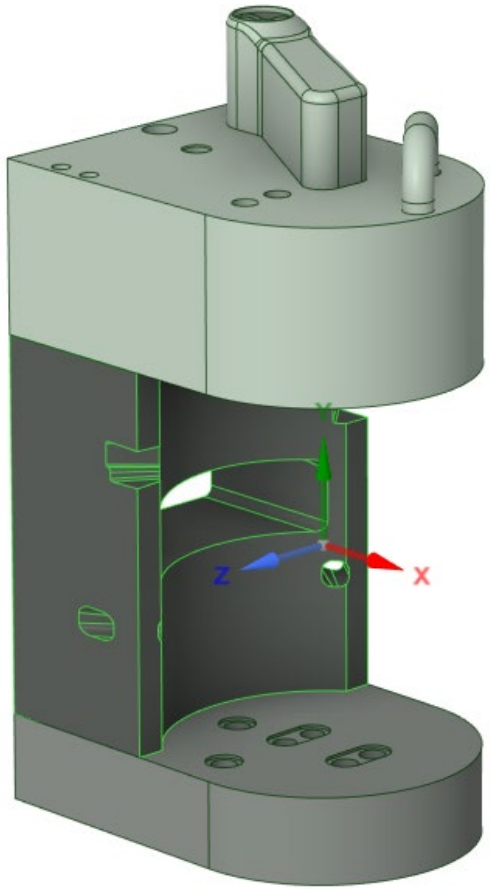
MRA



Hydrogen Loop



Backbone (SS316)



Sheild Block (A36, Carbon Steel)

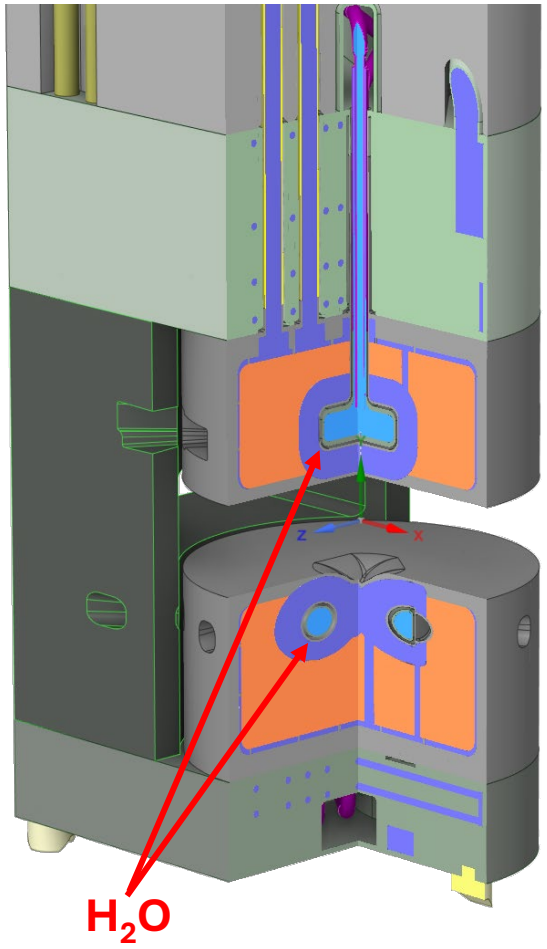


Kinetic Mounts (SS420)

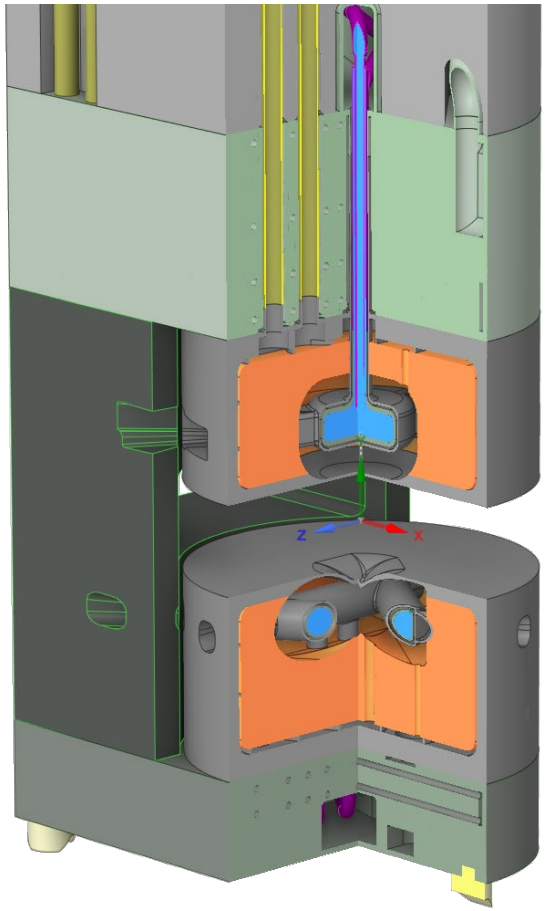


MRA, Geometry

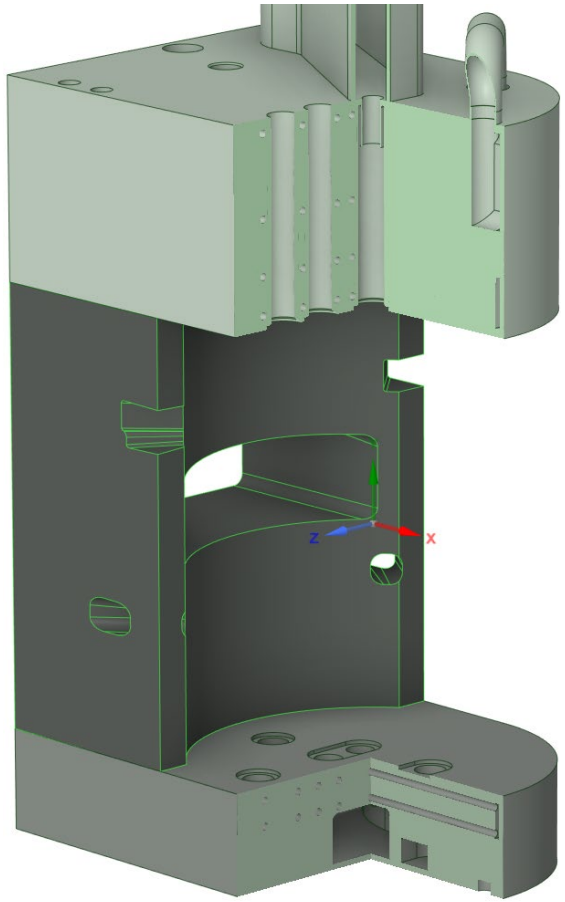
MRA



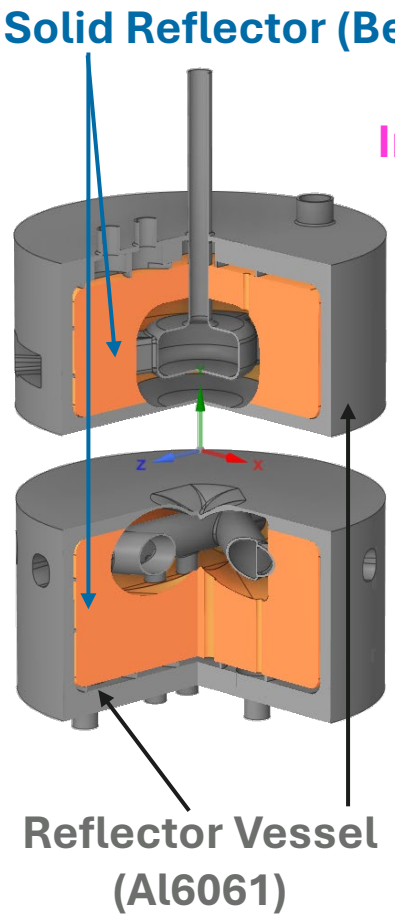
MRA with Water Hidden



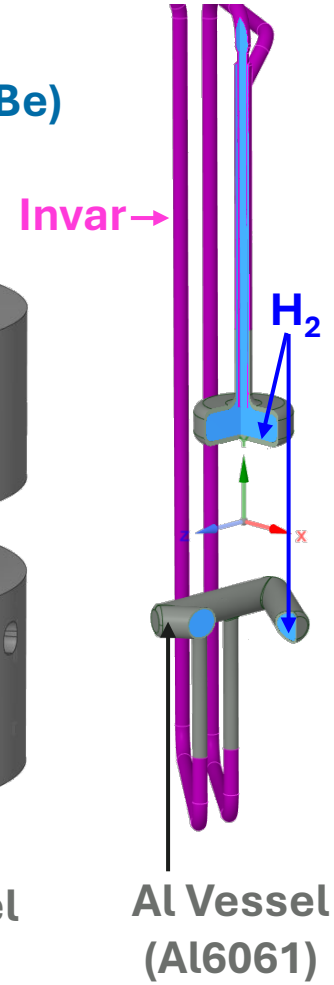
Backbone (SS316)



Reflector Vessel Assembly



H_2 Loop



Requirements

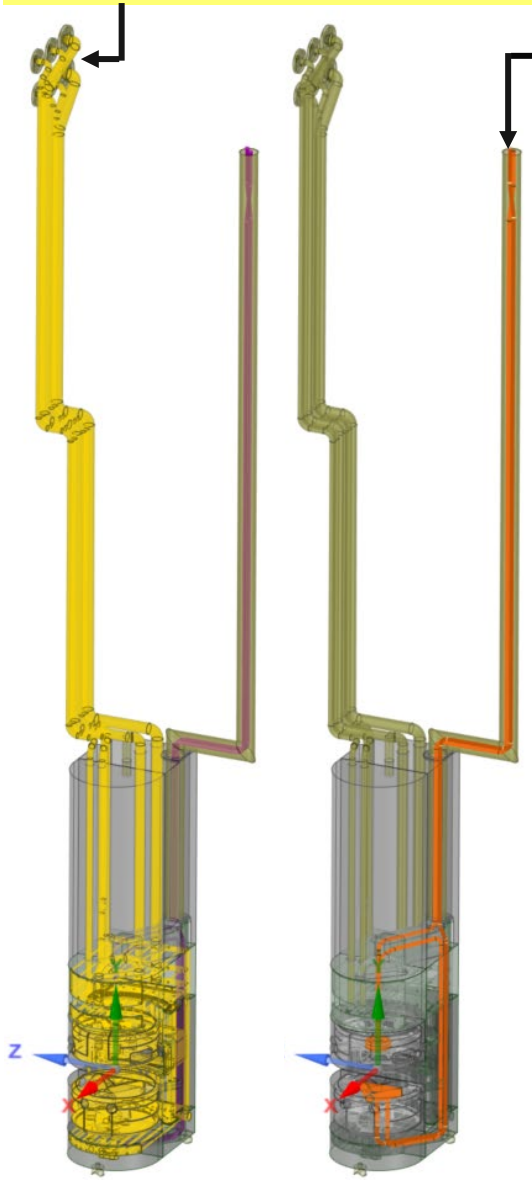
Requirement Name	Codebeamer ID	Requirement
MRA Water Loop		
MRA Aluminum Temperature Requirement	2325	The MRA **aluminum 6061-T6** structures shall have a maximum operating temperature of **100 °C**.
MRA Stainless Steel Temperature Requirement	2326	The MRA **stainless steel** structures shall have a maximum operating temperature of **200 °C**.
MRA Beryllium Temperature Requirement	2327	The MRA **beryllium** shall have a maximum operating temperature of **100 °C**.
MRA Water Temperature Requirement	2328	The MRA **cooling water** shall have a maximum temperature of **100 °C**.
MRA Upper Premoderator Pressure Drop Requirement	2362	The MRA upper premoderator water loop shall have a pressure drop of less than **15 psi** at 7.5 gpm and 32.2 °C inlet temperature.
MRA Lower Premoderator Pressure Drop Requirement	2363	The MRA lower premoderator water loop shall have a pressure drop of less than **15 psi** at 7.5 gpm and 32.2 °C inlet temperature.
MRA Upper Reflector Pressure Drop Requirement	2364	The MRA upper reflector water loop shall have a pressure drop of less than **15 psi** at 7.5 gpm and 32.2 °C inlet temperature.
MRA Lower Reflector Pressure Drop Requirement	2365	The MRA lower reflector water loop shall have a pressure drop of less than **15 psi** at 7.5 gpm and 32.2 °C inlet temperature.
MRA Backbone Pressure Drop Requirement	2366	The MRA backbone water loop shall have a pressure drop of less than **15 psi** at 15 gpm and 32.2 °C inlet temperature.
MRA Hydrogen Loop		
MRA Hydrogen Loop Pressure Drop Requirement	2356	The MRA hydrogen loop pressure drop shall be less than **0.15 bar** @ 0.5 l/s and 18.34 K.
MRA Moderator Hydrogen Density Requirement	2888	The **hydrogen** in both moderators shall have a minimum **average density** of **72.0 kg/m^3**.
MRA Moderator Hydrogen Maximum Temperature Requirement	2889	The **hydrogen** temperature shall at no point in the moderators exceed **32 K**.

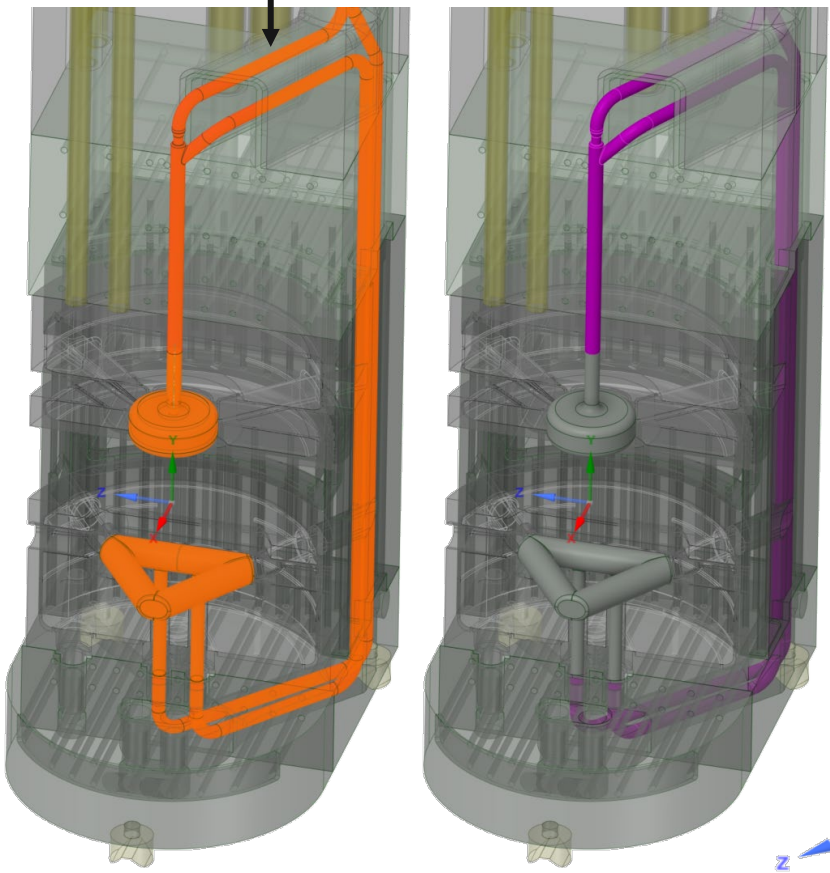
CFD Analysis for the MRA Hydrogen Loop

Geometry, Hydrogen Loop

Water (5 inlets, 1 outlet)

Hydrogen Loop

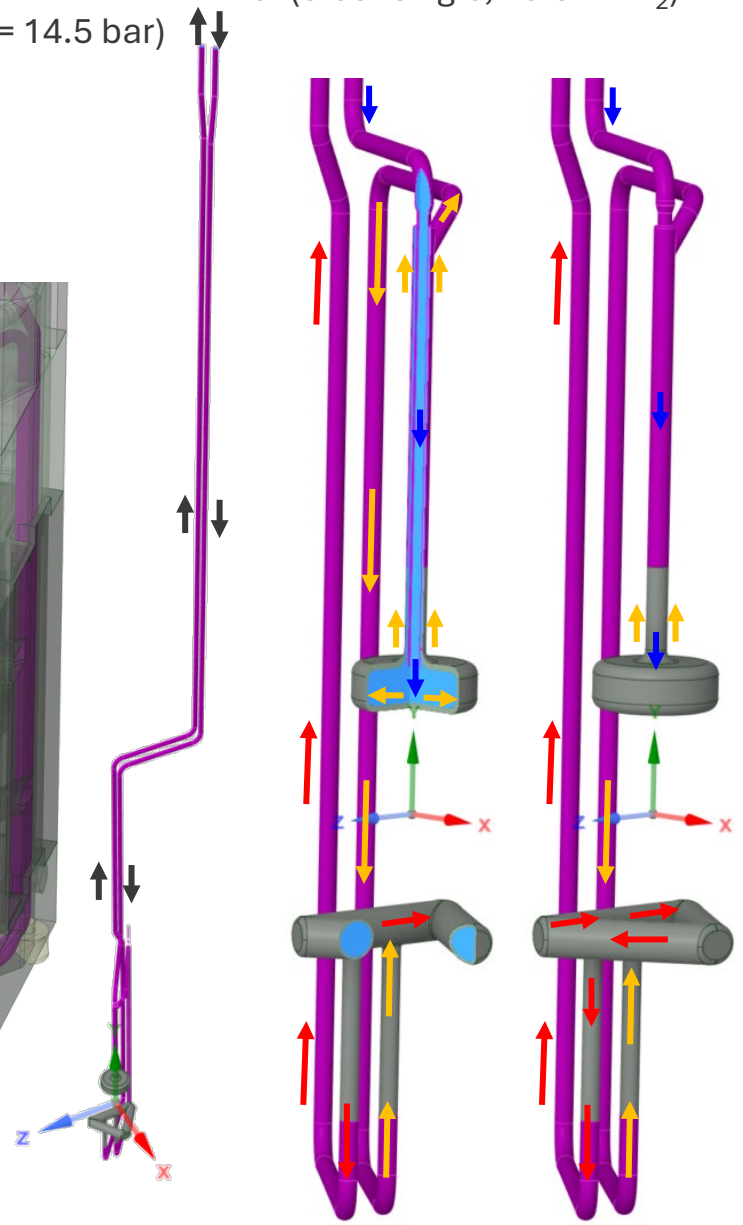


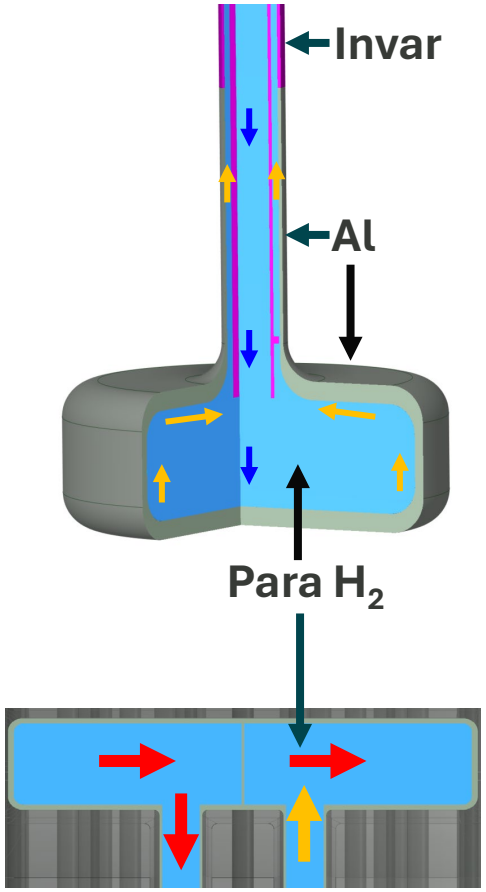


0.5 l/s

Inlet (0.0373 kg/s, 18.34 K H_2)

Outlet (1.45MPa = 14.5 bar)

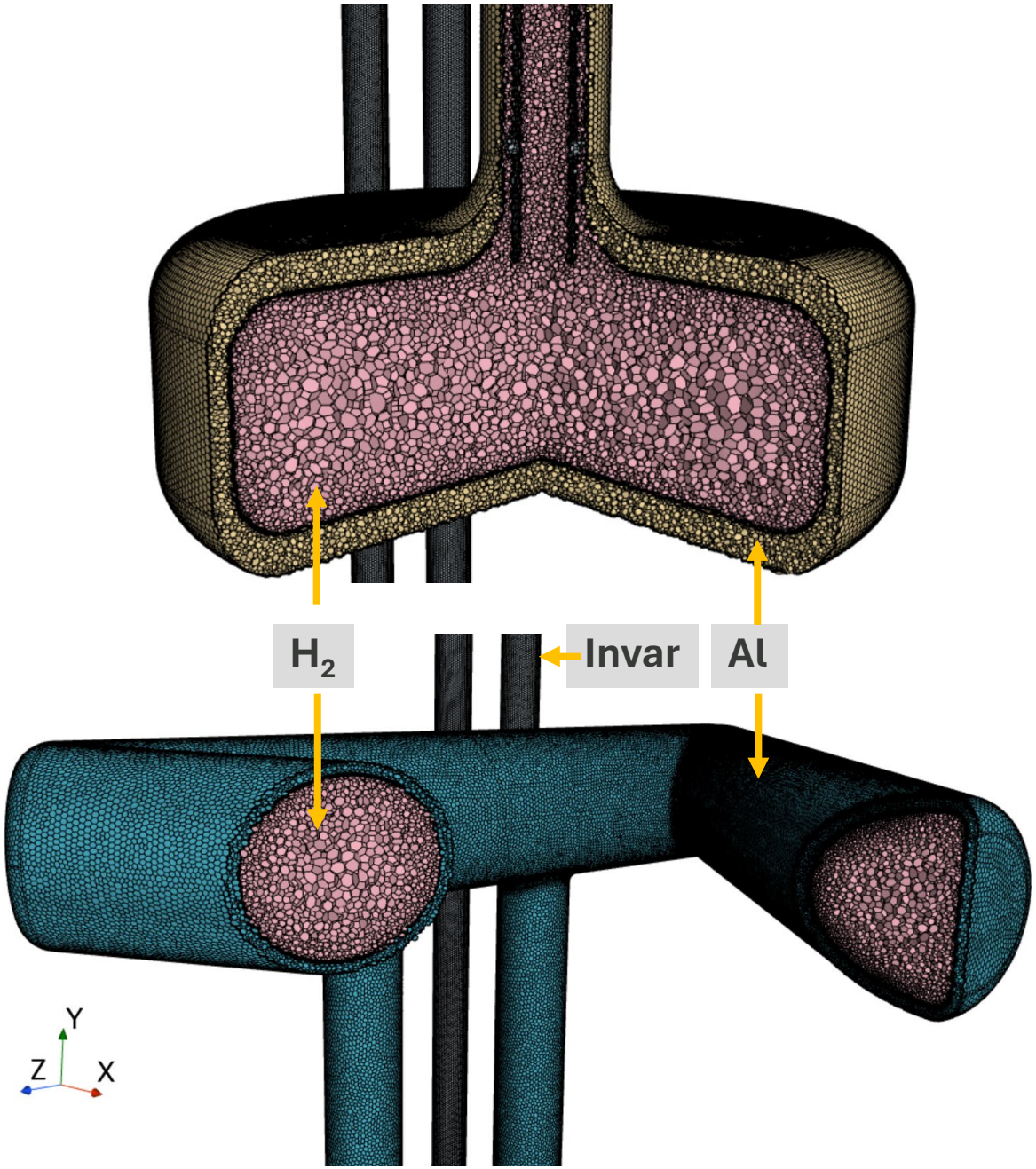




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Steady State Heat Transfer Analysis for MRA H_2 Loop, Mesh Configuration

MRA H_2 Loop	
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	**1.55E+06**
H_2	
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	**8.83E+06**
Invar	
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 Thin Layers	5
Number of Cells	**3.58E+06**
Total Cells (Al+H2)	**1.40E+07**



Material Property

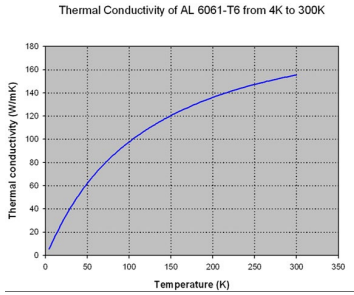
Material	Thermal Conductivity, k (W/m-K)	Density, rho(kg/m^3)	Specific Heat, Cp (J/kg-K)	Viscosity (Pa-s)
Al 6061 @20K (NIST)	28.43	2713	8.85	N/A
Al 6061 @room T (Ansys)	155.3	2713	915.7	N/A
A36 (Carbon Steel)	50.0	7850	470	N/A
Be	168	1850	1925	N/A
Invar	10.15	8050	515	N/A
Para H_2 (Liquid)	Table(T)	Polynomial in T	Table(T)	Table(T)
SS 316	14.58	8000	486.1	N/A
SS 420	24.9	7800	460	N/A
H_2O	0.620271	997.561	4181.72	8.89E-04

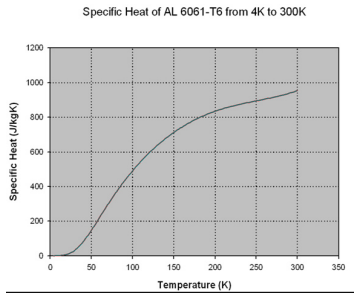
$$\rho_{H_2}(T) = a + bT + cT^2 + dT^3$$

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

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

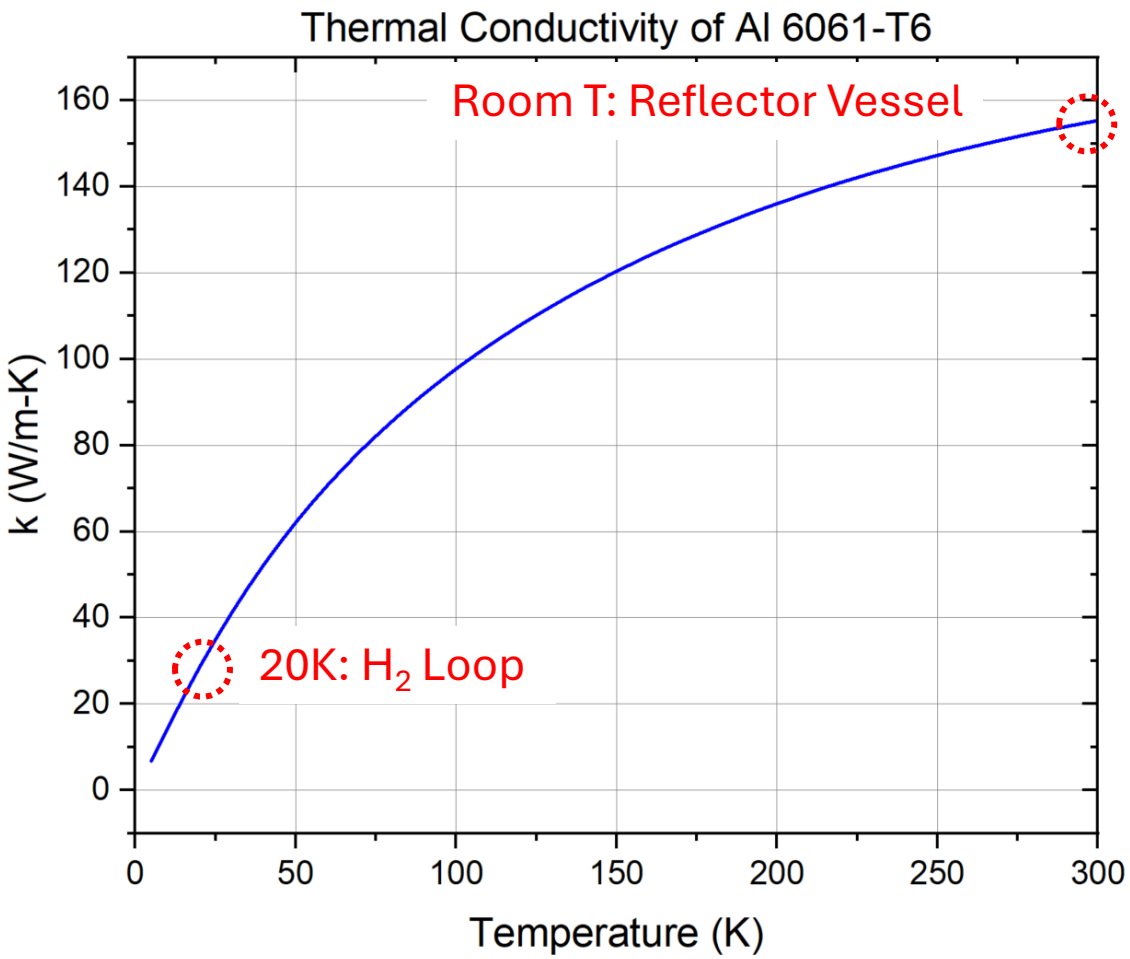
Coefficient	ρ_{H_2} (kg/m^3)	k_{Al} (W/m-K)	Cp_{Al} (J/kg-K)
a	138.907	0.07918	46.6467
b	-8.23187	1.0957	-314.292
c	0.370104	-0.07277	866.662
d	-0.00621765	0.08084	-1298.3
e		0.02803	1162.27
f		-0.09464	-637.795
g		0.04179	210.351
h		-0.00571	-38.3094
i		0	2.96344

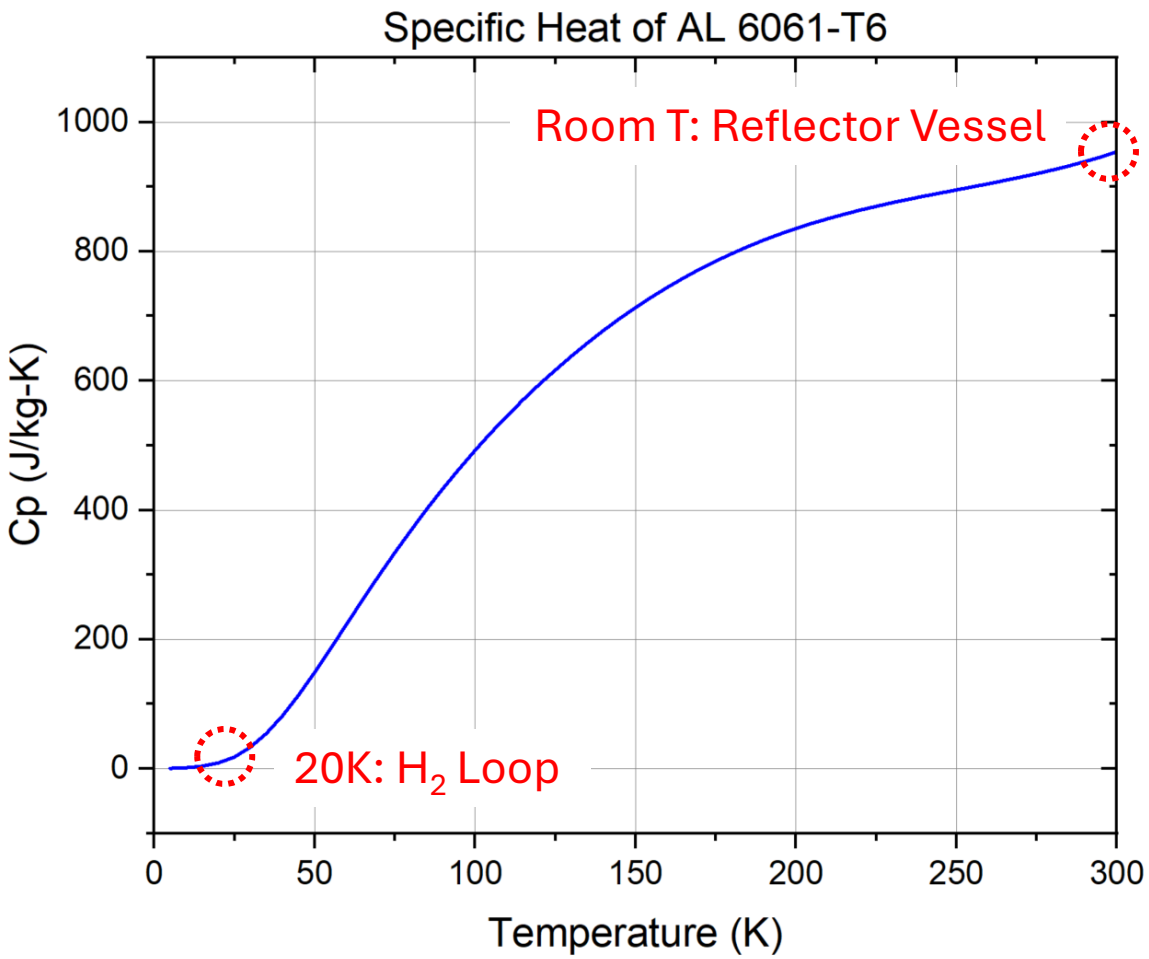




Reference:
Ansys, Inc. (2024). Ansys Mechanical 2024 R2. https://www.ansys.com
https://trc.nist.gov/cryogenics/materials/6061%20Aluminum/6061_T6Aluminum_rev.htm
https://matweb.com/search/DataSheet.aspx?MatGUID=b6fb00b235f0442da4d31a0cd04671c9&ckck=1
https://webbook.nist.gov/chemistry/fluid/ (para-H2)
https://www.matweb.com/search/datasheet.aspx?matguid=641544e4c9f1425390d05ae37d55440a&n=1

Material Property, Al Vessels





Data from NIST: https://trc.nist.gov/cryogenics/materials/6061%20Aluminum/6061_T6Aluminum_rev.htm

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

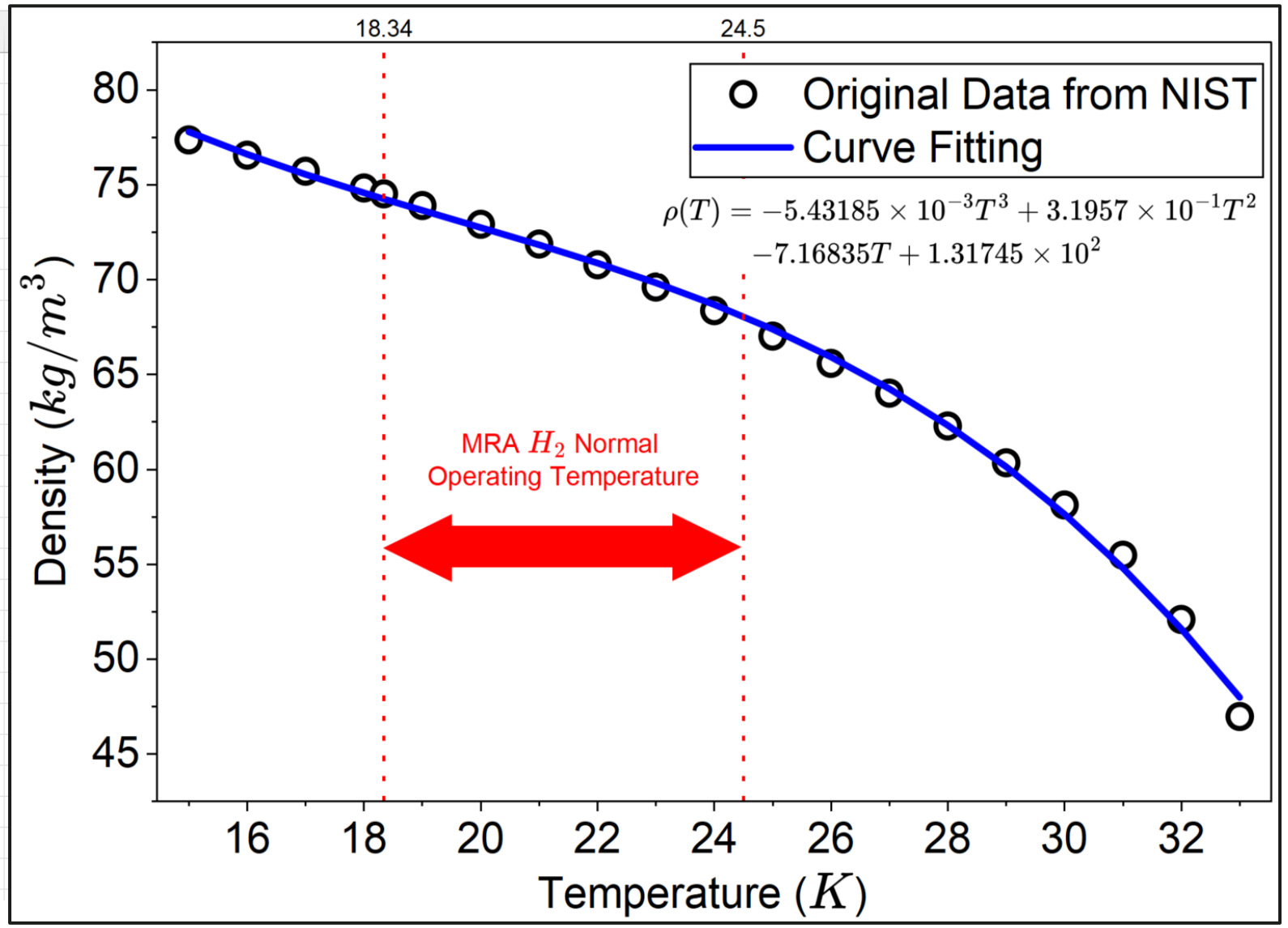
Temperature (K)	Pressure (MPa)	Density (kg/m3)	Volume (m3/kg)	Internal Energy (kJ/kg)	Enthalpy (kJ/kg)	Entropy (J/g*K)	Cv (J/g*K)	Cp (J/g*K)	Sound Spd. (m/s)	Joule-Thomson (K/MPa)	Viscosity (Pa*s)	Therm. Cond. (W/m*K)	Phase
15.000	1.4500	77.241	0.012946	-48.154	-29.382	-2.6918	5.2775	7.0899	1277.6	-1.5529	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	supercritical
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	supercritical
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	supercritical
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	supercritical
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	supercritical
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	supercritical
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	supercritical
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	supercritical

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
1		original data	Polynomial	
2	Temperature (K)	Density (kg/m3)		error(%)
3	15	77.365	77.79	-0.43
4	16	76.564	76.61	-0.05
5	17	75.723	75.55	0.17
6	18	74.839	74.58	0.26
7	18.34	74.528	74.26	0.27
8	19	73.907	73.65	0.25
9	20	72.925	72.75	0.17
10	21	71.886	71.84	0.05
11	22	70.786	70.87	-0.09
12	23	69.618	69.84	-0.22
13	24	68.371	68.69	-0.32
14	25	67.035	67.39	-0.36
15	26	65.593	65.93	-0.33
16	27	64.024	64.25	-0.23
17	28	62.295	62.33	-0.04
18	29	60.359	60.14	0.22
19	30	58.138	57.65	0.49
20	31	55.491	54.81	0.68
21	32	52.106	51.61	0.50
22	33	46.986	48.00	-1.01
23				
24		**H2 Inlet**		
25	m_dot(l/s)	0.5		
26	m_dot(m^3/s)	0.0005		
27	m_dot(kg/s)	0.0373		

Inlet mass flow rate

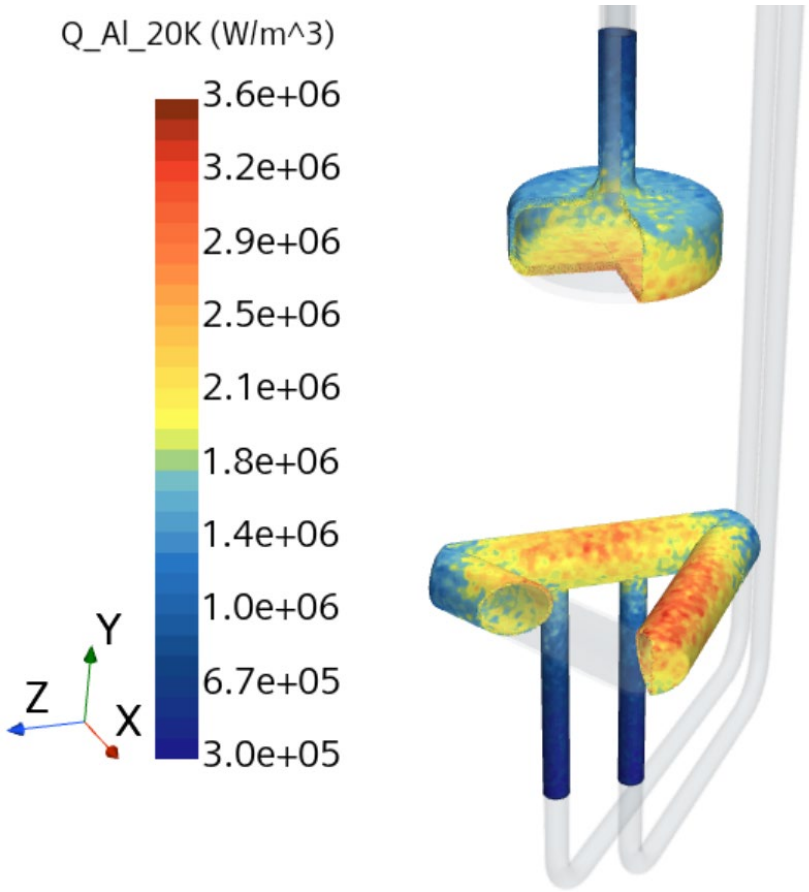


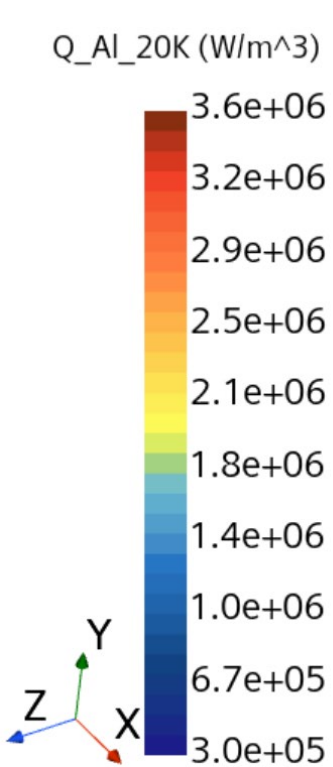
Steady State Heat Transfer Analysis for MRA H_2 Loop, Heat Source

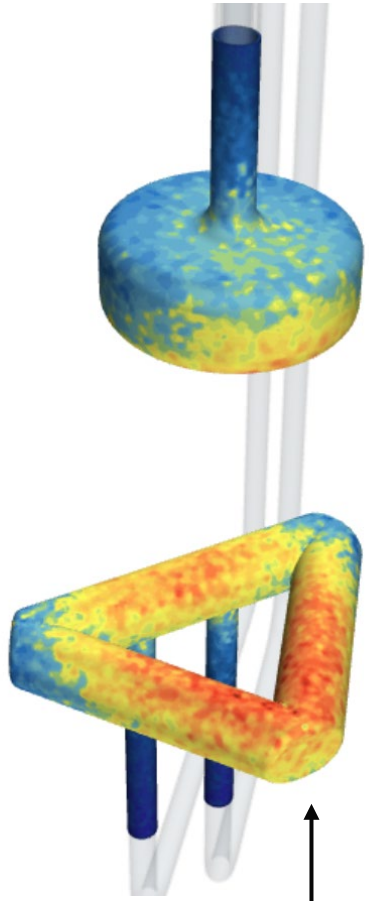
Q of Al

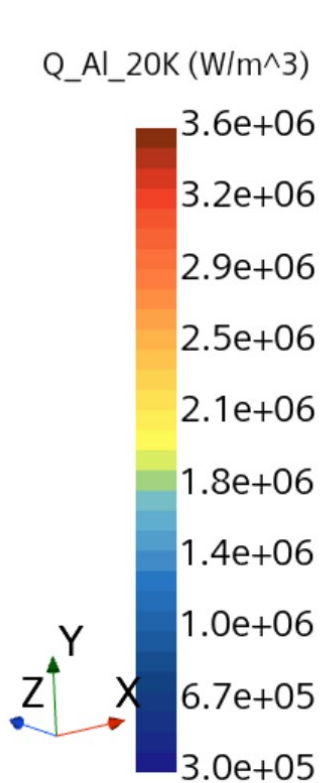
Q_Al = 409.5 W

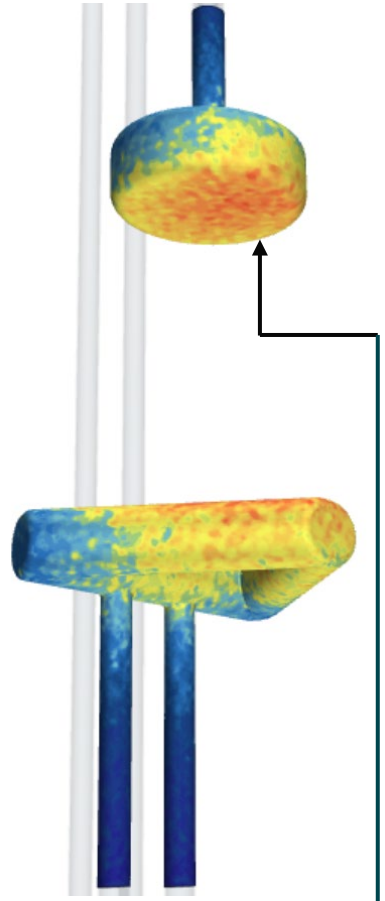
Component	Heat (W)
Upper Al Vessel (Cylinder)	220.92
Lower Al Vessel (Tube)	188.58
Total	**409.50**











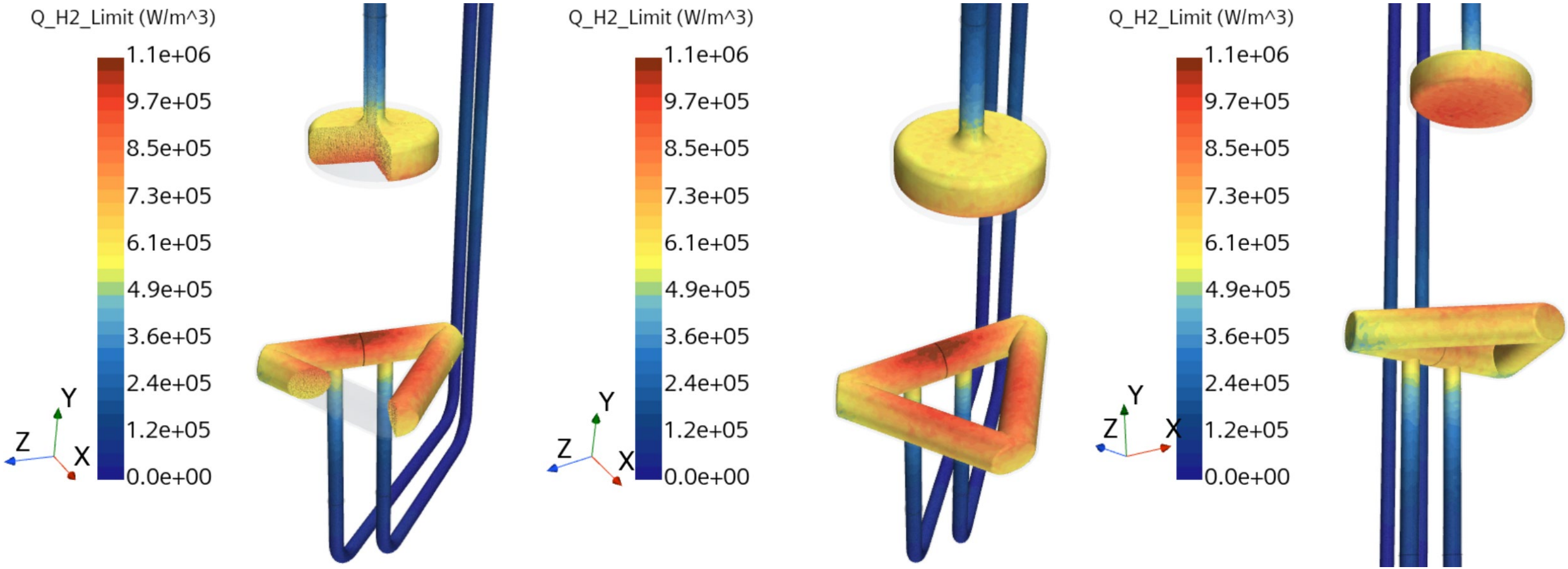
Heating peaks on the rear side of Al (+x, downstream of proton beam) due to the **slow** and **thermal neutrons** generated in the **rear** portion of **W target.**

Steady State Heat Transfer Analysis for MRA H_2 Loop, Heat Source

Q of H_2

Q_H_2 = 419.5 W

Component	Heat (W)
Upper Hydrogen (Cylinder)	183.95
Lower Hydrogen (Tube)	235.56
Total	**419.51**

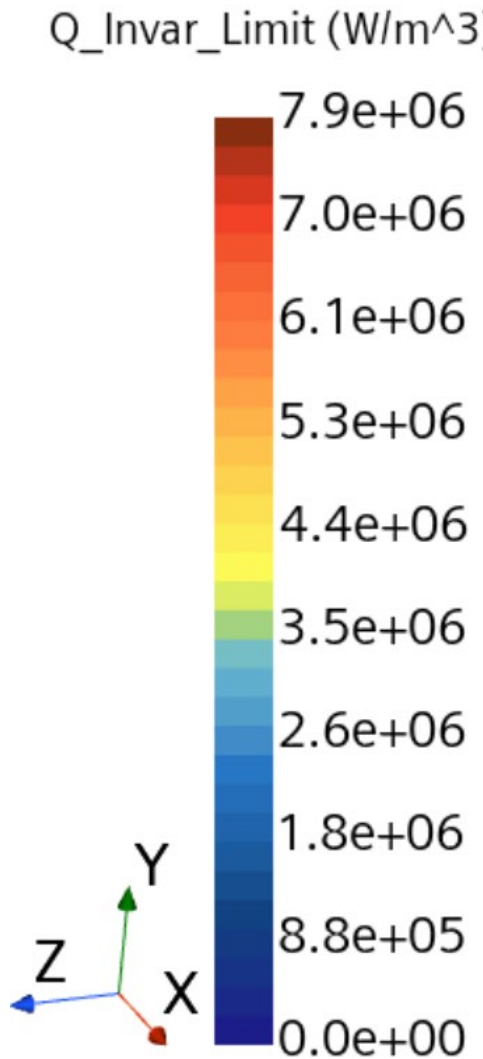


Steady State Heat Transfer Analysis for MRA H_2 Loop, Heat Source

Q of Invar

Q_Invar = 55 W

Component	Heat (W)
Invar	55.39

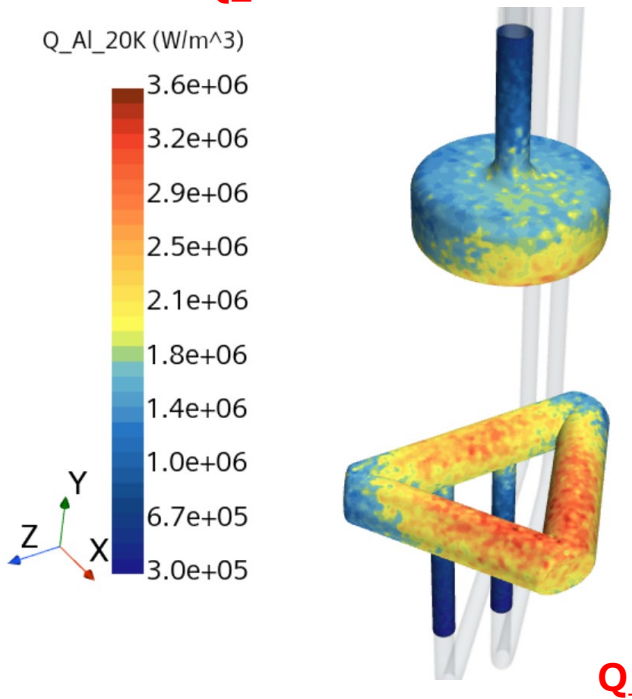




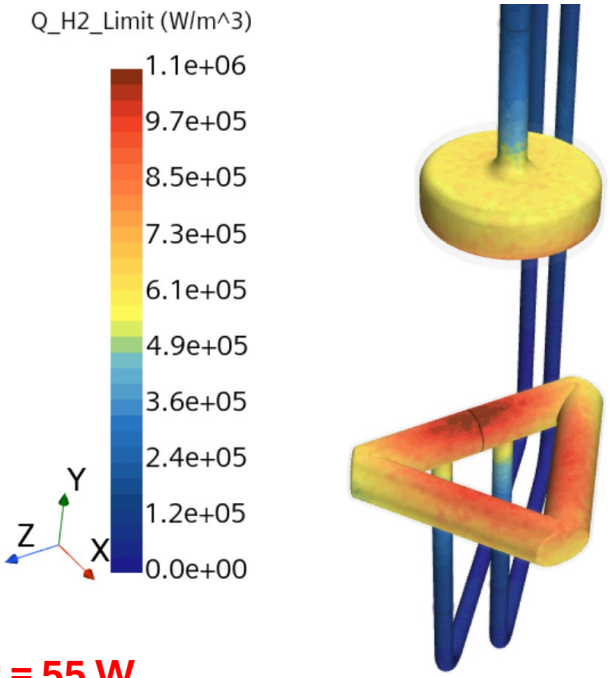
Steady State Heat Transfer Analysis for MRA H_2 Loop, Heat Source

MRA H_2 Loop		
Component	**Heat (W)**	
Upper Al Vessel (Cylinder)	220.92	409.50
Lower Al Vessel (Tube)	188.58	
Upper Hydrogen (Cylinder)	183.95	419.51
Lower Hydrogen (Tube)	235.56	
Invar		55.39
Total		**884.41**

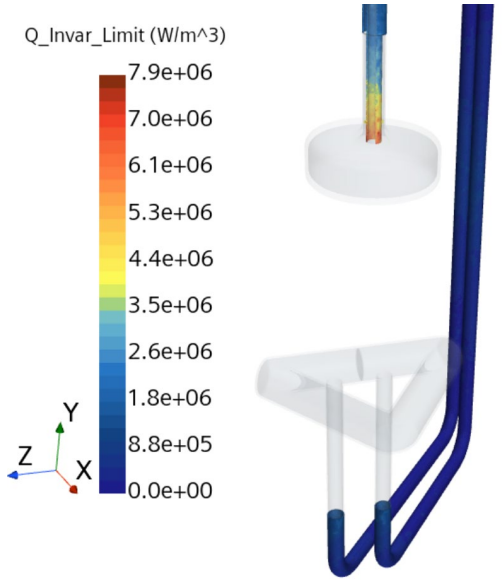
Q_Al = 409.5 W



Q_H_2 = 419.5 W



Q_Invar = 55 W

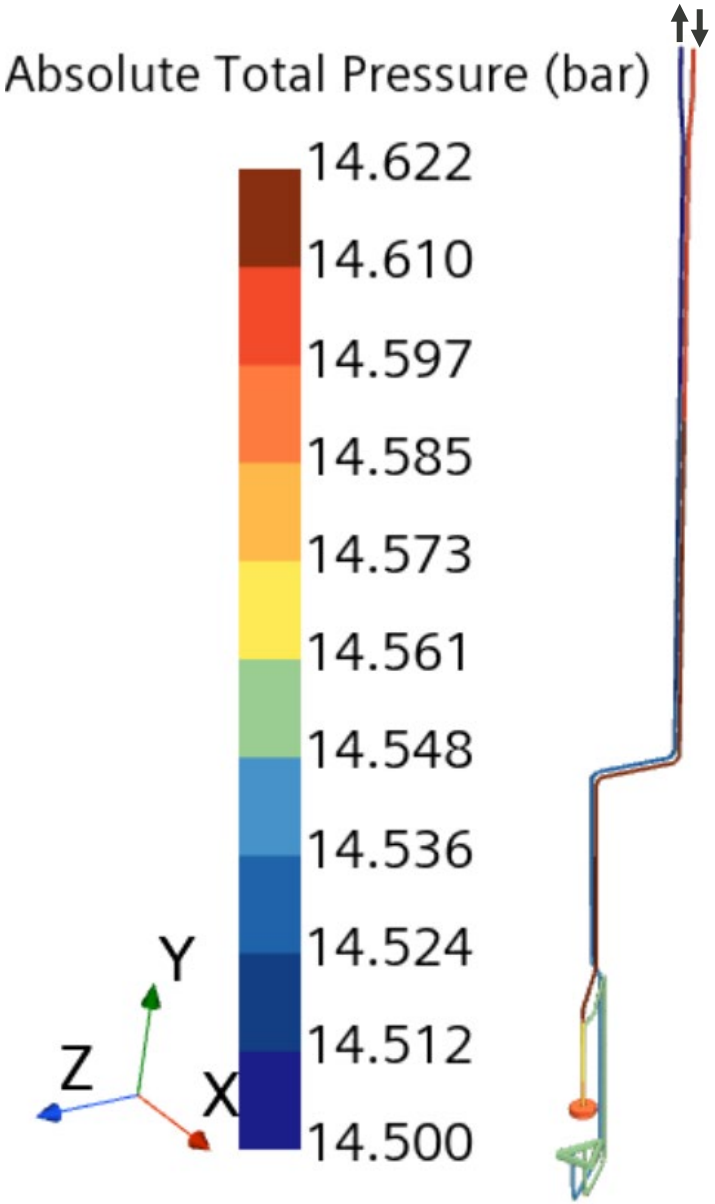


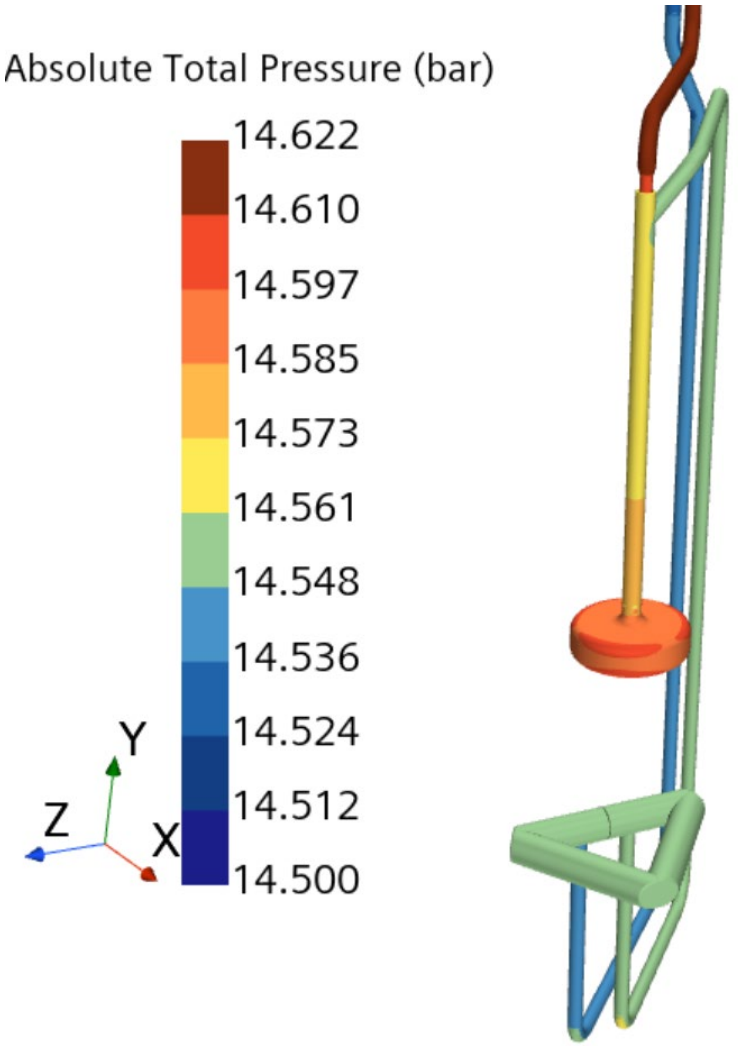
Steady State Heat Transfer Analysis for MRA H_2 Loop, Pressure

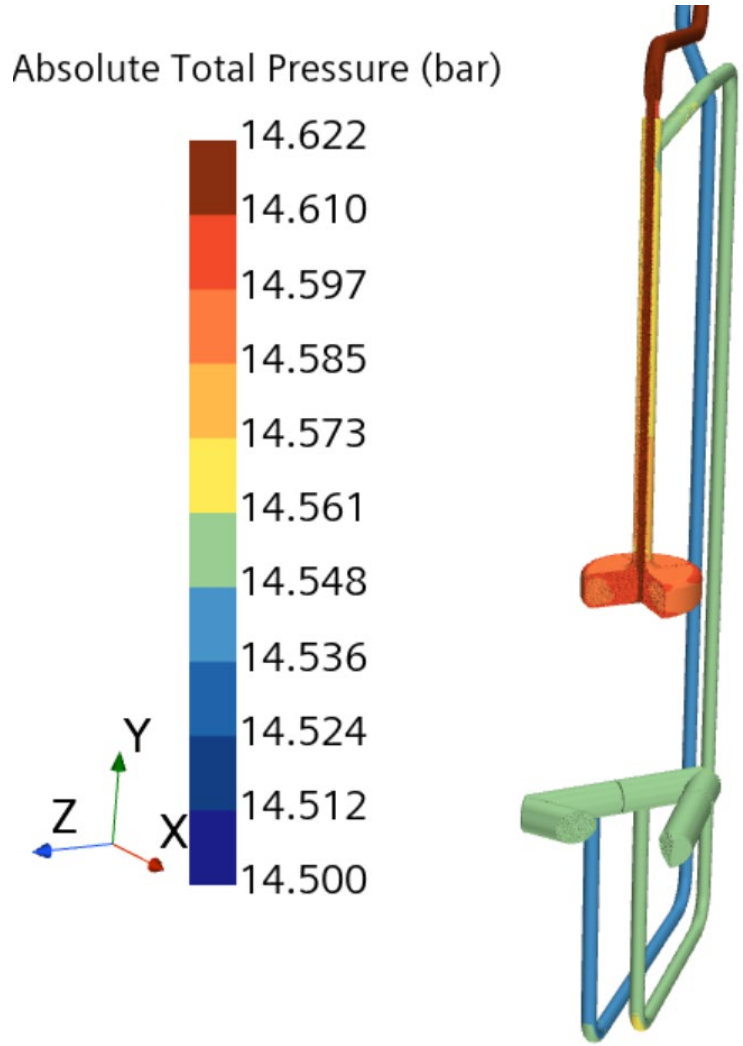
$\Delta P_{inlet-outlet} = 0.1048$ bar $(= 10.48$ kPa $= 1.52\ psi = 0.103\ atm)$

Outlet Inlet (0.0373 kg/s, 18.34 K H_2)

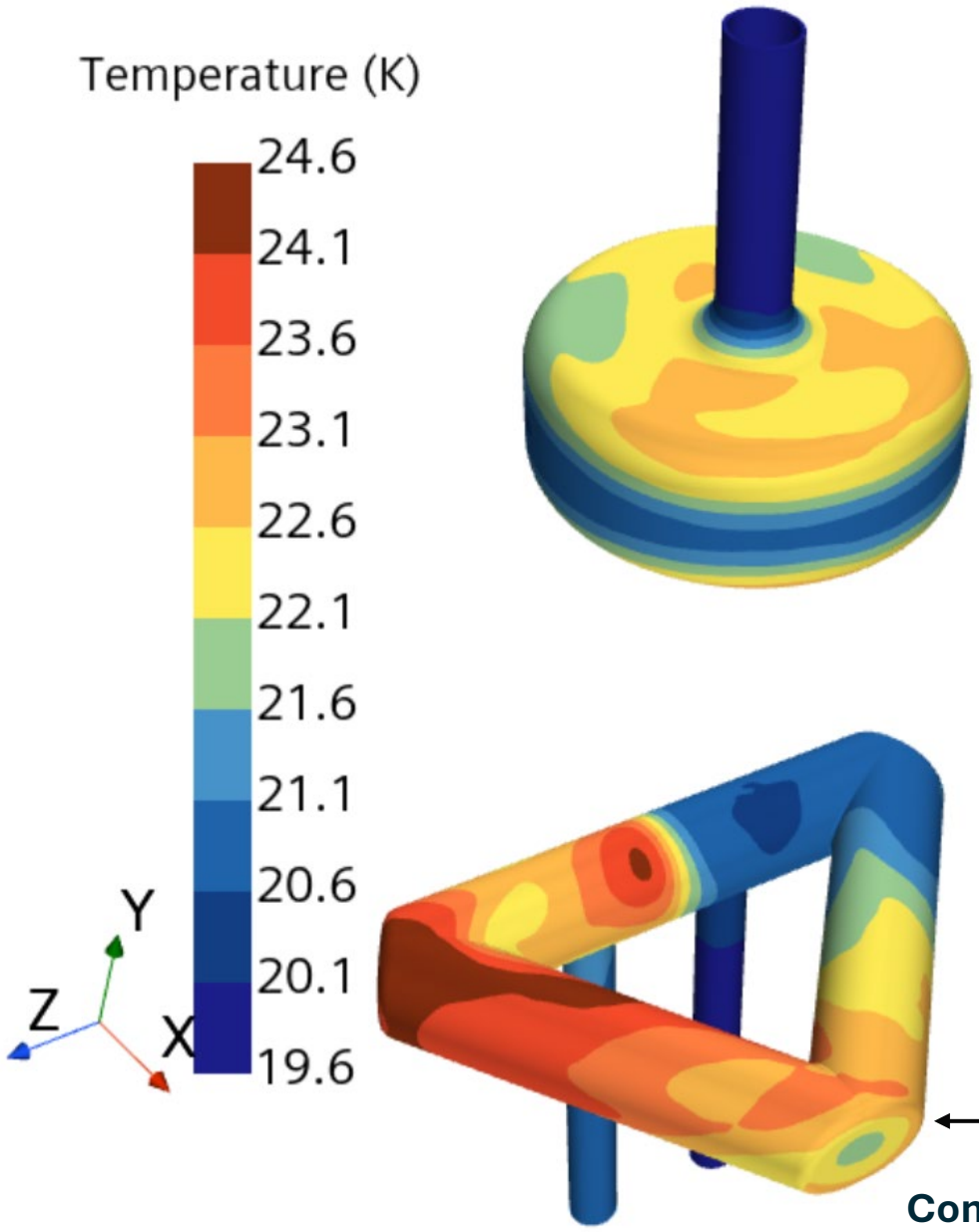
Requirement: < 0.15 bar

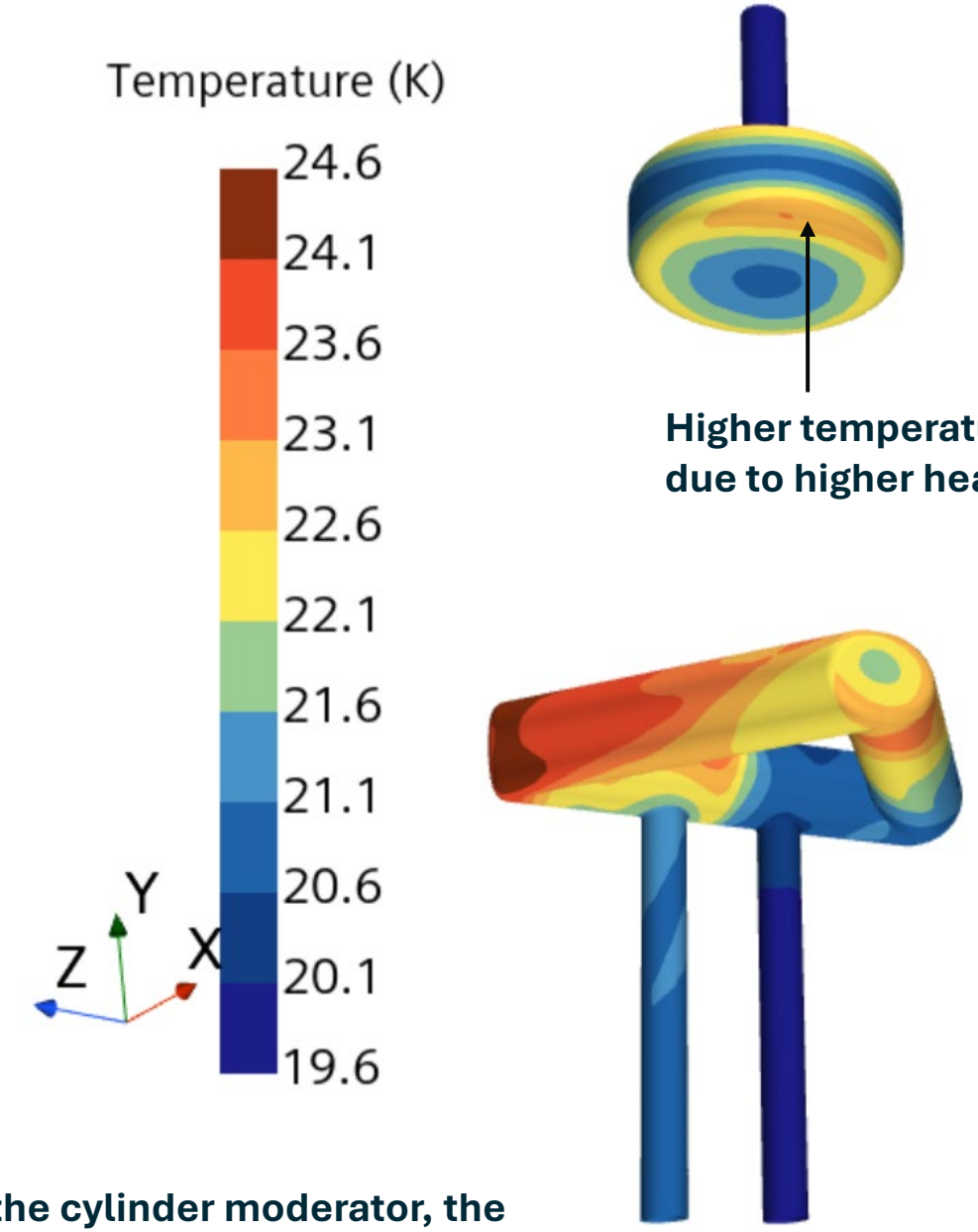






Steady State Heat Transfer Analysis for MRA H_2 Loop, Temperature of Al Vessel

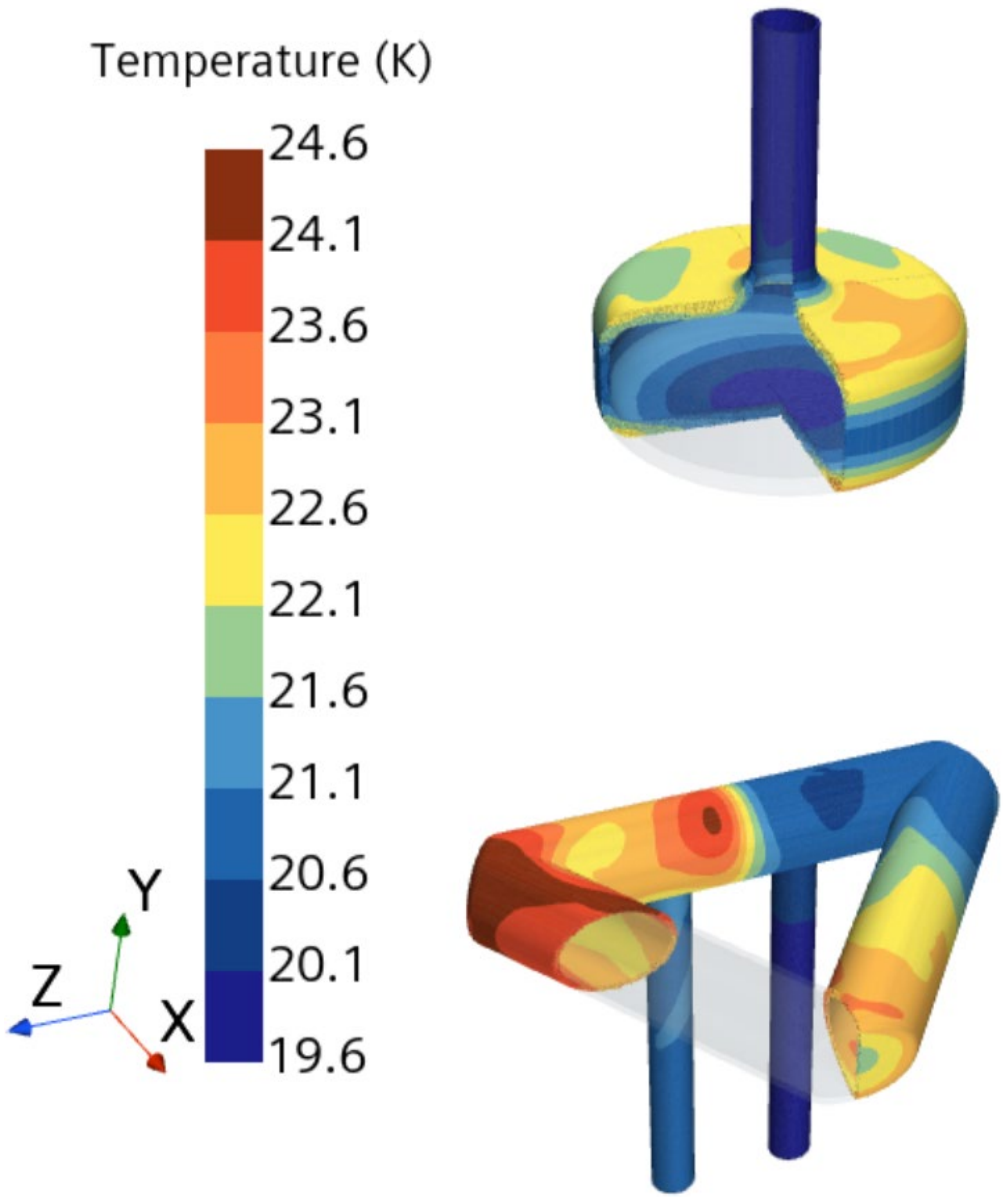


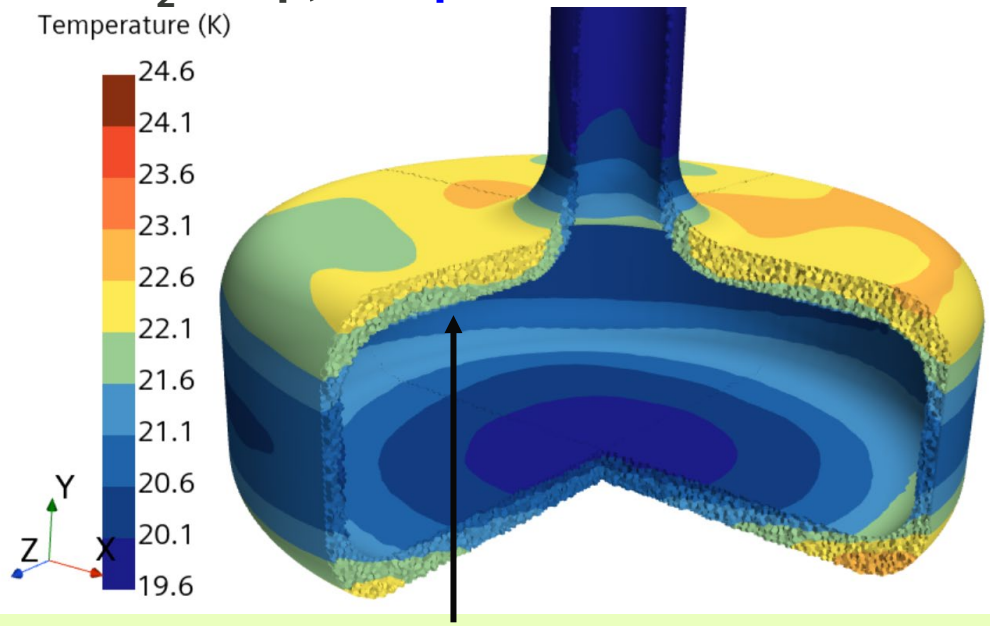


Higher temperature due to higher heating

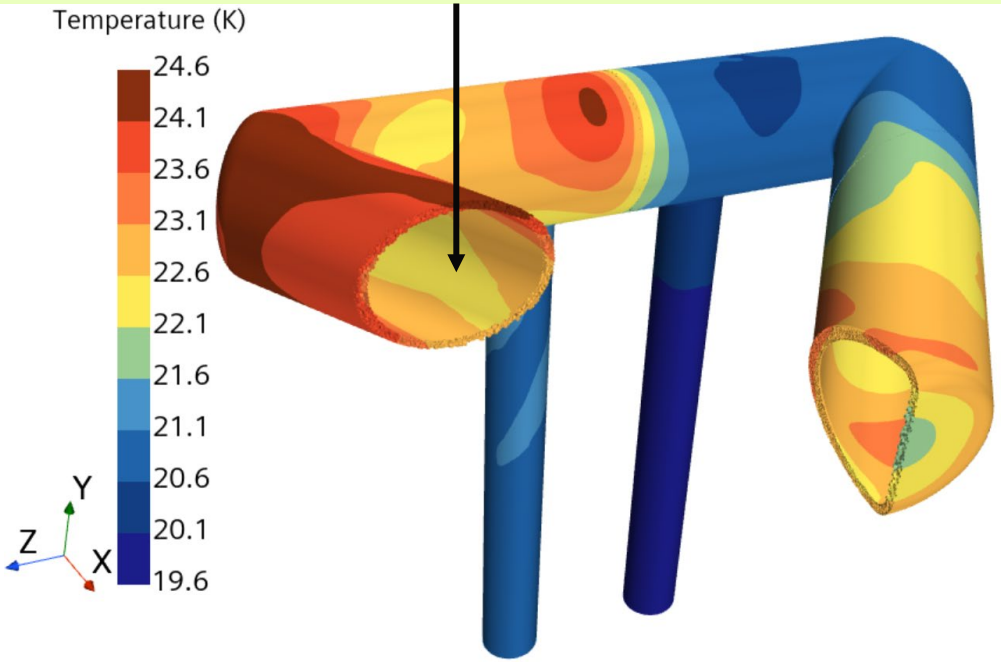
Compared to the cylinder moderator, the flow field of the tube moderator is less uniform, and so is the temperature field.

