ASIPP

Progress of Design and R&D of CFETR divertor

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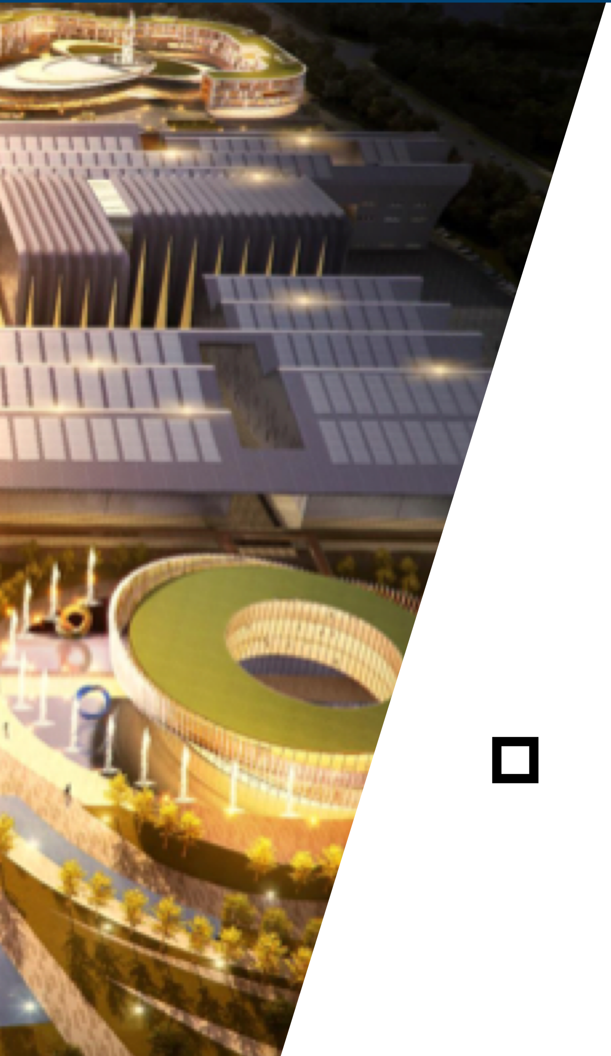
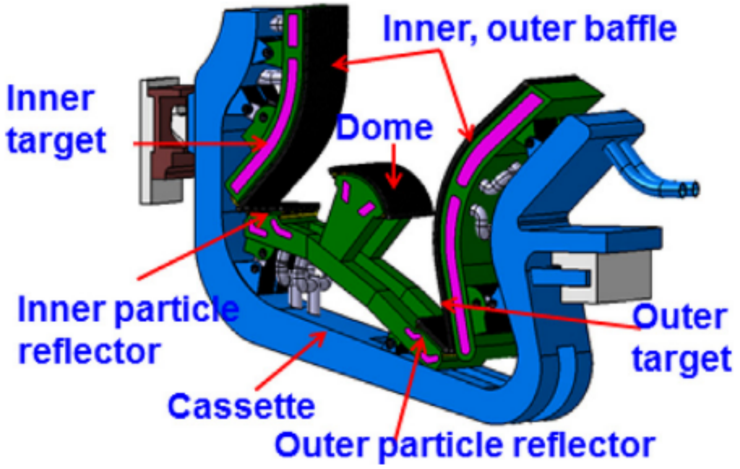
Outline



- CFETR divertor design
  - Introduction
  - Front-face remote handling targets
  - Divertor-blanket integration
- Progress of R&D
  - Target material
  - Small-sized mock-up tests
  - Medium-sized mock-up tests
- Summary and outlook

CFETR Divertor Design Stages

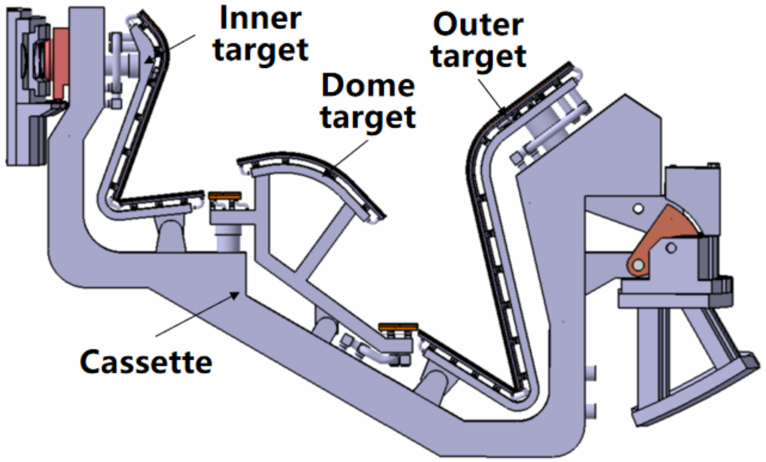


Conceptual design(2012-2017)

