Engineering Design and Key Technology Research of Moderator and Reflector System on CSNS-II

Chaoju Yu
yucj@ihep.ac.cn
CSNS Neutron Physics Group
CSNS-II Moderator and Reflector System

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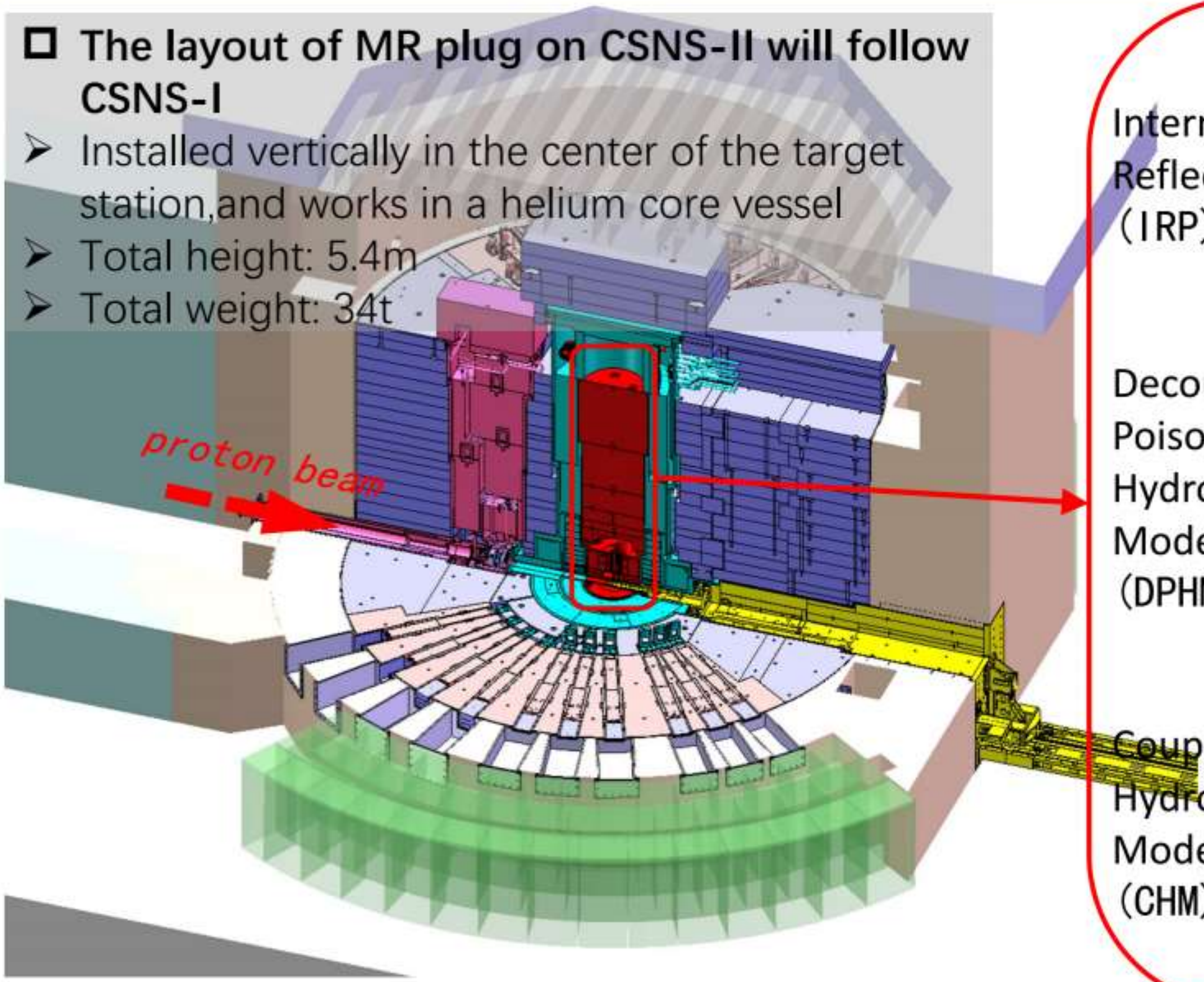
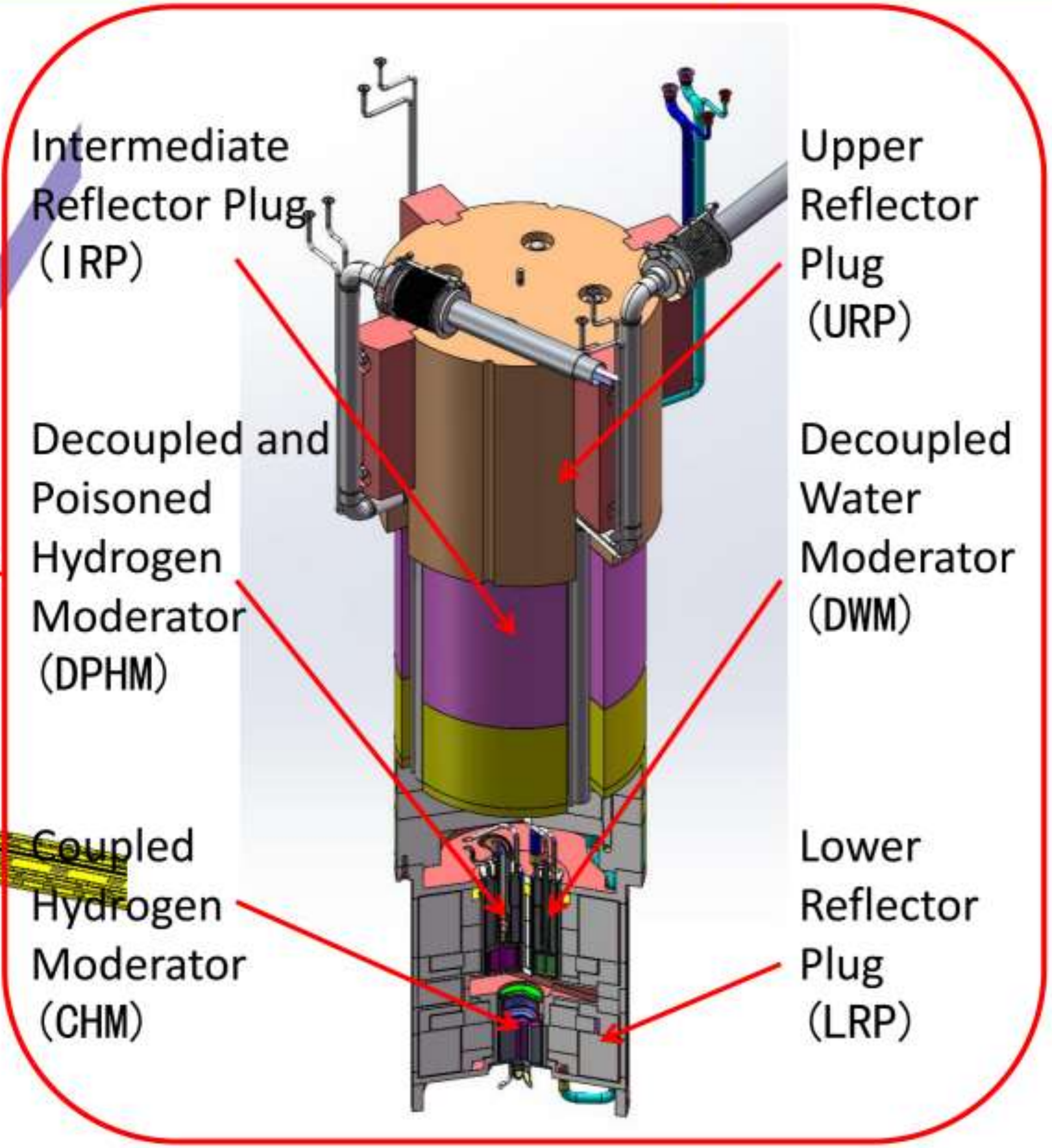
☐ Summary

Moderator and reflector (MR) plug layout

- **The layout of MR plug on CSNS-II will follow CSNS-I**
  - Installed vertically in the center of the target station,and works in a helium core vessel
  - Total height: 5.4m
  - Total weight: 34t

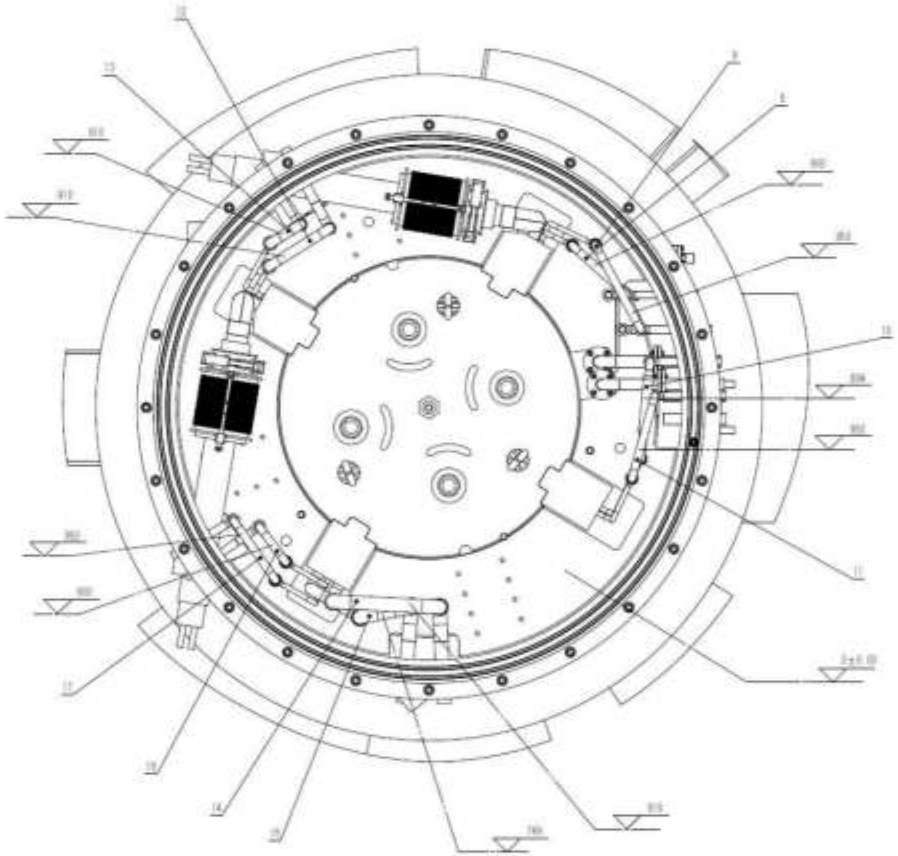


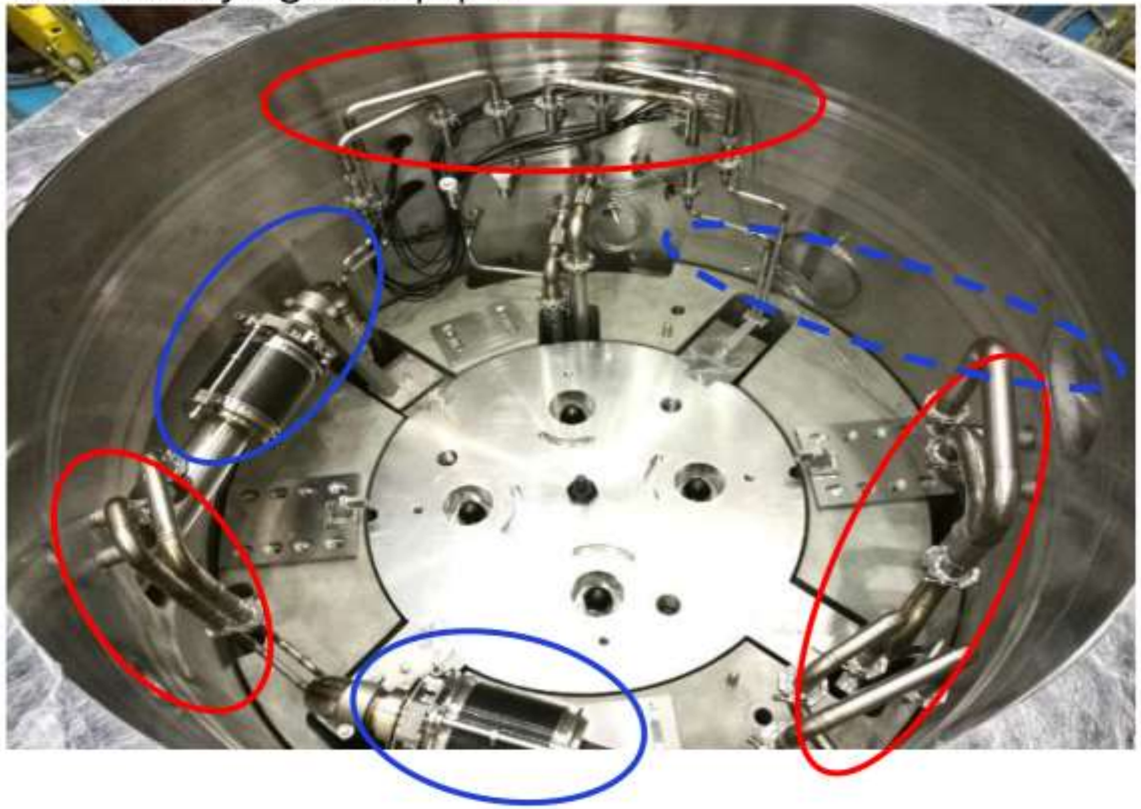


MR plug pipes layout (top view)

