SSR1 Cryomodule

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International workshop on cryomodule design and standardization

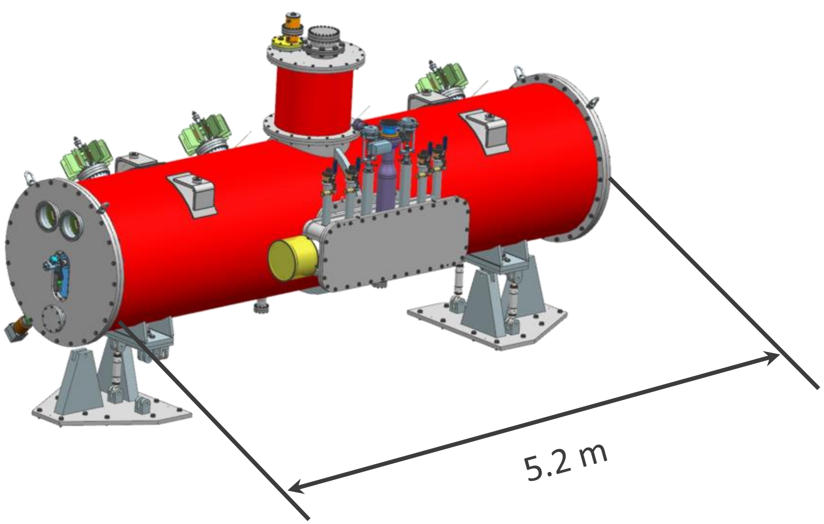
6th September 2018

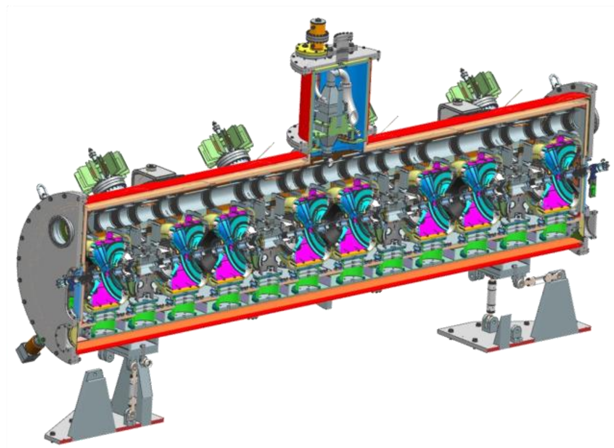
Layout

1. Description of the cryomodule
2. Thermal shield
3. Current leads
4. Piping engineering note
5. Valve sizing
6. LCLS II experiences
7. Internal interfaces
8. Assembly process
9. External Interfaces

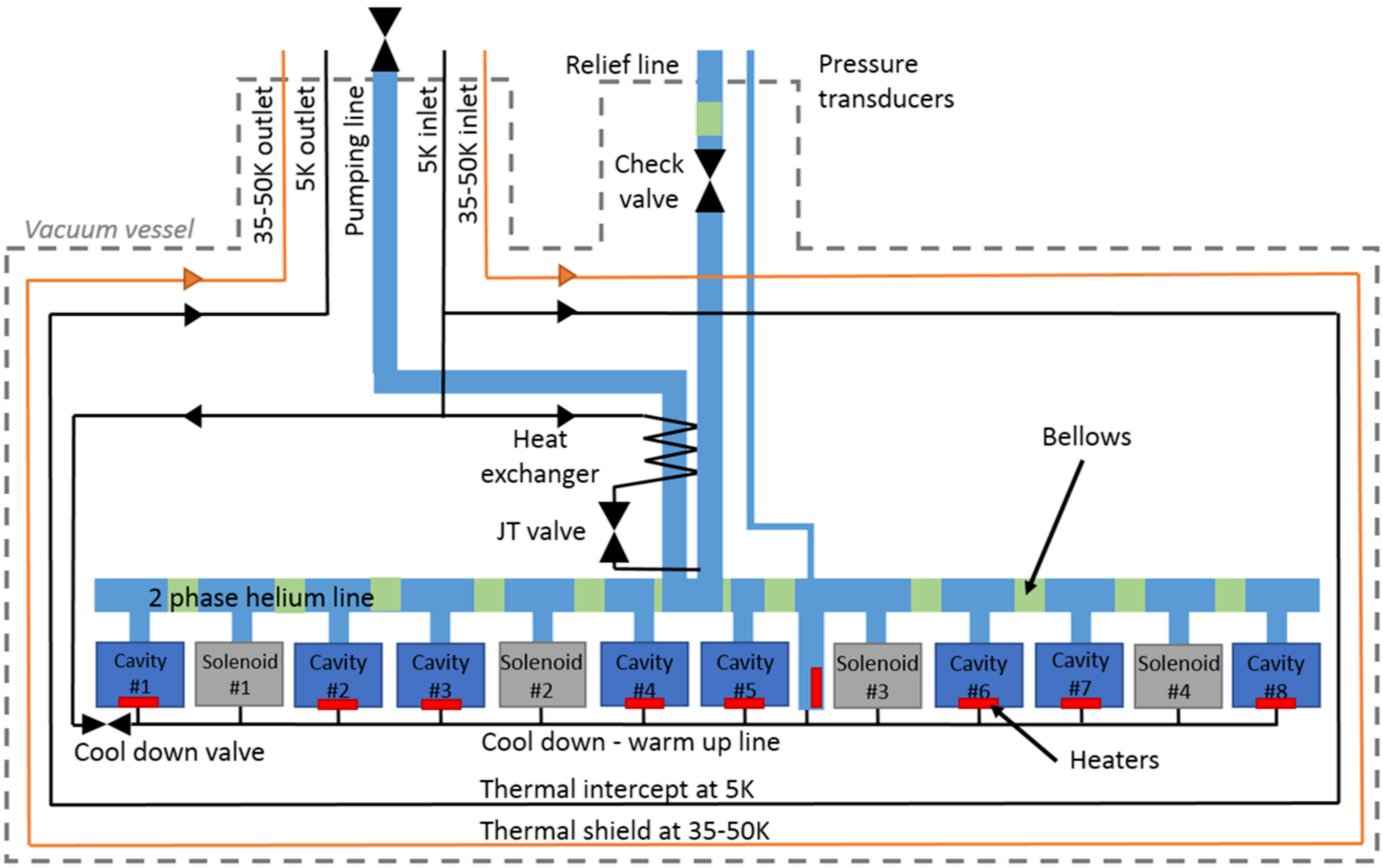
1. Description of the cryomodule

- Vacuum vessel : 5.2 m long and around 1.5 m high compared to the beam axis
- Magnetic shield at room temperature on the inner surface of the vacuum vessel
- Thermal shield at 35-50 K
- 5 K line used as thermal intercept & to cool down the cavities and solenoids
- 5 Bayonets
- 2 Cryogenic valves & an heat exchanger to reach 2 K
- 8 Cavities, tuners & couplers
- 4 Solenoids, BPMs & current leads





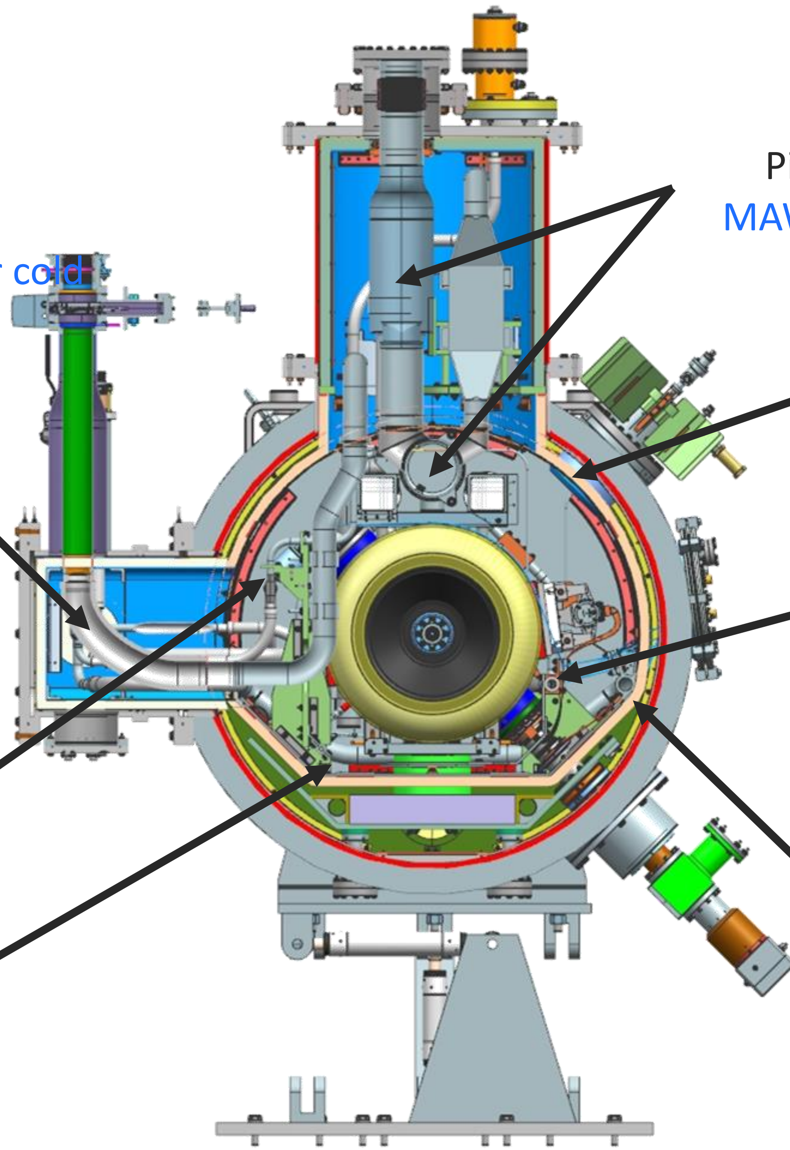
1. Description of the cryomodule



1. Description of the cryomodule

Pipe G - 2 phase He & chimney
MAWP: 2.05 bar warm, 4.1 bar cold

Pipe B - Pumping line
MAWP: 2.05 bar warm, 4.1 bar cold



Pipe I - Helium guard of the current leads
MAWP: 4.1 bar

Pipe C & D - 5 K line
MAWP: 20 bar

Pipe A - 2 K supply
MAWP: 20 bar

Pipe E & F - 35-50 K line
MAWP: 20 bar

Pipe H - Cool down / warm up line
MAWP: 20 bar

1. Description of the cryomodule

	Each unit (W)			#	Total (W)		
	35-50 K	5 K	2 K		35-50 K	5 K	2 K
Input coupler (static)	6.20	0.80	0.70	8	49.6	6.4	5.6
Input coupler (dynamic)	1.3	0.7	0.40	8	10.4	5.6	3.2
Cavity dynamic load			2.84	8			22.7
Support post	1.7	1.0	0.07	12	21.0	11.4	0.8
Thermal shield	29.3		2.5	1	29.3		2.5
Current leads (static)	7.0	4.5	3.6	4	28.0	18.0	14.4
Current leads (dynamic)	11.0	0.9	0.5	4	44.0	3.6	2.0
Conduction relief line	1.2		0.8	1	1.2		0.8
Conduction beam line	1.1	0.1	1E-03	2	2.3	0.1	3E-03

	35-50 K	5 K	2 K
Total static	131.4	35.9	24.1
Total dynamic	54.4	9.2	27.9
Total static + dynamic	185.8	45.1	52.0

The expected heat-loads have been updated based on the final calculations performed om the current leads and couplers.

Coldmass design

1. Description of the cryomodule
2. **Thermal shield**
3. **Current leads**
4. **Piping engineering note**
5. **Valve sizing**
6. **LCLS II experiences**
7. **Internal interfaces**
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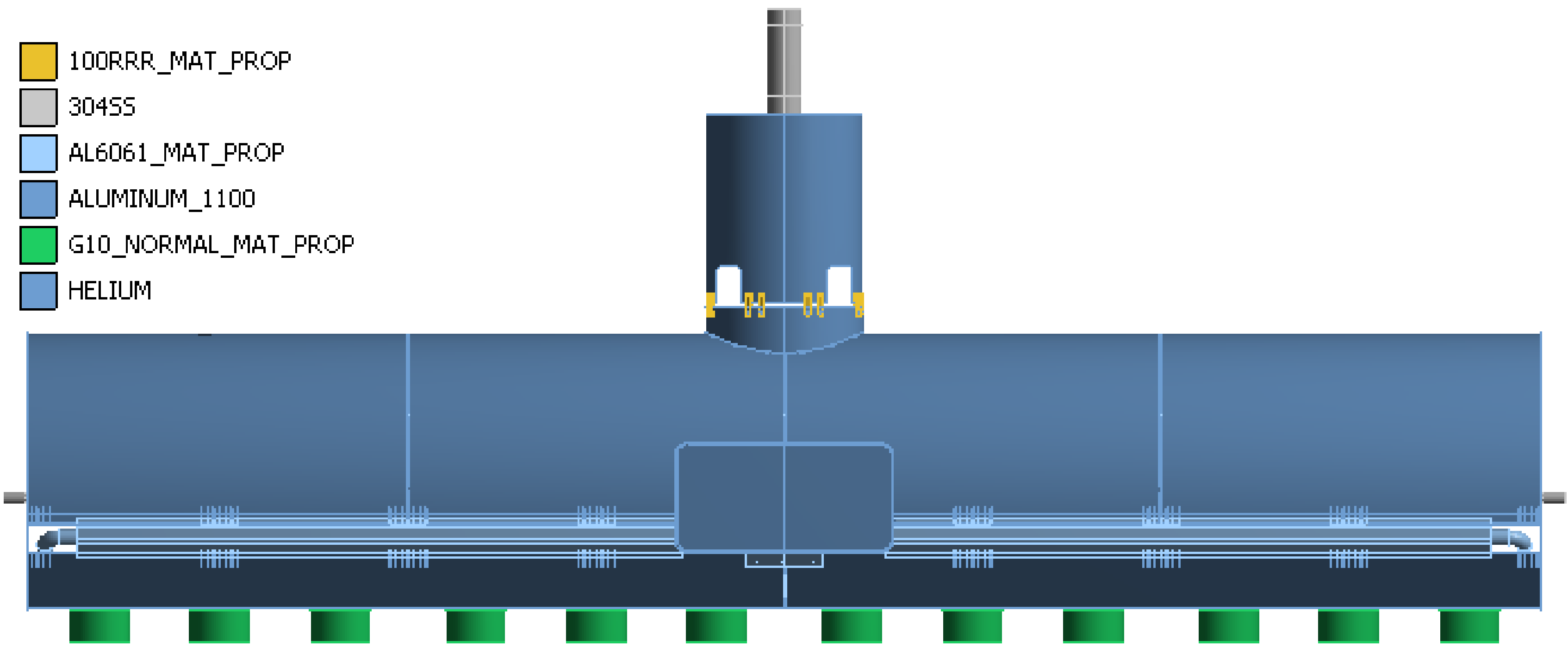
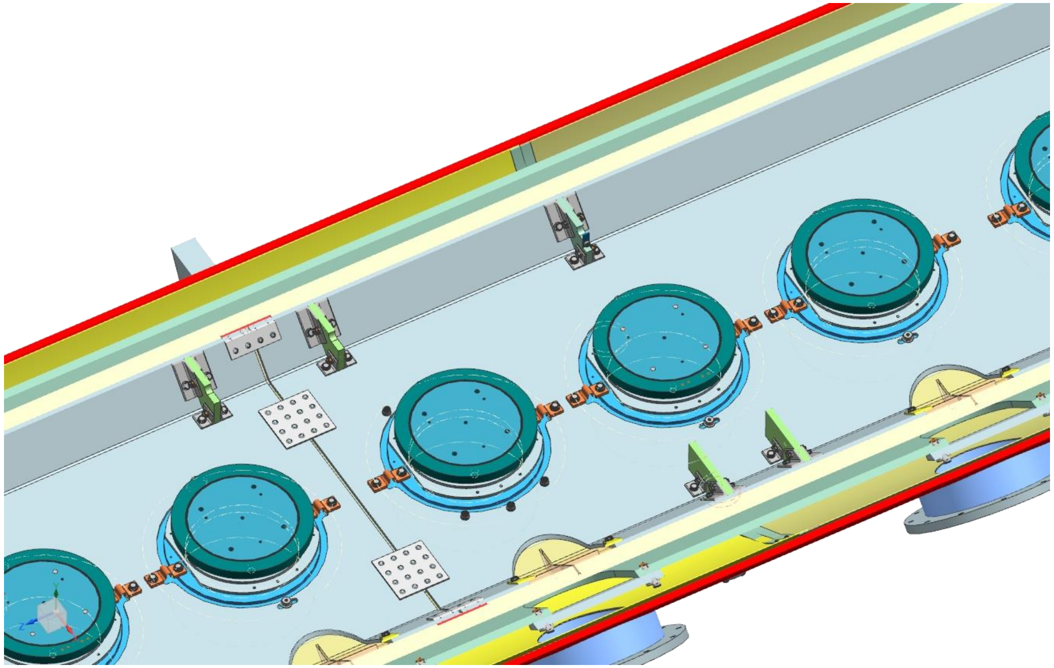
2. Thermal shield

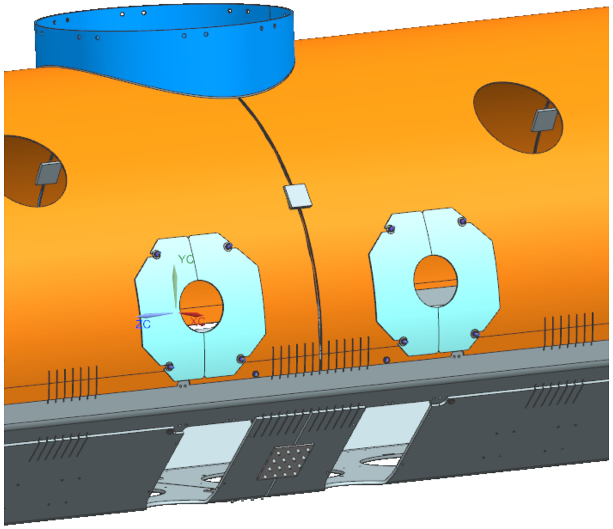
The thermal shield sit on the thermal intercept of each support post in G10. The top part is connected to the main part of the main thermal shield thanks to thermal straps.



2. Thermal shield

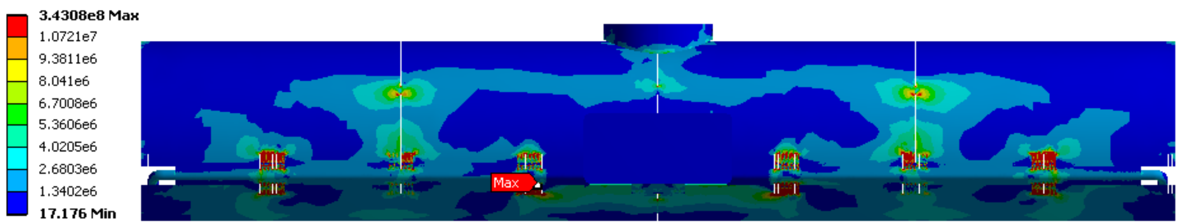
The thermal shield is fixed to a single support post and can slide on the others. A max longitudinal displacement of 11 mm is expected. Copper foil thermal straps connect the thermal shield to the support posts.

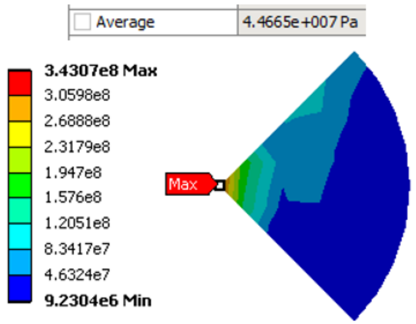


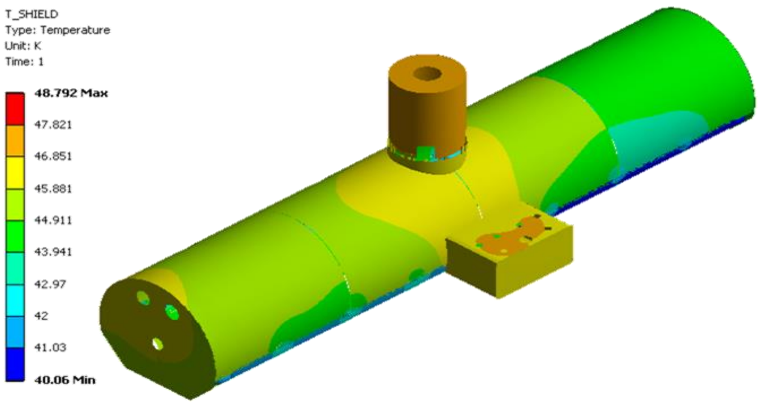


2. Thermal shield

The average stresses at weld at the moment of max thermal gradient will be 45 MPa for **5 K/hour** cool down rate compared to 55 MPa the max allowable stress for welded aluminum 6061-T6.





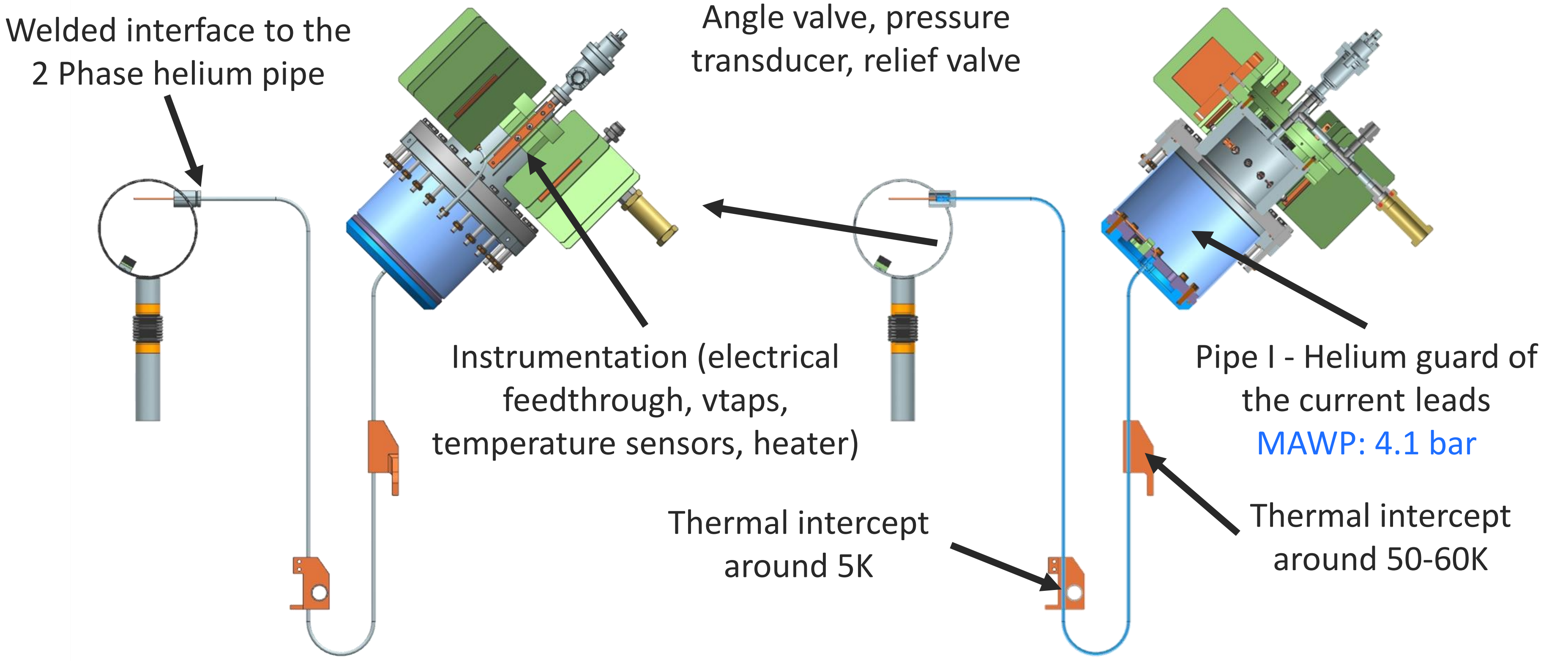


The maximum thermal gradient across shielding for steady state operation is 9 K. The max thermal gradient during cool down is 40 K for 5 K/hour cool down rate.

3. Current leads

The current leads are the last components still under designed.

- Nominal current for the solenoid: 66 A (2 copper wires 2.558 mm)
- Operating current of the corrector: 40 A (8 copper wires 3.264 mm)



4. Piping engineering note

All cryogenic lines have been designed according to FES&H requirements it means ASME B31.3 in USA. The piping engineering note includes all the calculations of standard part and non standard parts

9.2.11. Straight tube in stainless steel 316L, ID 1.682" - OD 1.9"

A wall thickness of 0.109" have been considered with regards to a design pressure of 20 bars (0.29 ksi). We will check in this chapter that this design follows the requirements according to 304.1, Ref. 3 (ASME B31.3-2008).

Geometry of the tube

D	Outside diameter of pipe	1.900	in
d	Inner diameter of pipe	1.682	in
tr	Thickness of the real pipe	0.109	in
D/6		0.32	in

Material properties

-	Material	316 L	
Y	Coefficient according to Table 304.1.1	0.4	
S	Stress value for material from Table A-1	16.7	ksi

Pressure design

P	Internal design gage pressure	2.00	MPa
		0.29	ksi

Calculations

According to 304.1.1, the required thickness of straight sections of pipe shall be determined in accordance with the following equation.

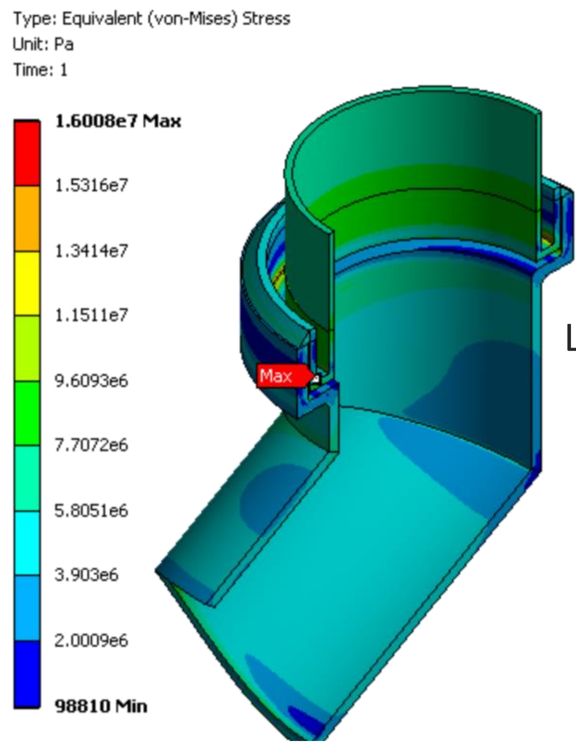
tm = t + c

tm	Minimum required thickness		
t	Pressure design thickness		
c	Sum of the mechanical allowances plus corrosion and erosion allowances. According to 304.1.1, A value of 0.5 mm (0.02 in) can be considered.	0.02	in

According to the standards 304.1.2, we have **t < D/6.** Therefore the internal pressure design thickness can be determined by using the following equation.

$$t = \frac{PD}{2(SEW + PY)}$$

E	Quality factor from Table A-1A or A-1B (seamless tube)	1	
W	Weld joint strength reduction factor 302.3.5(e) page 17	1	
t	Pressure design thickness	0.02	in
tm	Minimum required thickness	0.036	in
Pr	Pressure rating of the real pipe	1.63	ksi
		11.21	MPa
-	Capacity factor	5.6	

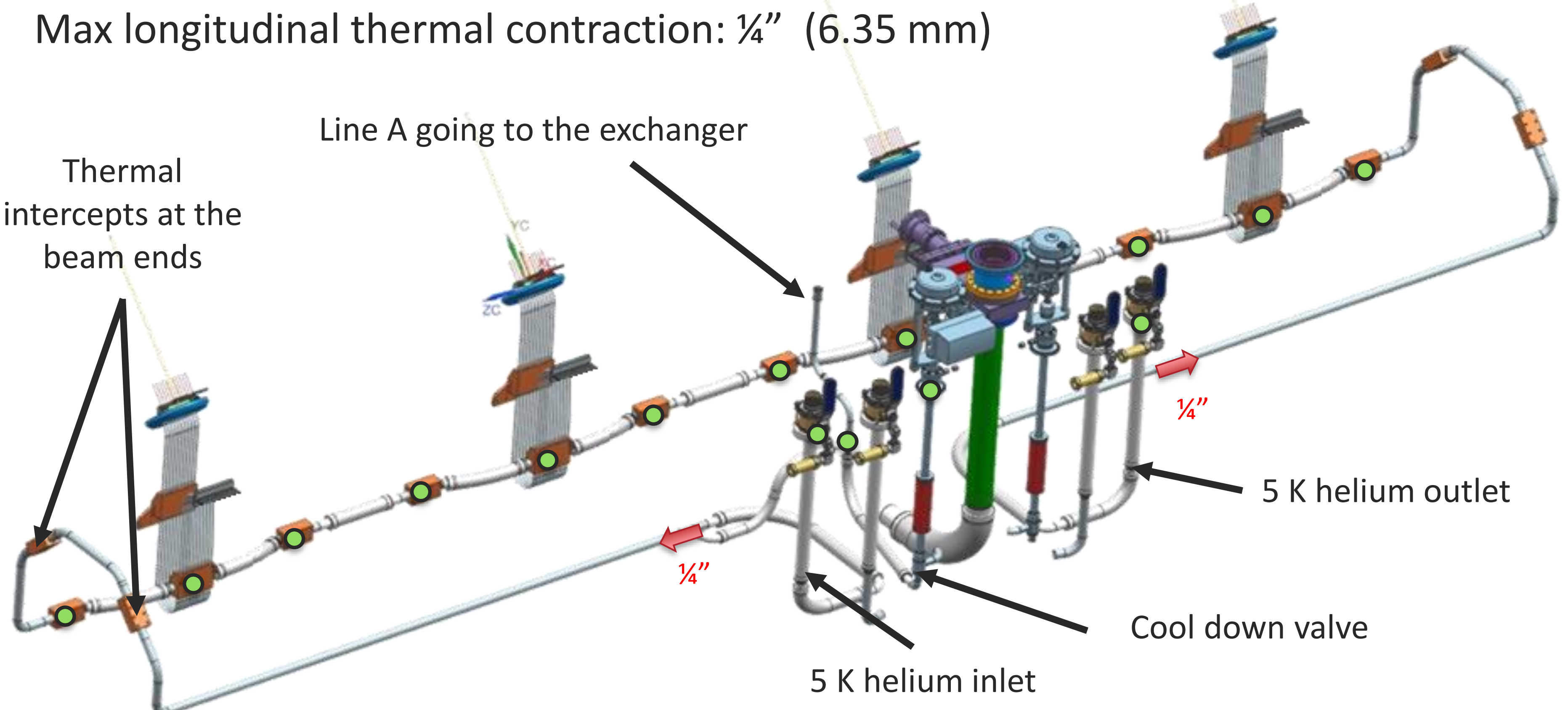


Low stress around 30 MPa max compared to the allowable stress of 316L: 110 MPa.