- Smaller-sized device:

  R=5.7 m, a=1.6 m, B_T=4–5 T and fusion power 200–500 MW
- Steady state heat flux:

  Max. 10 MW/m^2
- DM RH

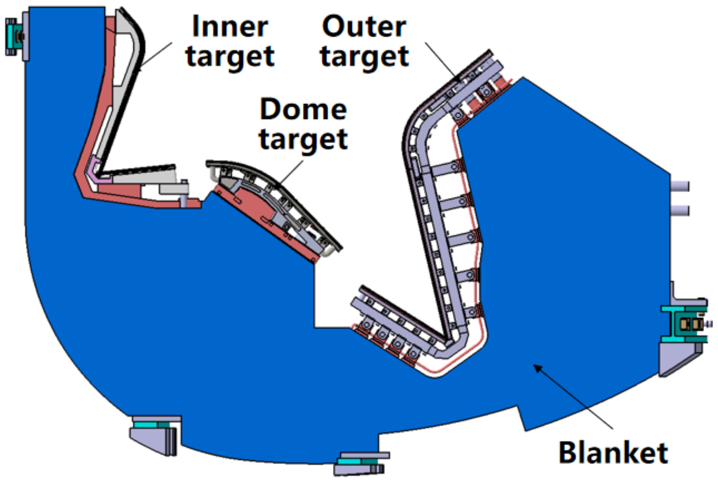


Preliminary design(2017-2020)

- Larger-sized device:

  R=7.2 m, a=2.2 m, B_T=6.5 T and fusion power over 1 GW
- Steady state heat flux:

  Max. 10-20 MW/m^2
- DM RH & Target RH



Divertor development(2020-2025)

- Larger-sized device
- Hybrid divertor-blanket

  Increase TBR>0.04
- Steady state heat flux:

  Max. 20 MW/m^2
- Target RH

CFETR Divertor Development

➢ Construction objectives

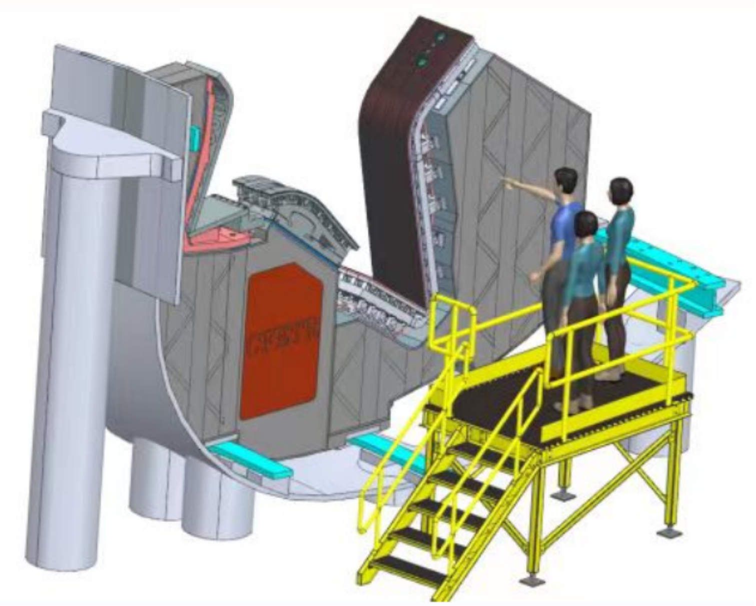
By optimizing preliminary design and implementing R&D of small, medium-sized test mock-ups and prototype fabrication based on advanced fusion reactor materials, it will detemine the final engineering design of CFETR divertor.