Layout of the pipes on CSNS-II will also be consistent with the CSNS-I

- All pipes are arranged along the inner edge of the helium core vessel, and all pipes are connected with quick-release connectors
- A large space in the center of the plug for easy maintenance
- We also reserved enough installation space for a third cryogenic pipe





water pipes　　cryogenic pipes

What will be upgraded for MR plug

The MR plug will be replaced as a whole on CSNS-II

Device name	Upgrades
Decoupled and Poisoned Hydrogen Moderator (DPHM)	• Upgrade the decoupling layer to remove the the heat deposition after proton beam increased to 500KW; • Upgrade structure for better physical performance
Coupled Hydrogen Moderator (CHM)	• Upgrade structure for better physical performance
Decoupled Water Moderator (DWM)	• Upgrade the manufacturing process of the cadmium decoupler • Upgrade structure for better physical performance
Lower Reflector Plug (LRP)	• Upgrade the cooling structure to remove the heat deposition after proton beam increased to 500KW • Upgrade the material of the reflector vessel and the welding process technique
Intermediate Reflector Plug,Upper Reflector Plug (IRP,URP)	• Some small structural improvements

Design requirements and reference standards

- High reliability, due to the activation, once the MR plug is put into the target station, it is basically impossible to repair it if there are some errors. So reliability is very important
- Design and manufacturing need to be based on nuclear facility design standards, so that to achieve a balance of high performance and high reliability
- The preliminary expected life time is 5 years (depends on the decoupling material)
- Main referenced standards:

  •ASME Code for the Construction of Components for Nuclear Facilities

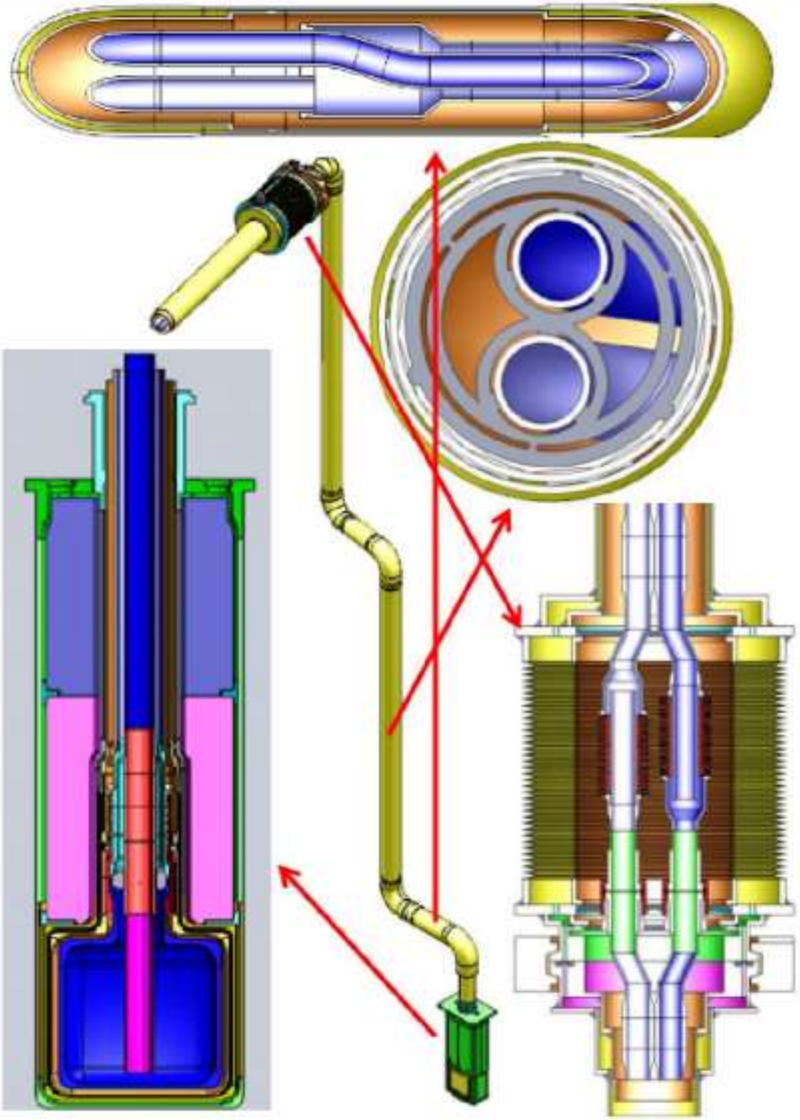
  •JB/T4734 Aluminium welded vessels

  •GB150 Pressure vessels

  •JB/T4732 Steel Pressure Vessels-Design by Analysis

Moderators configurations

- ◻ Each of the three moderators is designed and manufactured independently
- ➢ Height:
  DPHM & DWM, 4.6m
  CHM, 5.2m
- ➢ Weight:
  DPHM, 150Kg
  CHM, 160Kg
  DWM, 18Kg
- ➢ Principal materials:
  Moderator vessels, 6061-T6
  Cryogenic pipes, invar alloy
  Other pipes, SS316L