Steady State Heat Transfer Analysis for MRA H_2 Loop, Temperature of Al Vessel

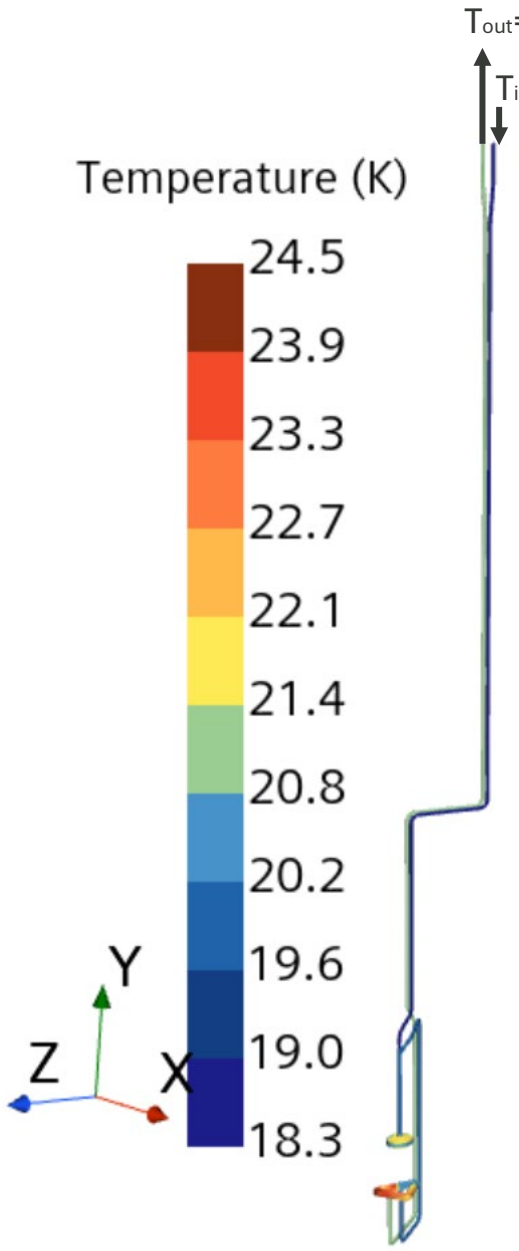


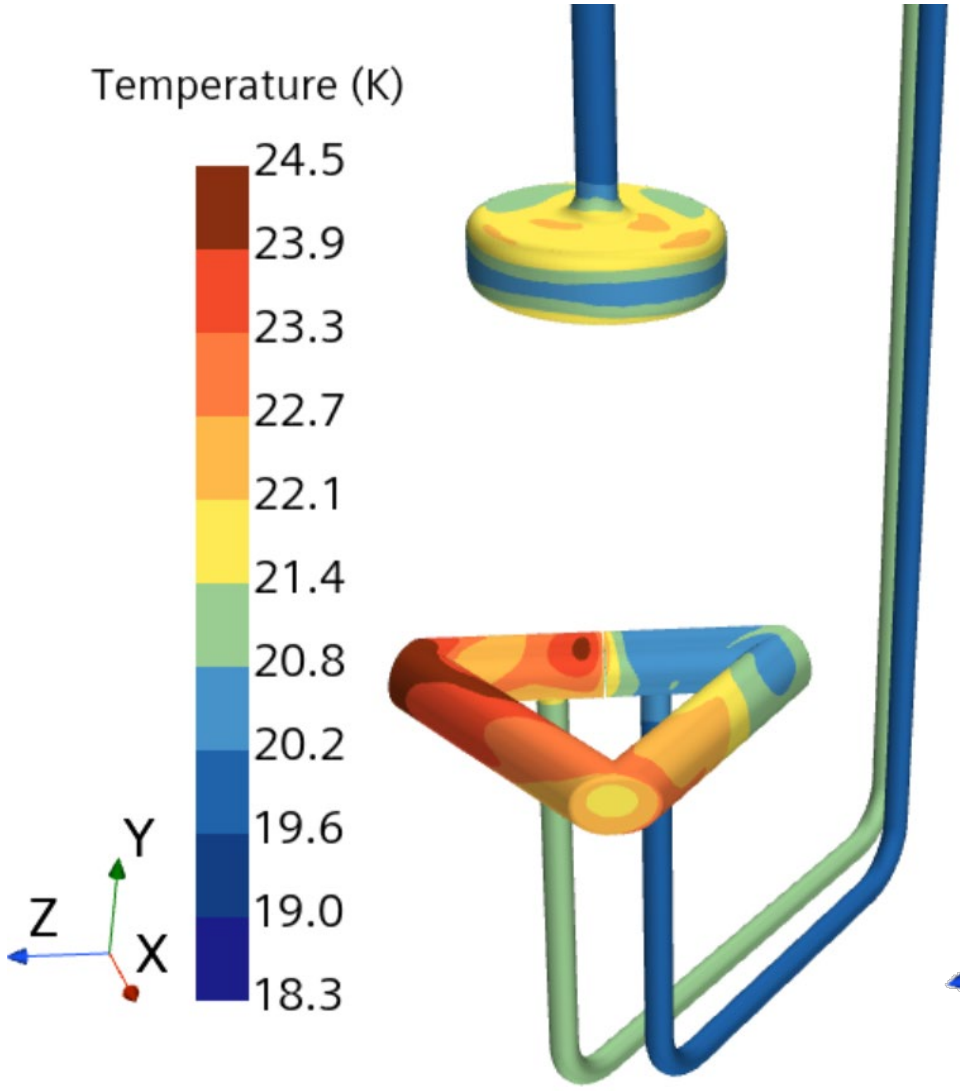


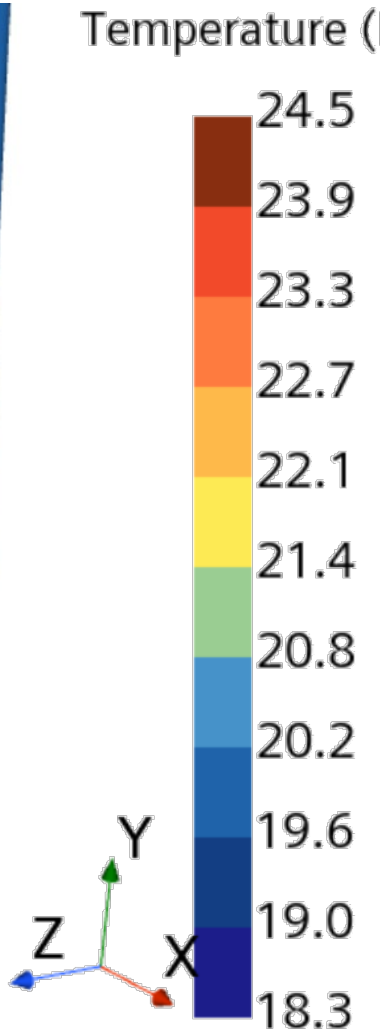
The **inner surface** of the Al vessel is in contact with H_2. Therefore, the **temperature** and **density** profiles of **H_2** are **not uniform** along this **contact surface**.

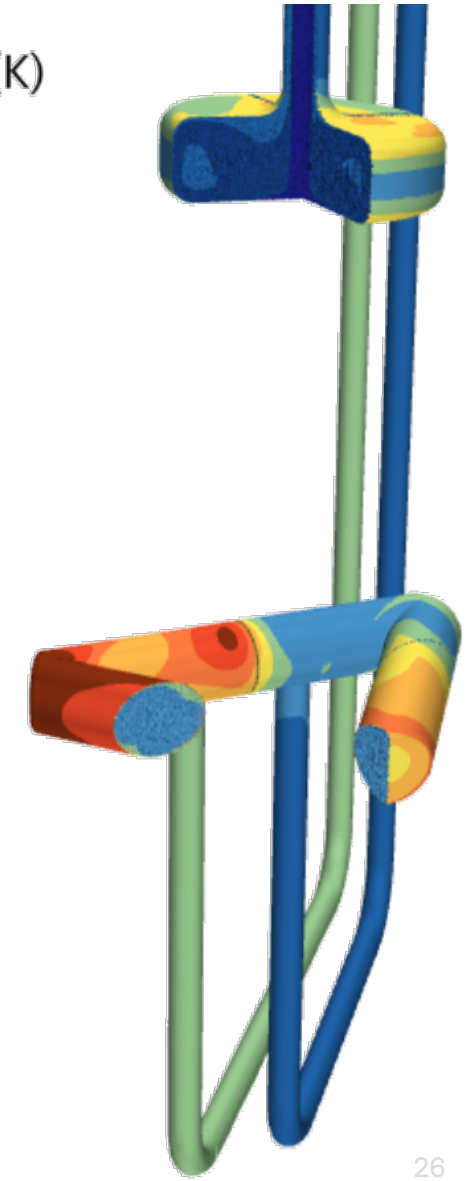


Steady State Heat Transfer Analysis for MRA H_2 Loop, Temperature of H_2







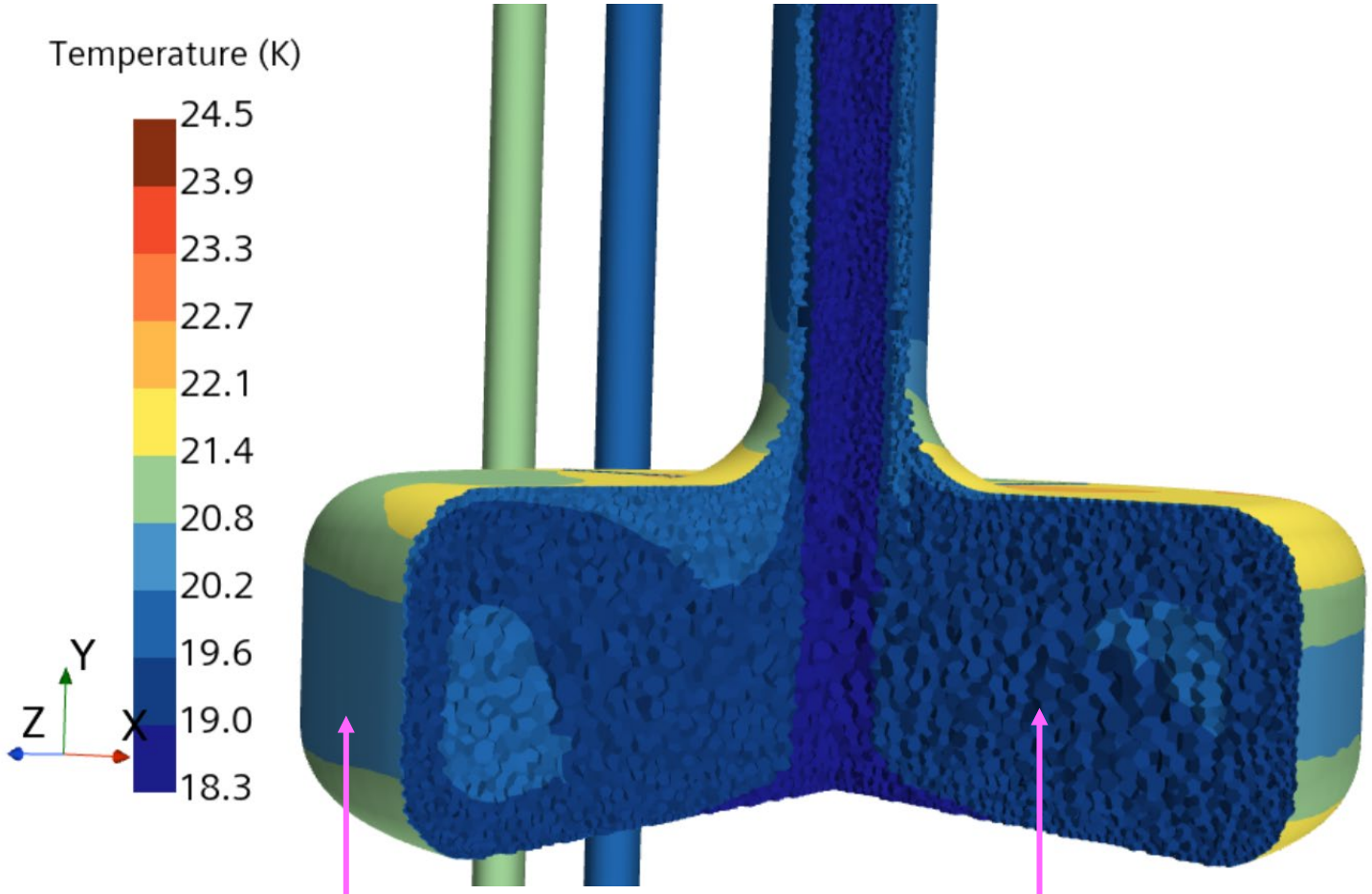


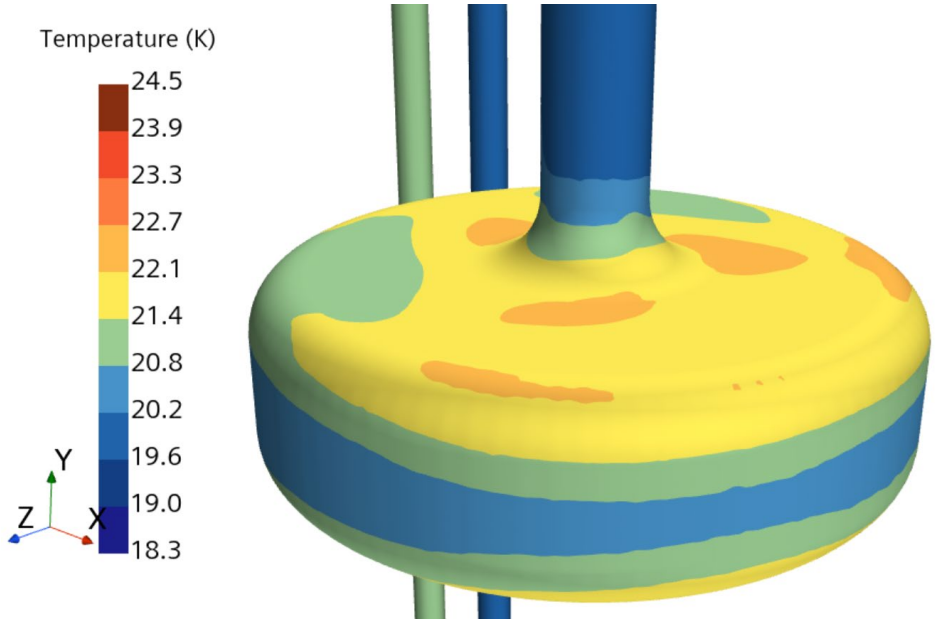
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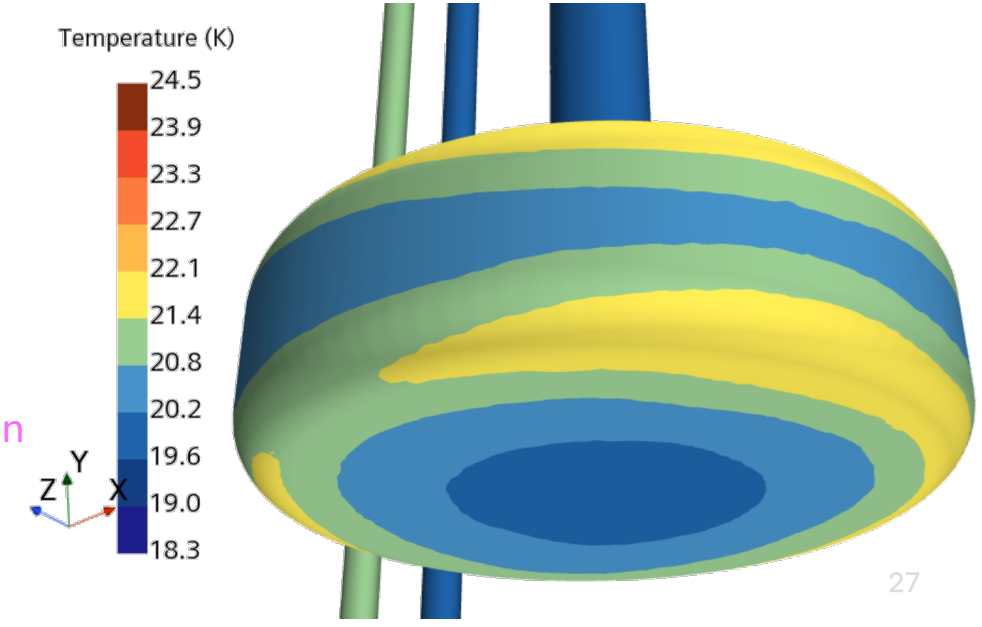
Steady State Heat Transfer Analysis for MRA H_2 Loop, Temperature of H_2

Cylindrical Moderator

Requirement: < 32K







In contact with Al vessel ➔ **non-uniform surface** temperature

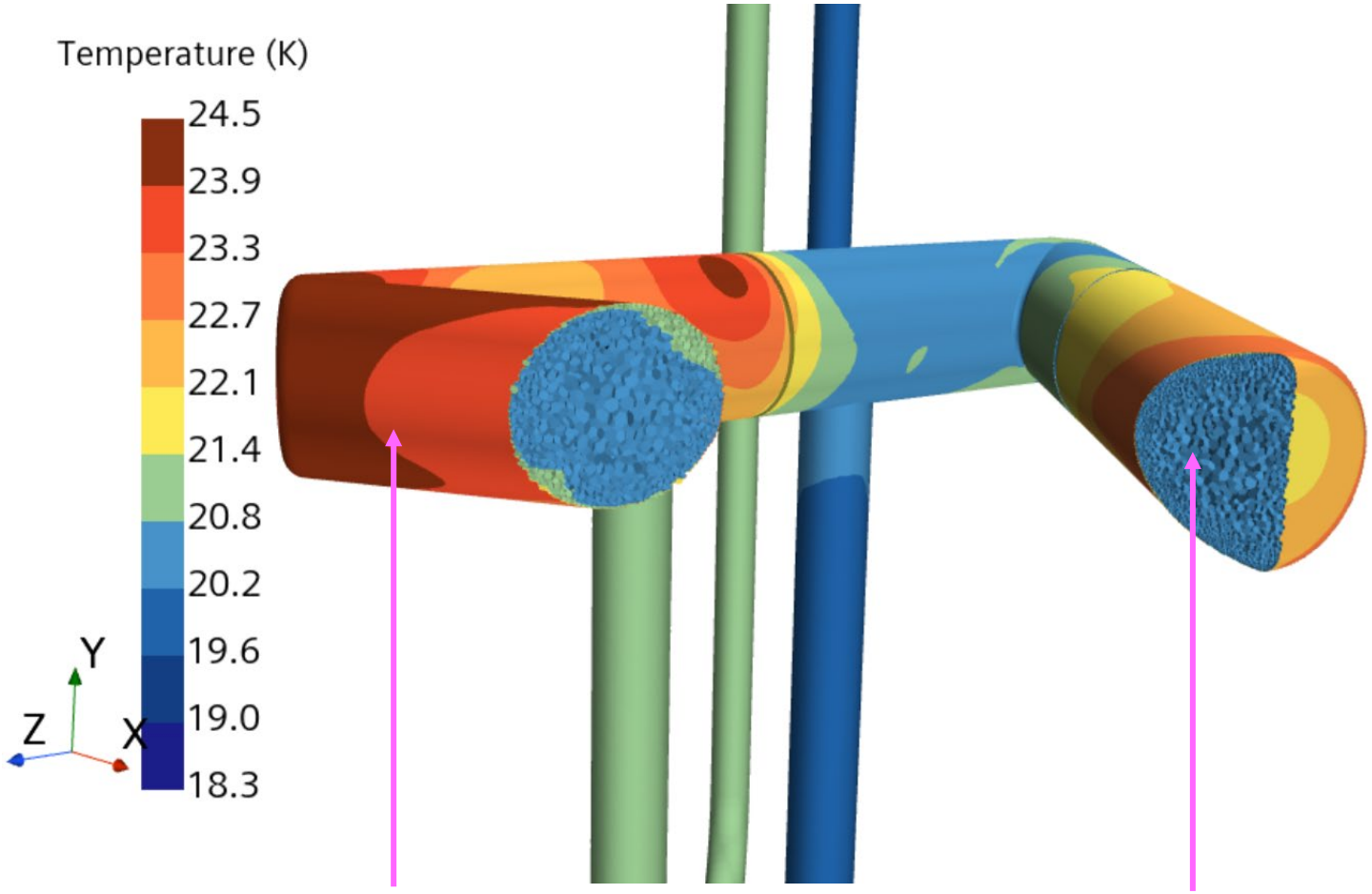
The **bulk temperature** of the hydrogen remains fairly **uniform**.

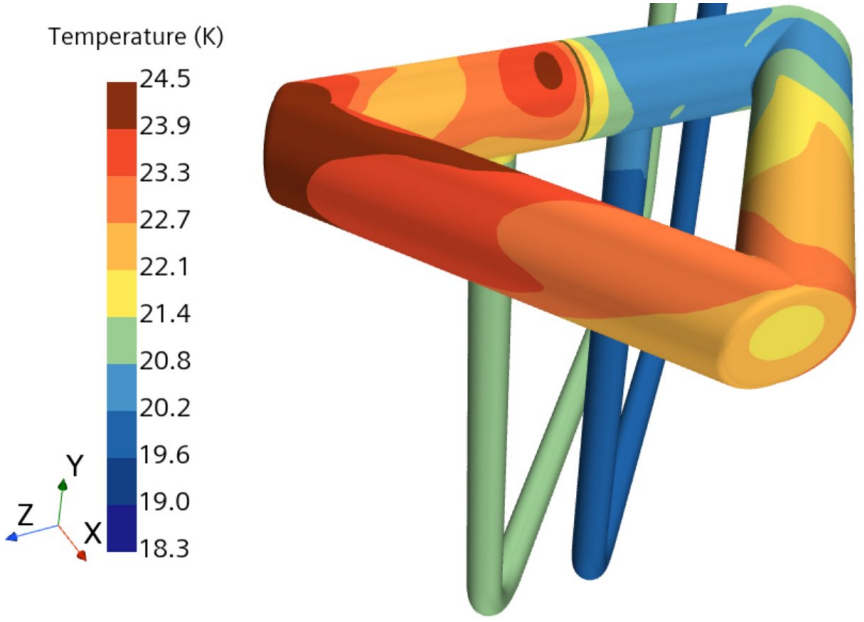
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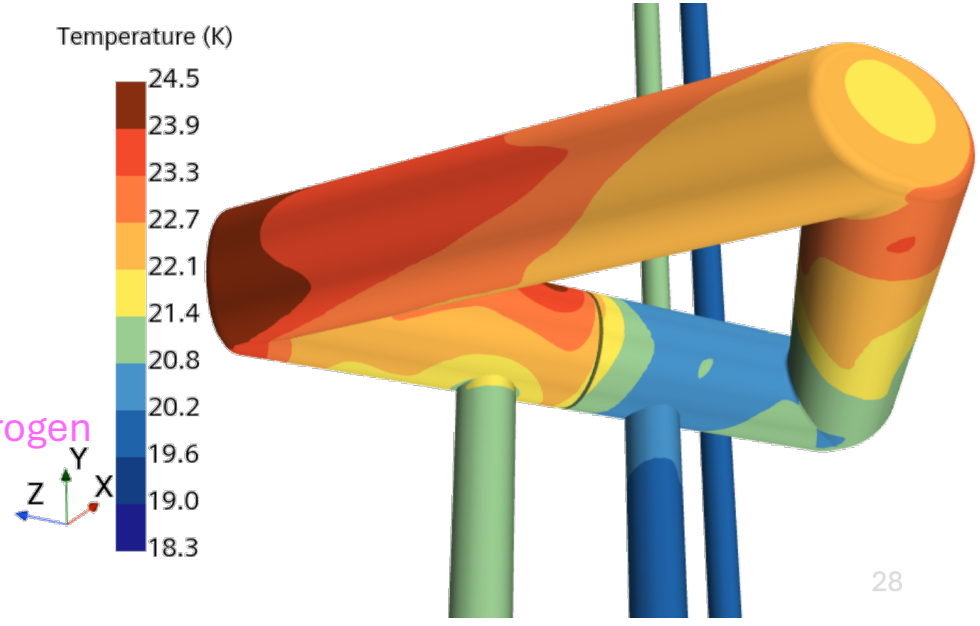
Steady State Heat Transfer Analysis for MRA H_2 Loop, Temperature of H_2

Tube Moderator

Requirement: < 32K







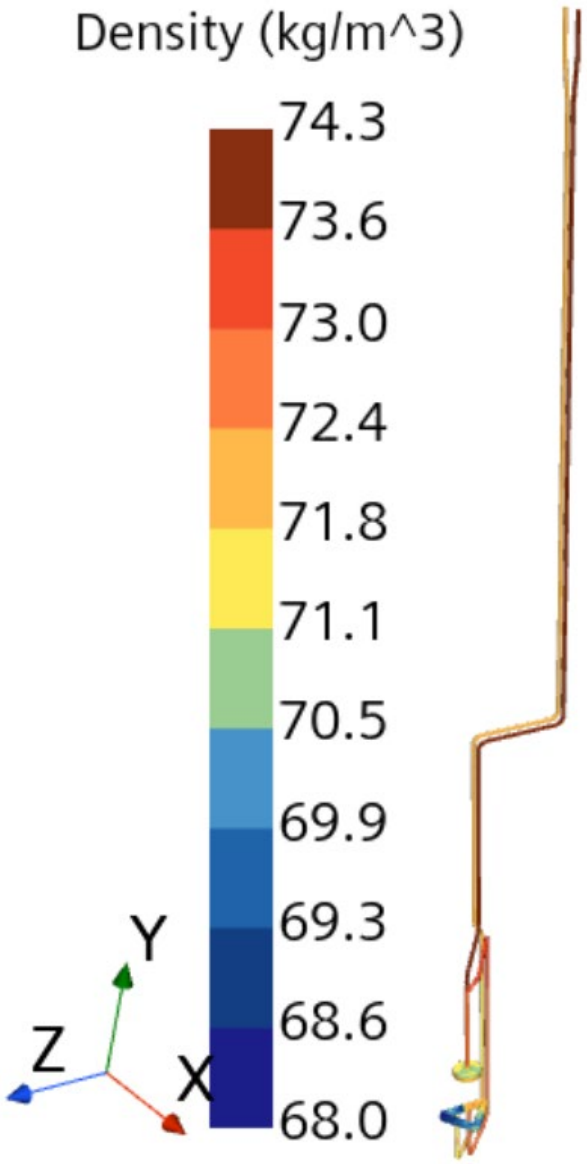
In contact with Al vessel ➔ **non-uniform surface** temperature

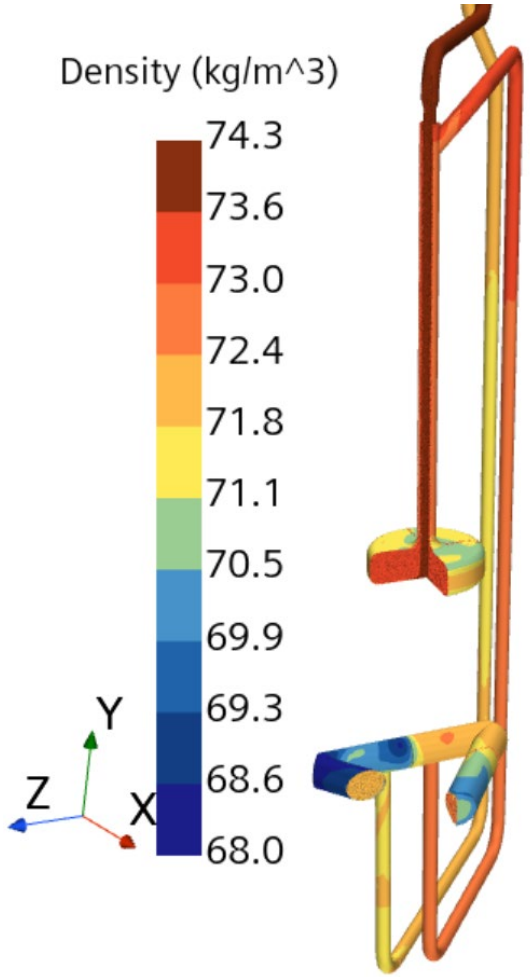
The **bulk temperature** of the hydrogen remains fairly **uniform**.

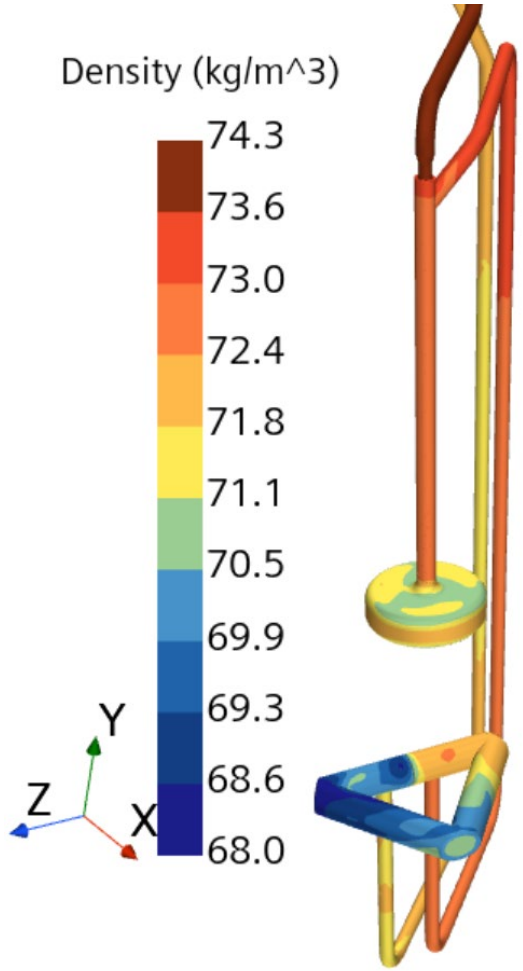
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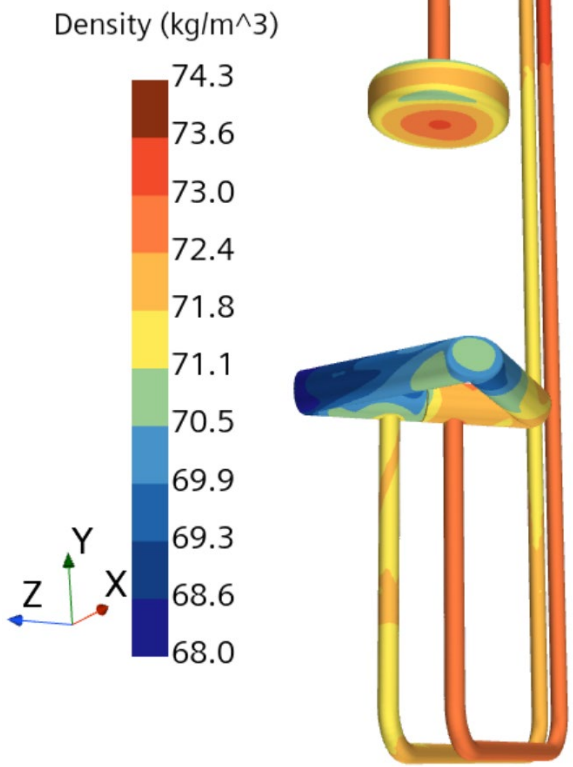
Steady State Heat Transfer Analysis for MRA H_2 Loop, Density of H_2

Requirement: average density of H_2 > 72 kg/m^3







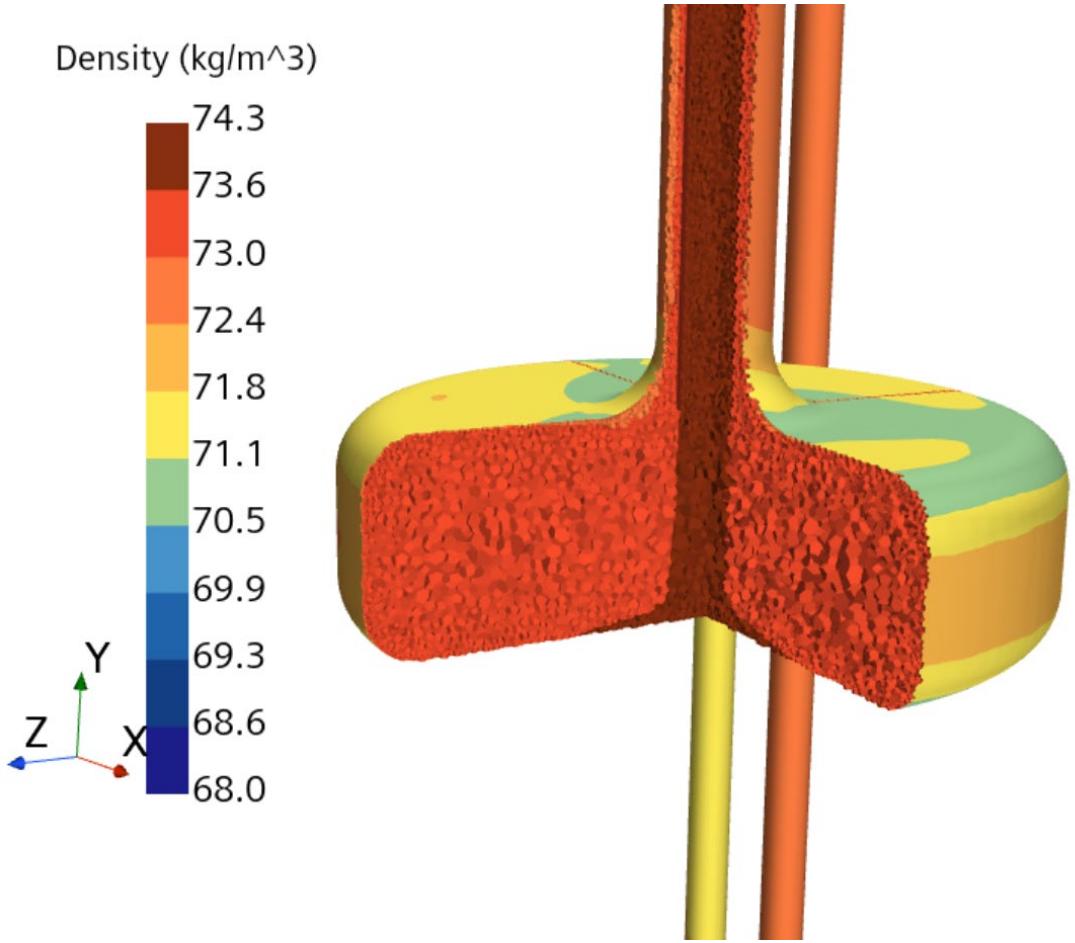


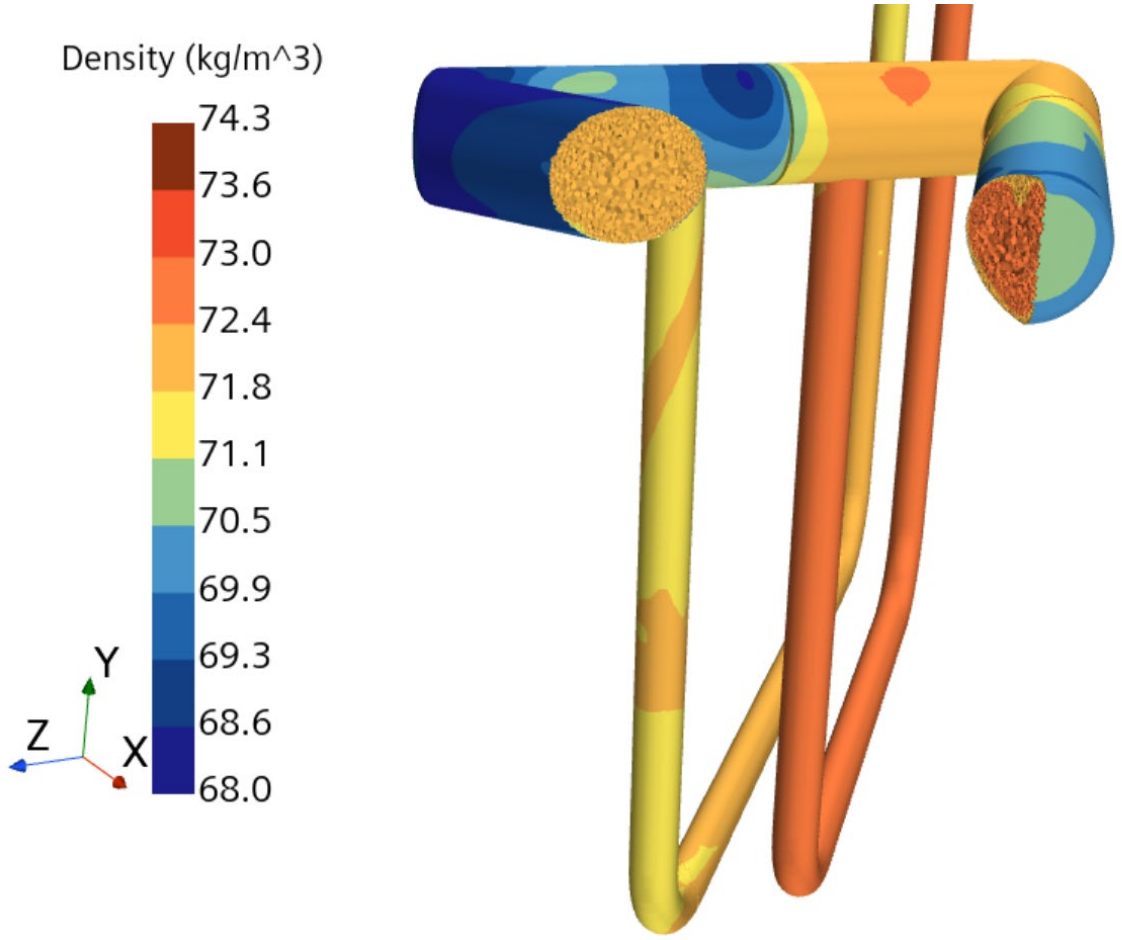
Moderator	
H_2 Density at 18.34 K (kg/m^3)	74.260
Average H_2 Density (kg/m^3)	72.883
Variation (%)	1.85

From the polynomial function used in the simulation

Steady State Heat Transfer Analysis for MRA H_2 Loop, Density of H_2

Requirement: average density of H_2 > 72 kg/m^3





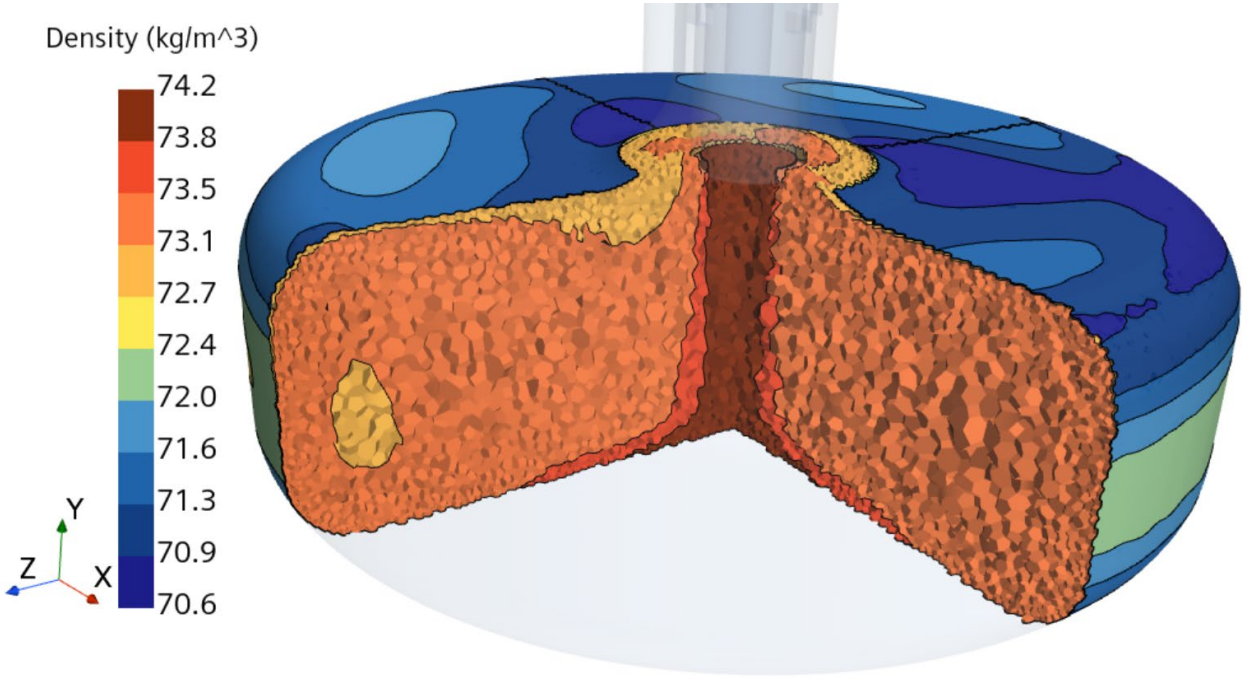
Moderator	
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Average H_2 Density (kg/m^3)	72.883
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From the polynomial function used in the simulation

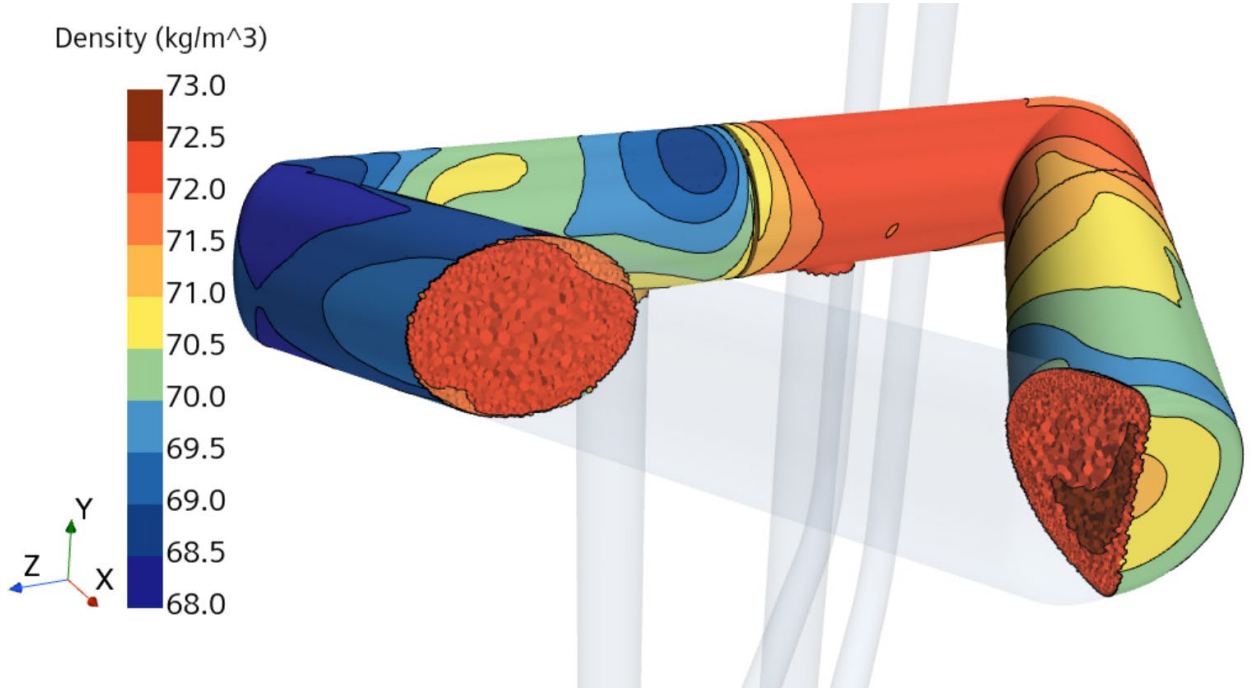
Steady State Heat Transfer Analysis for MRA H_2 Loop, Density of H_2

Requirement: average density of H_2 > 72 kg/m^3

Cylindrical Moderator



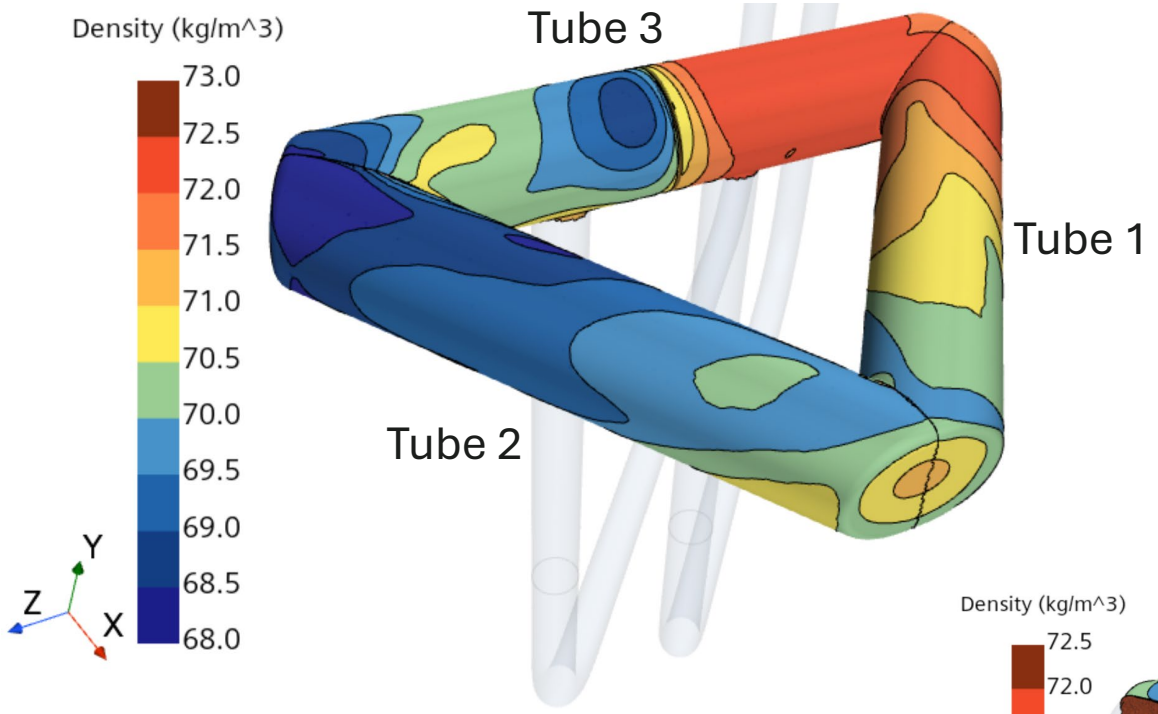
Tube Moderator

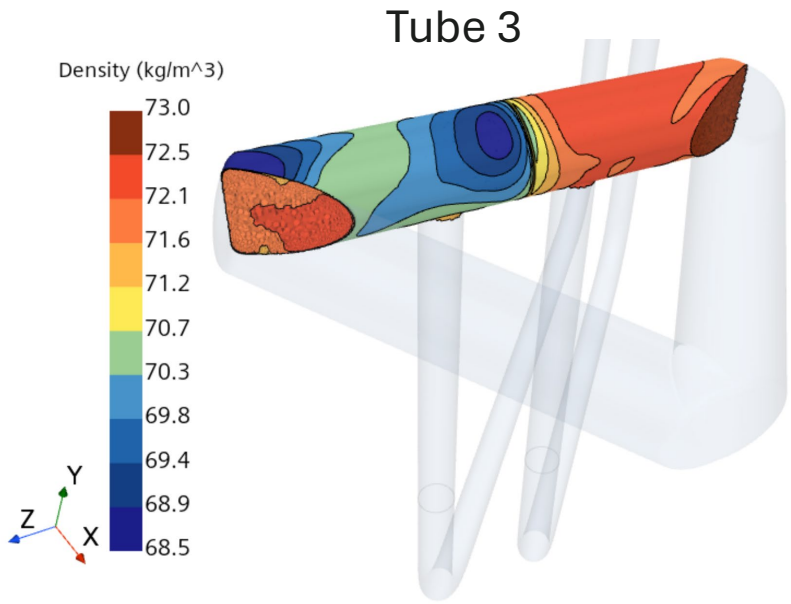


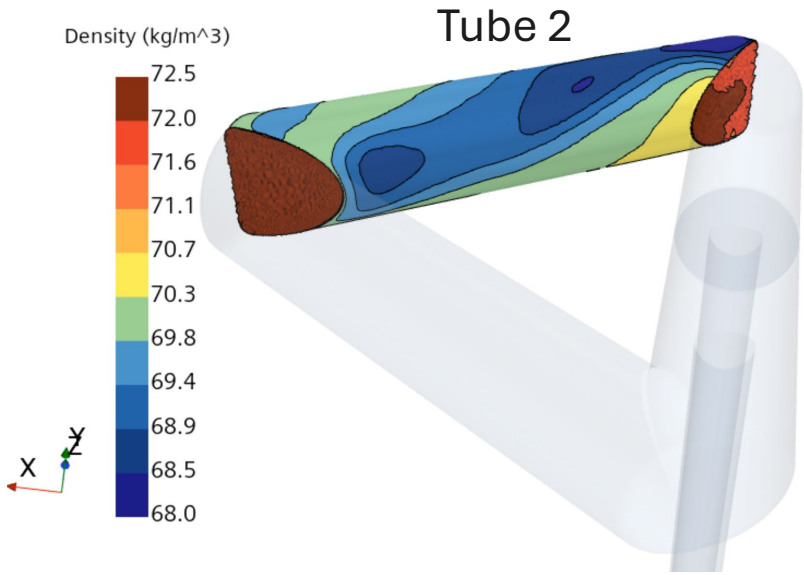
MRA H_2 Moderator		
	Average H_2 Density (kg/m^3)	Variation (%)
Cylindrical	73.185	1.45
Tube	72.353	2.57
Inlet at 18.34K	74.26	

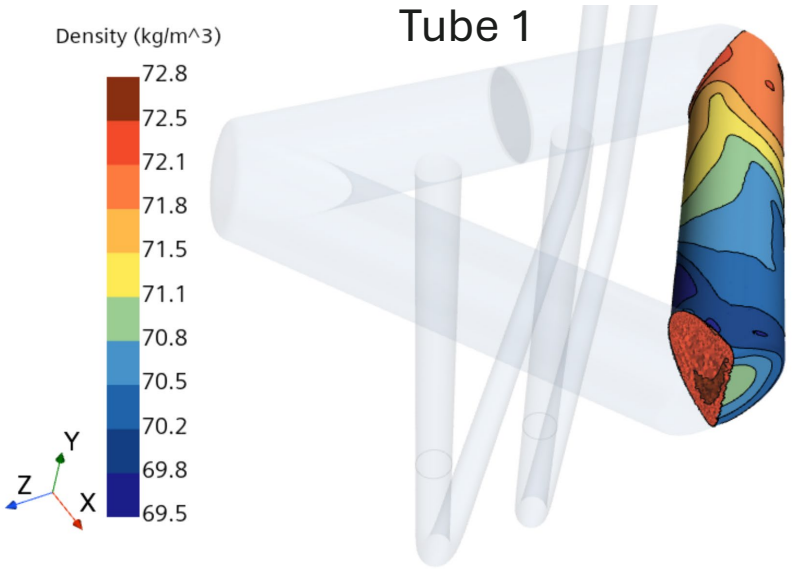
Steady State Heat Transfer Analysis for MRA H_2 Loop, Density of H_2

Requirement: average density of H_2 > 72 kg/m^3









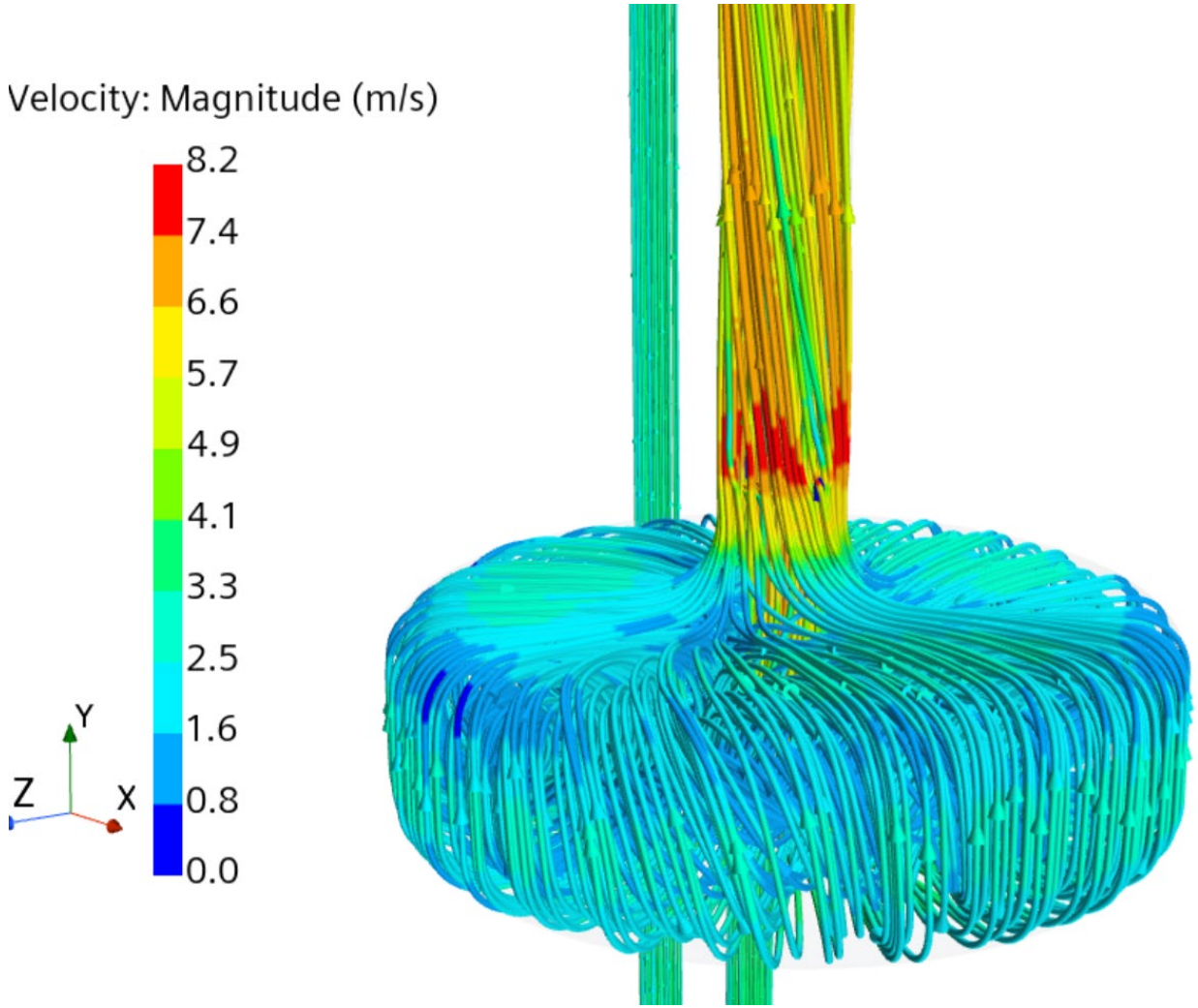
	Average H_2 Density (kg/m^3)
Tube 1	72.5749
Tube 2	72.1708
Tube 3	72.3183

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Steady State Heat Transfer Analysis for MRA H_2 Loop, Streamlines

Cylindrical Moderator

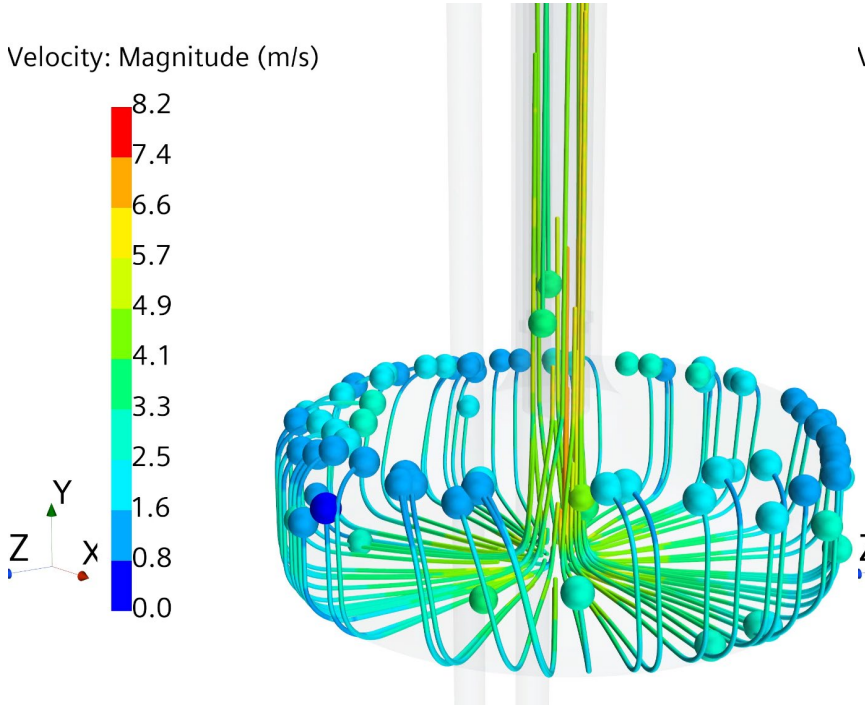
Velocity

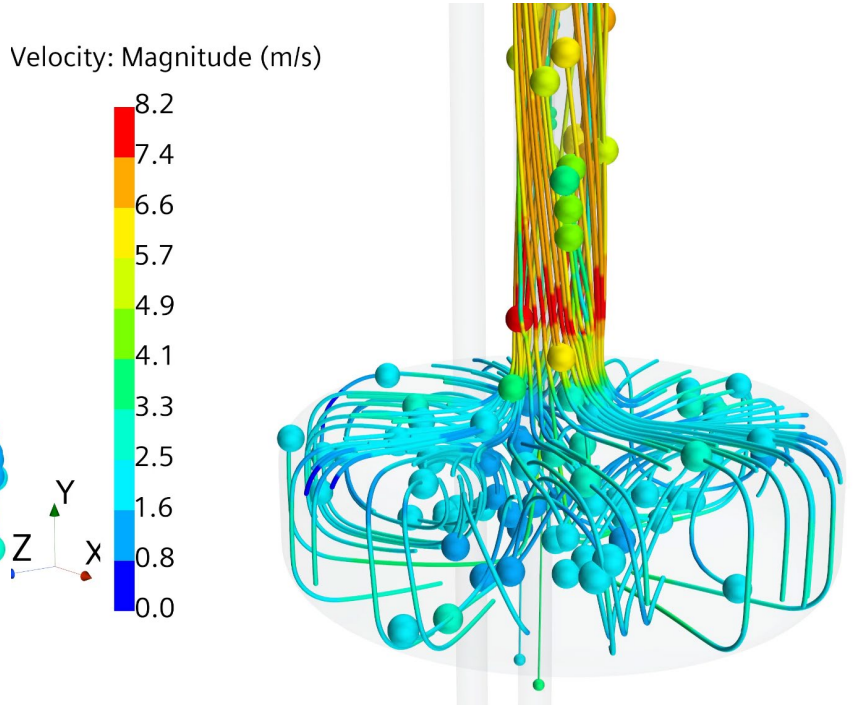


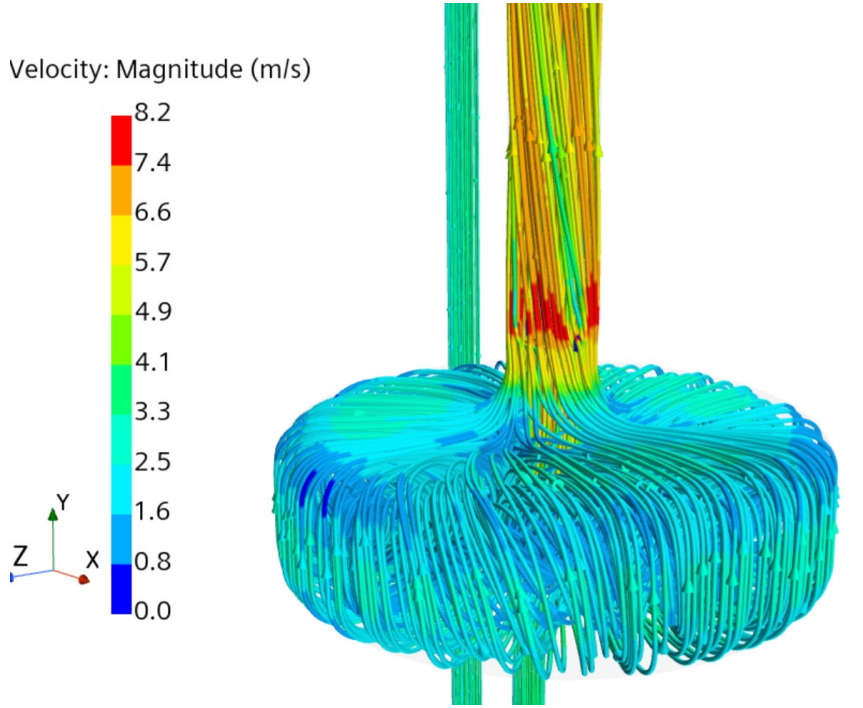
Steady State Heat Transfer Analysis for MRA H_2 Loop, Streamlines

Cylindrical Moderator

Velocity

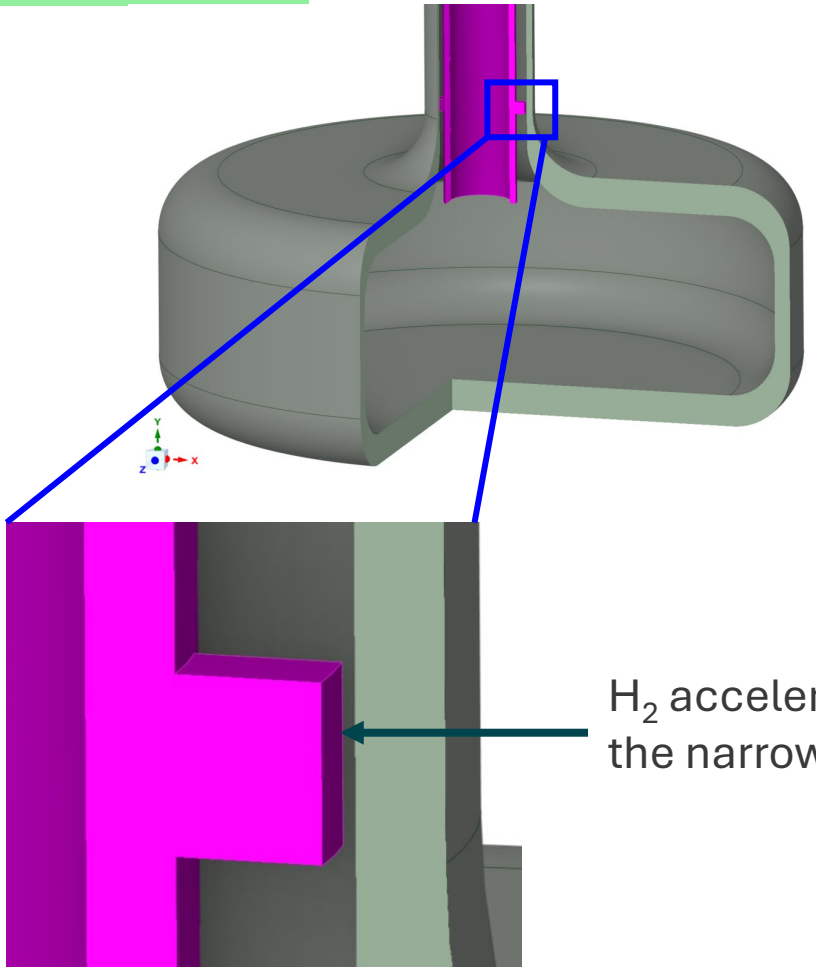






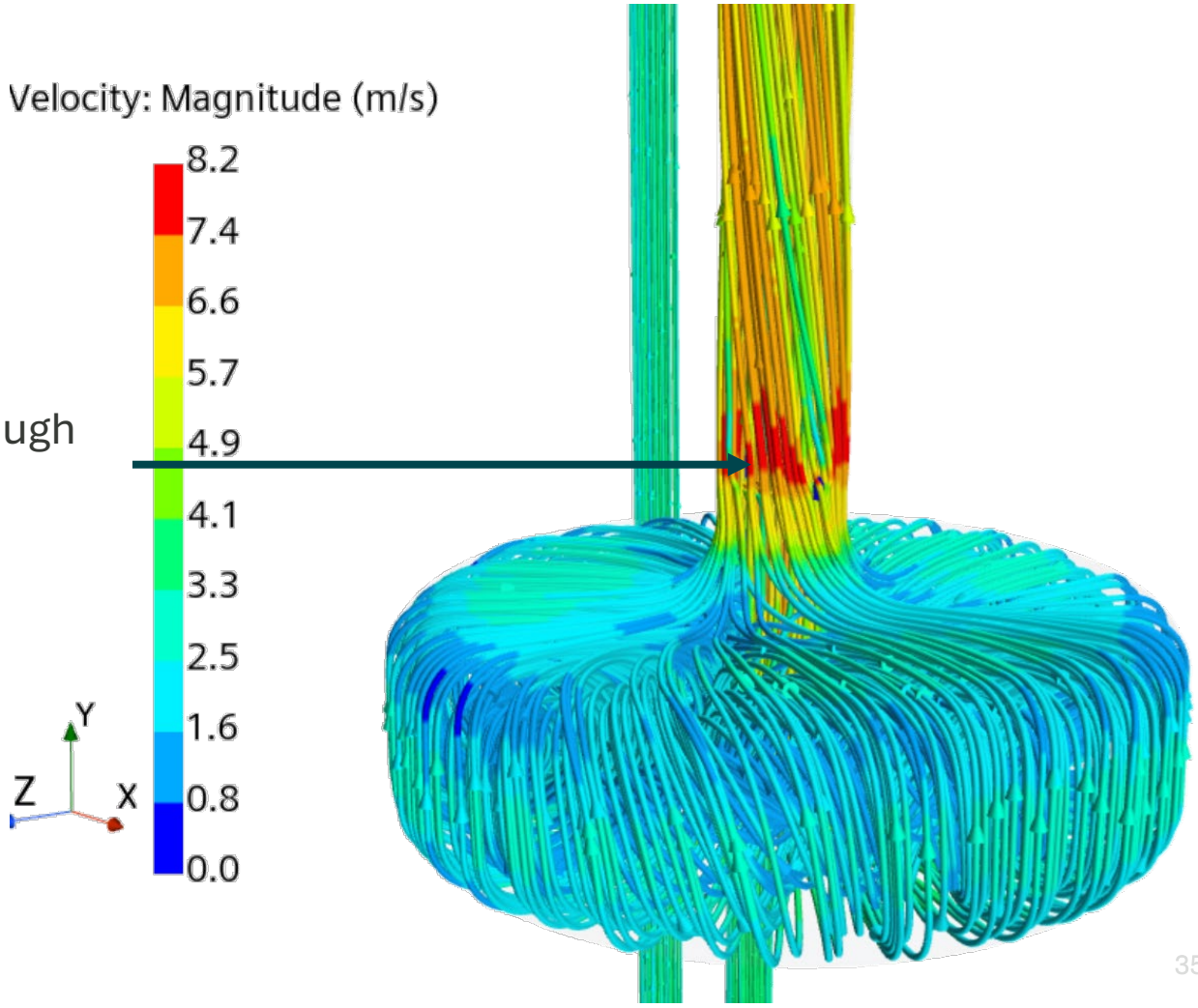
Steady State Heat Transfer Analysis for MRA H_2 Loop, Streamlines

Cylindrical Moderator



H_2 accelerates through the narrow gap.