➢ Main technical parameters

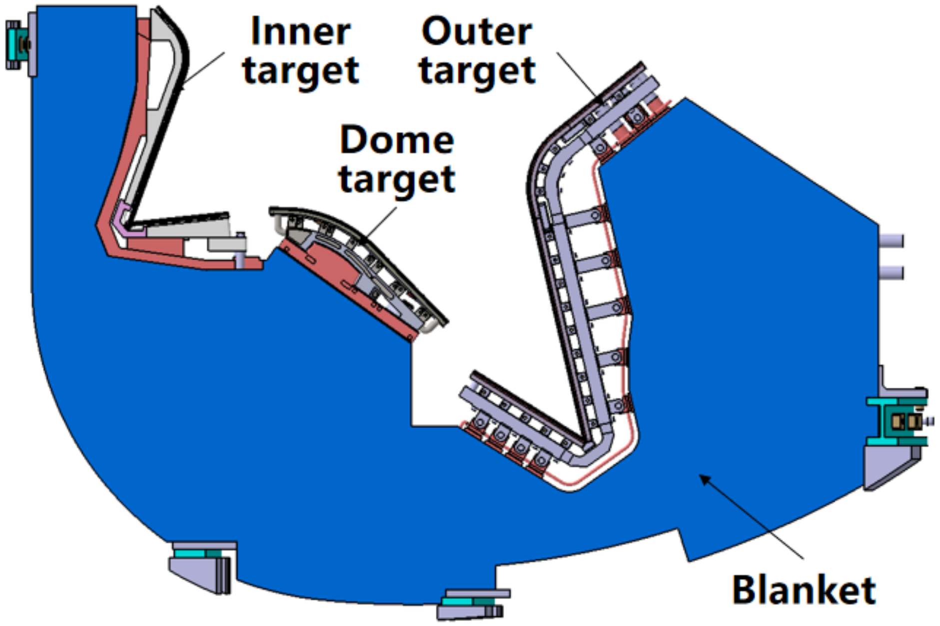
- Heat load capacity in strike point area withstands steady state heat flux of 20 MW/m^2 and 30 MW/m^2 in transient state.
- Profile error of plasma facing surfaces (PFCs) is less than 1 mm.

➢ Key technologies

- Independent RH dismounting technology for targets
- Hybrid divertor-blanket integration
- Material connection technology for fusion reactor materials
- High heat load (20MW/m^2 , SS) handling technologies



CFETR Divertor Development



CFETR hybrid divertor-blanket concept

1) Cassette is replaced to increase TBR

2) Max. 20 MW/m^2 SS for engineering test

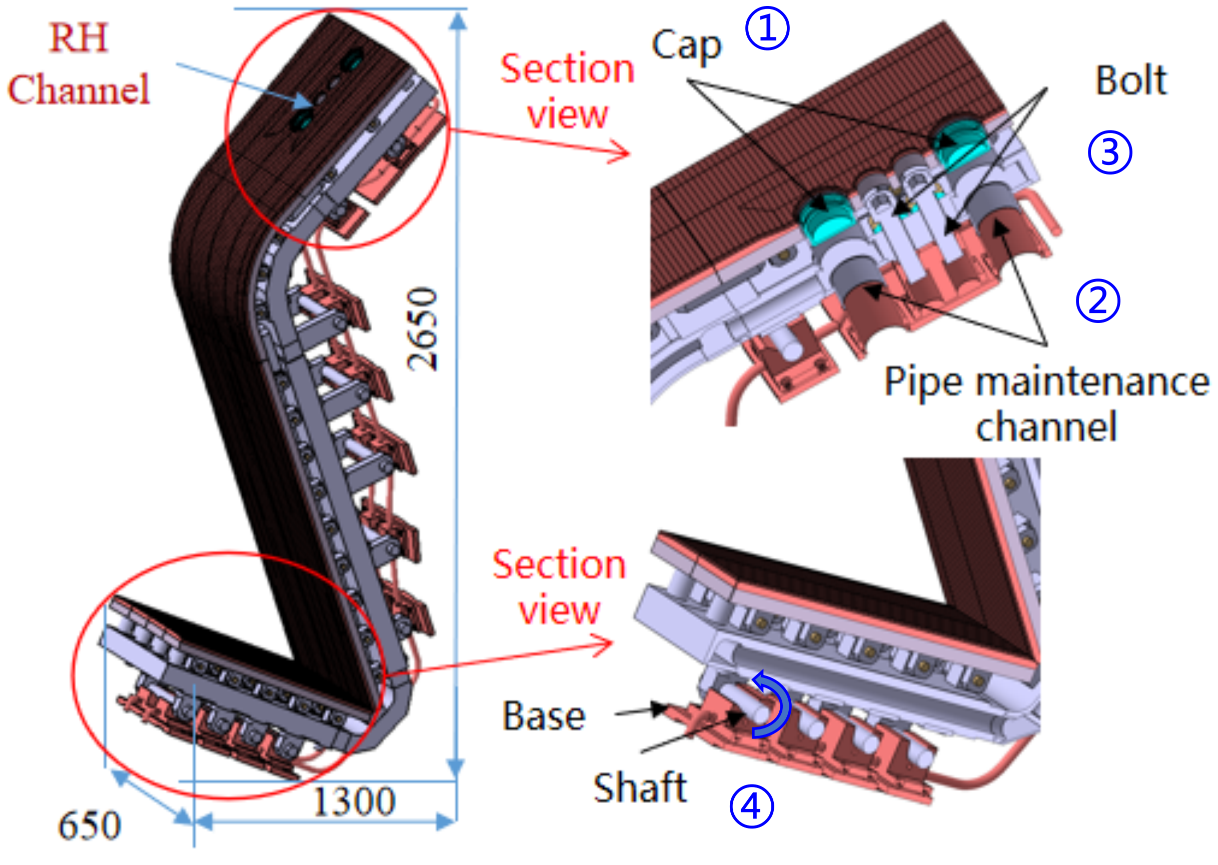
Fabrication based on advanced fusion reactor materials and realizable materials connection technology.