4. Piping engineering note

4.1 Line C&D - 5 K supply line

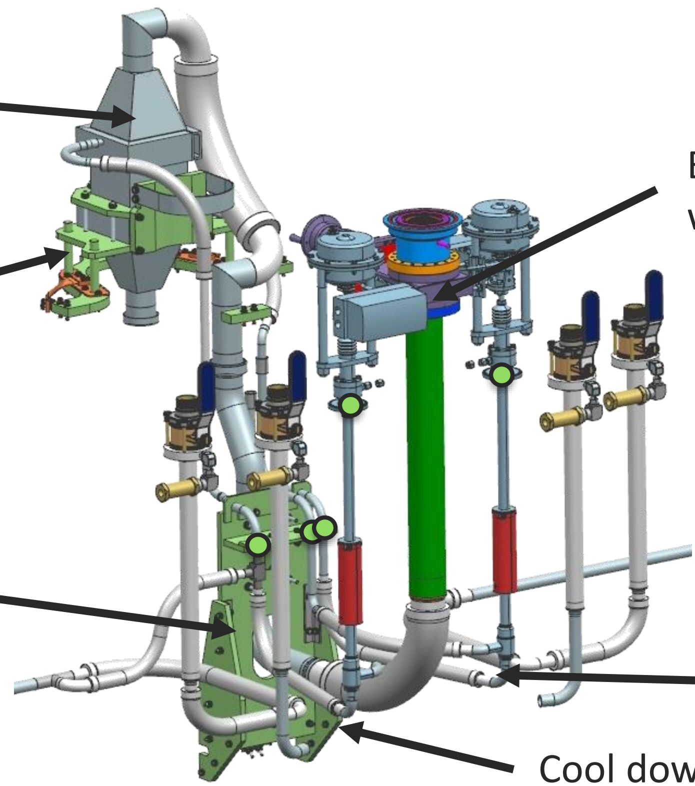
The 5 K line has an 1” OD. This line is used as a thermal intercept for the beam ends, the cavities & solenoids supports, the couplers and the current leads.
Max longitudinal thermal contraction: ¼” (6.35 mm)



4. Piping engineering note

4.2 Line A - 2 K supply line, Line B - Pumping line

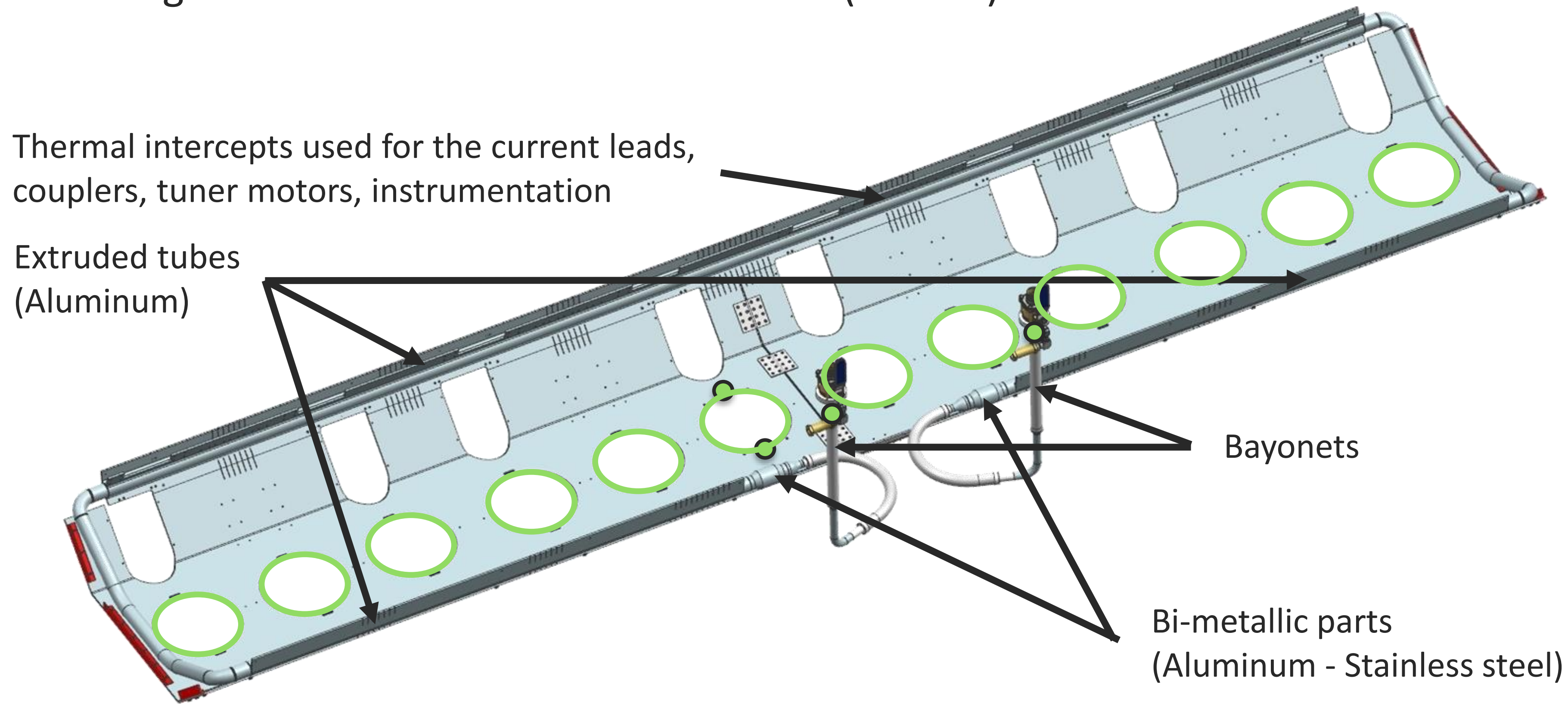
The line A has a ¾” OD (19.05 mm), and the pumping line has a 2.5” OD (63.5 mm).
Max vertical thermal contraction: 1/8” (3.15 mm)



4. Piping engineering note

4.3 Line E&F - 35-50 K line

The 35-50 K line has a 1.9” OD. This line is used to actively cool the thermal shield.
Max longitudinal thermal contraction: 0.45” (11 mm).



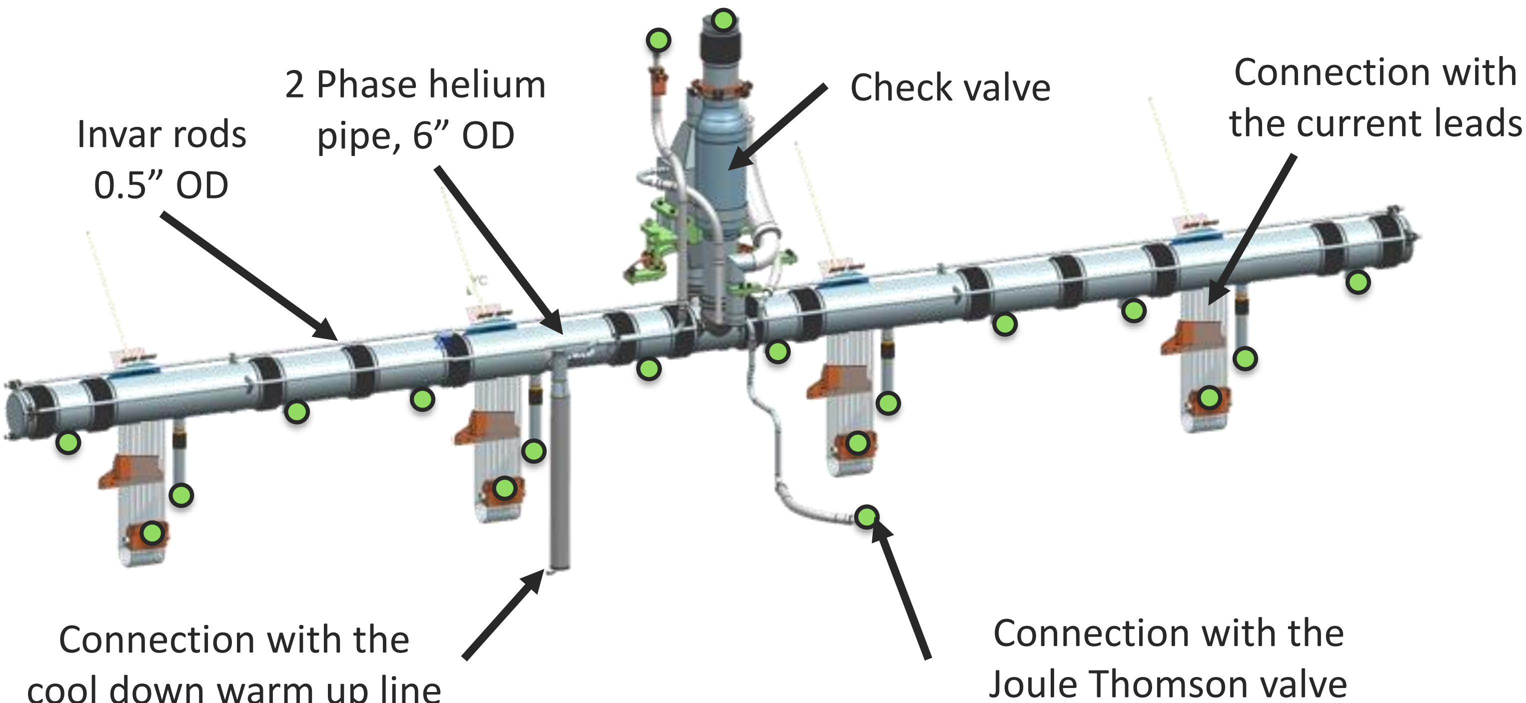
4. Piping engineering note

4.4 Line G - Two Phase helium pipe

The line G has a 6” OD. Calculations have been done to simulate the cool-down, the lost of insulating vacuum, and the beam vacuum lost.

Max longitudinal thermal contraction between cavities /solenoids : 0.05” (1.3 mm)

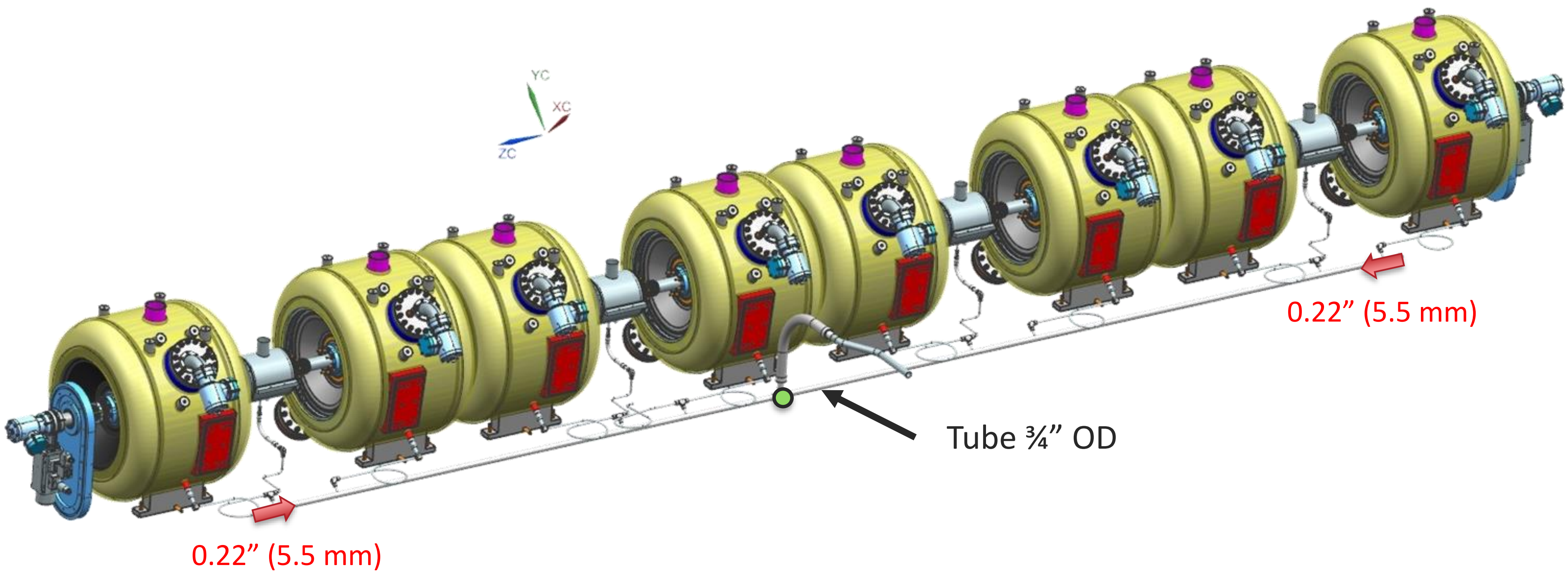
Max vertical thermal contraction between cavities /solenoids : 0.1” (2.4 mm)



4. Piping engineering note

4.5 Line H - Cool down / warm up line

The line H is used to cool down until 5 K the cavities and solenoids.
Max longitudinal thermal contraction between cavities /solenoids : 0.22” (5.5 mm)



4. Piping engineering note

4.6 Pressure relief calculation

Calculations have been done in order to demonstrate that all the pipes of SSR1 cryomodule have been designed per venting requirements.

	Needed diameter for the chimney of the solenoid	Needed diameter for the chimney of the dressed cavity	Needed diameter for the 2-phase helium pipe	Needed diameter for the relief line
Loss of insulating vacuum	6.3 mm	28.9 mm	84.7 mm	85.1 mm
Cavity vacuum loss	4.0 mm	29.7 mm	84.3 mm	84.3 mm
Magnet quench	24.6 mm	-	49.2 mm	49.2 mm
Considered diameter	35 mm	57 mm	146.8 mm	108.2 mm

Pressure drop analysis have ben performed to estimate the available relief capacity compared to the required mass flow rate.

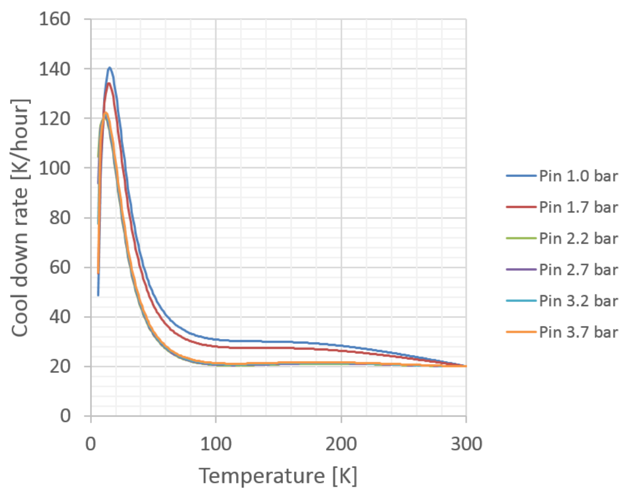
Each bayonet has a relief valve in order to protect the 35-50 K line and the 5 K line.

5. Valve sizing

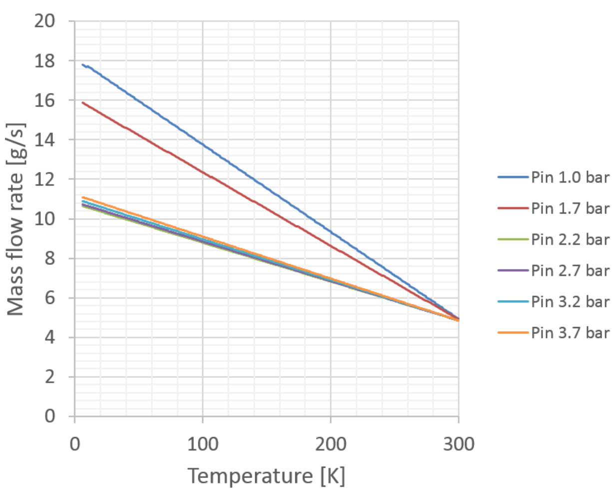
5.1 Cool down valve

Finite element analysis have shown that it was necessary to cool down the 35-50 K line at 5 K/hour in order to avoid high stresses. Nevertheless, the 5 K line can be cooled down independently and at a higher rate:

- Around 20 K/hour from 90 K to 175 K.
- Around 120 K/hour through the superconducting transition at 9.2 K



Required cool down rate



Required mass flow rate

5. Valve sizing

5.1 Cool down valve

By calculating the resistance of each part of the line, it is possible to estimate what is the mass flow percentage

	Mass flow percentage
In each cavity	10 %
In each Solenoid	3 %
In the level can	7 %

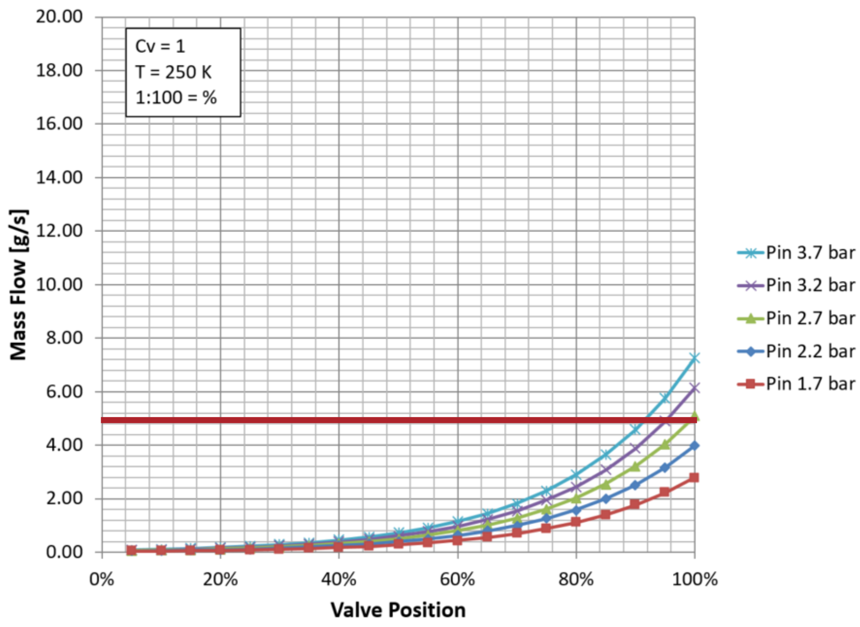
According to the pressure of the 5 K line, the pressure drop due the cool down valve will be different

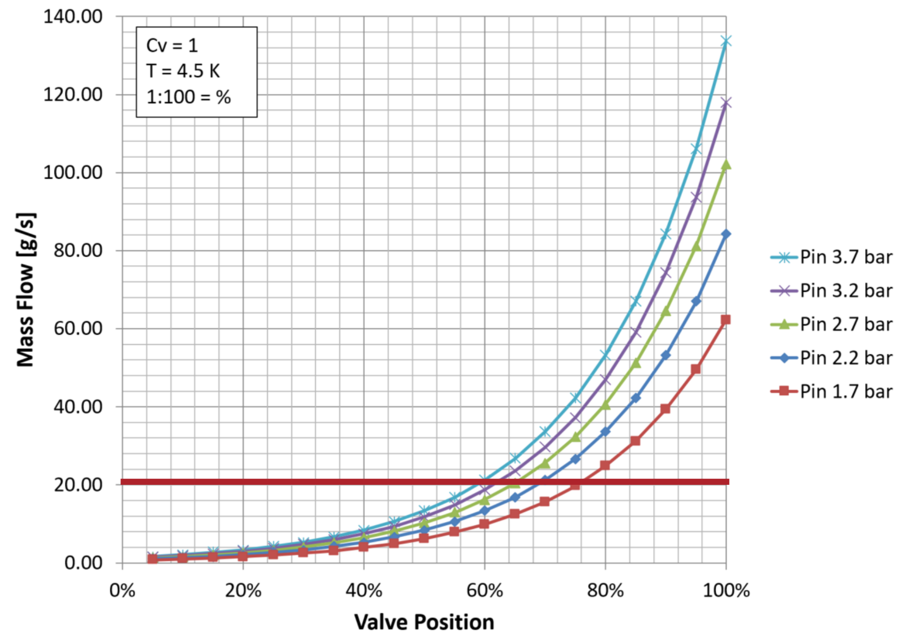
Pressure of the 5K line (bar)	Pressure drop due to the cool down valve at 4.5 K (bar)	Pressure drop due to the cool down valve with gas helium (bar)
3.7	2.36	2.20
3.2	1.86	1.72
2.7	1.43	1.34
2.2	0.99	0.95
1.7	0.55	0.55

5. Valve sizing

5.1 Cool down valve

Based on these pressure drops, the mass flow through the cool down valve has been calculated according to the valve position.



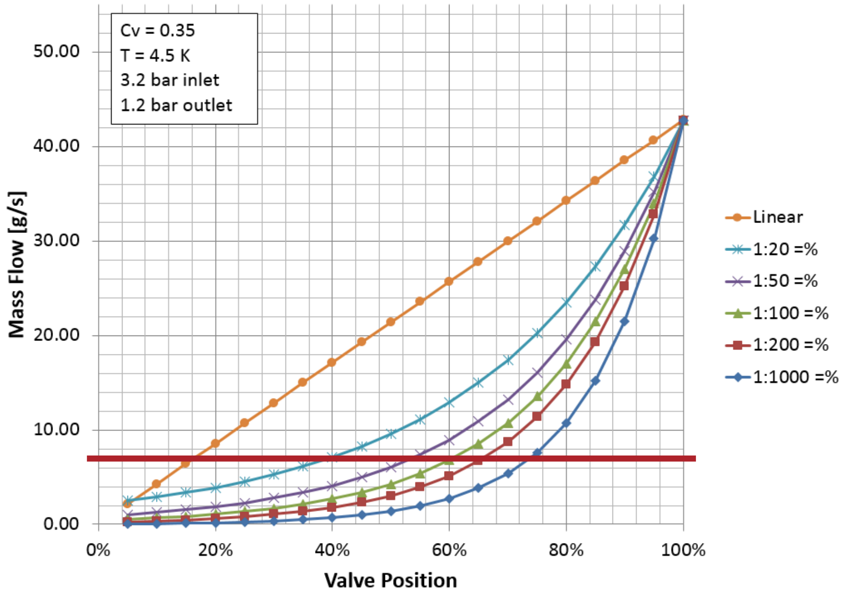


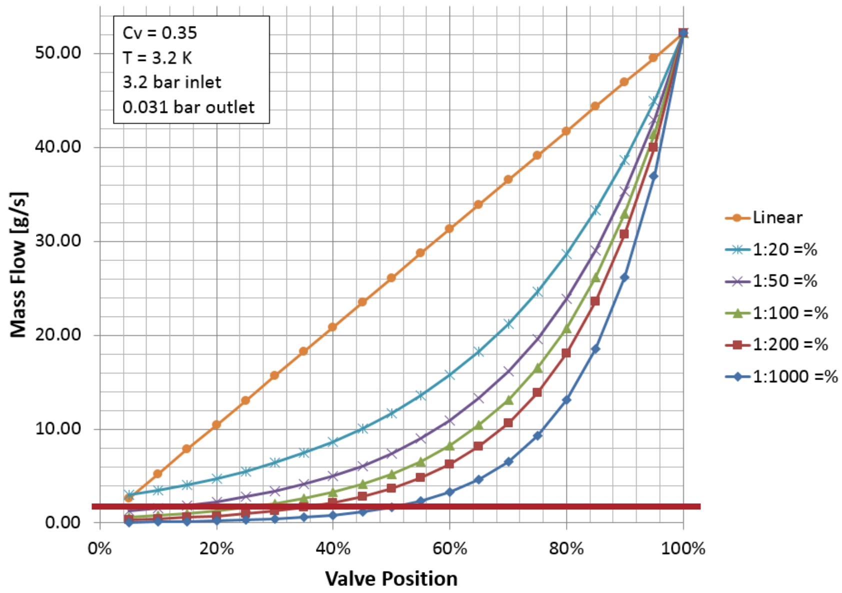
At the beginning of the cool down this valve Cv = 1 1:100 modified to zero will operate around 100 % open, and then around 65 % at 5 K.

5. Valve sizing

5.2 Joule-Thomson valve

During the cool down the JT valve should operate with a mass flow around 7 g/s which matches with the design mass flow of the heat exchanger.





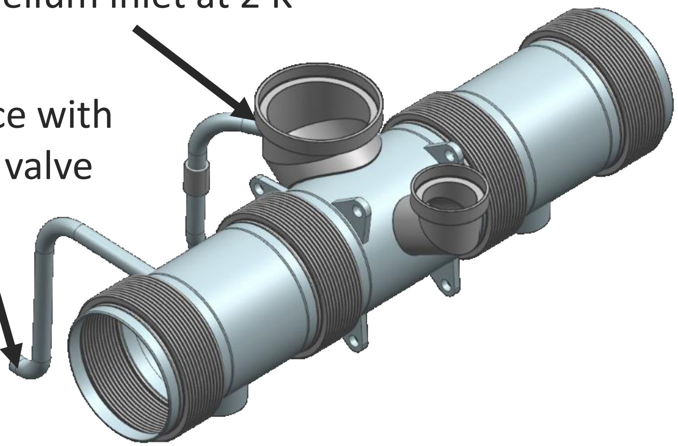
Before pumping, this valve “Cv = 0.35 1:1000 modified to zero” will operate around 70-75 % open, and during the operation around 50 %.

6. Experience from LCLS II

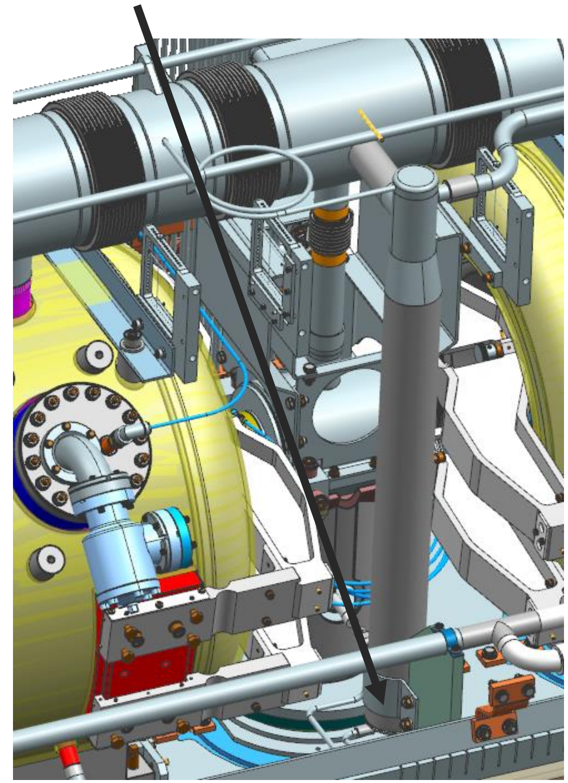
The design have been done in order to mitigate the thermal acoustic oscillations, helium bath instability, and structural vibrations.