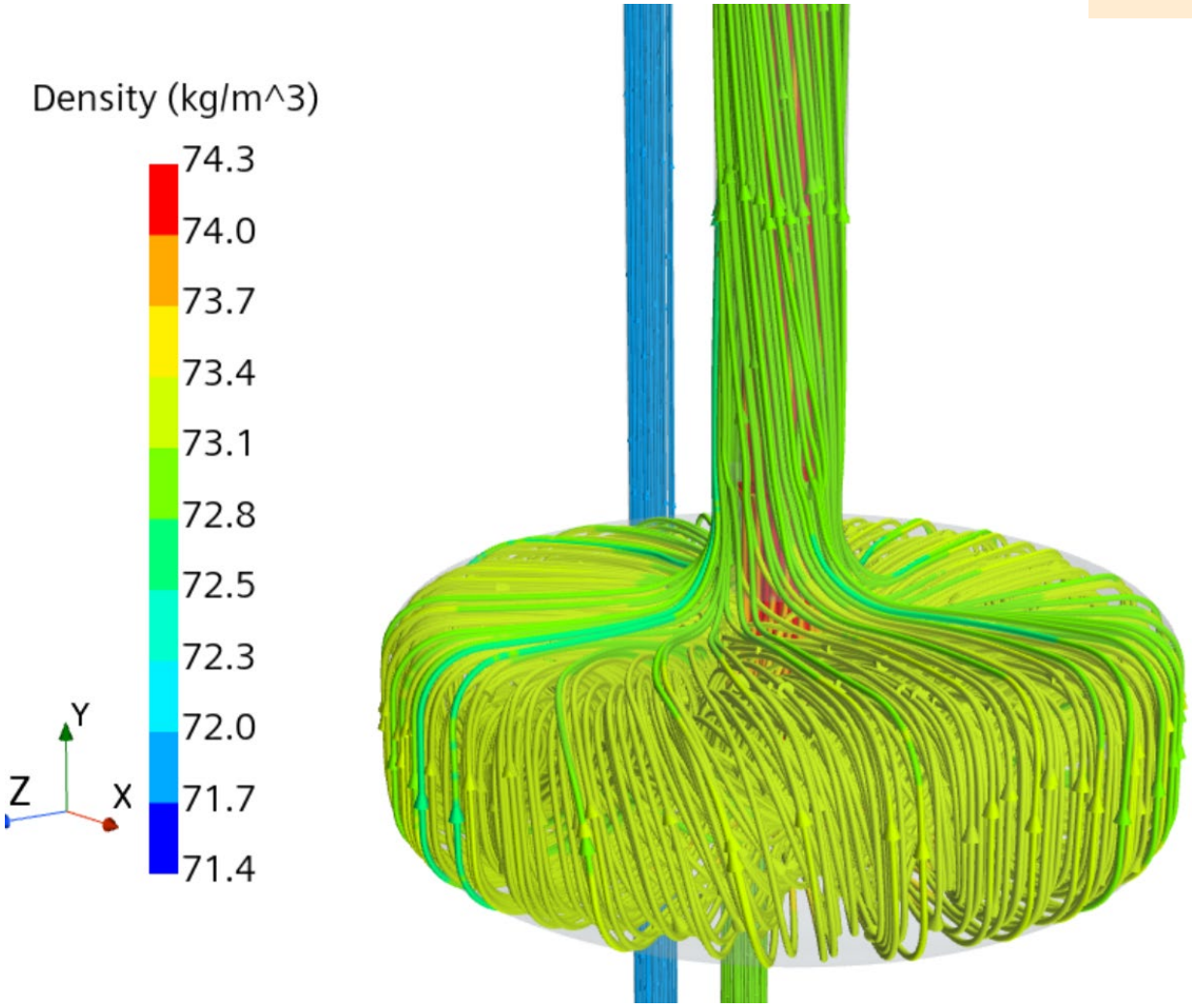
Velocity



Steady State Heat Transfer Analysis for MRA H_2 Loop, Streamlines

Cylindrical Moderator

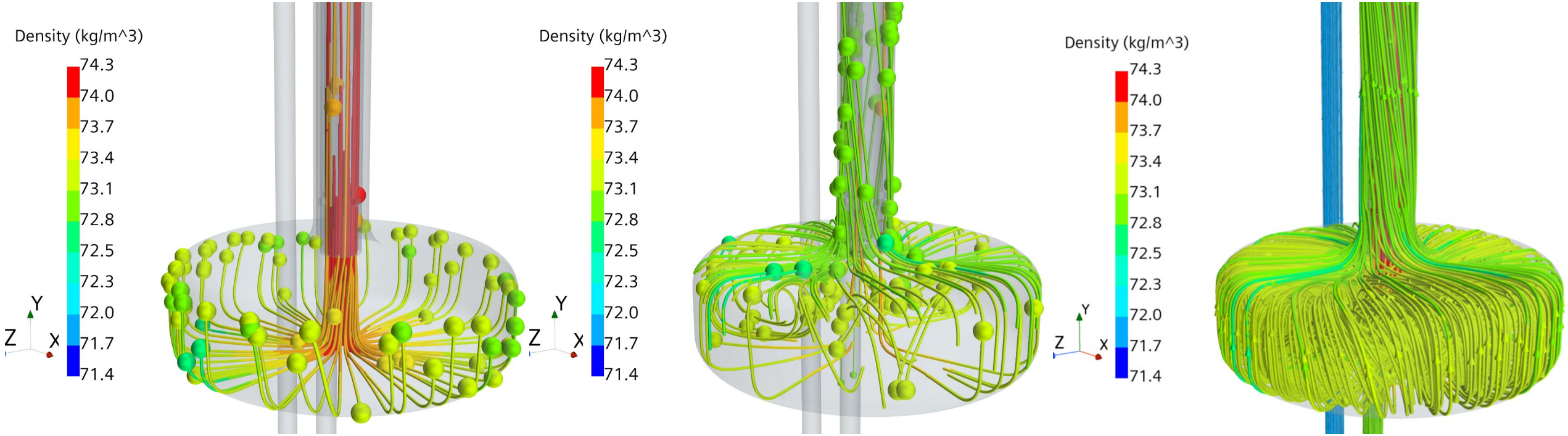
Density



Note that the density range shown on this slide depends on the number of streamlines plotted. Increasing or decreasing the number of streamlines may slightly change the displayed density range.

Steady State Heat Transfer Analysis for MRA H_2 Loop, Streamlines

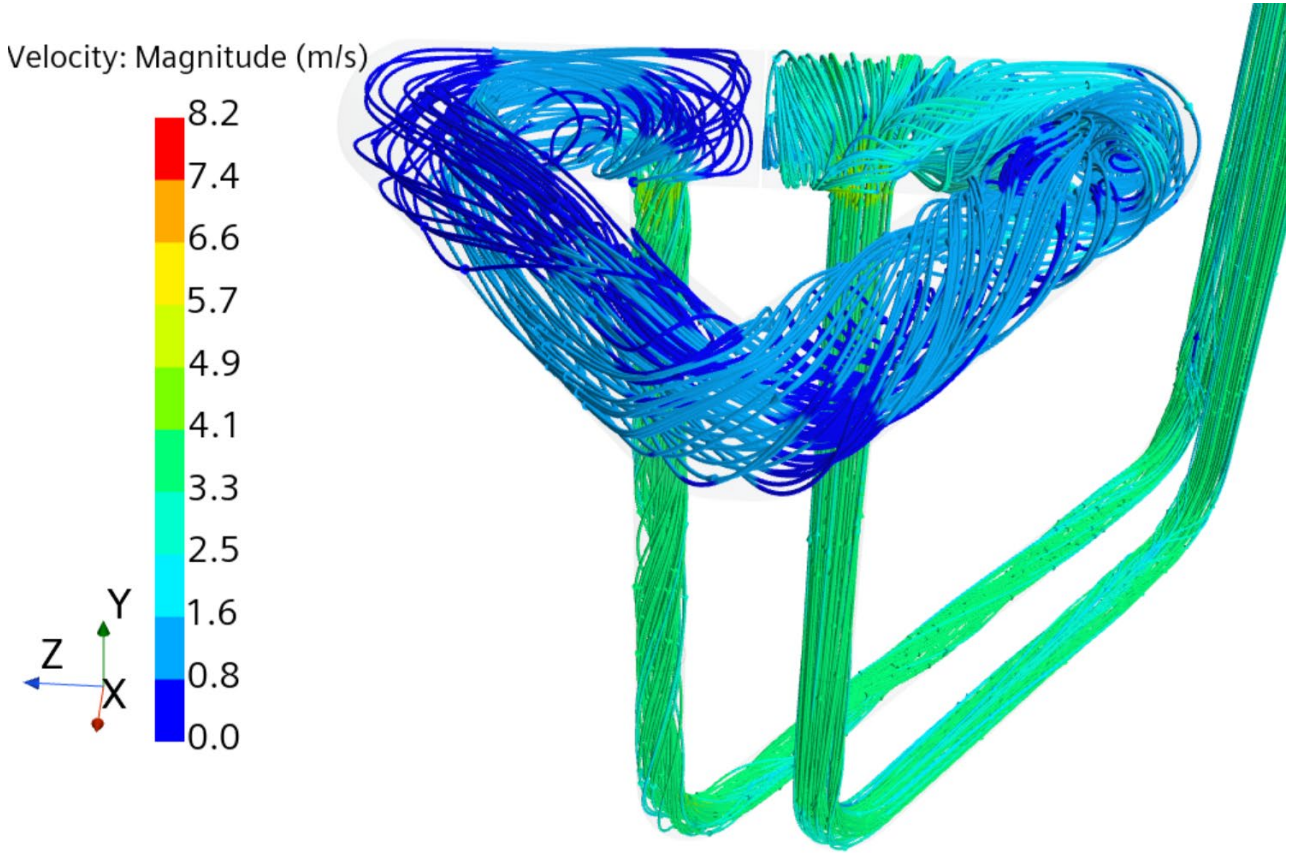
Cylindrical Moderator



Steady State Heat Transfer Analysis for MRA H_2 Loop, Streamlines

Tube Moderator

Velocity

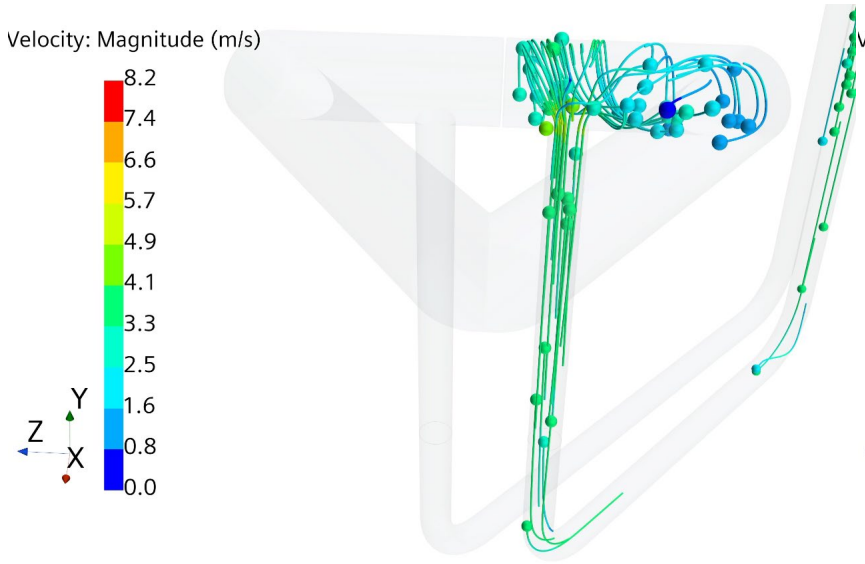


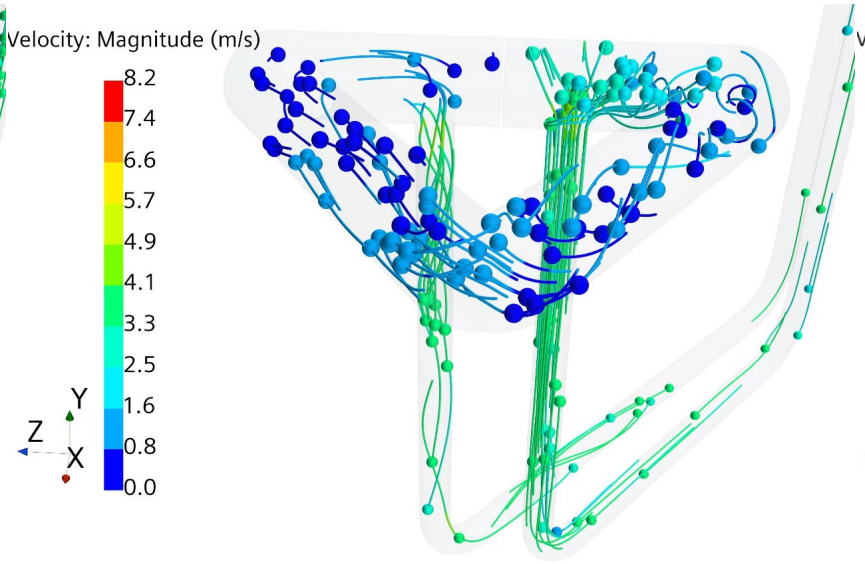
- Compared to the cylinder moderator, the **flow field** in the **tube** moderator is **less uniform.**

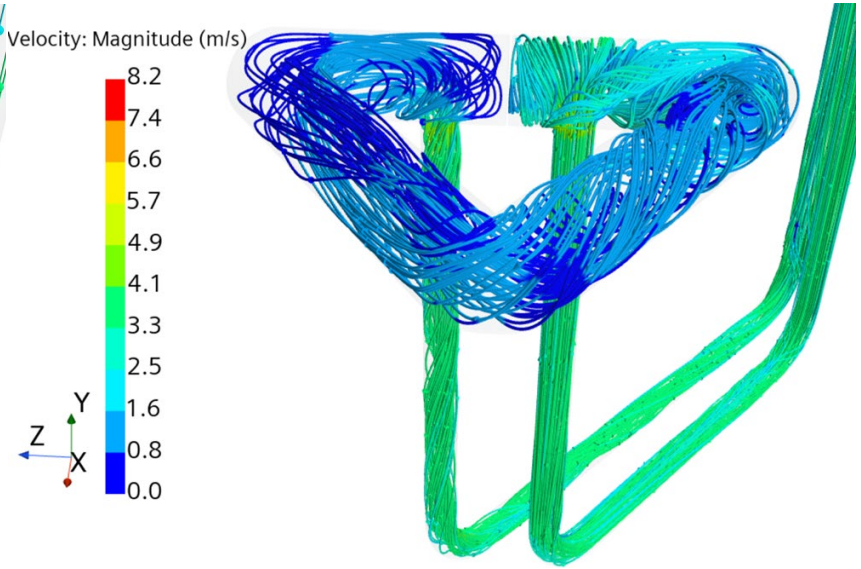
Steady State Heat Transfer Analysis for MRA H_2 Loop, Streamlines

Tube Moderator

Velocity





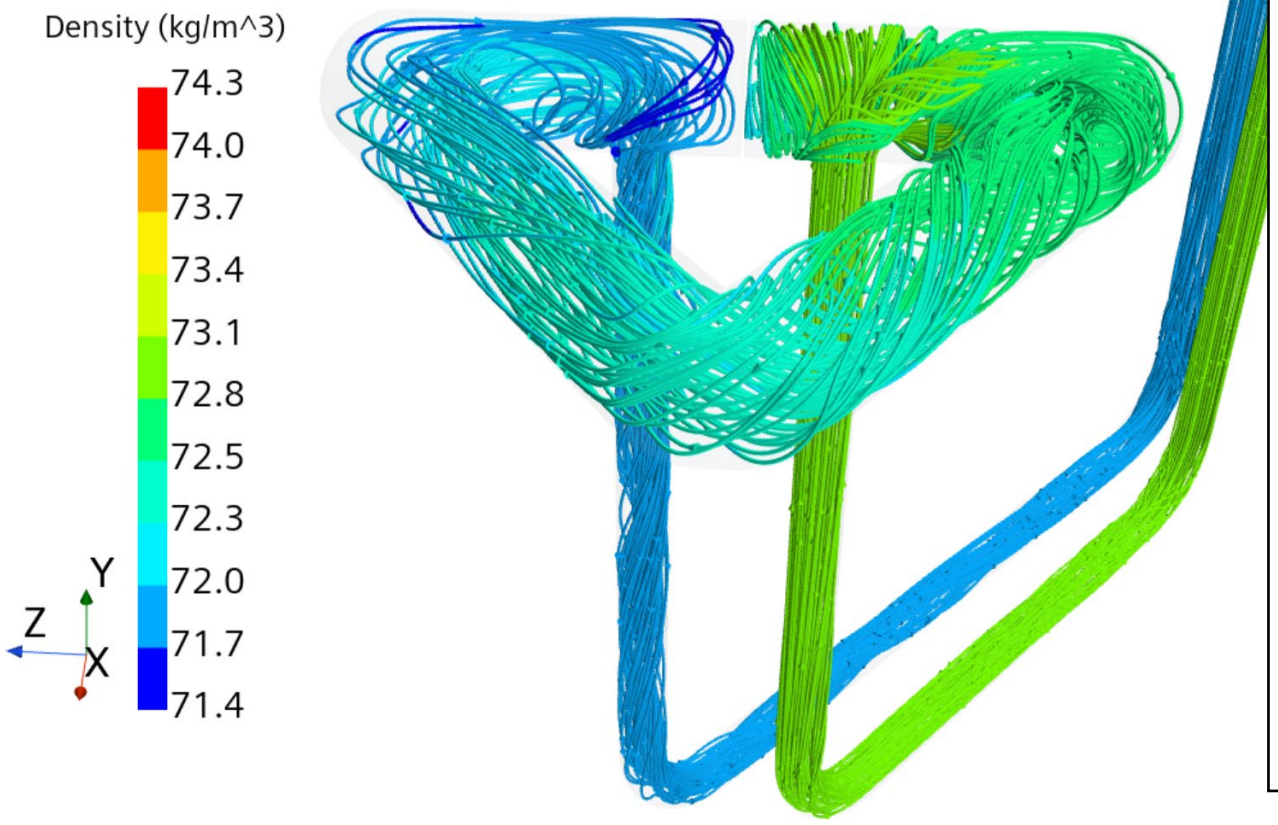


- Compared to the cylinder moderator, the **flow field** in the **tube** moderator is **less uniform.**

Steady State Heat Transfer Analysis for MRA H_2 Loop, Streamlines

Tube Moderator

Density

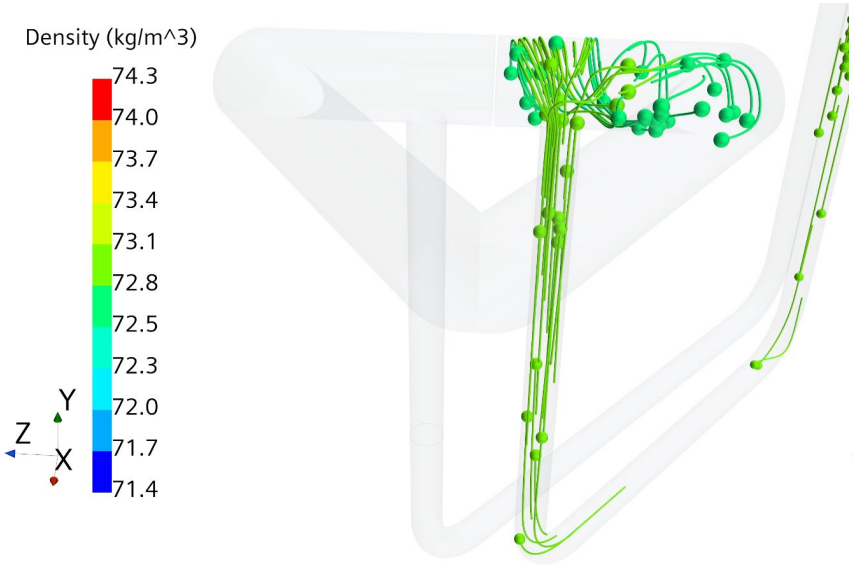


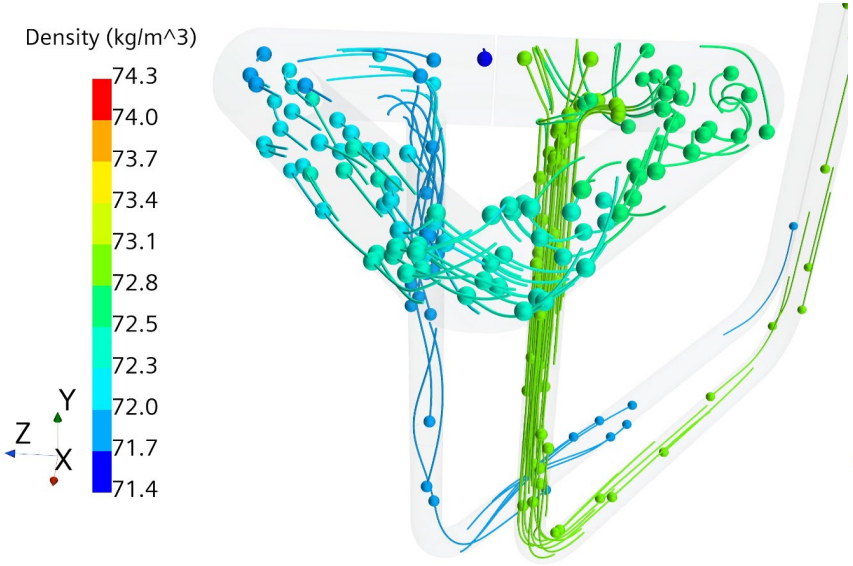
Note that the density range shown on this slide depends on the number of streamlines plotted. Increasing or decreasing the number of streamlines may slightly change the displayed density range.

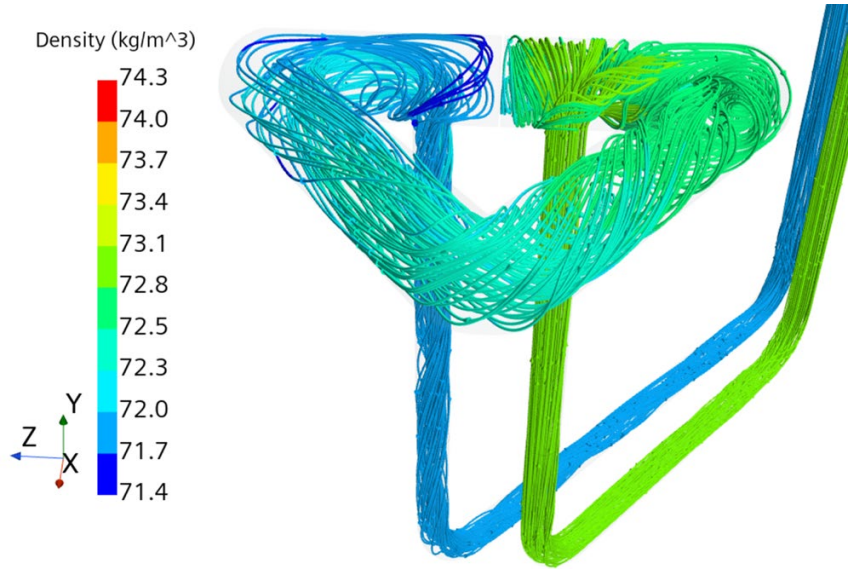
Steady State Heat Transfer Analysis for MRA H_2 Loop, Streamlines

Tube Moderator

Density

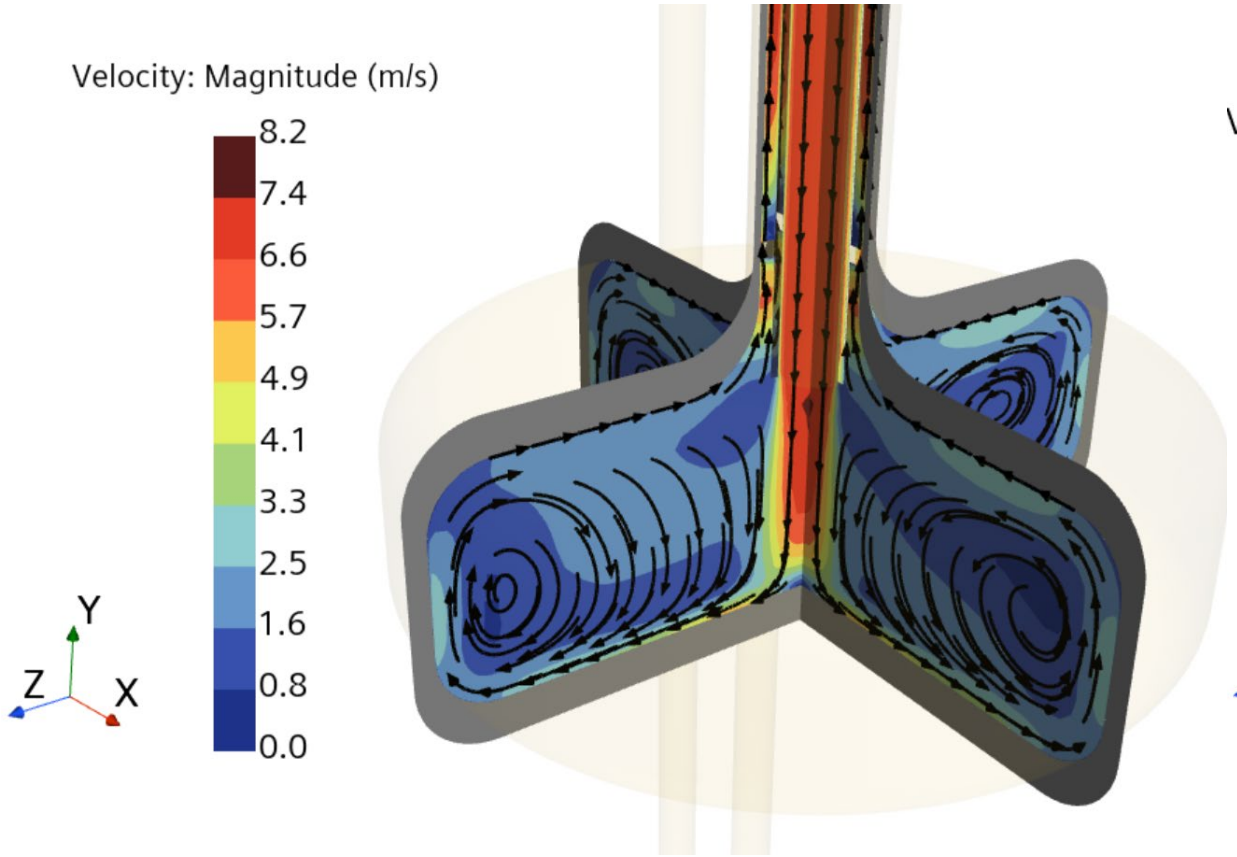




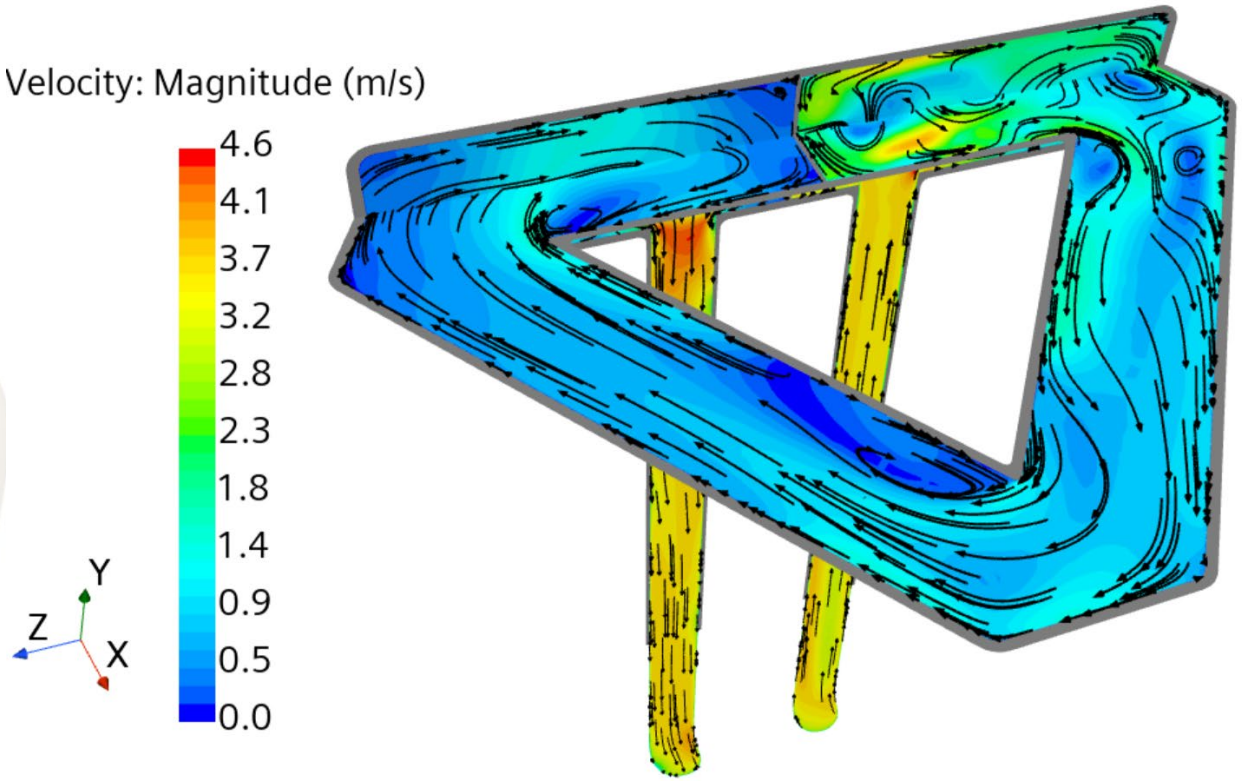


Steady State Heat Transfer Analysis for MRA H_2 Loop, Velocity

Cylindrical Moderator



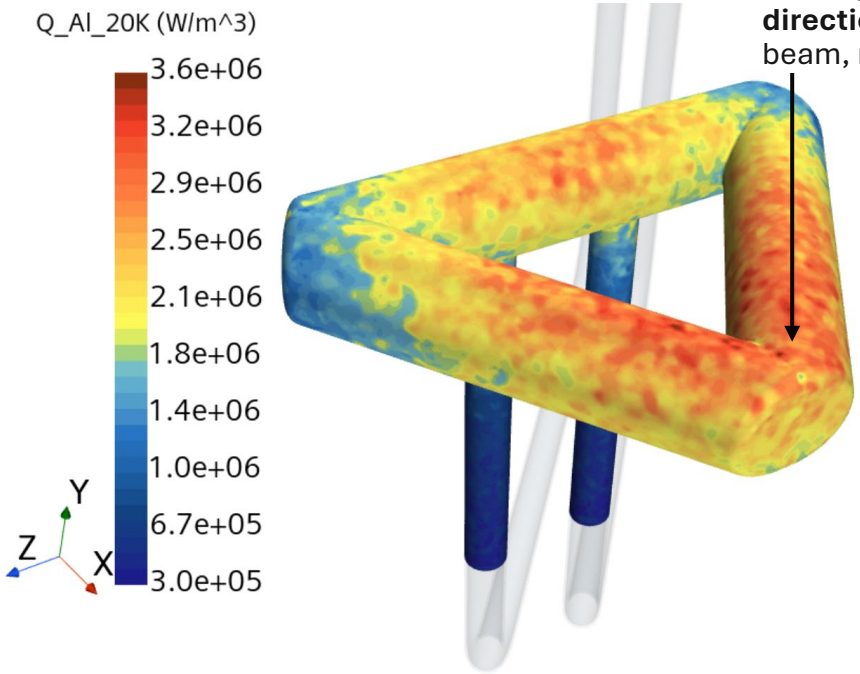
Tube Moderator



- Compared to the cylindrical moderator, the **flow field** in the **tube** moderator is **less uniform**.

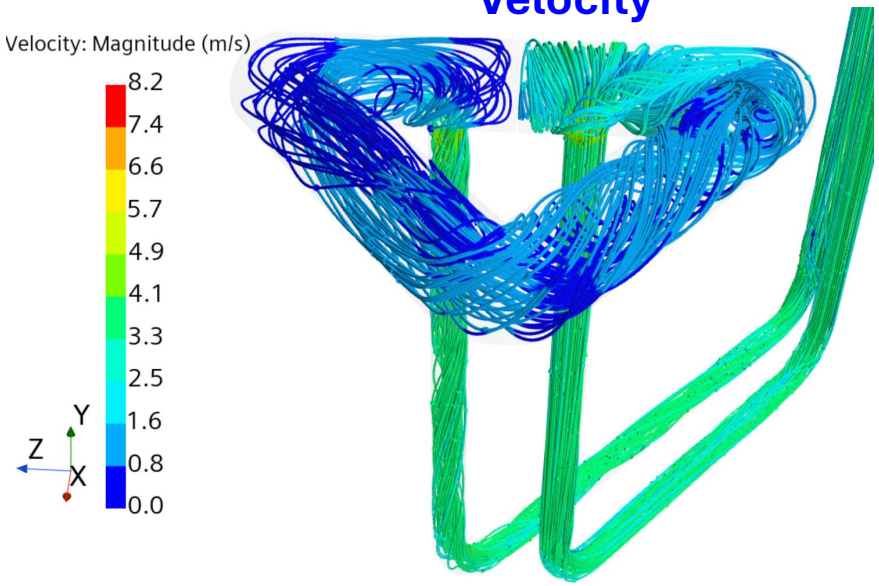
Steady State Heat Transfer Analysis for MRA H_2 Loop

Q of Al



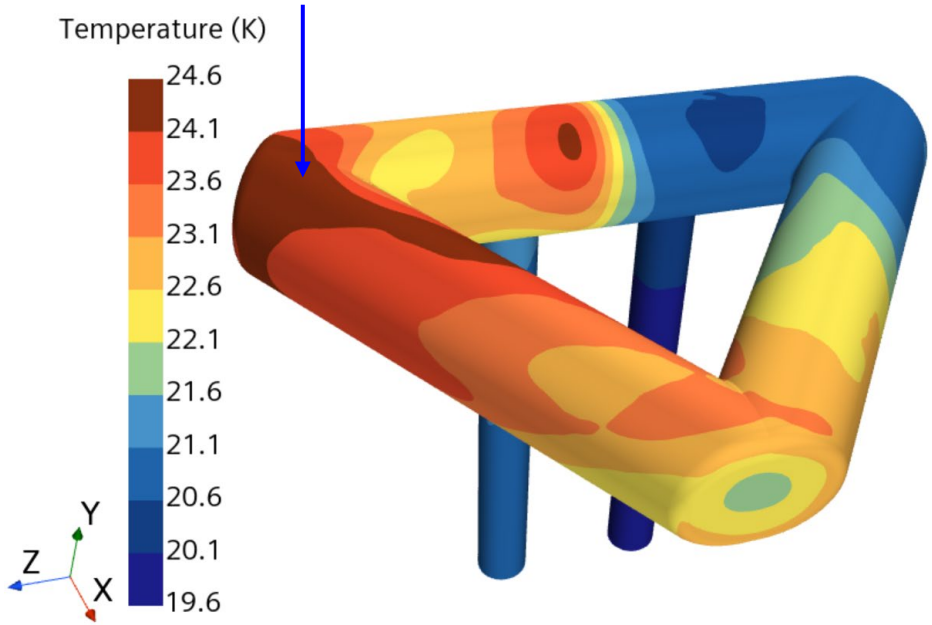
Heating is **higher** in **+x direction** (along the proton beam, rear of the target)

Velocity



Temperature of Al

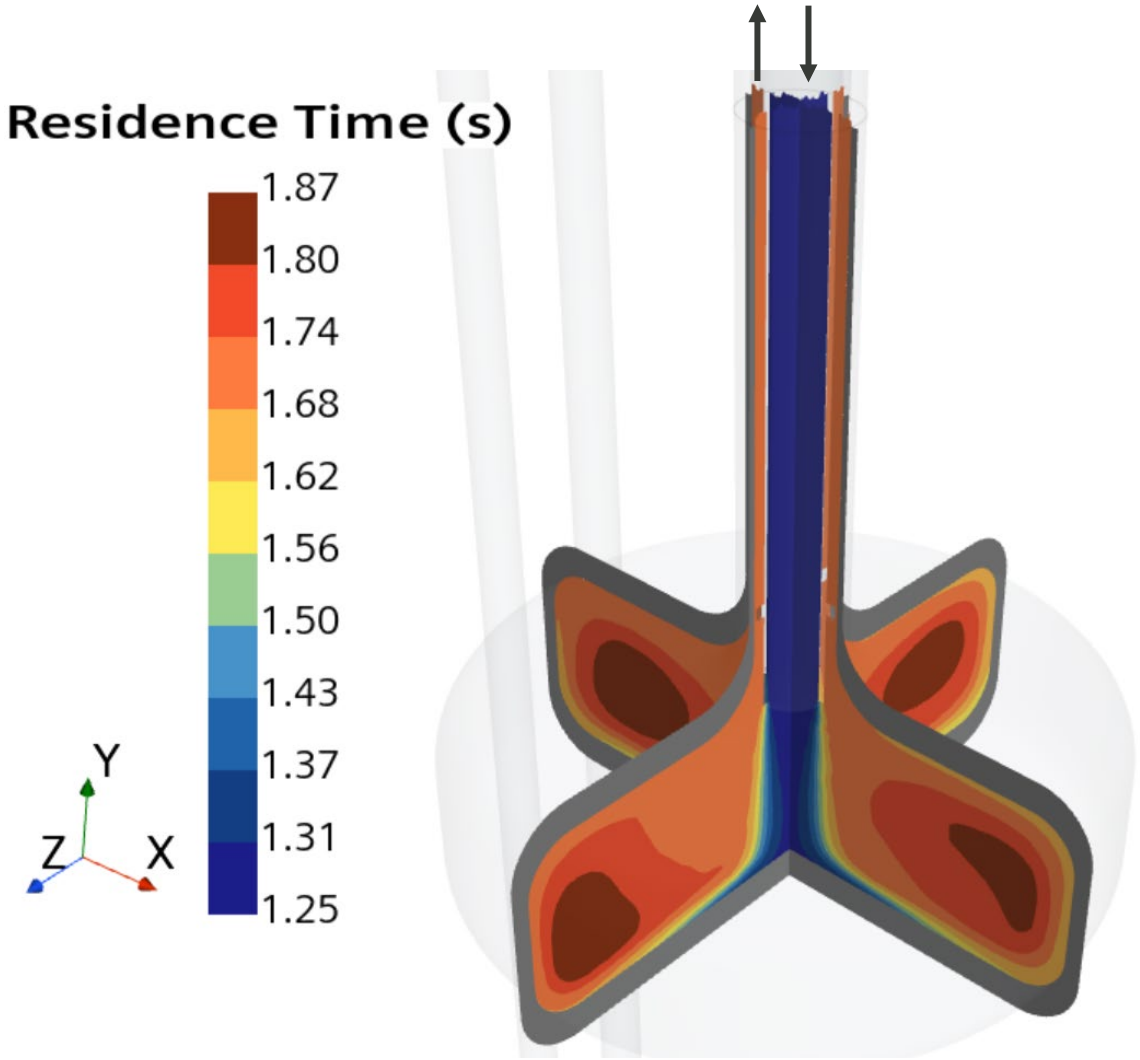
Higher temperature due to lower flow velocity



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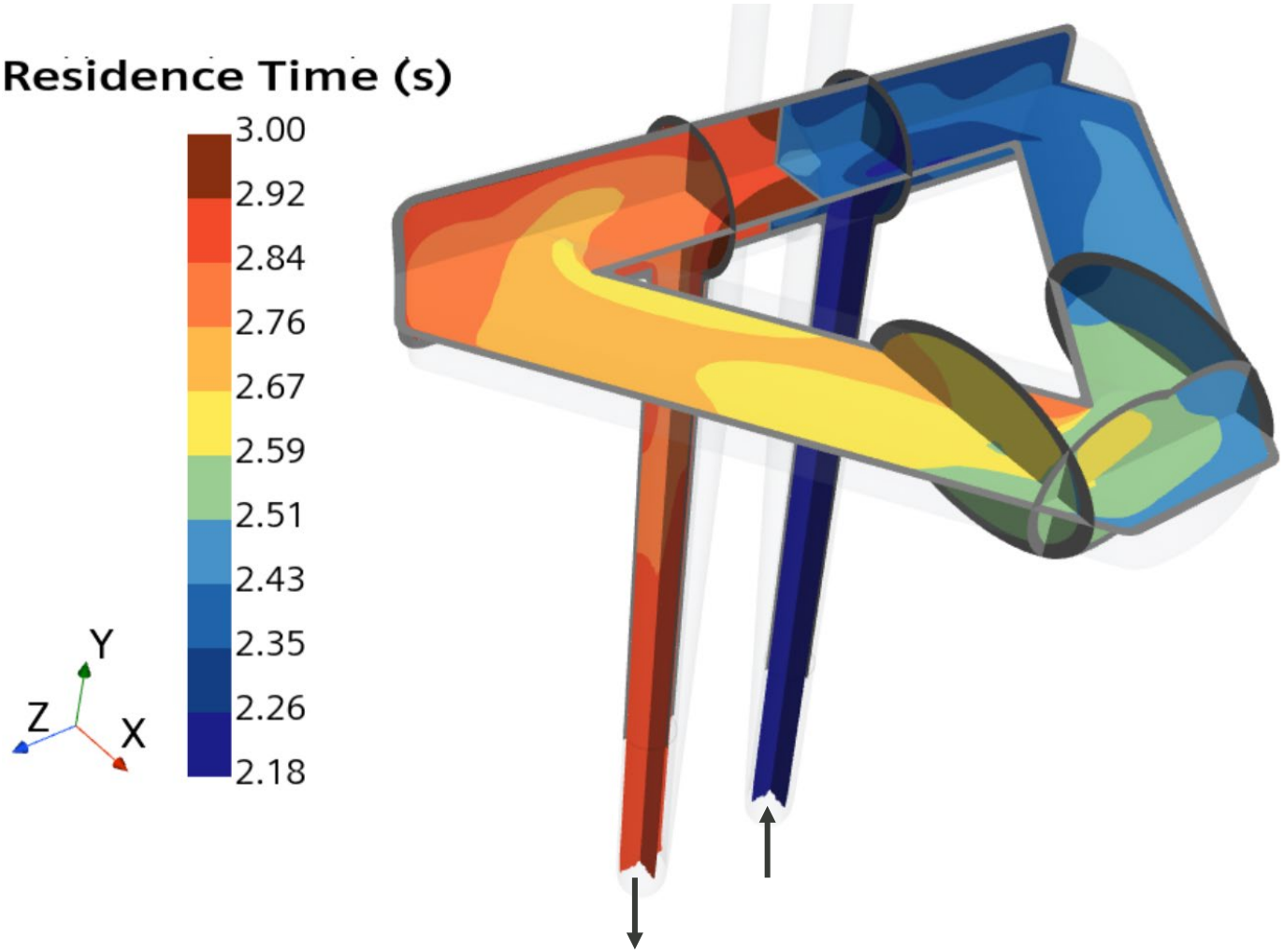
Steady State Heat Transfer Analysis for MRA H_2 Loop, Residence Time

Cylindrical Moderator



$\tau_c = 1.87 - 1.25 = 0.62\ s$

Tube Moderator



$\tau_t = 3.00 - 2.18 = 0.82\ s$

Steady State Heat Transfer Analysis for MRA H_2 Loop, Residence Time

$$t_{\text{pulse}} = \frac{1}{15\ \text{Hz}} = 0.067\ \text{s}$$

Effective Residence Time (from CFD)

Cylindrical moderator

$$\tau_c = 0.62\ \text{s}$$

Tube moderator

$$\tau_t = 0.82\ \text{s}$$

$t_{\text{pulse}} \ll t_{\text{residence}}$

Number of Proton Pulses During One Residence Time

Cylindrical moderator

$$N_c = 15\text{Hz} * \tau_c = 15 \times 0.62 \approx 9$$

Tube moderator

$$N_t = 15\text{Hz} * \tau_t = 15 \times 0.82 \approx 12$$

Temperature Rise During One Residence Time

Cylindrical moderator

$$\Delta T_c = 0.75\ \text{K}$$

Tube moderator

$$\Delta T_t = 0.96\ \text{K}$$

$\Delta T_{\text{residence}} < 1\ \text{K}$

Temperature Rise Per Pulse

Cylindrical moderator

$$\Delta T_{c,p} = \frac{0.75}{9} = 0.083\ \text{K/pulse}$$

Tube moderator

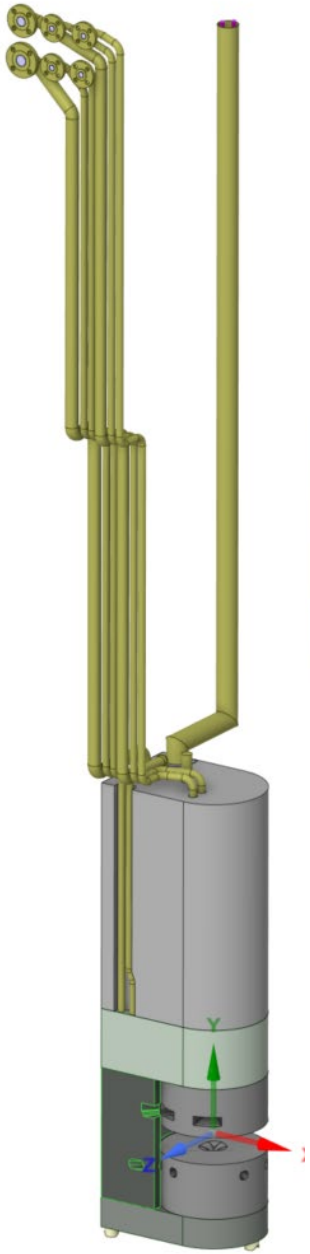
$$\Delta T_{t,p} = \frac{0.96}{12} = 0.080\ \text{K/pulse}$$

$\Delta T_{\text{pulse}} \approx 0.08\ \text{K/pulse}$

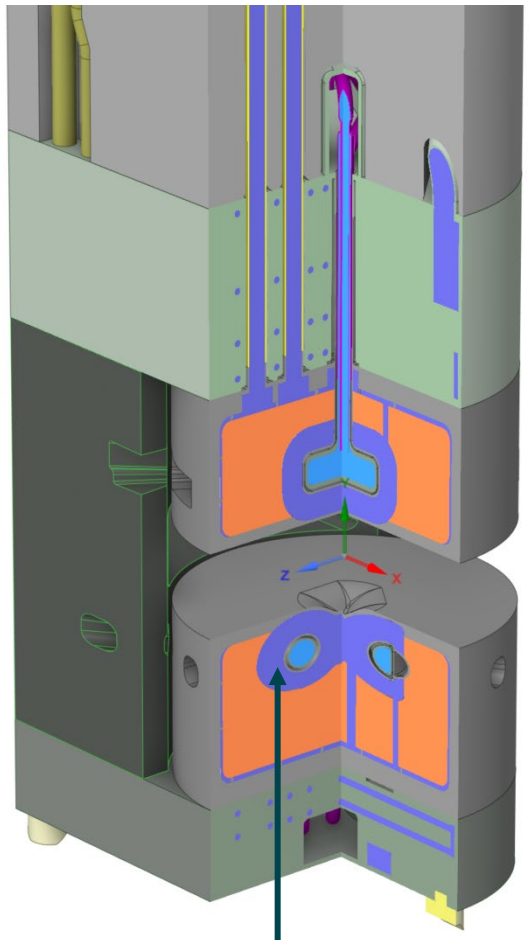
quasi-steady thermal behavior rather than significant transient fluctuations

CFD Analysis for the MRA without the Hydrogen Loop (Isolated Under Vacuum)

Geometry

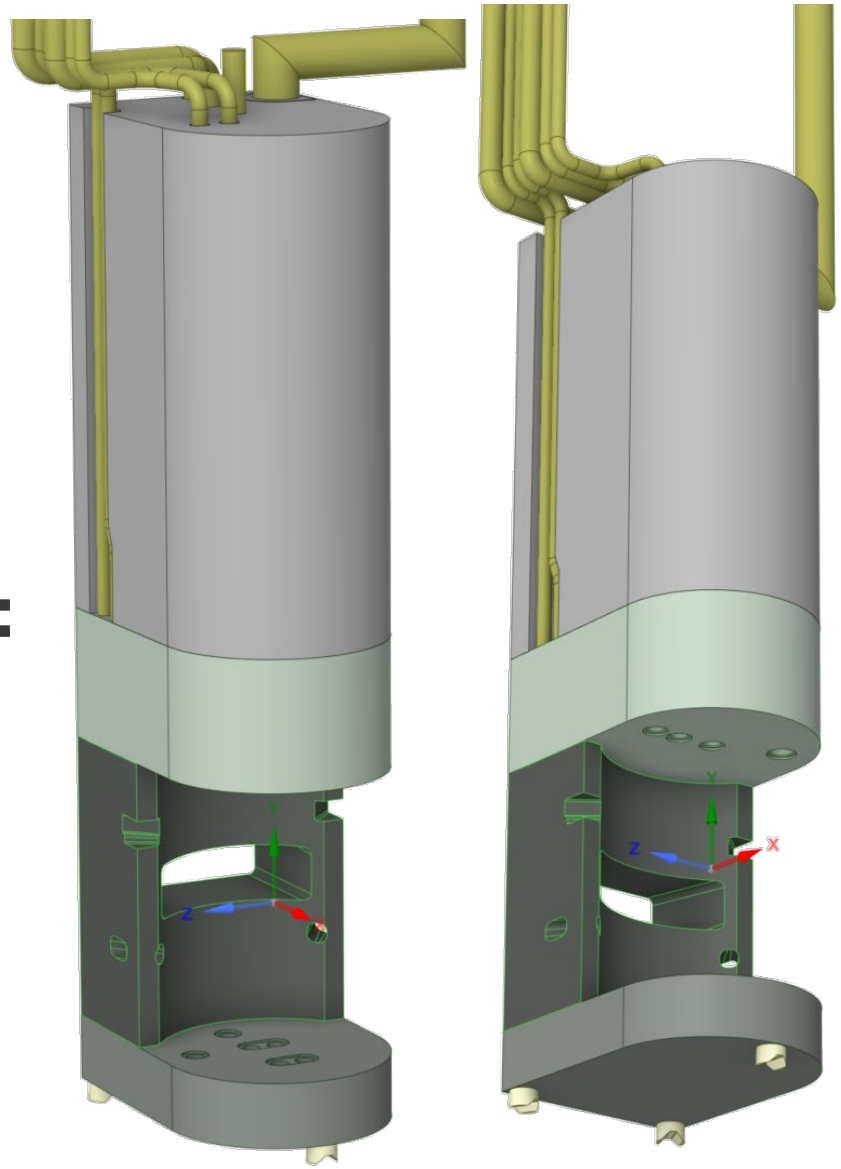


MRA Assembly

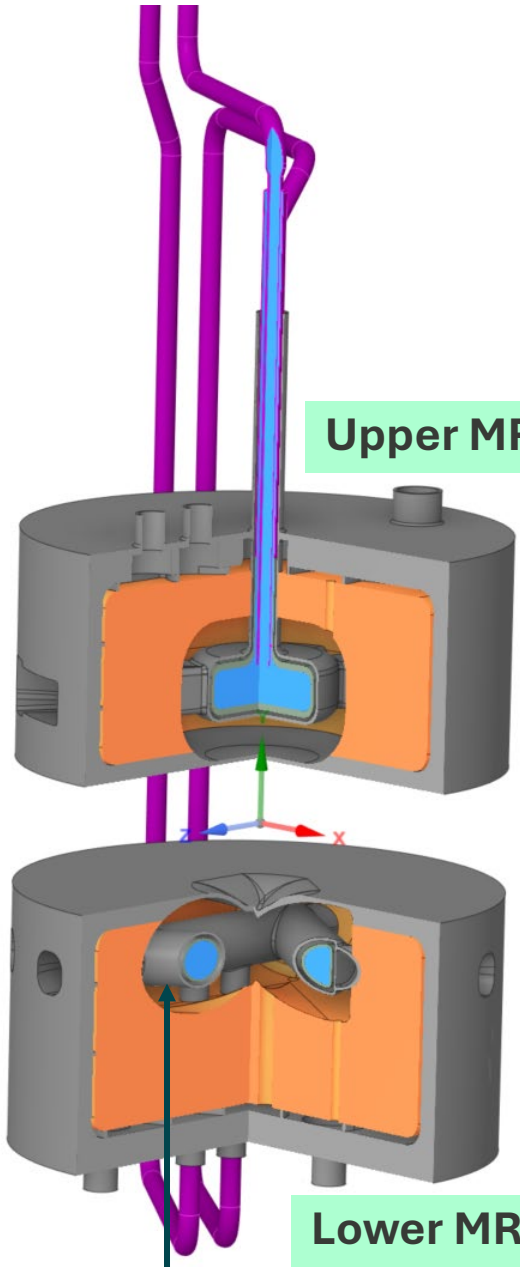


=

MRA Backbone + Shield Block



+



Geometry

- Inlet_1 – 7.5 GPM (= 0.47 kg/s), 90°F (= 32.22°C), Upper MRA, Outer region (Reflector cooling water)
- Inlet_2 – 7.5 GPM (= 0.47 kg/s), 90°F (= 32.22°C), Upper MRA, Inner region (Premoderator water)
- Inlet_3 – 7.5 GPM (= 0.47 kg/s), 90°F (= 32.22°C), Lower MRA, Outer region (Reflector cooling water)
- Inlet_4 – 7.5 GPM (= 0.47 kg/s), 90°F (= 32.22°C), Lower MRA, Inner region (Premoderator water)
- Inlet_5 – 15 GPM (= 0.94 kg/s), 90°F (= 32.22°C), MRA Backbone
- Common Outlet



Pipe (SS316)

Shielding Block (A36, Carbon Steel)

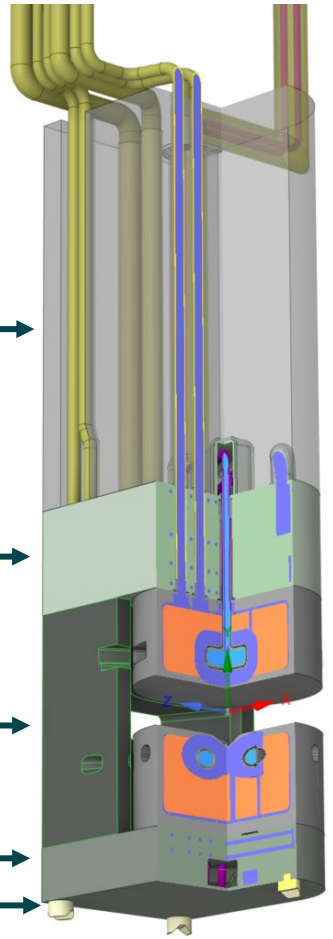
- Thermal conductivity ~3 times higher than SS316
- Improved heat transfer

Upper Block (SS316)

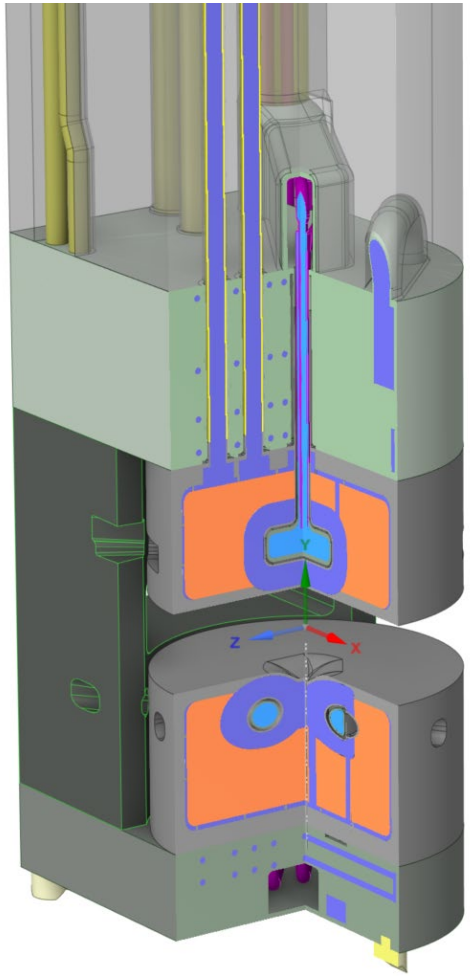
Middle Block (SS316)

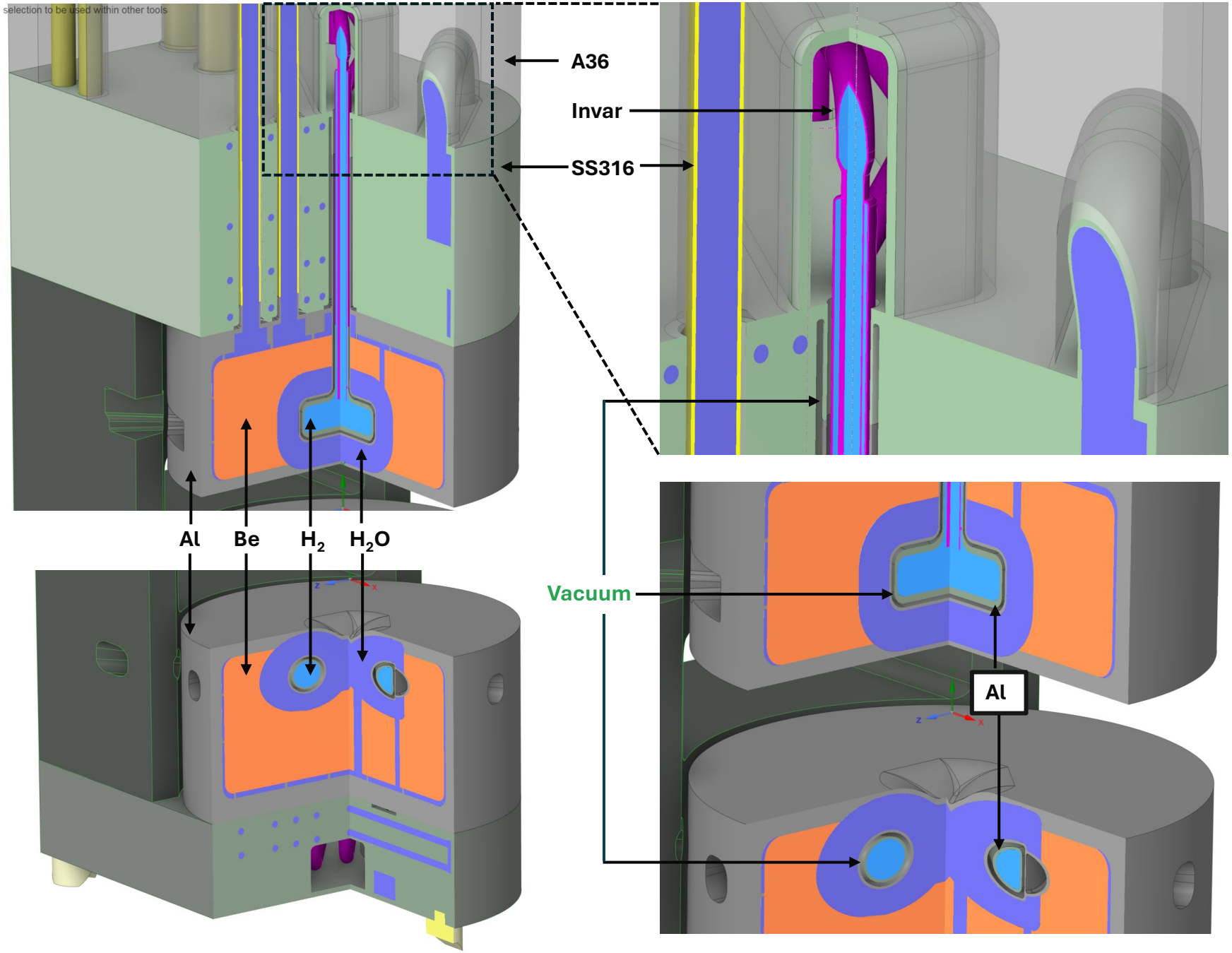
Lower Block (SS316)

Kinetic mount (SS420)