Items		CFETR Divertor
DM Number		80
Weight of one DM (ton)	Inner target	0.7
	Dome Target	0.65
	Outer Target	1.5
Target	PFC & Heat sink	K-doped W/ODS-Cu/Cu/RAFM
	Water T(°C)/P_{in}(MPa)	140/5

3) Target RH is optimized and final only RH selection

- Dome geometry is lowered to facilitate engineering design. Physical results are comparable.
- RH access is opened.
- Flat tile units are finally chosen as basic units for PFCs due to lower surface temperature and cost.

Front-face Remote Handling Targets



Outer Target

- **RH area protection**

Lower field area; Wall shaping; Depth of channel.

- **Support connection**

Two bolts and ten shaft/axle seat; Additional rotation movement between target and base.

- **Maximum SS heat flux**

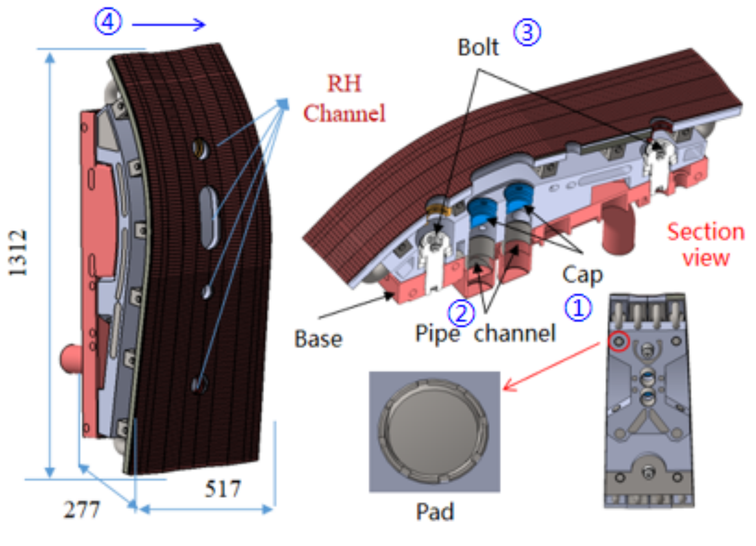
Plasma strike section consisting of ultra-high heat flux flat-tile units sustaining 20 MW/m^2