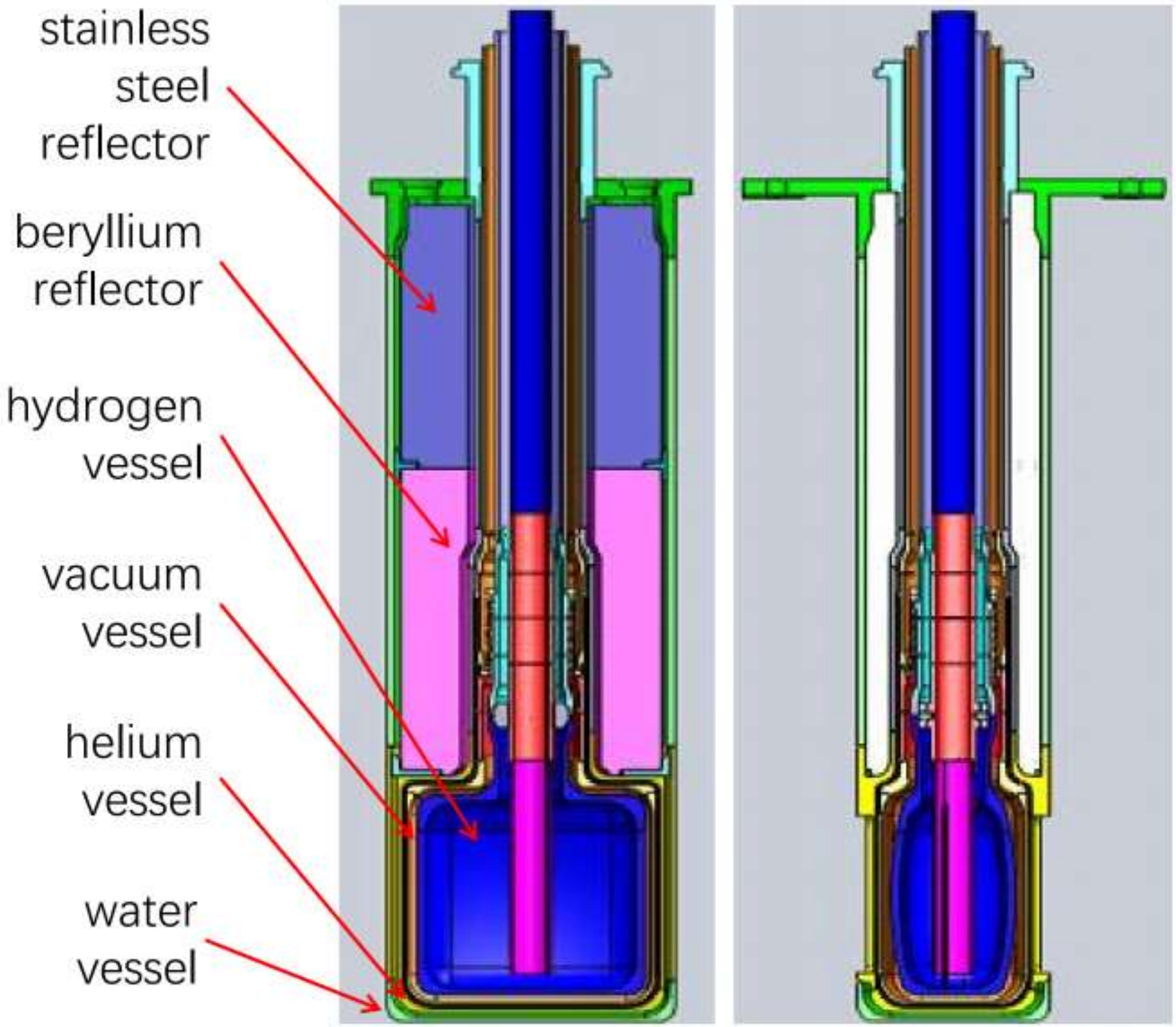


Main internal structure of DPHM

What will be upgraded for DPHM

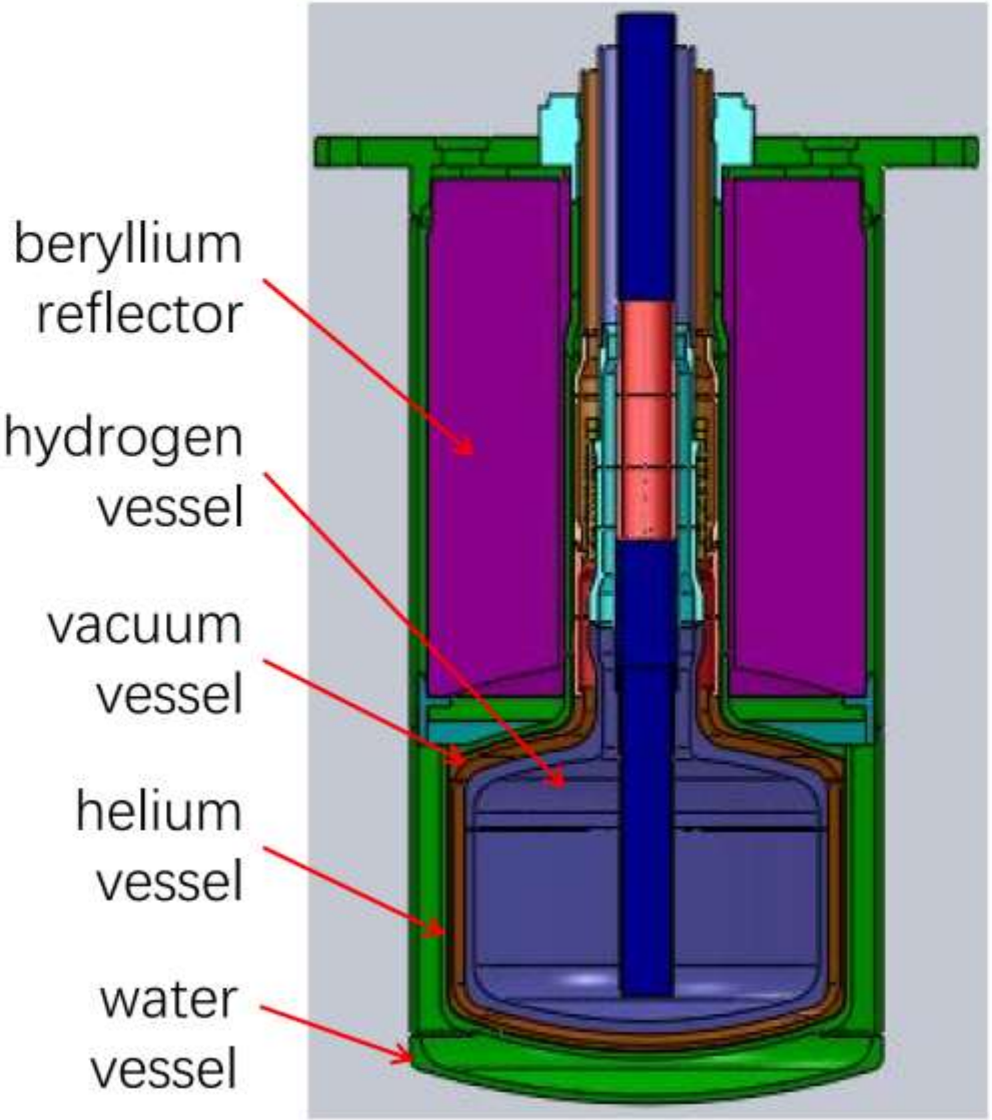
- DPHM contains four hexahedral vessels, from the inside to the outside are the cryogenic liquid hydrogen vessel, vacuum vessel, helium vessel and cooling water vessel
- Decoupling layer out side the vacuum vessel will be upgraded for a better heat transfer
- New decoupling material developing is in operation
- Neutron performance optimization is also in operation

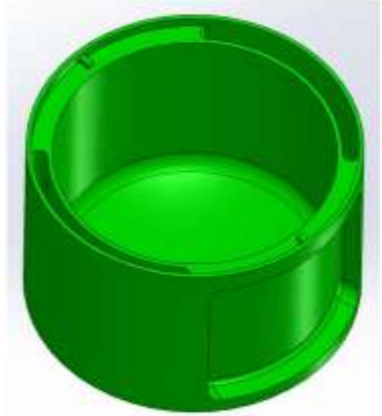
Cadmium sheet decoupling layer(CSNS-I)

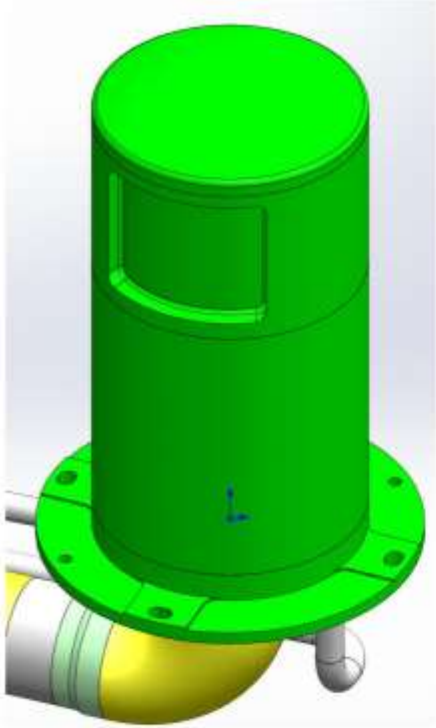


What will be upgraded for CHM

- CHM contains four cylinder vessels, from the inside to the outside are the cryogenic liquid hydrogen vessel, vacuum vessel, helium vessel and cooling water vessel
- The helium container and water container are integrally formed
- In order to obtain better neutron physical properties, the shape of the hydrogen container may be partly modified



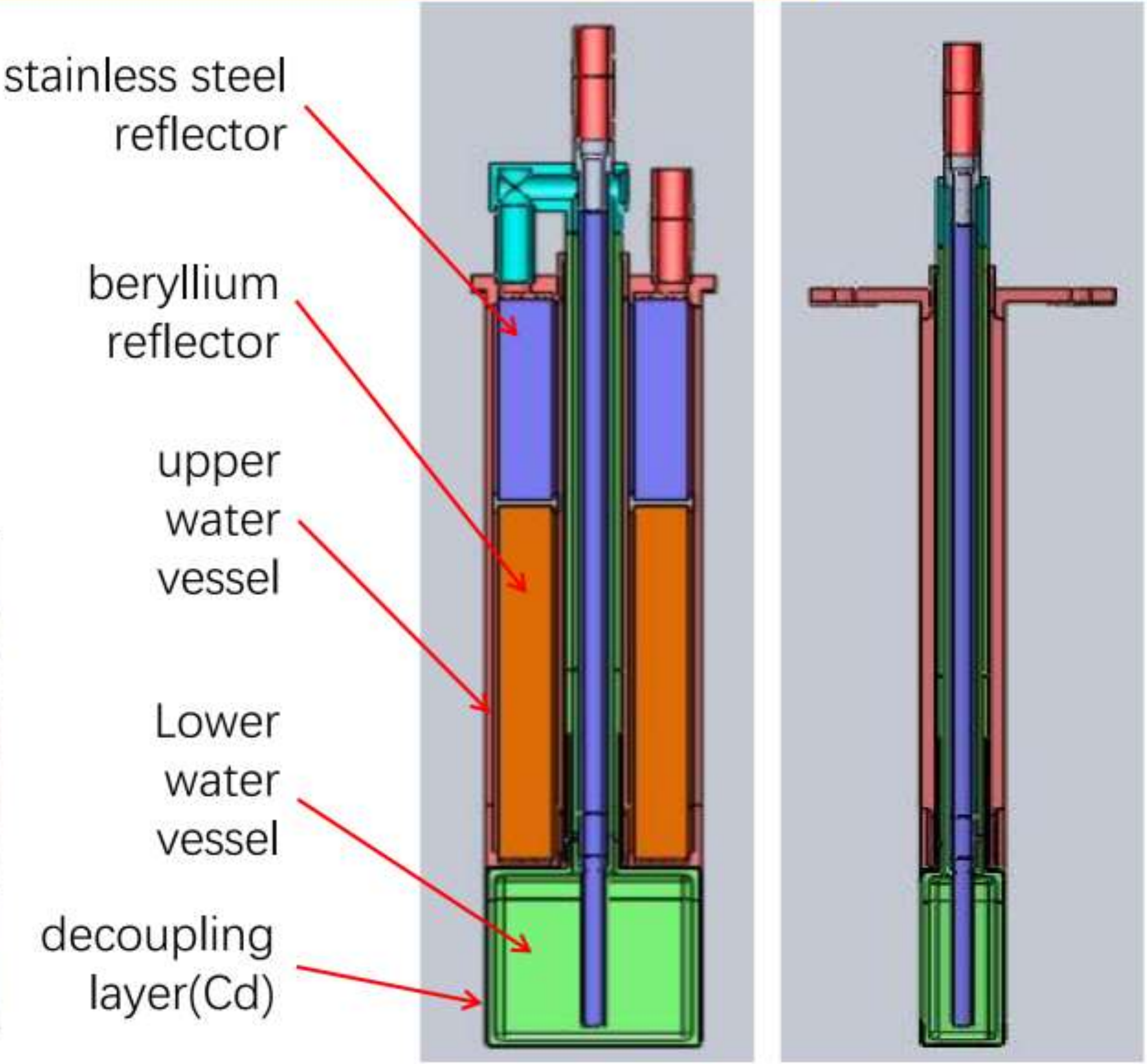




What will be upgraded for DWM

- Decoupling layer of the DWM is out side the lower water vessel
- Because the bonding strength of large-thickness electroplating is too low, cadmium powder falls off on the target
- A better coating processing technique should be developed

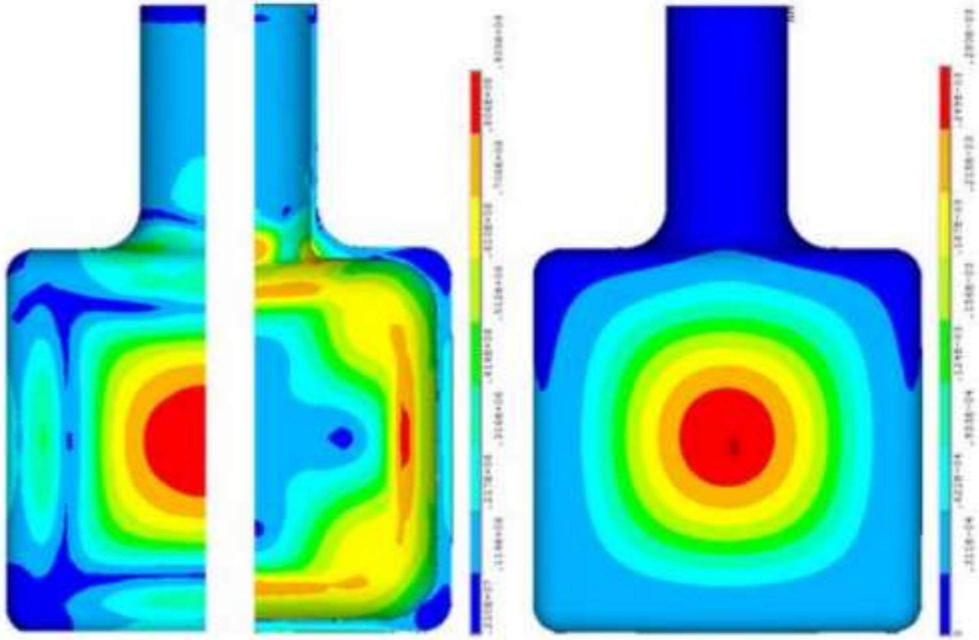
cadmium powder falls off on the target(CSNS-I)



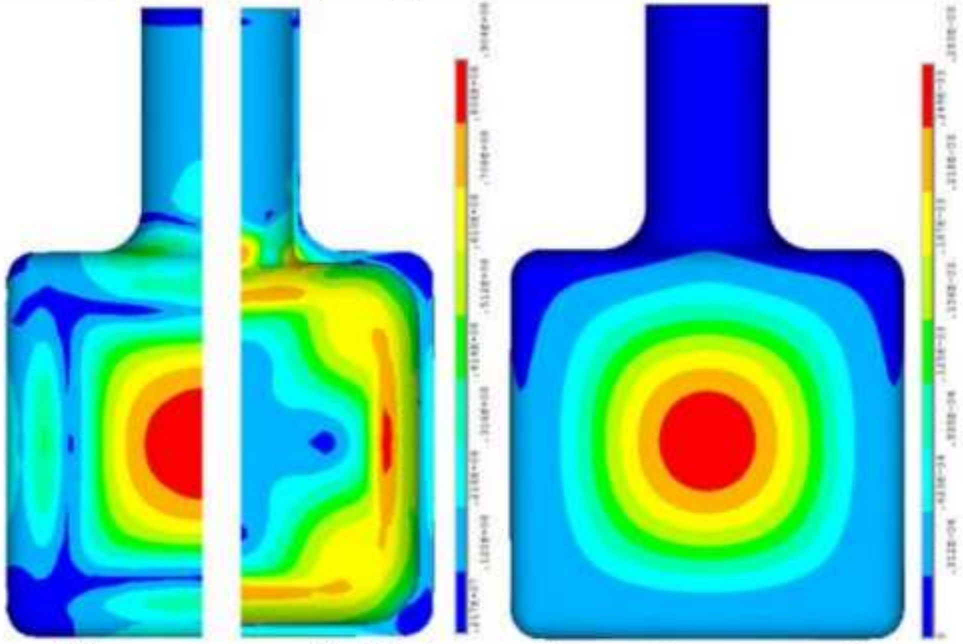
Moderator vessel strength intensity calculation