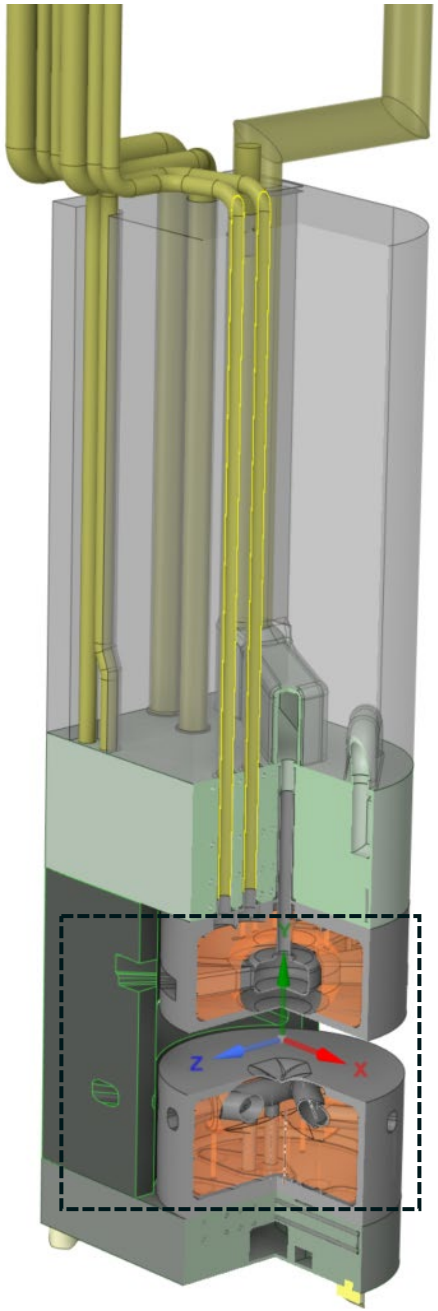
Geometry



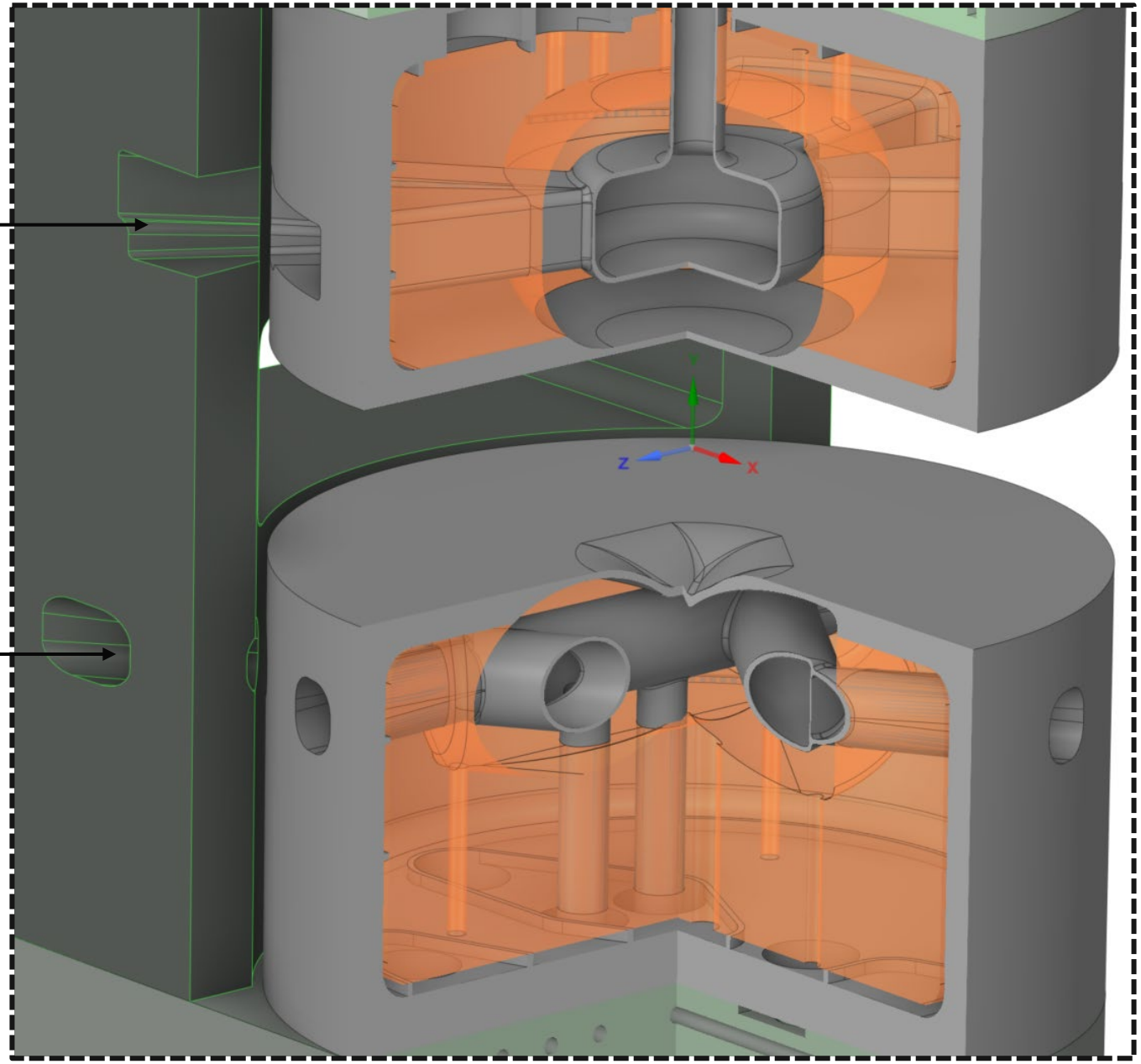


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Geometry (Water and H_2 Loop Hidden)

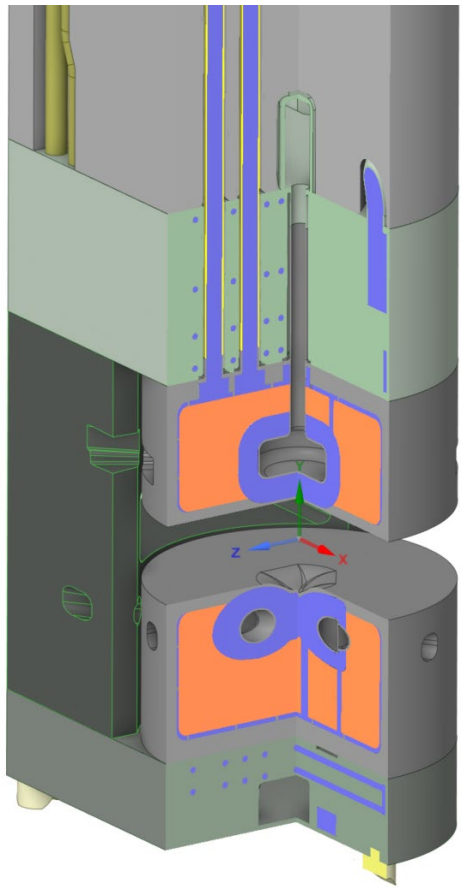


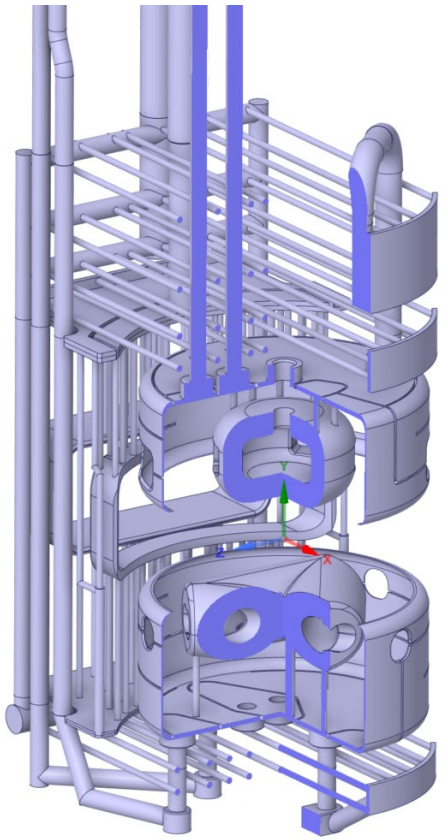
Neutron beam port

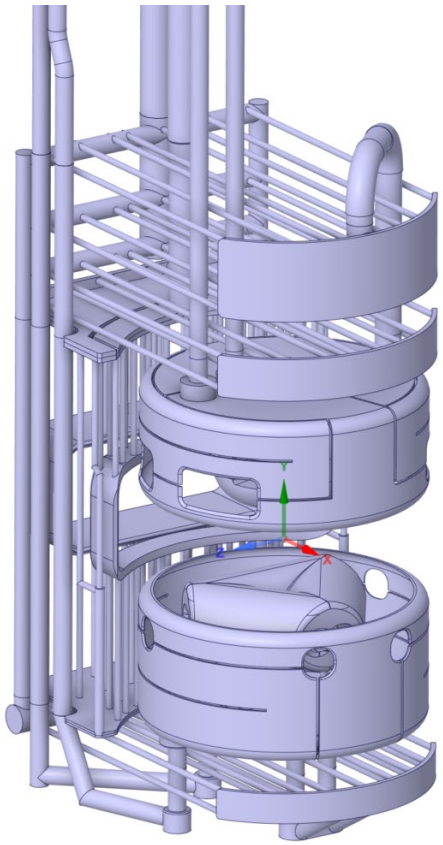


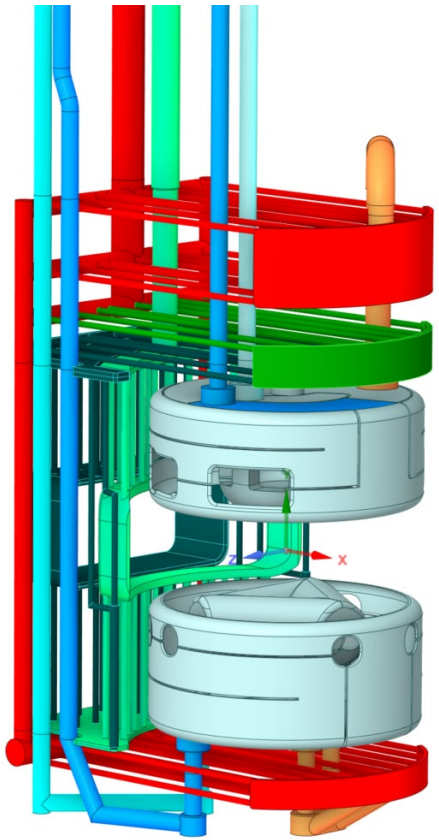
Geometry (H_2 Loop Hidden)

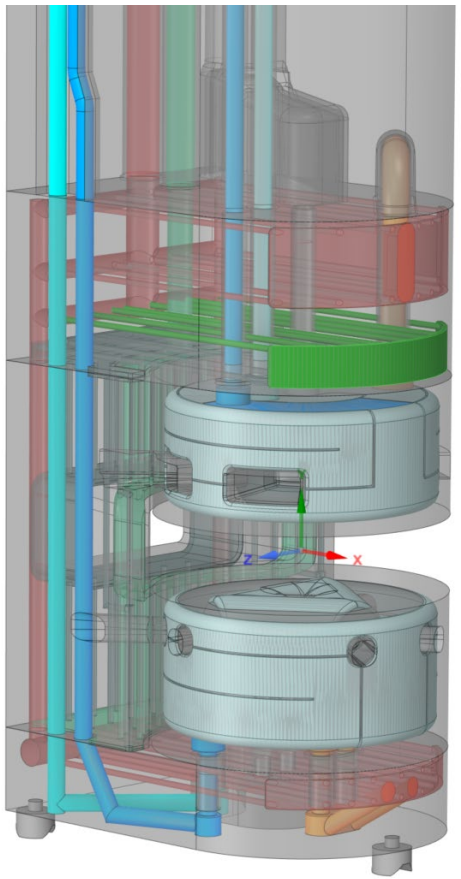
Water





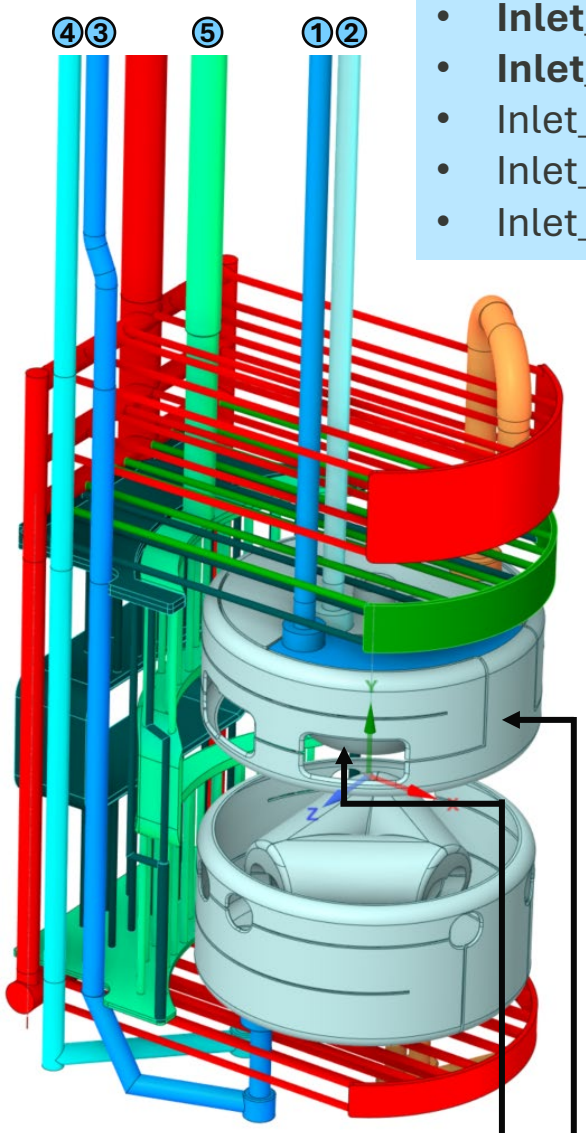


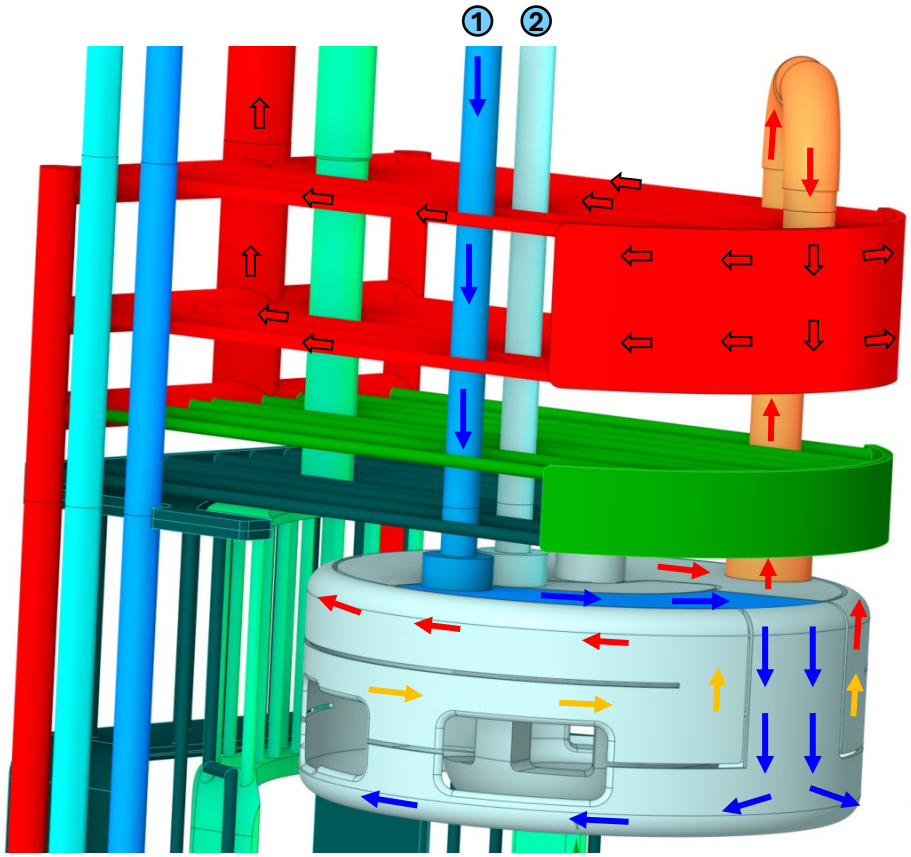


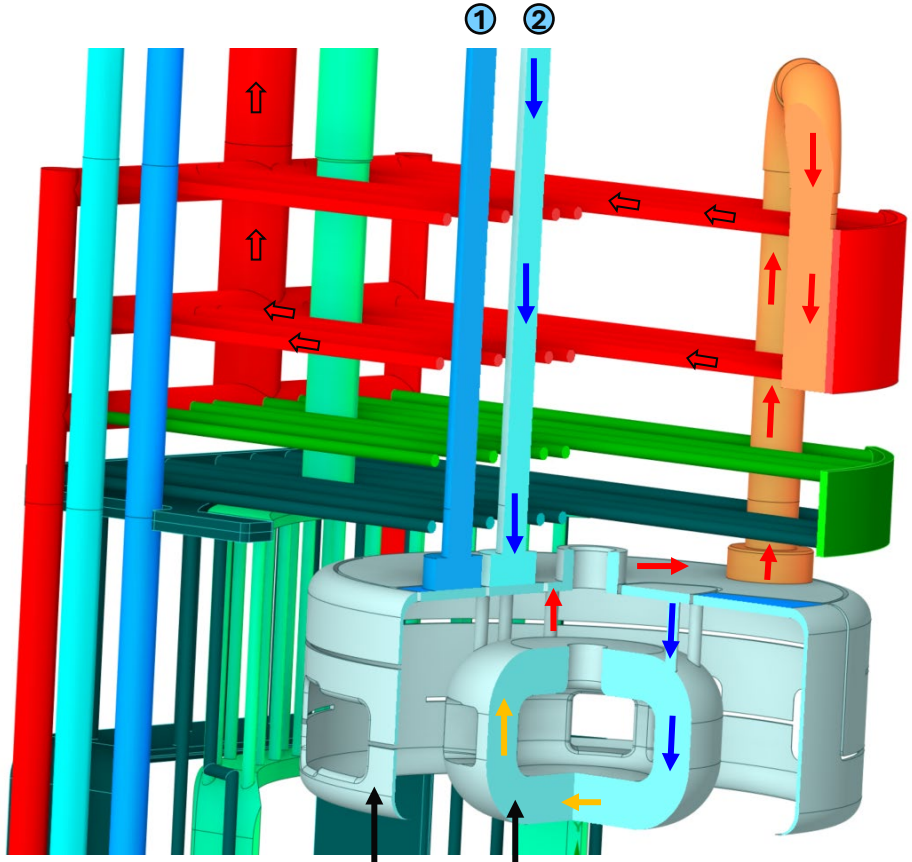


Geometry (H_2 Loop Hidden), Water

- **Inlet_1 – 7.5 GPM (= 0.47 kg/s), 90°F (= 32.22°C), Upper MRA, Outer region (Reflector cooling water)**
- **Inlet_2 – 7.5 GPM (= 0.47 kg/s), 90°F (= 32.22°C), Upper MRA, Inner region (Premoderator water)**
- Inlet_3 – 7.5 GPM (= 0.47 kg/s), 90°F (= 32.22°C), Lower MRA, Outer region (Reflector cooling water)
- Inlet_4 – 7.5 GPM (= 0.47 kg/s), 90°F (= 32.22°C), Lower MRA, Inner region (Premoderator water)
- Inlet_5 – 15 GPM (= 0.94 kg/s), 90°F (= 32.22°C), MRA Backbone



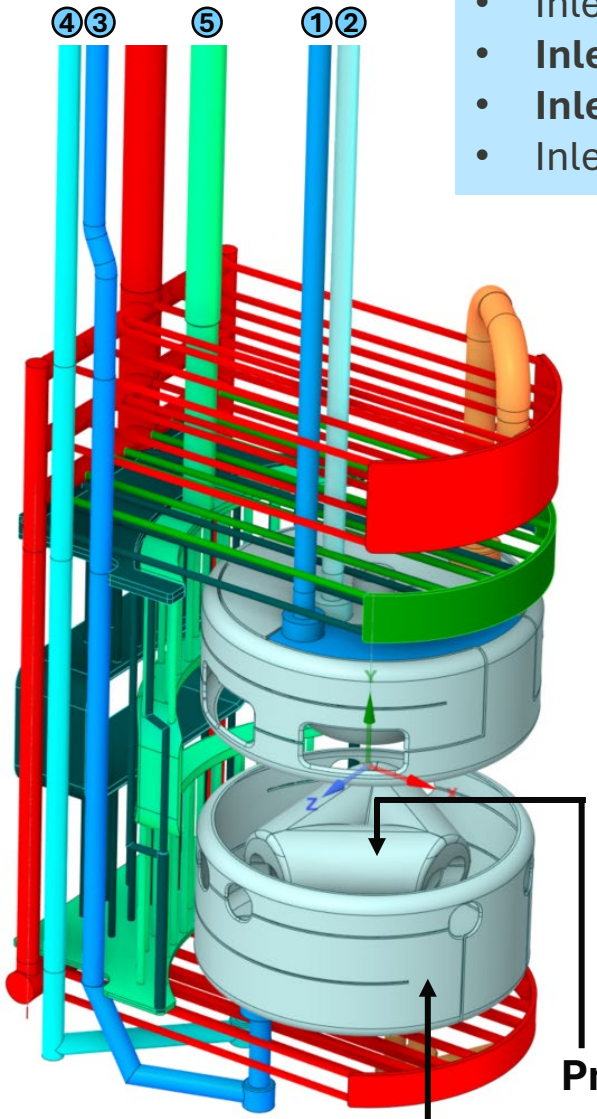


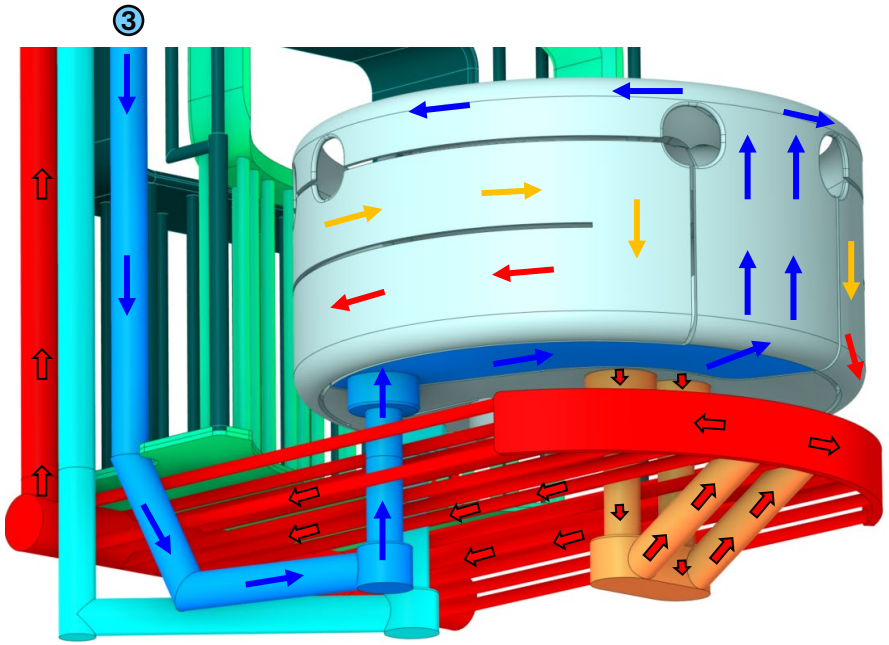


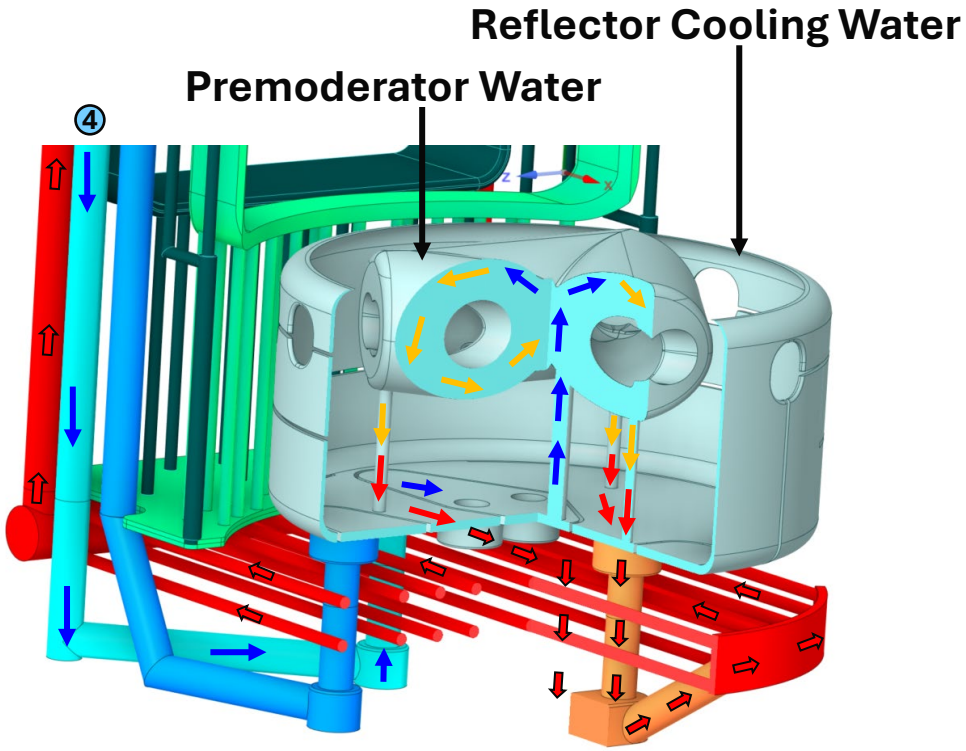
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Geometry (H_2 Loop Hidden), Water

- Inlet_1 – 7.5 GPM (= 0.47 kg/s), 90°F (= 32.22°C), Upper MRA, Outer region (Reflector cooling water)
- Inlet_2 – 7.5 GPM (= 0.47 kg/s), 90°F (= 32.22°C), Upper MRA, Inner region (Premoderator water)
- **Inlet_3 – 7.5 GPM (= 0.47 kg/s), 90°F (= 32.22°C), Lower MRA, Outer region (Reflector cooling water)**
- **Inlet_4 – 7.5 GPM (= 0.47 kg/s), 90°F (= 32.22°C), Lower MRA, Inner region (Premoderator water)**
- Inlet_5 – 15 GPM (= 0.94 kg/s), 90°F (= 32.22°C), MRA Backbone



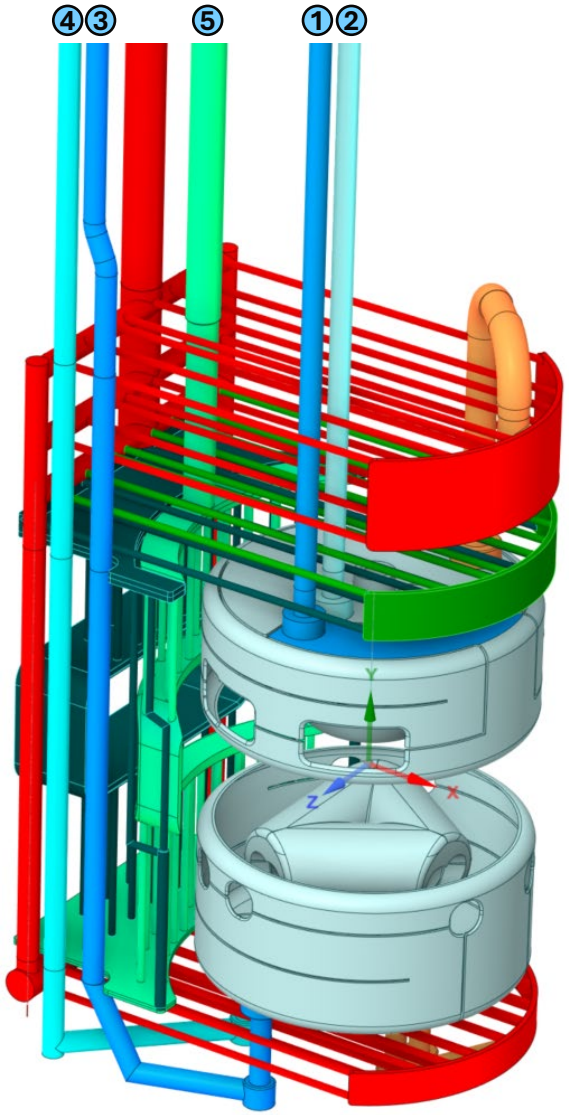


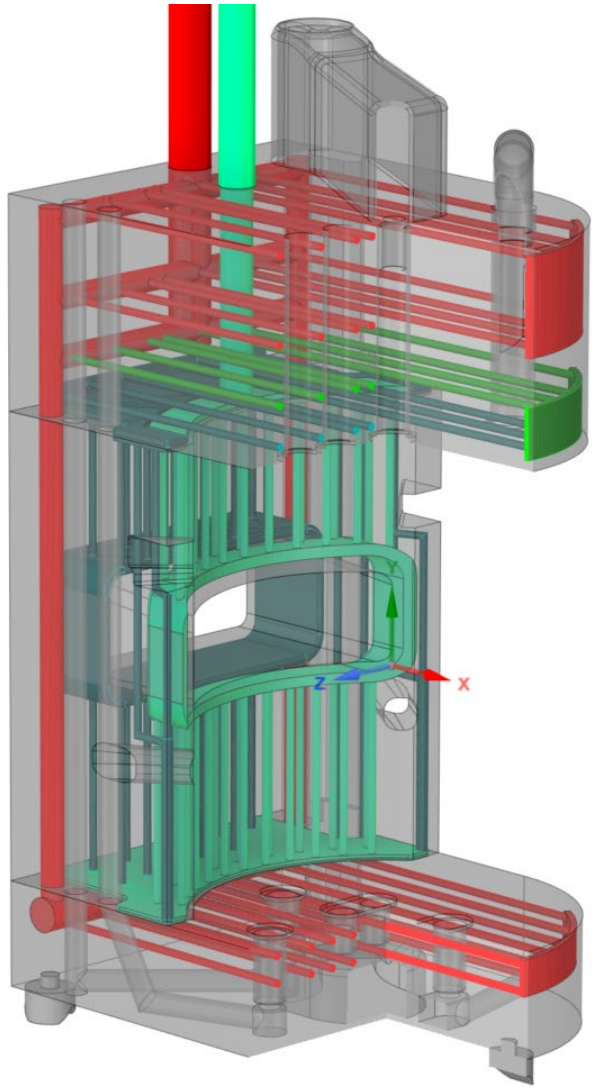


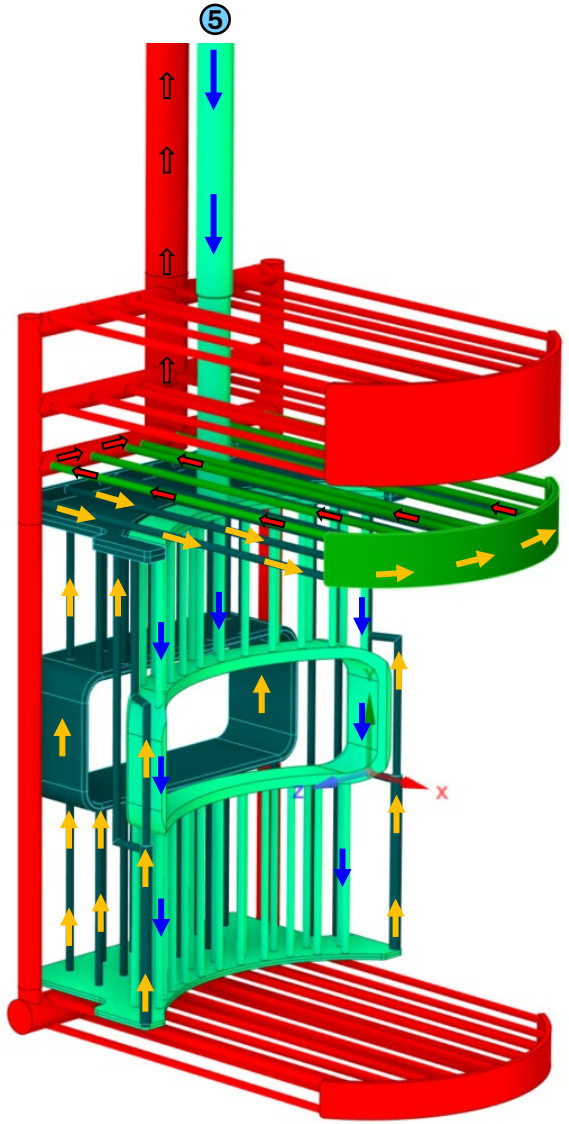
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Geometry (H_2 Loop Hidden), Water

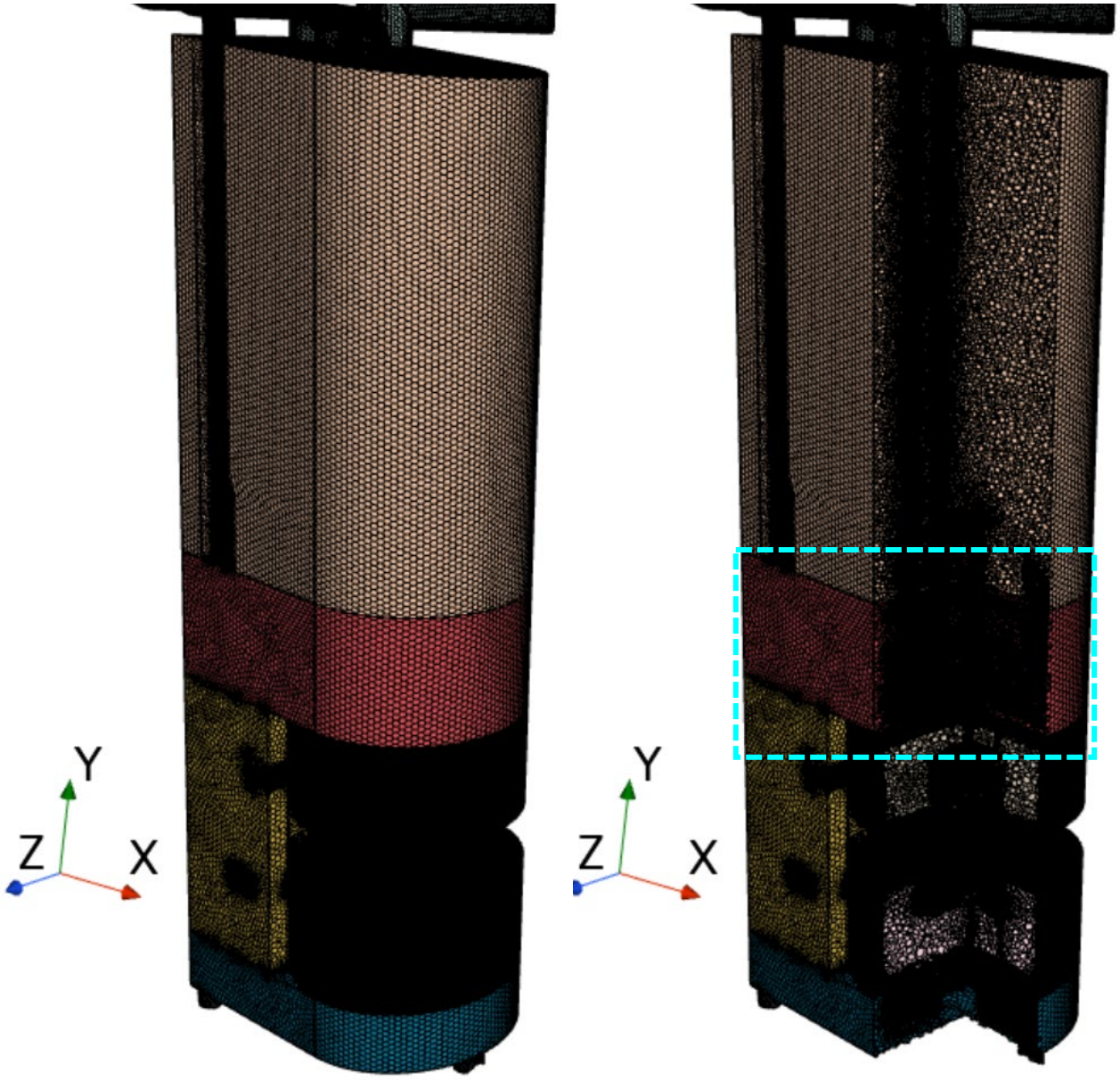
- Inlet_5 – 15 GPM (= 0.94 kg/s), 90°F (= 32.22°C), MRA Backbone

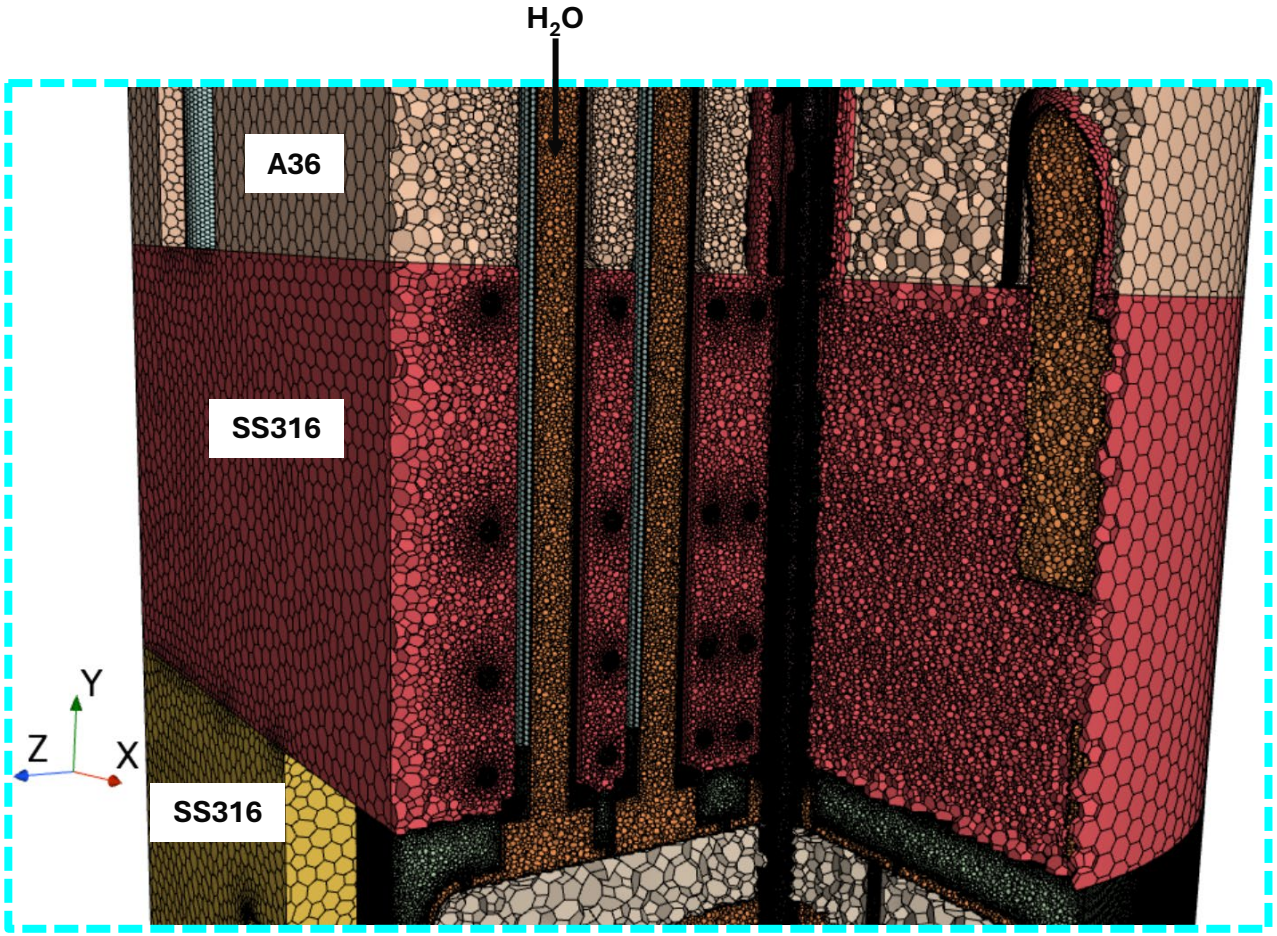




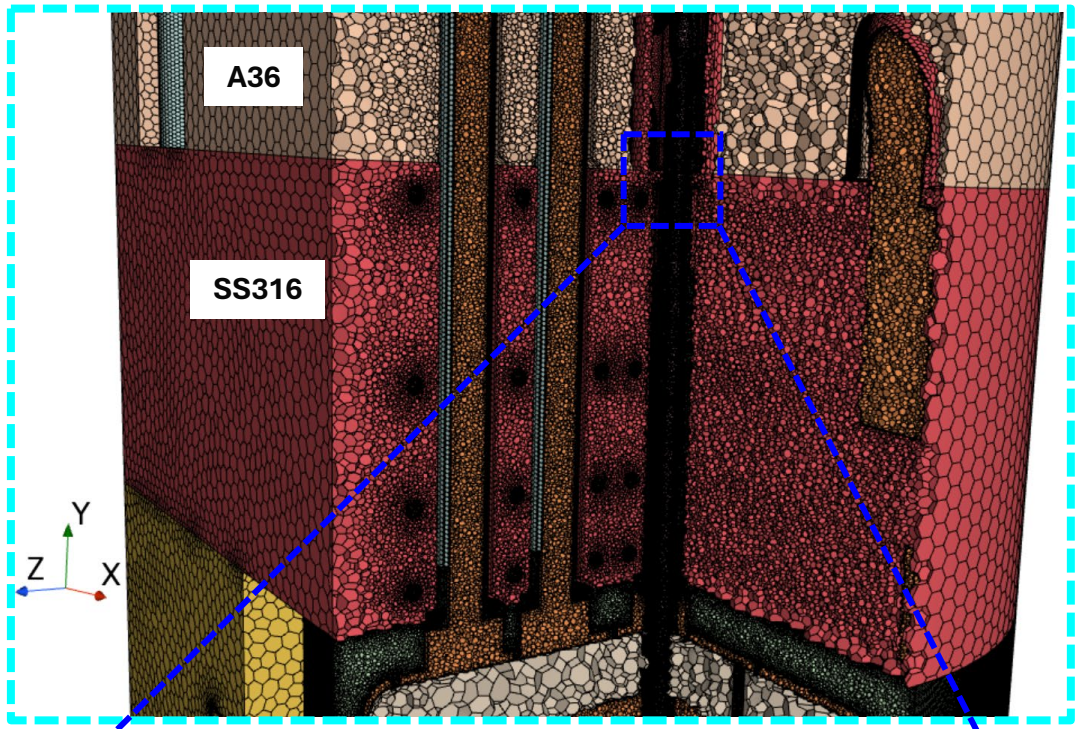


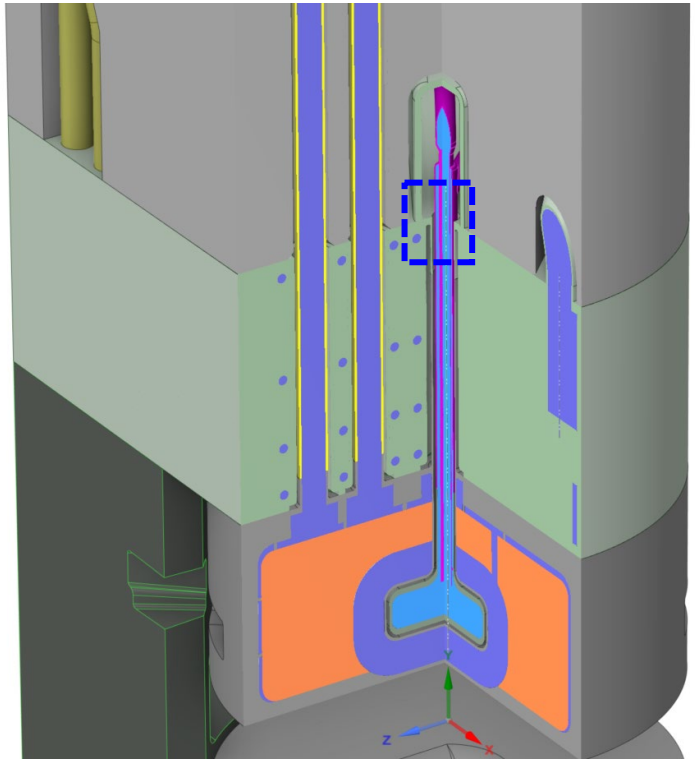
Steady State Heat Transfer Analysis for MRA, Mesh Configuration

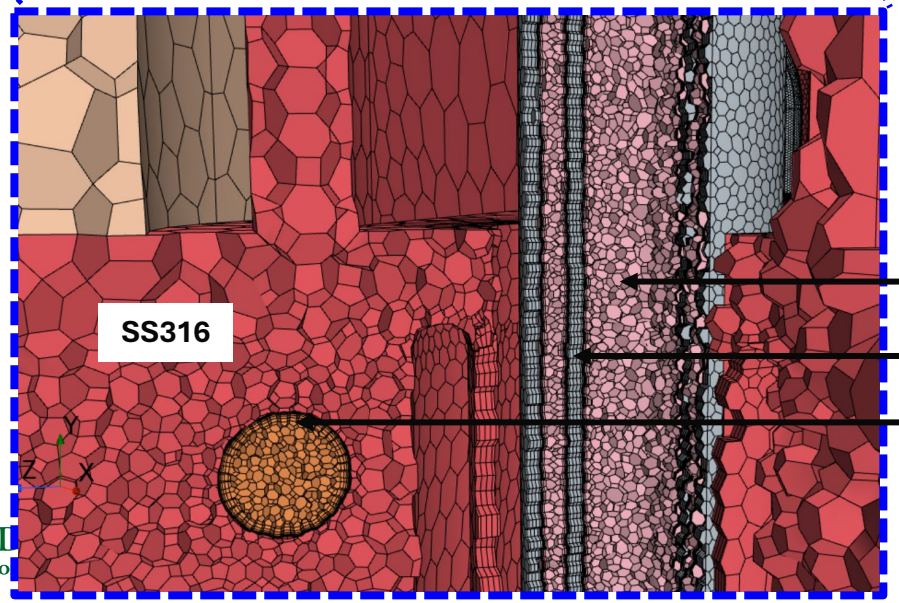




Steady State Heat Transfer Analysis for MRA, Mesh Configuration



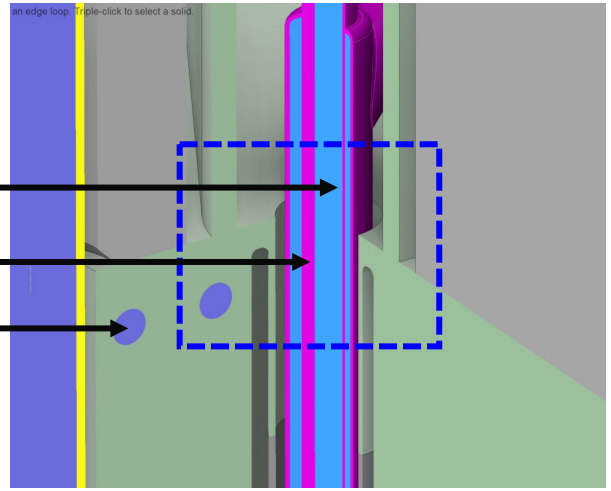




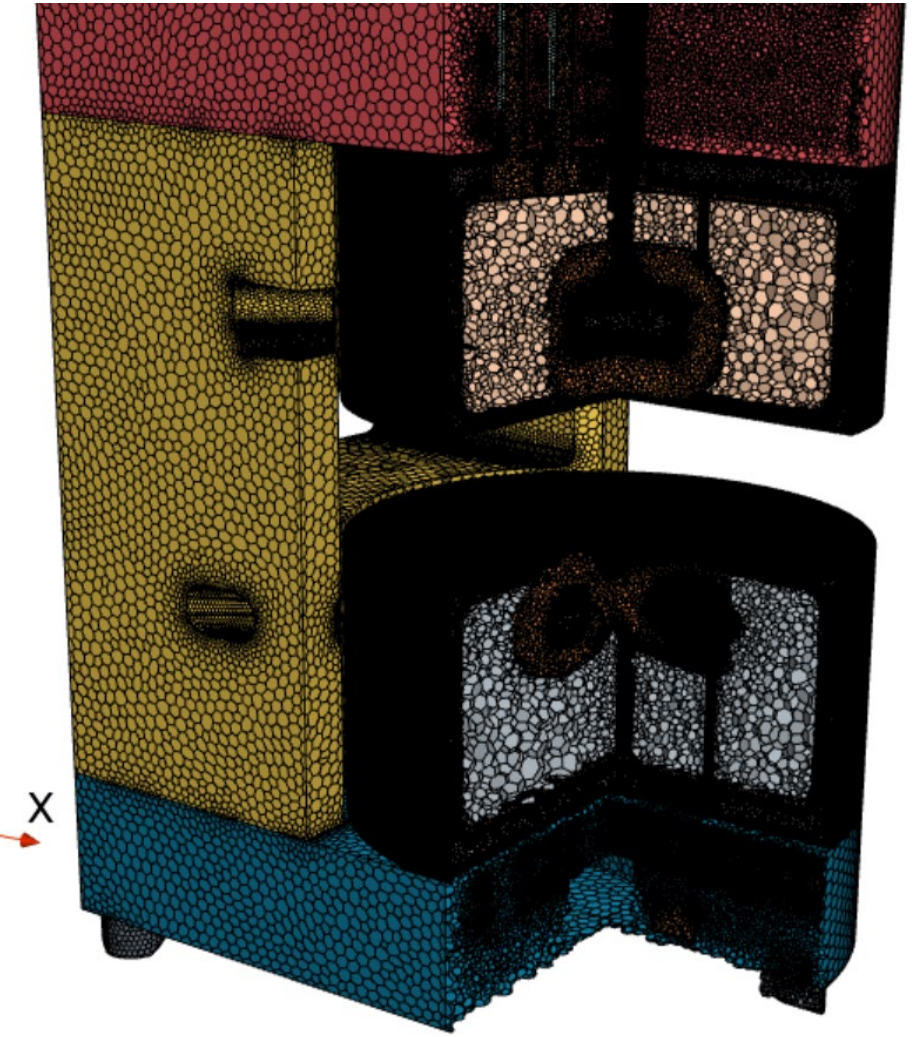
H_2

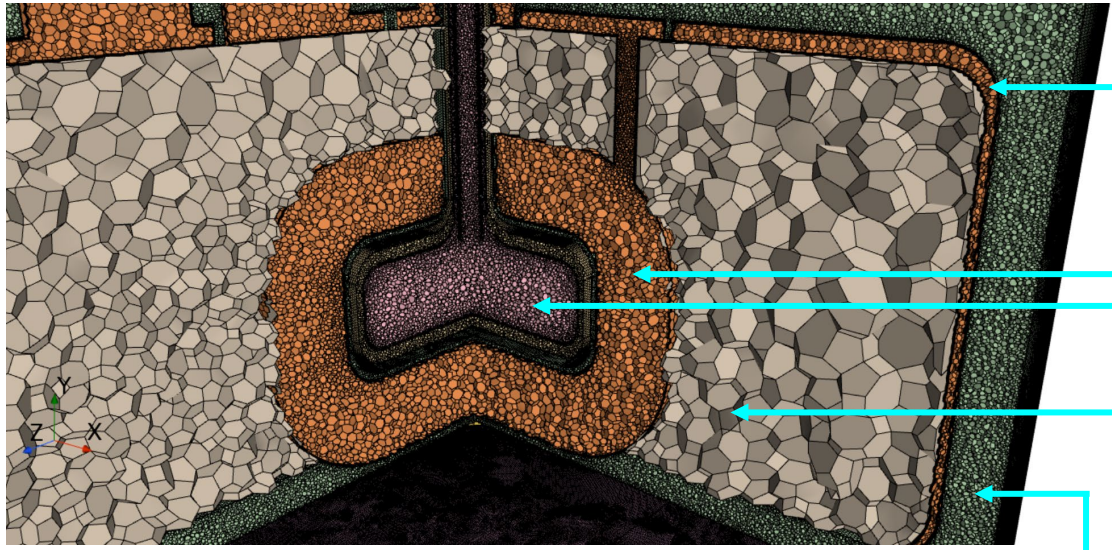
Invar

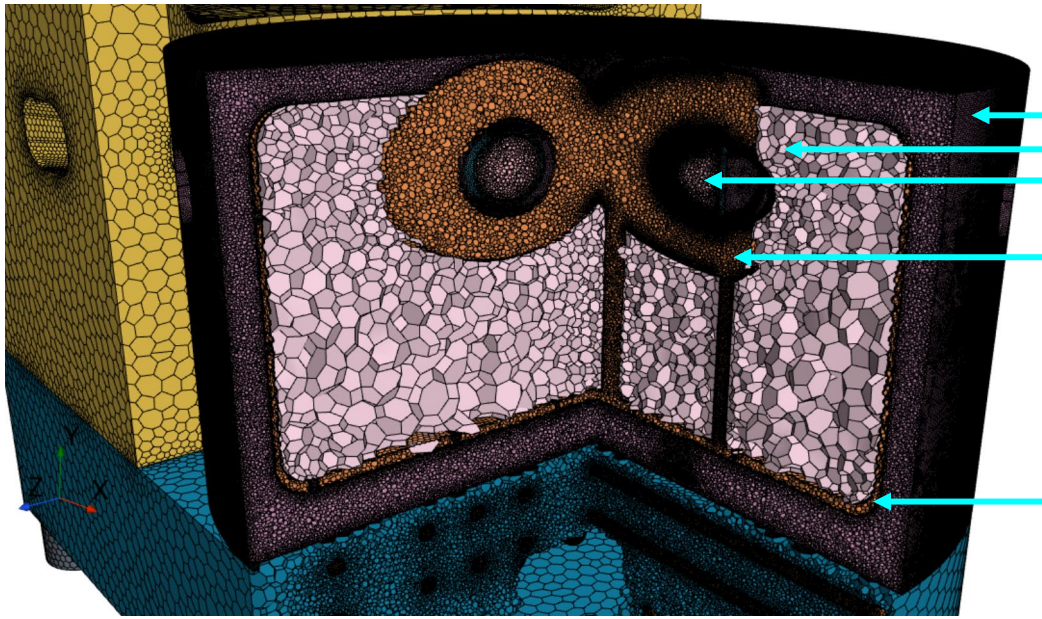
H_2O



Steady State Heat Transfer Analysis for MRA, Mesh Configuration





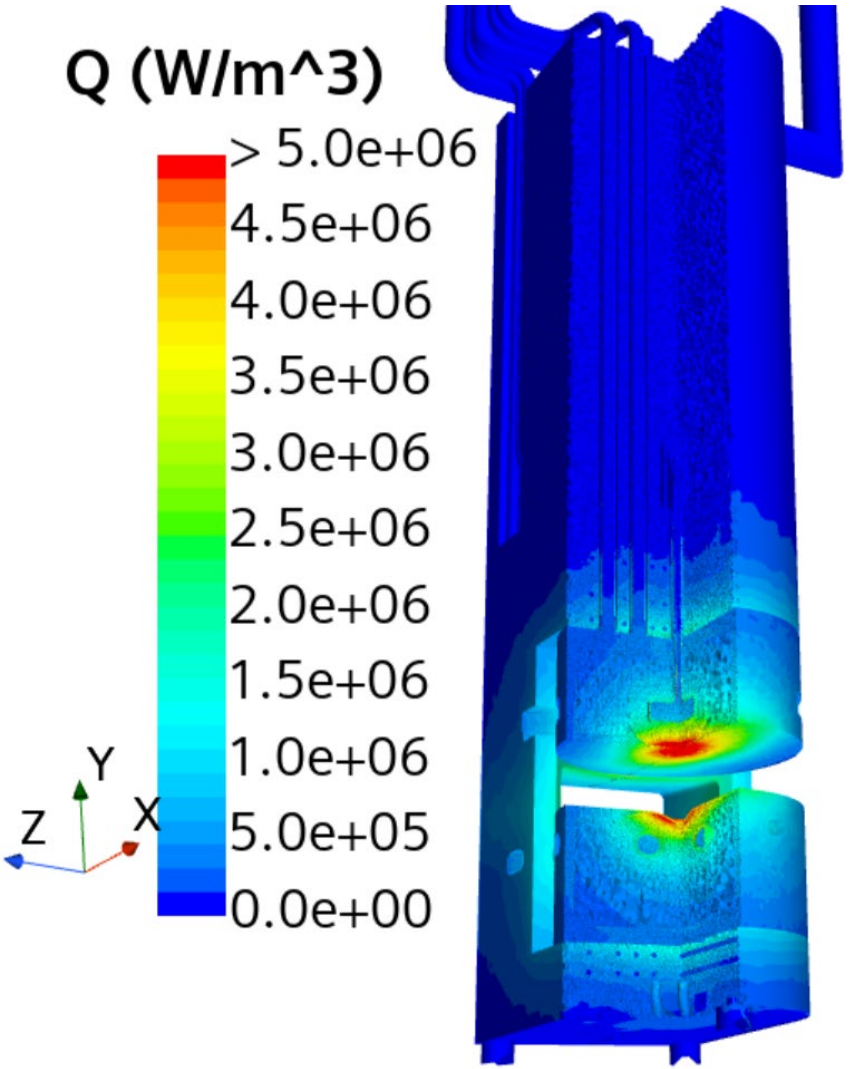


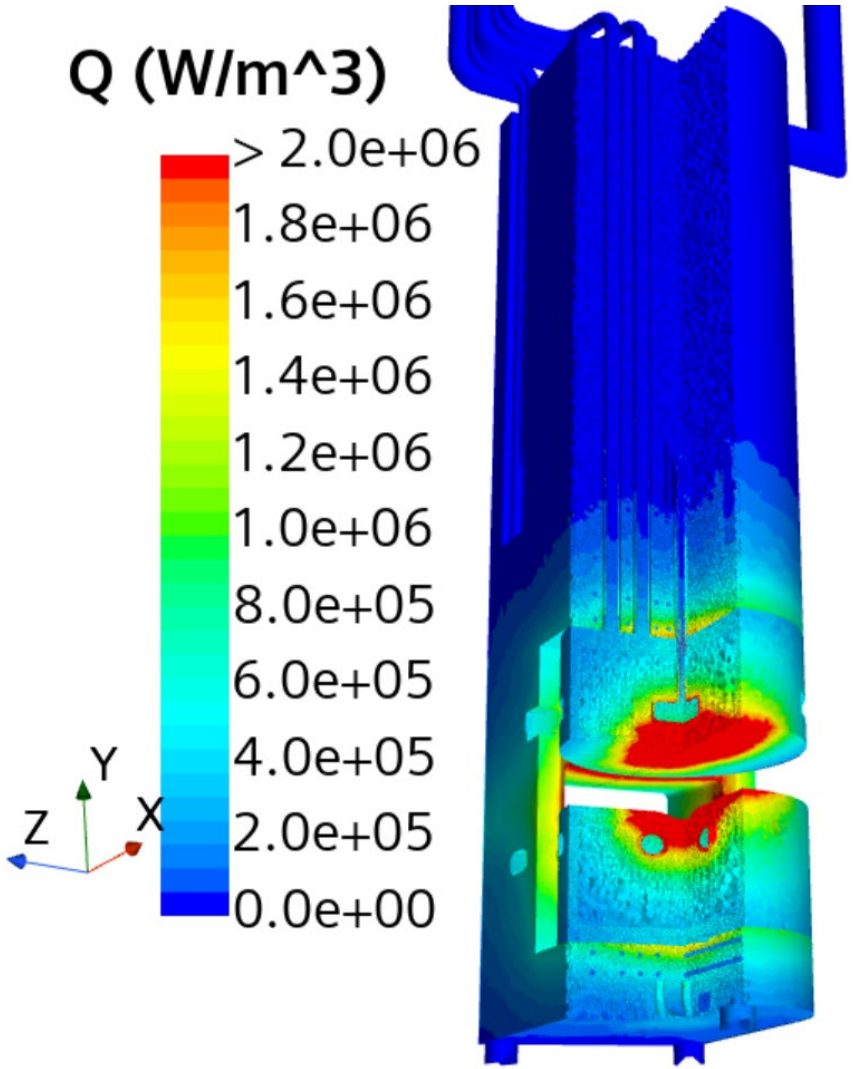
Al Be H_2 H_2O

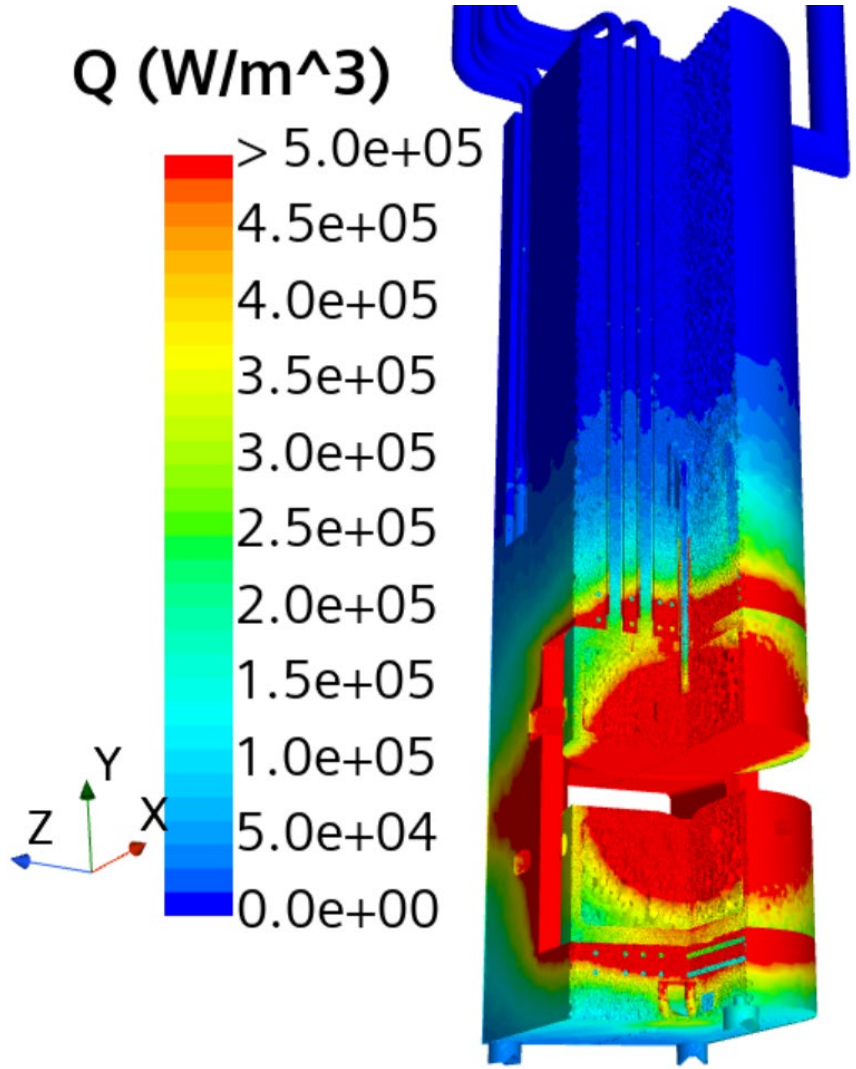
Steady State Heat Transfer Analysis for MRA, Mesh Configuration

MRA (with H_2 Loop)						
	Al	**Be**	**H_2**	**Water**	**Invar**	**SS**
Mesh Type	Polyhedral mesh	Polyhedral mesh	Polyhedral mesh	Polyhedral mesh	Polyhedral mesh	Polyhedral mesh
Base Size (m)	0.0025	0.05	0.0025	0.0025	0.0025	0.01
Target Surface Size (m)	9.00E-04	2.50E-02	9.00E-04	2.50E-03	9.00E-04	1.00E-02
Minimum Surface Size (m)	2.50E-04	5.00E-03	2.50E-04	2.50E-04	2.50E-04	1.00E-03
Volume Growth Rate	1.2	1.2	1.2	1.2	1.2	1.1
Number of Prism Layers	4	N/A	8	8	N/A	N/A
Prism Layer Stretching	1.5	N/A	1.5	1.5	N/A	N/A
Prism Layer Total Thickness (m)	2.50E-04	N/A	3.50E-04	6.25E-04	N/A	N/A
Number of Thin Layers	N/A	N/A	N/A	N/A	5	5
Number of Cells	**2.56E+07**	**3.77E+04**	**8.83E+06**	**3.58E+07**	**3.58E+06**	**7.34E+06**
Total Cells	**8.12E+07**					

Steady State Heat Transfer Analysis for MRA (without H_2 Loop), Heat Source





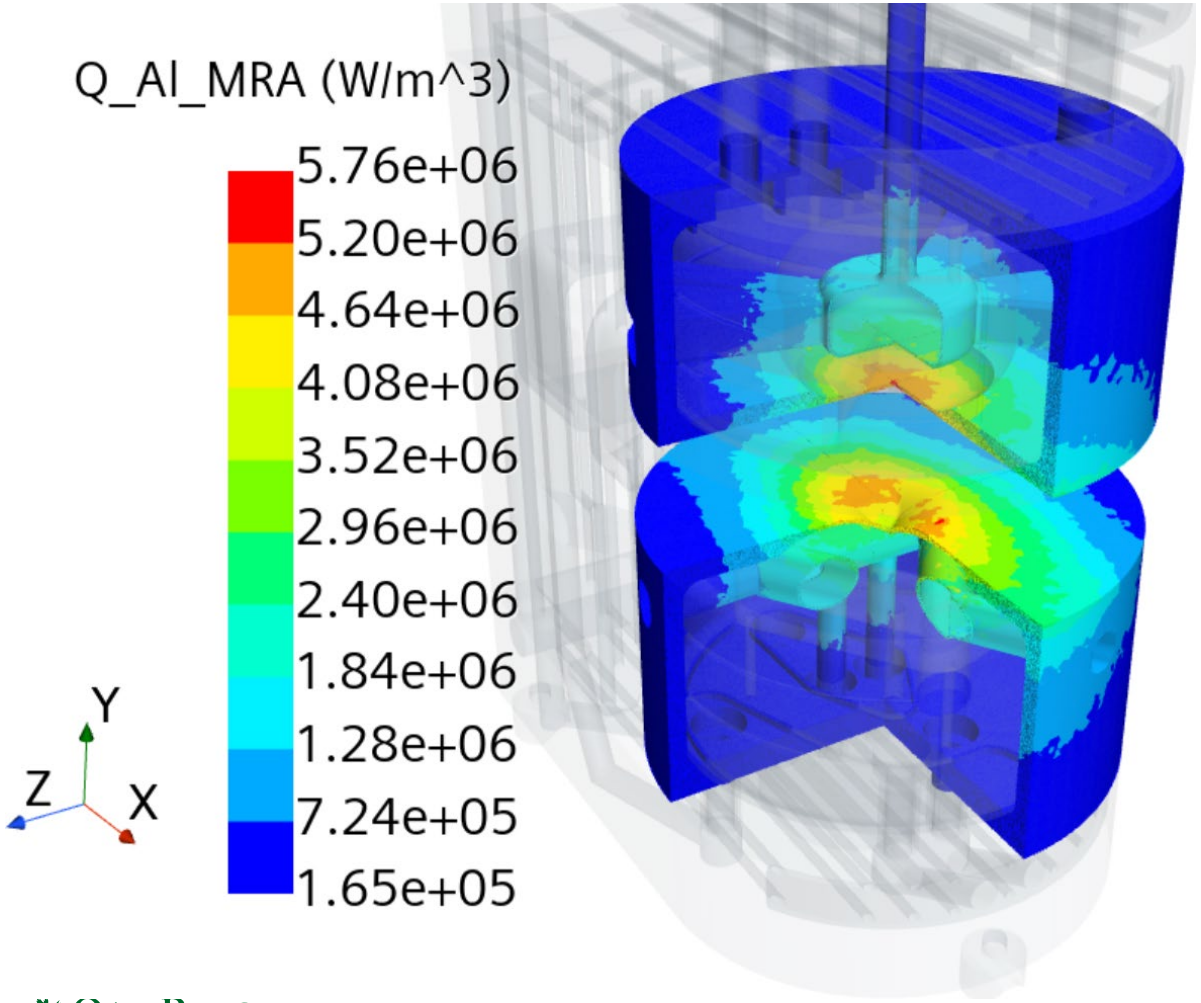


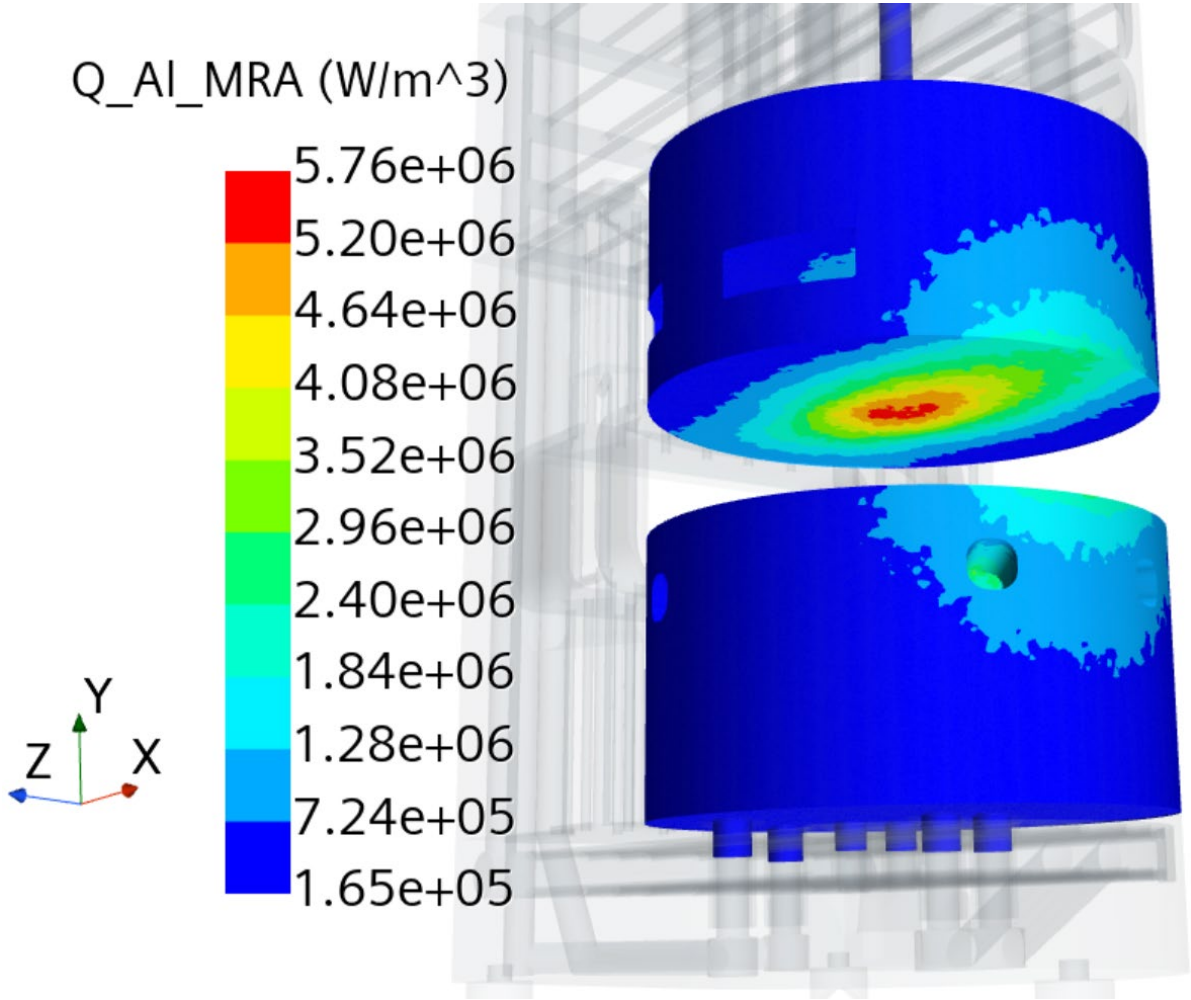
Steady State Heat Transfer Analysis for MRA (without H_2 Loop), Heat Source

Q_Al = 8.95 kW

Component	Heat (W)
Upper Al Vessel (Cylinder)	4354.10
Lower Al Vessel (Tube)	4592.46
Total	**8946.56**

Al vessel for the H_2 Loop is **not** included.