- **Key steps of disassembly scheme**

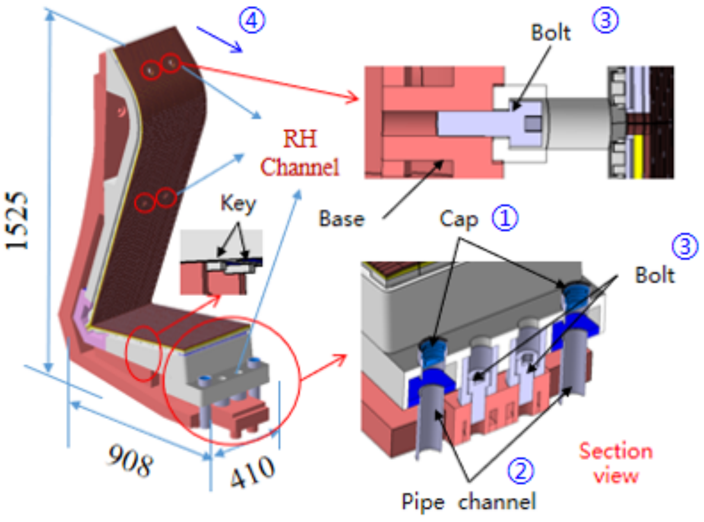
① Remove two water pipes cap
② Cut off two water pipes
③ Dismantle two bolts
④ Grab target, rotate around the bottom-left axle seat at a certain angle and remove

Front-face Remote Handling Targets

Components	Max. heat flux (MW/m^2)	Guide type	Surface on support base	Number of surface support	Bolts specification	Bolts number	Pipe diameter (O/I) (mm/mm)
Outer target	20	Shaft mount	Cylindrical	10	M36	2	89/83
DOME target	10	Pad	Upper/side plane	8	M64	2	89/83
Inner target	20	Key	Upper plane	3	M30/M36	6	51/45



Dome Target

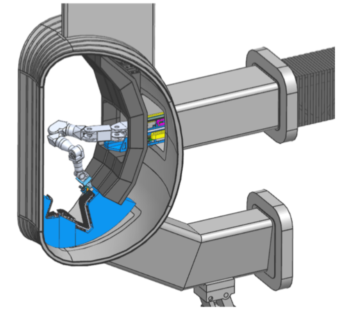


Inner Target

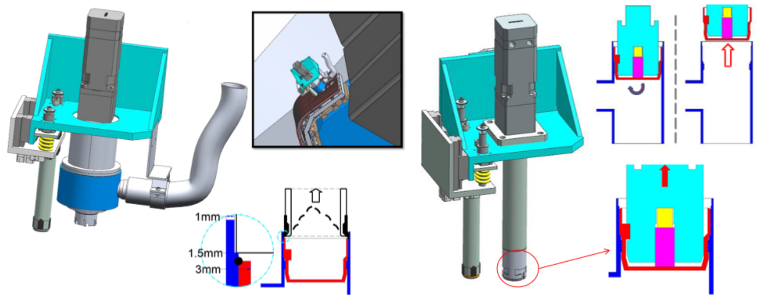
The enginnering design of divertor is completed

- The pump system exhausts neutral particle larger than 250Pa·m^3/s using COMSOL prediction.
- All targets could RH from plasma side in design.
- The analysis with respect to hydraulic, thermal and structural with combined loads meets the design requirements.

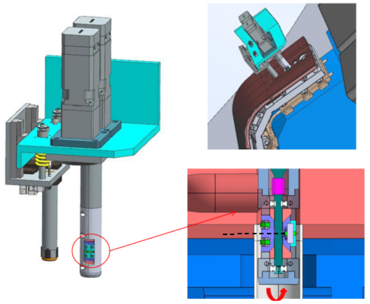
RH Maintenance Procedure



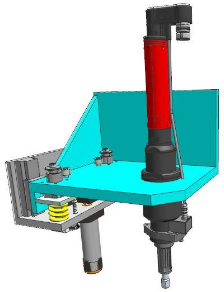
MPD carries actuator to scheduled location