- All the designs are assurance to ASME Code and Chinese local standard
- Variety of working conditions are classified according to three situations: normal, abnormal and emergency

	Pm	P_L	P_L+P_b	P_L+P_b+Q
Allowable Stress Instensity(MPa)	87.6	131.4	131.4	262.8
Maximum Stress under Normal Operating Conditions(MPa)	37.5	34.9	91	90.9
Allowable Deformation(mm)	1			
Maximum deformation under Normal Operating Conditions(mm)	0.28			



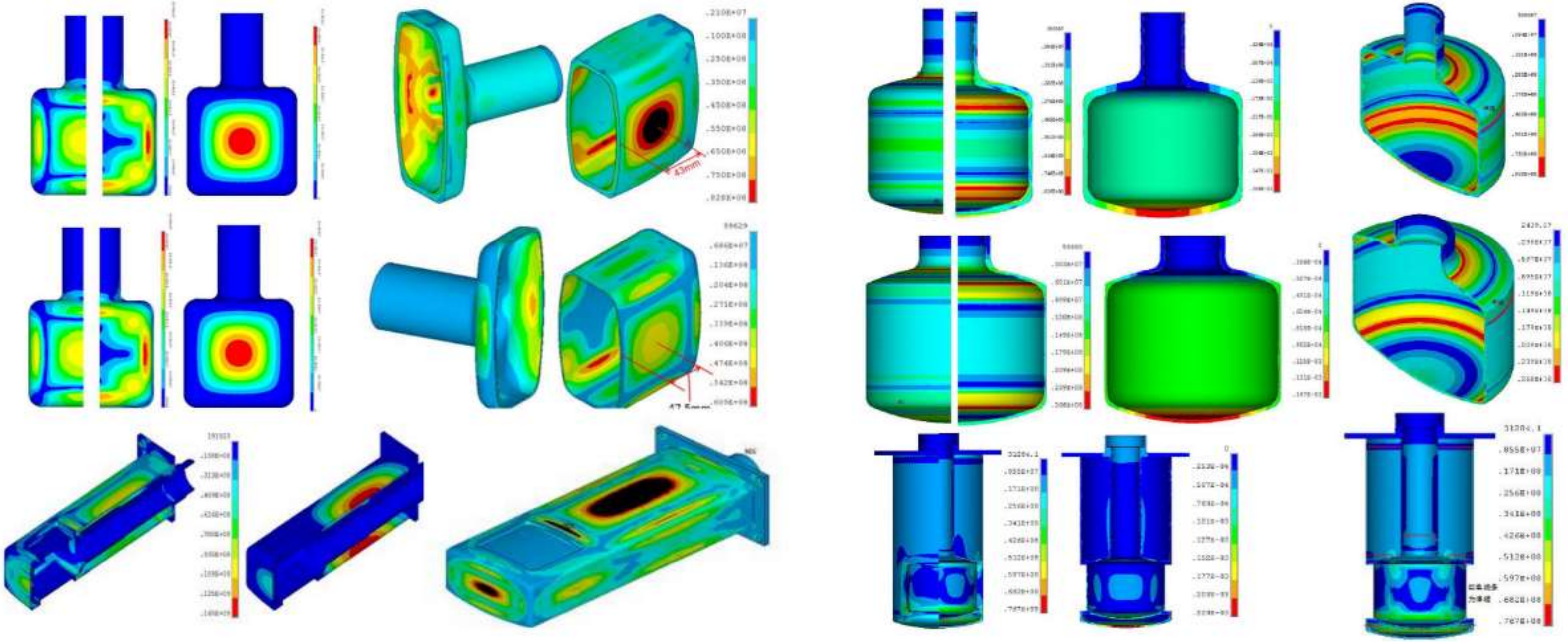
Stress strength and deformation distribution of under normal working conditions(DPHM Hydrogen vessel)



Thermo-solid interaction stress and deformation distribution on normal operating conditions(DPHM Hydrogen vessel)

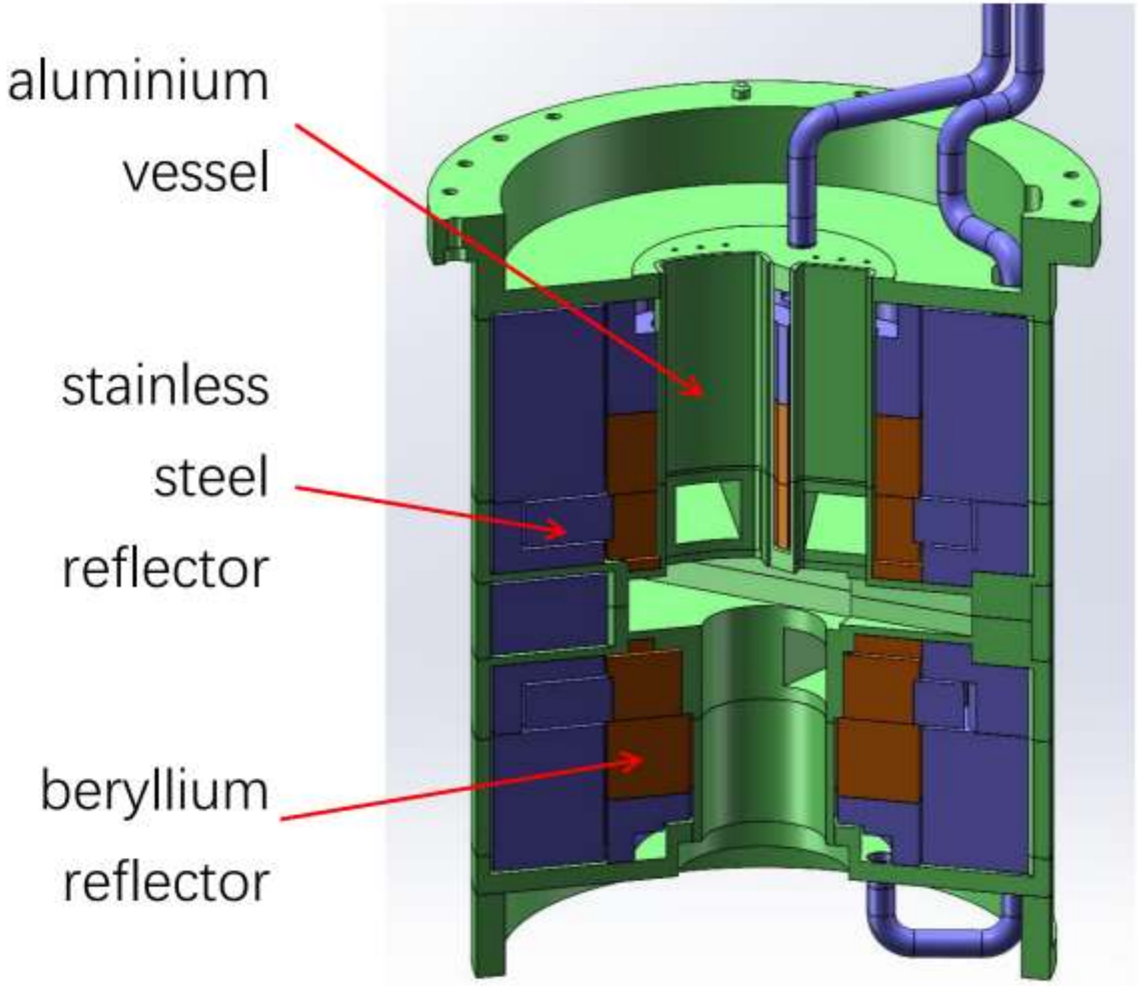
Moderator vessel strength intensity optimization

- Strength intensity optimization design were performed for each vessel of the three moderators
- Weldding line for each vessel is designed in an low stress area



What will be upgraded for LRP

- LRP is assembled and welded from an aluminum vessel on the outside, beryllium reflector and a stainless steel reflector inside.
- The material of the LRP vessel is aluminum 5083 on CSNS-I, allowable temperature is only 65℃, we plan to change the material to 6061-T6 for a bigger allowable temperature of 100℃ or more.
- Refletor vessel will be manufactured using EB-welding for a smaller welding deformation
- Continue to maintain fewer flow channels to increase neutron physical performance if possible



Operating temperature limits of 6061-T6 and 5083

- ASME Code specifies a temperature limit of 65°C (150°F) for Aluminum Alloy 5083
- Aluminum 6061-T6 has a higher operating temperature than the 5083

GBT38106,China 表 A.1 铝合金板材的最高许用应力

牌号	状态	板材厚度 mm	最低抗拉强度 MPa	最低屈服强度 MPa	最高使用温度 ℃
5083	O	>1.295～38	275	125	65
		>38～76	270	115	65
		>76～125	260	110	65
	H112	>6～38	275	125	65
		>38～76	270	115	65
5454	O	1.295～75	215	85	204
6061	T6	1.295～6	290	240	204

AD 2000W6/1,Germany

EN symbol	Composition according to	Delivery condition according to product form (see Table 2)	Working temperature range
A. Materials for general application			
EN AW-1098	DIN EN 573-3	O/H111, H112	−270 °C to 100 °C
EN AW-1080A	DIN EN 573-3	O/H111, H112	−270 °C to 100 °C
EN AW-1070A	DIN EN 573-3	O/H111, H112	−270 °C to 100 °C
EN AW-1050A	DIN EN 573-3	O/H111, H112	−270 °C to 300 °C
EN AW-5754	DIN EN 573-3	O/H111, H112	−270 °C to 150 °C
EN AW-5049	DIN EN 573-3	O/H111, H112	[illegible]
EN AW-5083	DIN EN 573-3	O/H111, H112	−270 °C to 80 °C[1])
B. Materials for certain low-temperature applications (see Table C.2)			
EN AW-3003	DIN EN 573-3	F, O	−270 °C to 50 °C[1])
EN AW-3103	DIN EN 573-3	O/H111, H112	[illegible]
EN AW-6060	DIN EN 573-3	T4	−196 °C to 50 °C[1])

PD5500,UK

Aluminium magnesium alloys

Pressure vessels in aluminium alloys containing 3.0% or more of magnesium for use at temperatures above 65 °C shall be constructed only from material supplied in the annealed (O) condition.

NOTE Extended service of alloys containing 3.0% or more magnesium at temperatures above 65 °C can result in grain boundary precipitation of Mg-Al intermetallic compounds which corrode in some process fluids leading to disintegration in weld areas. Alloys of this type should not be used at temperatures above 65 °C unless tests or service experience have demonstrated that they are suitable for specific duty.