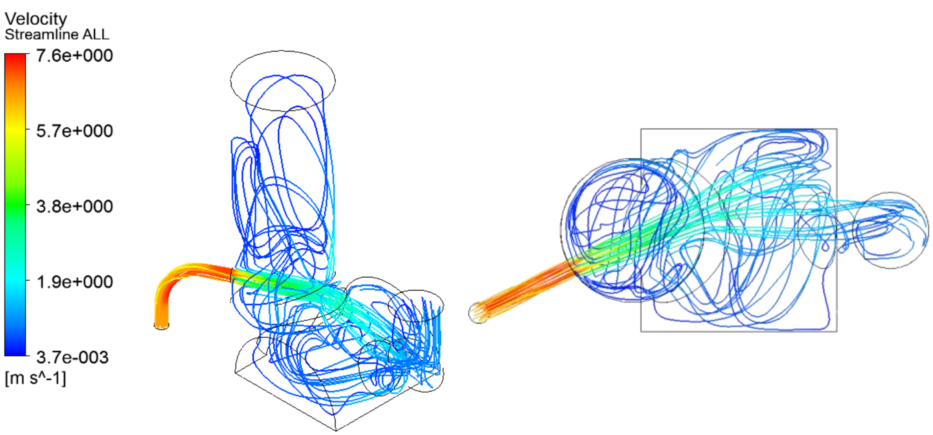
Helium inlet at 2 K

Interface with the JT valve



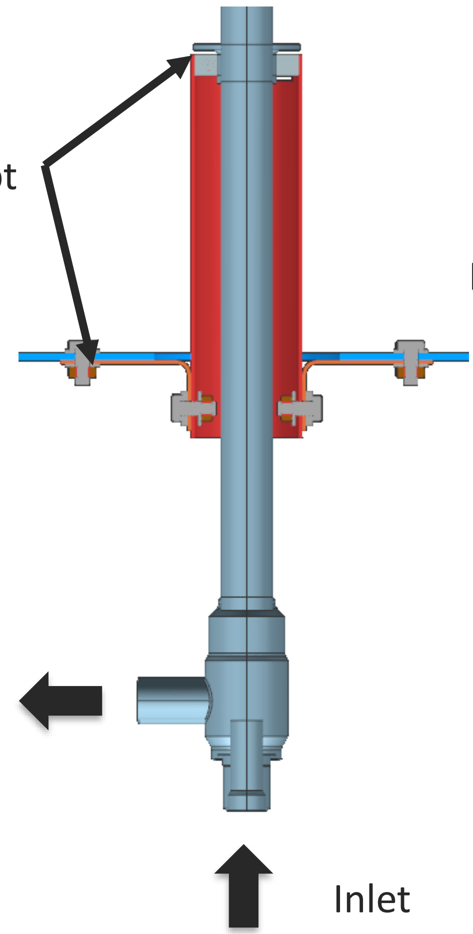
A bracket has been designed in order to avoid vibration on the two phase helium pipe

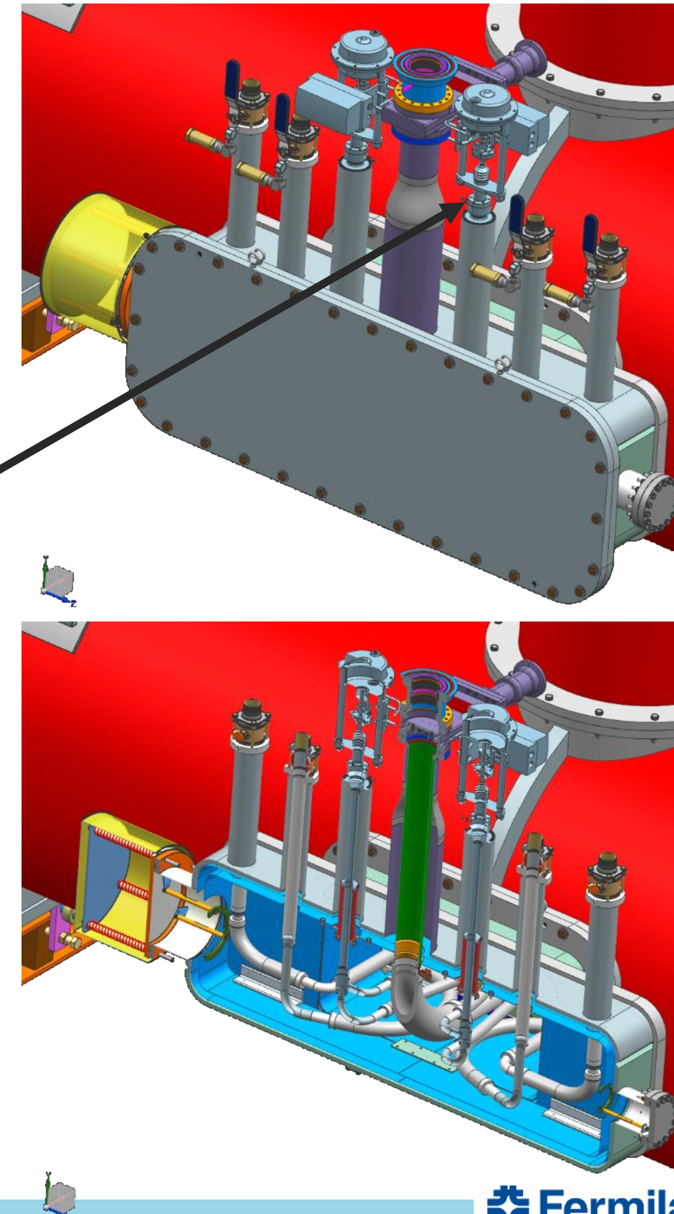




6. Experience from LCLS II

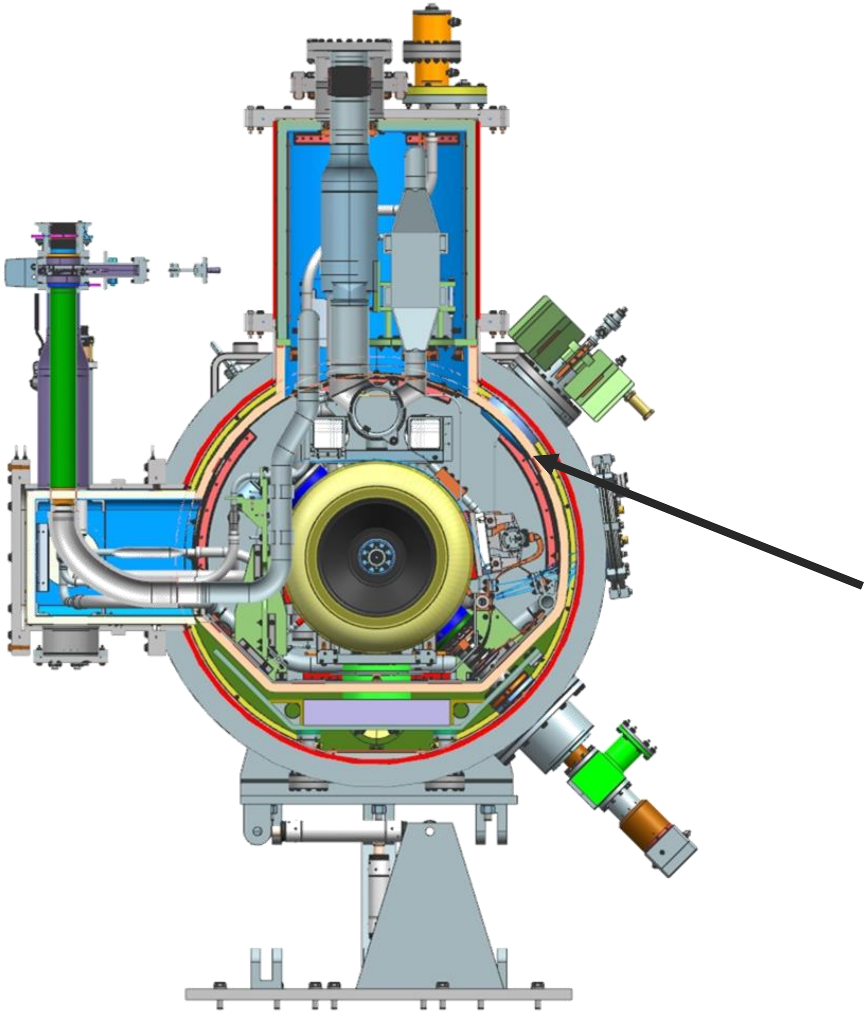
The cryogenic valves have been set up in the same way as LCLS II cryomodule:





7. Internal interfaces

7.1 Coldmass / Vacuum vessel



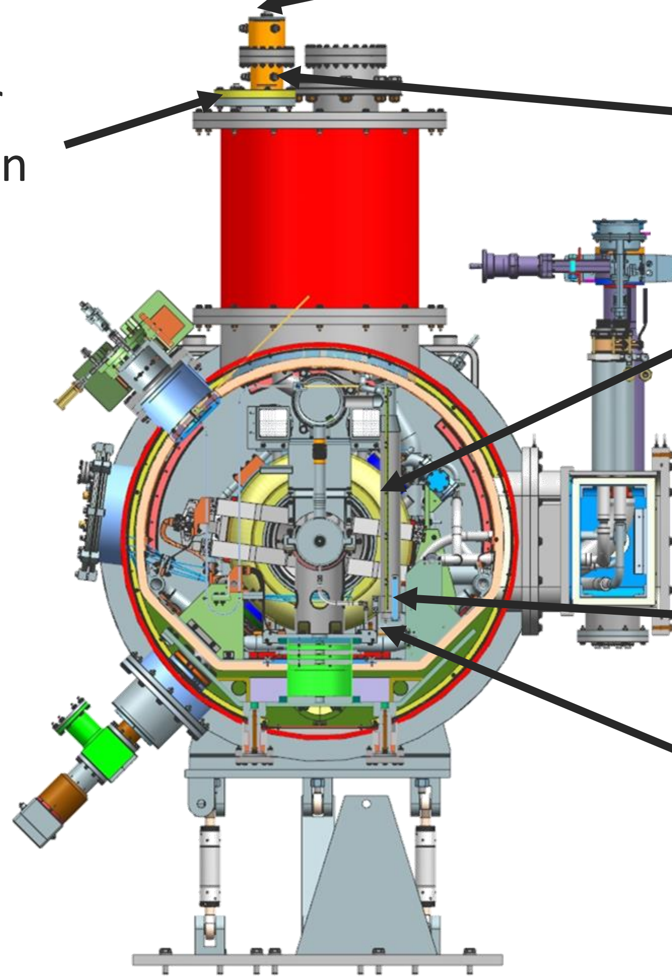
Between the coldmass and the vacuum vessel we have at least 35 mm which is enough in order to be able to set up 20 layers of MLI and the magnetic shield.

Here the distance is more important in order to be able to slide the coldmass in the vacuum vessel. **Margin 20 mm, This was an input for the insertion tooling.**

The thermal shield will be covered by 30 layers of MLI.

7. Internal interfaces

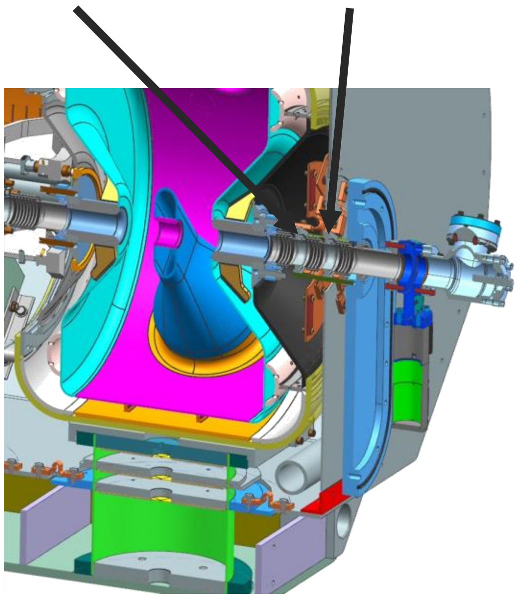
7.3 Helium level probe



7. Internal interfaces

The design of the thermal straps have been checked thanks to analytical calculations.

7.4 Thermal straps: Beam line



Heat by conduction:

- On the 1st thermal intercept : 1.1 W
- On the 2nd thermal intercept : 0.06 W

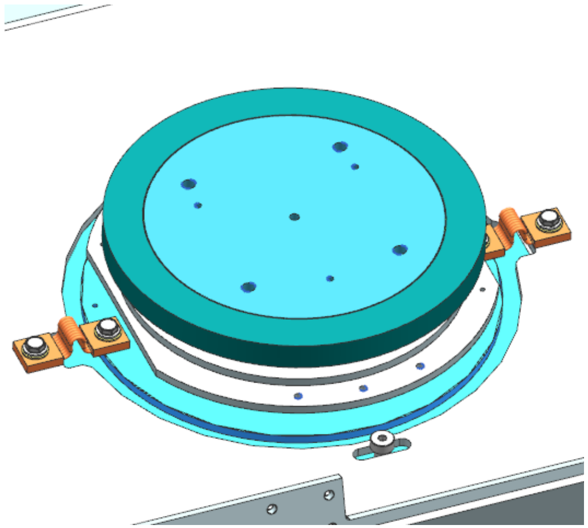
Shield at 50 K and equilibrium at 55 K	
Surface area (m2)	1.2E-04
Length (m)	0.055
Int (λ.dT)	4031.6
Heat load by conduction (W)	8.6

Shield at 5 K and equilibrium at 10 K	
Surface area (m2)	1.2E-04
Length (m)	0.045
Int (λ.dT)	2918.8
Heat load by conduction (W)	7.6

The thermal straps are properly designed

7. Internal interfaces

7.4 Thermal straps : Support post



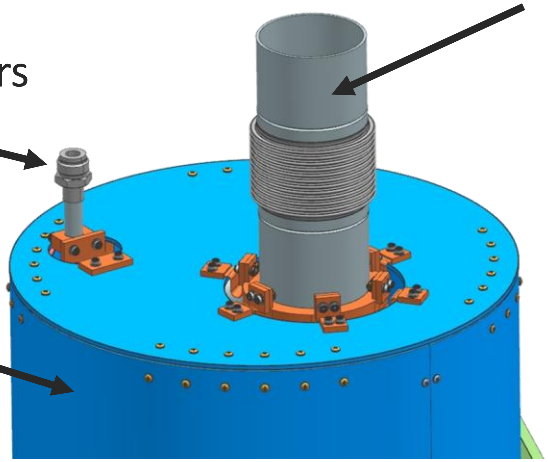
Heat by conduction on the 35-50 thermal intercept : 1.7 W

Shield at 50 K and equilibrium at 55 K	
Surface area (m2)	3.927E-05
Length (m)	0.060
Int (λ.dT)	4031.6
Heat load by conduction (W)	2.6

The thermal straps are properly designed

7. Internal interfaces

7.4 Thermal straps : Relief line / Pressure transducer



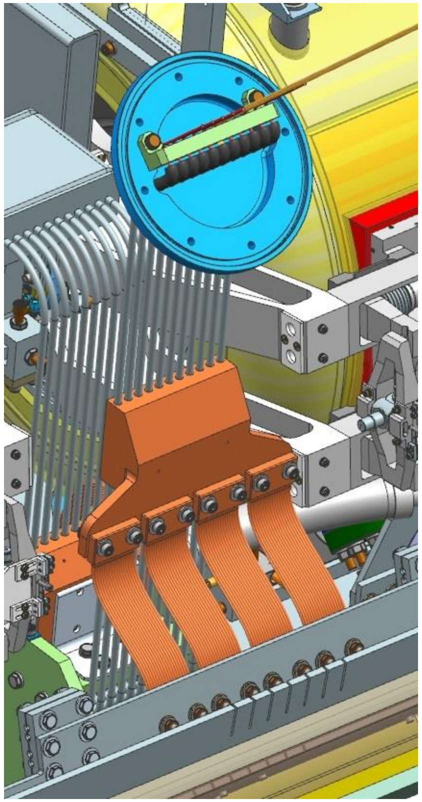
Heat by conduction on the thermal intercept ≈ 0.8 W
Heat by radiation on the top of the relief line ≈ 1W

Shield at 60 K and equilibrium at 65 K	
Surface area (m2)	2.4E-04
Length (m)	0.065
Int (λ.dT)	3186.6
Heat load by conduction (W)	11.55

The top part of the thermal shield being the warmest part, additional margin has been taken. Robust design, the thermal straps are properly designed.

7. Internal interfaces

7.4 Thermal straps : Current leads



Heat by conduction and Joule effect on the 1st thermal intercept of the current leads ≈ 25 W

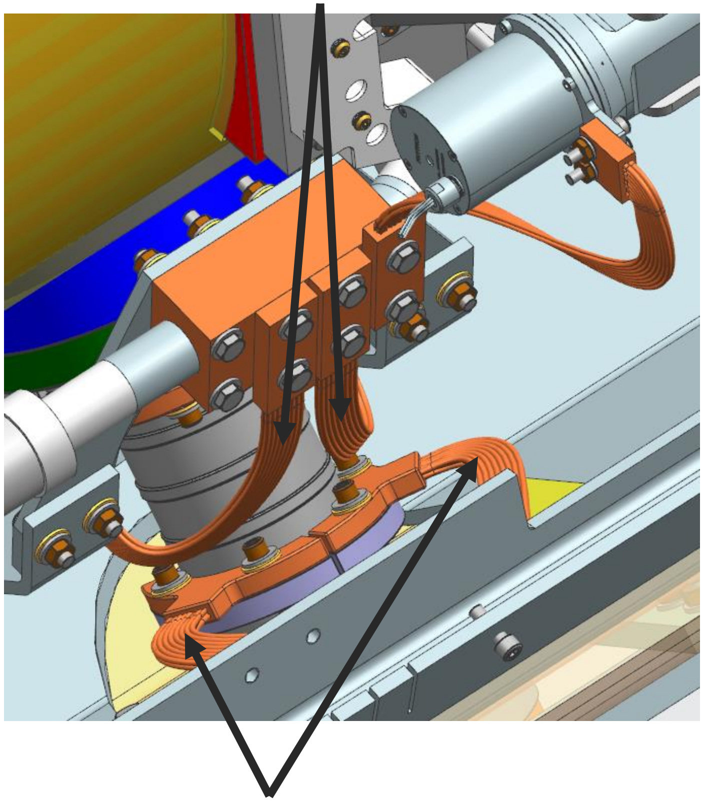
Shield at 50 K and equilibrium at 60 K	
Surface area (m2)	6.7E-04
Length (m)	0.200
Int (λ.dT)	7581.1
Heat load by conduction (W)	25.3

The thermal straps are properly designed

7. Internal interfaces

7.4 Thermal straps : Coupler 5 K
Coupler 50 K

5 K thermal straps



35-50 K thermal straps

Requirements:

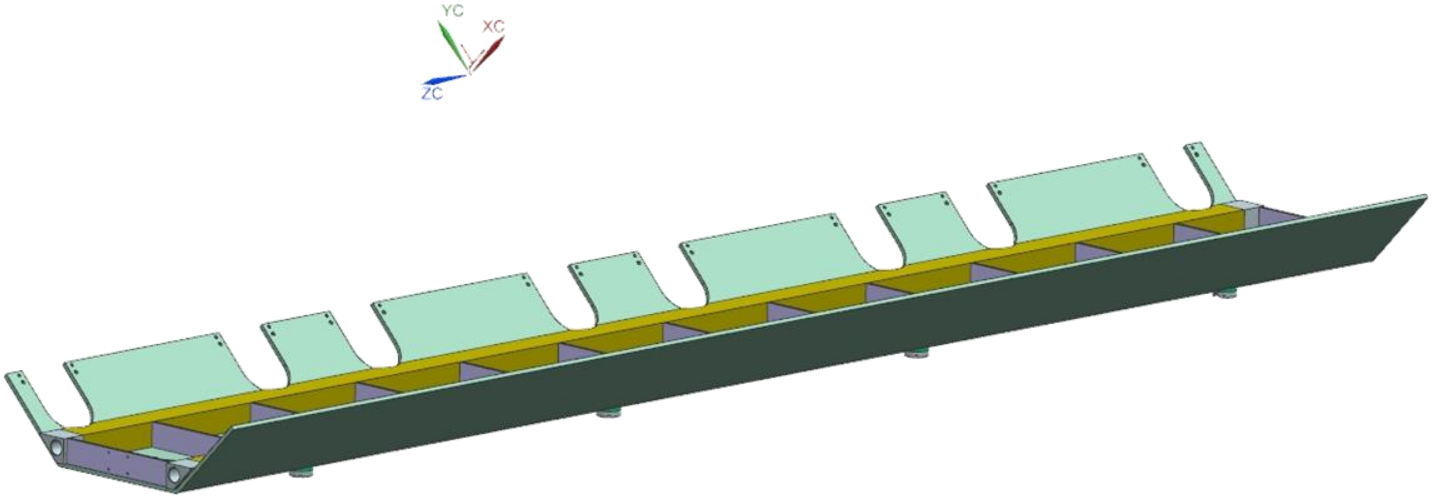
Temperature at 5 K intercept	**< 15 K**
Temperature at 35-50 K intercept	**< 125 K**
Maximum 2K heat load SSR1	**< 0.8 W**
Maximum 5K heat load SSR1	**< 3.4 W**
Maximum 35-50K heat load SSR1	**< 11.0 W**

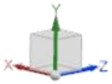
Shield at 5 K and equilibrium at 15 K	
Surface area (m2)	1.6E-04
Length (m)	0.200
Int (λ.dT)	7714.7
Heat load by conduction (W)	6.1

Shield at 50 K and equilibrium at 125 K	
Surface area (m2)	1.6E-04
Length (m)	0.200
Int (λ.dT)	39038.3
Heat load by conduction (W)	30.7

The thermal straps are properly designed

8. Assembly process





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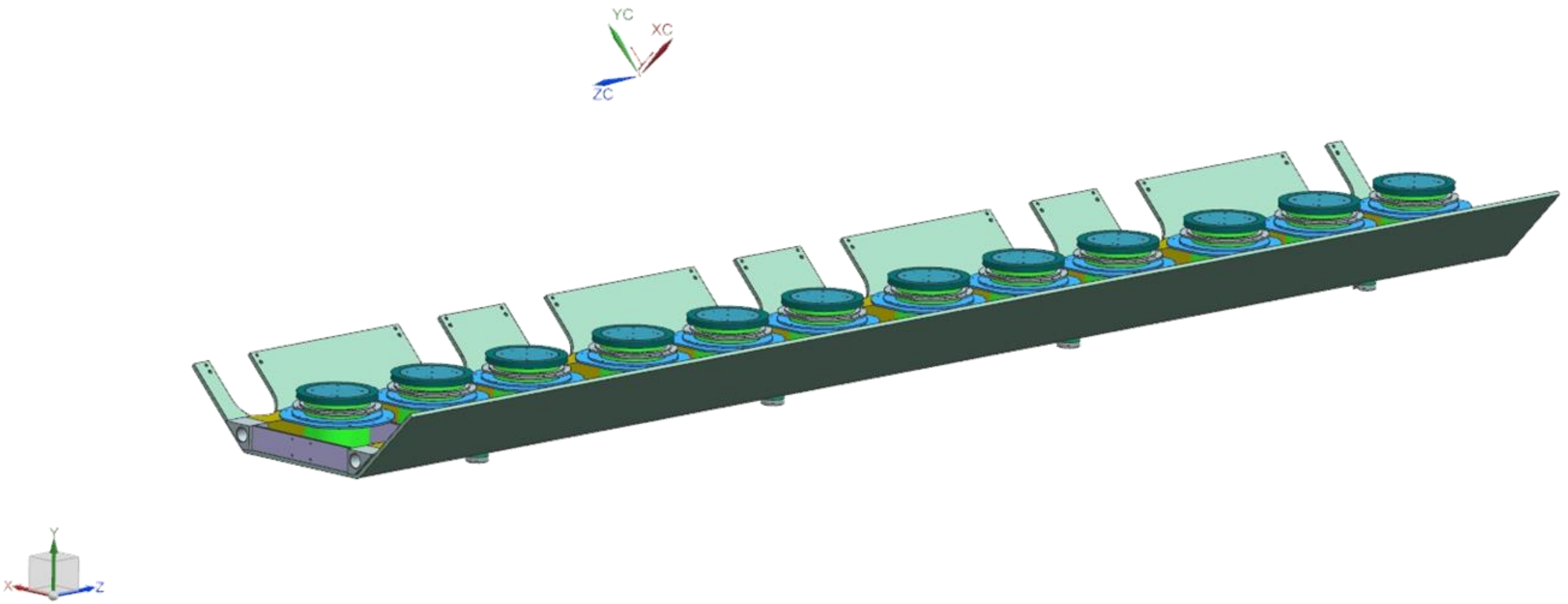
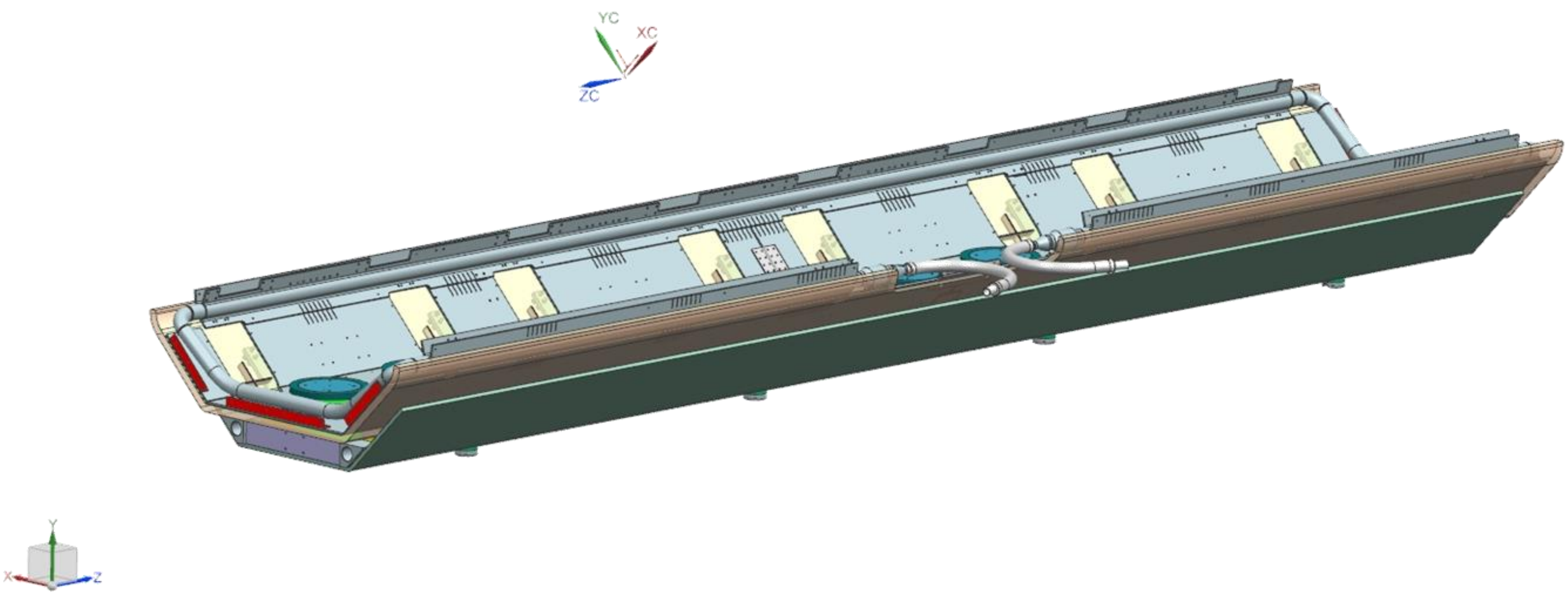
8. Assembly process



WS3a

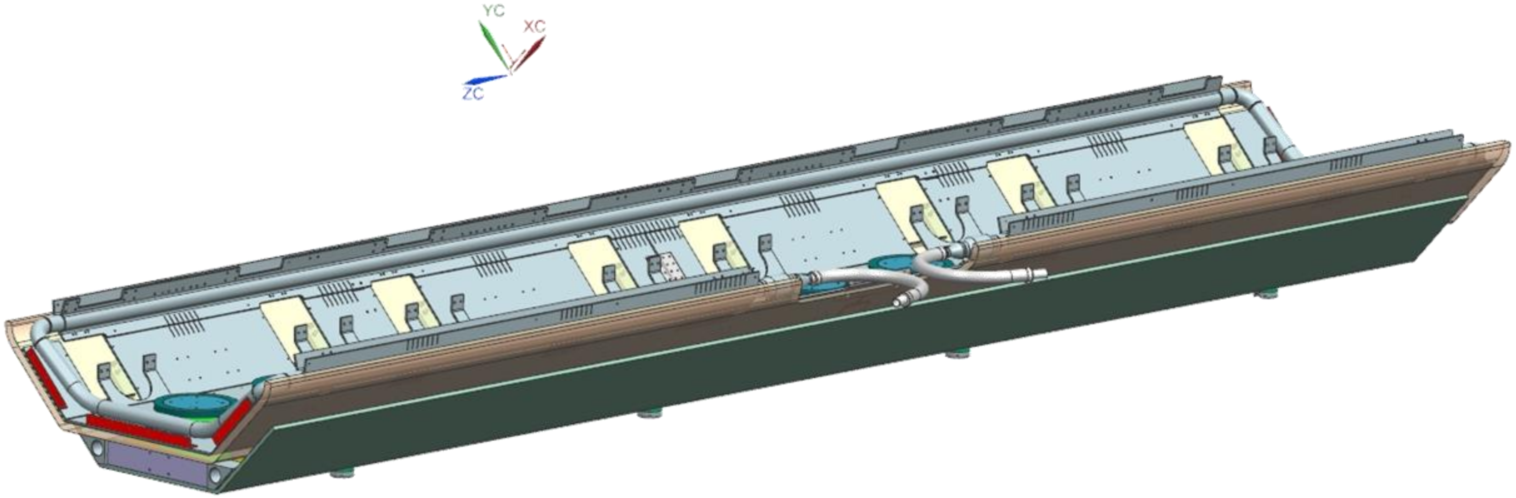
8. Assembly process

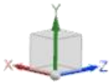
A company will deliver the lower part of the thermal shield in a single piece.
A leak test and a pressure test will be done during the manufacturing.
Design pressure: 20 barg