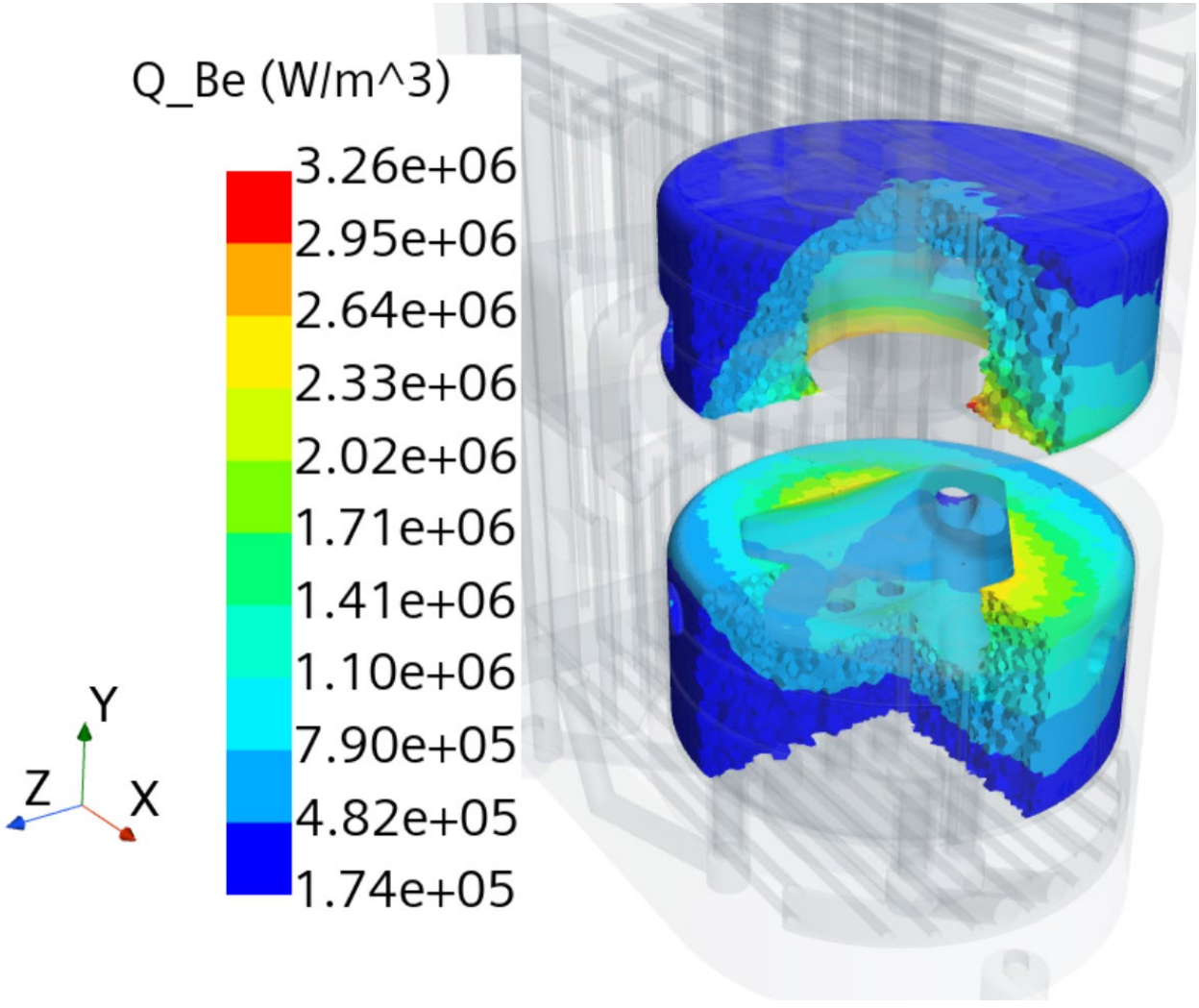


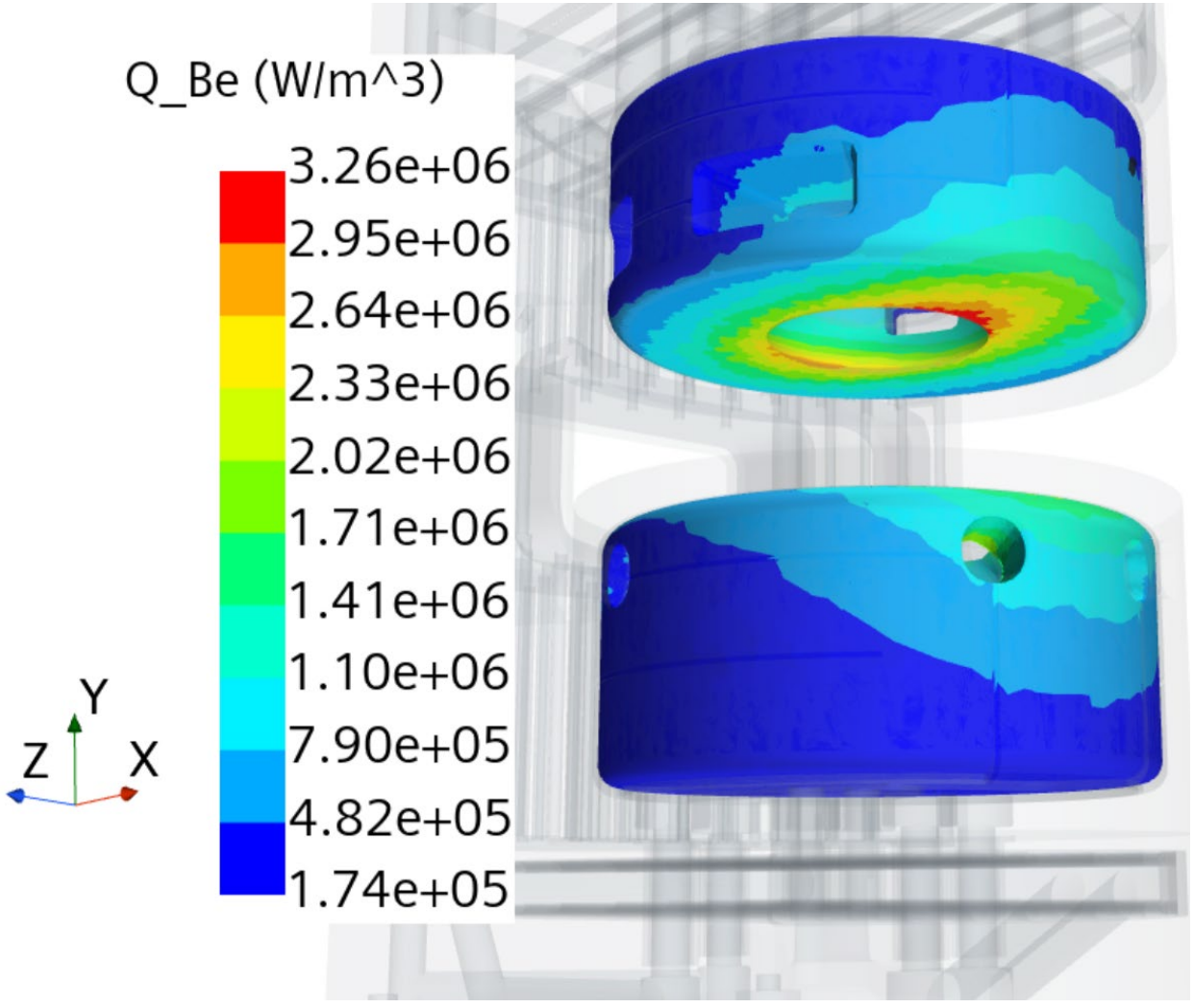


Steady State Heat Transfer Analysis for MRA (without H_2 Loop), Heat Source

Q_Be = 12.3 kW

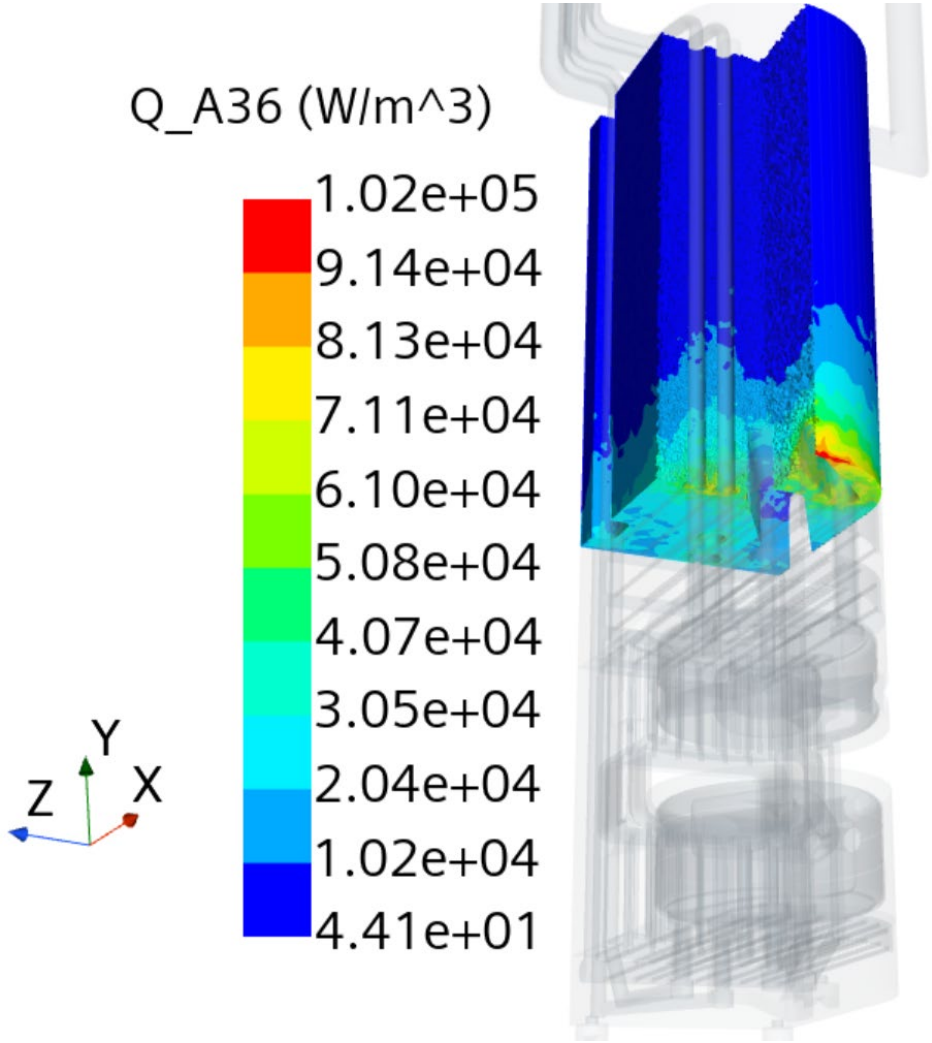
Component	Heat (W)
Upper Beryllium	6006.45
Lower Beryllium	6313.60
Total	12320.05



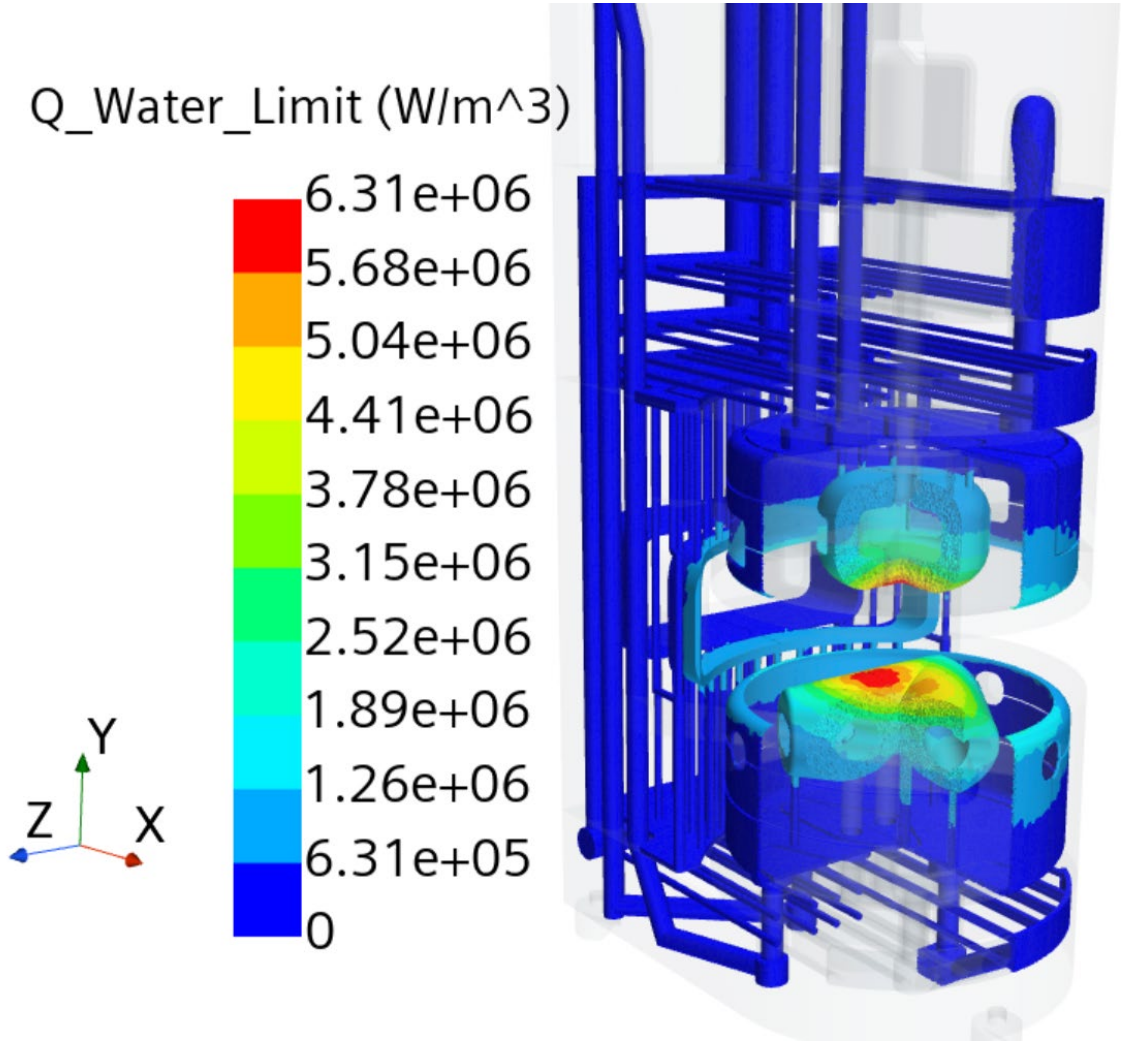


Steady State Heat Transfer Analysis for MRA (without H_2 Loop), Heat Source

Q_A36 = 798.7 W



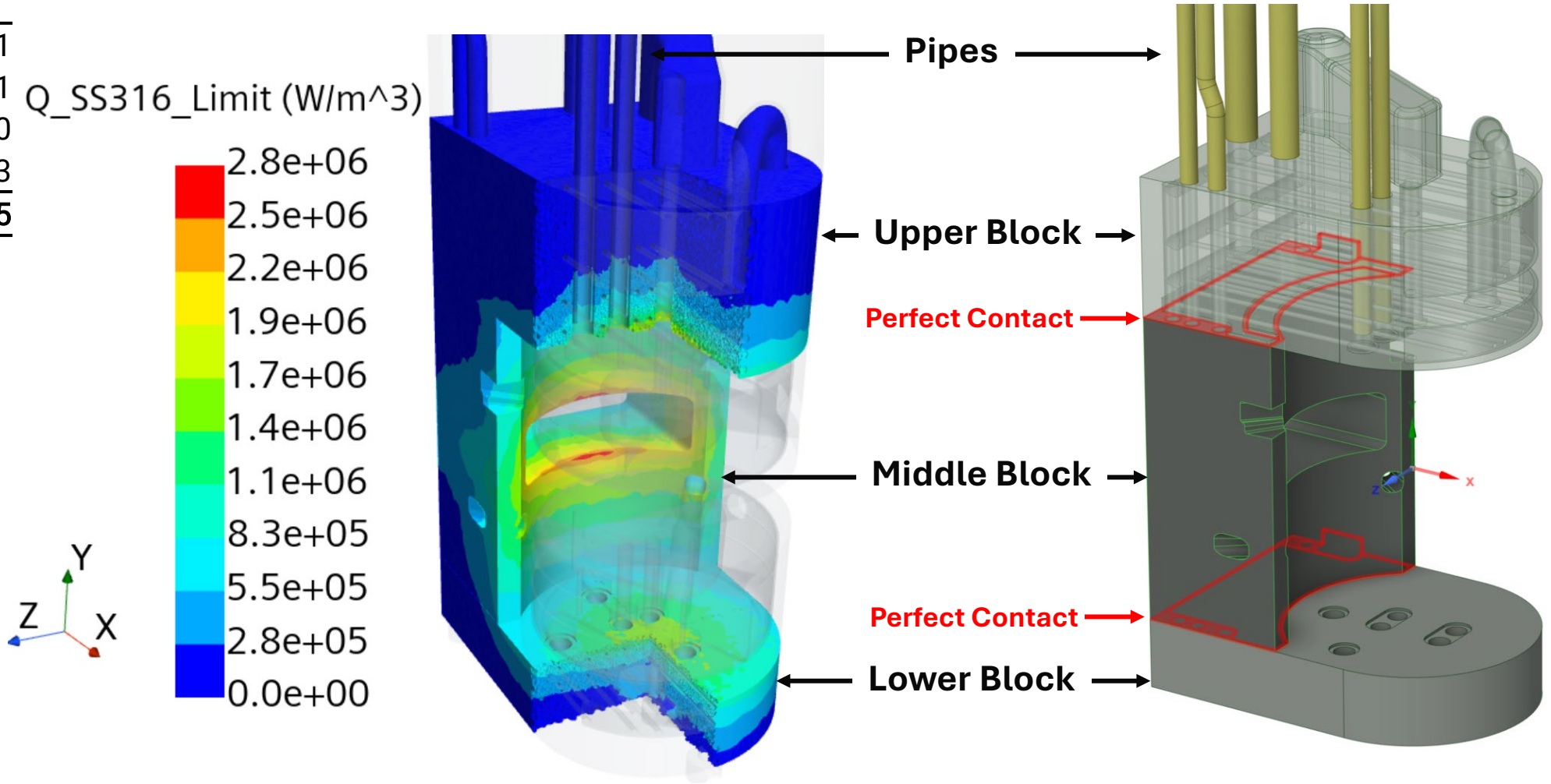
Q_Water = 9.2 kW



Steady State Heat Transfer Analysis for MRA (without H_2 Loop), Heat Source

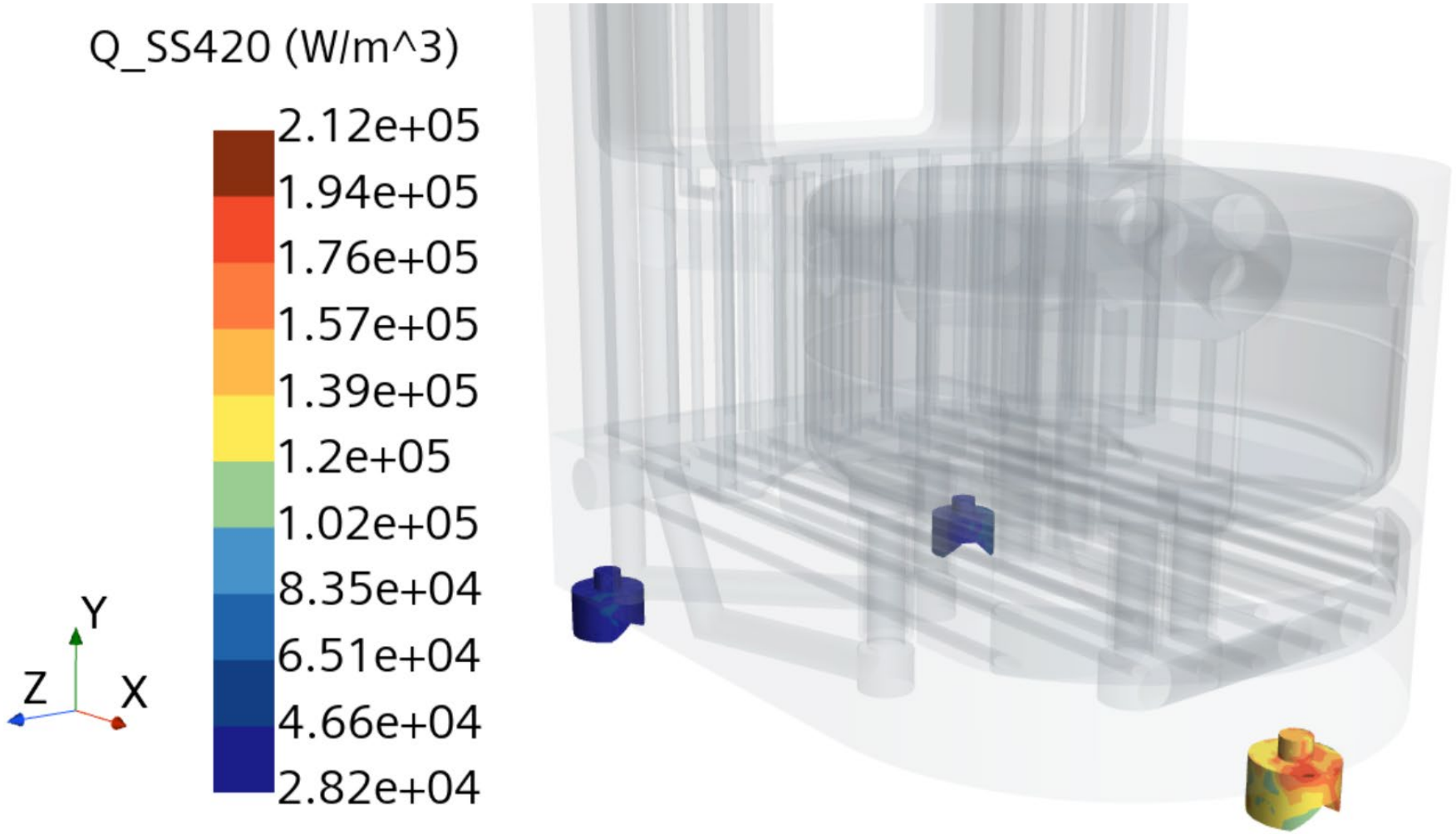
MRA SS316	
Component	**Heat (W)**
SS316 Pipes	28.91
Upper Block	7725.11
Middle Block	12525.80
Lower Block	5635.93
Total	**25915.75**

Q_SS316 = 25.9 kW



Steady State Heat Transfer Analysis for MRA (without H_2 Loop), Heat Source

Q_SS420 = 11 W



Steady State Heat Transfer Analysis for MRA, Heat Source

	Component	Heat (W)		Total Heat (W)
MRA Moderator (H_2 Loop)	Upper Al Vessel (Cylinder)	188.58	409.50	884.41
	Lower Al Vessel (Tube)	220.92		
	Upper Hydrogen (Cylinder)	183.95	419.51	
	Lower Hydrogen (Tube)	235.56		
	Invar		55.39	
MRA Non-H_2 Loop (Reflectors, Shielding Block, and Backbone)	Upper Al Vessel (Cylinder)	4354.10	8946.56	57194.97
	Lower Al Vessel (Tube)	4592.46		
	Upper Beryllium	6006.45	12320.05	
	Lower Beryllium	6313.60		
	A36_Shielding		798.72	
	SS316 Pipes	28.91	25915.75	
	SS316 Upper Block	7725.11		
	SS316 Middle Block	12525.80		
	SS316 Lower Block	5635.93		
	SS420		11.01	
	Water		9202.89	
	Sum			**58079.38**

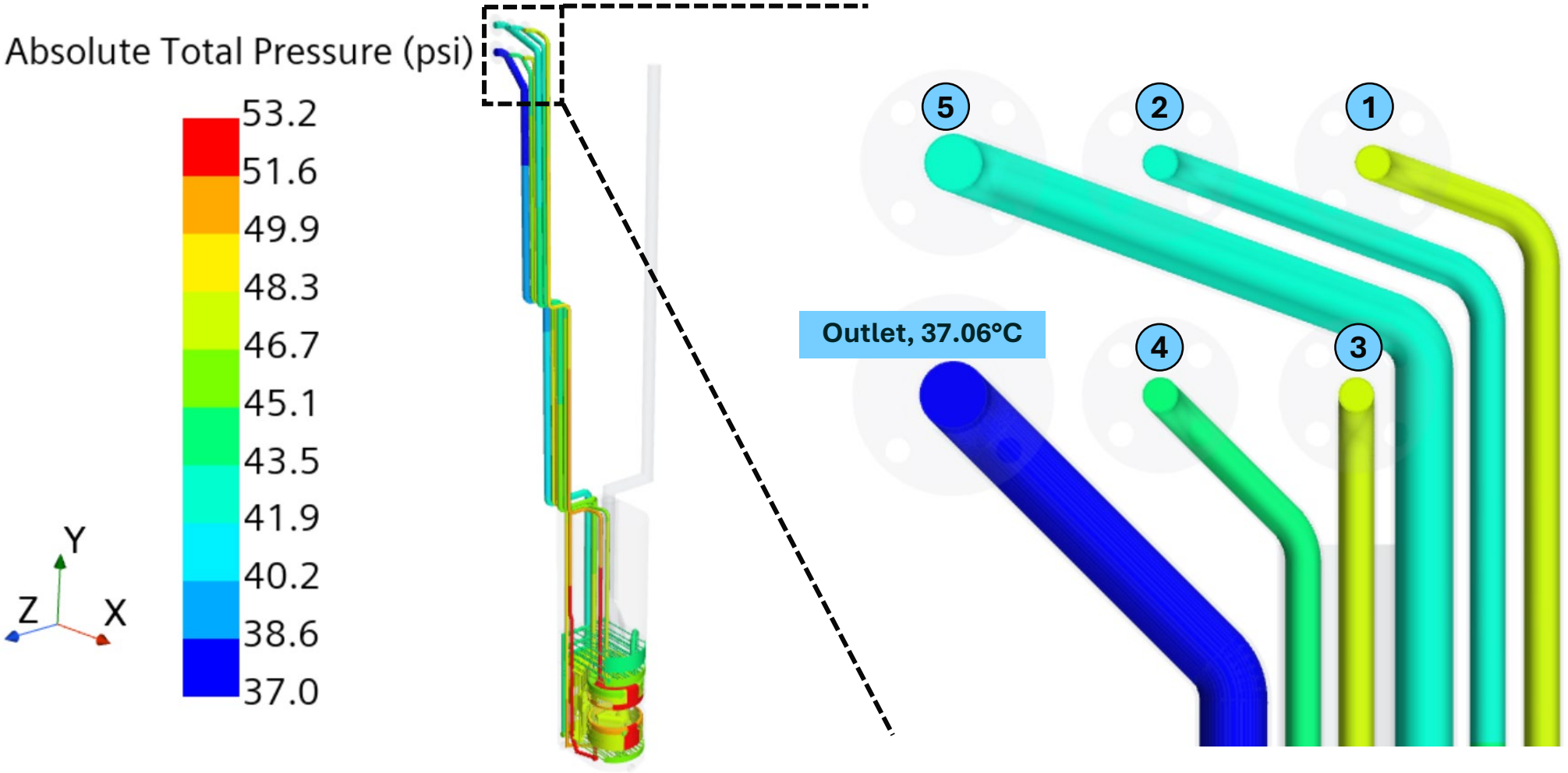
- **The total heat deposited in MRA is 58 kW (8.29% of 700 kW).**

Steady State Heat Transfer Analysis for MRA(without H_2 Loop), Water Pressure

Requirement: < 15 psi

- Inlet_1 – 7.5 GPM (= 0.47 kg/s), 90°F (= 32.22°C), Upper MRA, Outer region (Reflector cooling water)
- Inlet_2 – 7.5 GPM (= 0.47 kg/s), 90°F (= 32.22°C), Upper MRA, Inner region (Premoderator water)
- Inlet_3 – 7.5 GPM (= 0.47 kg/s), 90°F (= 32.22°C), Lower MRA, Outer region (Reflector cooling water)
- Inlet_4 – 7.5 GPM (= 0.47 kg/s), 90°F (= 32.22°C), Lower MRA, Inner region (Premoderator water)
- Inlet_5 – 15 GPM (= 0.94 kg/s), 90°F (= 32.22°C), MRA Backbone

$$\Delta P_{inlet-outlet} = 9.65\ psi\ (Loop_1\ , 7.5GPM)$$
$$\Delta P_{inlet-outlet} = 5.20\ psi\ (Loop_2\ , 7.5GPM)$$
$$\Delta P_{inlet-outlet} = 9.55\ psi\ (Loop_3\ , 7.5GPM)$$
$$\Delta P_{inlet-outlet} = 6.86\ psi\ (Loop_4\ , 7.5GPM)$$
$$\Delta P_{inlet-outlet} = 4.29\ psi\ (Loop_5\ , 15GPM)$$

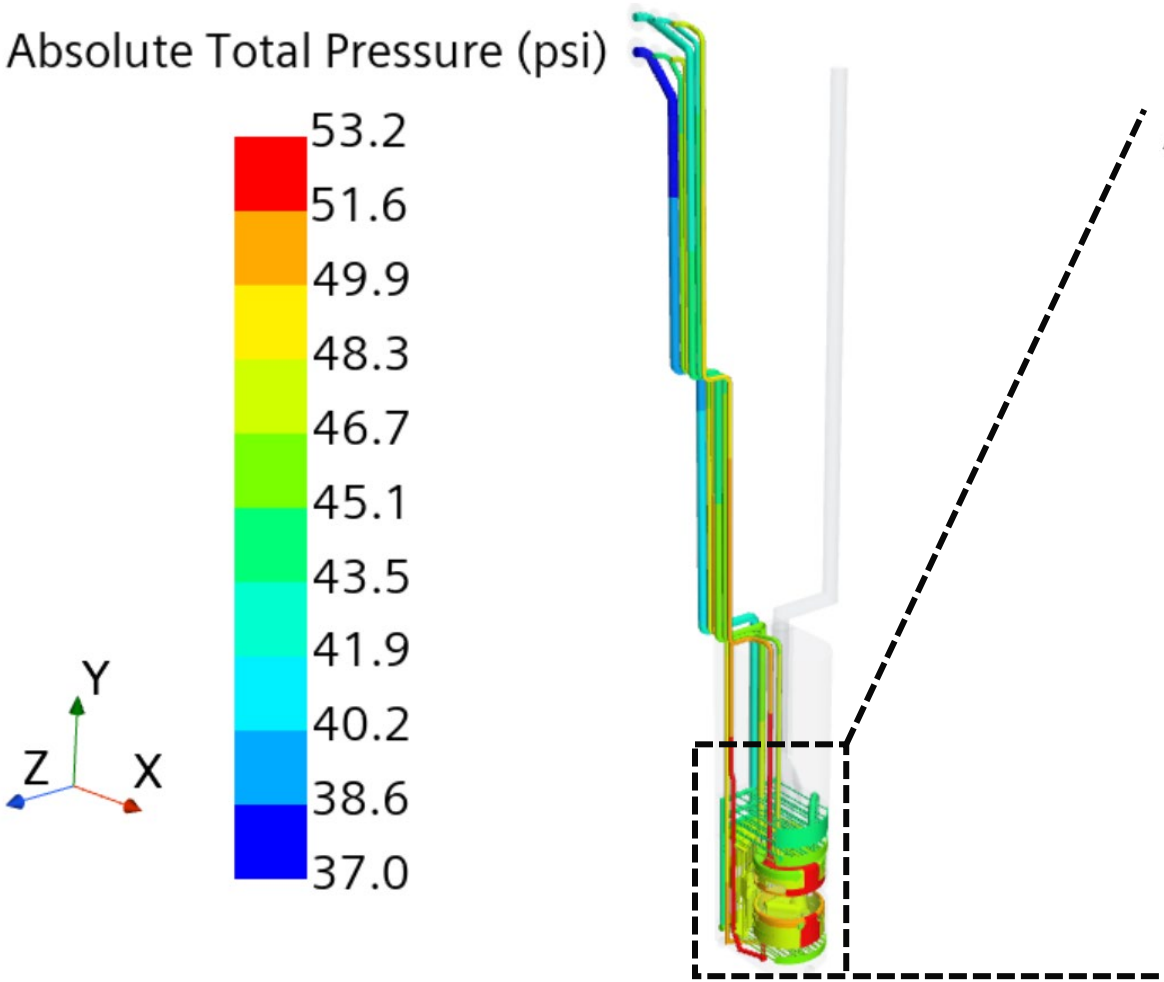


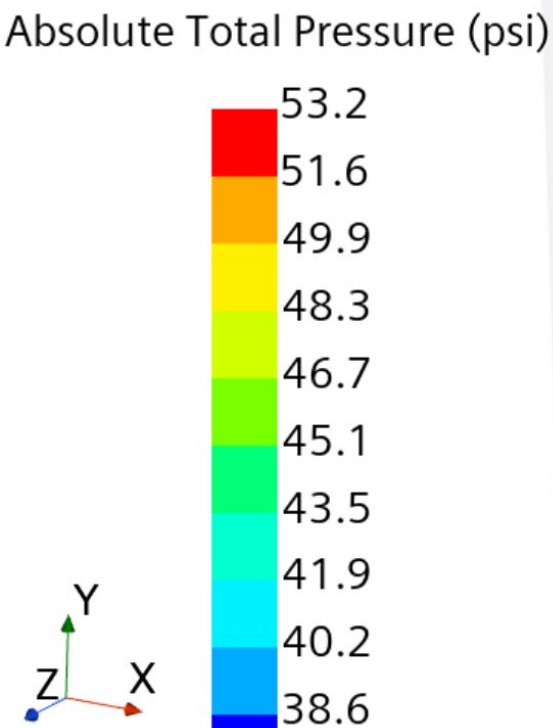
Steady State Heat Transfer Analysis for MRA(without H_2 Loop), Water Pressure

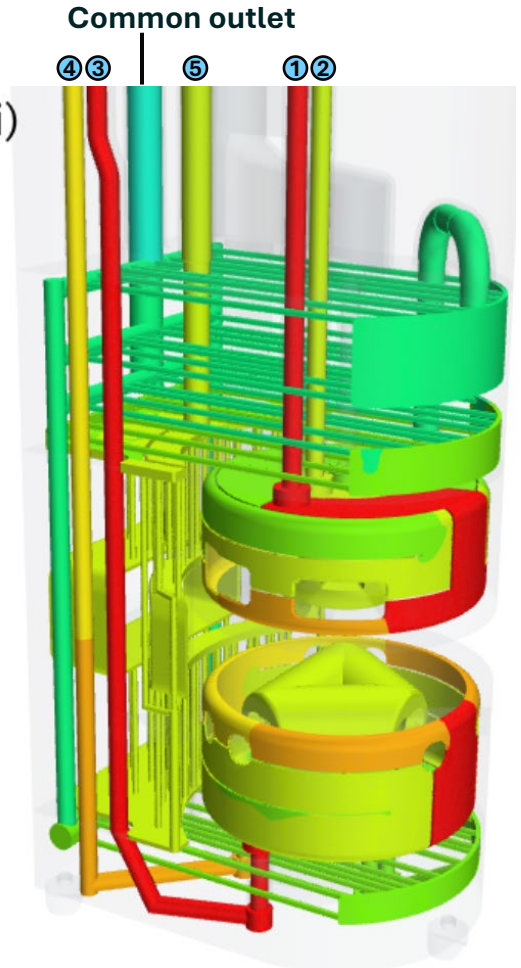
Requirement: < 15 psi

- Inlet_1 – 7.5 GPM (= 0.47 kg/s), 90°F (= 32.22°C), Upper MRA, Outer region (Reflector cooling water)
- Inlet_2 – 7.5 GPM (= 0.47 kg/s), 90°F (= 32.22°C), Upper MRA, Inner region (Premoderator water)
- Inlet_3 – 7.5 GPM (= 0.47 kg/s), 90°F (= 32.22°C), Lower MRA, Outer region (Reflector cooling water)
- Inlet_4 – 7.5 GPM (= 0.47 kg/s), 90°F (= 32.22°C), Lower MRA, Inner region (Premoderator water)
- Inlet_5 – 15 GPM (= 0.94 kg/s), 90°F (= 32.22°C), MRA Backbone

$$\Delta P_{inlet-outlet} = 9.65\ psi\ (Loop_1\ , 7.5GPM)$$
$$\Delta P_{inlet-outlet} = 5.20\ psi\ (Loop_2\ , 7.5GPM)$$
$$\Delta P_{inlet-outlet} = 9.55\ psi\ (Loop_3\ , 7.5GPM)$$
$$\Delta P_{inlet-outlet} = 6.86\ psi\ (Loop_4\ , 7.5GPM)$$
$$\Delta P_{inlet-outlet} = 4.29\ psi\ (Loop_5\ , 15GPM)$$



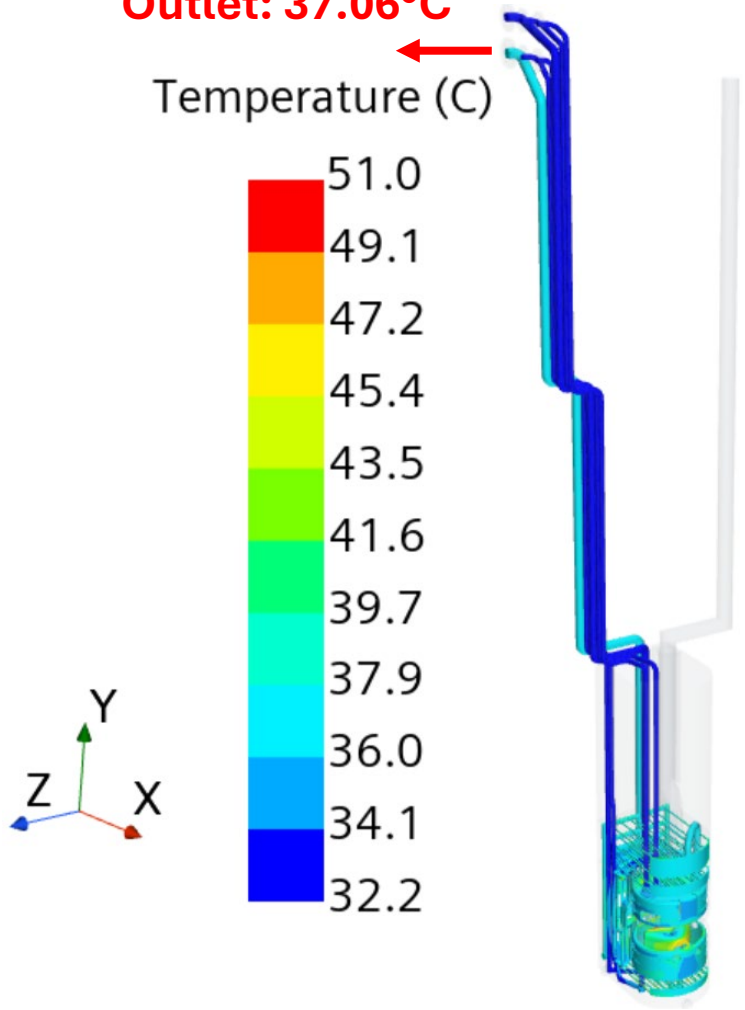




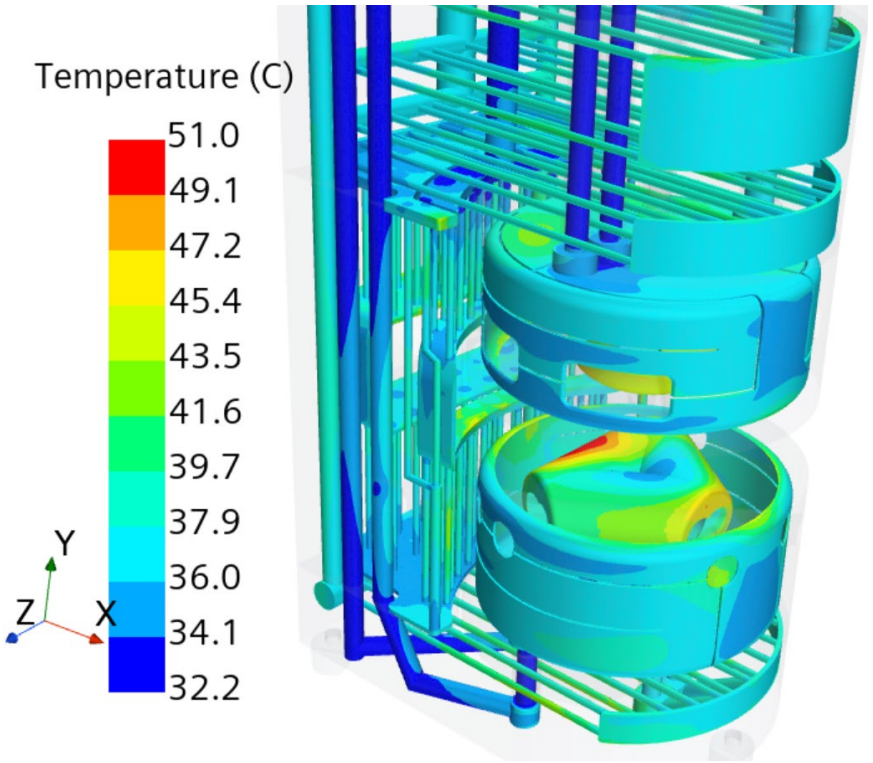
Steady State Heat Transfer Analysis for MRA(without H_2 Loop), Water Temperature

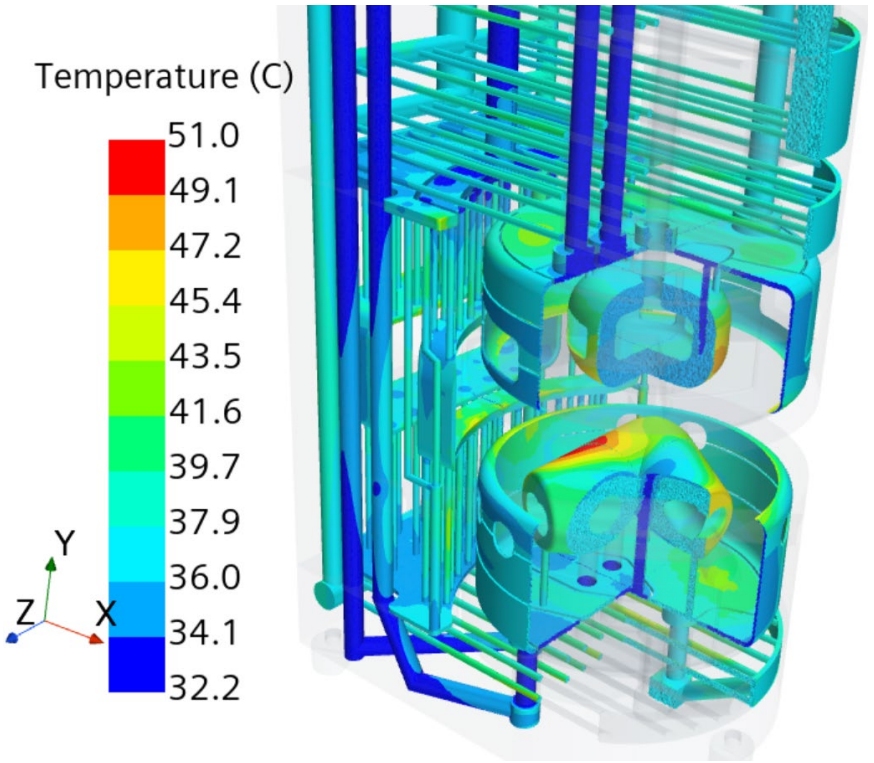
Requirement: < 100°C

Outlet: 37.06°C

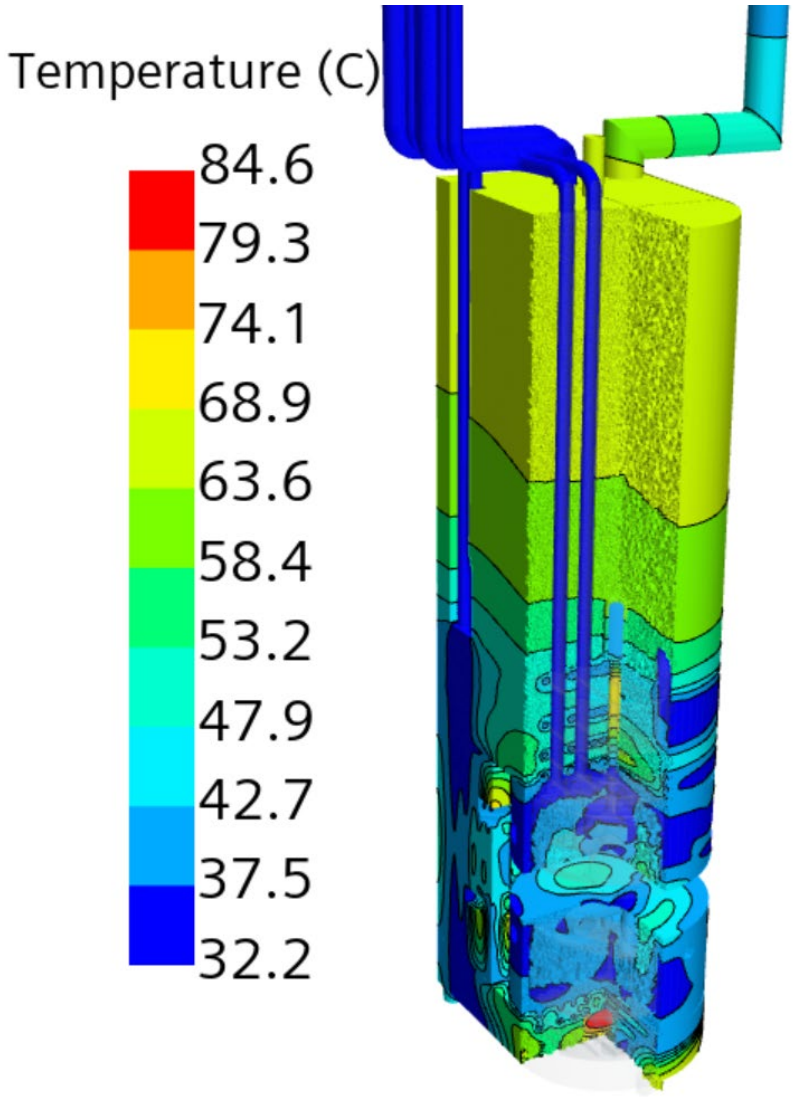


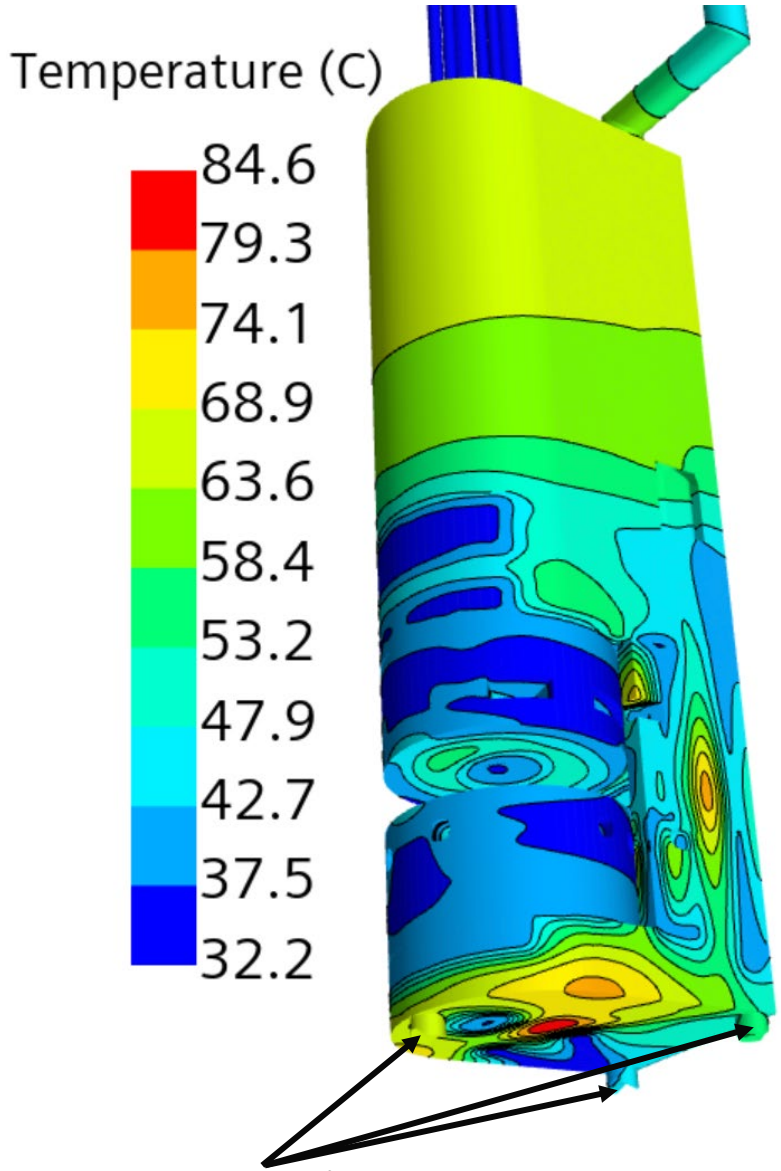
Peak: 51.0°C





Steady State Heat Transfer Analysis for MRA (without H_2 Loop), Temperature



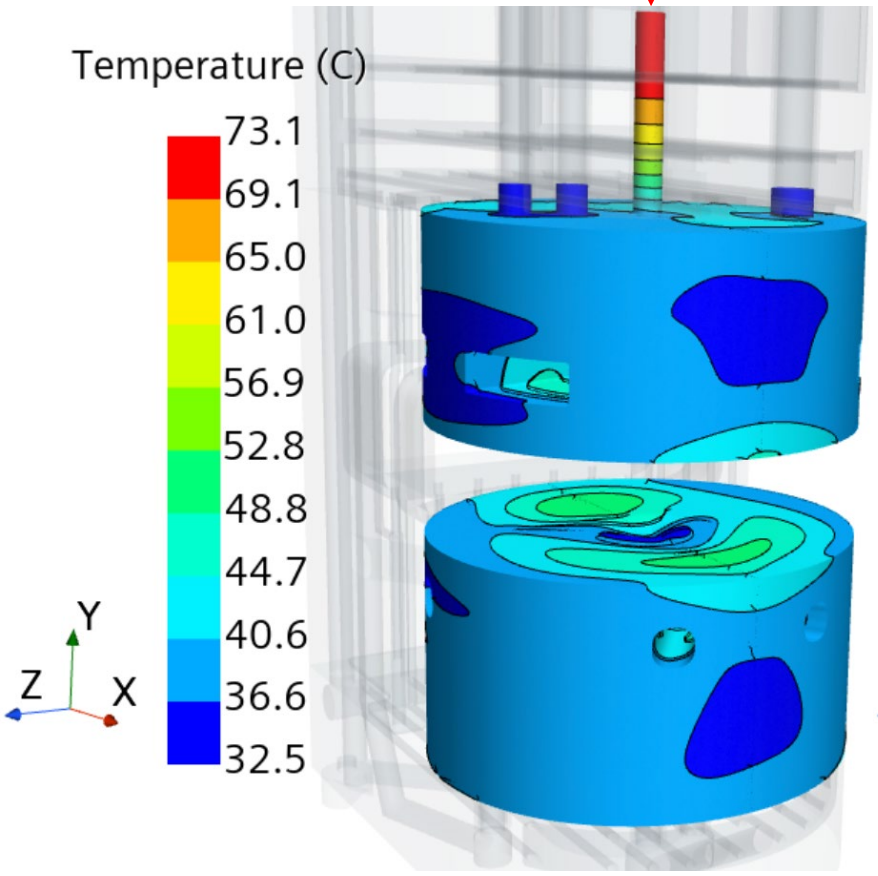


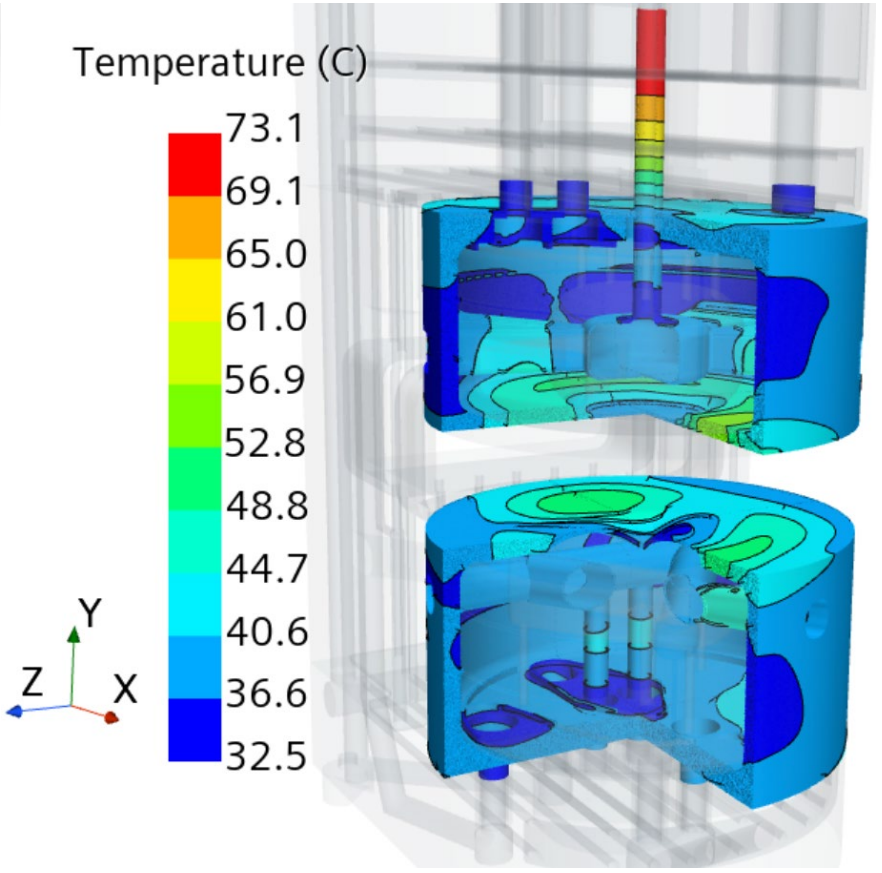
Non-uniform temperature for kinetic mounts due to the non-uniform heat source

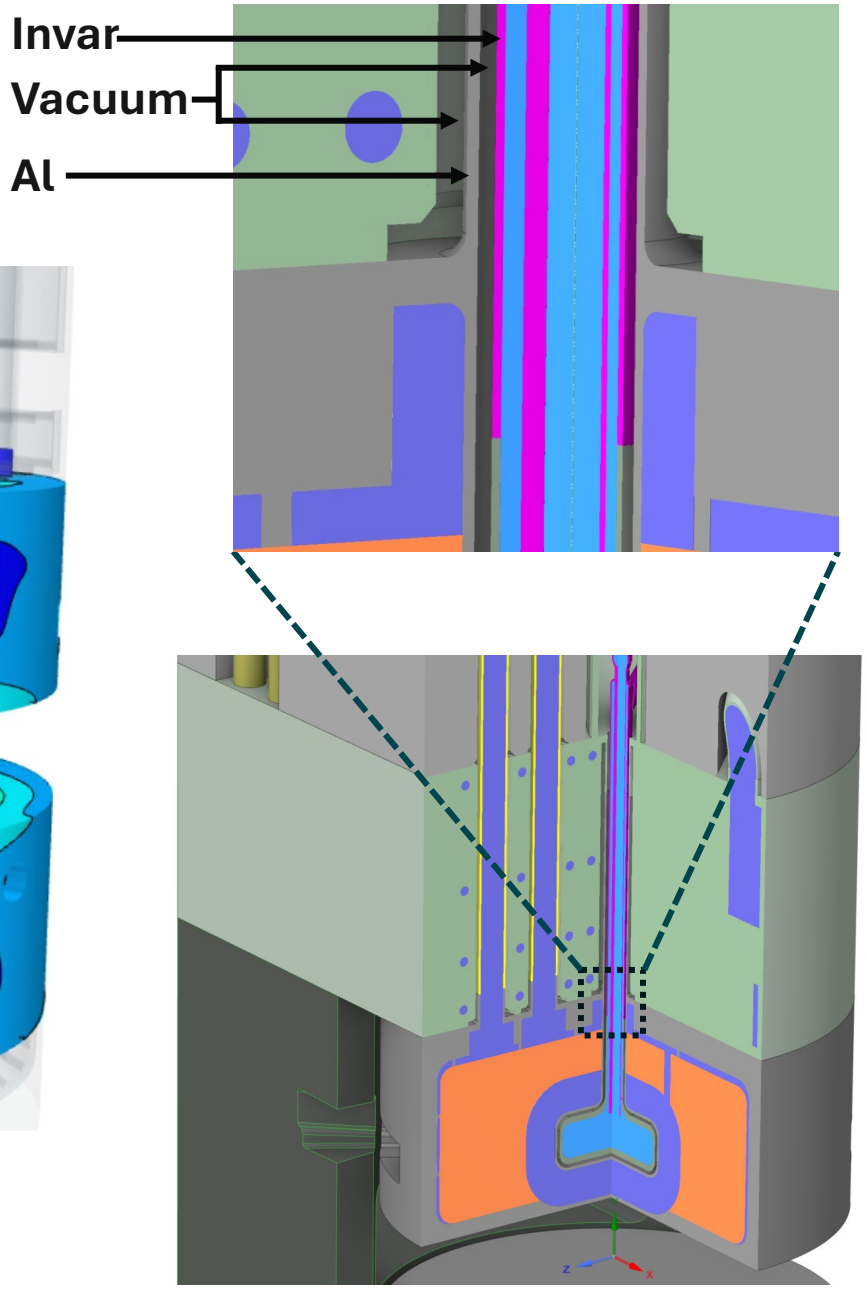
Steady State Heat Transfer Analysis for MRA(without H_2 Loop), Al Temperature

Requirement: < 100°C

Higher temperature due to the vacuum environment around the Al.