Upgrade parameters of the MR plug

Increase the allowable operation temperature after upgraded to 500KW on CSNS-II

Moderator and reflector plug technical characteristics table					
	Hydrogen layer of moderators	Vacuum layer of moderators	Helium layer of moderators	Water layer of moderators	Water layer of reflector
medium	Supercritical hydrogen	Vacuum	Helium	Deionized water	Deionized water
Operating temperature	17K	373K	350K	350K	350K
Design temperature	15K	398K	366K	366K	366K
Working pressure	1.55MPa	External pressure 0.1MPa	0.15MPa	0.4MPa	0.45MPa
Design pressure	1.7MPa	External pressure 0.18MPa	0.18MPa	0.45MPa	0.50MPa
Barometric test pressure	1.9MPa	0.2MPa	0.2MPa	0.5MPa	0.55MPa
Safety valve start-up	1.7MPa	—	—	—	—
Rupture disc action	1.8MPa	0.18MPa	0.18MPa	—	—
Overpressure Limit*	1.9MPa	0.2MPa	0.2MPa	0.5MPa	0.55MPa
Helium Leakage rate	$\leqslant 6.7\times10^{-9}Pa.m^3/s$@77-	$\leqslant 1\times10^{-8}Pa.m^3/s$	$\leqslant 1\times10^{-7}Pa.m^3/s$	$\leqslant 1\times10^{-7}Pa.m^3/s$	$\leqslant 1\times10^{-7}Pa.m^3/s$
Corrosion margin	0mm	0mm	0mm	0mm	0mm
Weld joint coefficient	0.9	0.9	0.9	0.9	0.8
Heat treatment after	natural ageing	natural ageing	natural ageing	natural ageing	natural ageing
Anti-corrosion requirements	—	—	—	—	—
Non-destructive testing	100% radiographic inspection	100% radiographic inspection	100% radiographic inspection	100% radiographic inspection	100% radiographic inspection
Other features	Flammable and explosive				

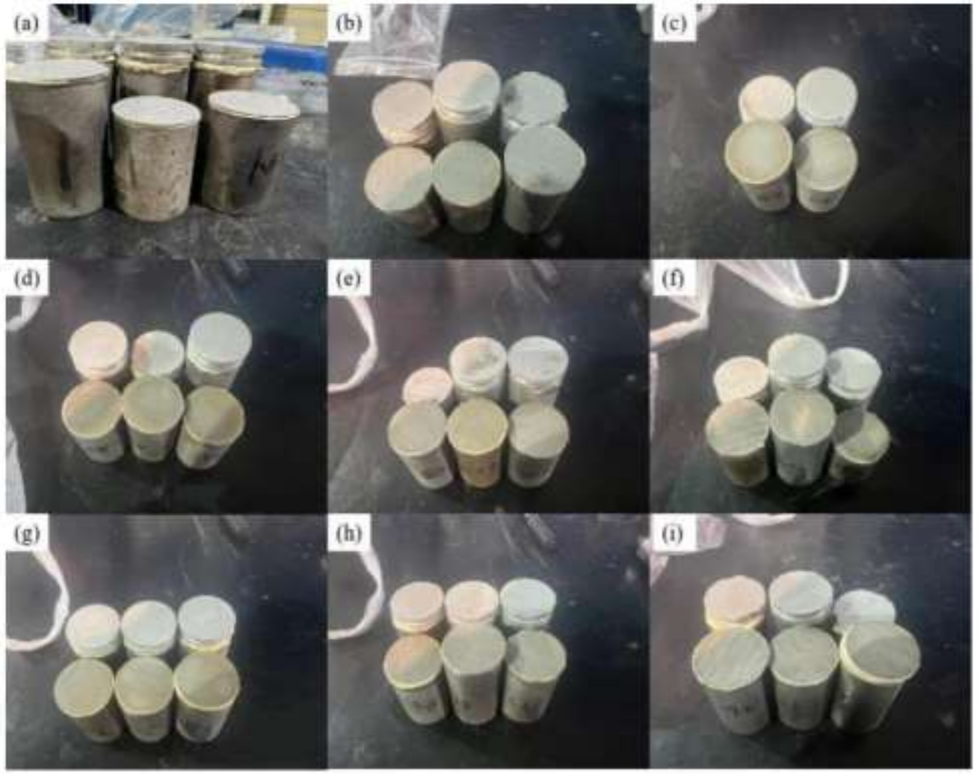
Note: All pressures refer to absolute pressure, and when running, debugging and pressure tests, the gauge pressure should be determined separately according to the pressure in the table and considering the influence of adjacent containers and atmospheric pressure.

*The discharge amount of the overpressure drain device should be sufficient to prevent the maximum pressure inside the vessel and pipe from exceeding this value.

Cadmium decoupling layer development

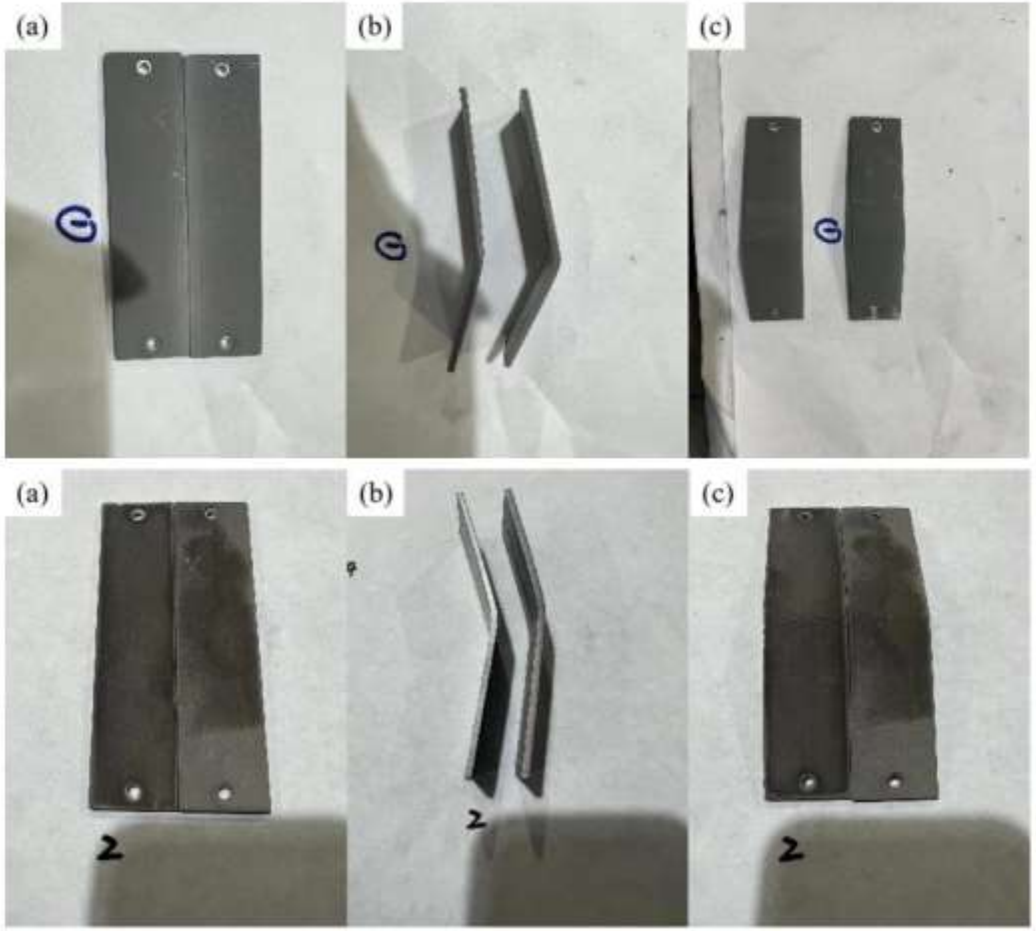
- Process techniques: Flame spraying
- Base material: 6061-T6 aluminum alloy
- Spray coating: cadmium
- Thickness: 0.6mm
- Change the three key process parameters to optimise the process techniques, and the best bonding strength is 35MPa, and he porosity is less than 2%

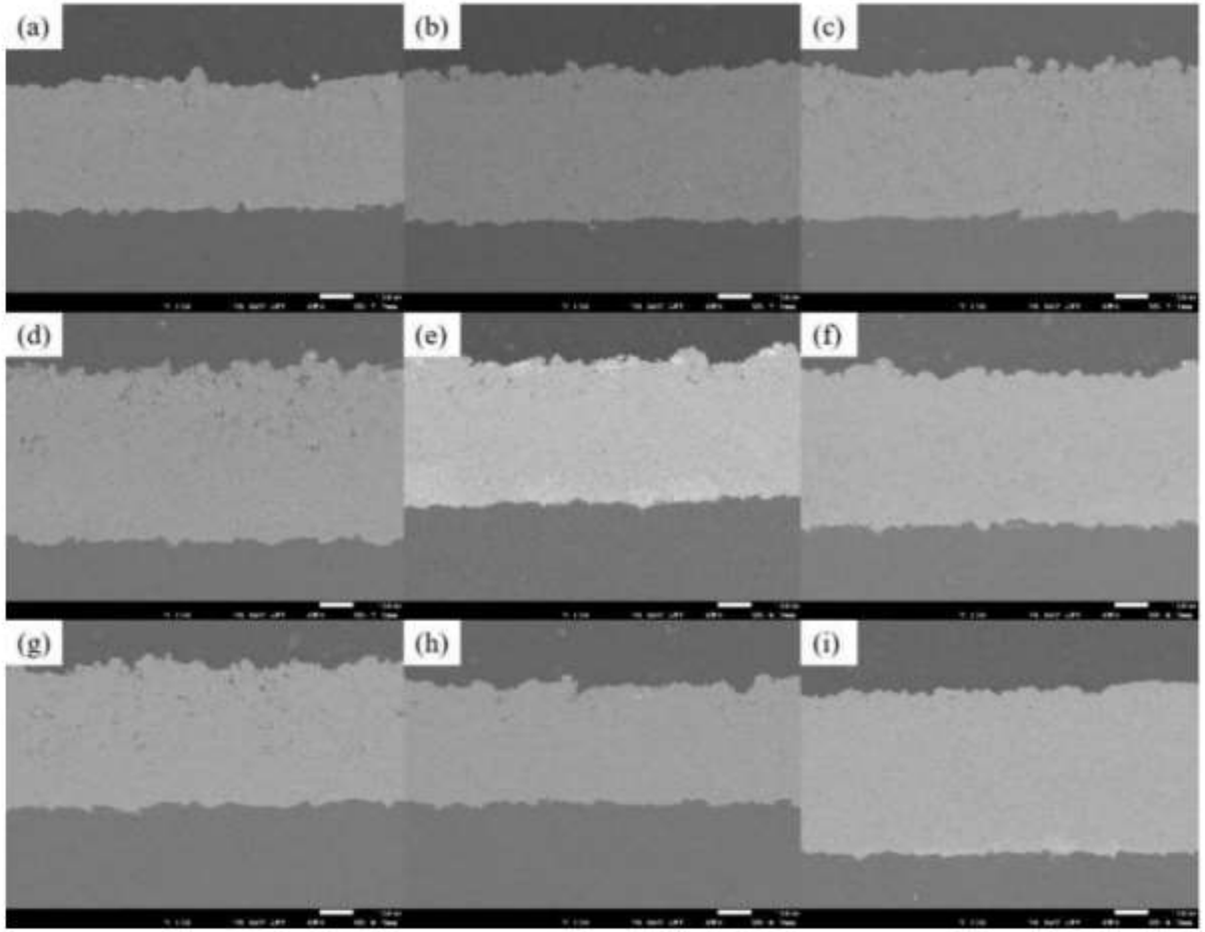
	Acetylene flow	Oxygen flow	Spraying distance	Bonding strength
	L/min	*L/min*	*mm*	*MPa*
1	40	25	130	31.33
2	40	20	150	35.10
3	40	15	170	19.95
4	35	25	150	8.77
5	35	20	170	28.03
6	35	15	130	20.93
7	30	25	170	11.53
8	30	20	130	17.63
9	30	15	150	25.67