WS3a

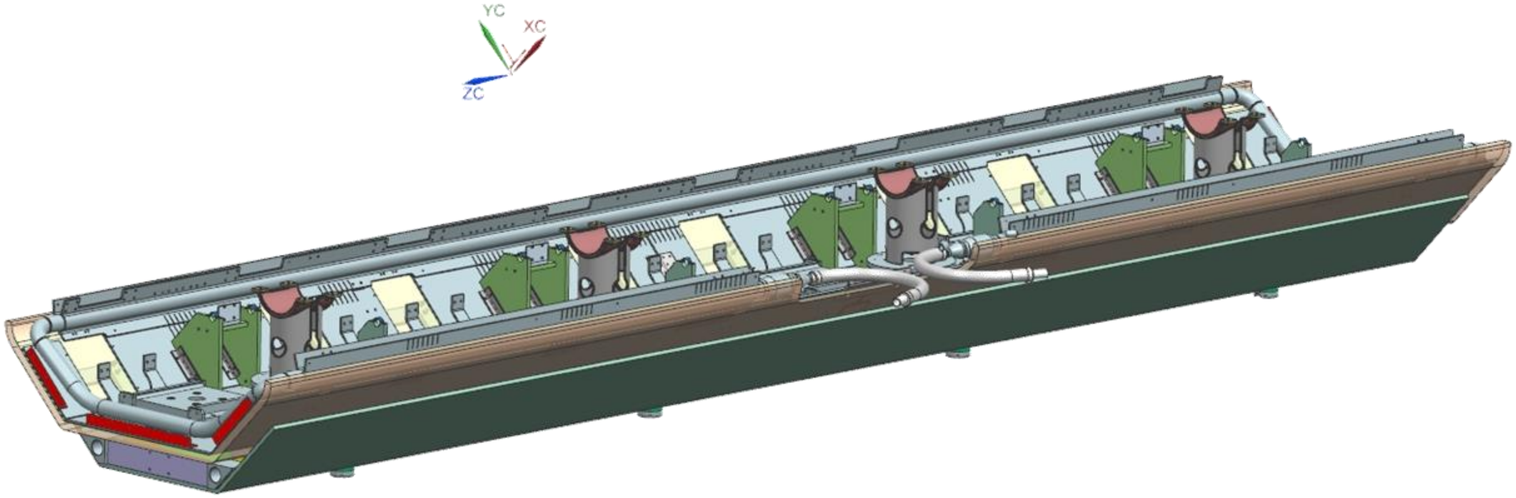
8. Assembly process

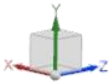




WS3a

8. Assembly process

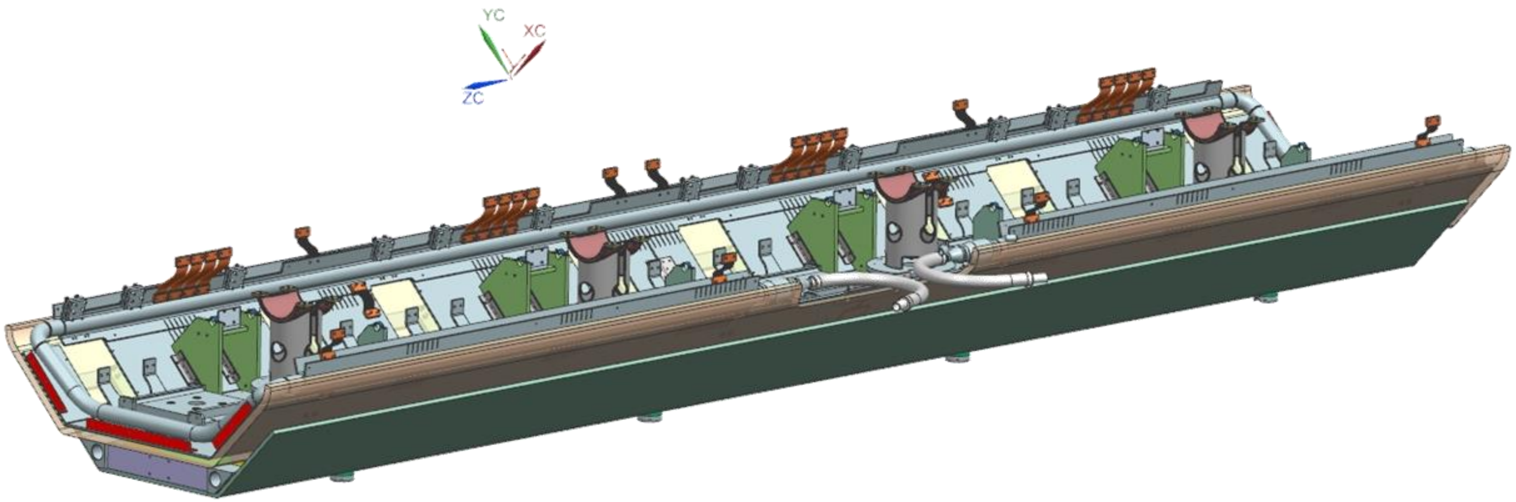


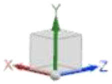


WS3a

8. Assembly process

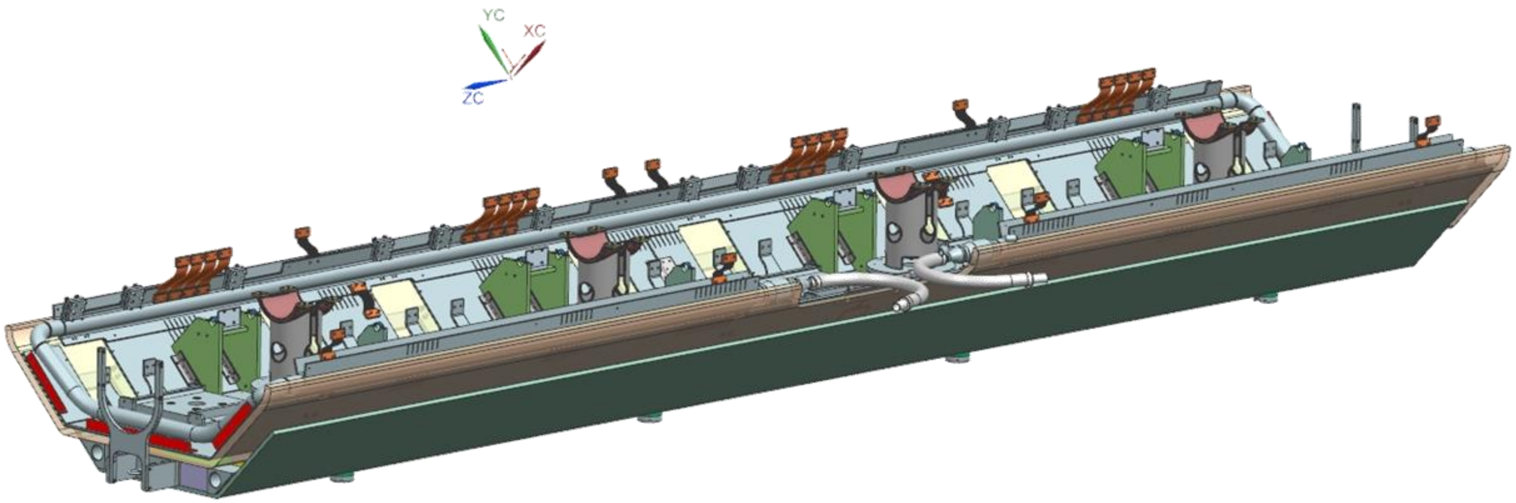
The thermal straps will be set up on the lower thermal shield using Indium.





WS3a

8. Assembly process



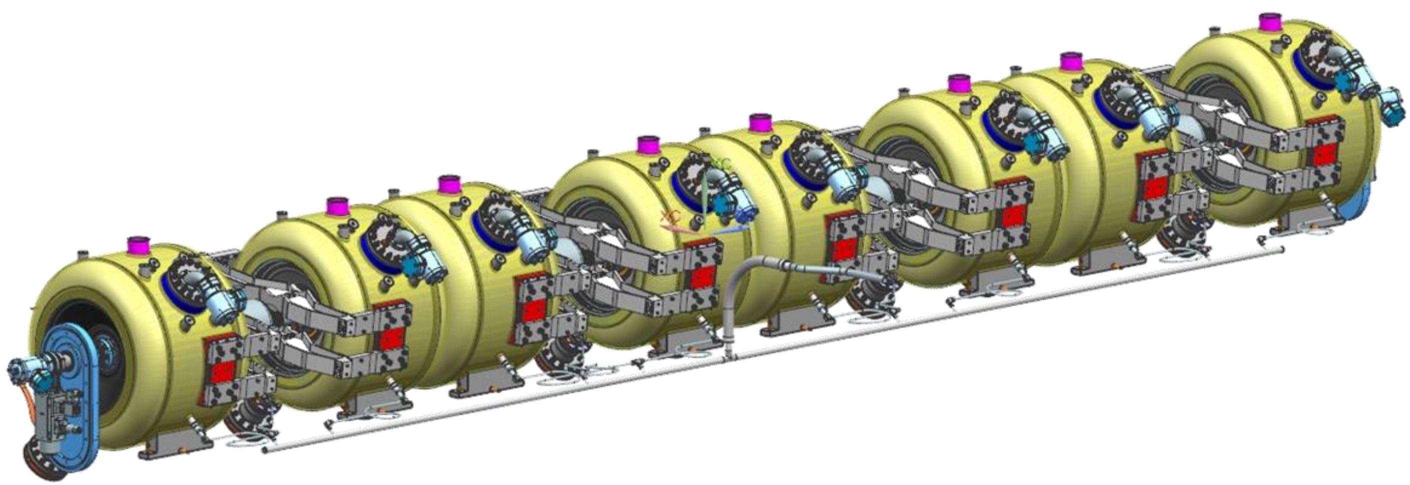
WS3a

8. Assembly process

A company will deliver the cool down line in a single piece.

A leak test and a pressure test will be done during the manufacturing.

- Design pressure of the down line: 20 barg
- Design pressure of the weld making the connection with the dressed cavities: 2.05 barg at warm, 4.1 barg at cold



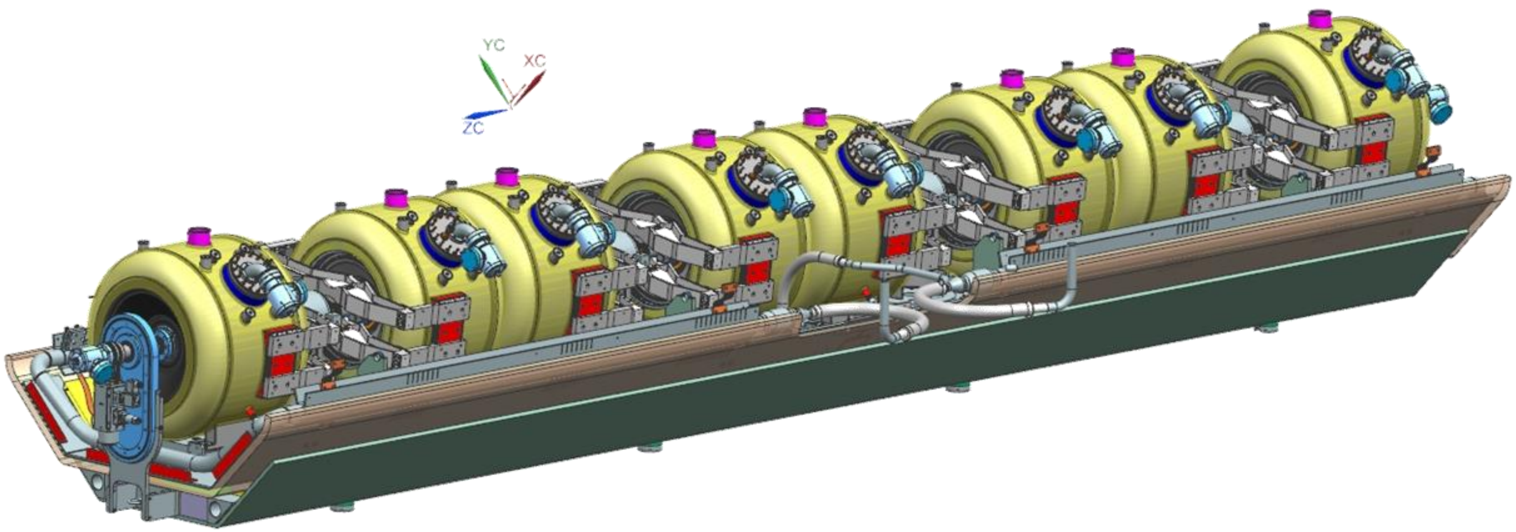
WS2

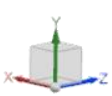
The cool down line will be welded to the cavities at Fermilab, then the MLI will be set on each cavity and on eth cryogenic lines. Finally the tuners will be set up.

8. Assembly process

Rough alignment of the cavities and solenoids with regards to the strong-back taking into account the shift due to the thermal contraction during the cool-down.

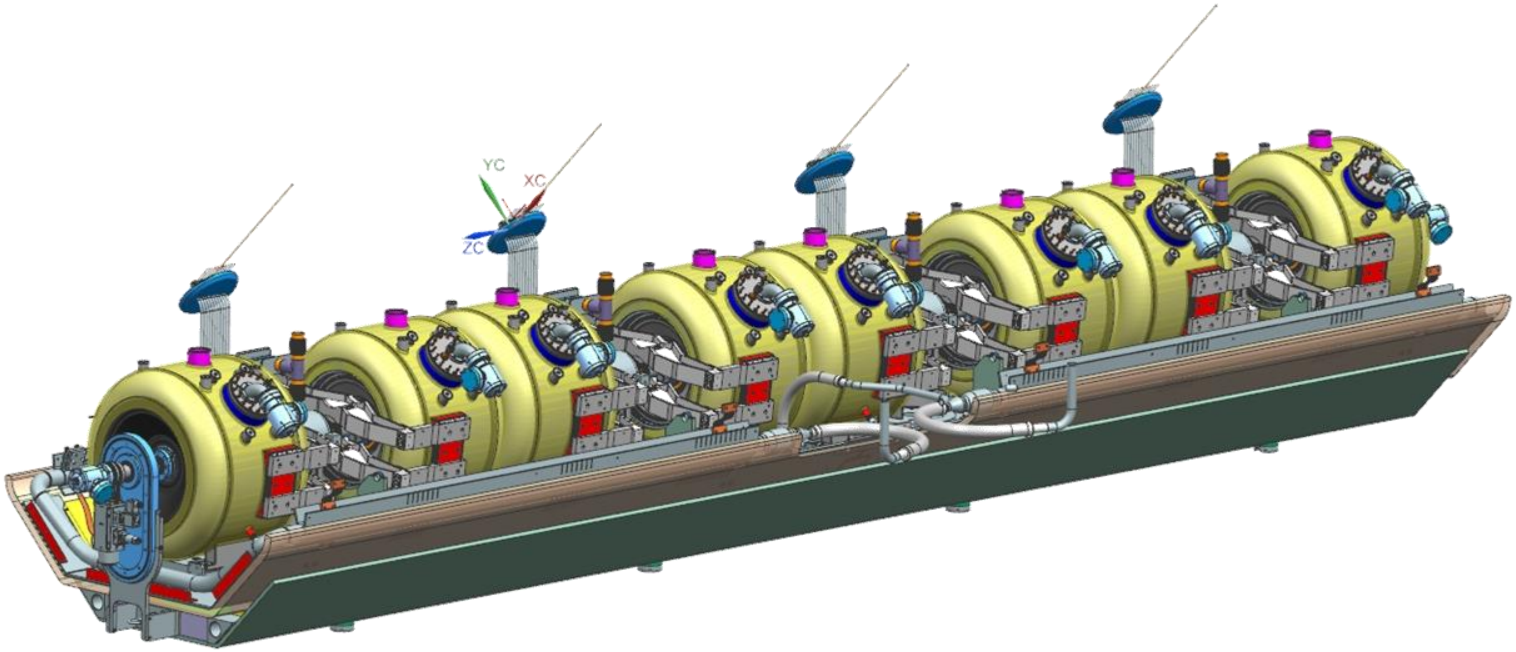
RF measurements.





WS3b

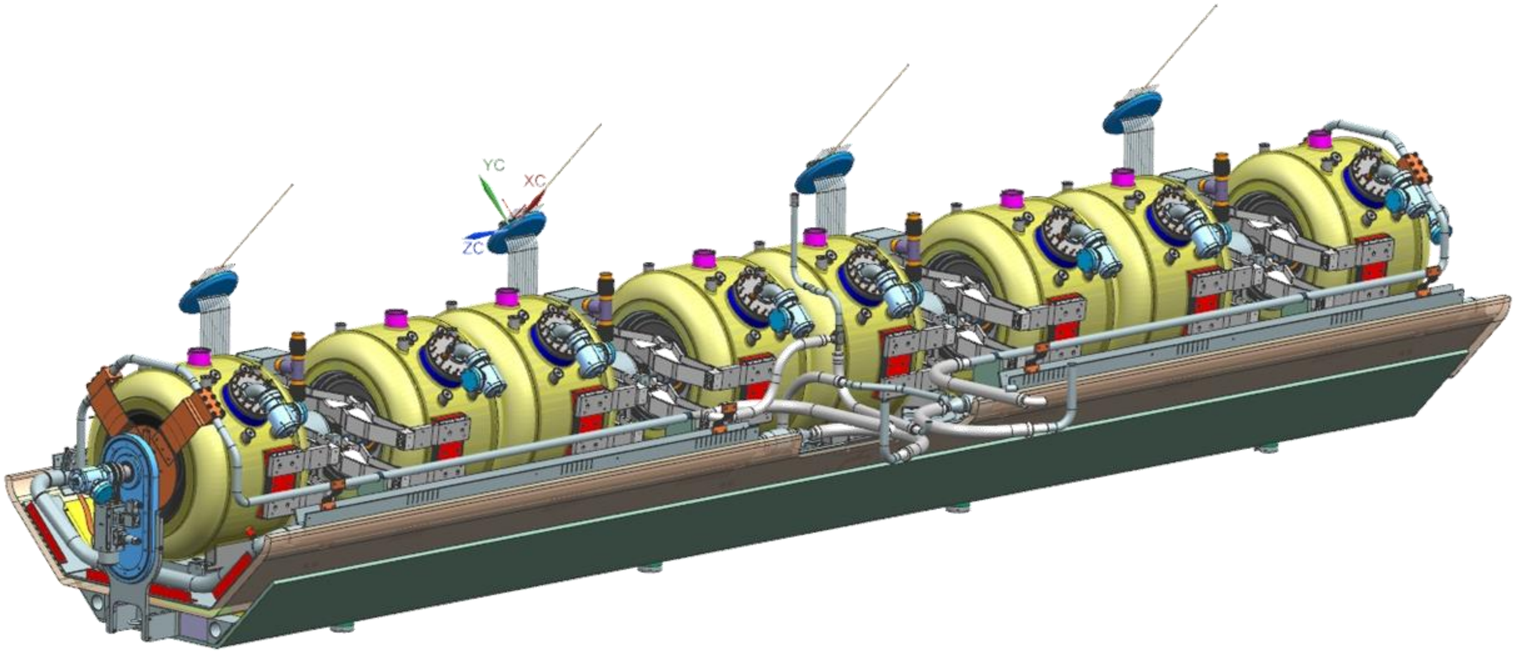
8. Assembly process

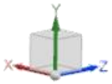


WS3b

8. Assembly process

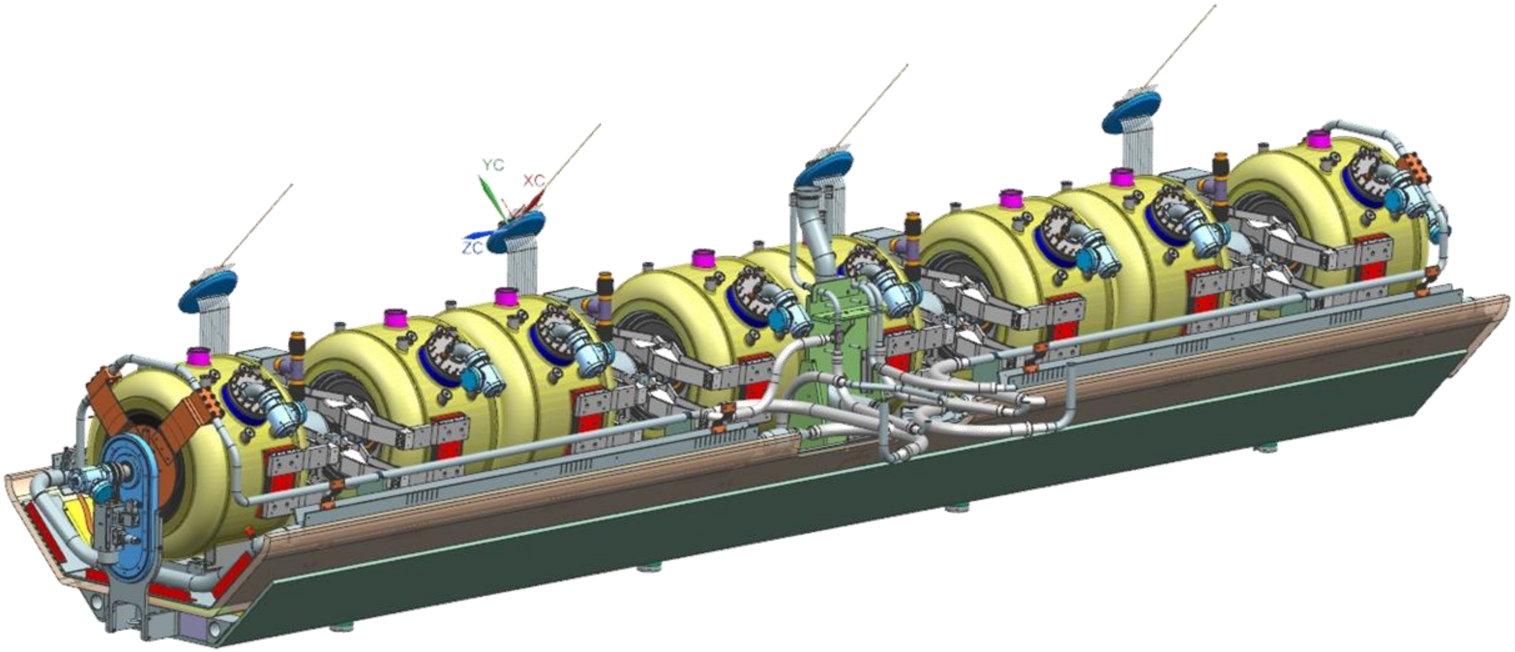
The 5 K lines and 2K lines will be leak-tested by the manufacturer.

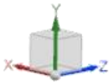




WS3b

8. Assembly process

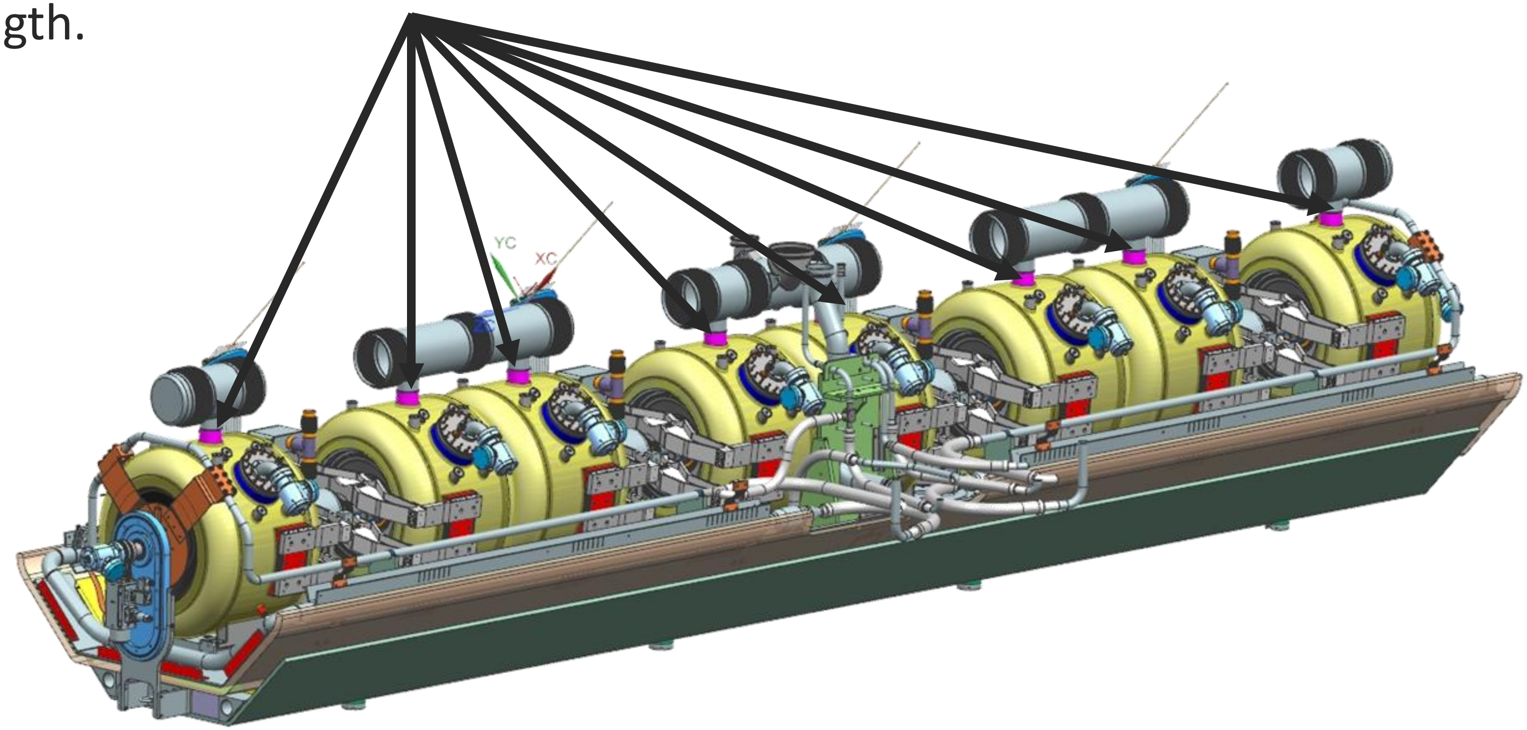


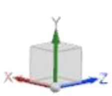


WS3b

8. Assembly process

The tubes connecting the two phase helium pipe to the cavities will be ordered ½” longer than needed. During the welding process at Fermilab these tubes will be cut to length.

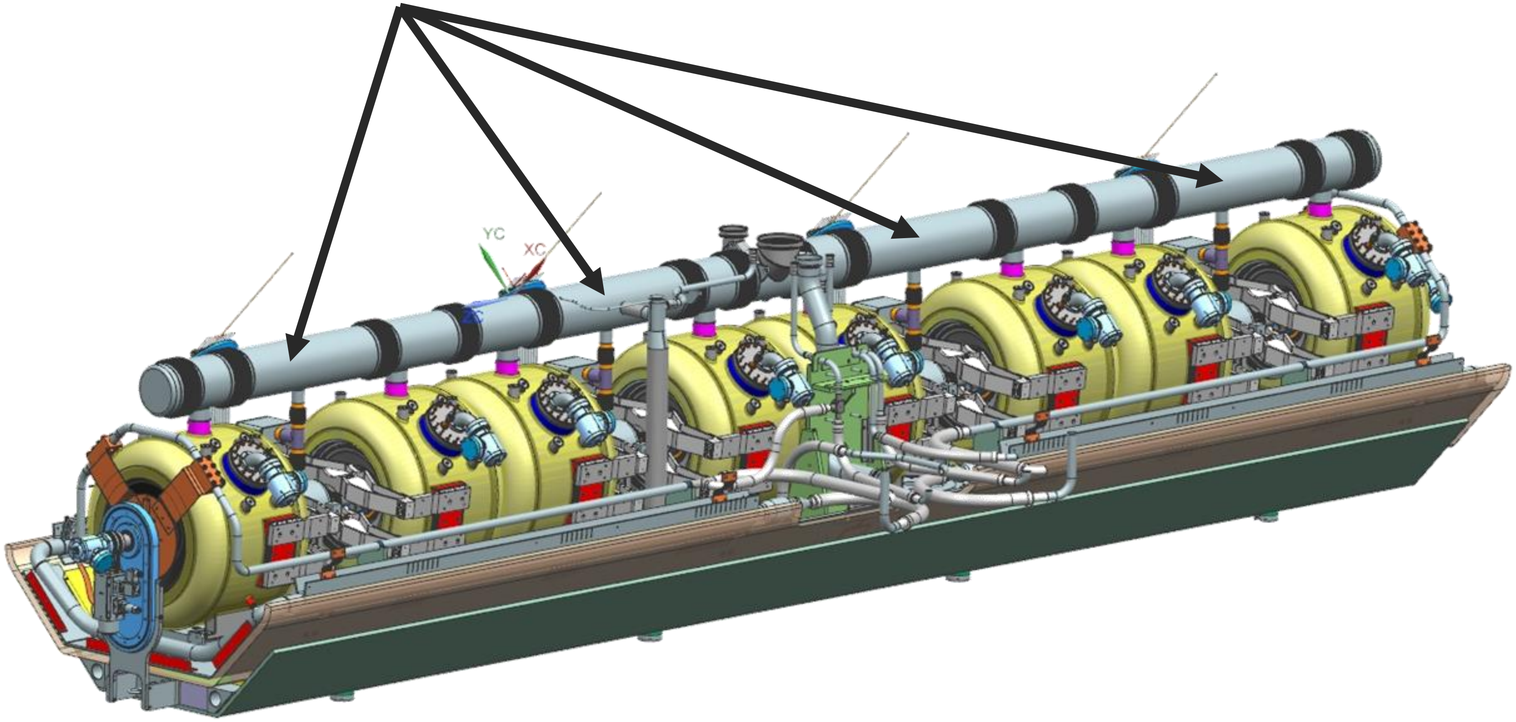


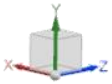


WS3b

8. Assembly process

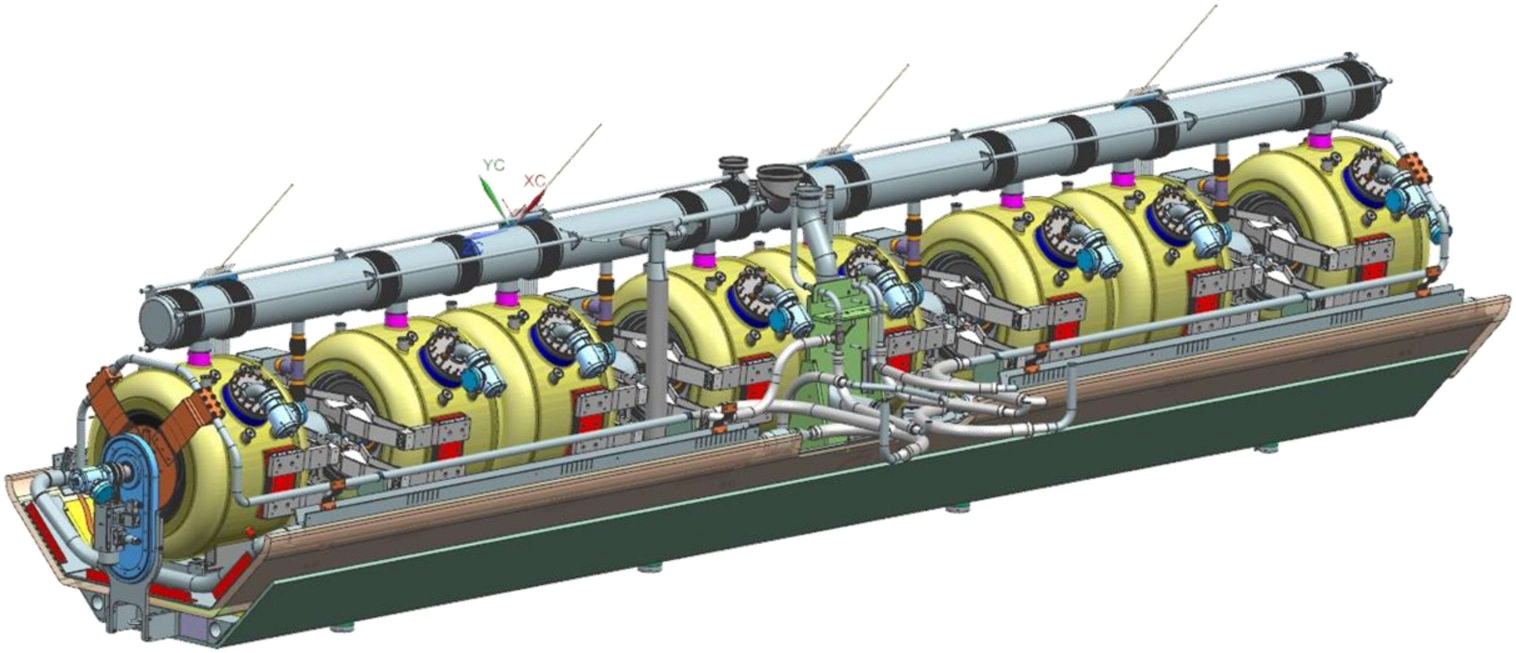
The tubes connecting on the two phase helium pipe will be ordered ½” longer than needed. During the welding process at Fermilab these tubes will be cut to length.