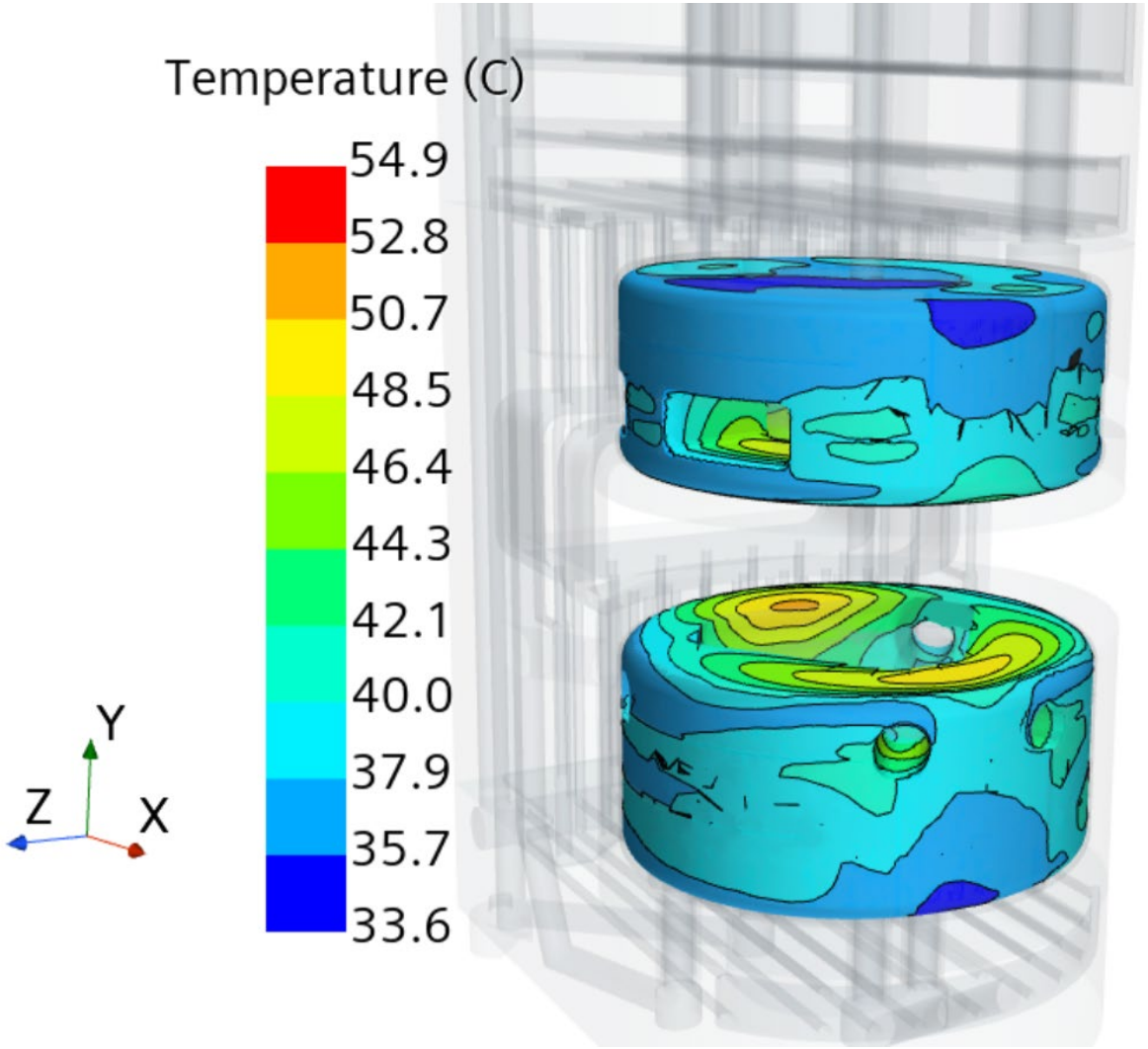


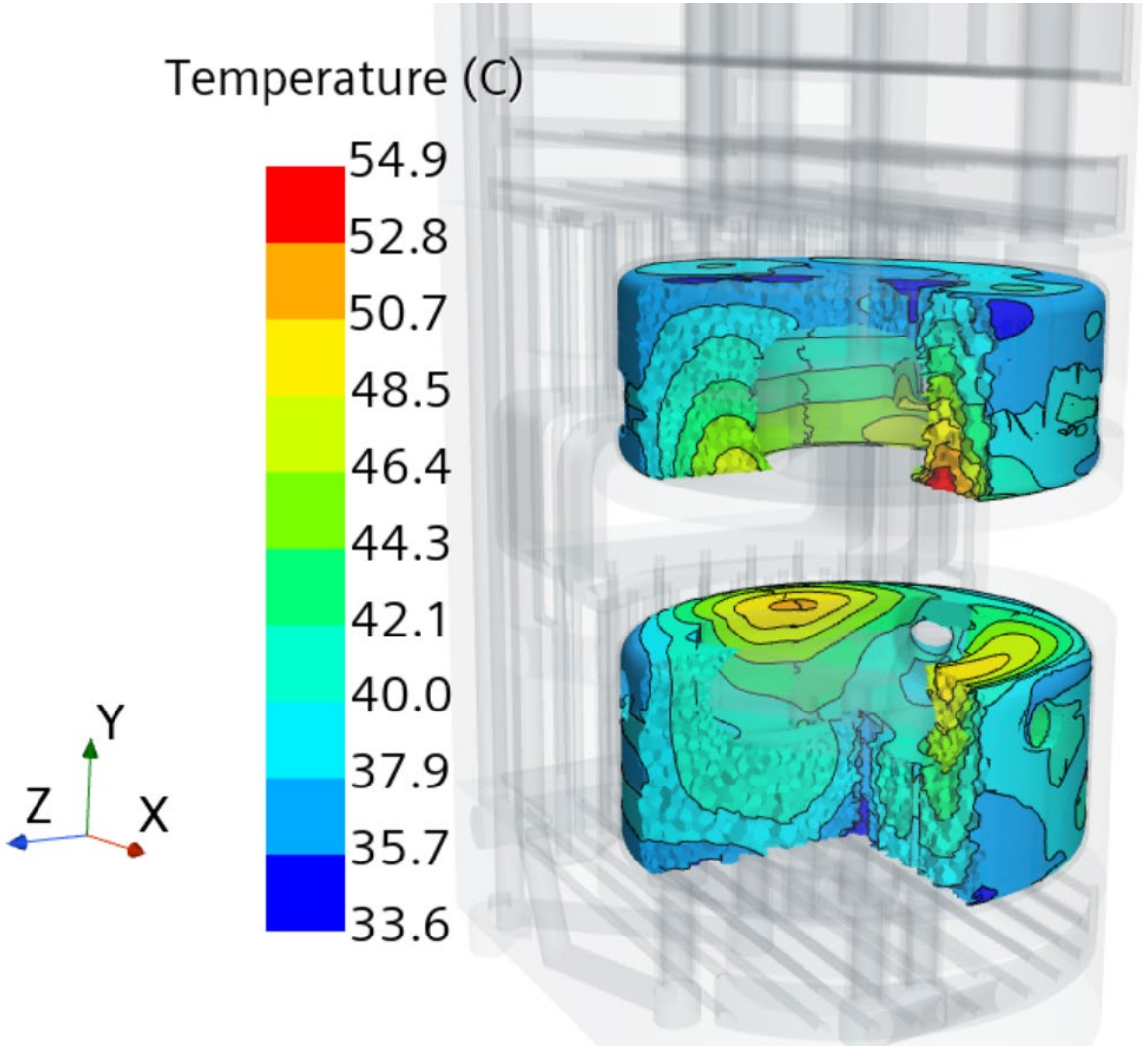


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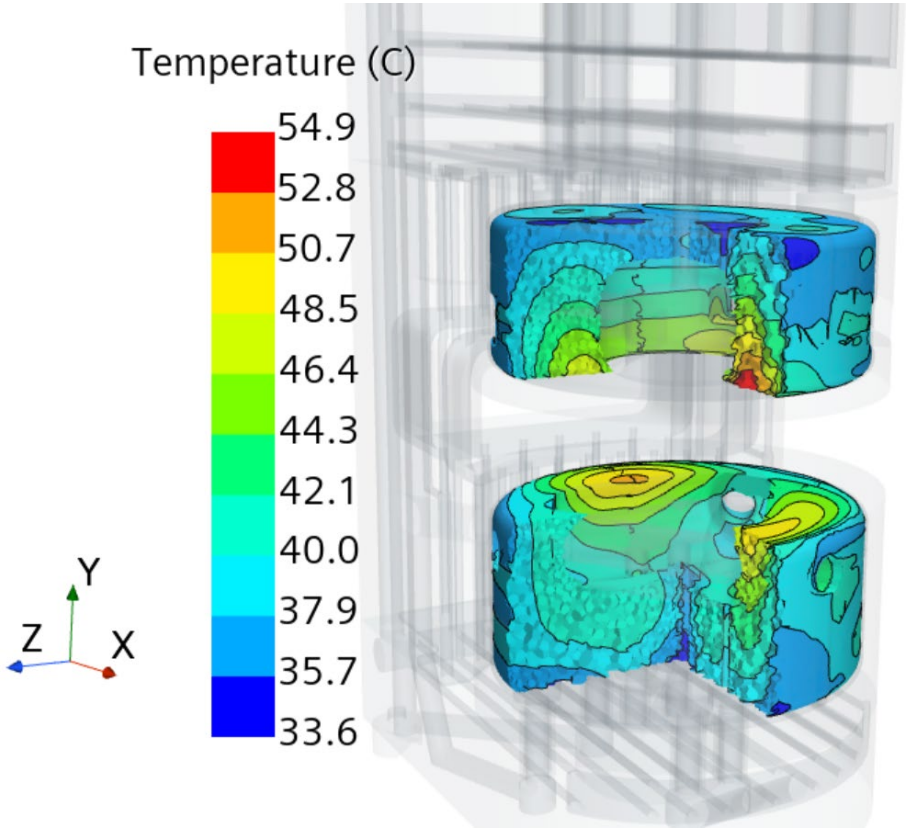
Steady State Heat Transfer Analysis for MRA(without H_2 Loop), Be Temperature

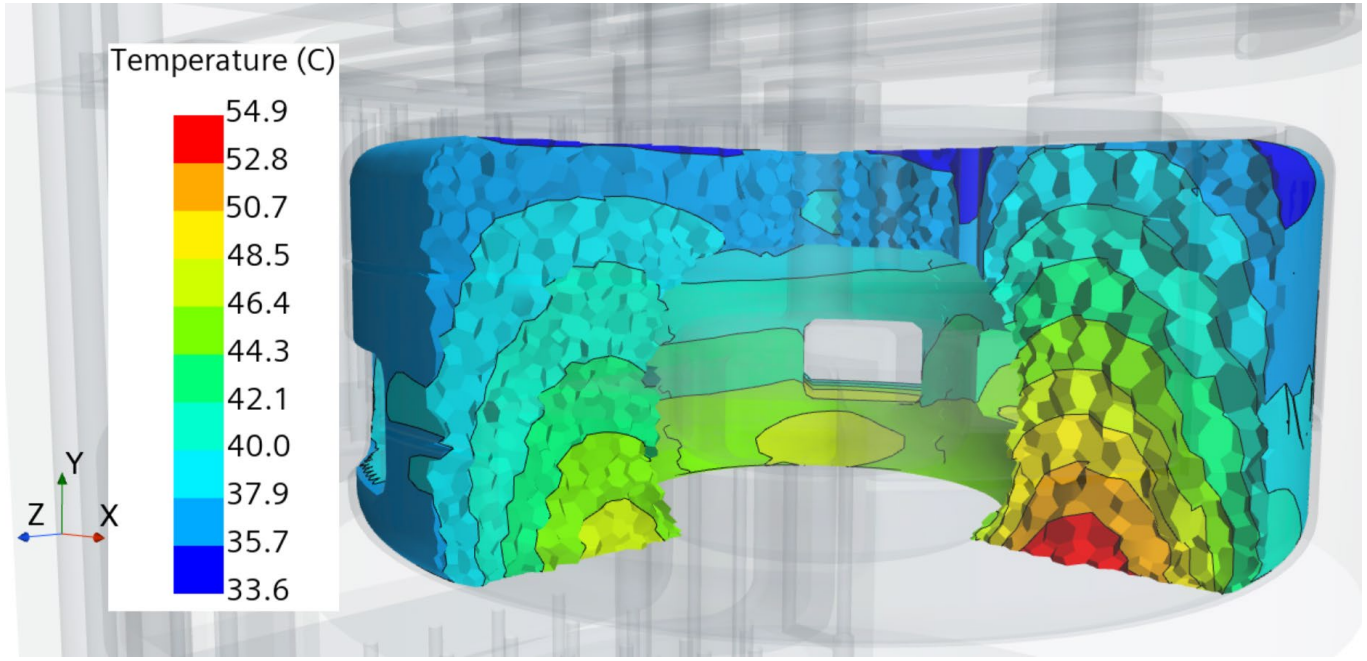
Requirement: < 100°C

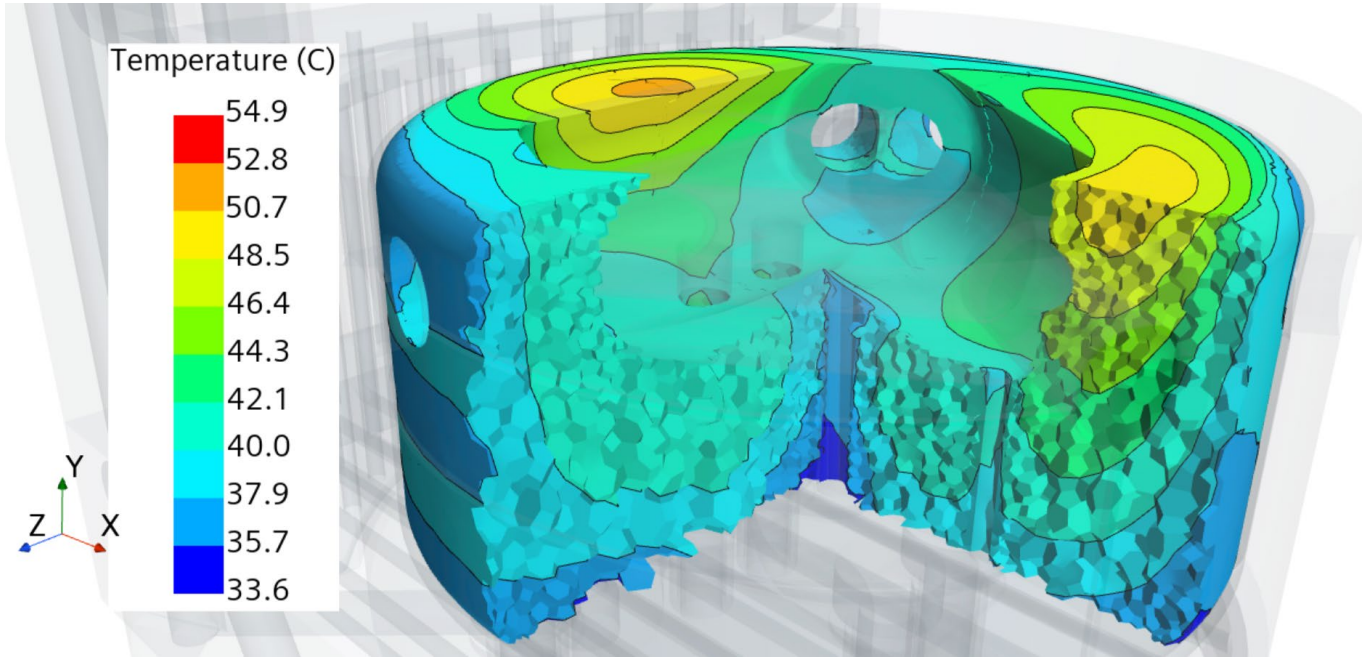




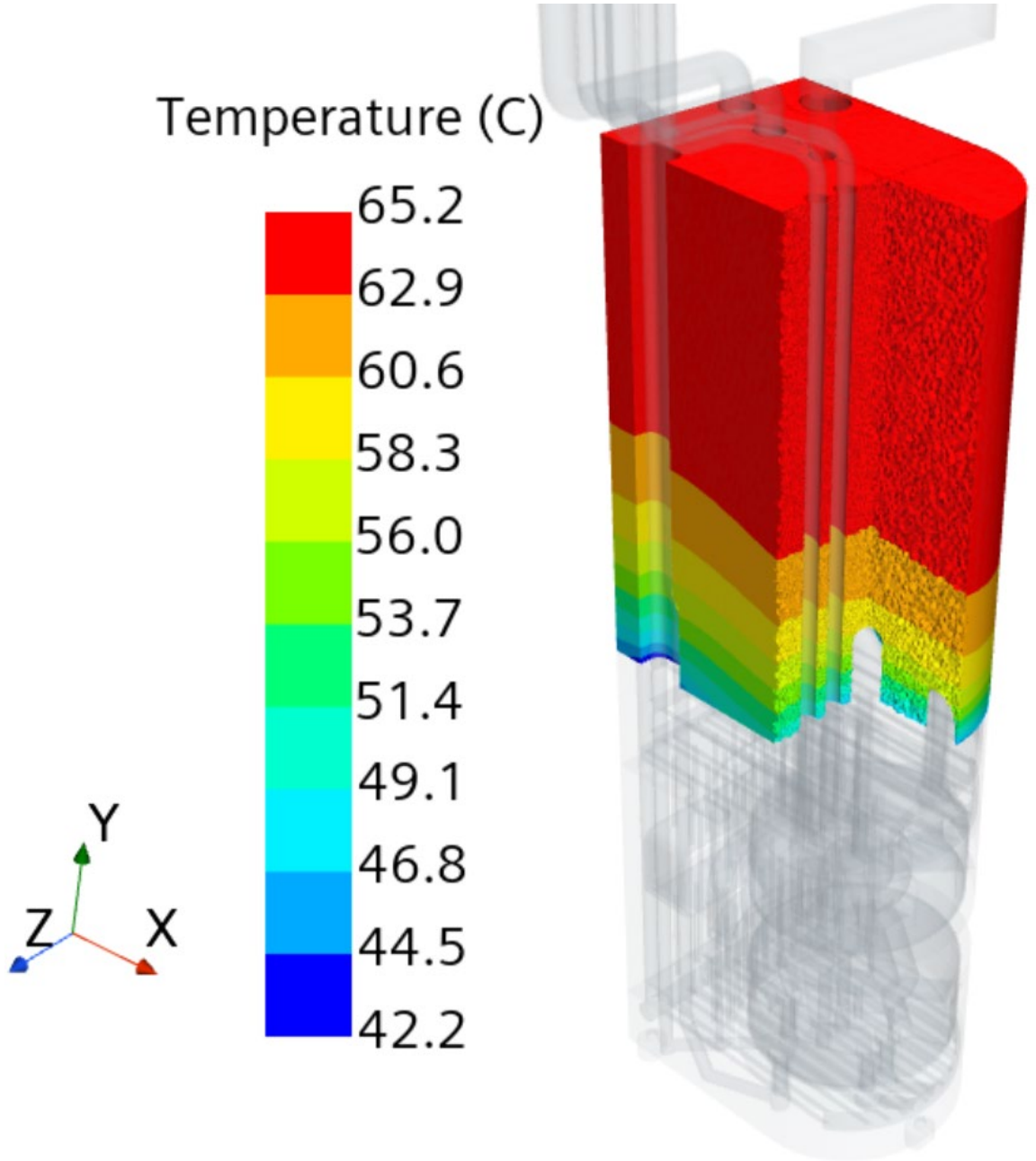
Steady State Heat Transfer Analysis for MRA(without H_2 Loop), Be Temperature





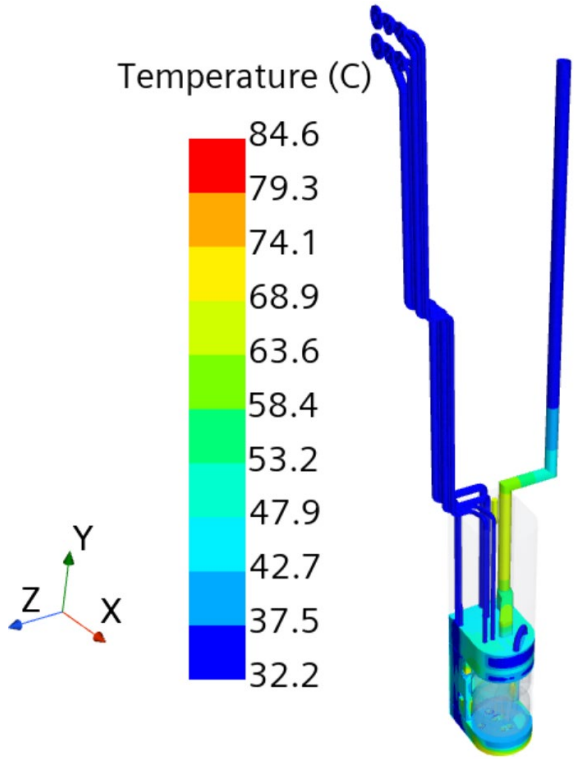


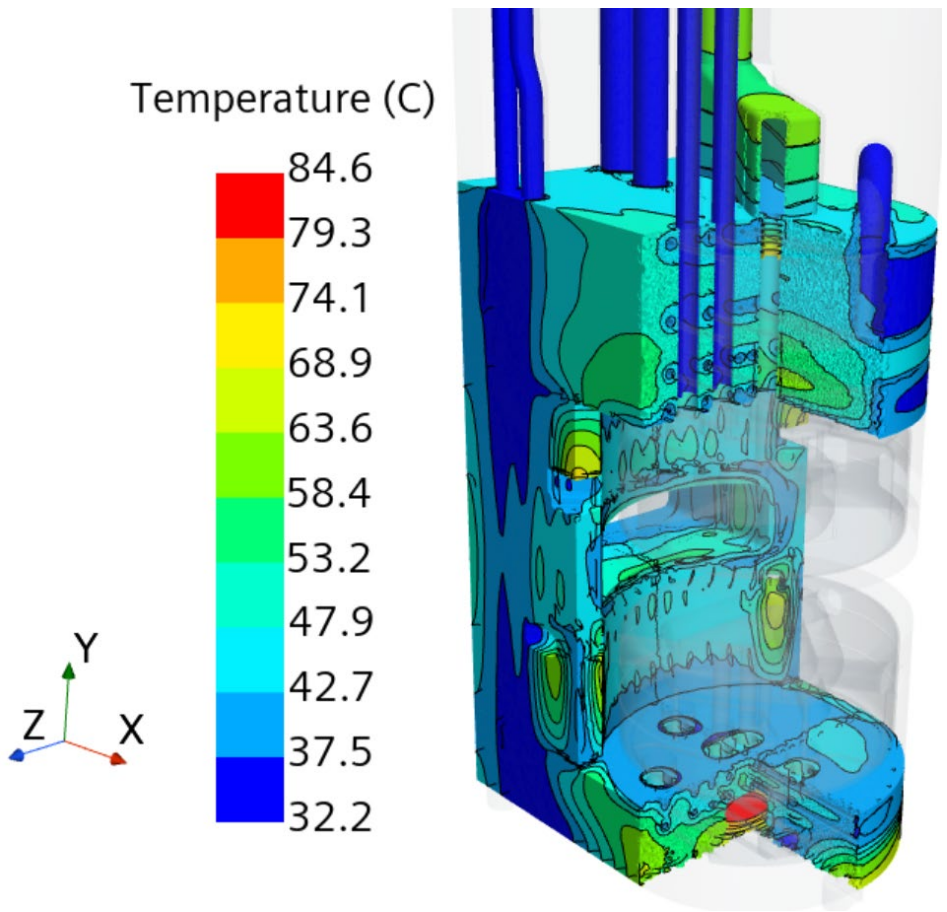
Steady State Heat Transfer Analysis for MRA(without H_2 Loop), A36 Temperature

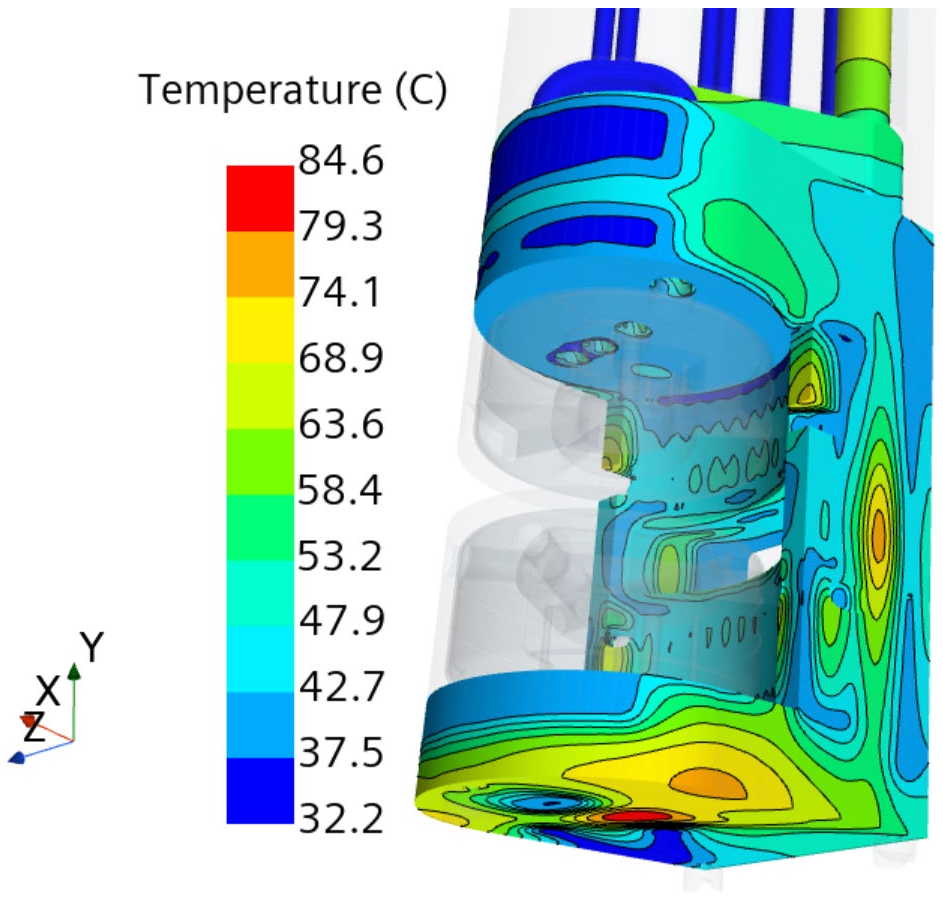


Steady State Heat Transfer Analysis for MRA(without H_2 Loop), SS316 Temperature

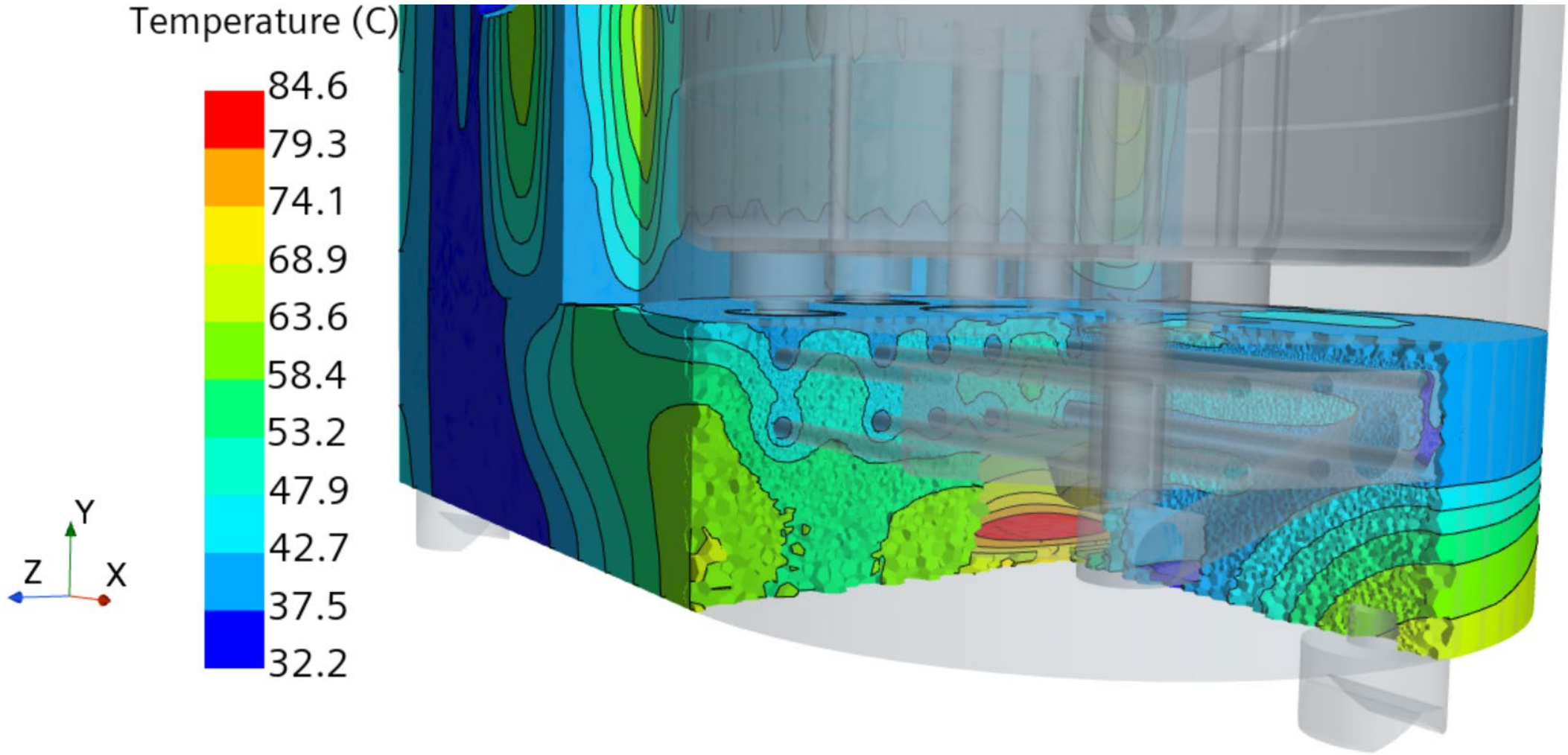
Requirement: < 200°C



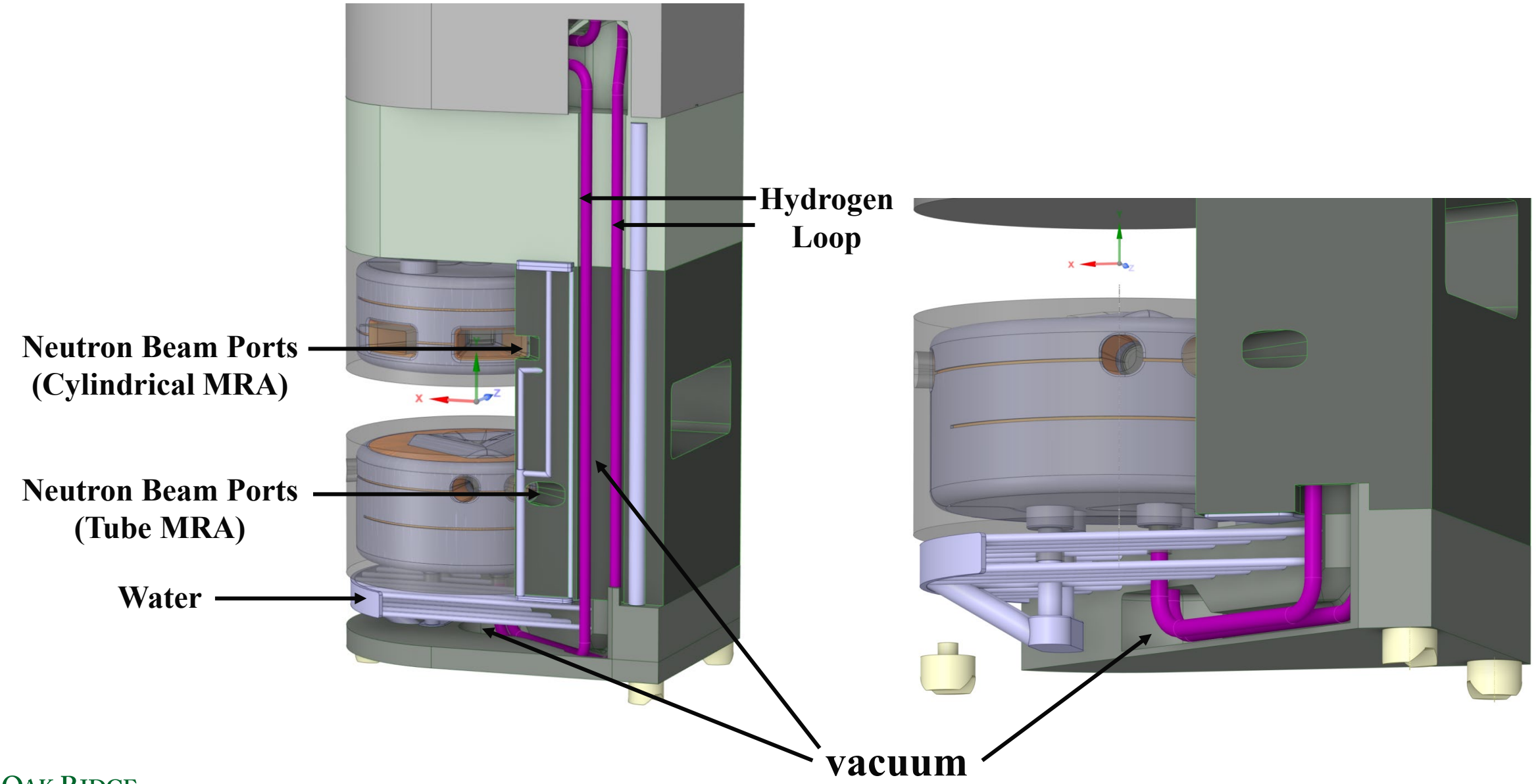




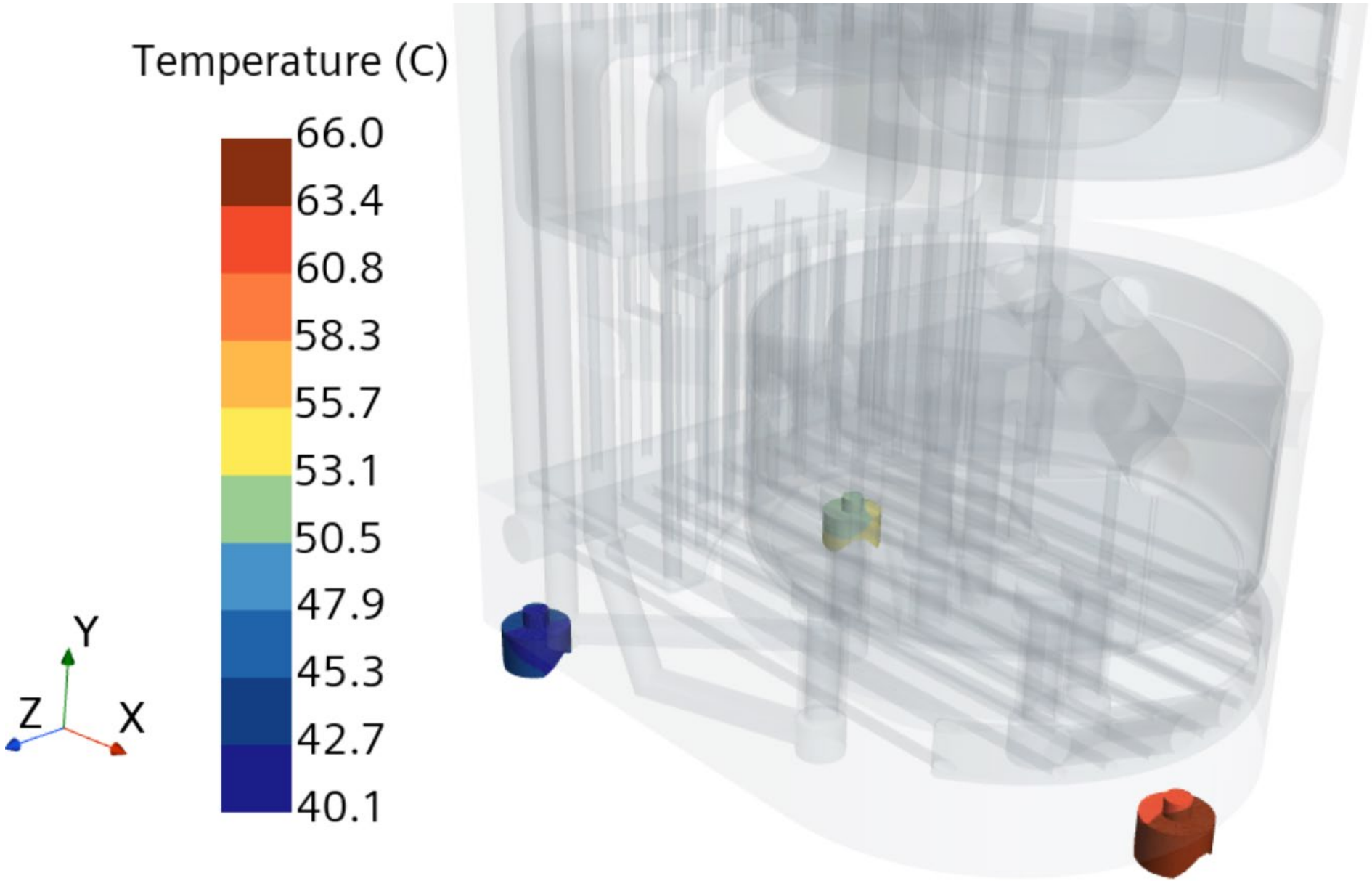
Steady State Heat Transfer Analysis for MRA(without H_2 Loop), SS316 Temperature



Steady State Heat Transfer Analysis for MRA(without H_2 Loop), SS316 Temperature

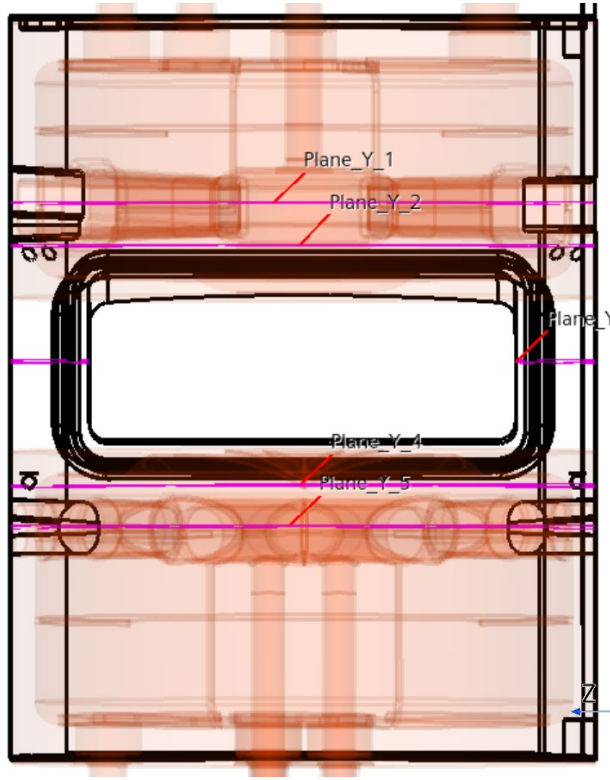


Steady State Heat Transfer Analysis for MRA(without H_2 Loop), SS420 Temperature

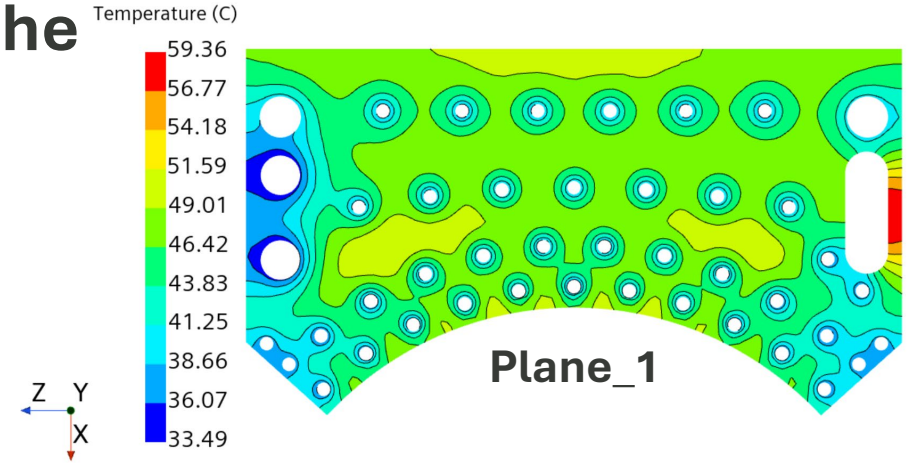


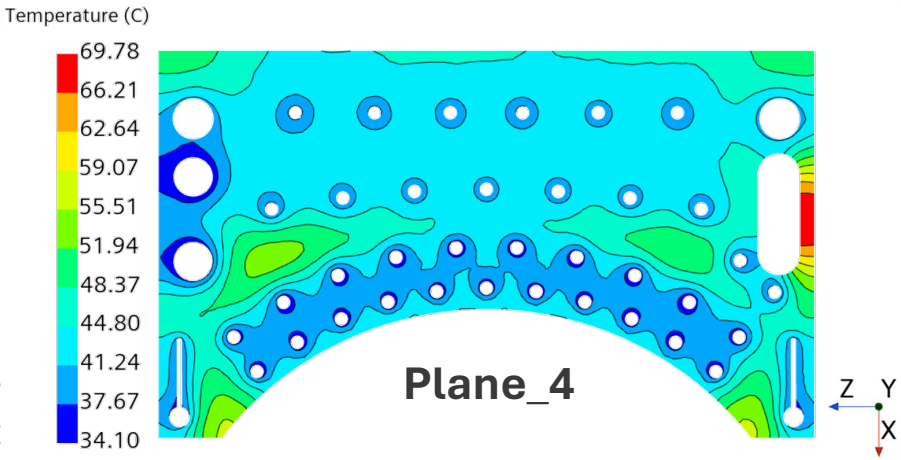
Temperature distribution in MRA backbone around the neutron beam ports

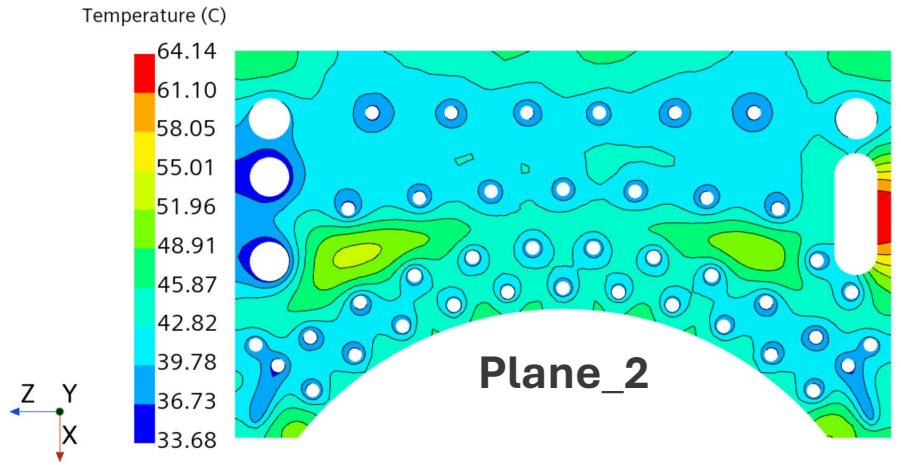
Plane_1
Plane_2
Plane_3
Plane_4
Plane_5

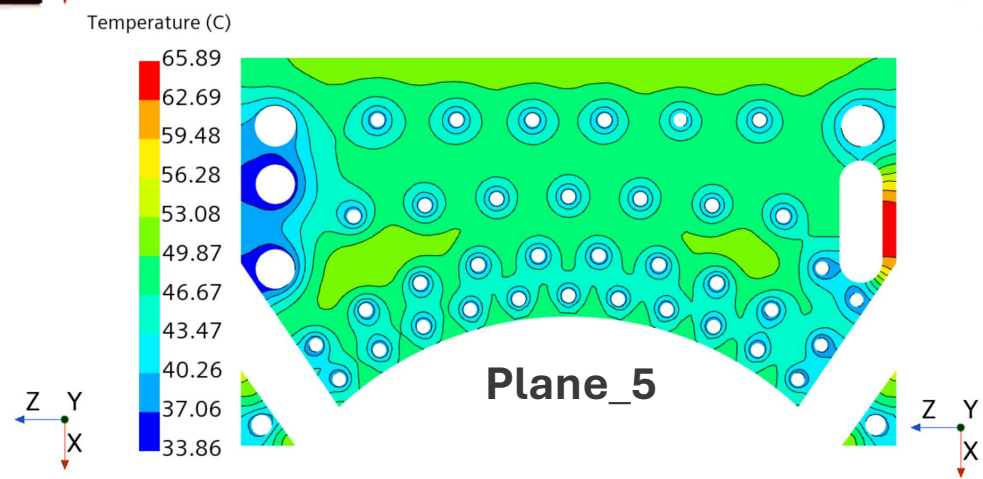


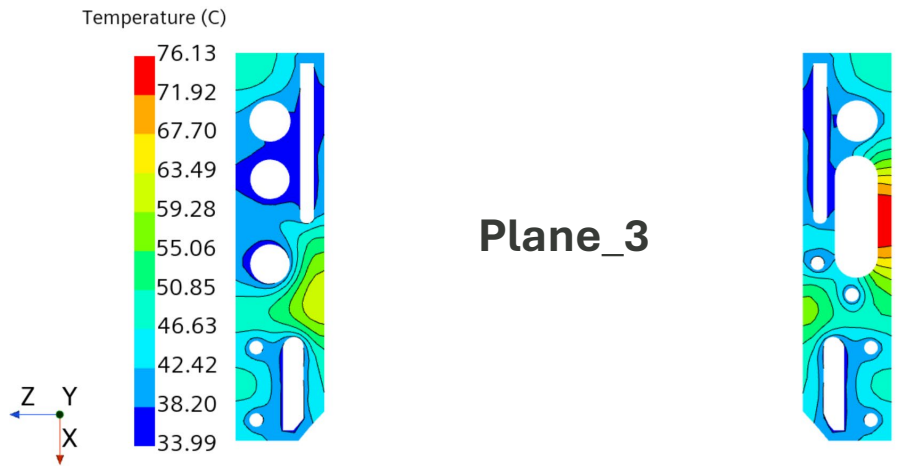
Plane_1 : y = 0.10886m
Plane_2 : y = 0.08110m
Plane_3 : y = 0.00557m
Plane_4 : y = -0.07534m
Plane_5 : y = -0.10205m





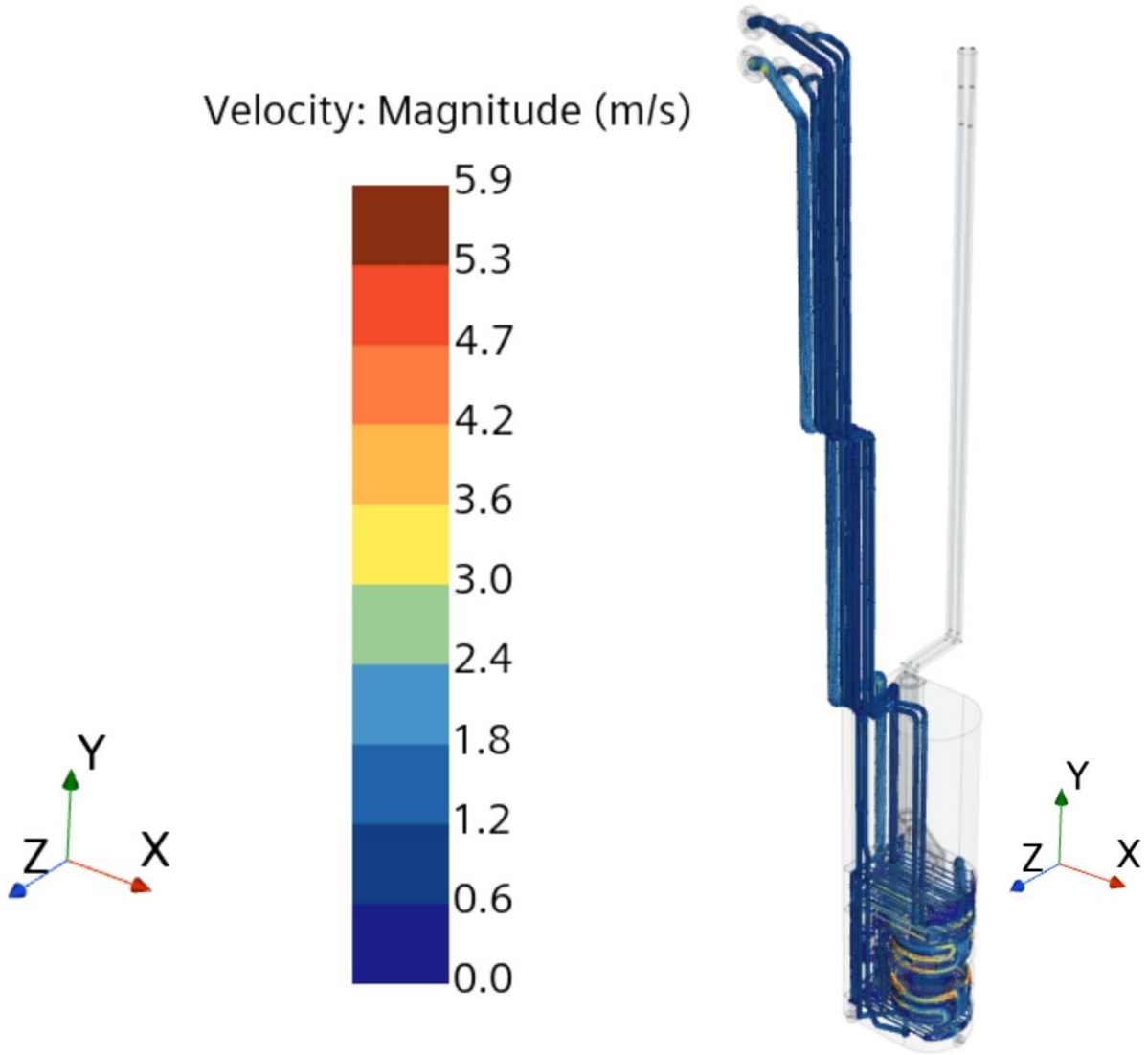


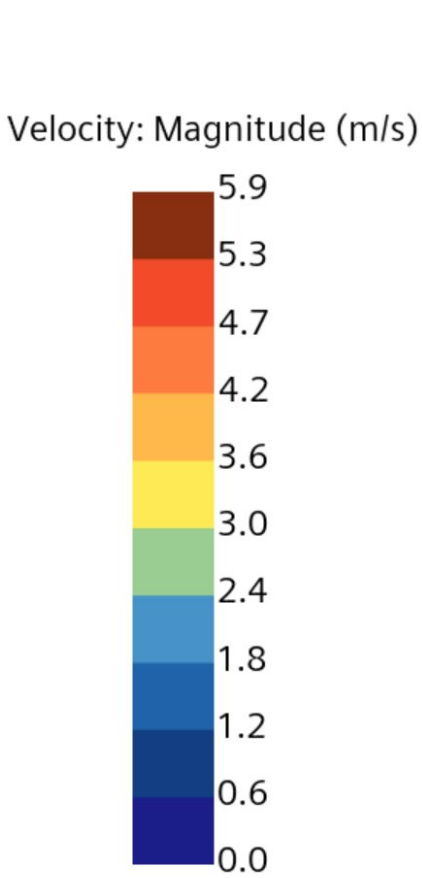


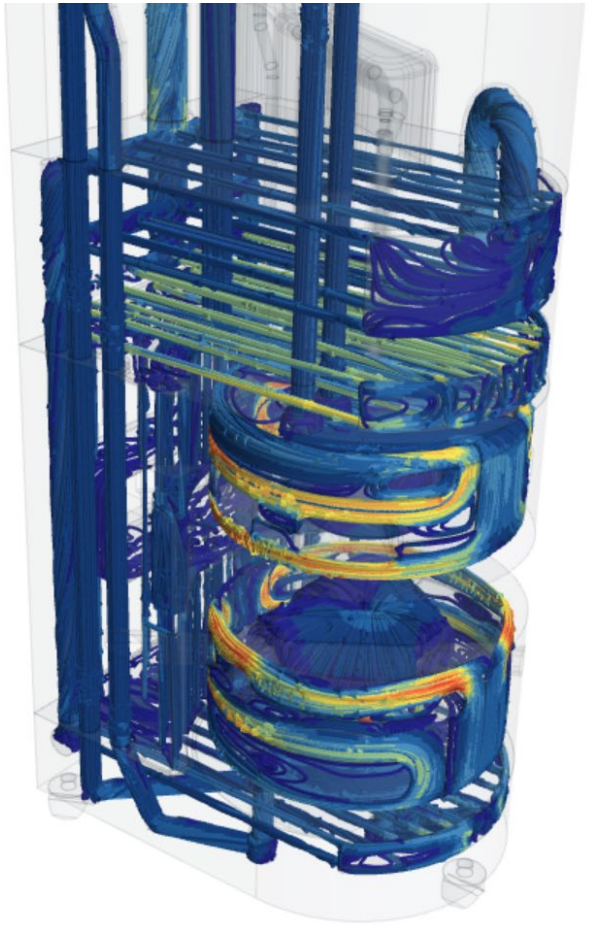


OAK RIDGE National Laboratory

Steady State Heat Transfer Analysis for MRA(without H_2 Loop), Water Streamlines

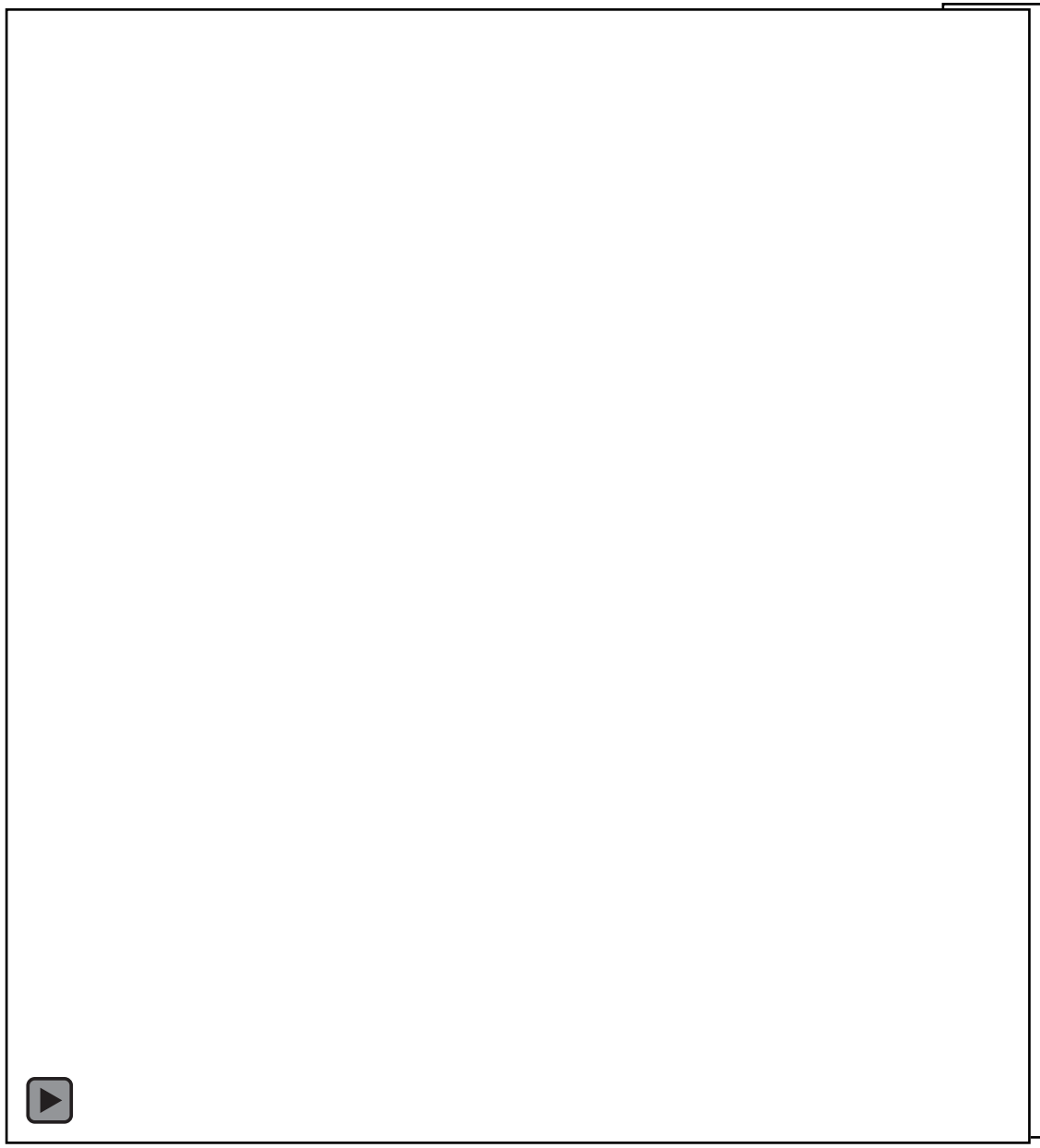






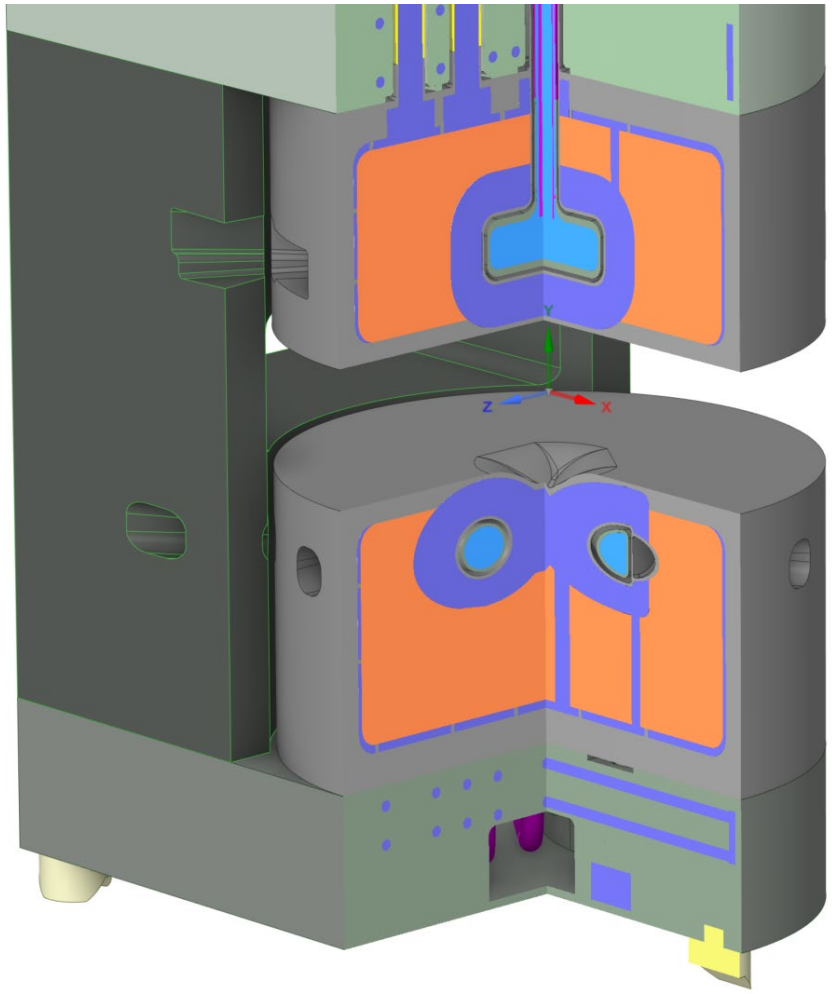
Steady State Heat Transfer Analysis for MRA(without H_2 Loop), Water Streamlines

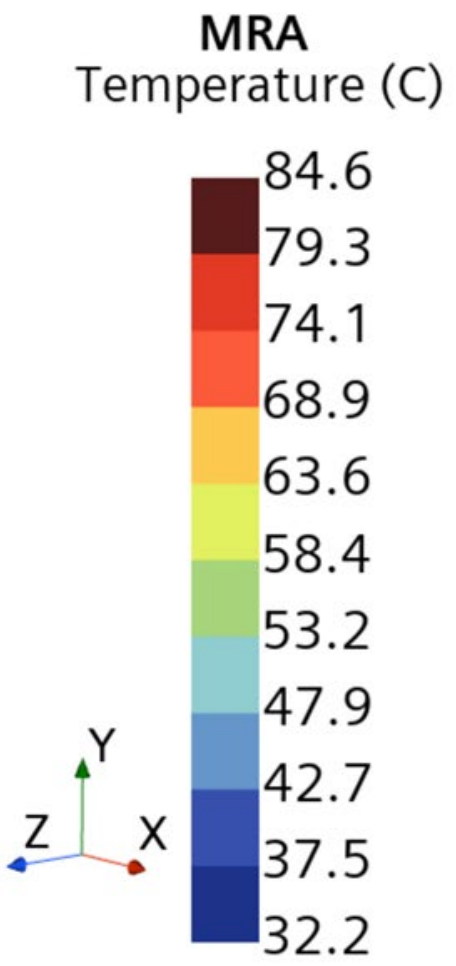
Streamline Animation

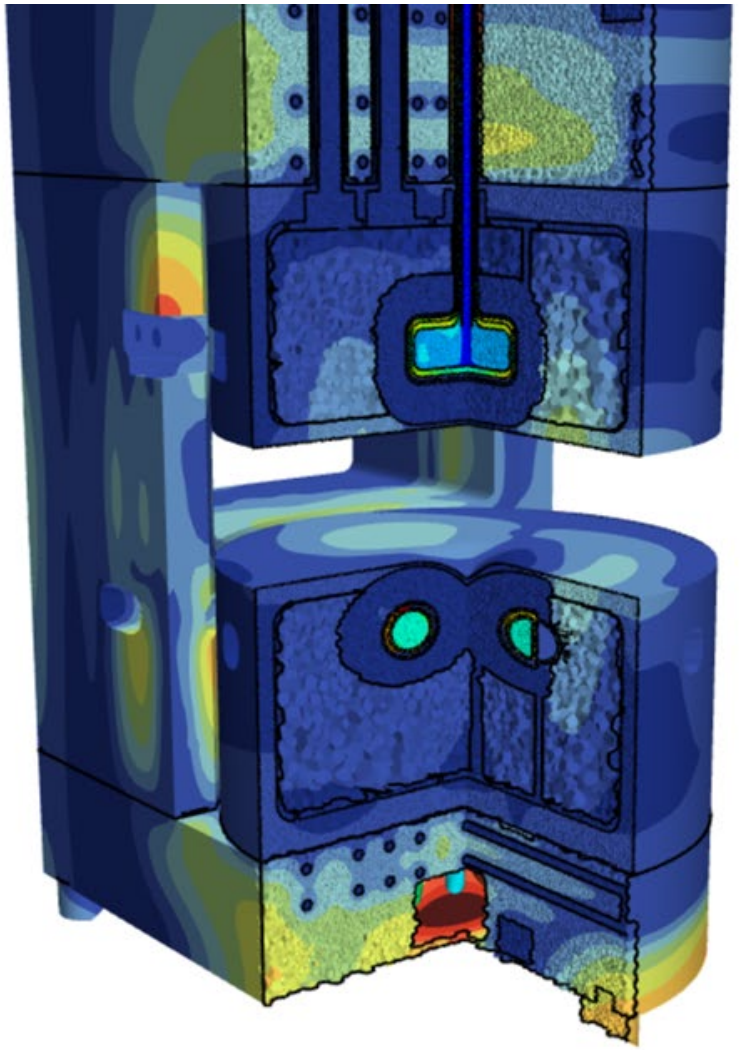


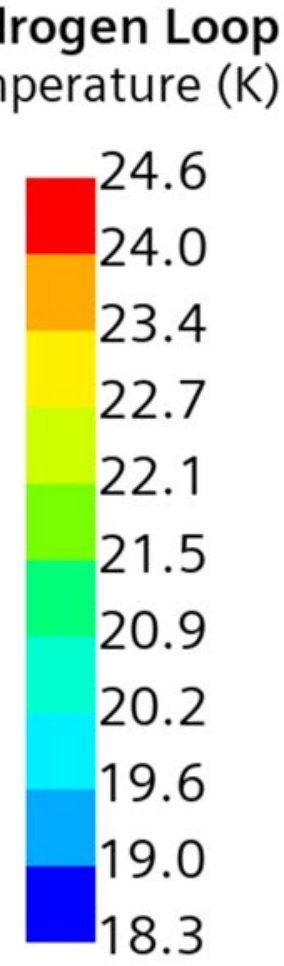


Temperature Distribution in MRA



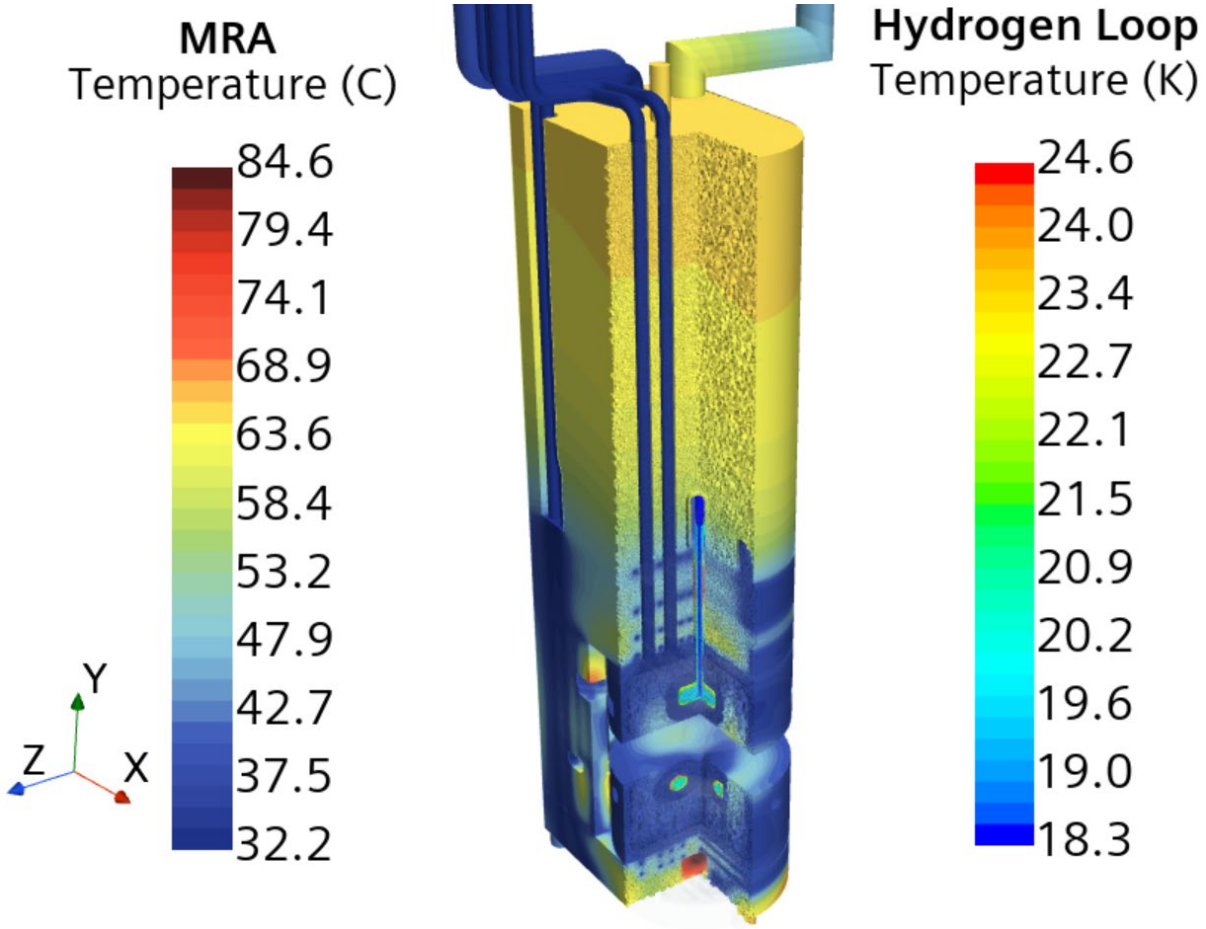




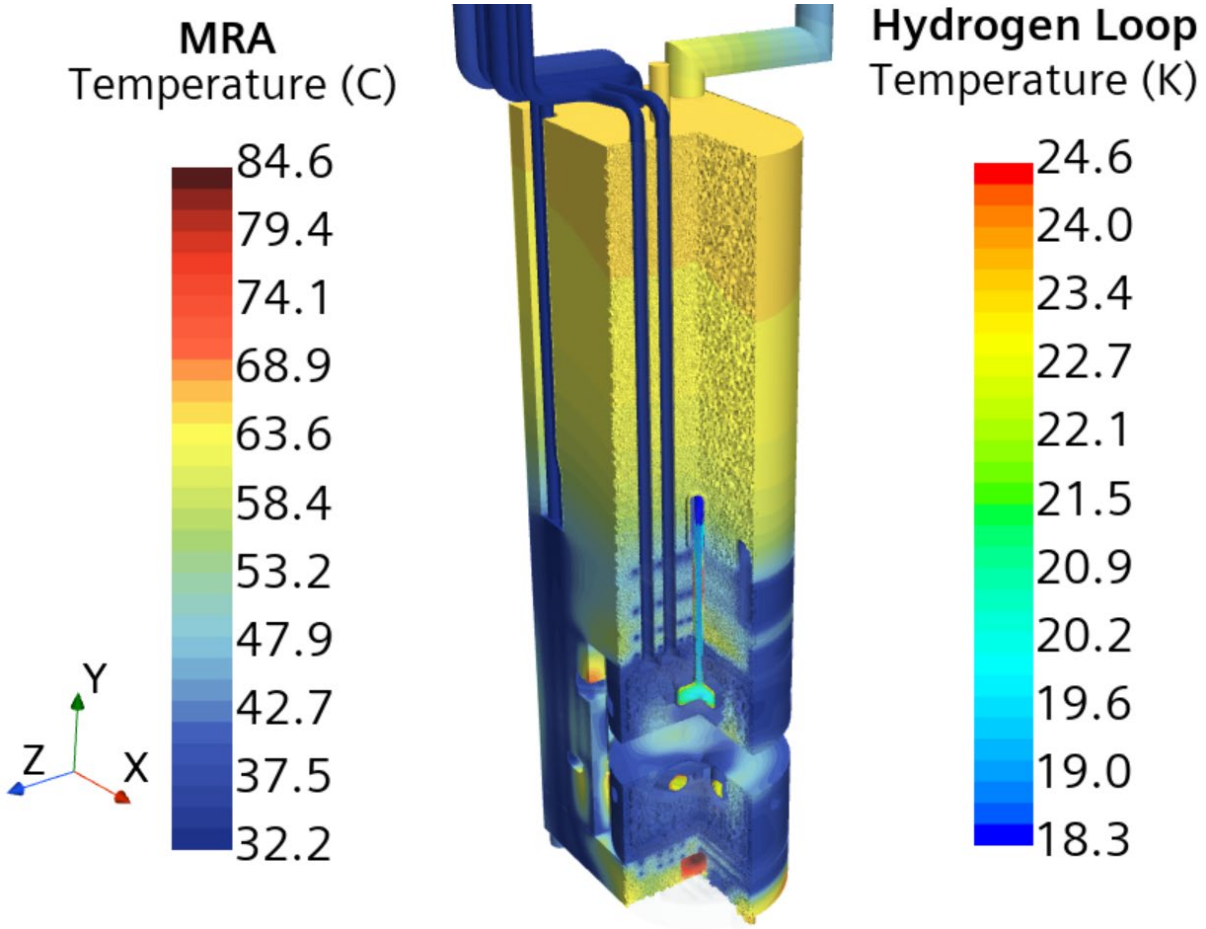


Temperature Distribution in MRA

With Fluids (H_2O and H_2)

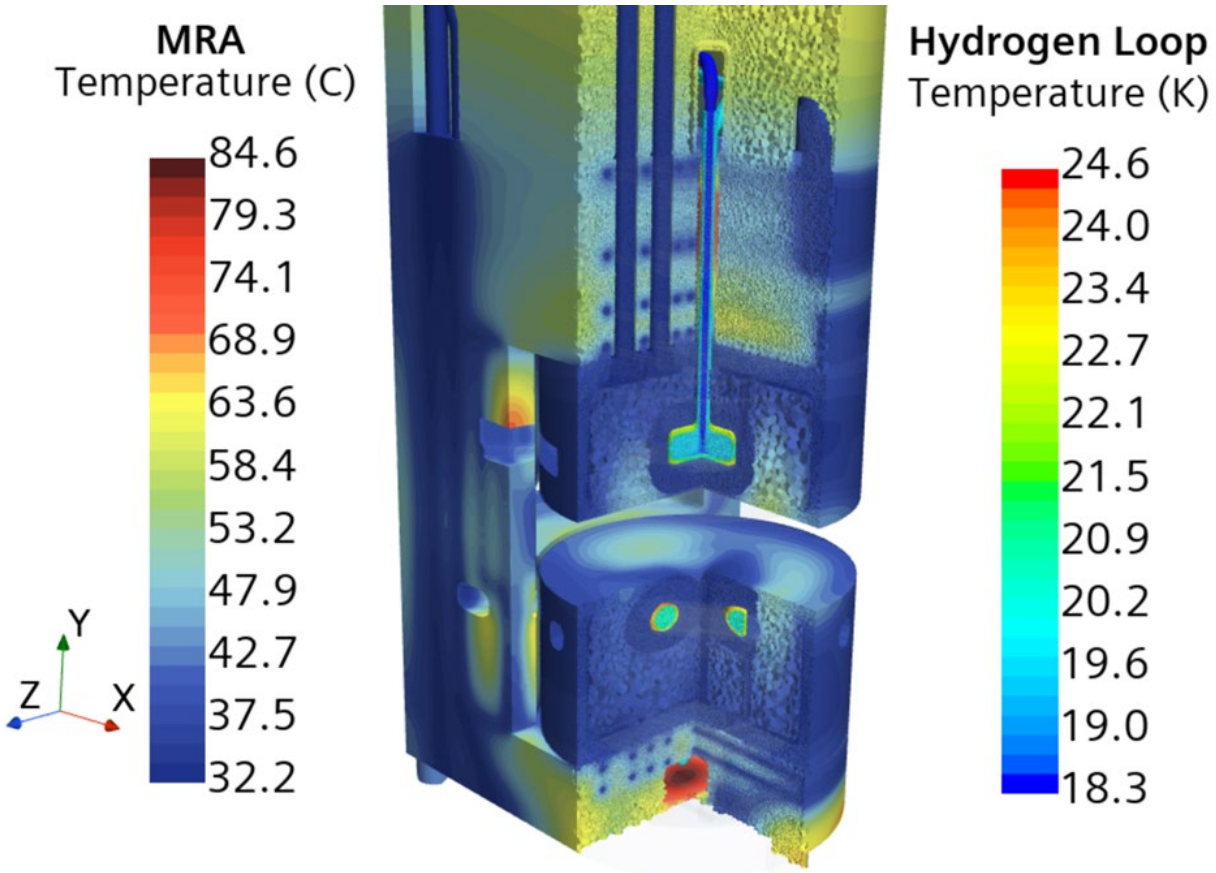


Without Fluids (H_2O and H_2)

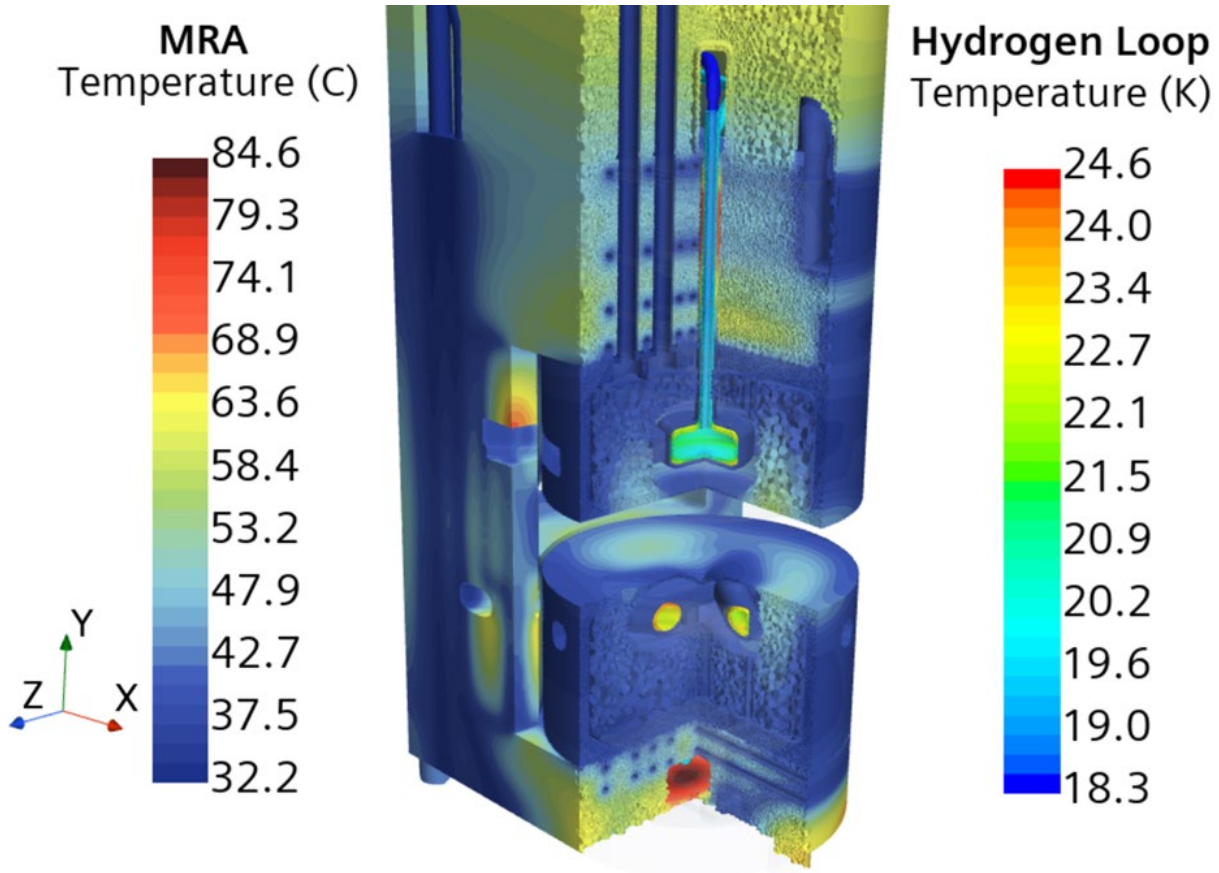


Temperature Distribution in MRA

With Fluids (H_2O and H_2)