Cadmium decoupling layer development

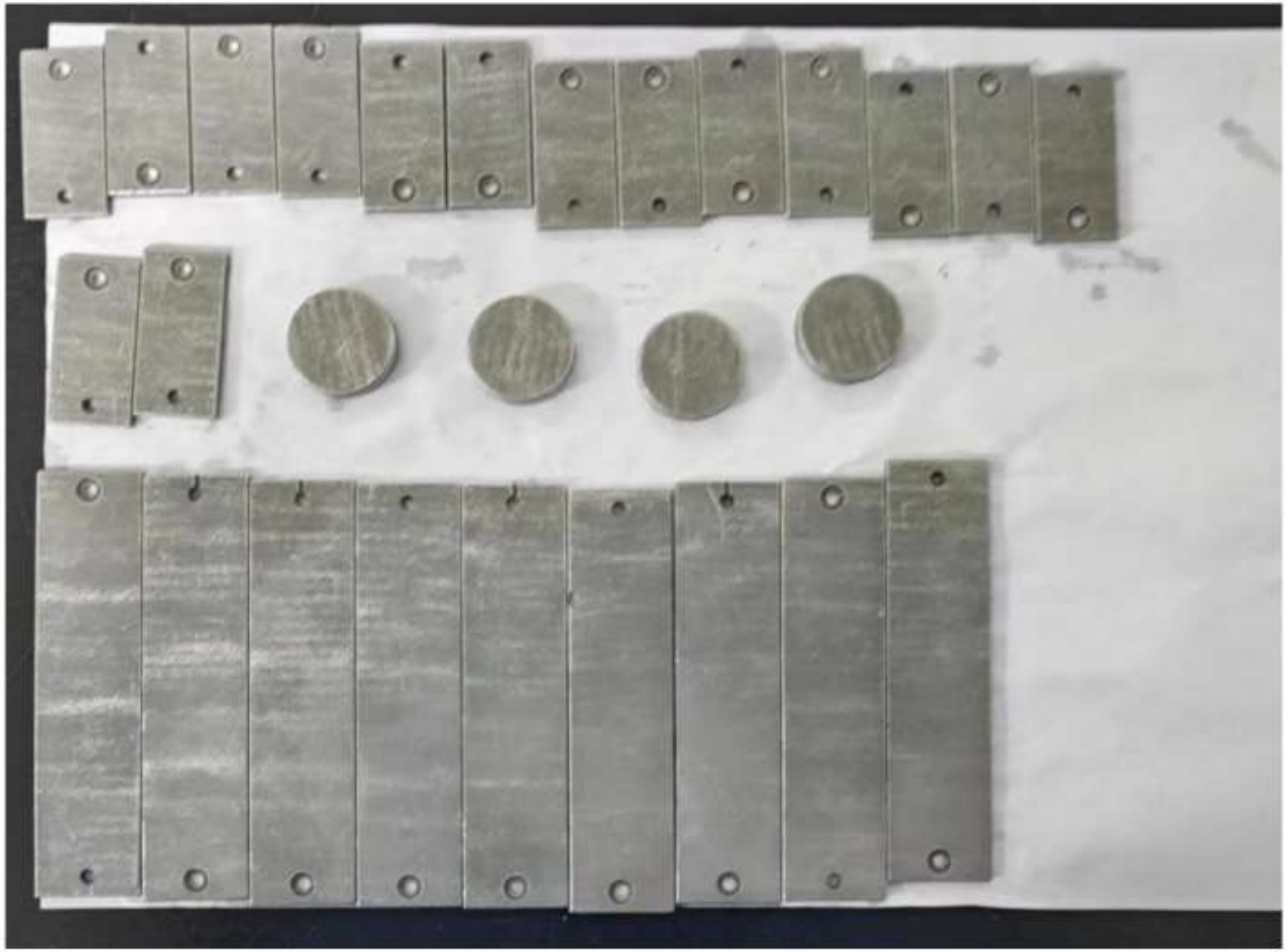
- The 10°and 30° bending test were carried out, and all specimens have no overall spalling
- The interface between the aluminum and the coating is well combined, and there are no cracks inside





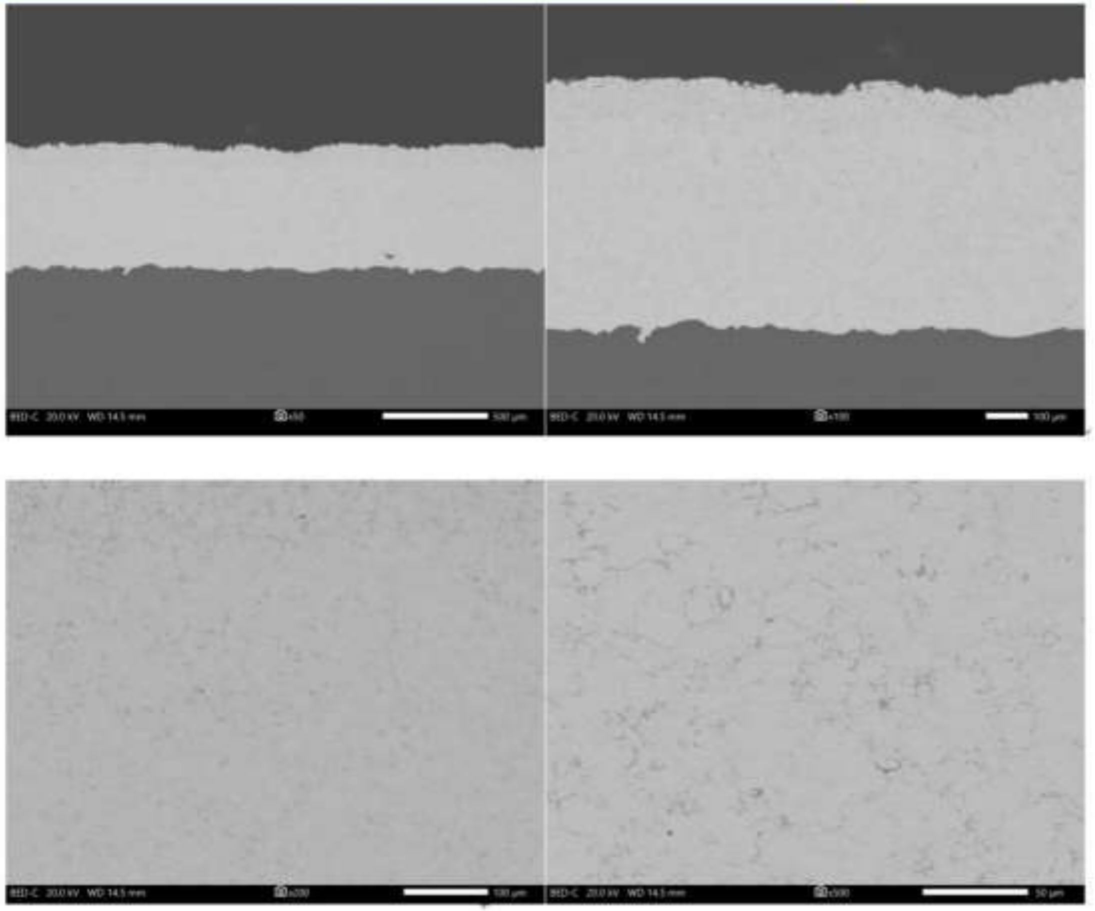
Cadmium decoupling layer development

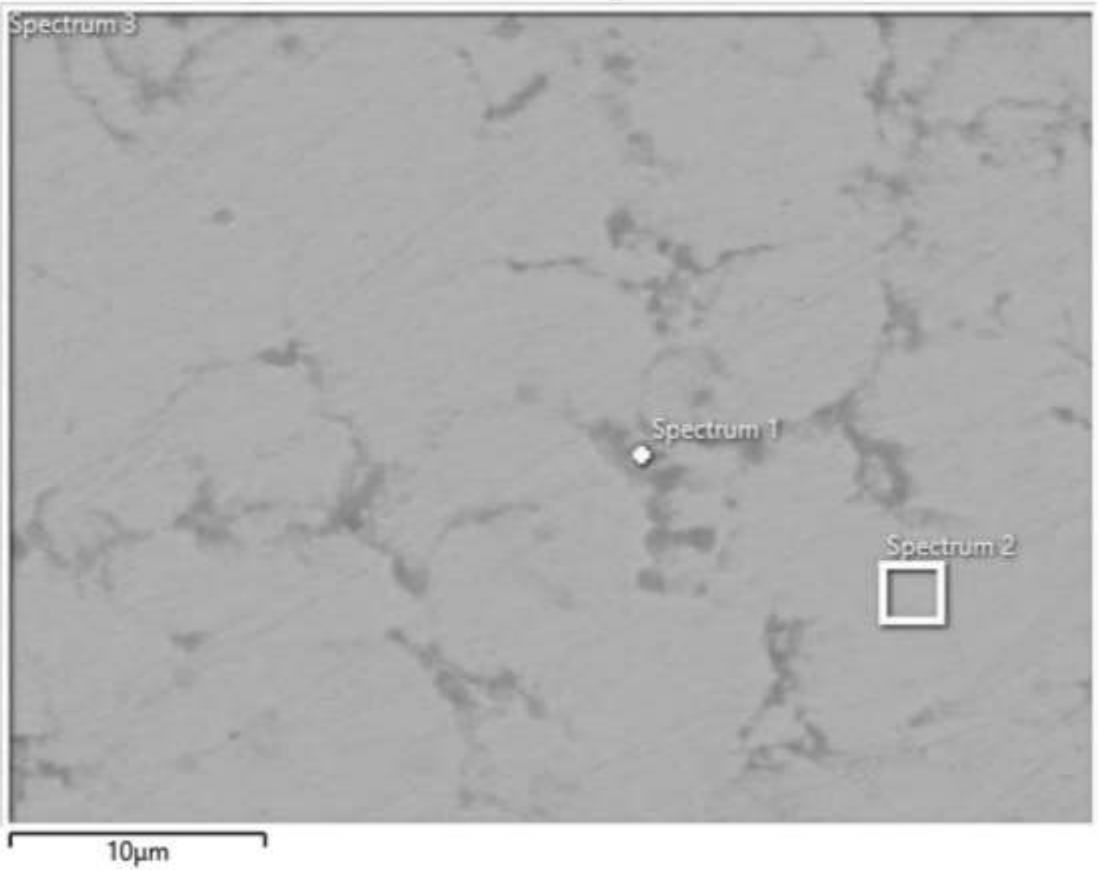
- Thermal cycle test: The cadmium coating on the surface of the aluminum alloy was subjected to a 100°C water-cooled hot cycle test (5min heat preservation)
- After 100 cycles no cracking and peeling occurred between the coating and the aluminum
- The surface of the coating showed a slight oxidation color



Cadmium decoupling layer development

- Further testing of the microstructure of the coating and EDS testing of the characteristic areas, a dark gray oxide was formed inside the coating after thermal cycling. The coating is well bonded to the substrate, and no oxidation occurs at the interface





Spectrum Label	Spectrum 1	Spectrum 2	Spectrum 3
O	11.72	4.01	5.51
Cd	88.28	95.99	94.49
Total	100.00	100.00	100.00

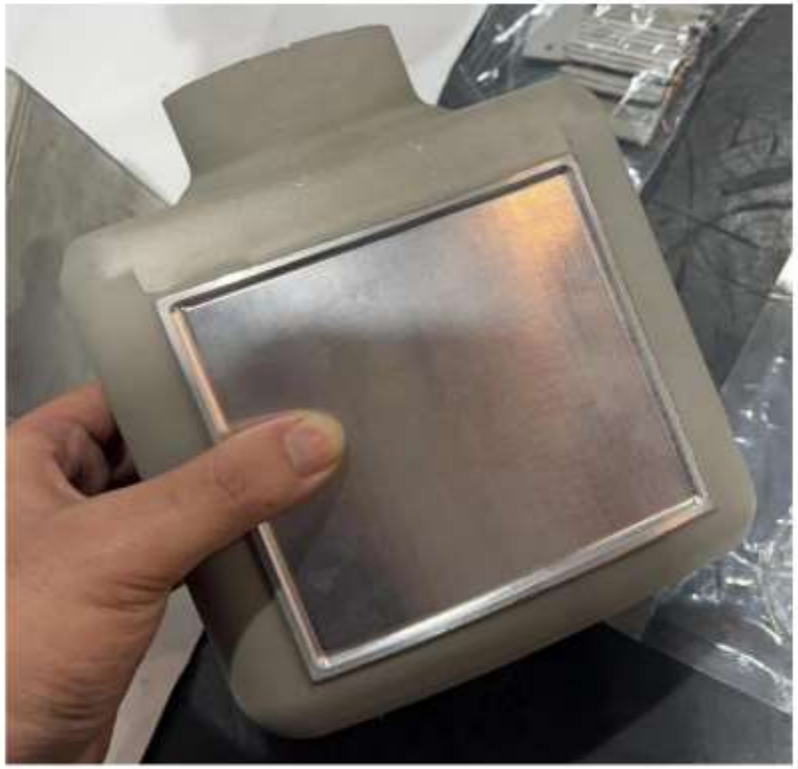
Cadmium decoupling layer development

- After the thermal cycling test, the Bonding strength of the coating decreases (but still more than 10MPa). The fracture location is located inside the coating
- The decrease in the binding strength of the coating due to the oxides generated inside
- After thermal cycling, the bending test of 10~20° was carried out on the coating specimens, and cracks appeared in the coating, but there was no overall peeling