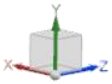




WS3b

8. Assembly process



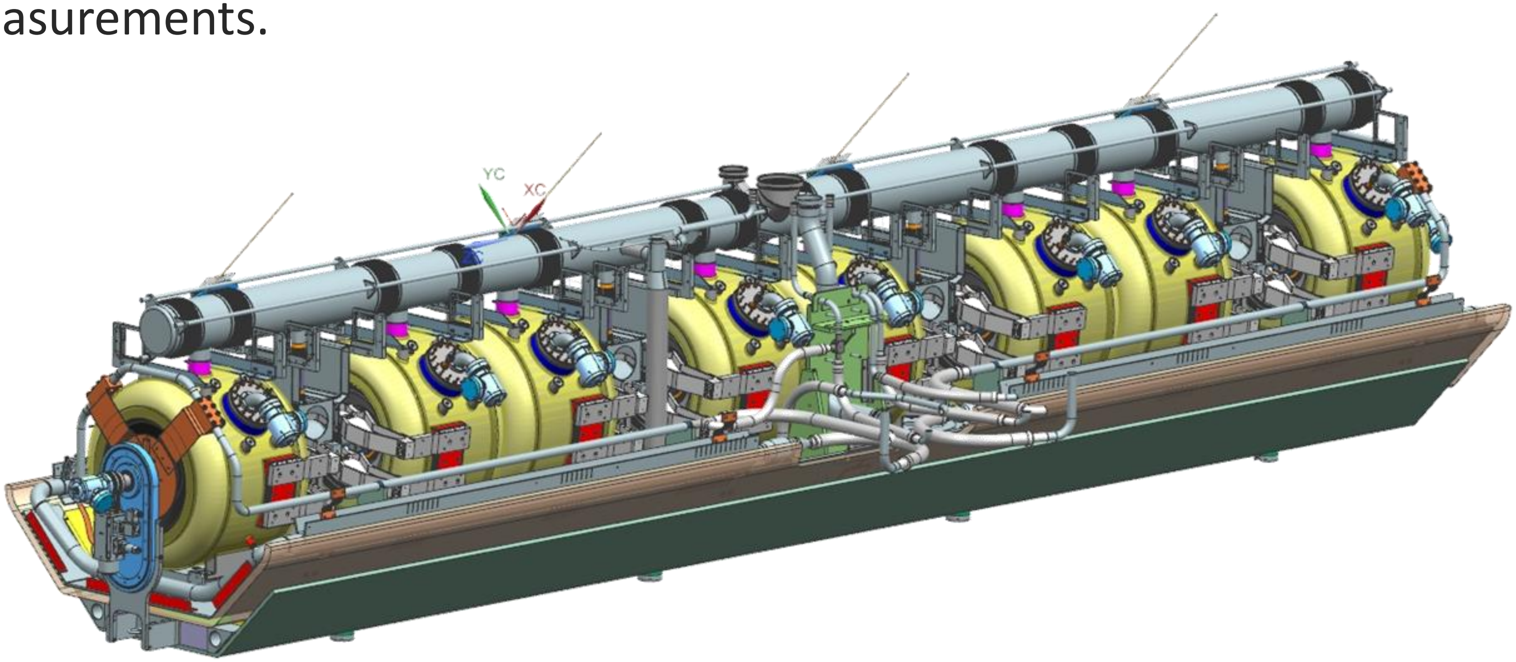


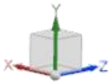
WS3b

8. Assembly process

Final alignment of the cavities and solenoids with regards to the strong-back taking into account the shift due to the thermal contraction during the cool-down.

RF measurements.

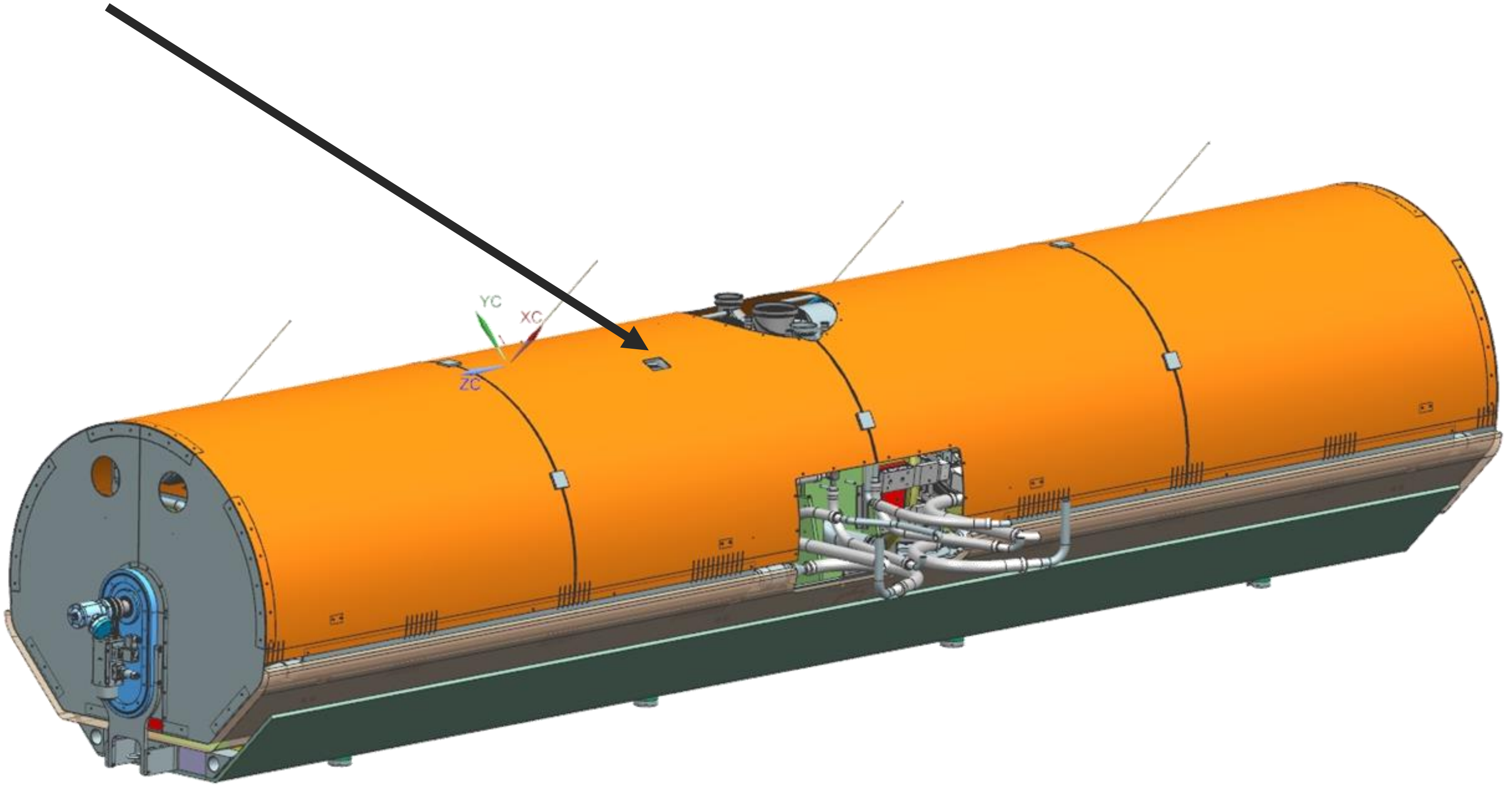


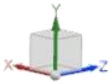


WS3b

8. Assembly process

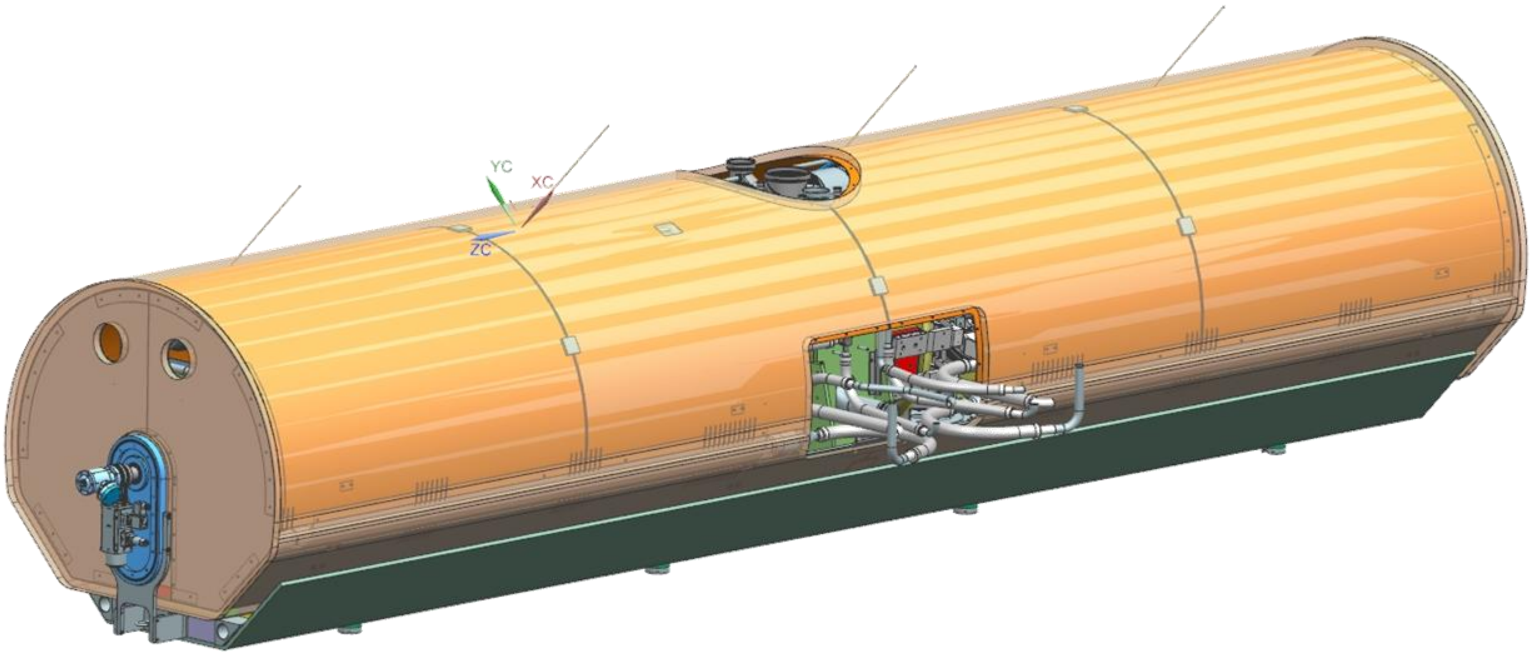
A small opening on the thermal shield is needed due to the helium container.

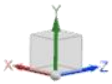




WS3b

8. Assembly process

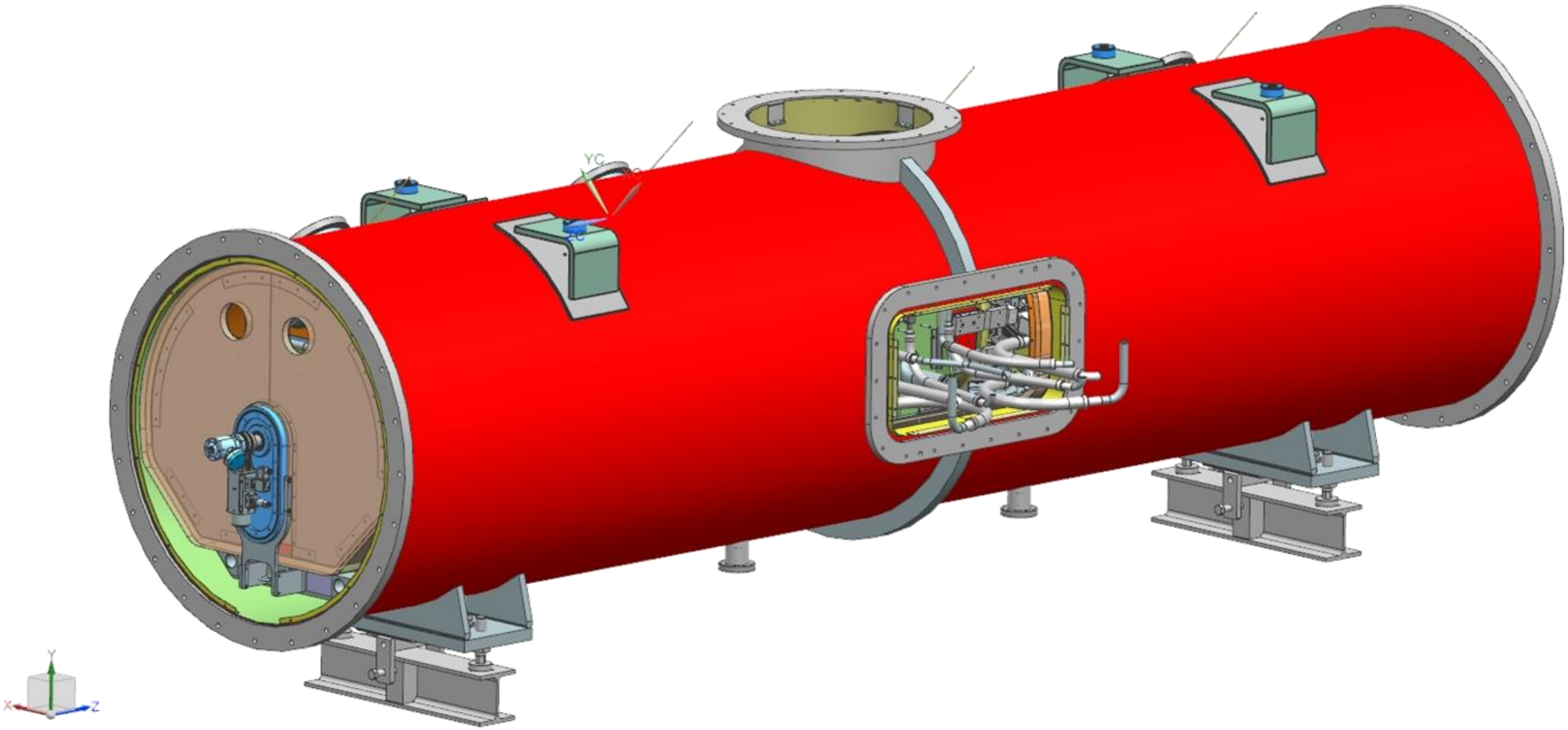




WS3b

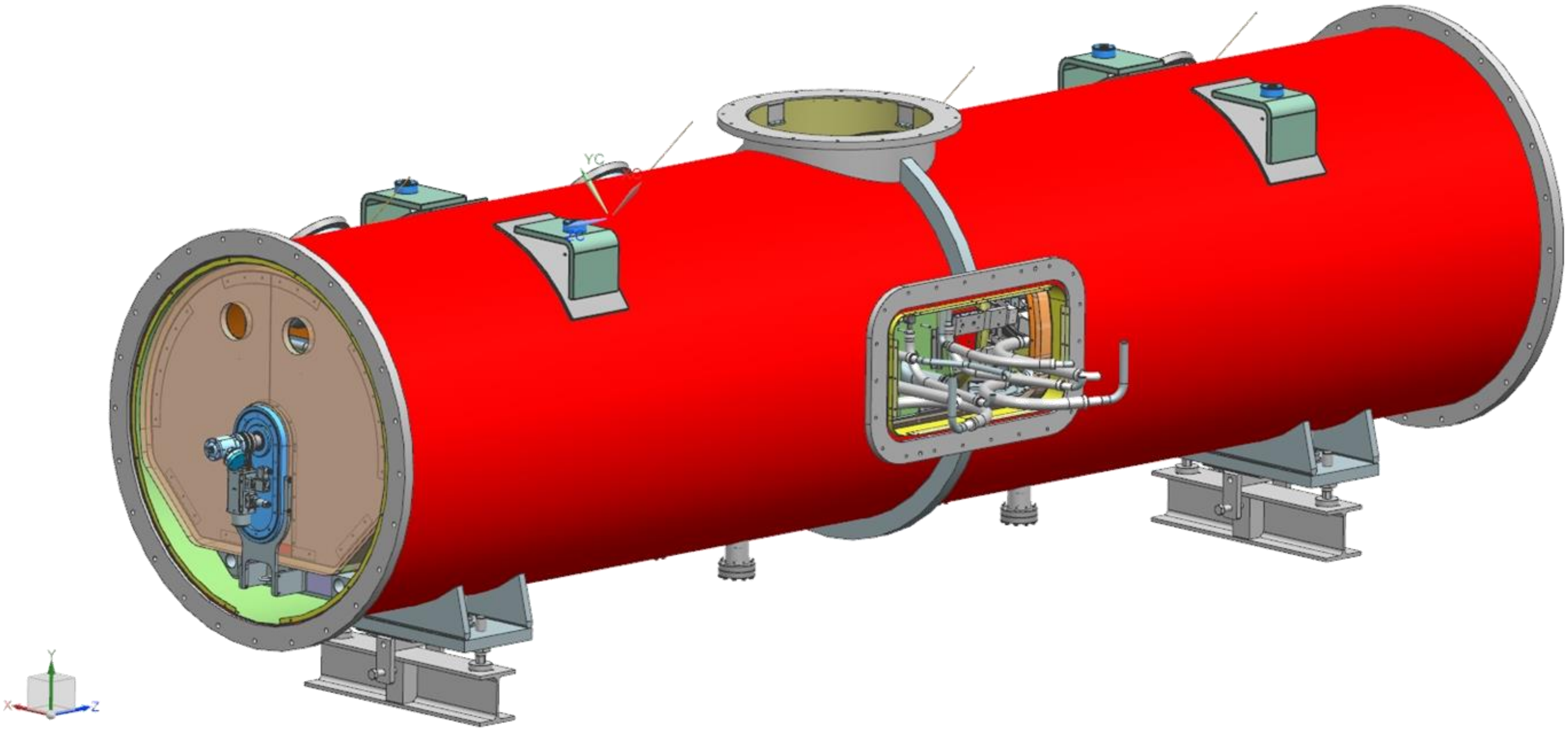
8. Assembly process

Alignment of the coldmass with regards to the vacuum vessel taking into account the shift due to the thermal contraction during the cool-down.



WS4

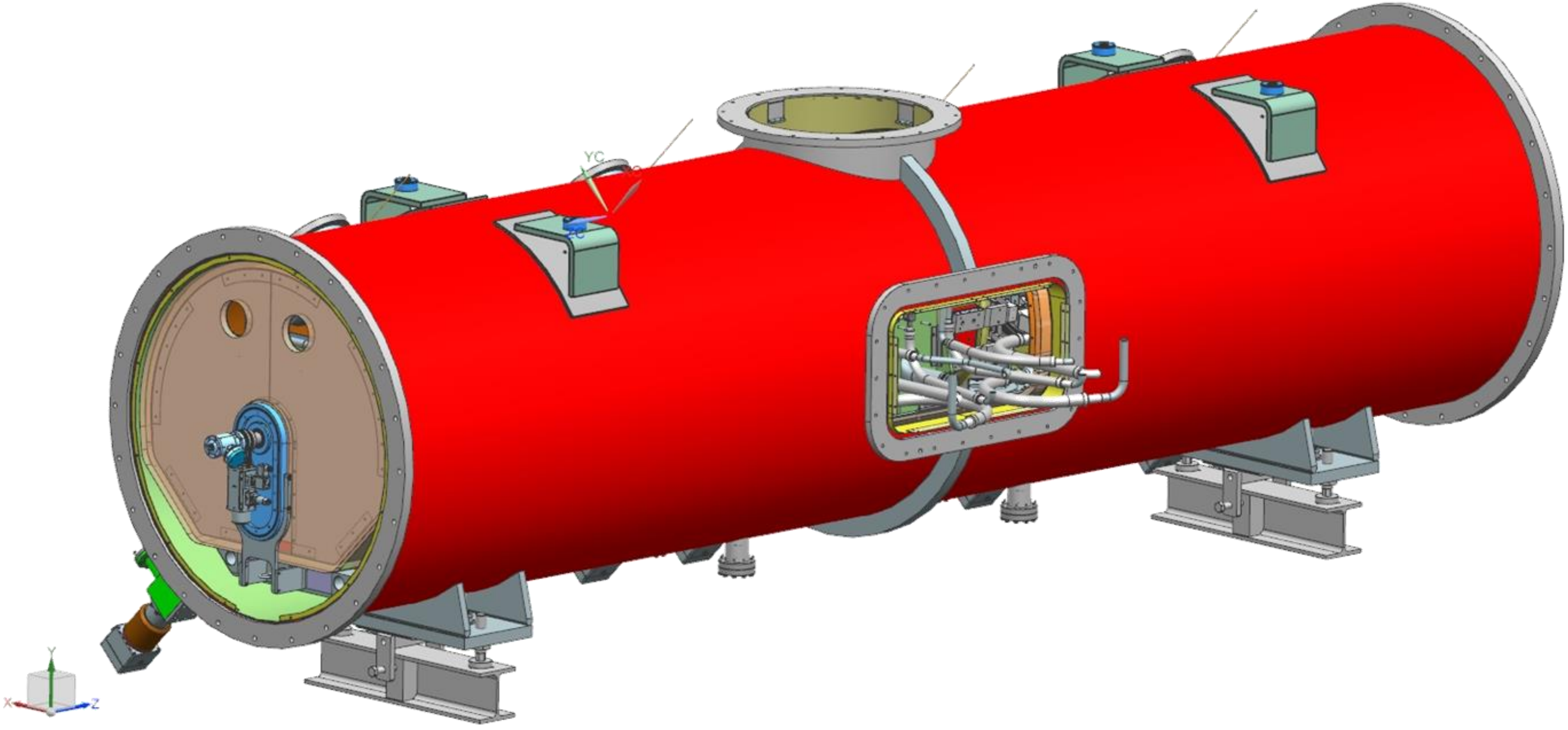
8. Assembly process



WS4

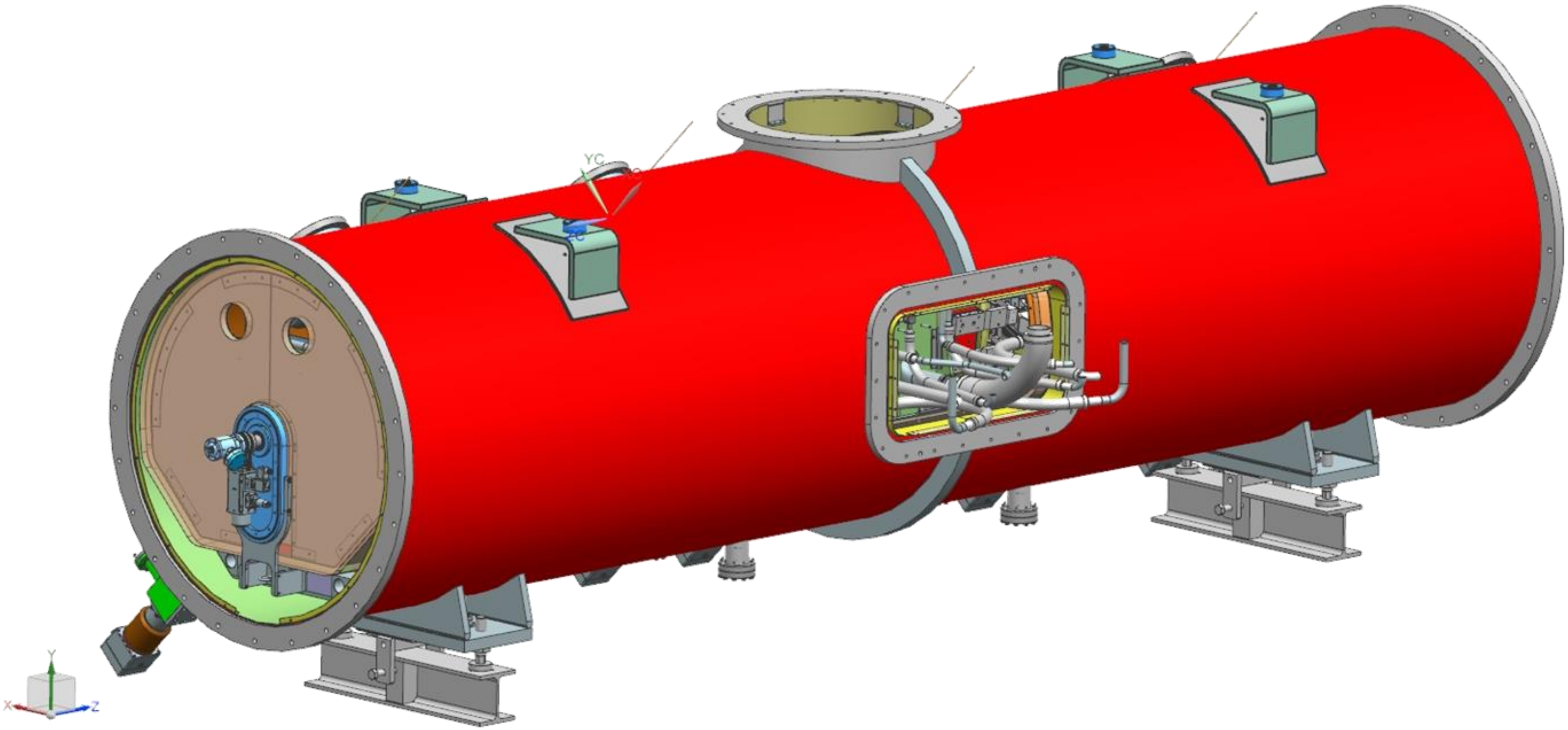
8. Assembly process

RF measurements.