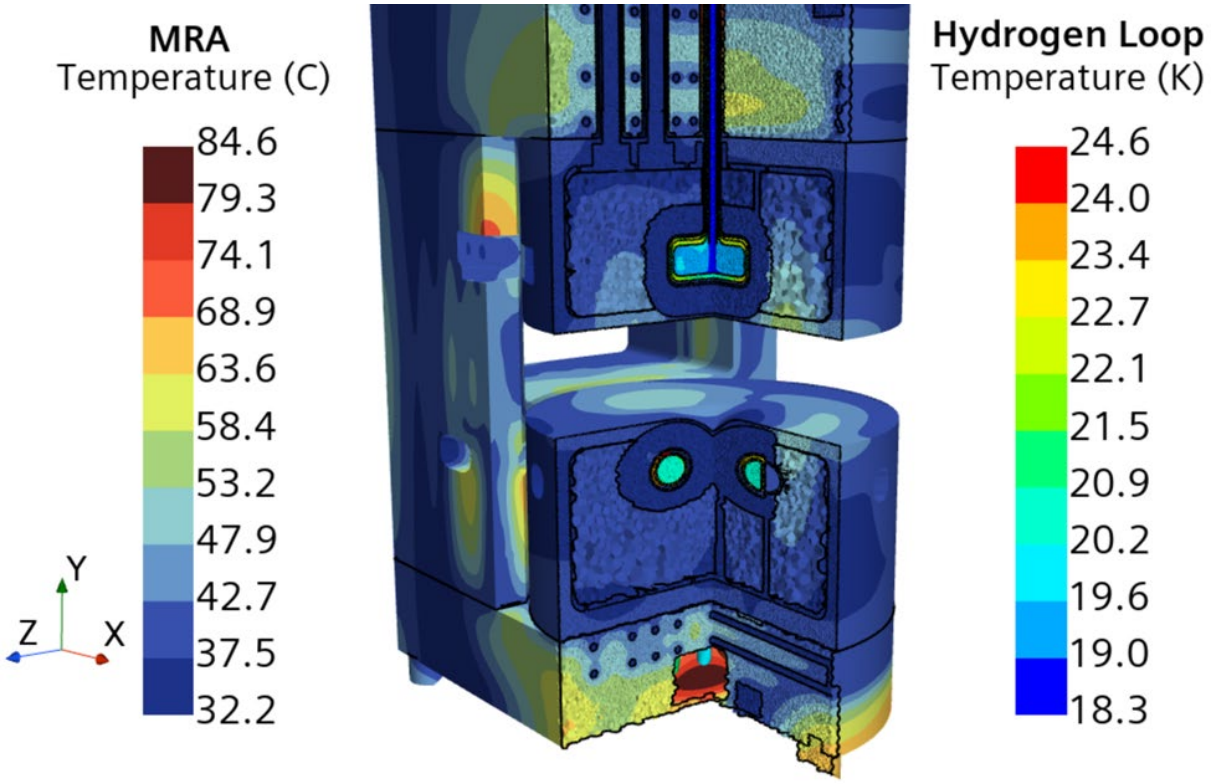


Without Fluids (H_2O and H_2)

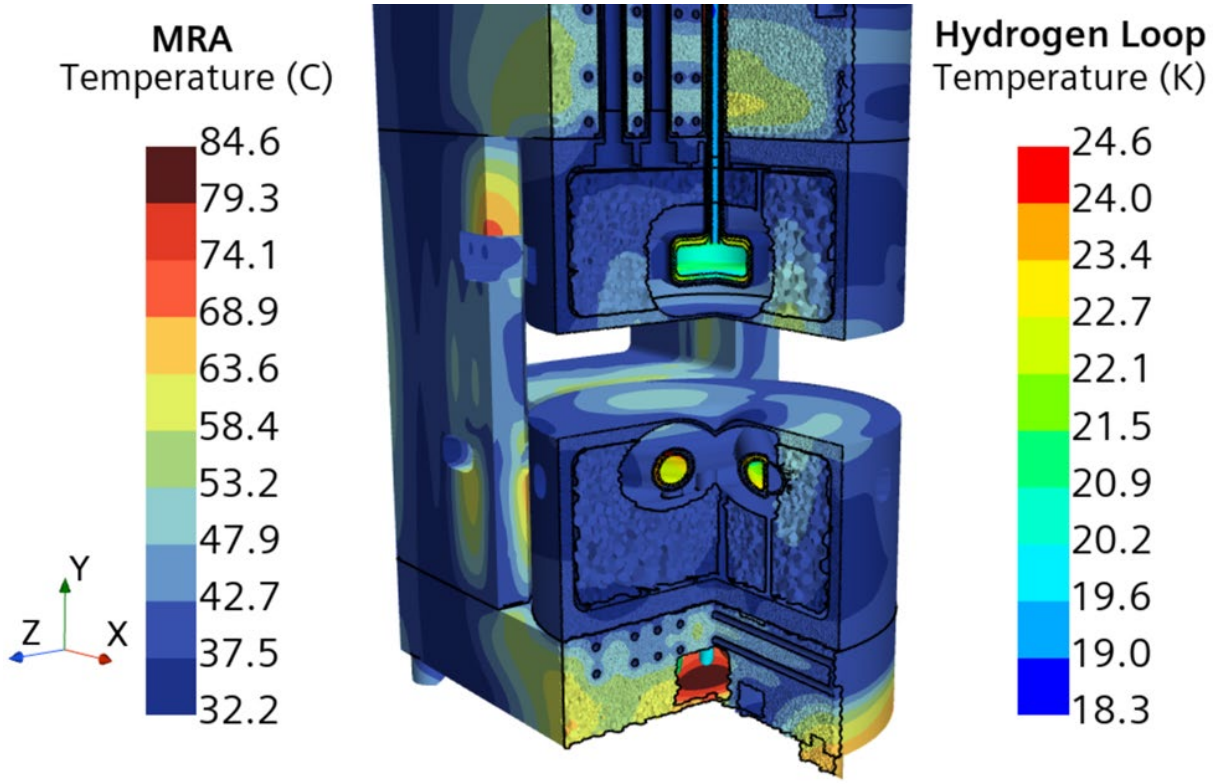


Temperature Distribution in MRA

With Fluids (H_2O and H_2)

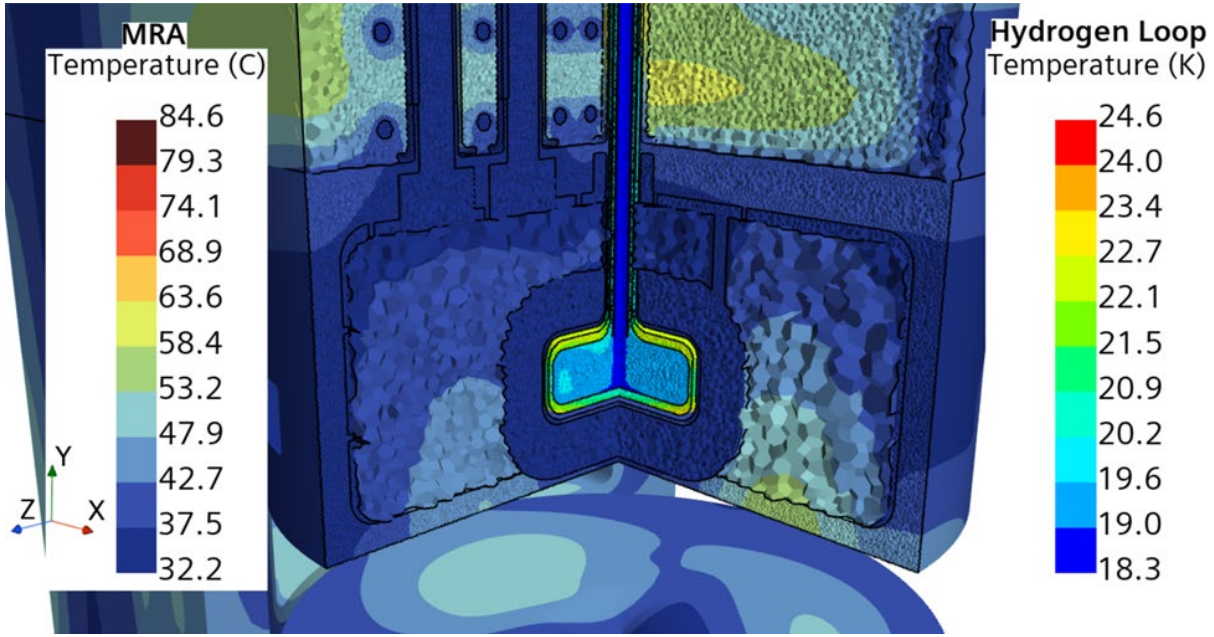


Without Fluids (H_2O and H_2)

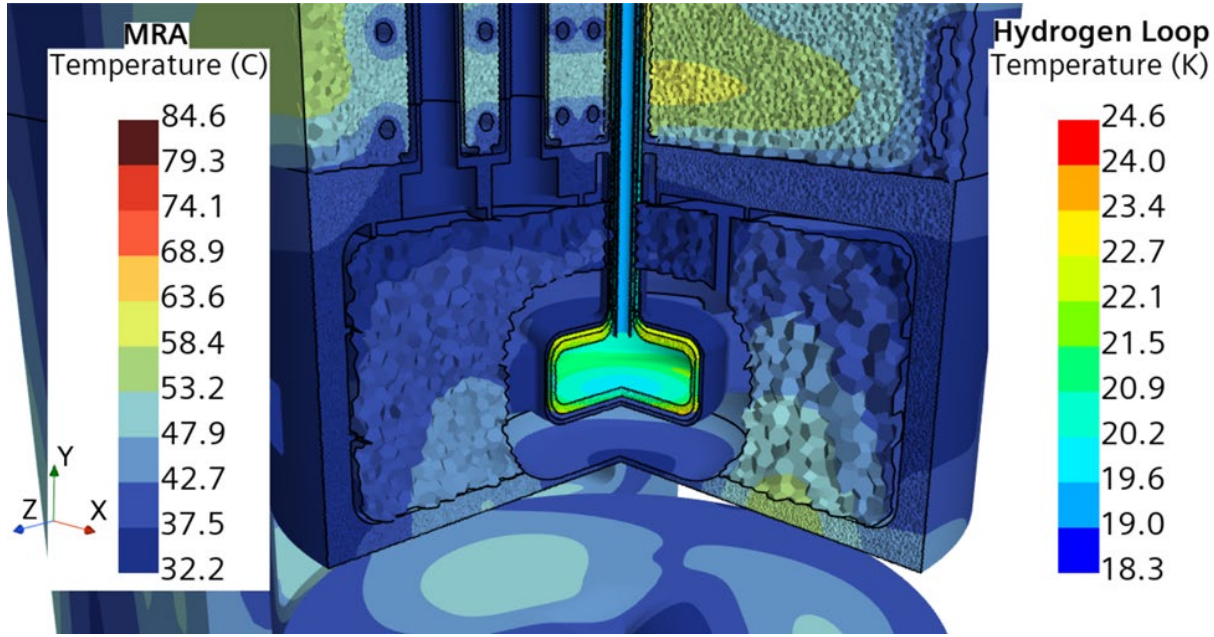


Temperature Distribution in Upper MRA

With Fluids (H_2O and H_2)

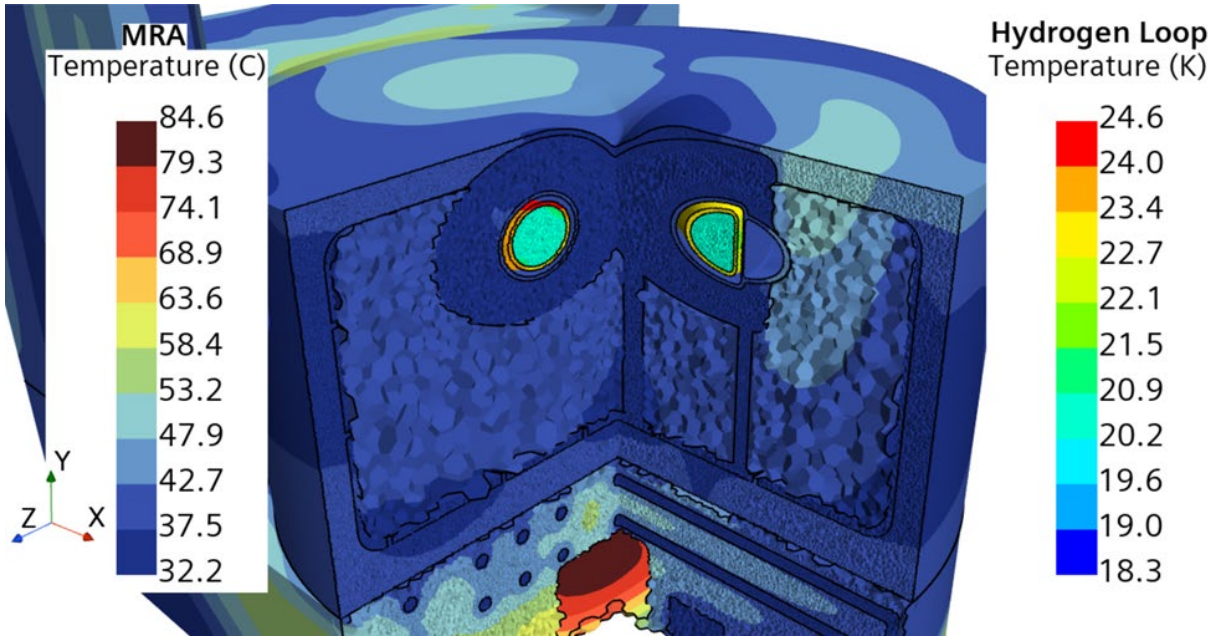


Without Fluids (H_2O and H_2)

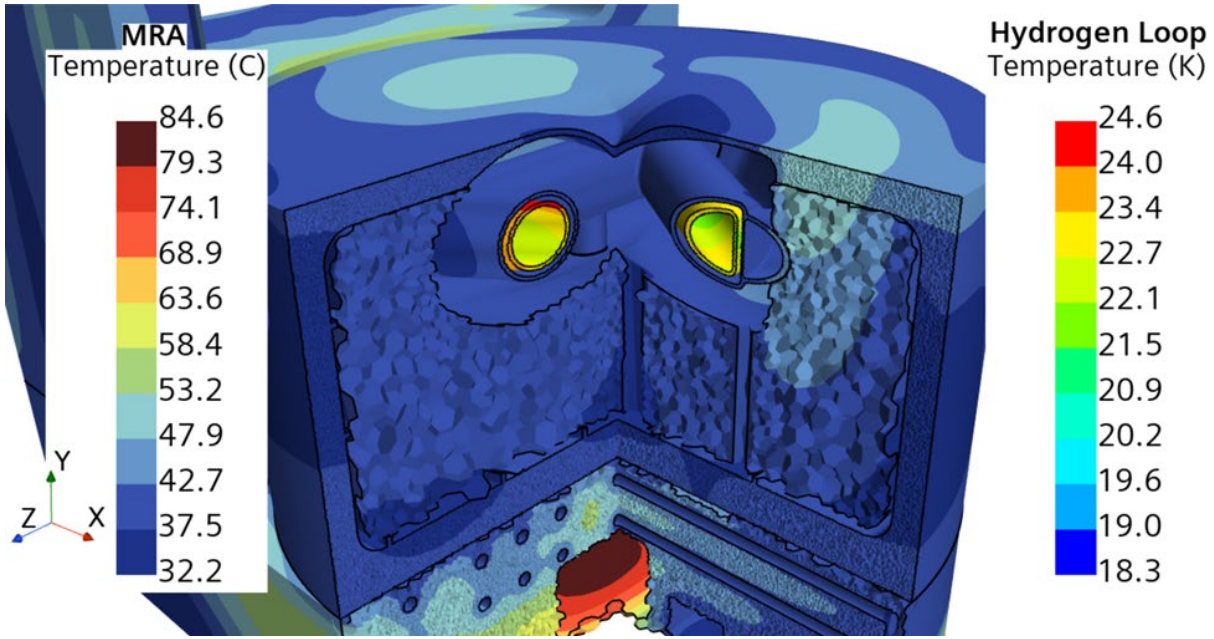


Temperature Distribution in Lower MRA

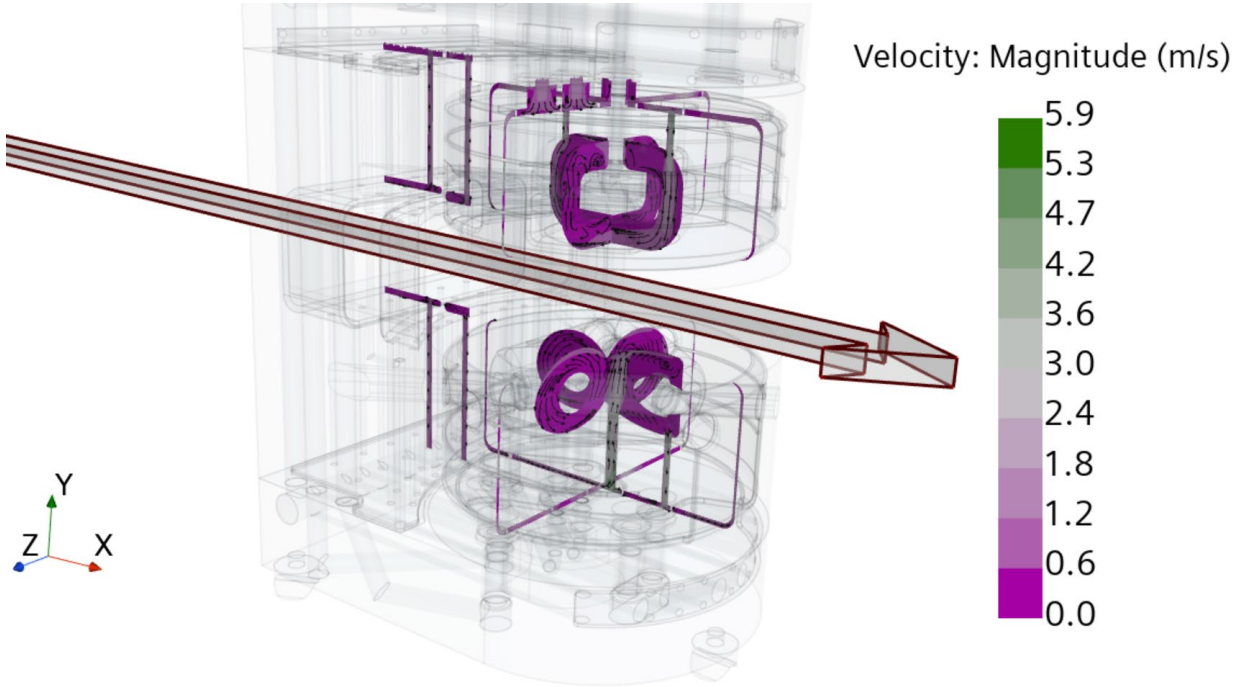
With Fluids (H_2O and H_2)

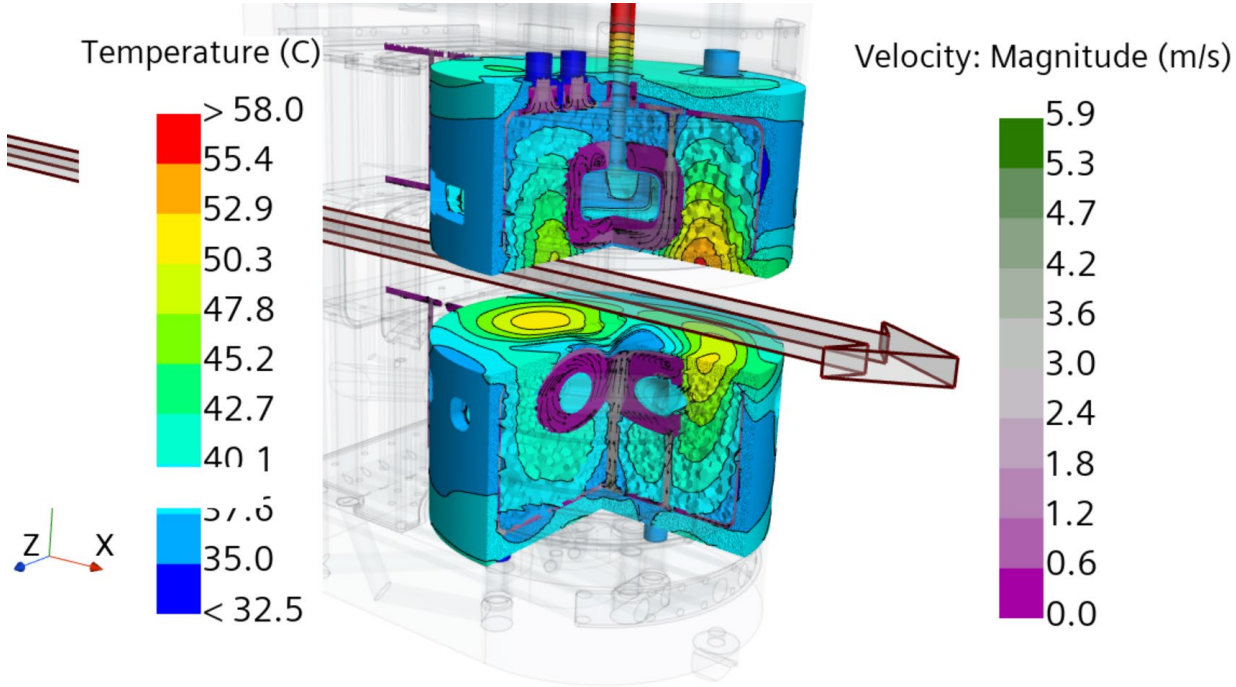


Without Fluids (H_2O and H_2)

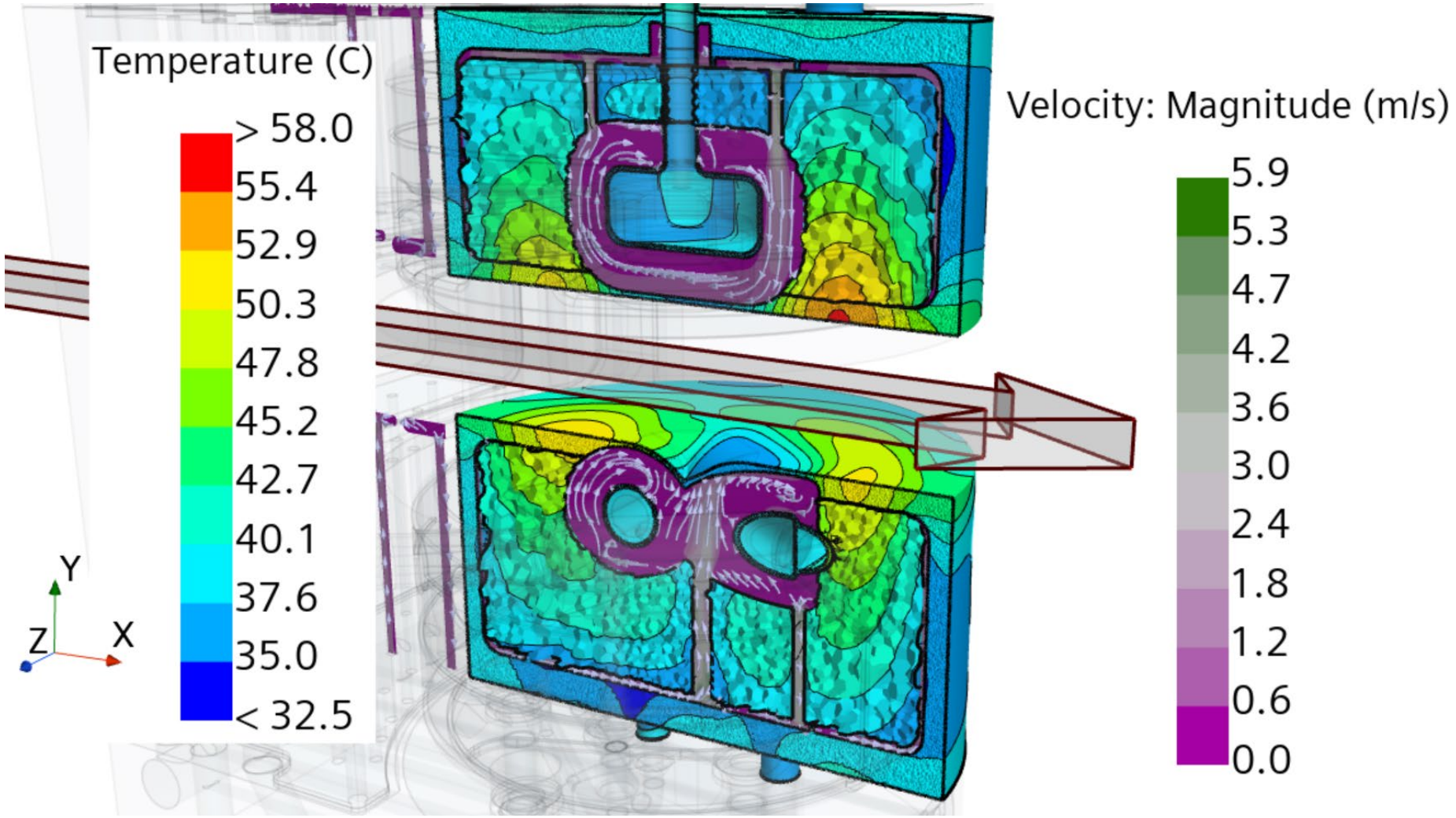


Temperature and Velocity Distributions in Reflector Vessel Assembly

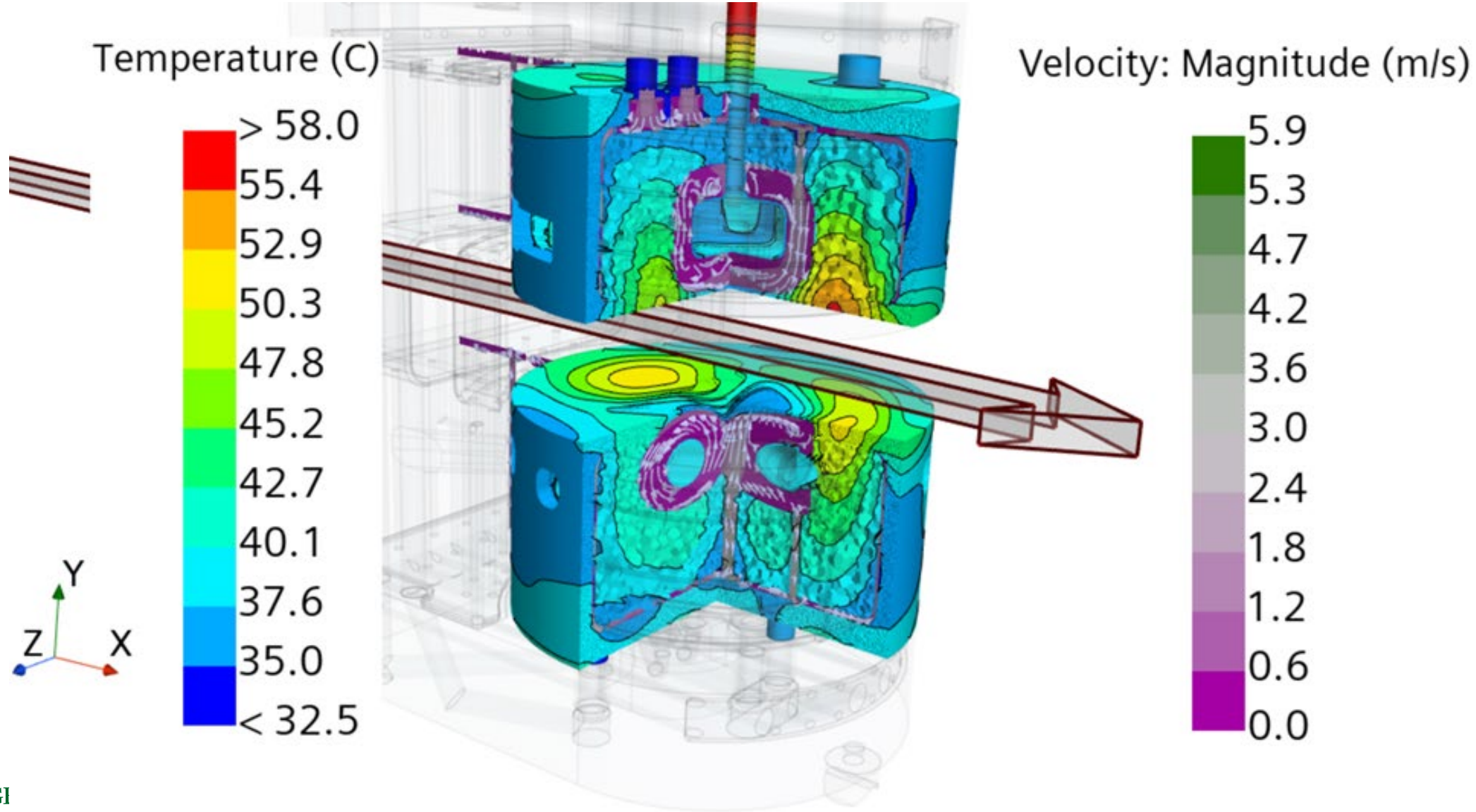




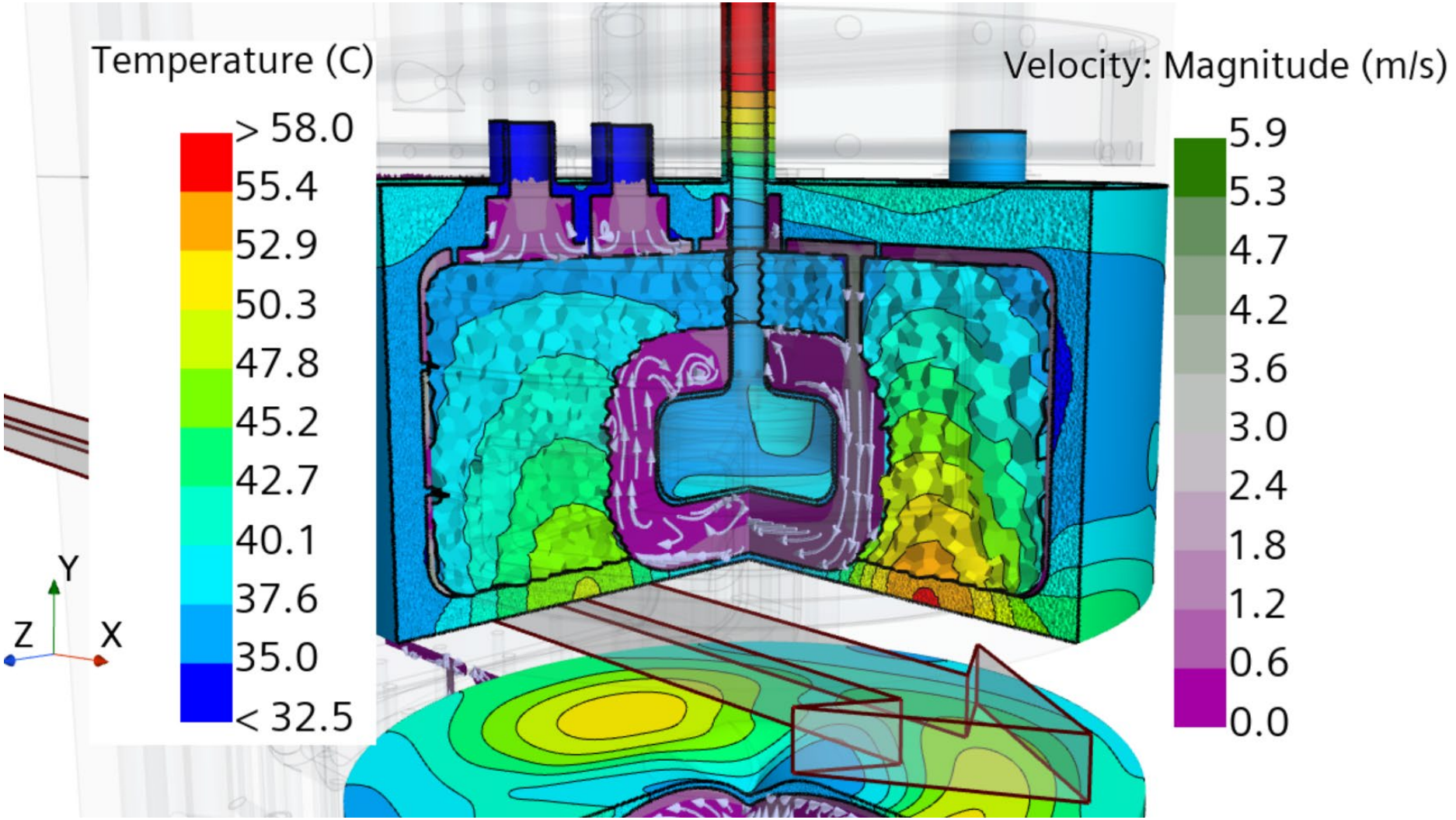
Temperature and Velocity Distributions in Reflector Vessel Assembly



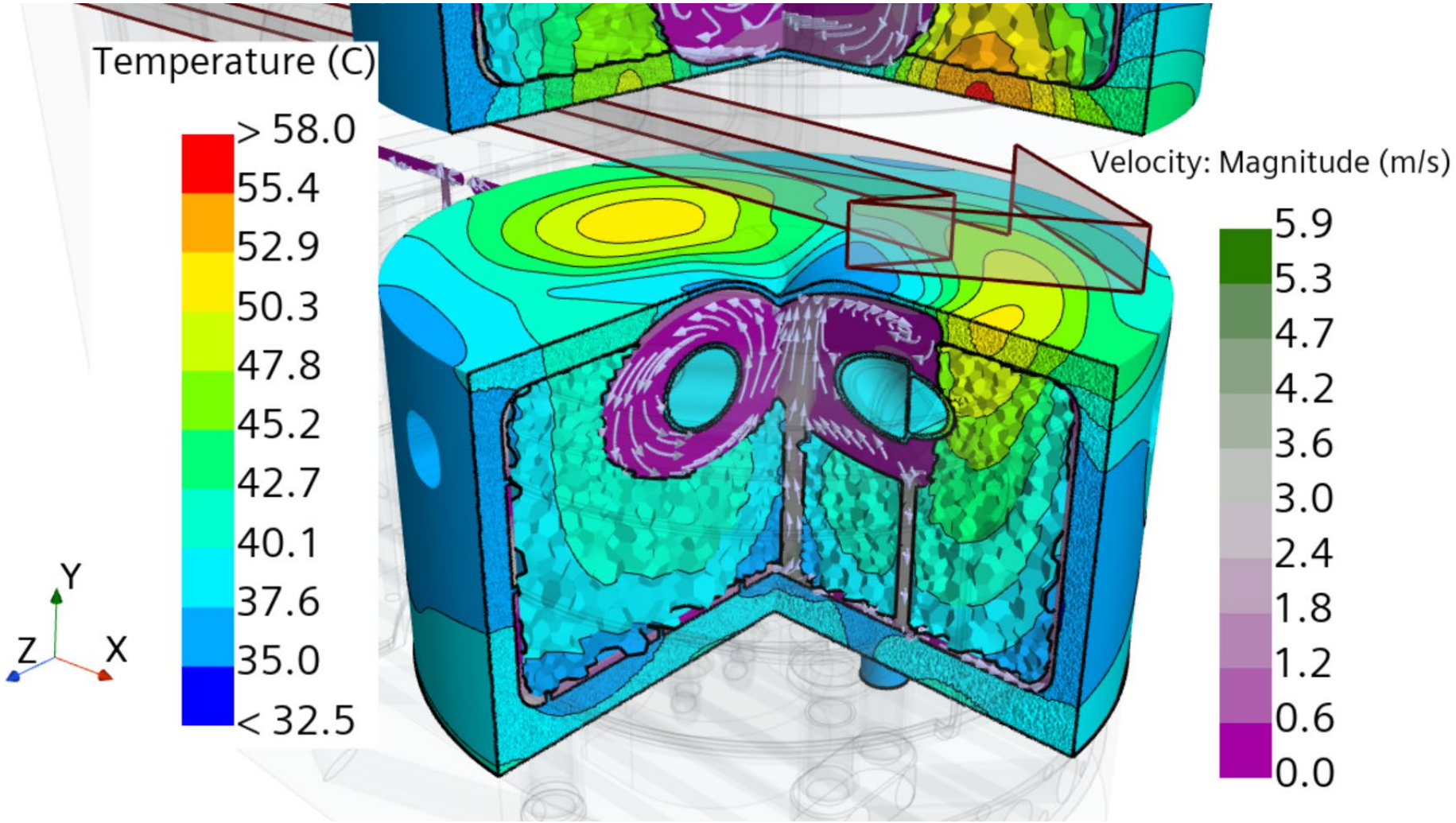
Temperature and Velocity Distributions in Reflector Vessel Assembly



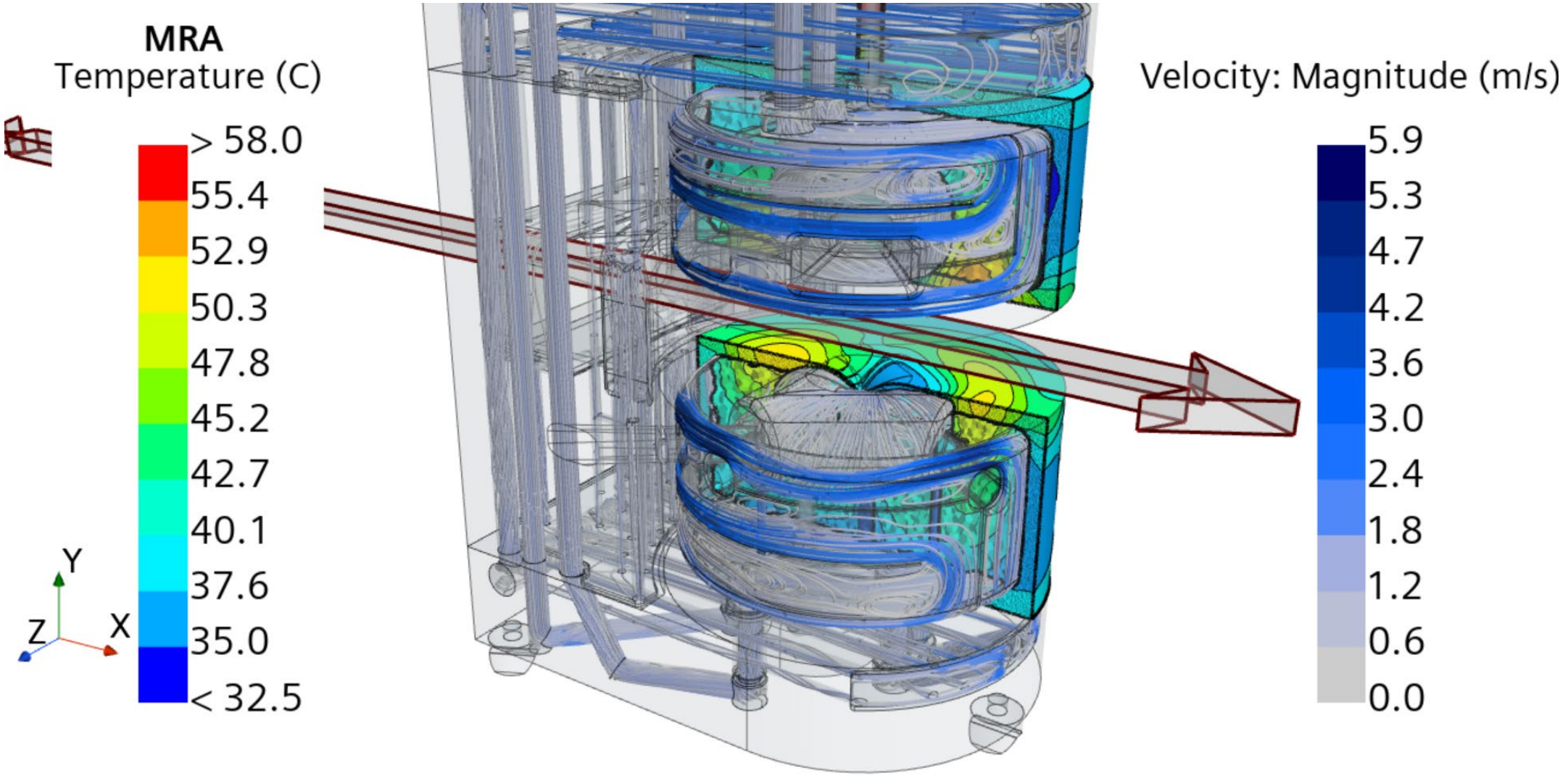
Temperature and Velocity Distributions in Upper Reflector Vessel Assembly



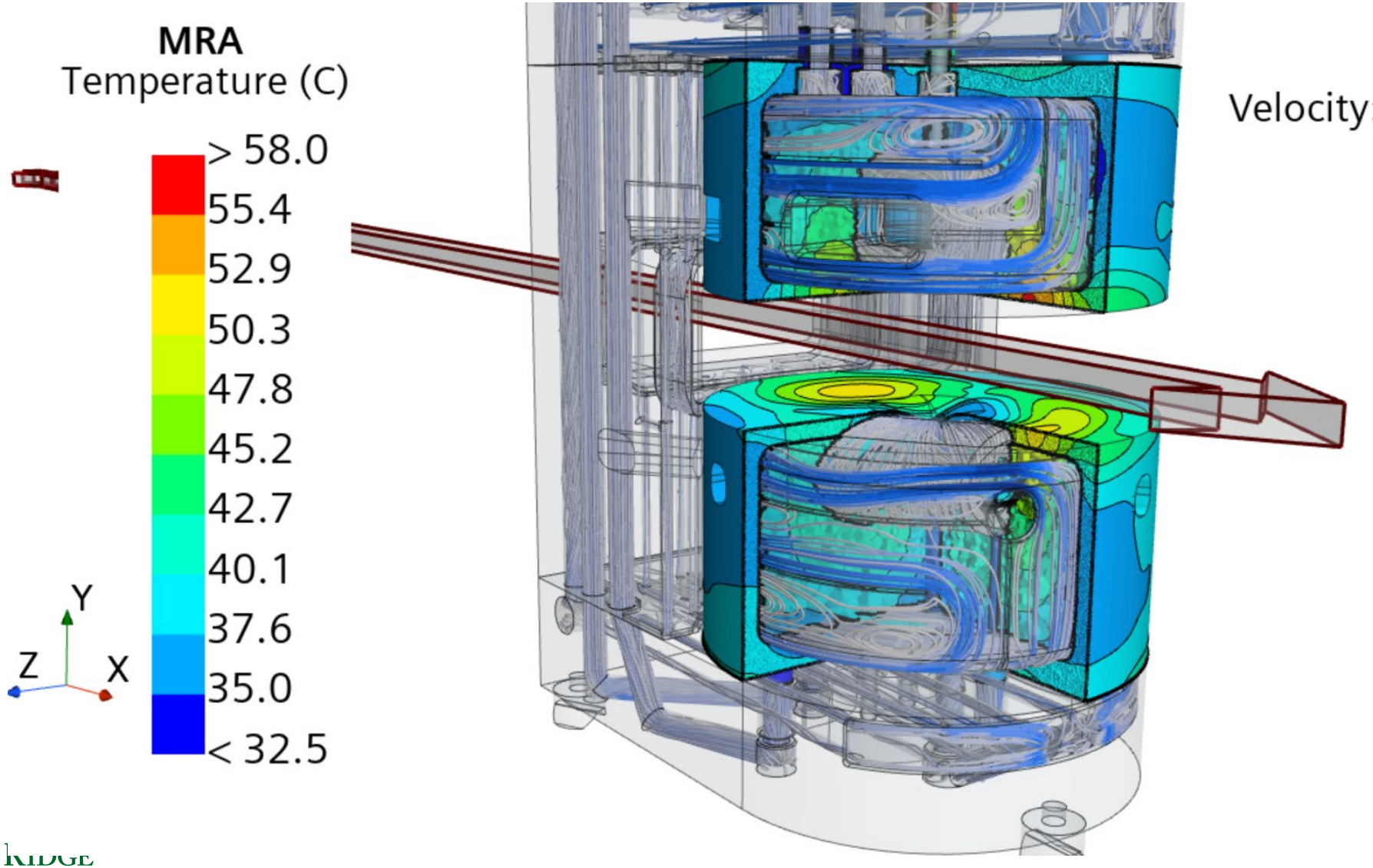
Temperature and Velocity Distributions in Lower Reflector Vessel Assembly



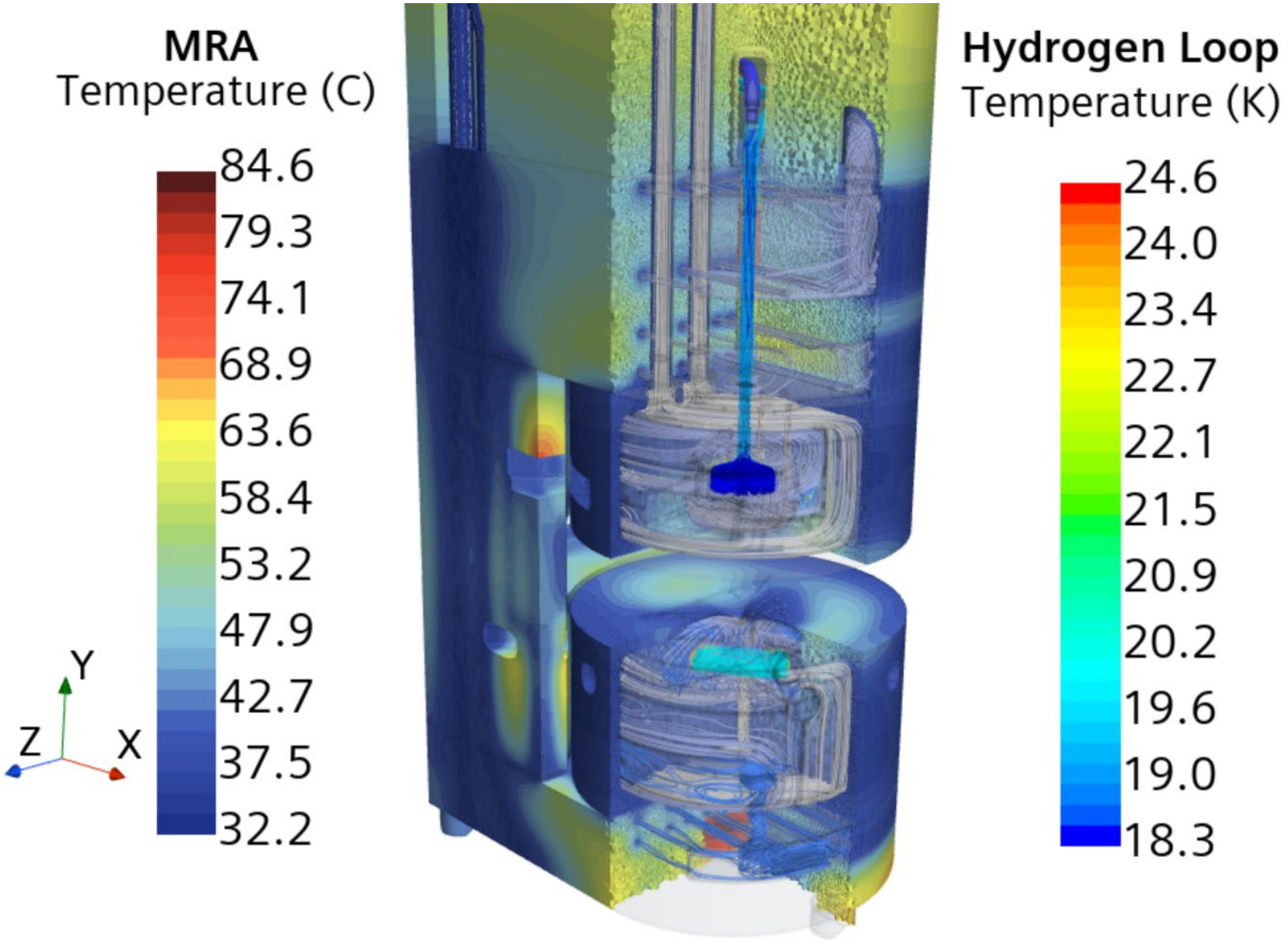
Temperature Distribution and Streamlines in Reflector Vessel Assembly



Temperature Distribution and Streamlines in Reflector Vessel Assembly



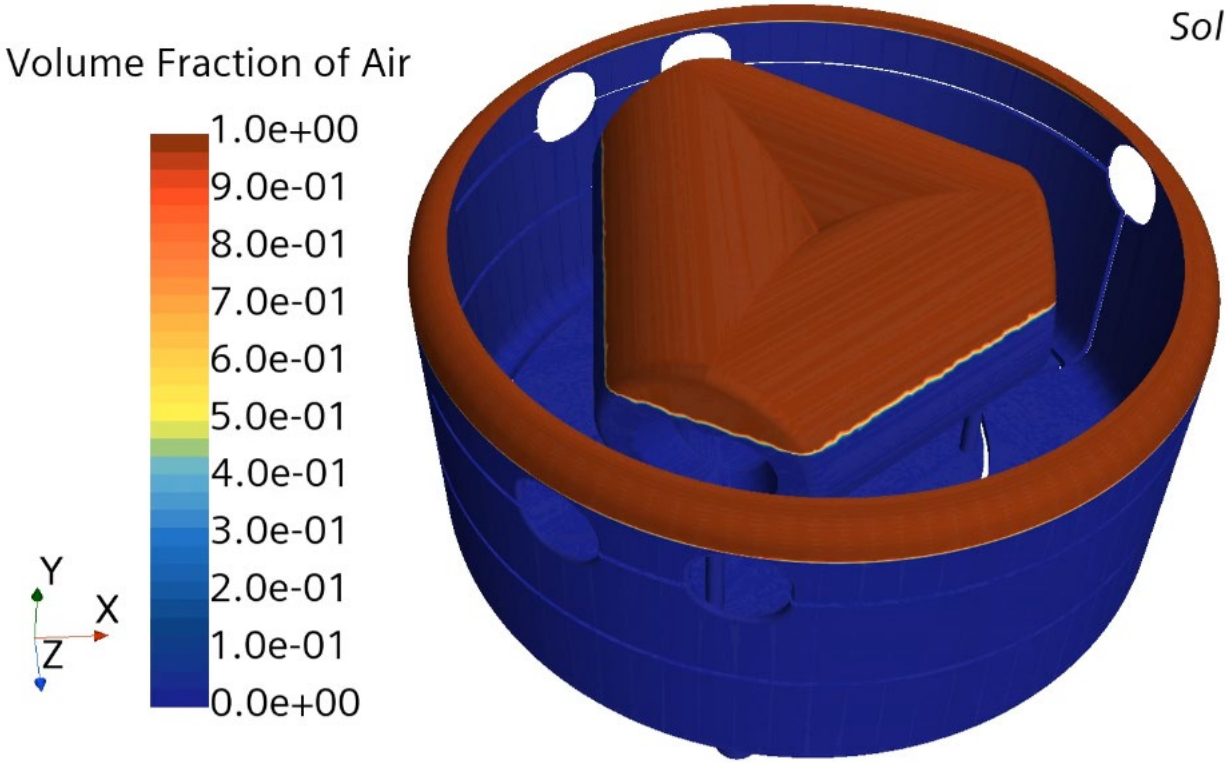
Temperature Distribution and Streamlines in MRA



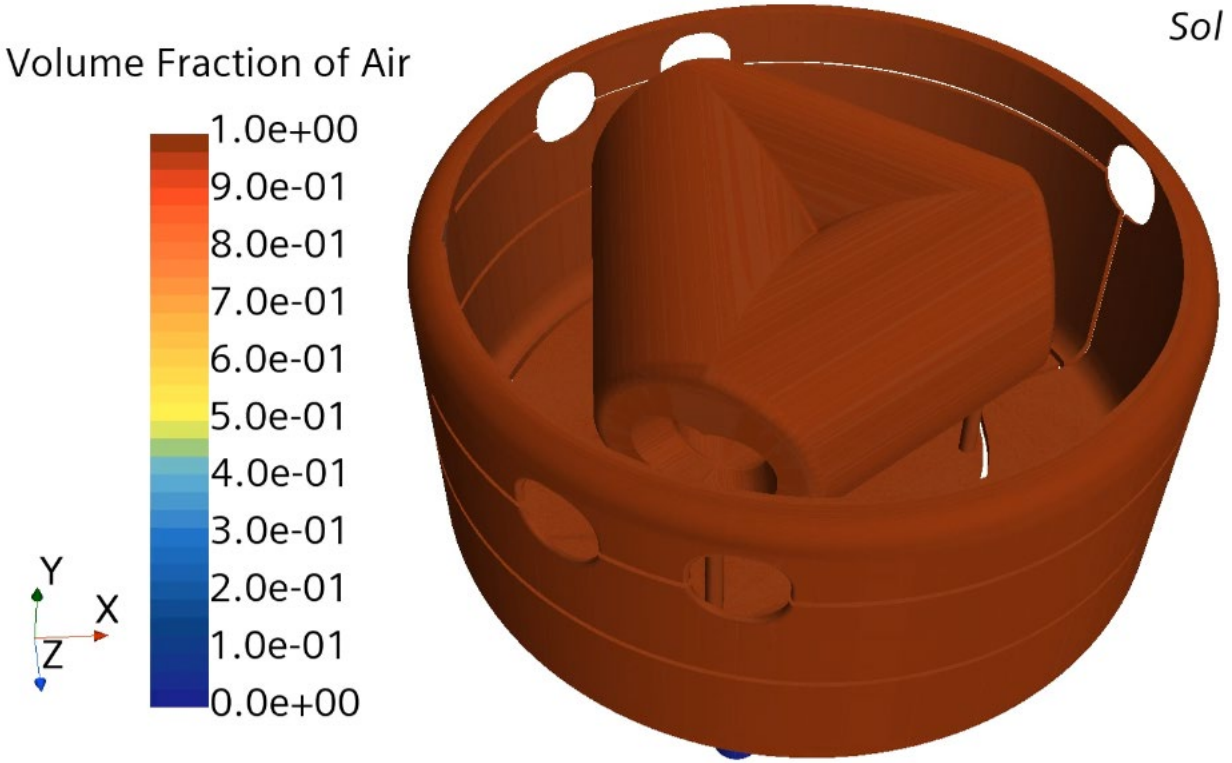
- **Air Accumulation** in **Lower Reflector Vessel**
  - **Transient Results without Heat Transfer**
  - Transient Results with Heat Transfer

MRA Air Accumulation in the Lower Reflector

CASE 1(IC_1): Initially 23.4% of volume is air.

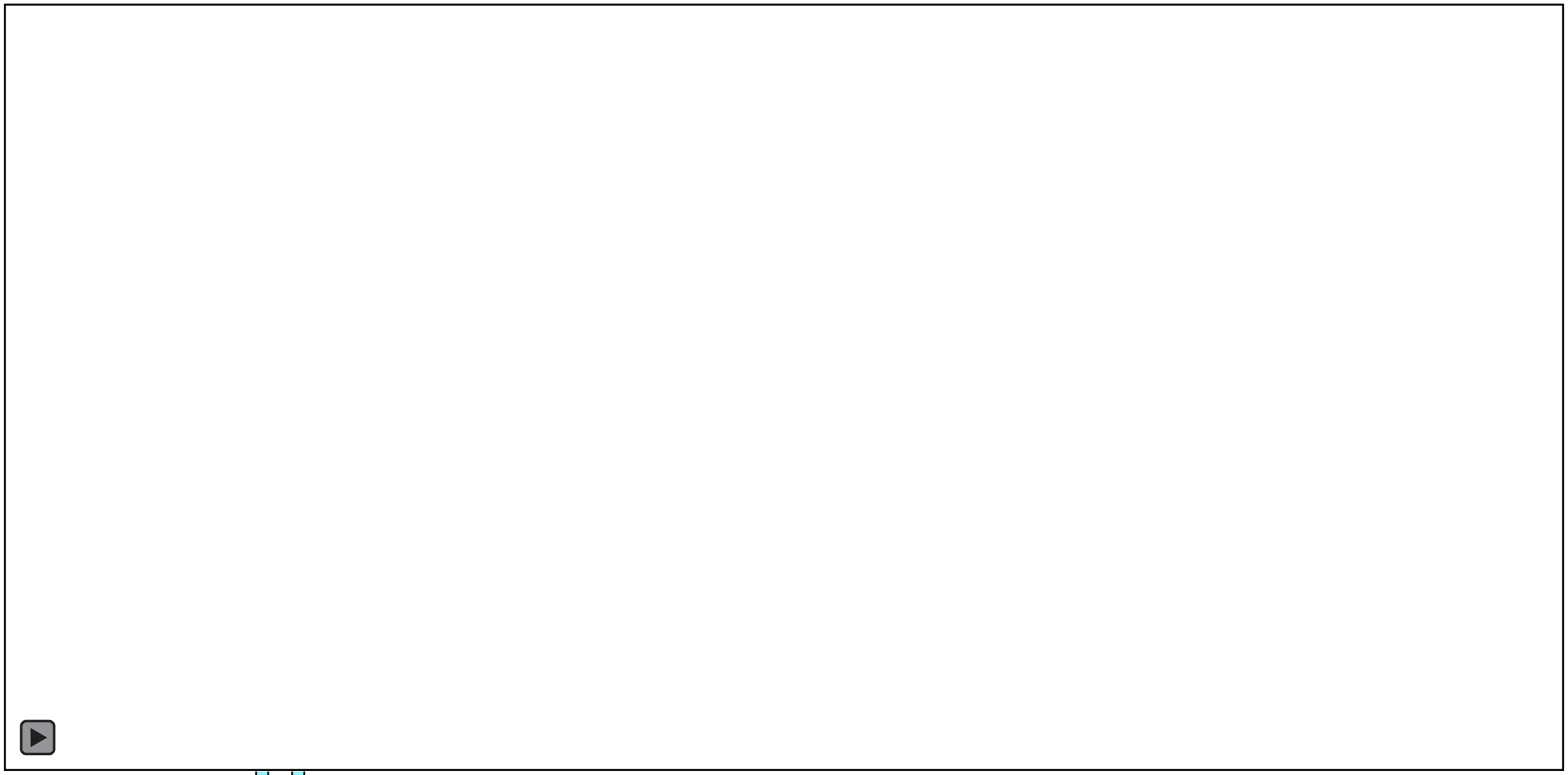


CASE 2(IC_2): Initially 98.7% of volume is air.



MRA Air Accumulation in the Lower Reflector

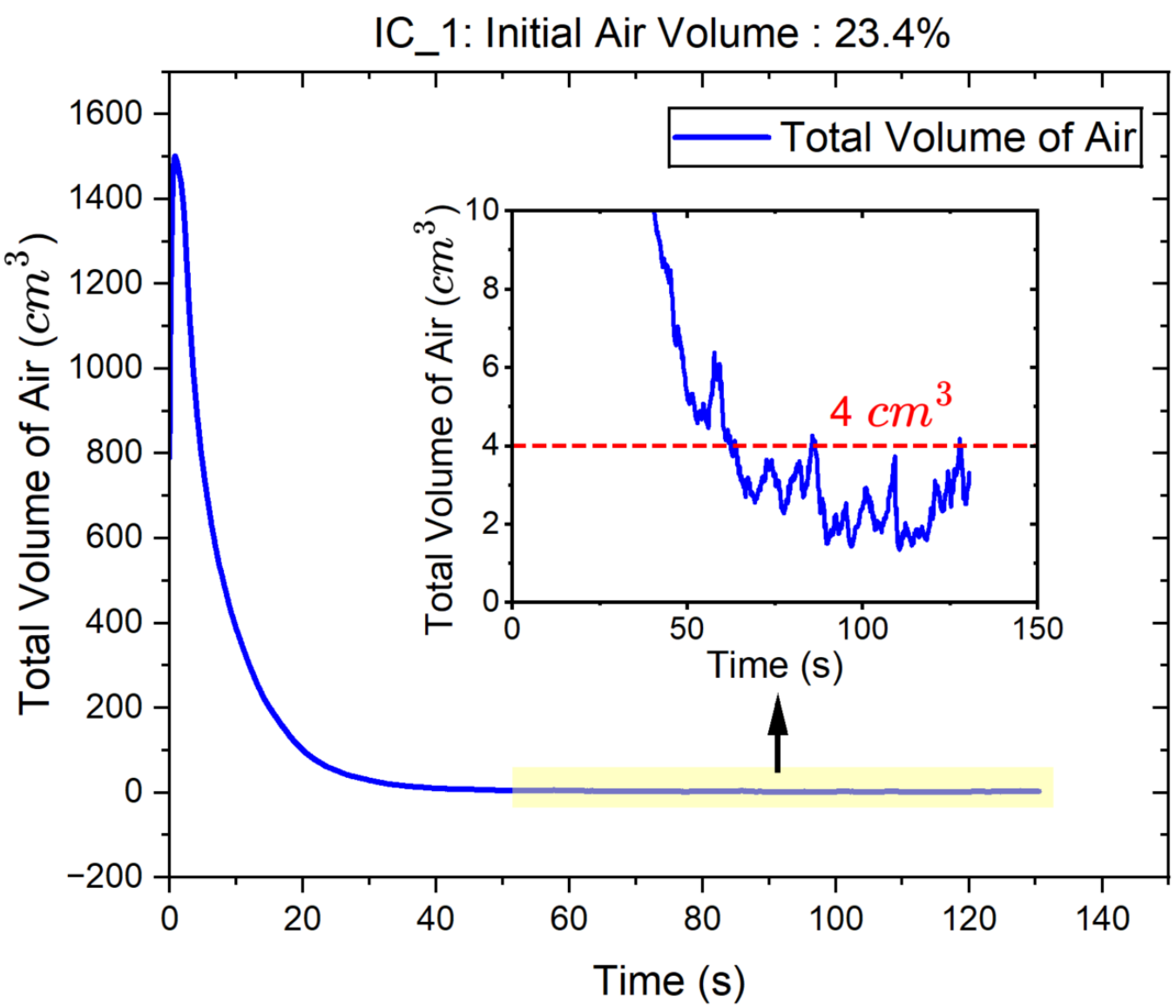
CASE 1(IC_1): Initially 23.4% of volume is air.



Water

MRA Air Accumulation in the Lower Reflector, Volume of Air

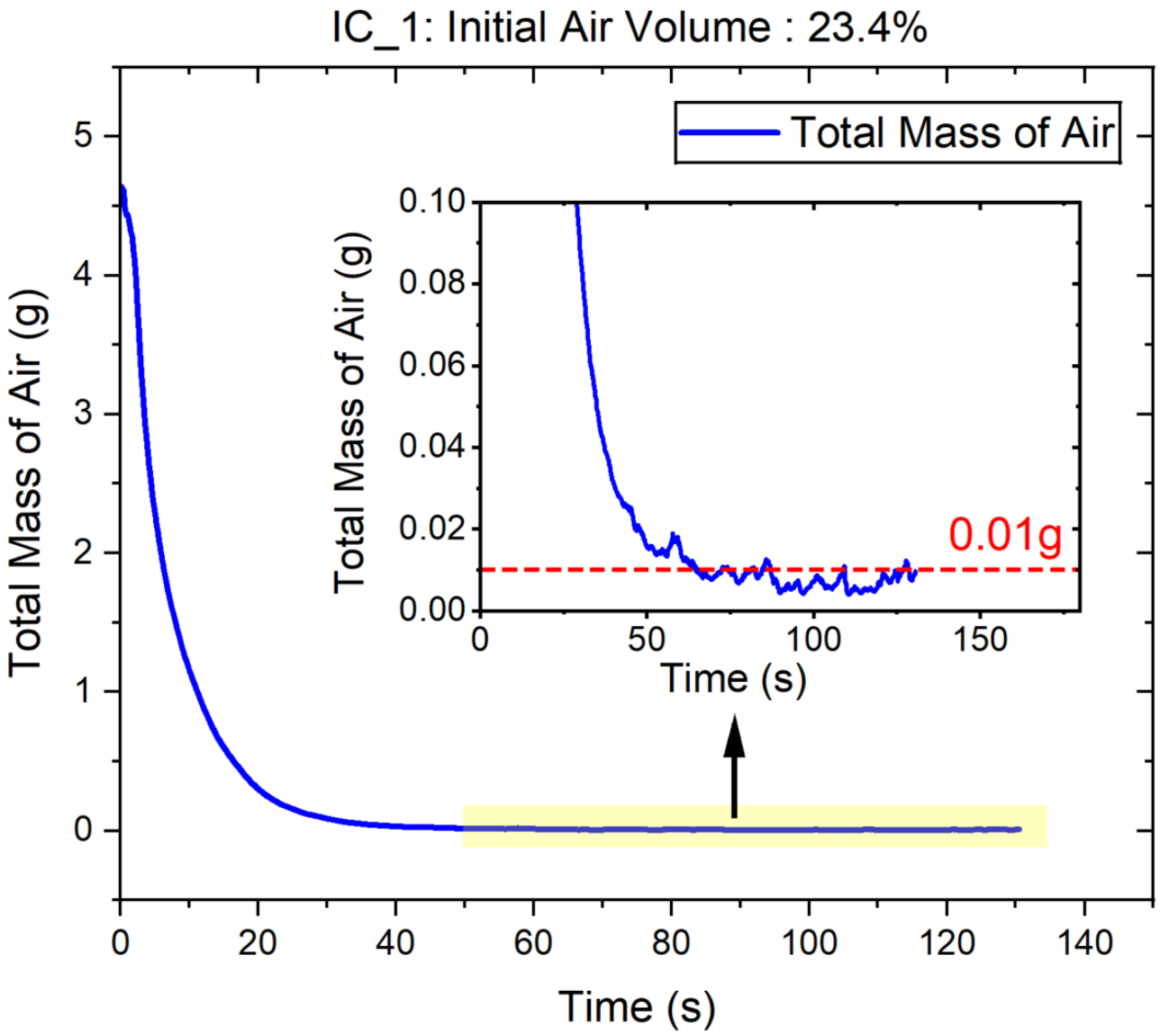
CASE 1(IC_1): Initially 23.4% of volume is air.



~ 4ml air accumulated in the lower reflector

MRA Air Accumulation in the Lower Reflector, Mass of Air

CASE 1(IC_1): Initially 23.4% of volume is air.



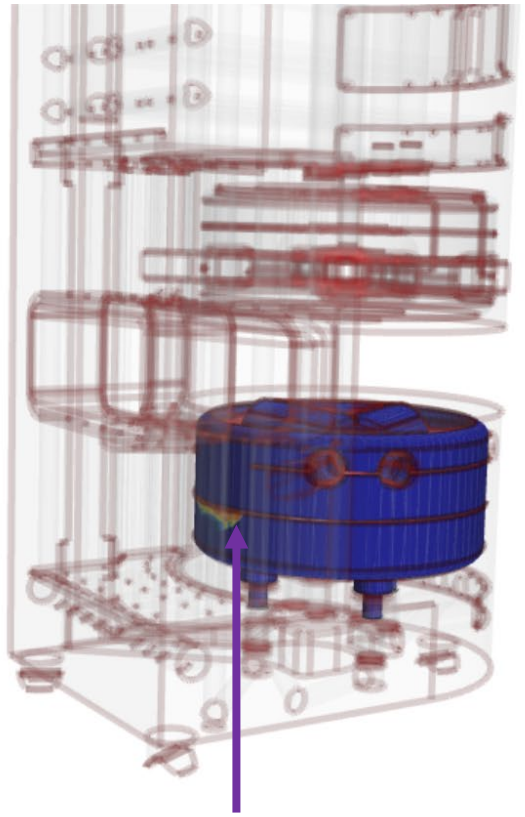
~ 0.01g air accumulated in the lower reflector

MRA Air Accumulation in the Lower Reflector

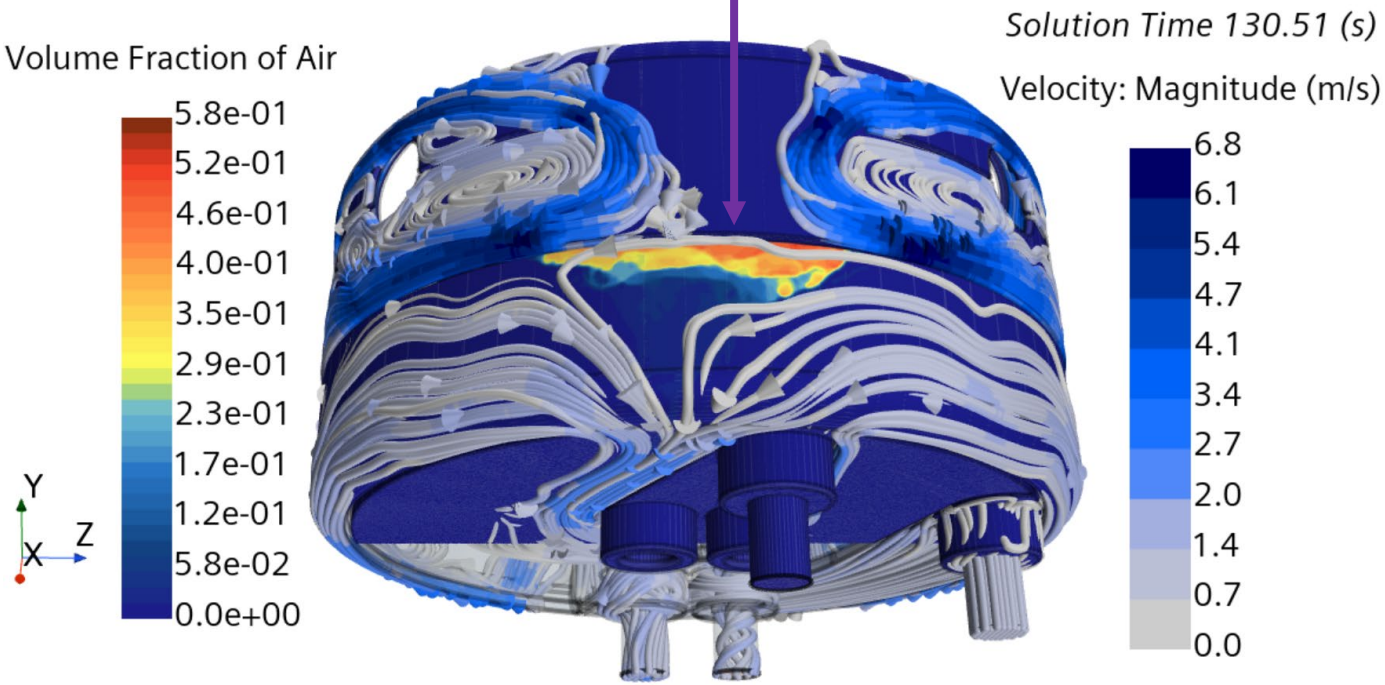
CASE 1(IC_1): Initially 23.4% of volume is air.