Cadmium decoupling layer development

- Three prototypes of the moderator vessels were sprayed with optimized process parameters

Cadmium spray coating for water vessel of DWM



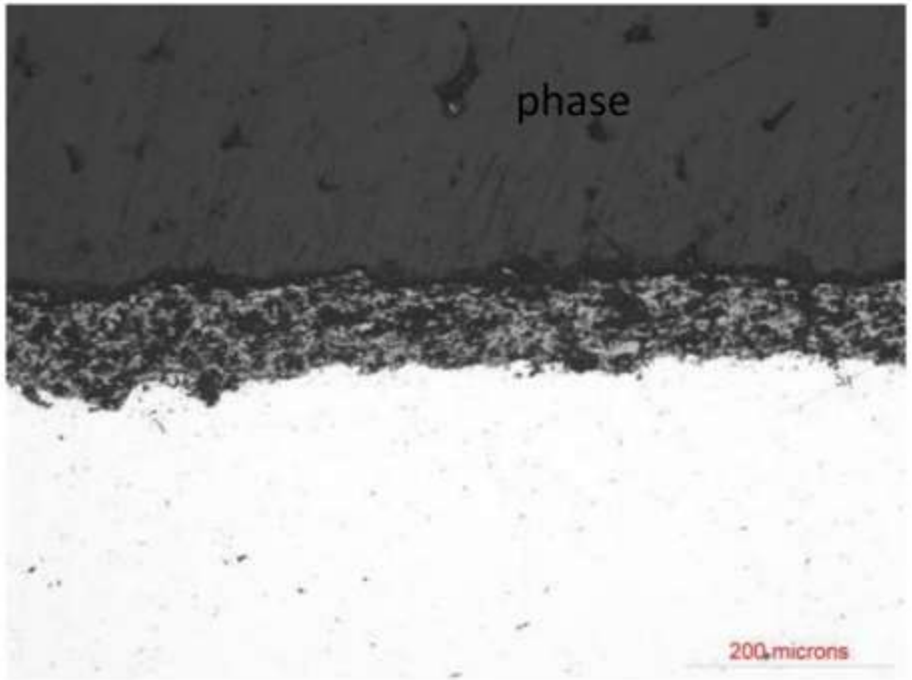
Cadmium spray coating for vacuum vessel of DPWM

Cadmium spray coating near Neutron Window of DPHM

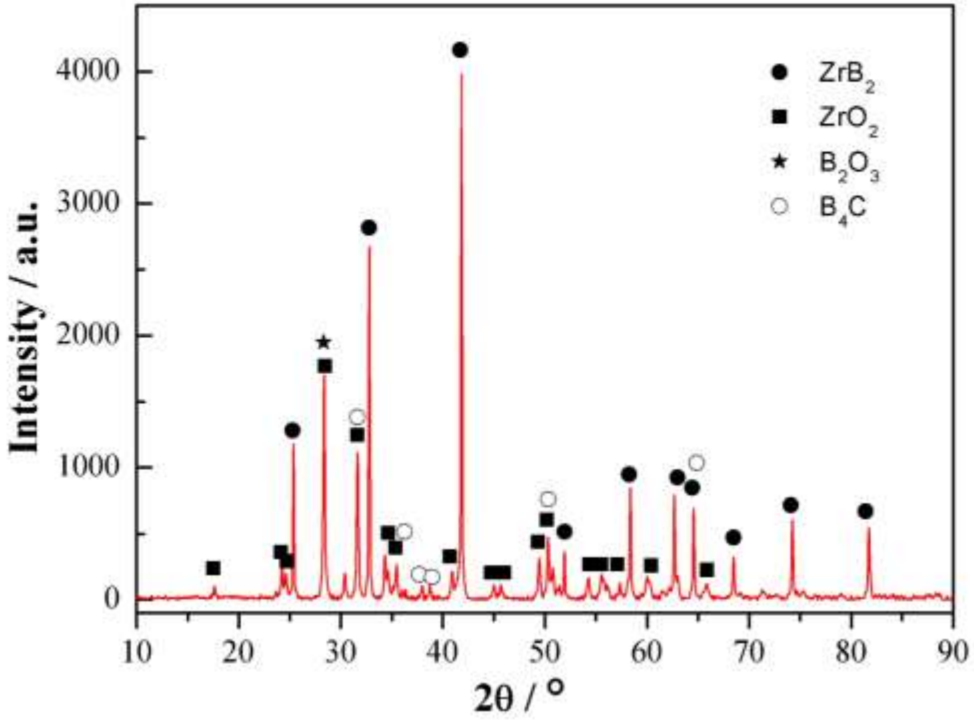
Boracic decoupling layer development (preliminary)

- Process techniques: plasma spraying
- Base material: 6061-T6 aluminum alloy
- Spray coating: 50%B4C+50%ZrO2(zirconium dioxide)
- Thickness: 0.1mm
- Due to the addition of ZrO2, oxygen is introduced, and the oxidation of B4C occurs during spraying

Sample number	1	2	3	4
Bonding strength/MPa	10.6	11.7	11.8	10.3
Average value/MPa	11.1			



microstructure of the spraied layer



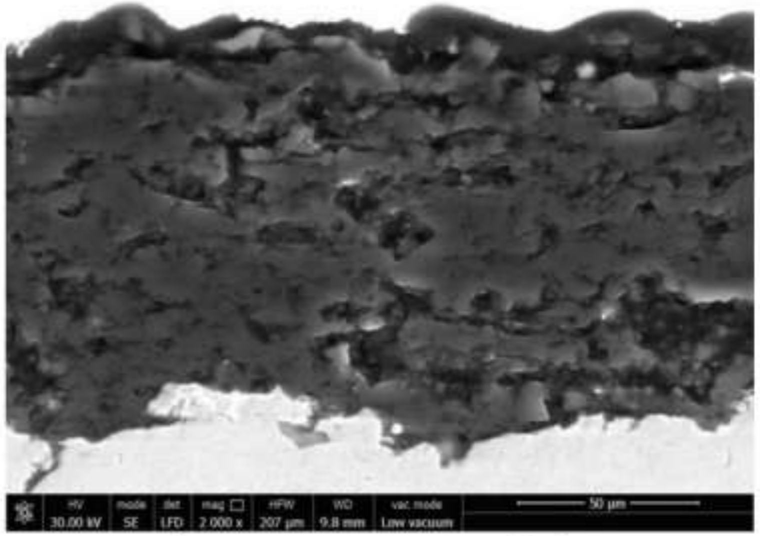
XRD result of the spraied layer

Boracic decoupling layer development (preliminary)

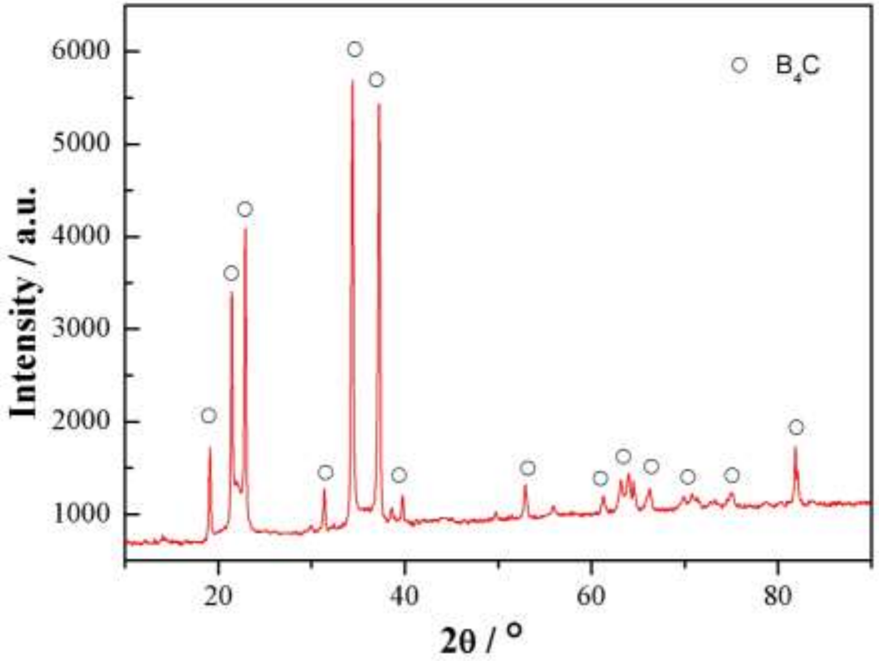
- Process techniques: plasma spraying
- Base material: 6061-T6 aluminum alloy
- Spray coating: 100% B4C
- Thickness: 0.1mm
- The average bonding strength of the coating was 21.3MPa, which was much higher than the previous test,The XRD results showed that the coating was composed of pure B4C

Sample number	1	2	3	4	5	6
Bonding strength/MPa	23.6	18.2	19.6	21.5	22.2	22.7
Average value/MPa	21.3					

sprayed specimens



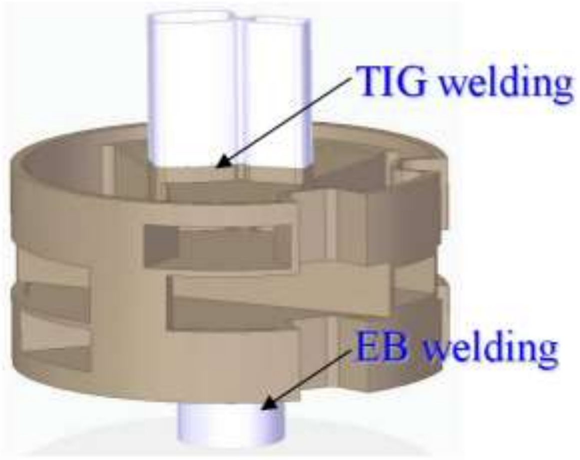
microstructure of the sprayed layer

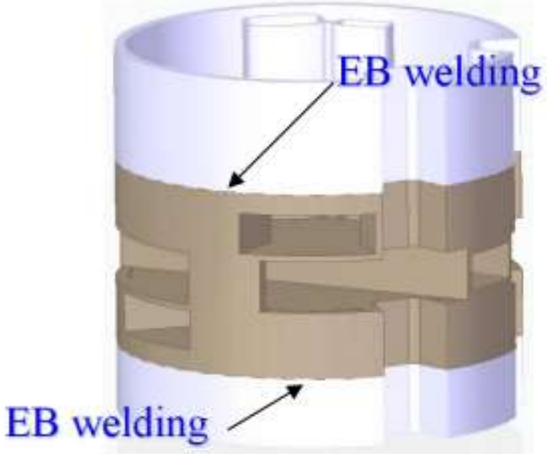


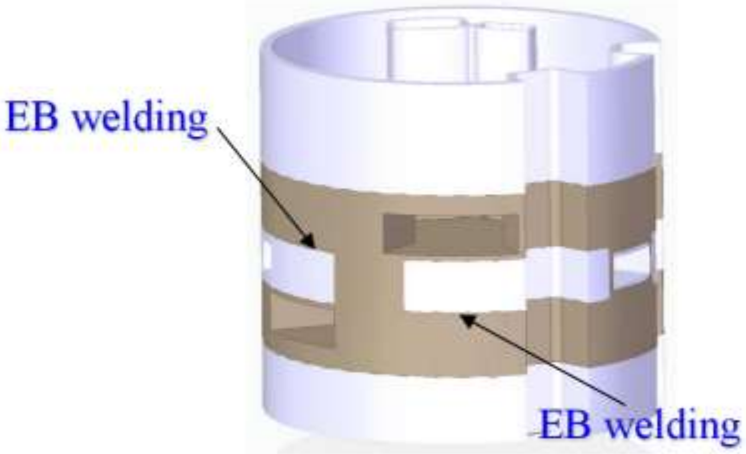
XRD result of the spraied layer

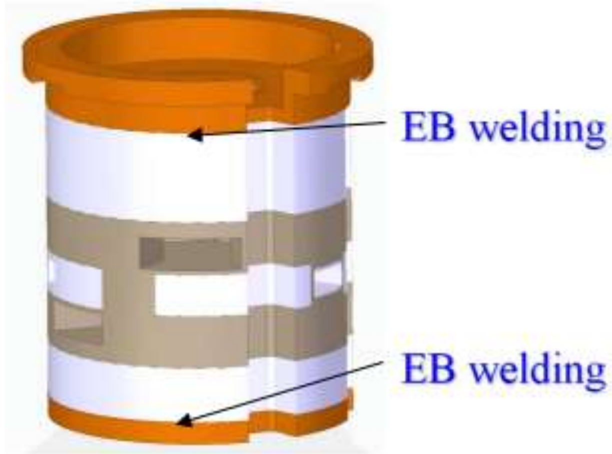
Welding assembly scheme for reflector vessel