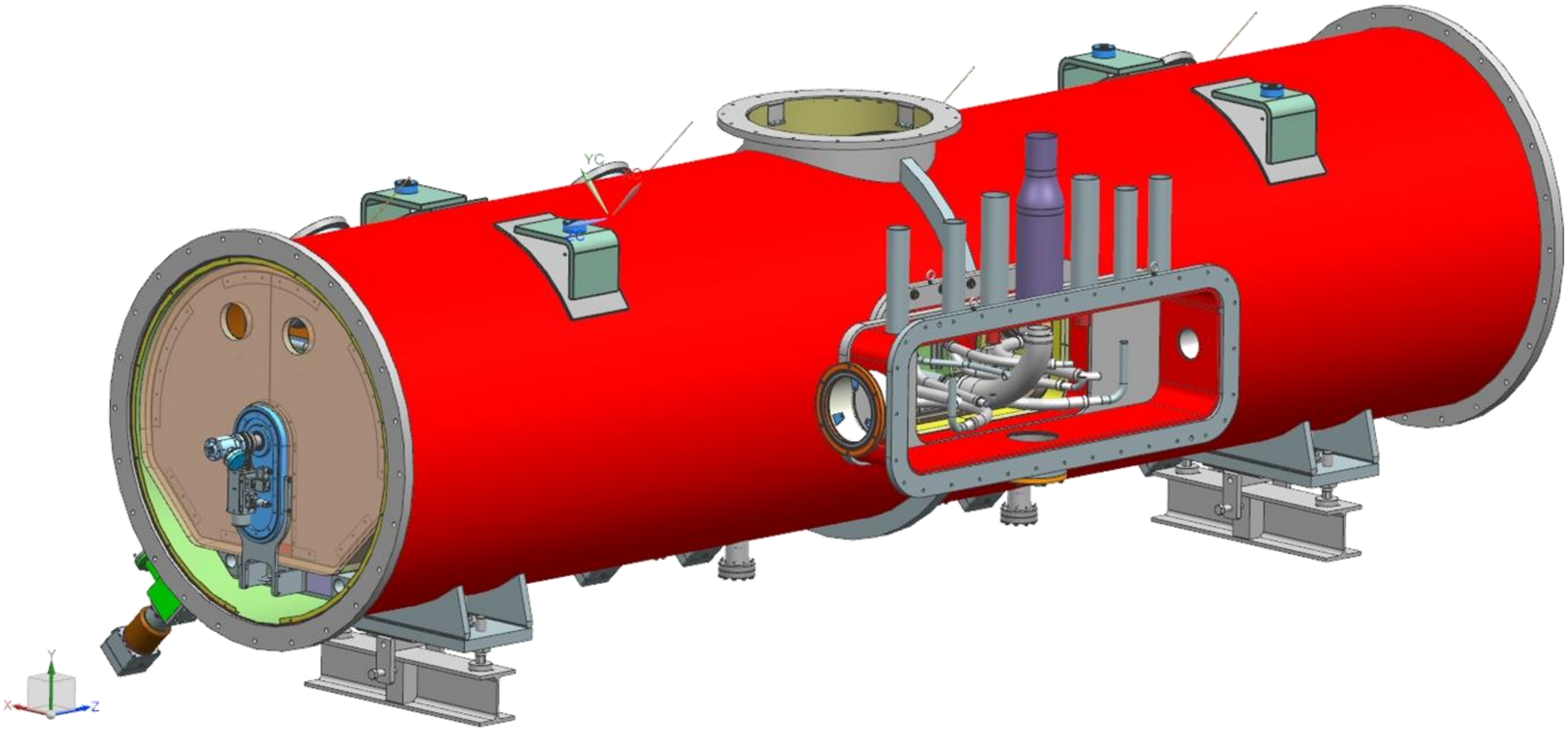
WS4

8. Assembly process



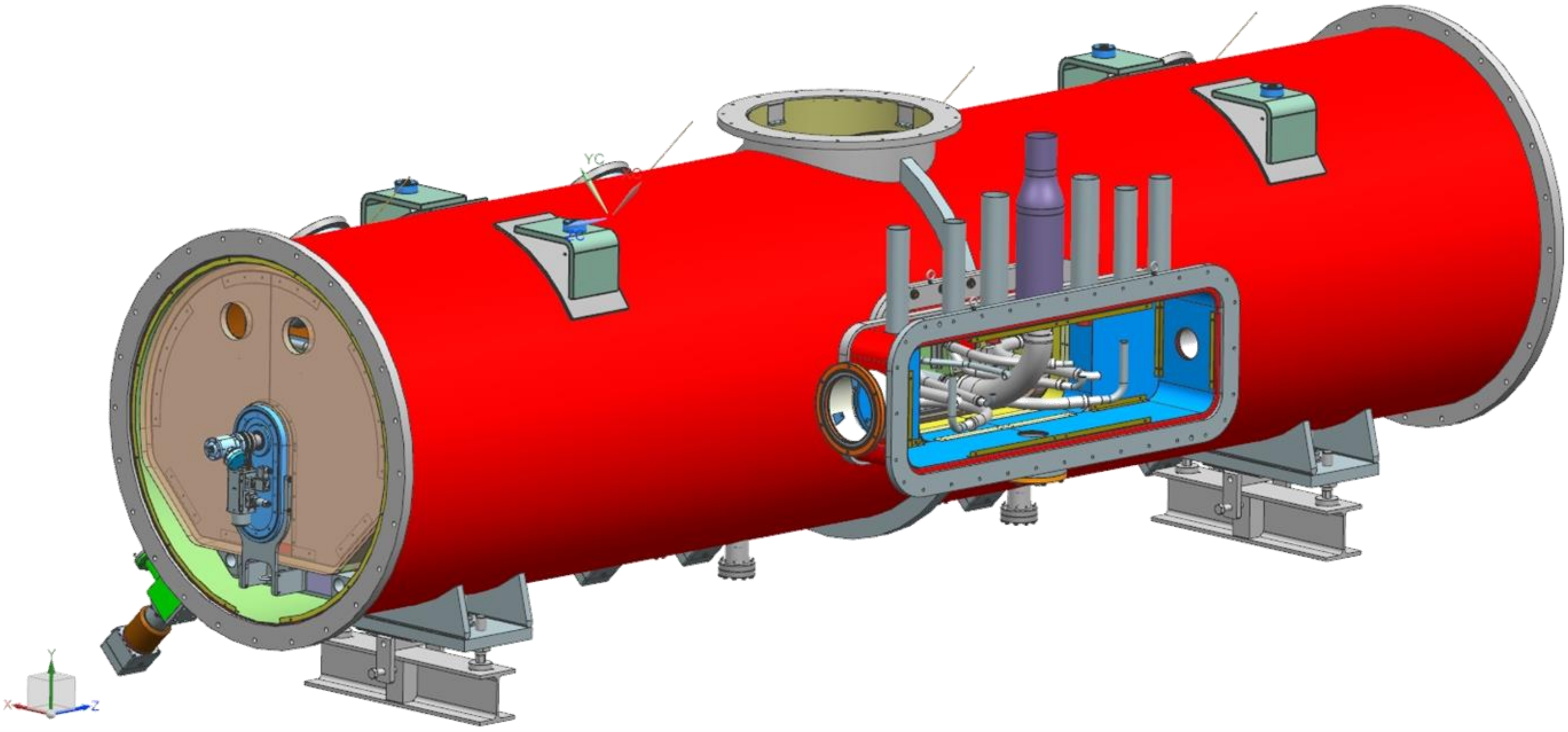
WS4

8. Assembly process



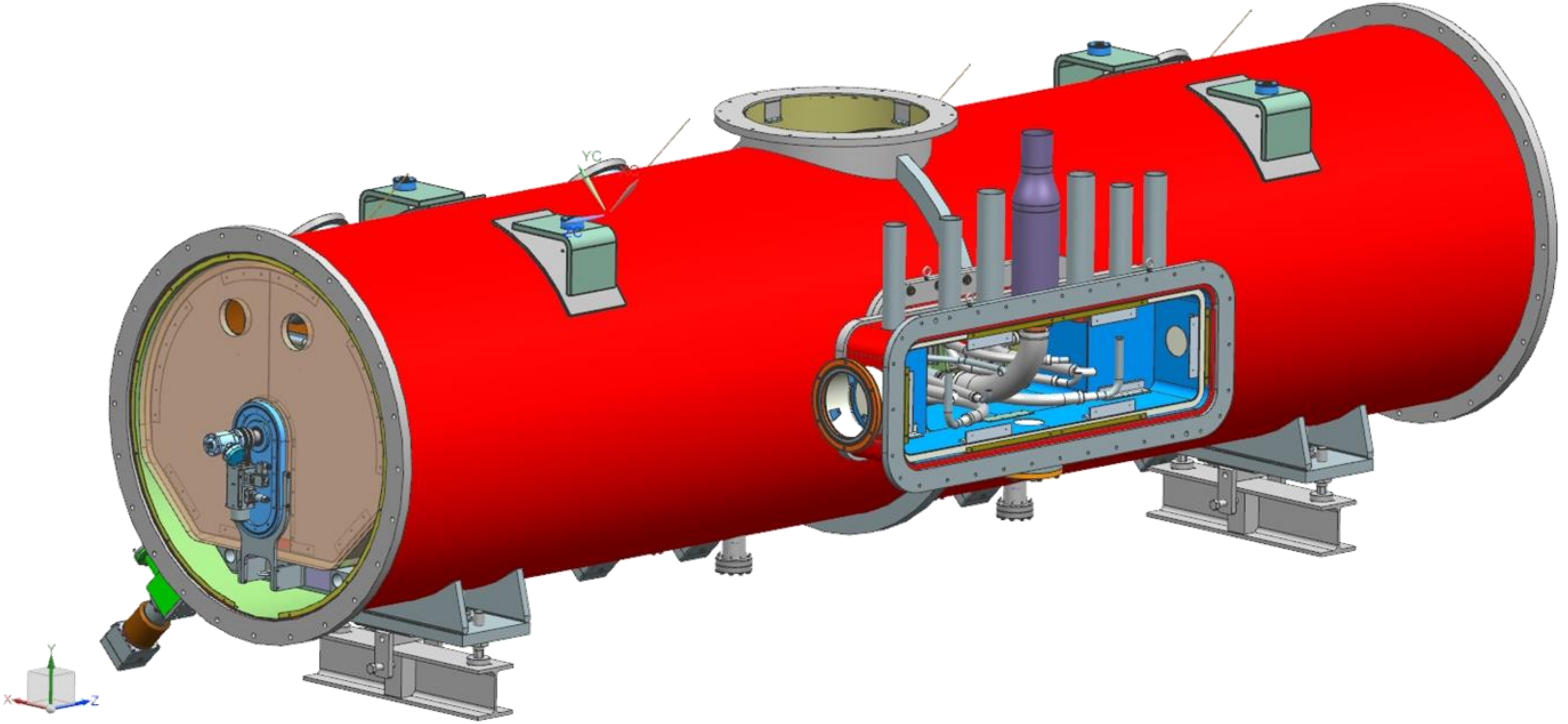
WS4

8. Assembly process



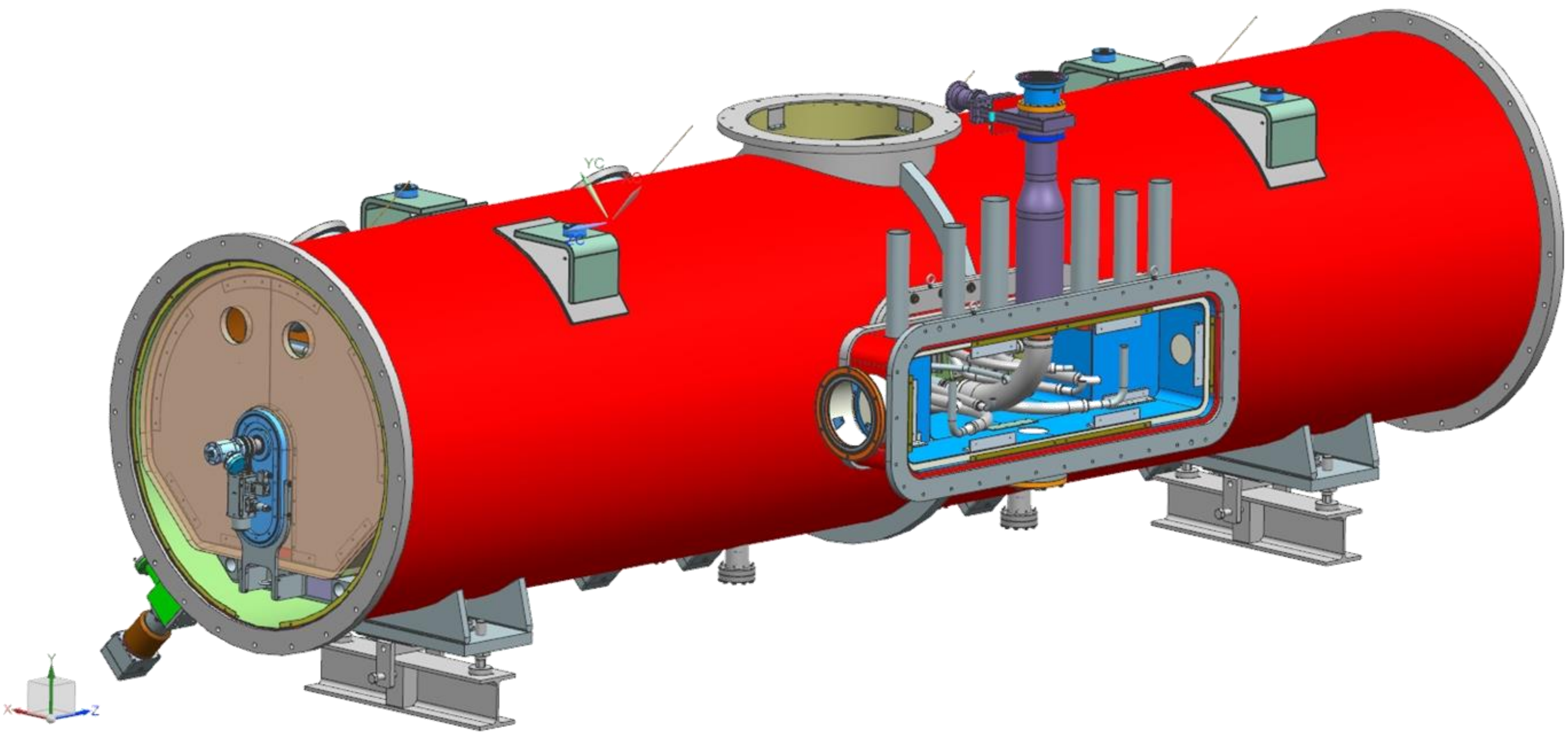
WS4

8. Assembly process



WS4

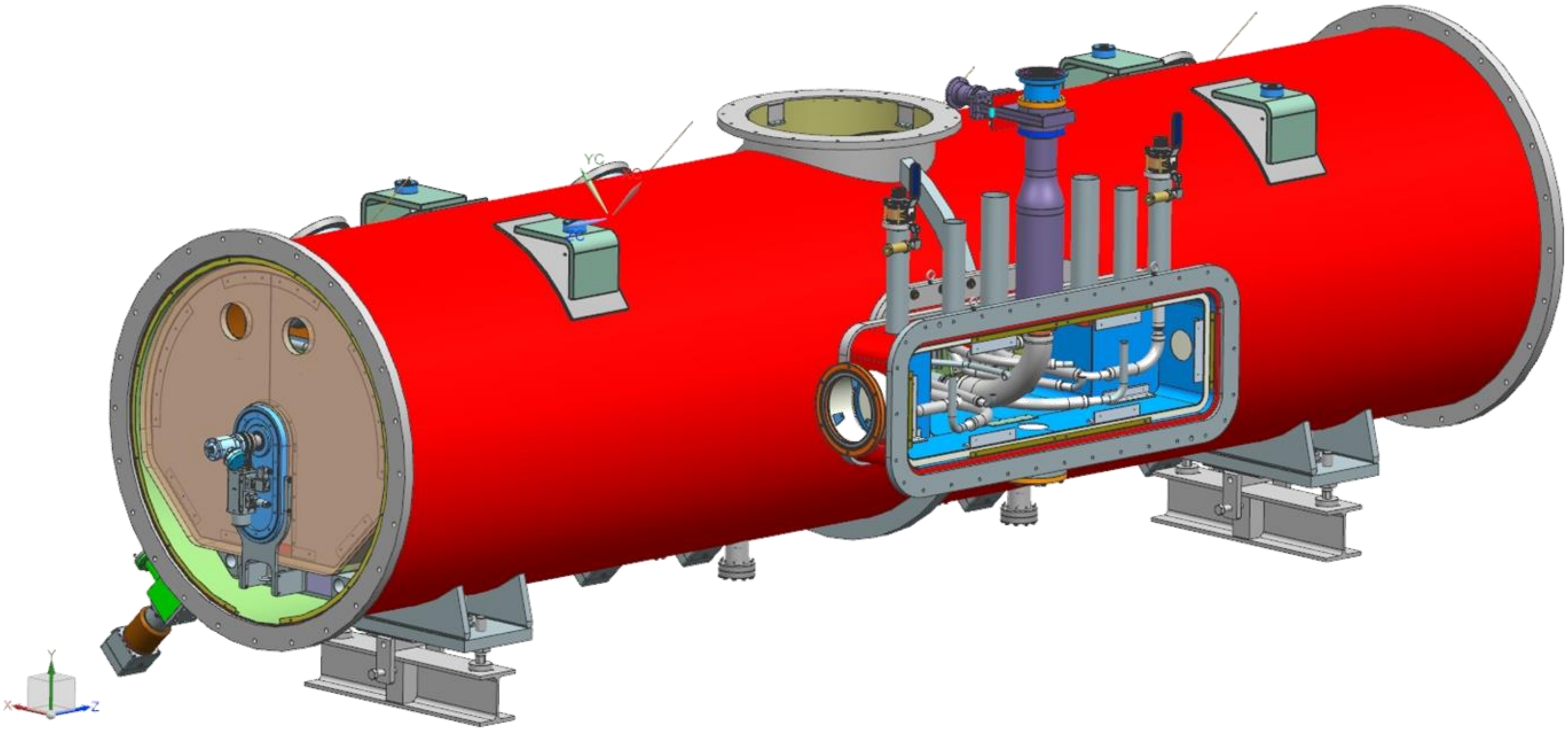
8. Assembly process



WS4

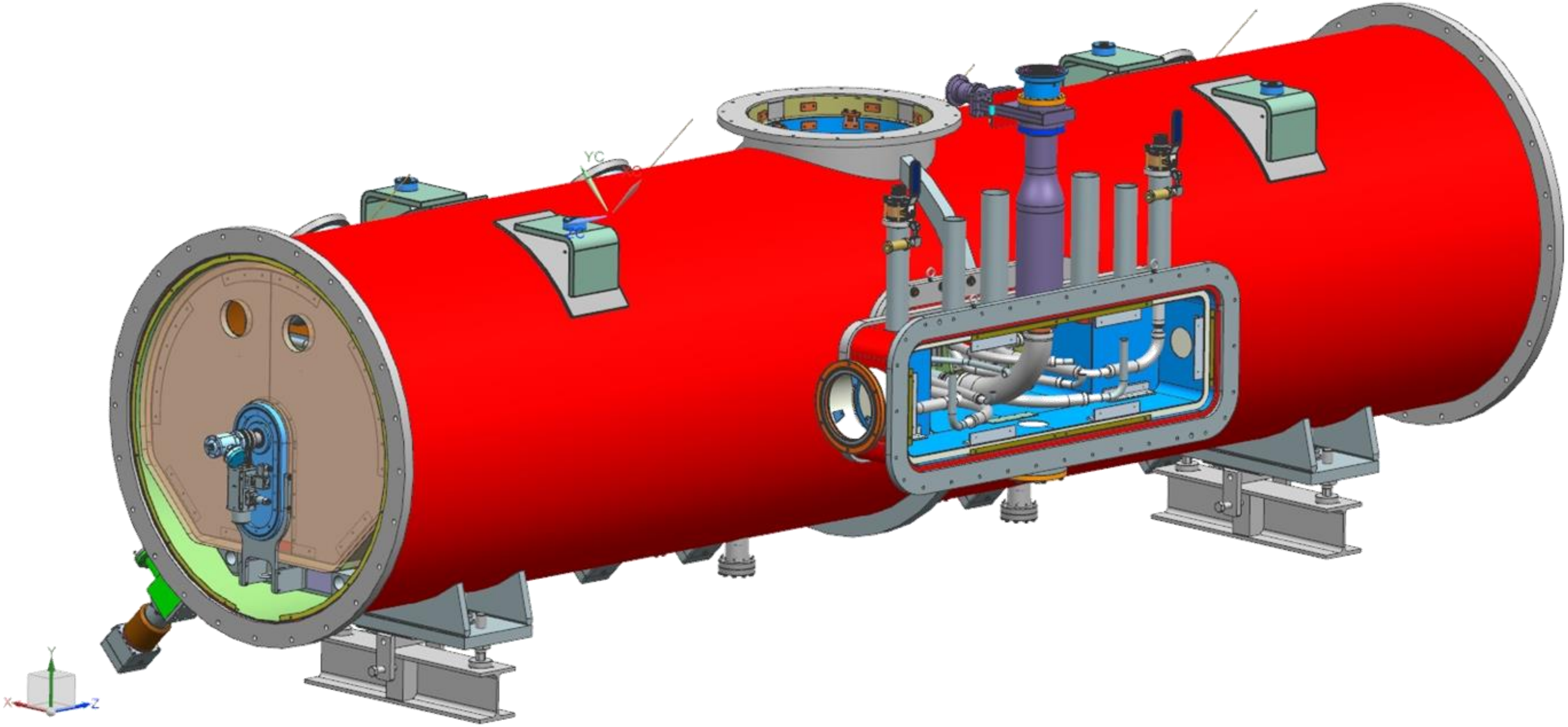
8. Assembly process

A pressure test of the 35-50 K line will be performed at 22 barg.



WS4

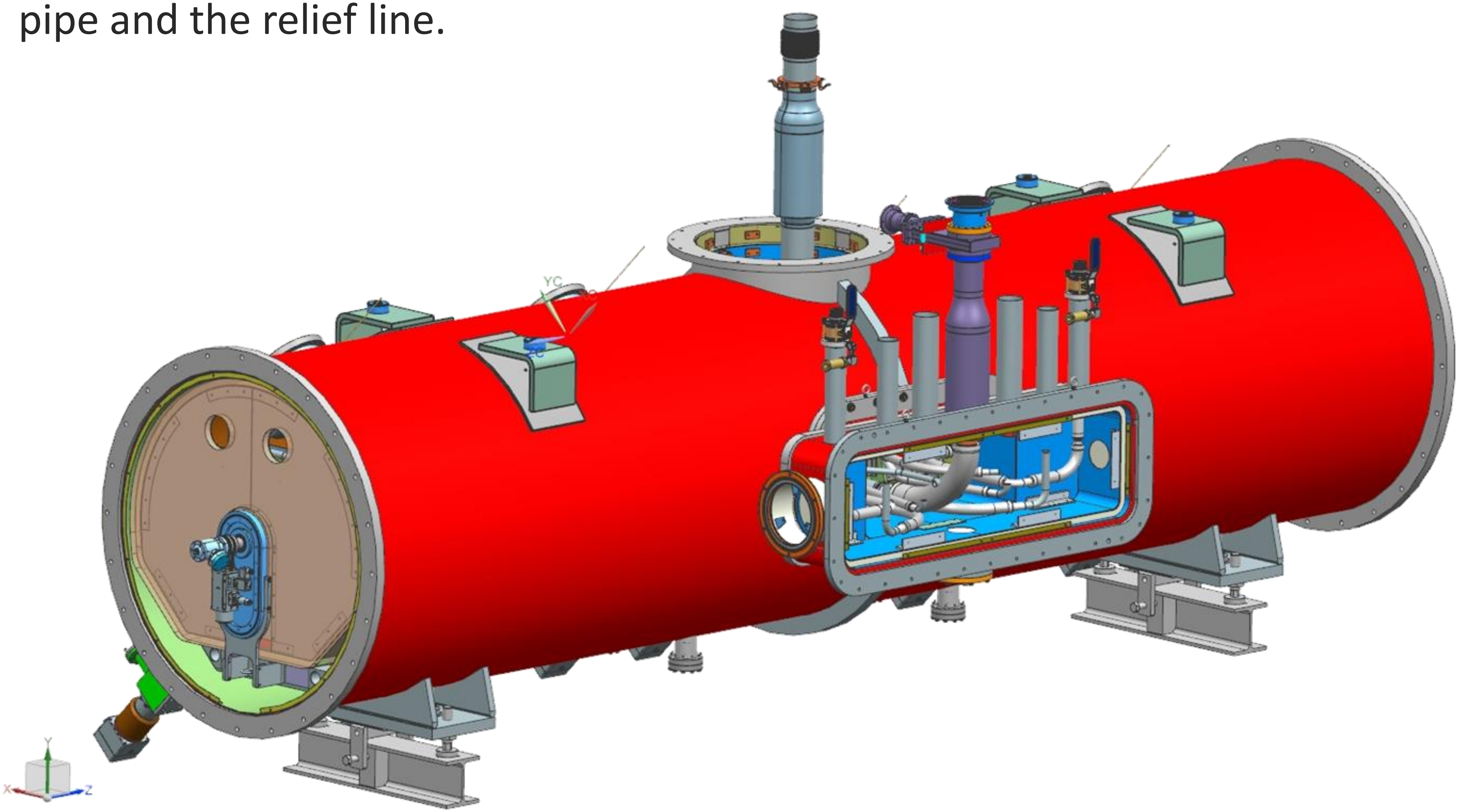
8. Assembly process



WS4

8. Assembly process

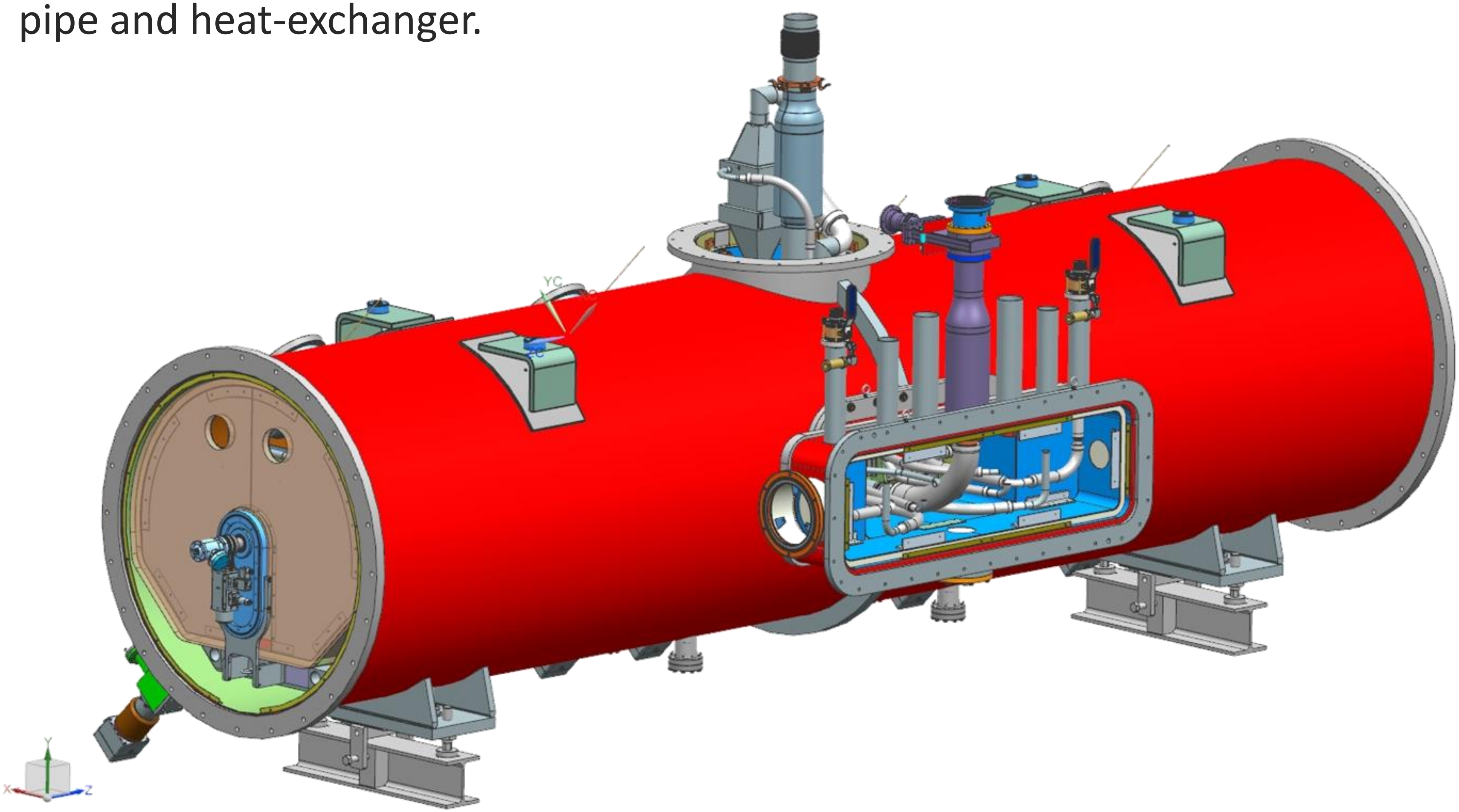
The welding chief validated the welding process between the two phase helium pipe and the relief line.



WS4

8. Assembly process

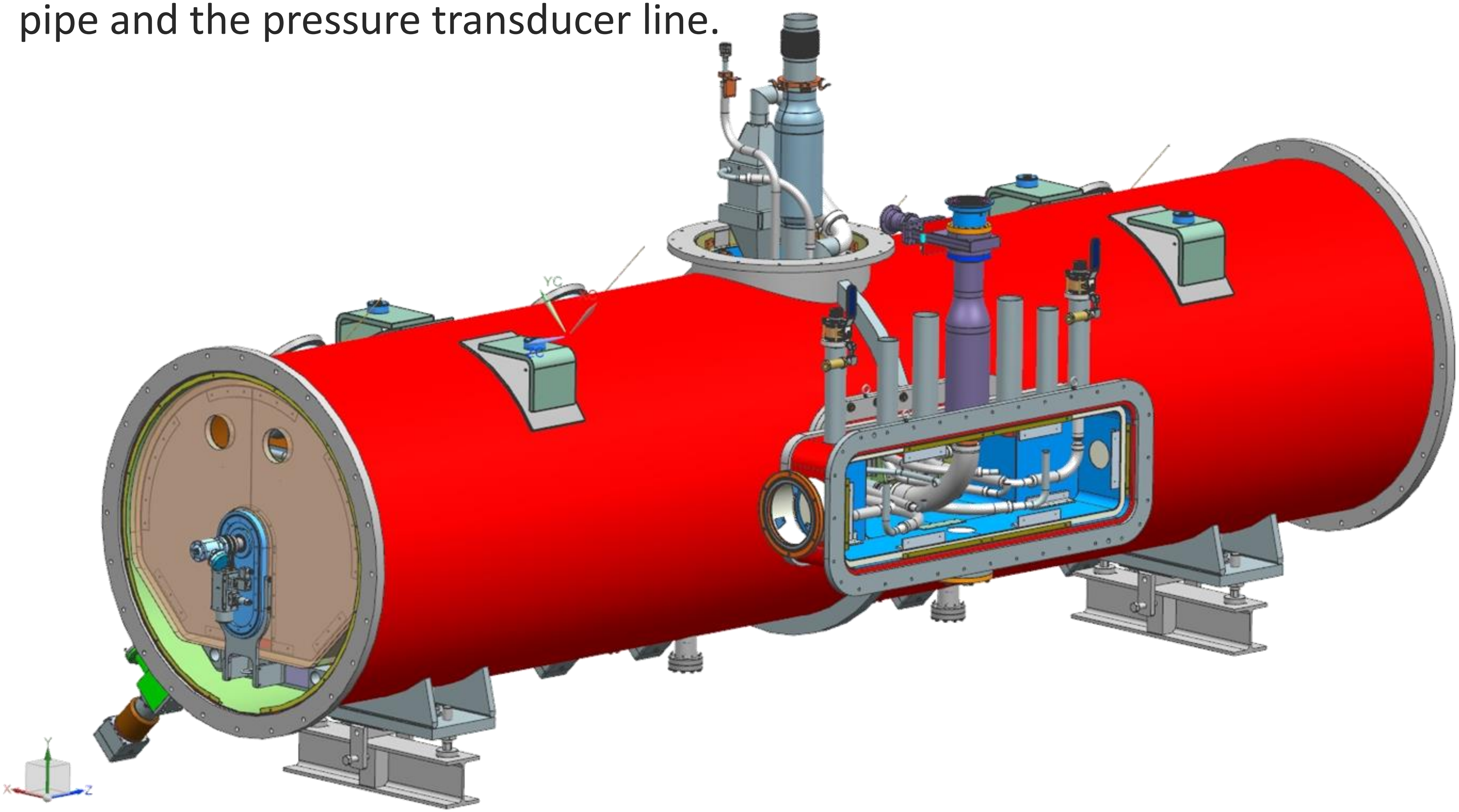
The welding chief validated the welding process between the two phase helium pipe and heat-exchanger.