Air is accumulated in the **stagnation zone** (two streams of fluid come from opposite directions and meet). Watch the animation in the next slide.

ction of Air
5.8e-01
5.2e-01
4.6e-01
4.0e-01
3.5e-01
2.9e-01
2.3e-01
1.7e-01
1.2e-01
5.8e-02
0.0e+00

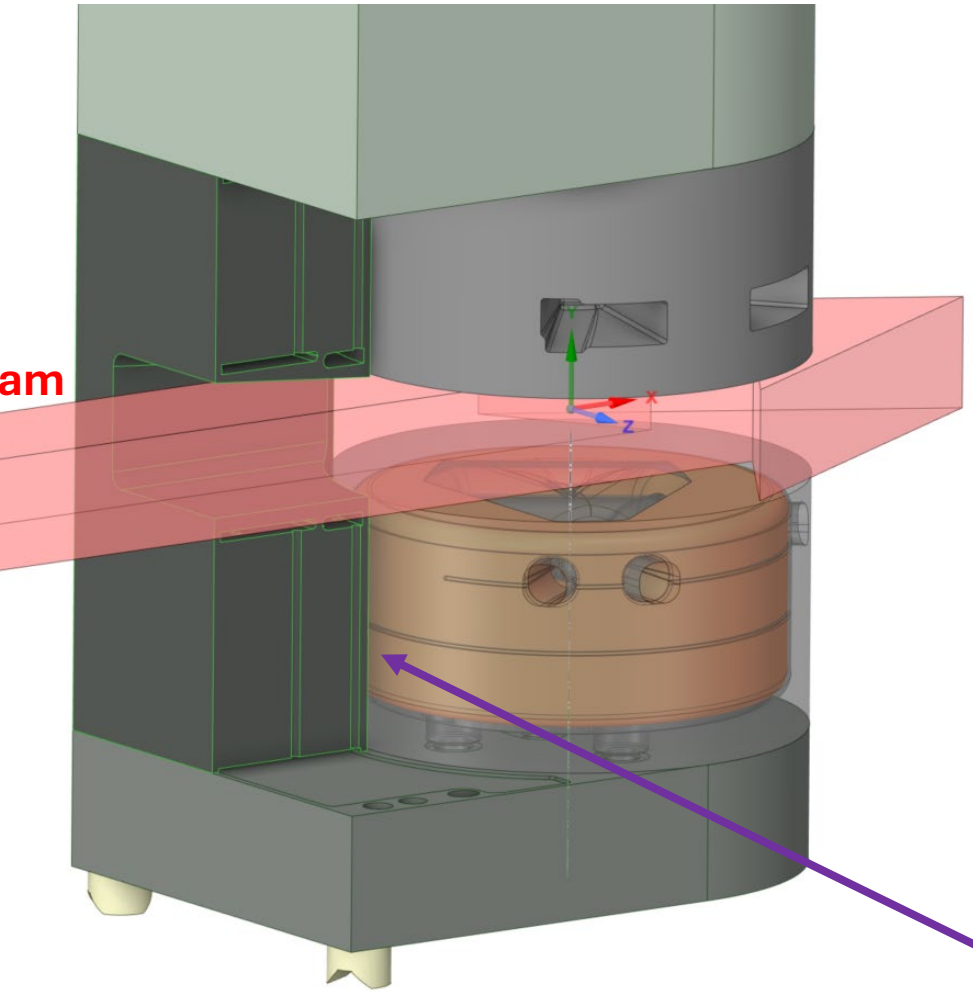


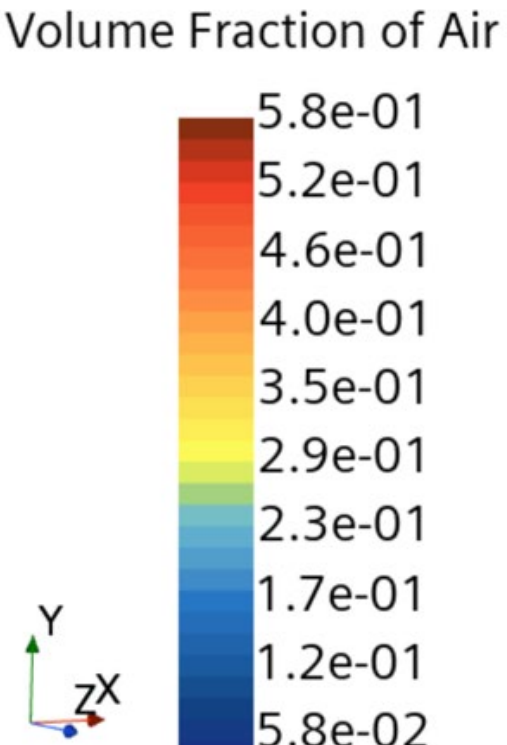
Air accumulation

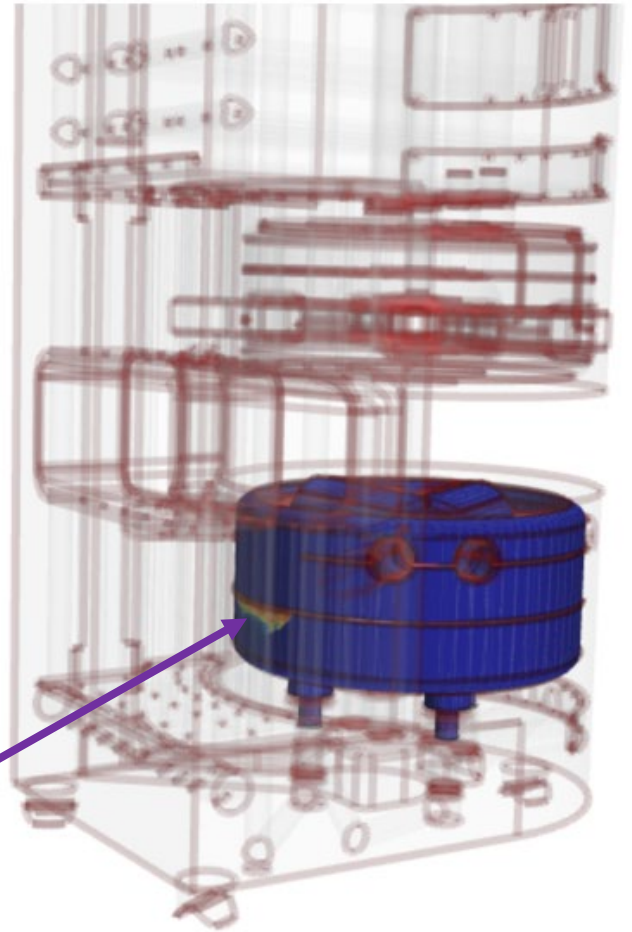


MRA Air Accumulation in the Lower Reflector

CASE 1(IC_1): Initially 23.4% of volume is air.





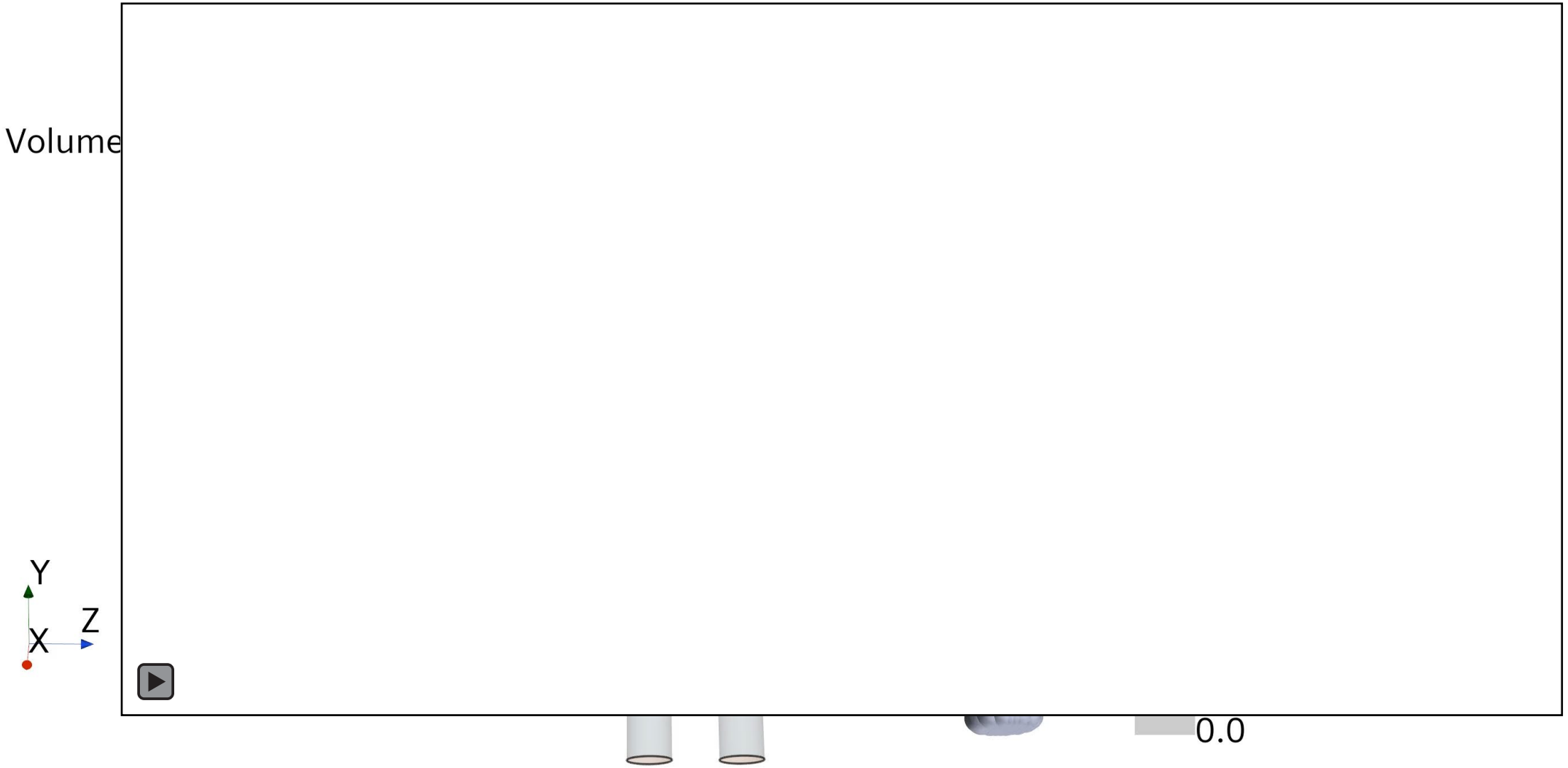


Air accumulation

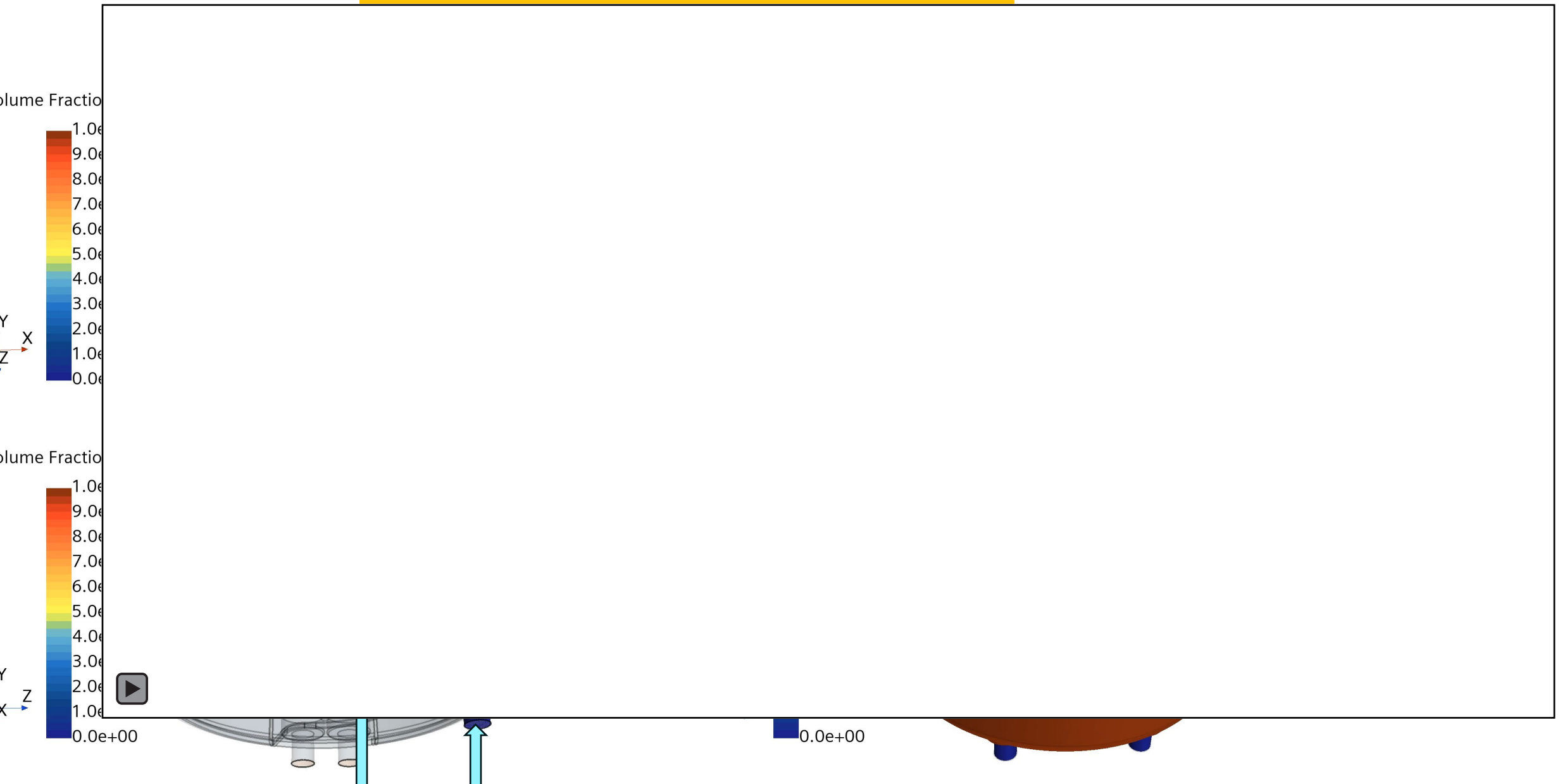
MRA Air Accumulation in the Lower Reflector

CASE 1(IC_1): Initially 23.4% of volume is air.

Volume fraction of air and streamlines (Animation)

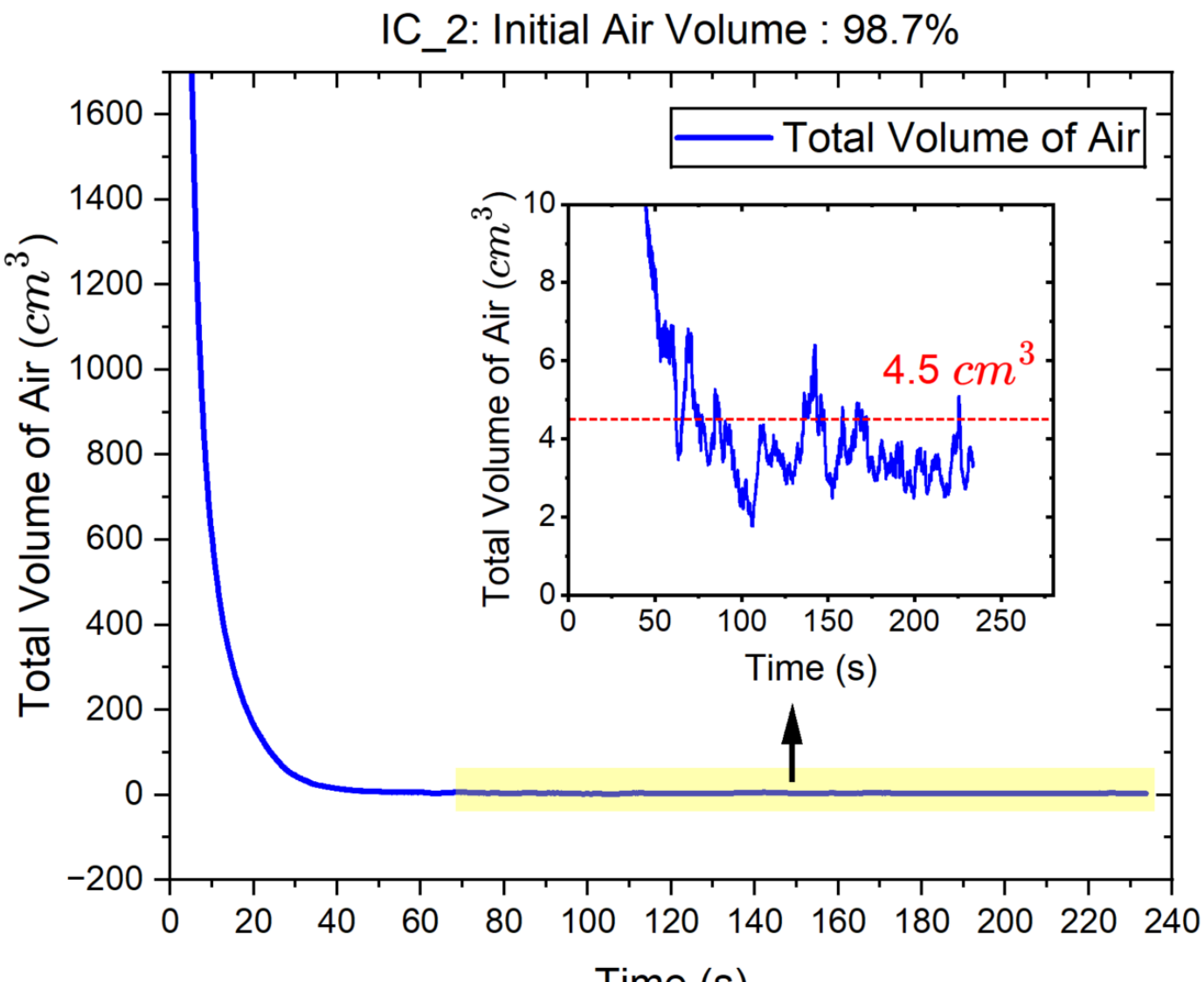


MRA Air Accumulation in the Lower Reflector



RA Air Accumulation in the Lower Reflector, Volume of Air

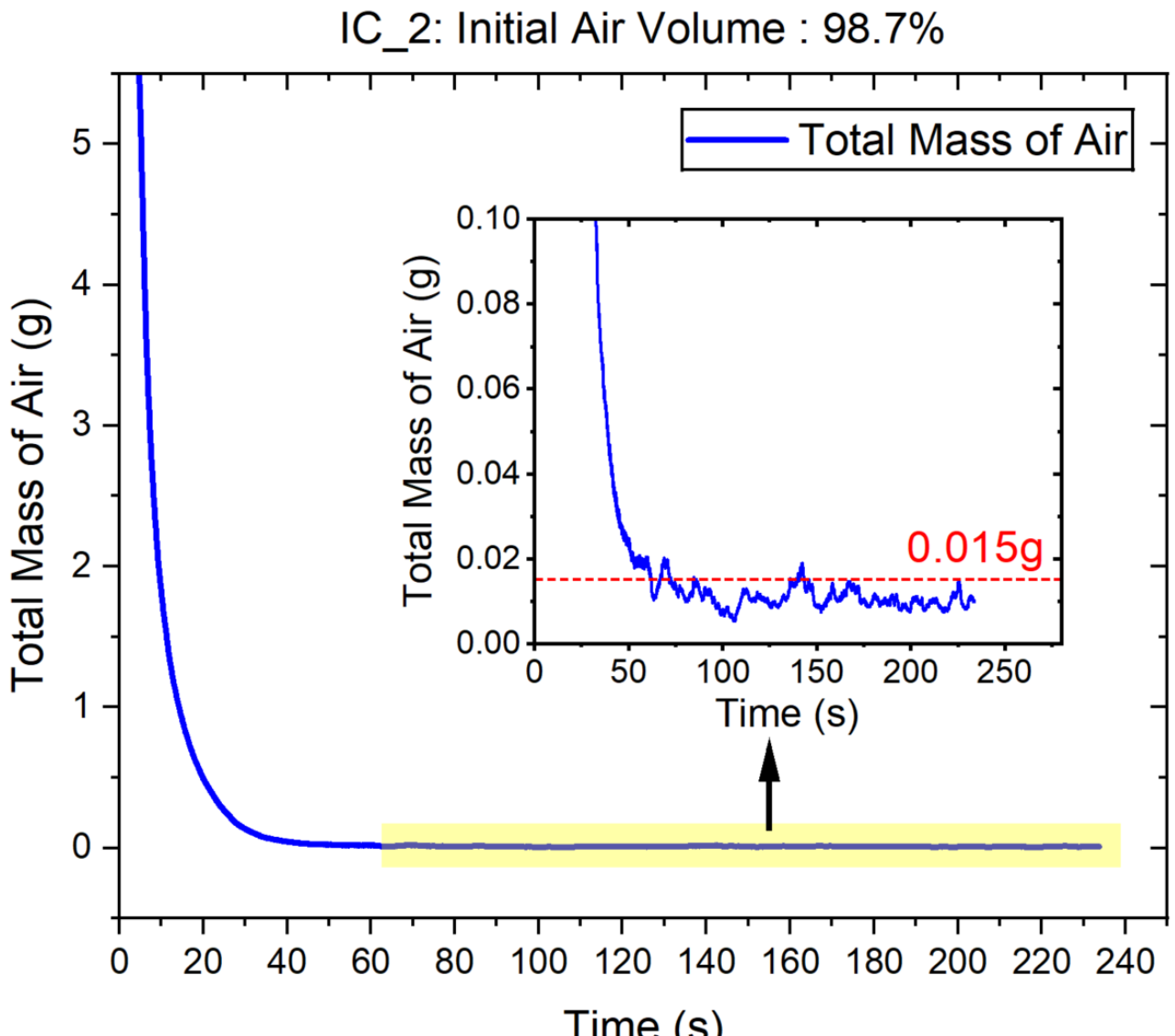
CASE 2(IC_2): Initially 98.7% of volume is air.



~ 4.5ml air accumulated in the lower reflector

MRA Air Accumulation in the Lower Reflector, Mass of Air

CASE 2(IC_2): Initially 98.7% of volume is air.

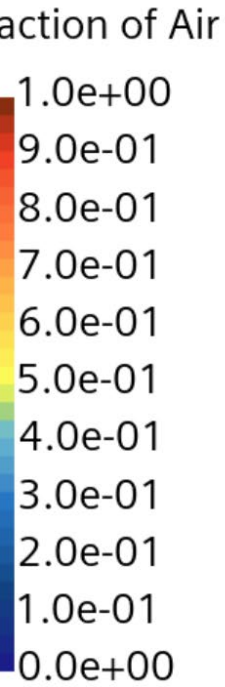


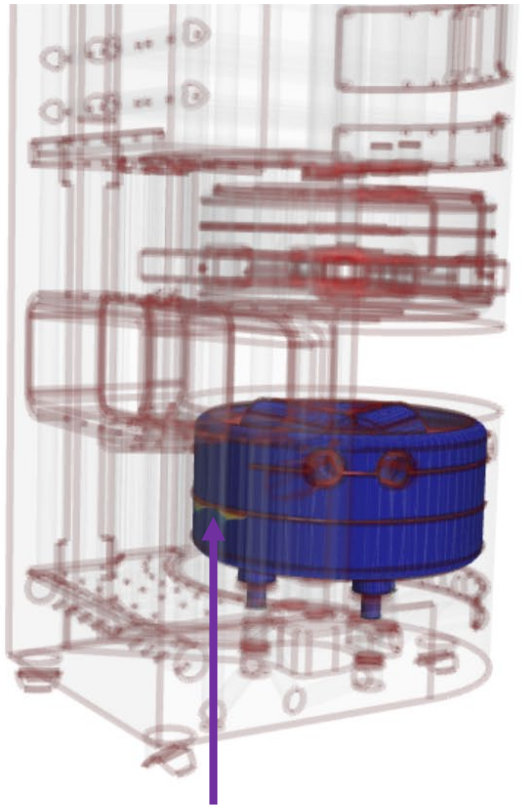
~ 0.015g air accumulated in the lower reflector

MRA Air Accumulation in the Lower Reflector

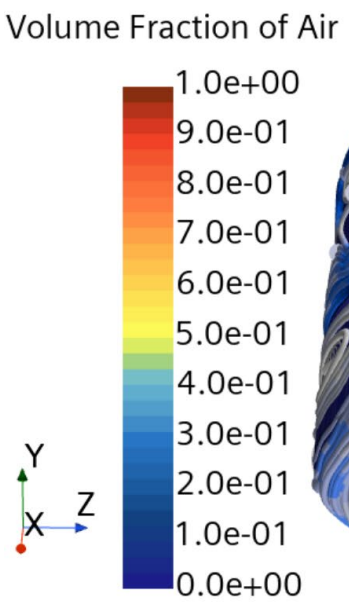
CASE 2(IC_2): Initially 98.7% of volume is air.

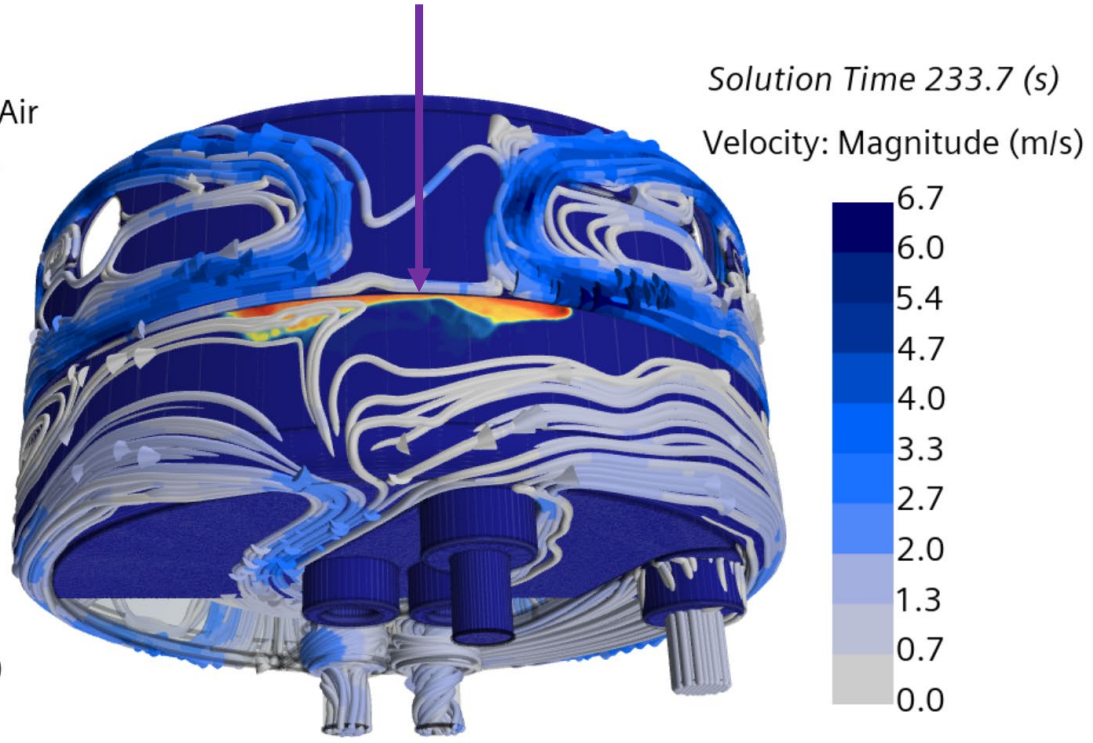
Air is accumulated in the **stagnation zone** (two streams of fluid come from opposite directions and meet). Watch the animation in the next slide.





Air accumulation

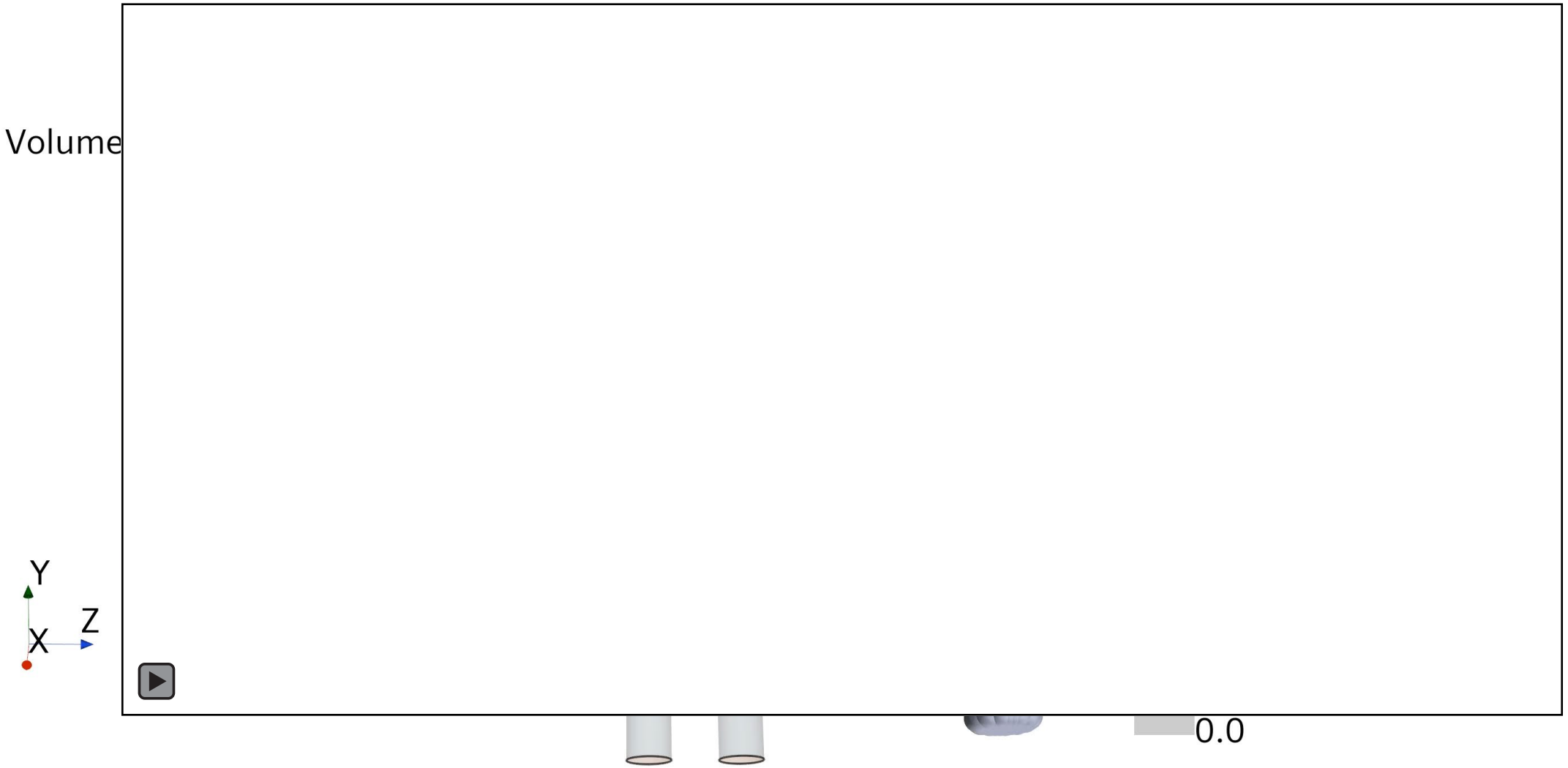




MRA Air Accumulation in the Lower Reflector

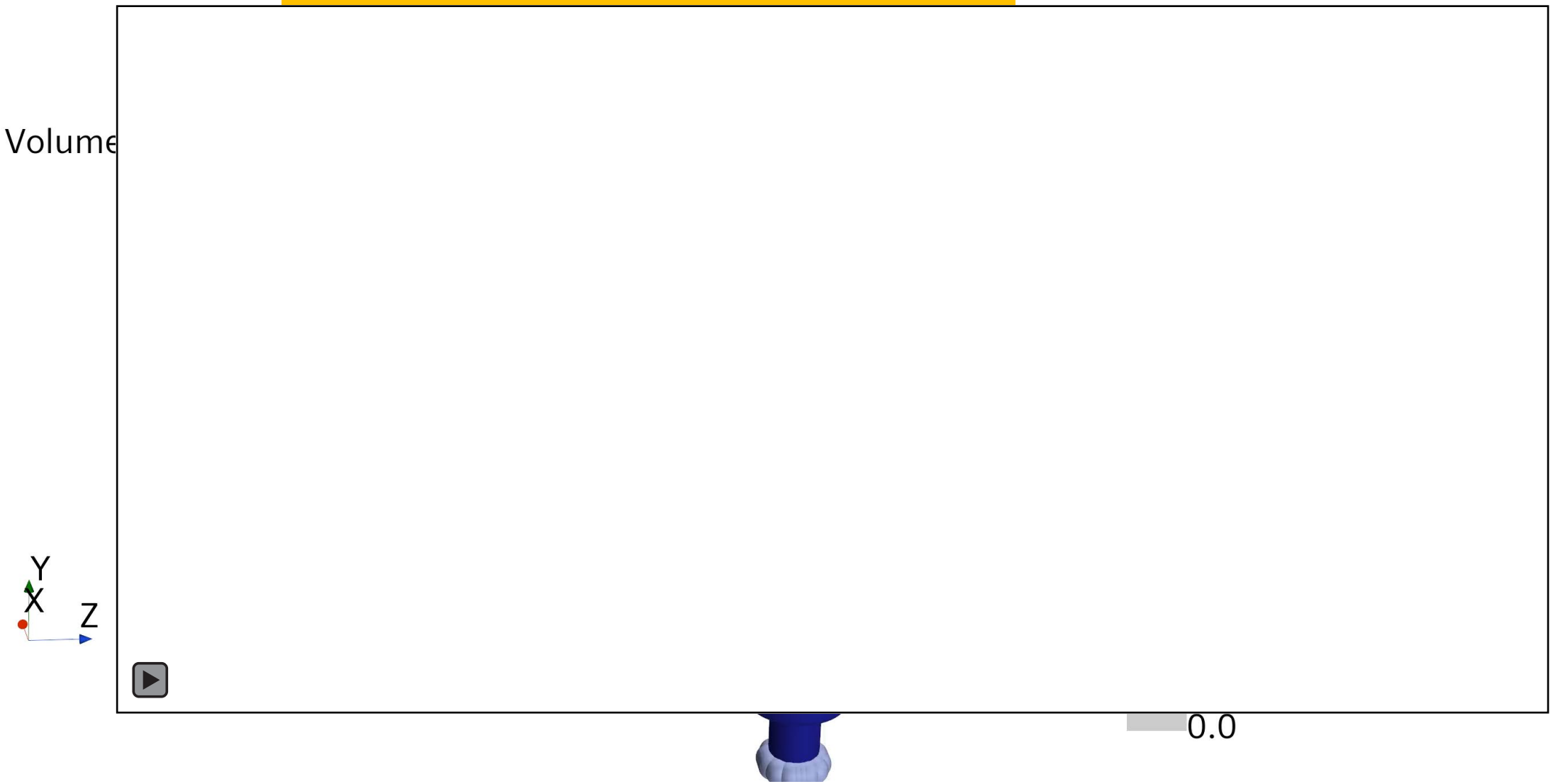
CASE 2(IC_2): Initially 98.7% of volume is air.

Volume fraction of air and streamlines (Animation)



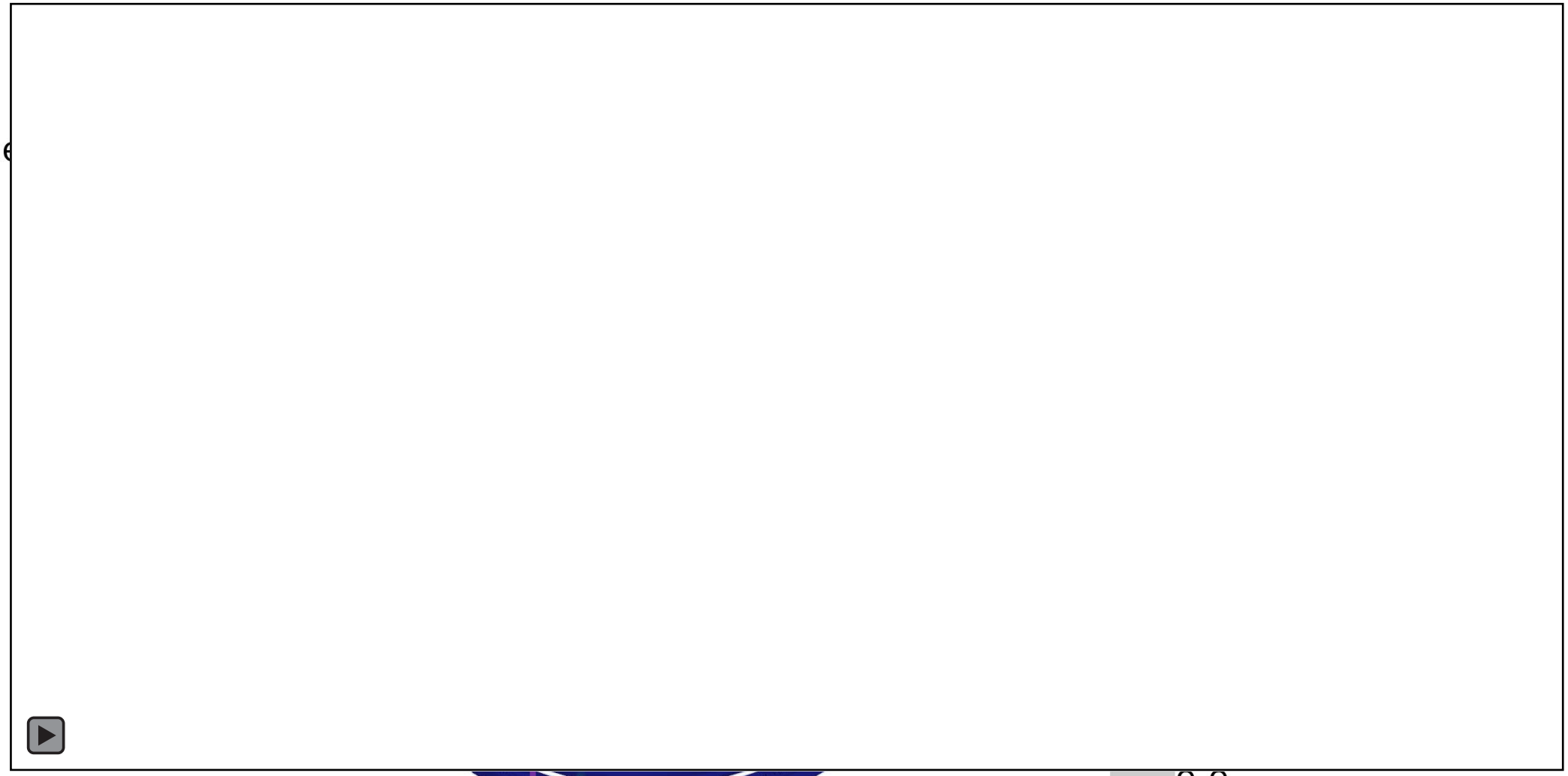
MRA Air Accumulation in the Lower Reflector

CASE 2(IC_2): Initially 98.7% of volume is air.



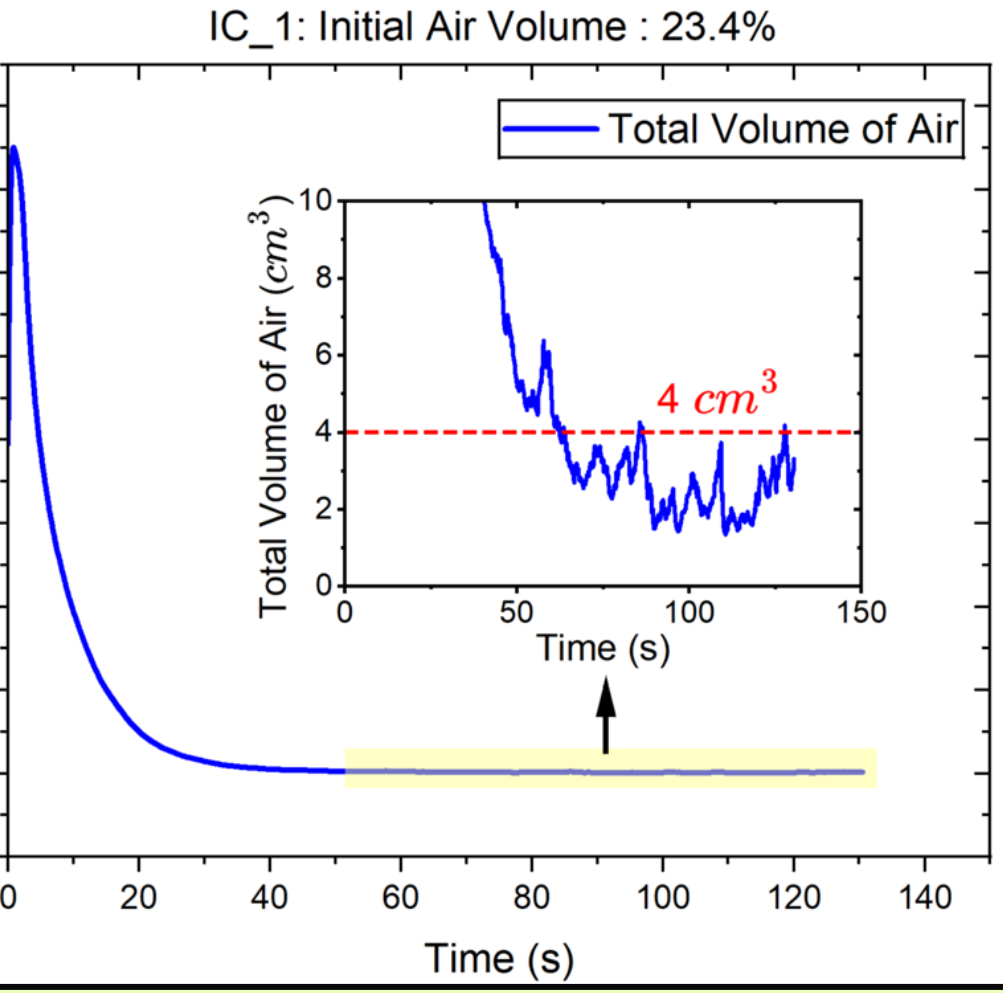
MRA Air Accumulation in the Lower Reflector

CASE 2(IC_2): Initially 98.7% of volume is air.



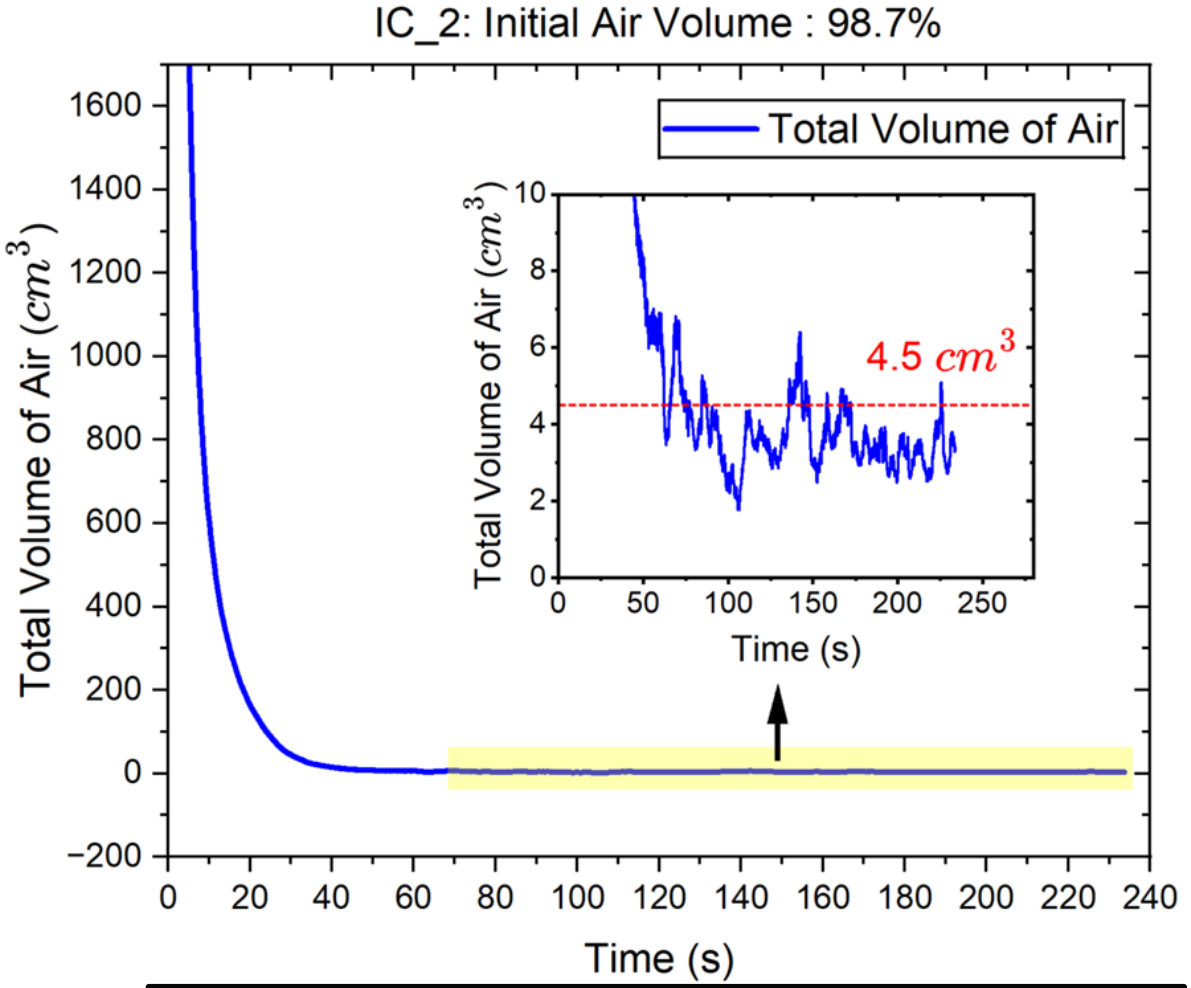
RA Air Accumulation in the Lower Reflector , Volume of Air

CASE 1(IC_1): Initially 23.4% of volume is air.



~ 4ml air accumulated in the lower reflector

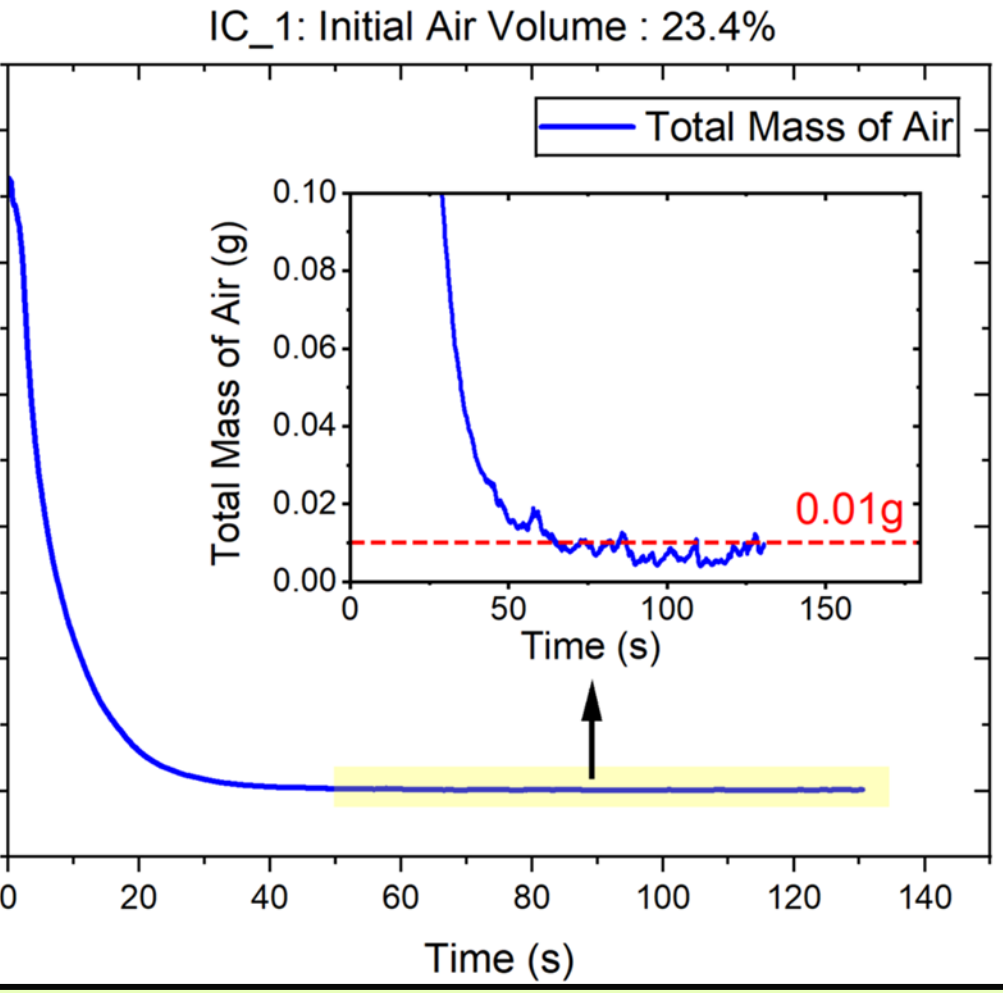
CASE 2(IC_2): Initially 98.7% of volume is air.



~ 4.5ml air accumulated in the lower reflector

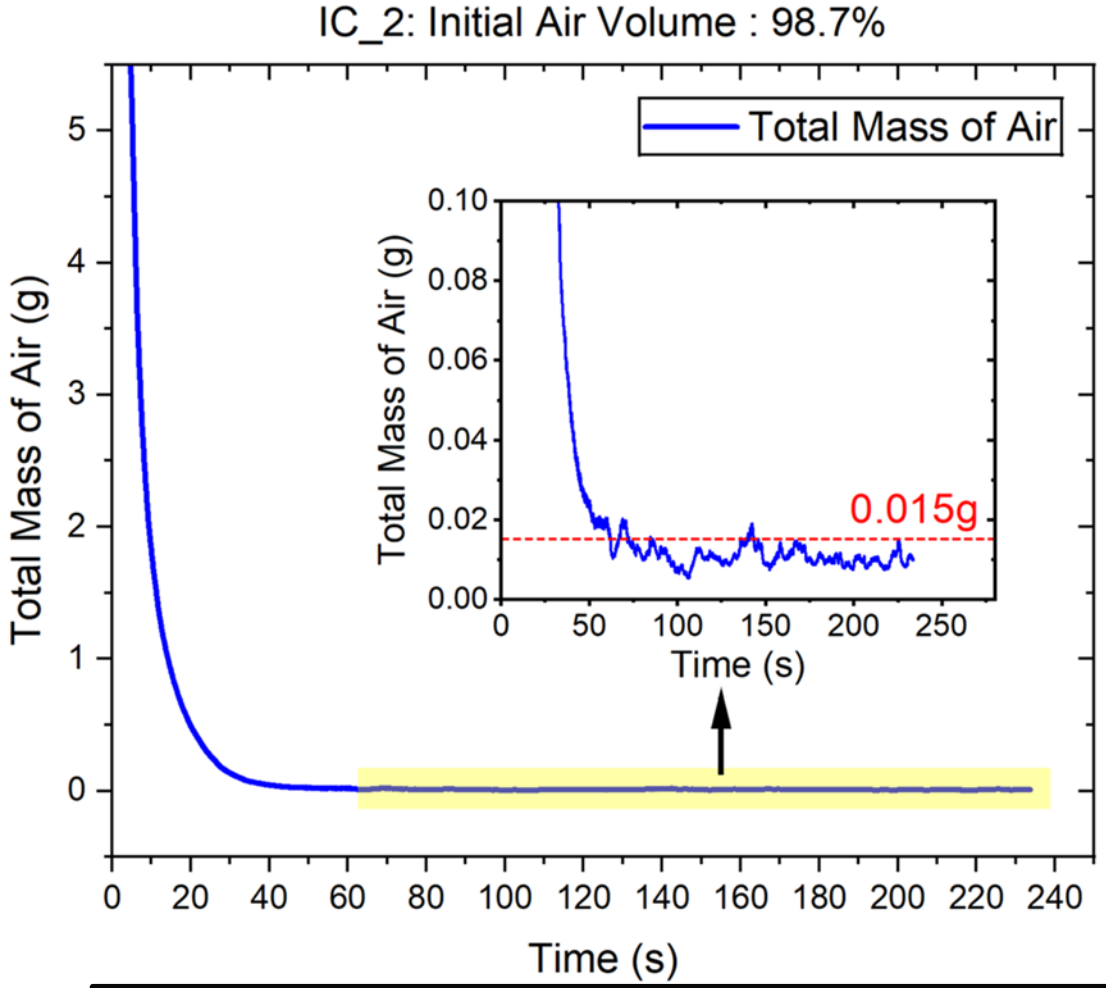
MRA Air Accumulation in the Lower Reflector , Mass of Air

CASE 1(IC_1): Initially 23.4% of volume is air.



~ 0.01g air accumulated in the lower reflector

CASE 2(IC_2): Initially 98.7% of volume is air.



~ 0.015g air accumulated in the lower reflector

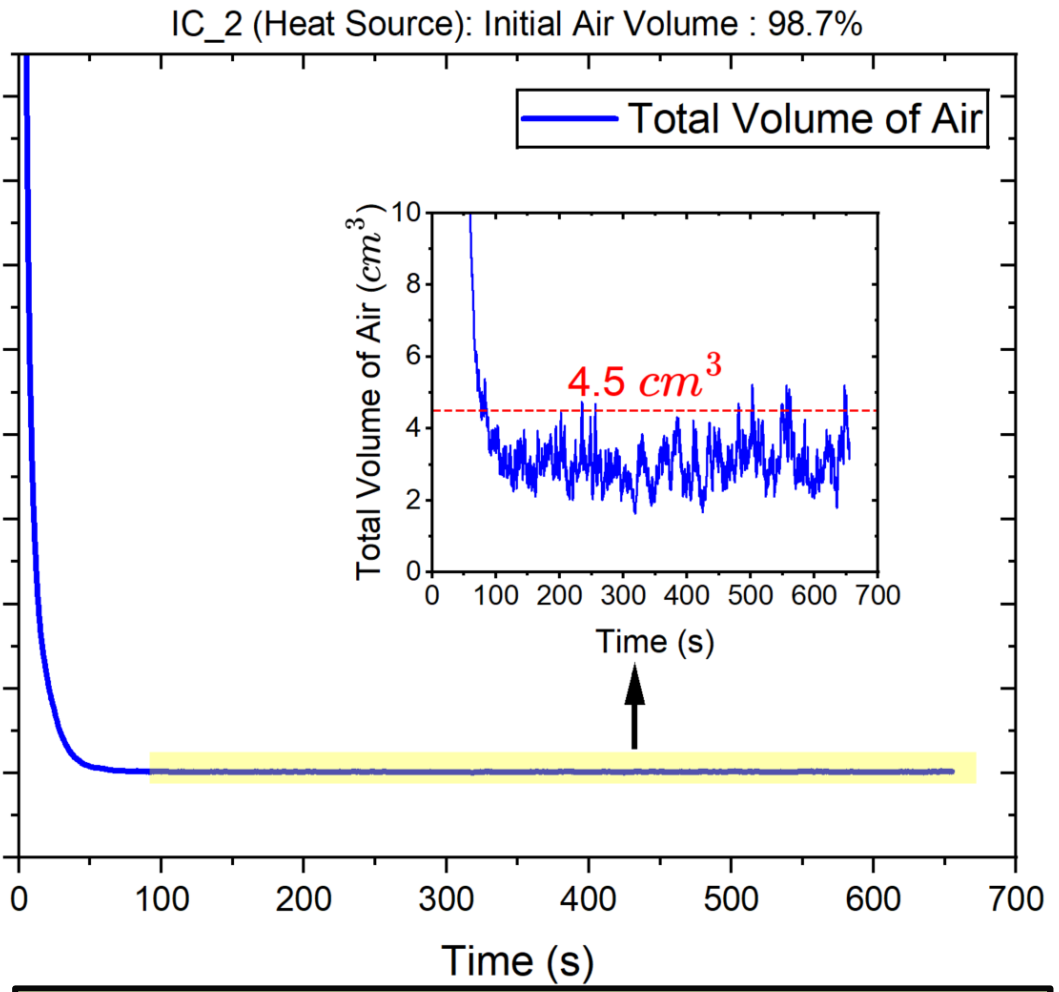
Air Accumulation in Lower Reflector Vessel

- Transient Results without Heat Transfer
- **Transient Results with Heat Transfer**

nsient Heat Transfer Analysis for Air Accumulation in the Lower Reflector

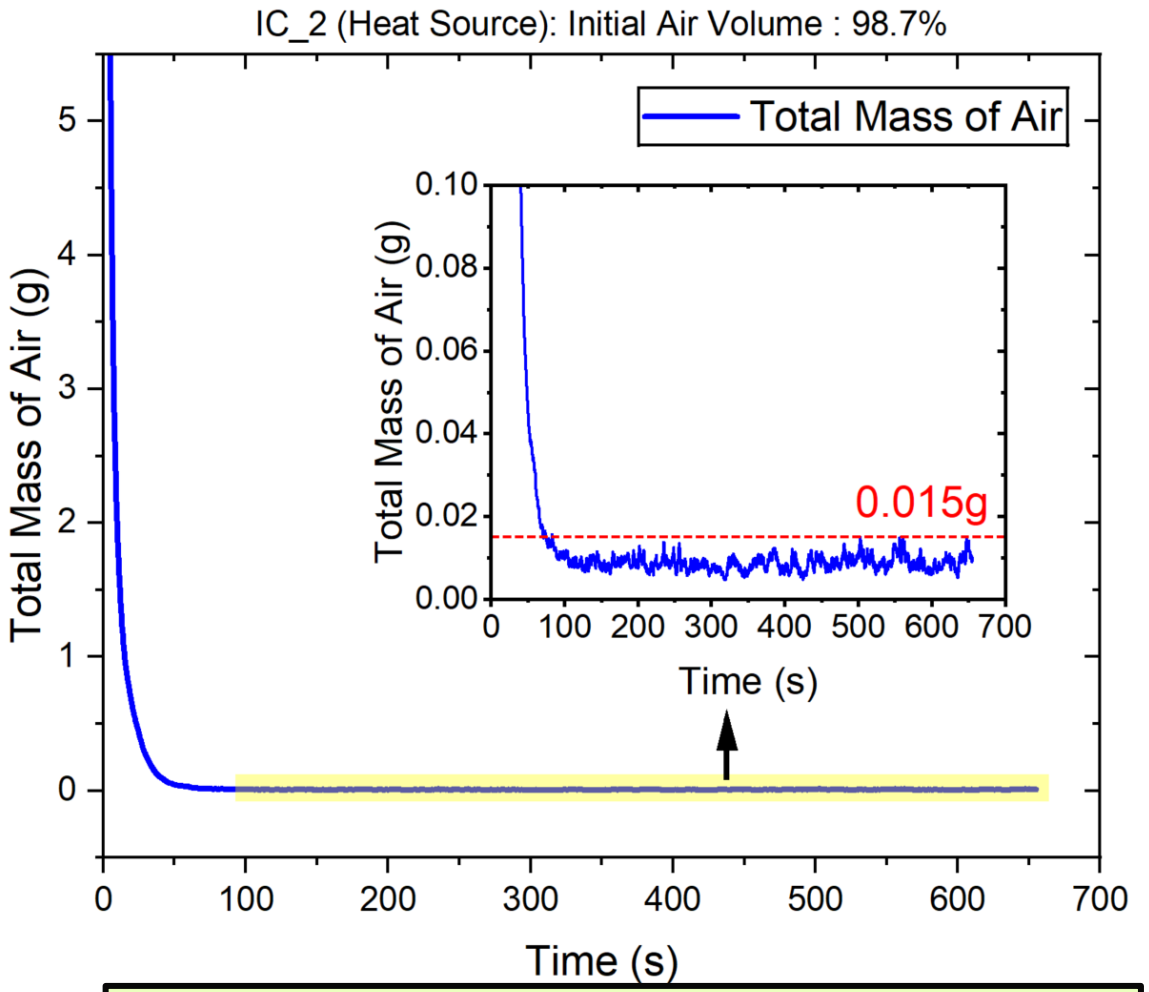
CASE 2(IC_2): Initially 98.7% of volume is air.

Volume of Air



~ 4.5ml air accumulated in the lower reflector

Mass of Air

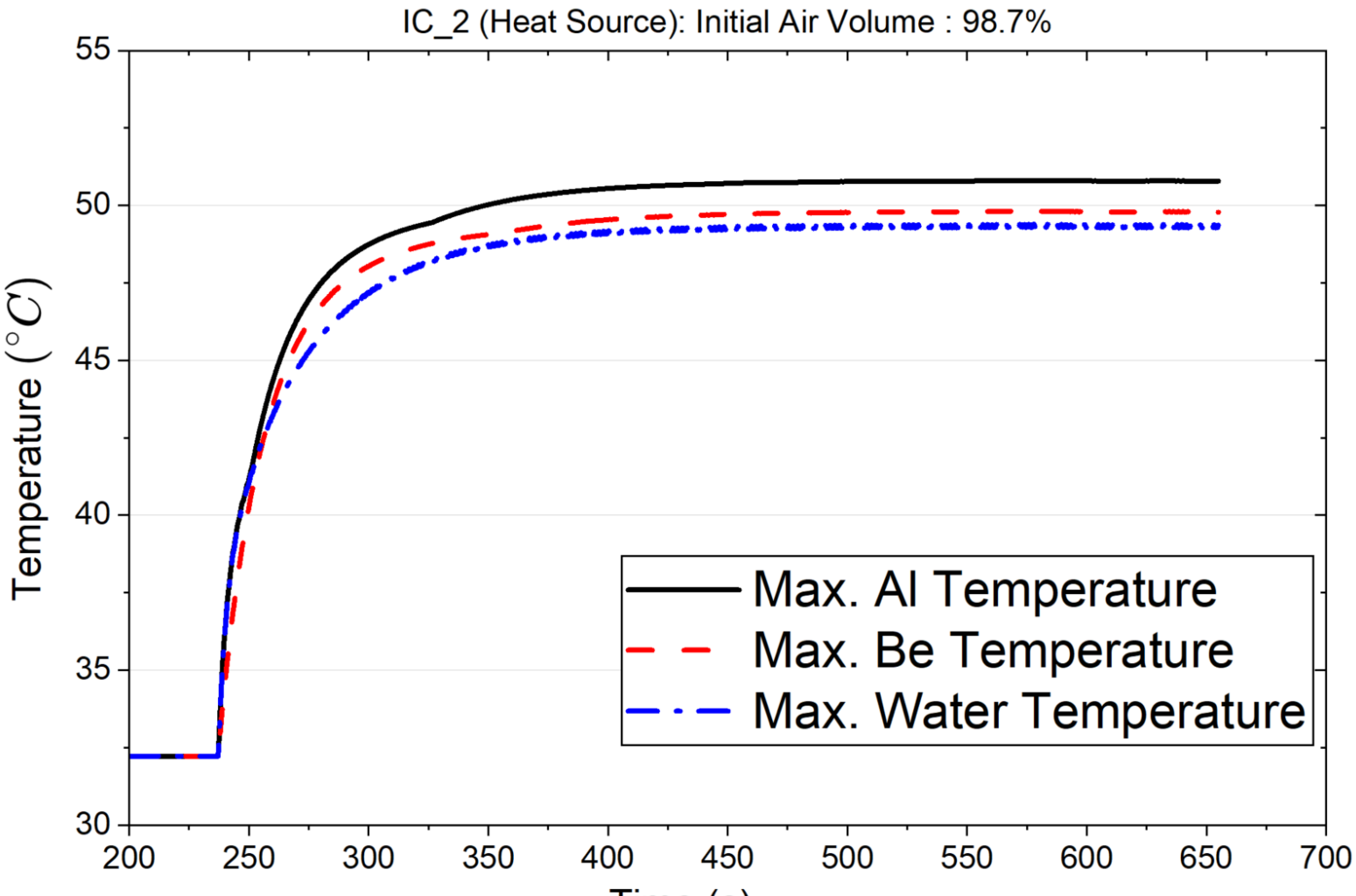


~ 0.015g air accumulated in the lower reflector

nsient Heat Transfer Analysis for Air Accumulation in the Lower Reflector

CASE 2(IC_2): Initially 98.7% of volume is air.

Maximum Temperature in the Lower Reflector Vessel Assembly



Requirement Verification

irement Name	Codebeamer ID	Requirement	CFD Result	Status
		MRA Water Loop		
um Temperature	2325	The MRA aluminum 6061-T6 structures shall have a maximum operating temperature of 100 °C.	73.1 °C	**Pass**
s Steel Temperature	2326	The MRA stainless steel structures shall have a maximum operating temperature of 200 °C.	84.6 °C	**Pass**
m Temperature	2327	The MRA beryllium shall have a maximum operating temperature of 100 °C.	54.9 °C	**Pass**
emperature Requirement	2328	The MRA cooling water shall have a maximum temperature of 100 °C.	51.0 °C	**Pass**
Premoderator Pressure ment	2362	The MRA upper premoderator water loop shall have a pressure drop of less than 15 psi at 7.5 gpm and 32.2 °C inlet temperature.	5.20 psi	**Pass**
Premoderator Pressure ment	2363	The MRA lower premoderator water loop shall have a pressure drop of less than 15 psi at 7.5 gpm and 32.2 °C inlet temperature.	6.86 psi	**Pass**
Reflector Pressure Drop	2364	The MRA upper reflector water loop shall have a pressure drop of less than 15 psi at 7.5 gpm and 32.2 °C inlet temperature.	9.65 psi	**Pass**
Reflector Pressure Drop	2365	The MRA lower reflector water loop shall have a pressure drop of less than 15 psi at 7.5 gpm and 32.2 °C inlet temperature.	9.55 psi	**Pass**
ne Pressure Drop	2366	The MRA backbone water loop shall have a pressure drop of less than 15 psi at 15 gpm and 32.2 °C inlet temperature.	4.29 psi	**Pass**
		MRA Hydrogen Loop		
en Loop Pressure Drop	2356	The MRA hydrogen loop pressure drop shall be less than 0.15 bar @ 0.5 l/s and 18.34 K.	0.105 bar	**Pass**
tor Hydrogen Density	2888	The hydrogen in both moderators shall have a minimum average density of 72.0 kg/m^3.	Upper Cylindrical Moderator: 73.185 kg/m^3 Lower Tube Moderator: 72.353 kg/m^3	**Pass**
tor Hydrogen Maximum	2889	The hydrogen temperature shall at no point in the moderators	24.5 K	**Pass**

Conclusions

hermal-hydraulic requirements are satisfied.

nponent temperatures remained well below their specified limits (Al6061:
°C, Stainless Steel: 84.6°C, Beryllium: 54.9°C, Cooling Water: 51.0°C).

ssure drops in all water loops met the design requirements with adequate
gin (4.29–9.65 psi vs. 15 psi limit; Hydrogen loop: 0.105 bar vs. 0.15 bar limit).

rogen moderator performance met all thermal-hydraulic requirements,
uding minimum density (72.35–73.19 kg/m^3) and maximum temperature (24.5
. 32 K limit).

**CFD results demonstrate that the MRA cooling system design complies
all specified thermal and hydraulic performance requirements.**