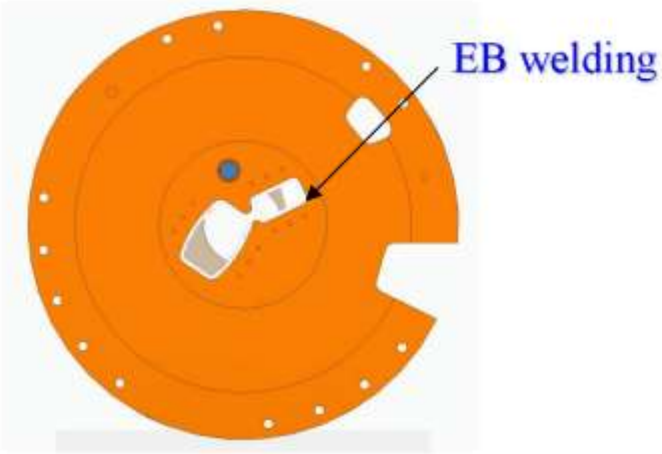
- The material of reflector vessel is 5083 on CSNS-I, and welded by TIG
- On CSNS-II, we plan to replace the material with 6061-T6 , and replace the TIG welding with EB-welding

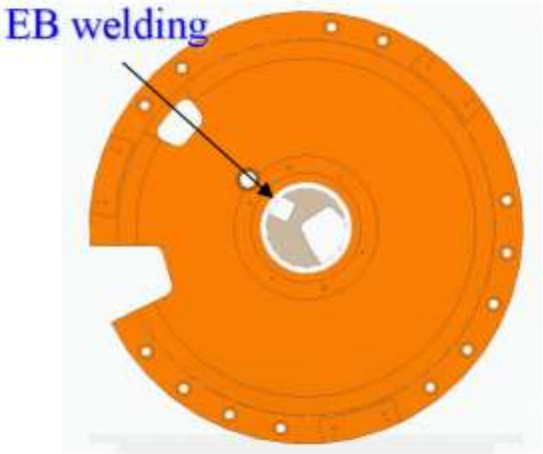






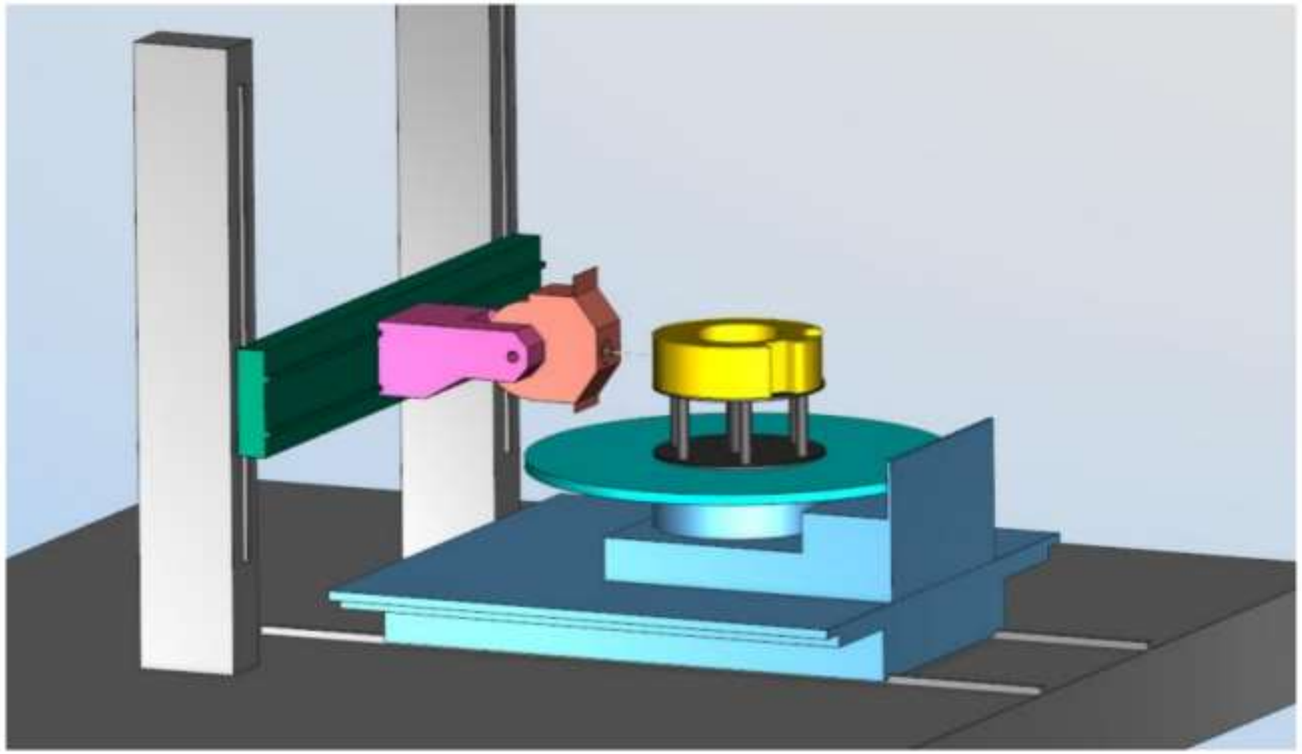


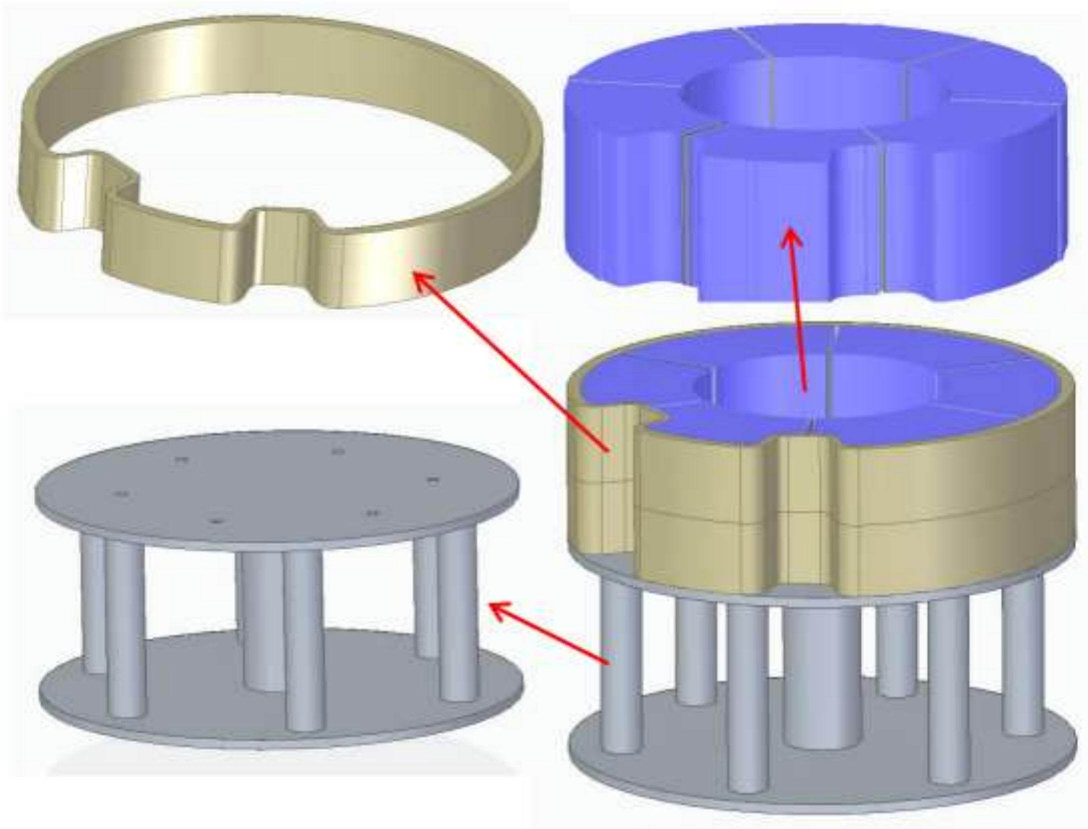




6061-T6 EB-welding test for reflector vessel

- Base Metal: 6061-T6, Bevel form: stop butting
- The effective welding depth is 10mm where the total thickness is 15mm;The effective welding depth is 15mm where the total thickness is 25mm
- Technical difficulty: (1) 6061 is more likely to produce welding cracks than 5083; (2) The local concave area is not easy to weld



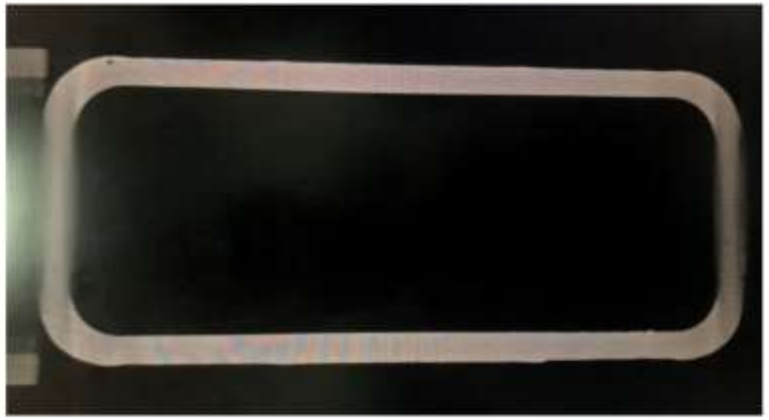


EB-welding optimization for moderator vessels

- Process technology: vacuum electron beam welding
- Base material: 6061-T6 aluminum alloy
- Execution standard: GJB1718A
- Weld grade: grade I

water vessel electron beam welding for DWM

vacuum vessel electron beam welding for DPHM



water vessel CT photo after welding

vacuum vessel CT photo after welding

Summary

- We had completed the MR plug preliminary design for CSNS-II
- The basic guaranteed process technology has been successfully developed for CSNS-II
- Some new manufacturing processes to improve physical performance are developing, but if the technology is not mature, it will not be used in formal engineering parts
- Based on the past experience, we have only one year to do the physical design and fabrication process optimization, then we will take 3 years to fabricate a new MR plug for CSNS-II


Thank you for your
attention.