WS4

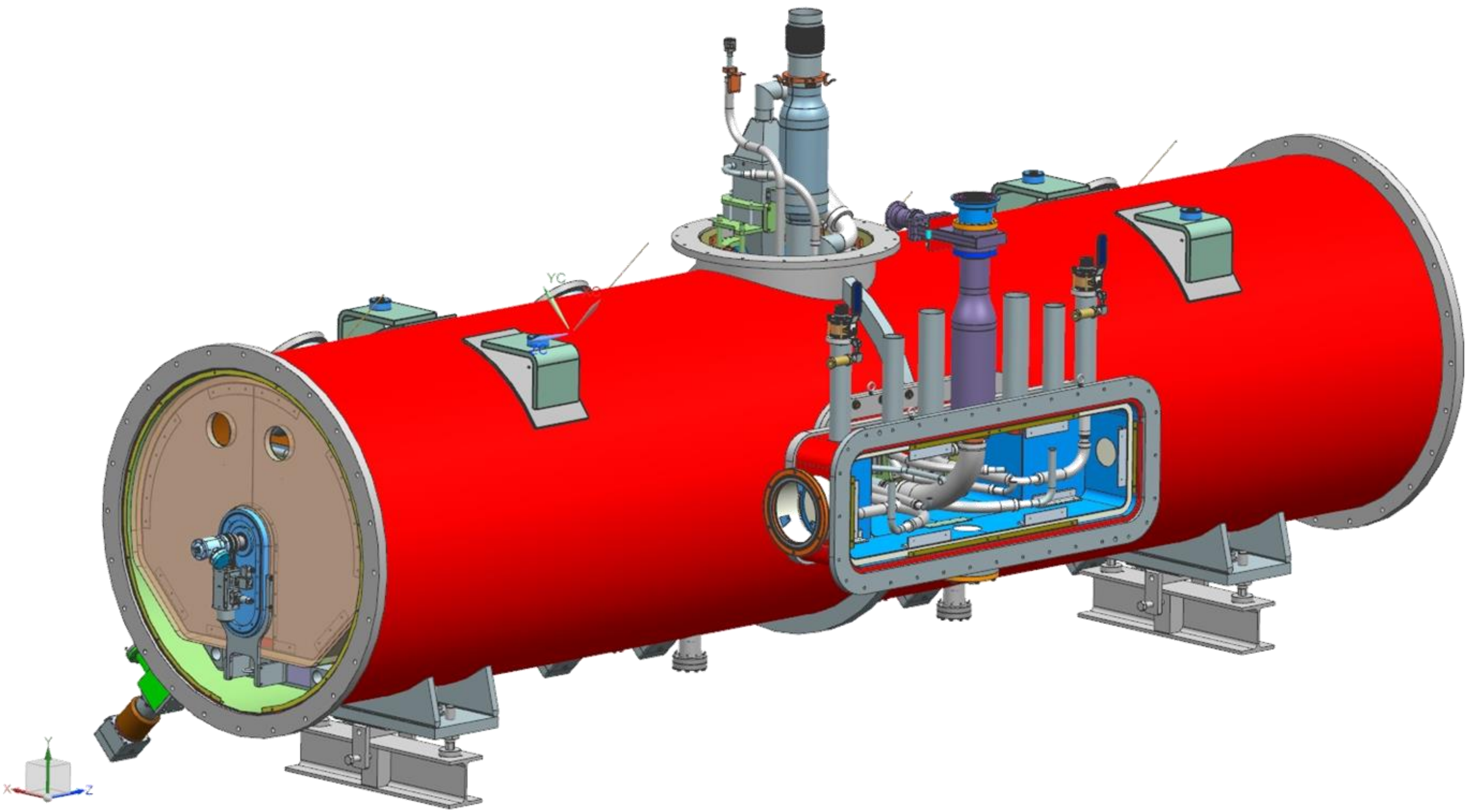
8. Assembly process

The welding chief validated the welding process between the two phase helium pipe and the pressure transducer line.



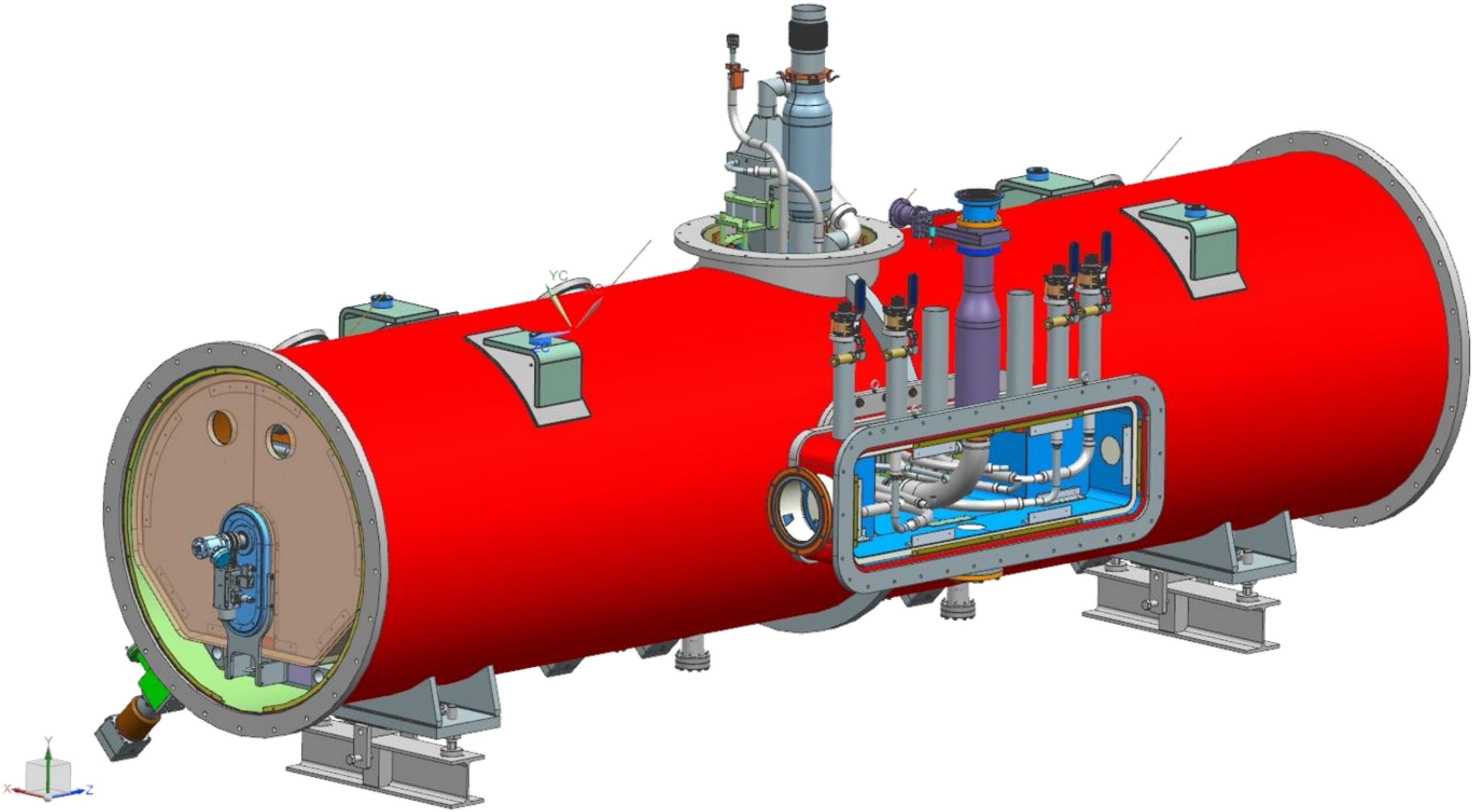
WS4

8. Assembly process



WS4

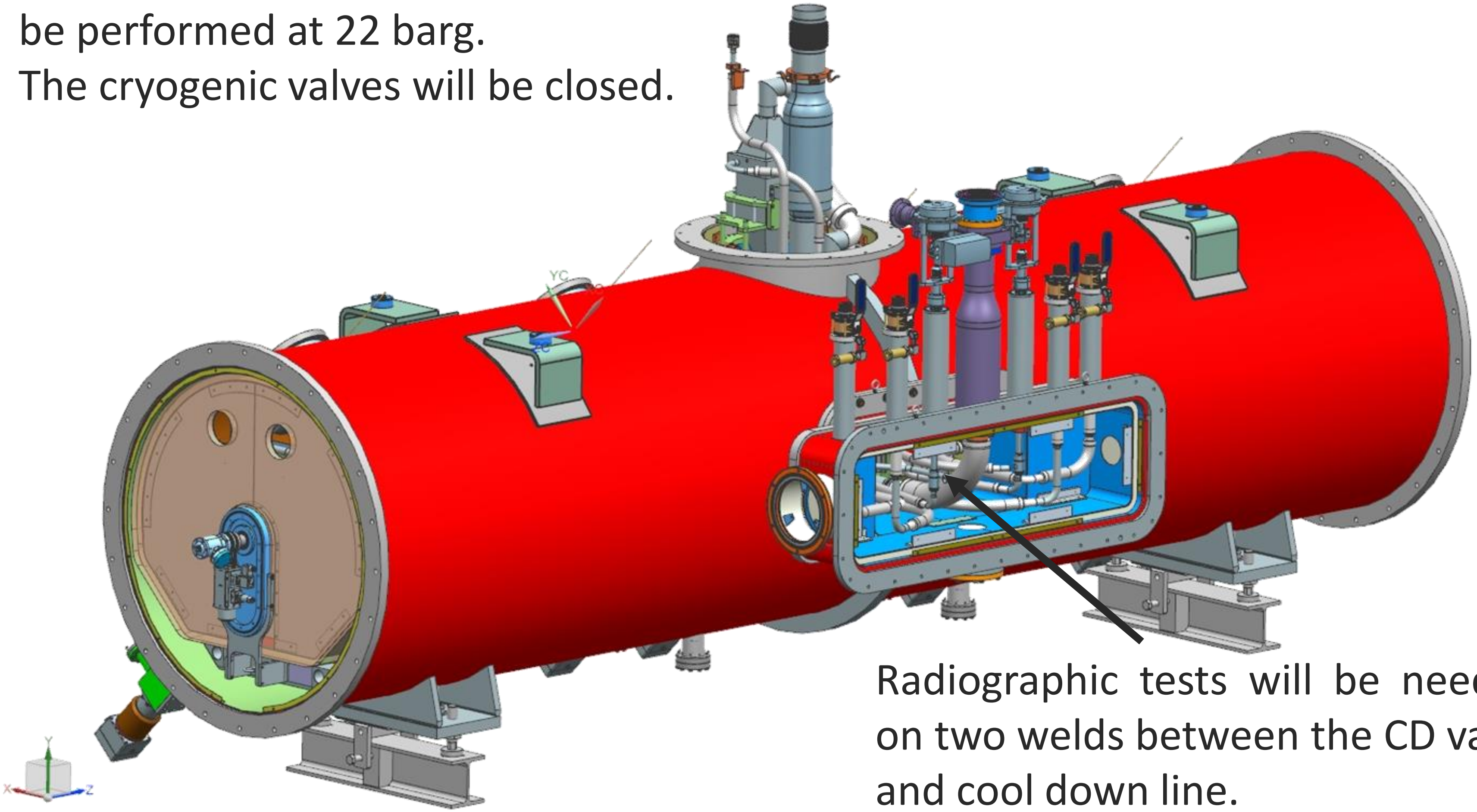
8. Assembly process



WS4

8. Assembly process

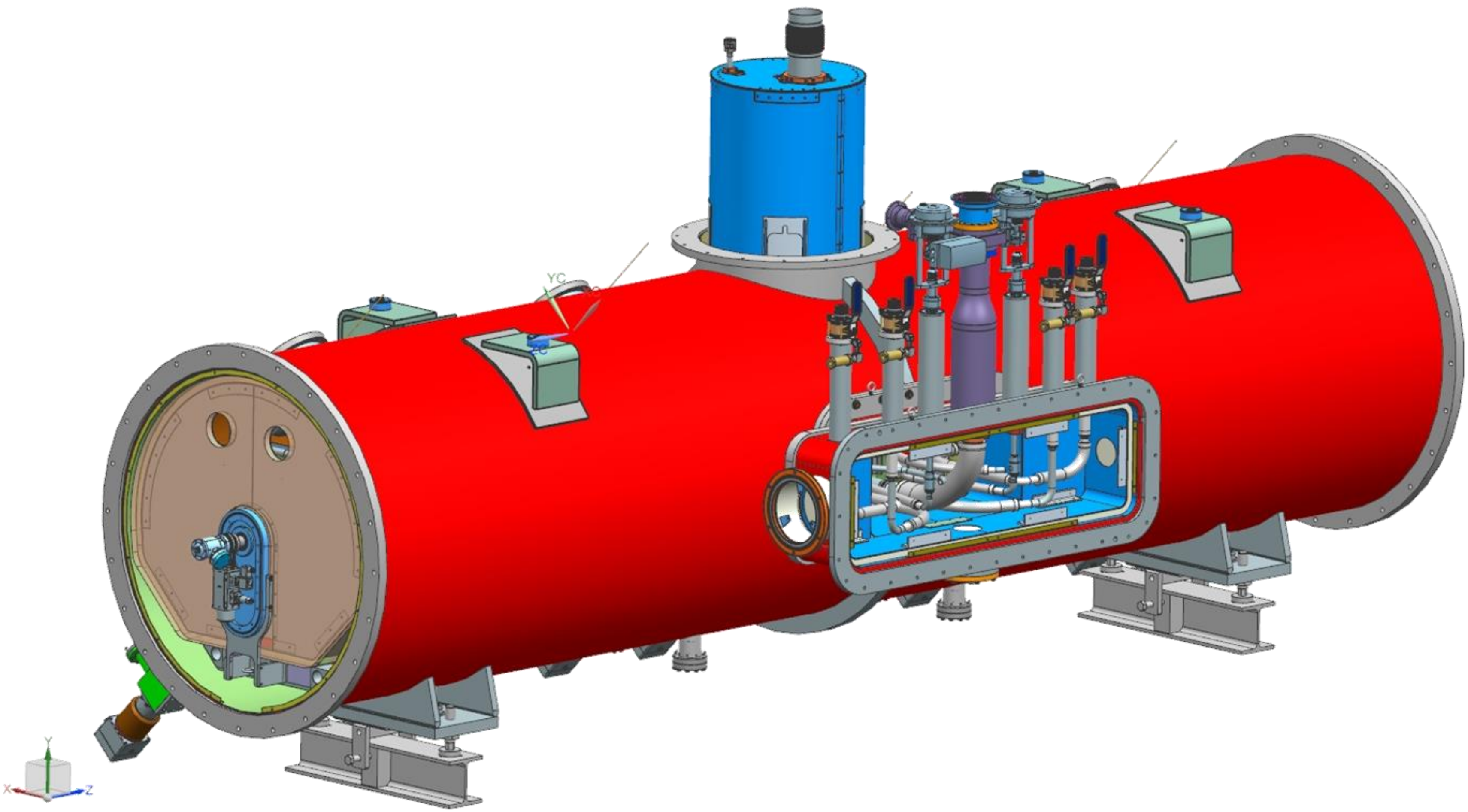
A pressure test of the 5 K line will be performed at 22 barg.
The cryogenic valves will be closed.



Radiographic tests will be needed on two welds between the CD valve and cool down line.

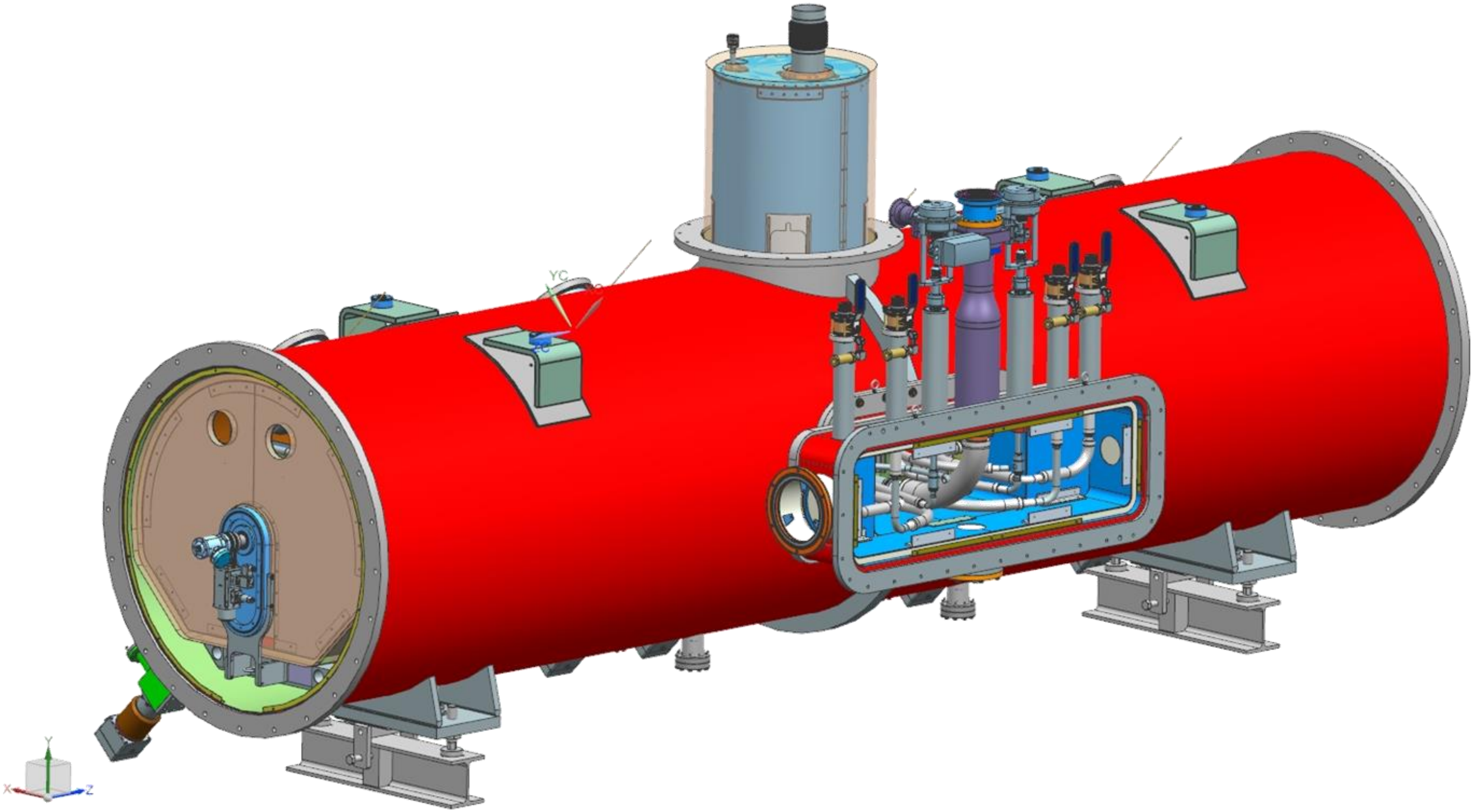
WS4

8. Assembly process



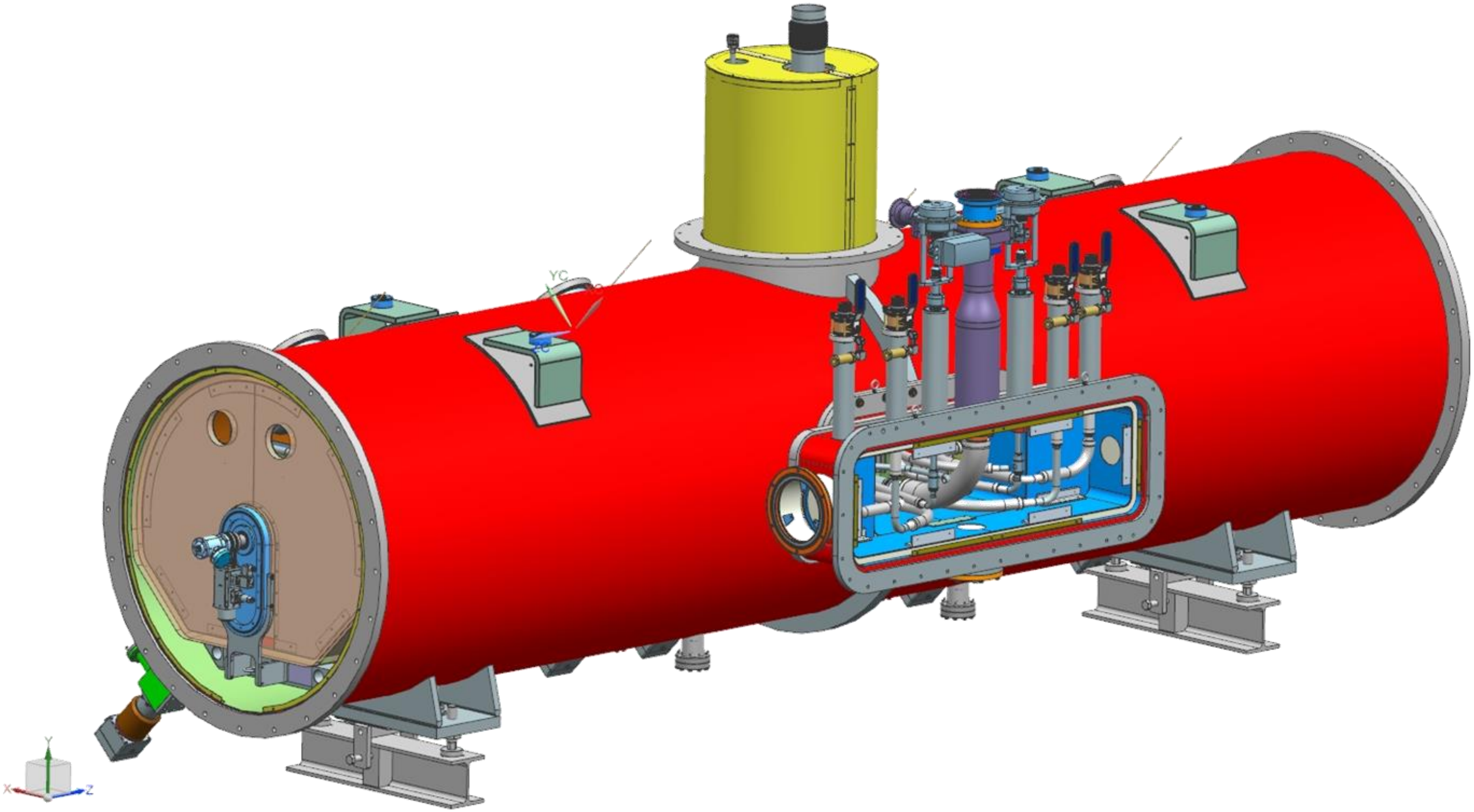
WS4

8. Assembly process



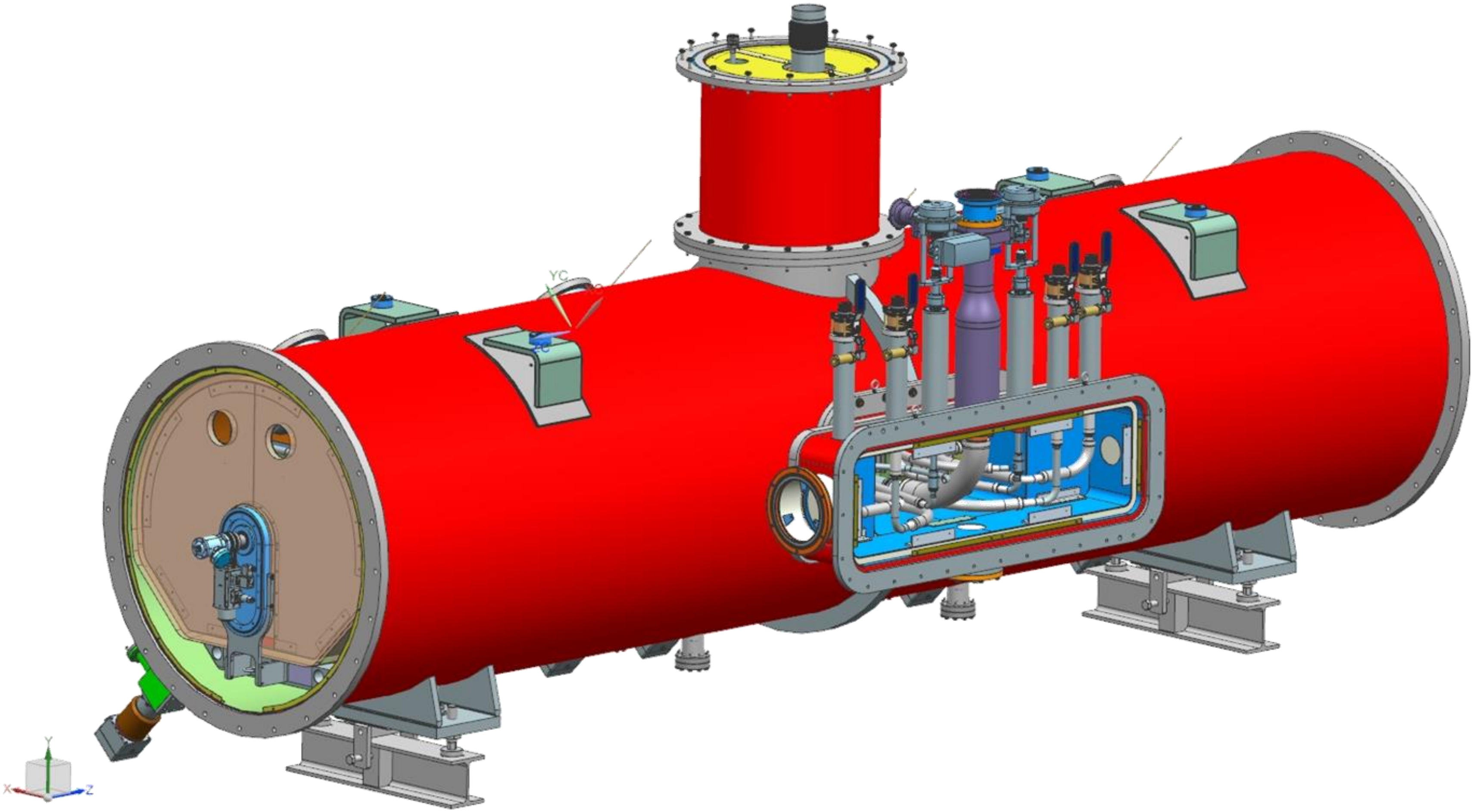
WS4

8. Assembly process



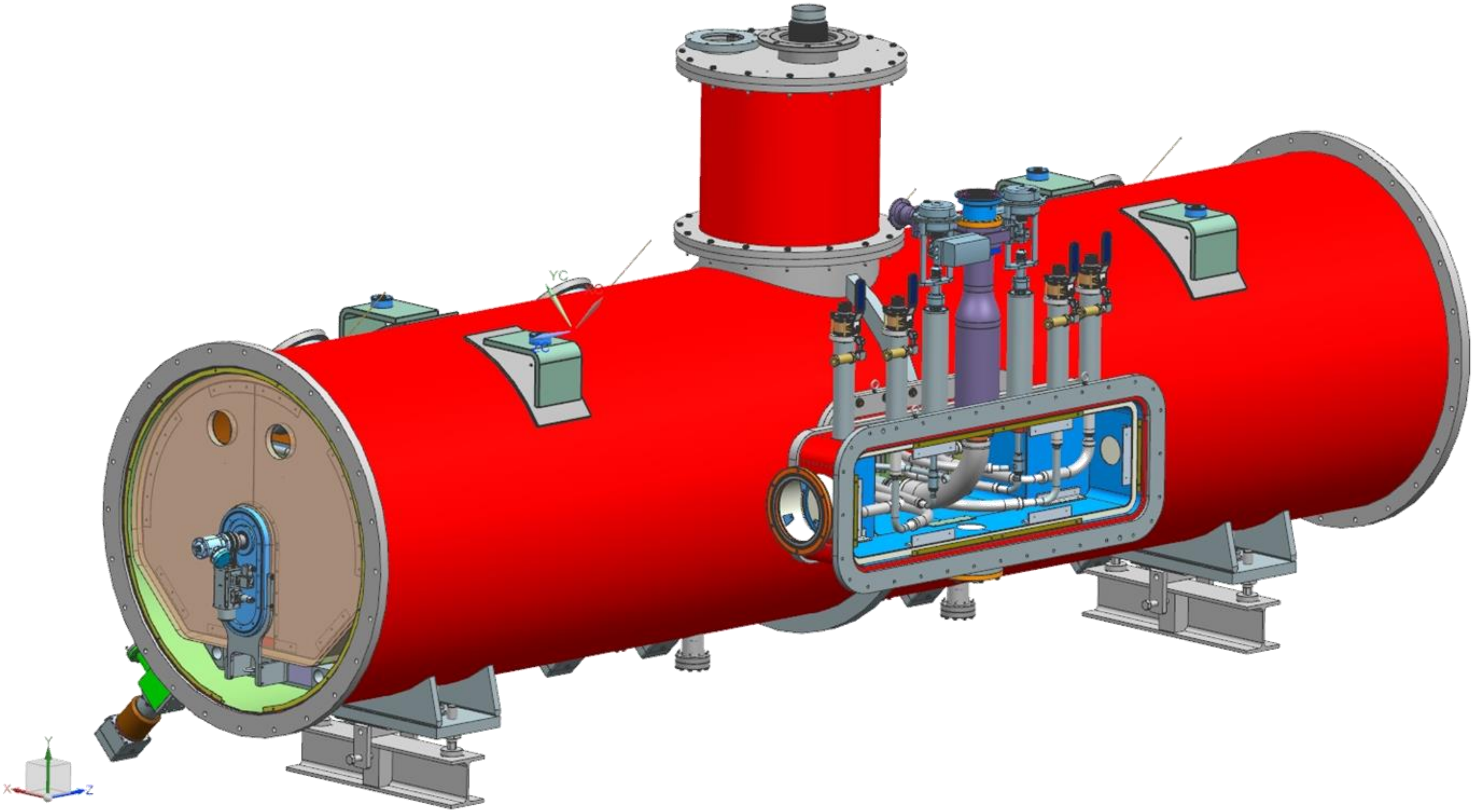
WS4

8. Assembly process



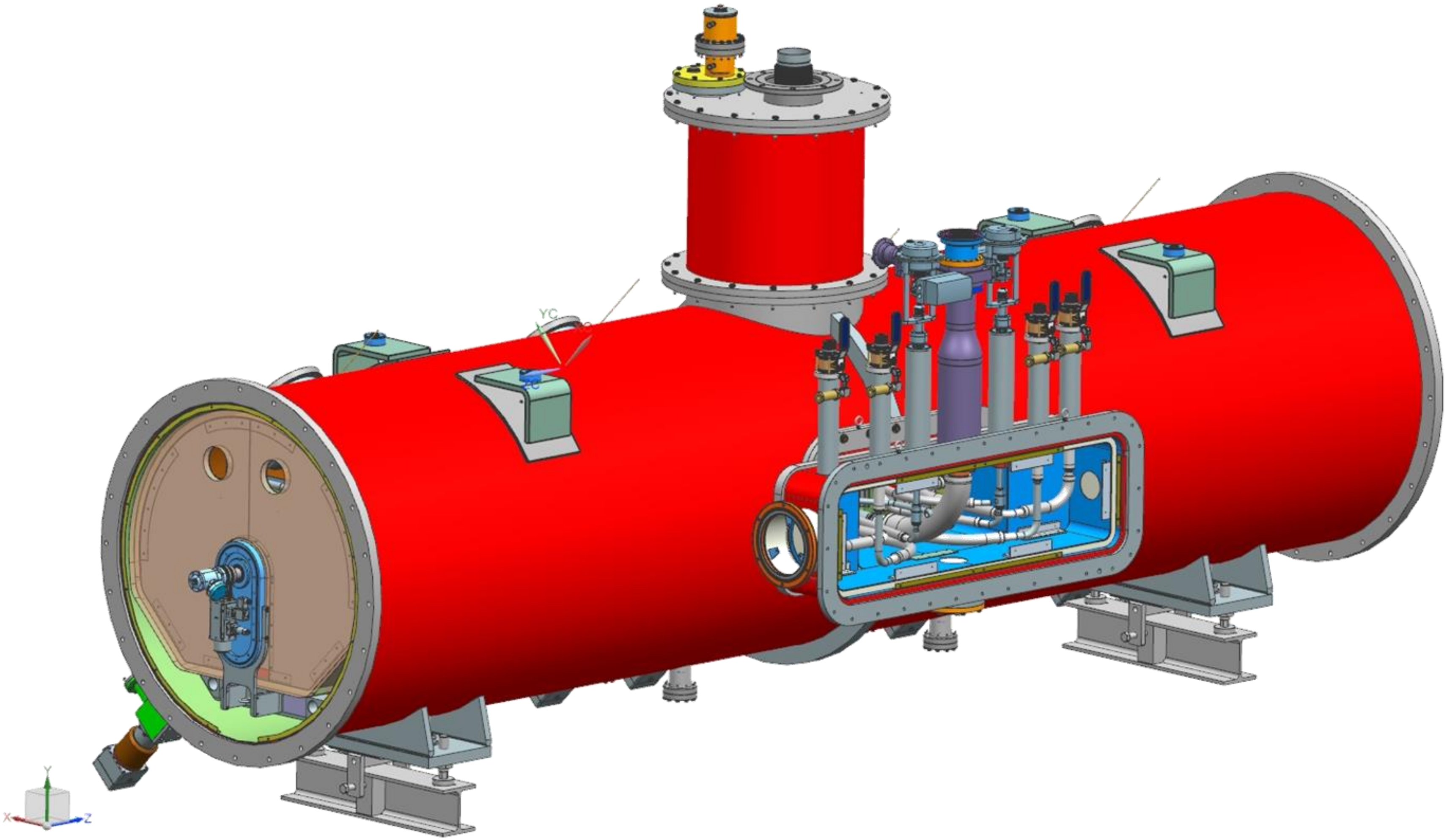
WS4

8. Assembly process



WS4

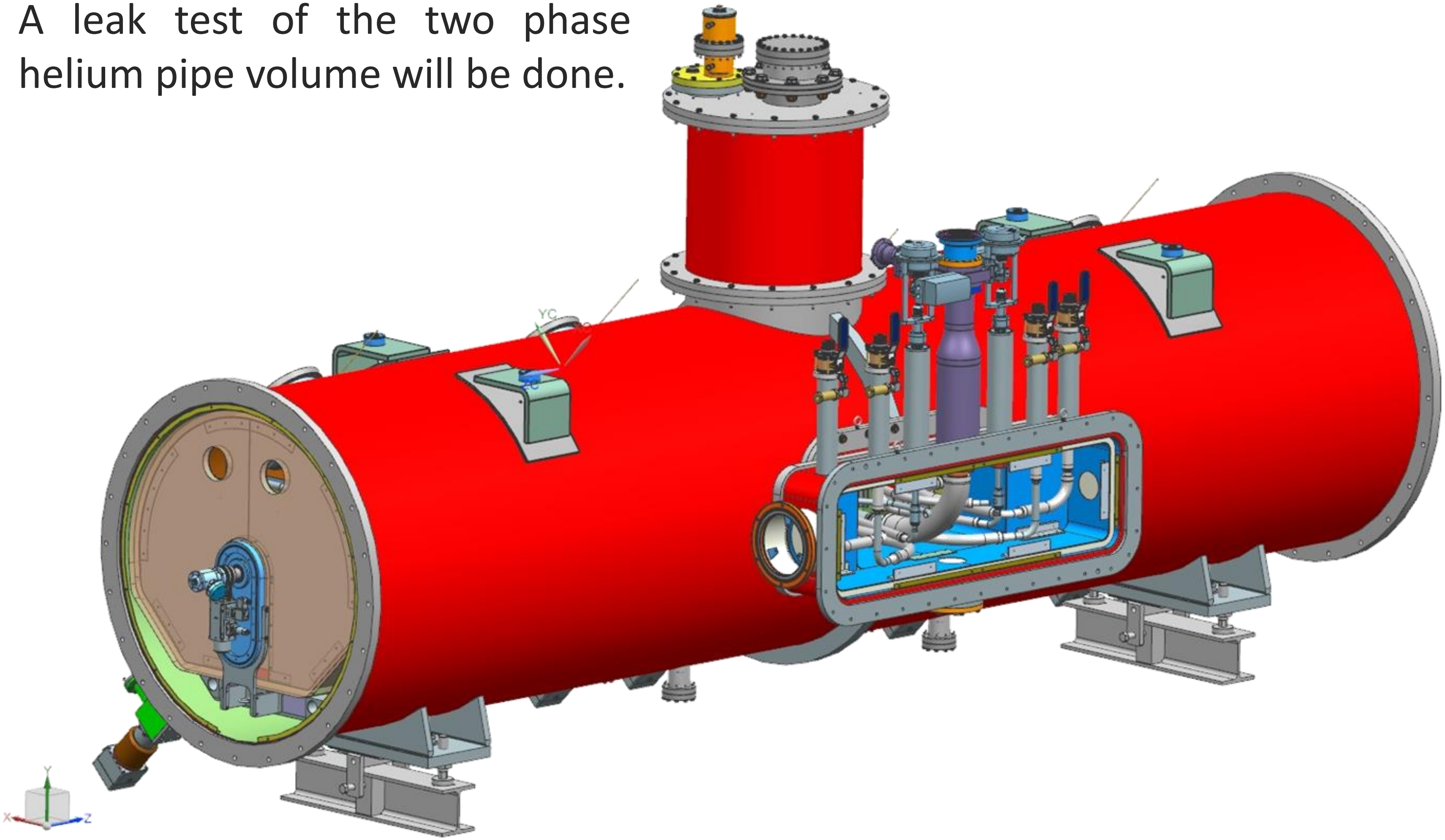
8. Assembly process



WS4

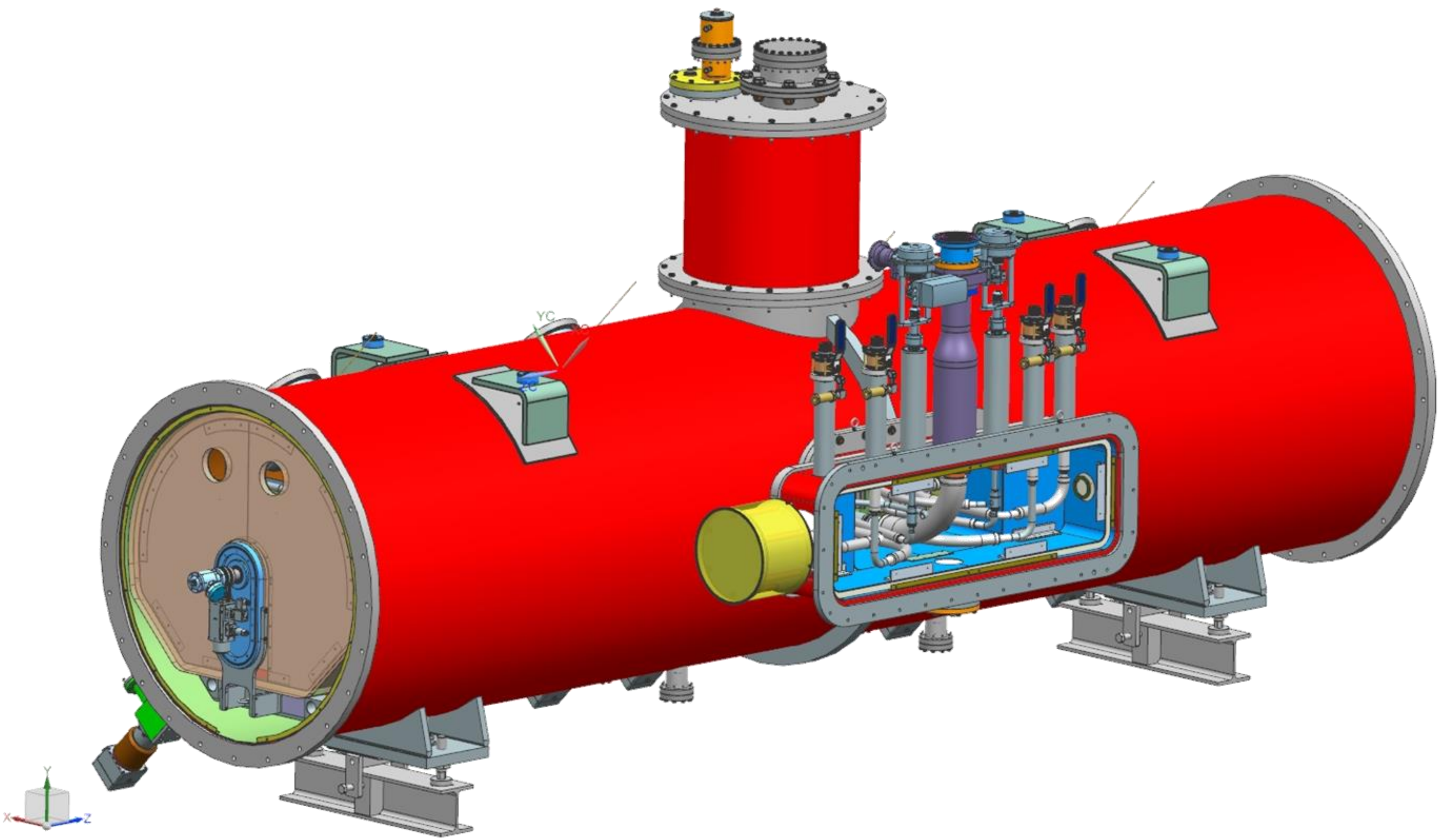
8. Assembly process

A leak test of the two phase helium pipe volume will be done.



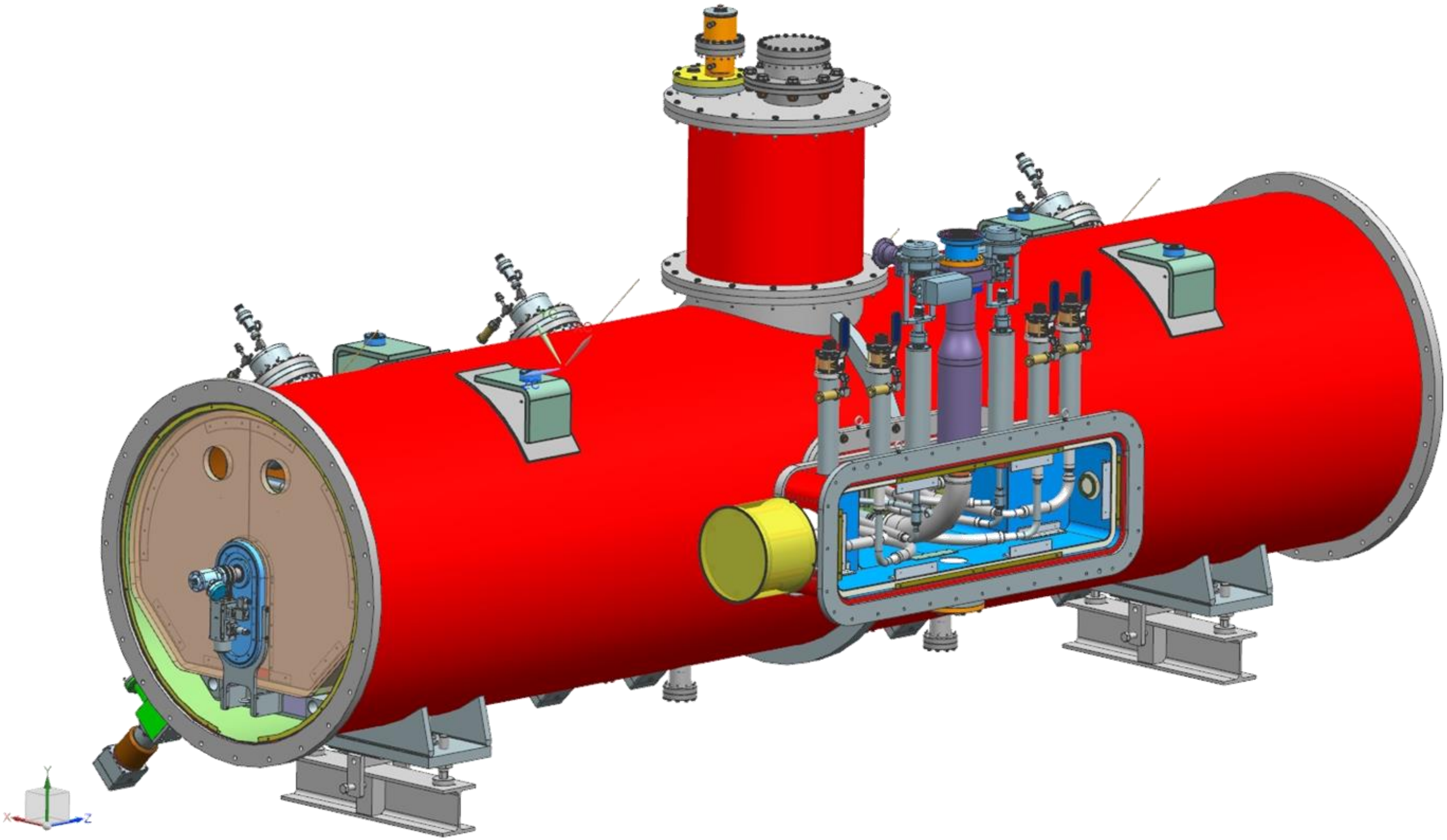
WS4

8. Assembly process



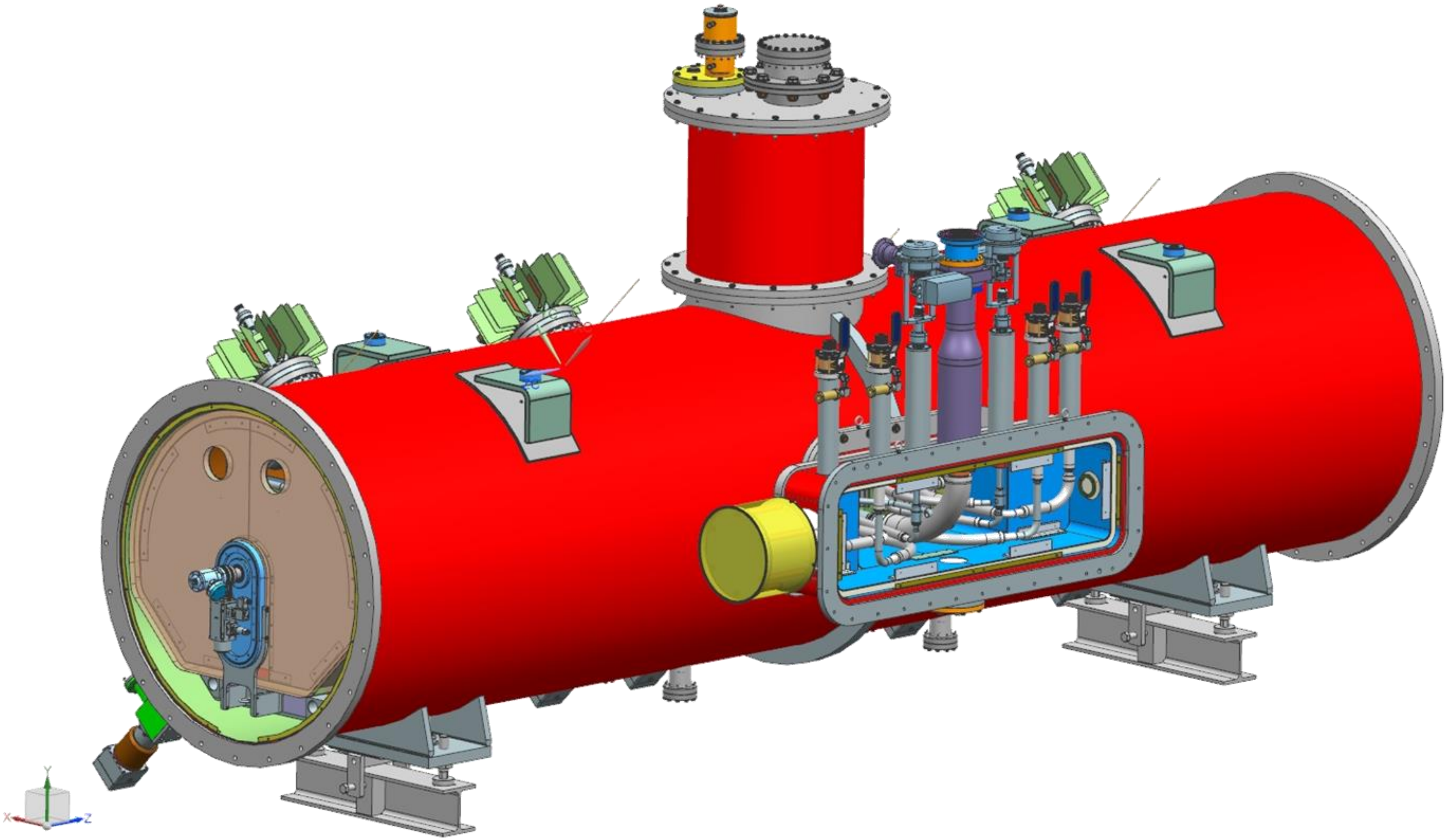
WS4

8. Assembly process



WS4

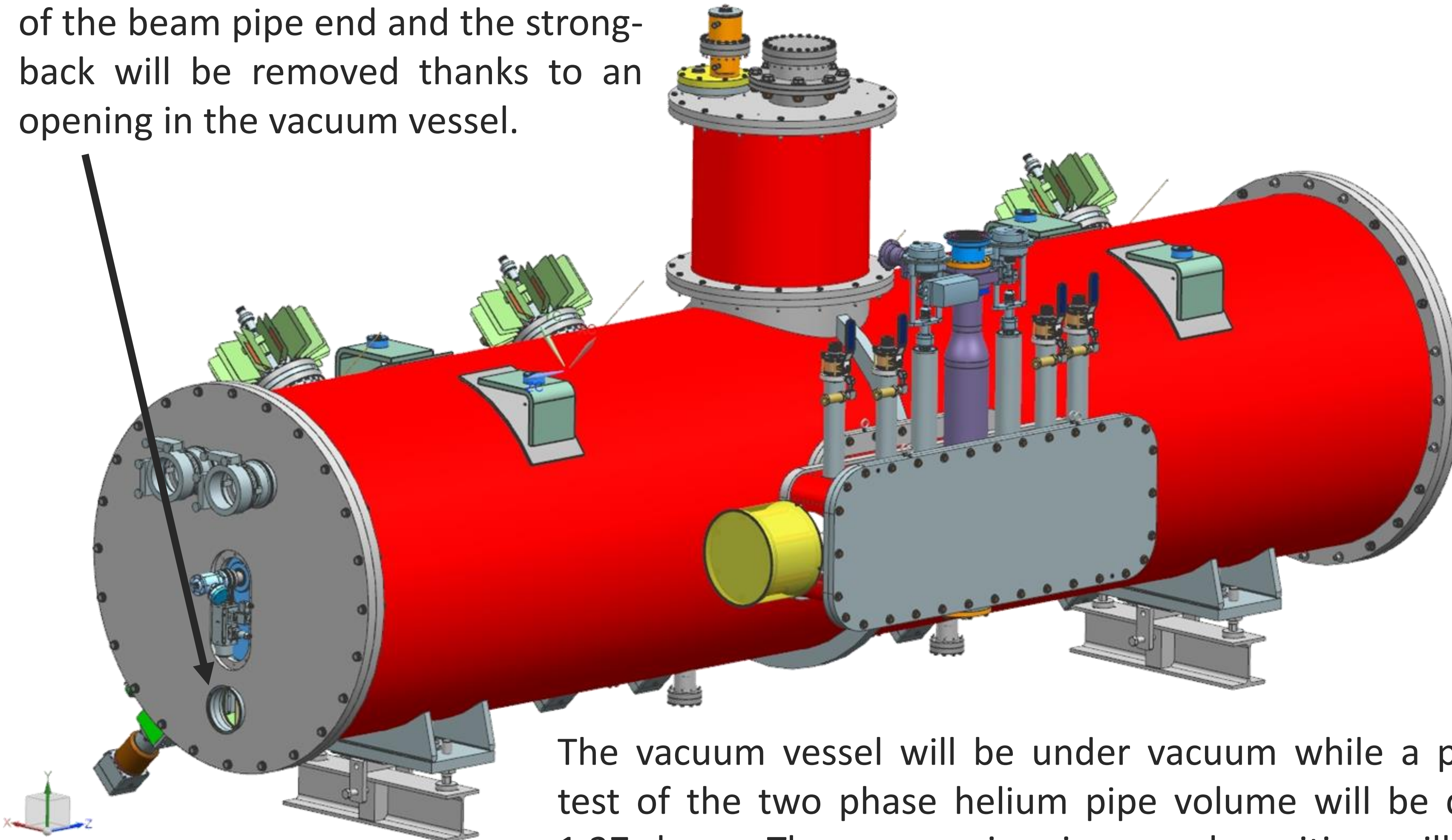
8. Assembly process



WS4

8. Assembly process

The connection between the support of the beam pipe end and the strong-back will be removed thanks to an opening in the vacuum vessel.



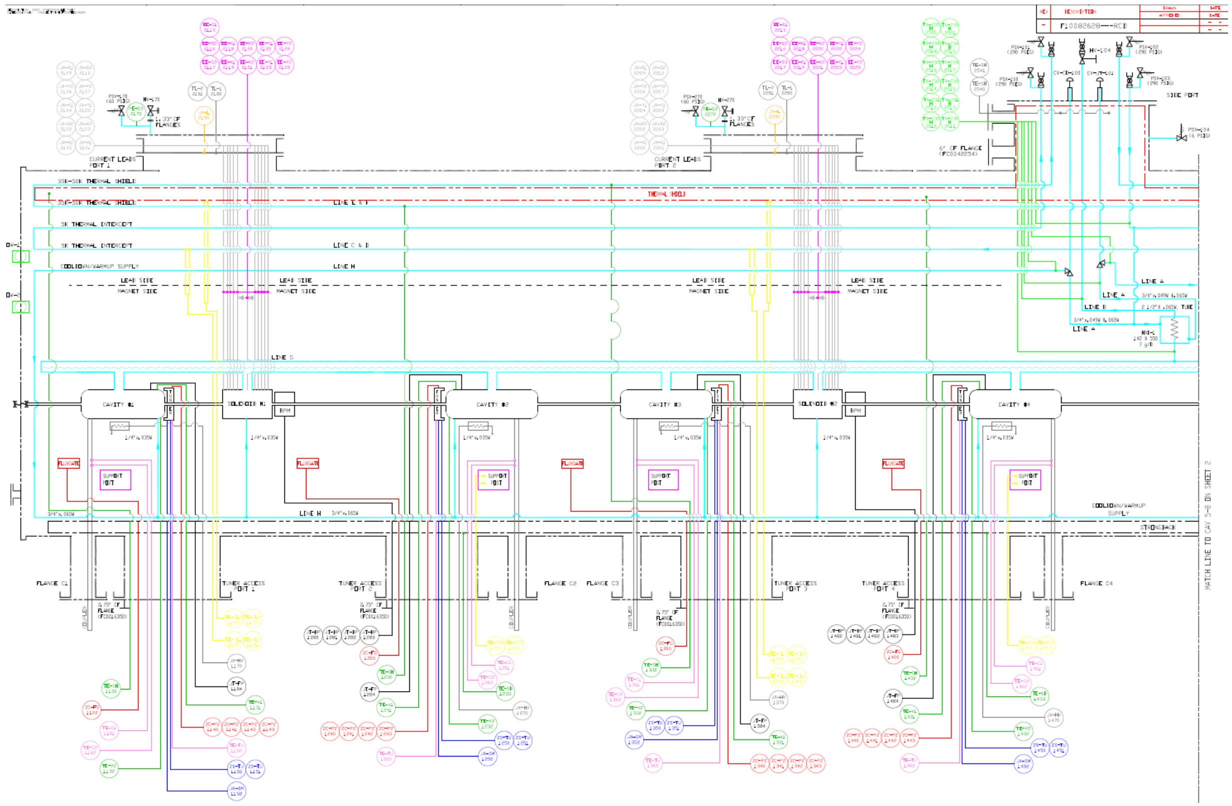
The vacuum vessel will be under vacuum while a pressure test of the two phase helium pipe volume will be done at 1.27 barg. The cryogenic pipes and cavities will see a pressure of 2.27 barg. RF measurements will be done.

WS4

9. External interfaces

In the interface document all the external interfaces of SSR1 Cryomodule have been mapped out, how it interfaces with the connected systems of PIP-II and the PIP-II Injector Test (formerly known as PXIE).

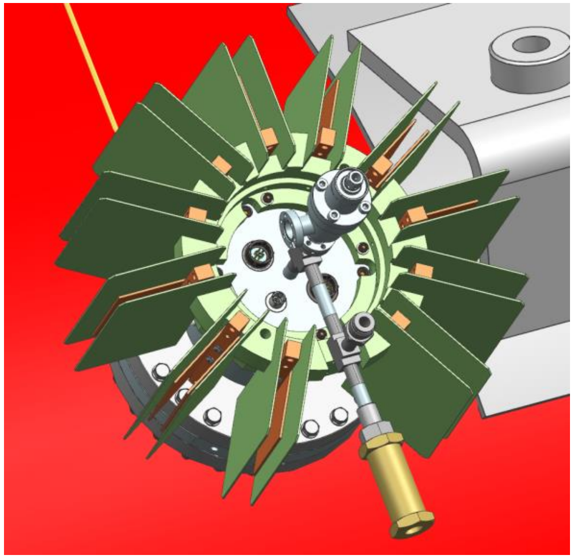
9.1 Piping and Instrumentation Diagram



9. External interfaces

The instrumentation has been defined flange by flange.
All the temperatures sensors, heaters, vtaps, pressure transducers have been defined.

9.2 Leads port



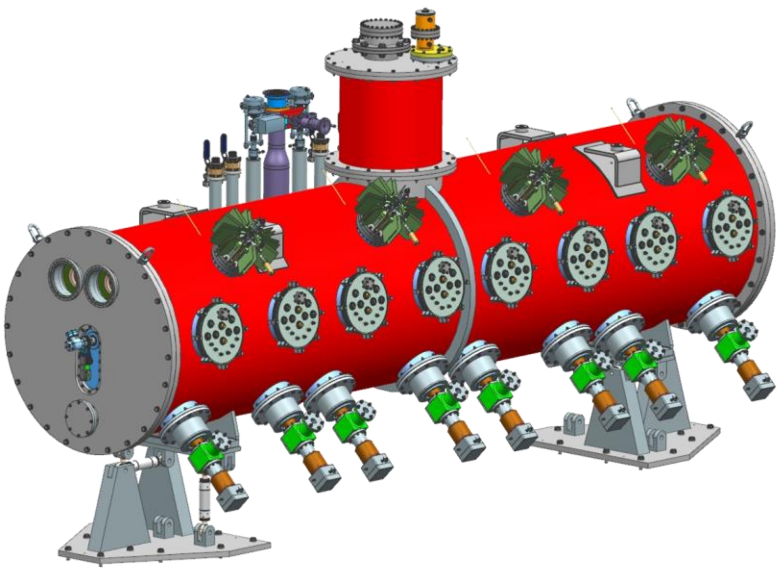
- 2 temperature sensors in the helium guard
- Measure of the voltage between the helium guard and the splice (lead side). (22 vtaps)
- Heater 20 W in the helium guard
- Relief valve 60 psig,
- Pressure transducer
- Angle valve
- Electrical feedthroughs with fins
- Two ¼” holes spaced by 5/8” apart used for the interface with the wire coming from the power supply

9. External interfaces

9.3 Tuner Access port

Each tuner access port will have the same connectors on it, but the instrumentation will be different.

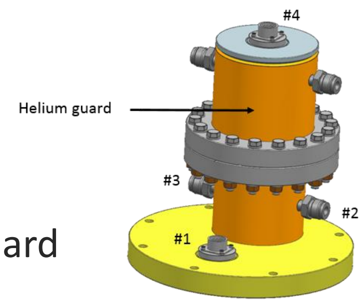
- 2 temperature sensors on each cavity
- 1 heater on each cavity
- 1 cavity field probe per cavity
- 1 coupler filed probe
- 4 wires per BPM
- 2 temperature sensors on each coupler
- 1 temperature sensors on each tuner
- 4 piezo actuator on each tuner
- 1 stepper motor with 2 switch tuners on each tuner
- 2 helium level sensor
- 2 temperature sensor in the helium can
- 1 heater on the helium can
- Several temperature sensors
- 8 fluxgates
- 2.75” conflat flange on each tuner access port

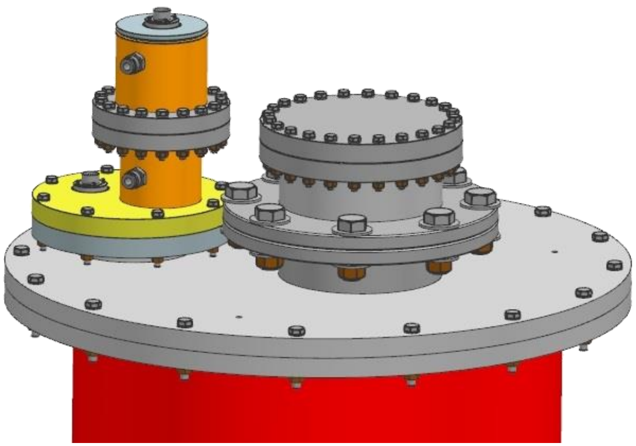


9. External interfaces

9.4 Top port

- 2 pressure transducers,
  one sensor 0-100 Torr
  one sensor 0-100 psi
- 2 VCR connectors for the helium guard
- 2 19-pins connectors
- 10” Conflat flange for the relief line





9.5 Side port

- 4 bayonets used for the 35-50 K line and for the 5 K line
- 1 bayonet used on the pumping line
- 1 cool down warm up valve
- 1 Joule-Thomson valve
- 1 relief valve
- 6” conflat flange for vacuum pumping
- 1 instrumentation port