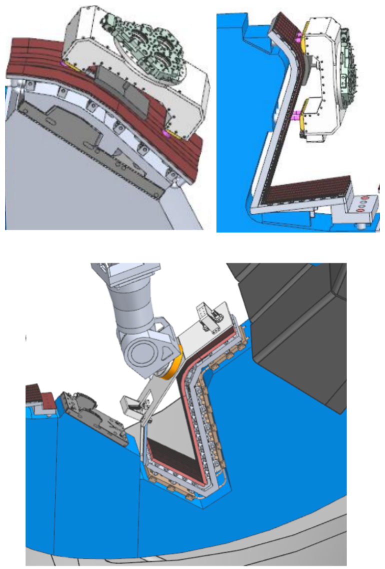
Pipe cap cutting and removal



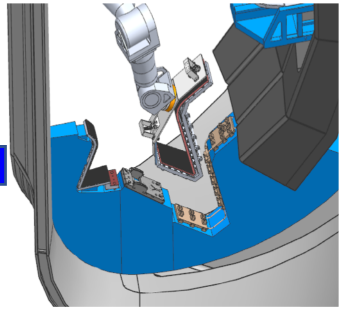
Pipe internal cutting



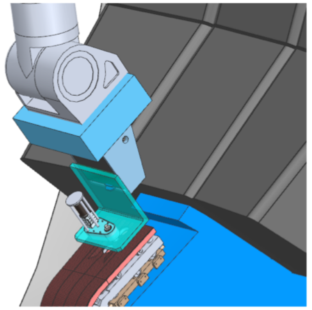
Fastener disassembly



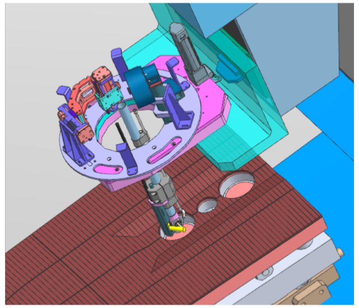
Target gripping and removal



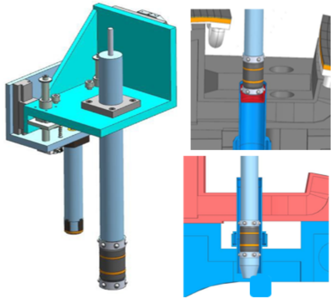
Replacement of new target



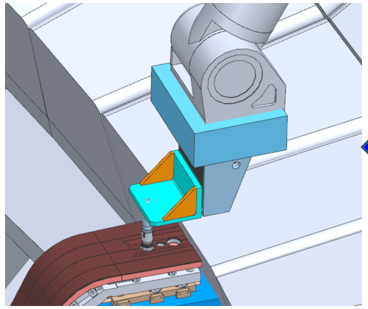
Fastener mounting



Pipe internal welding

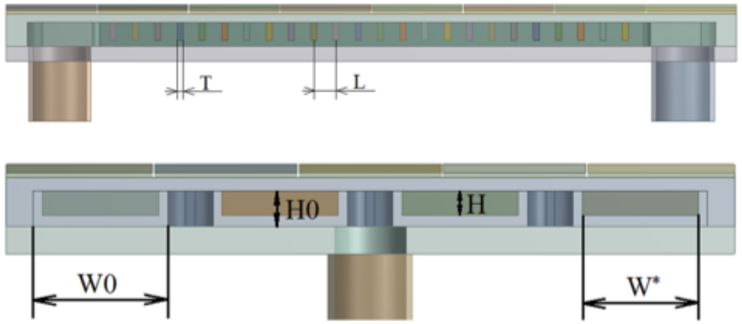


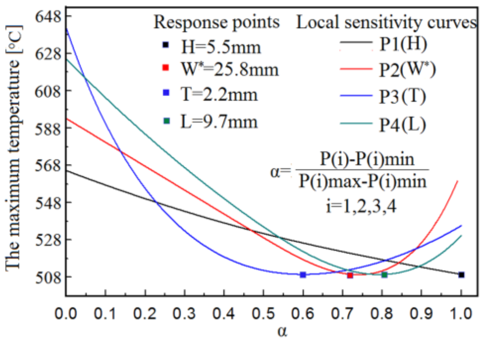
Weld flaw NDT detection



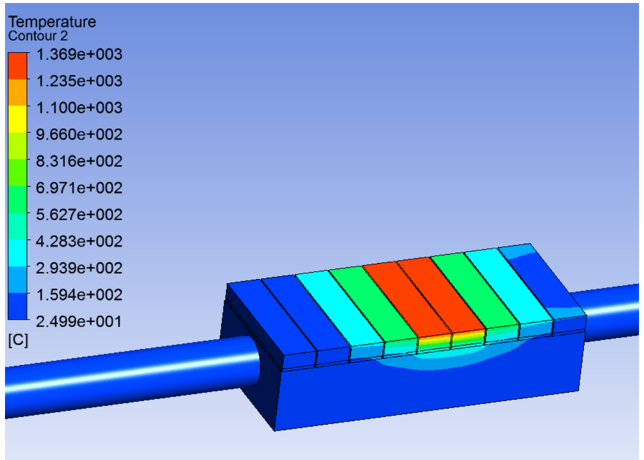
Pipe cap welding and leak detection

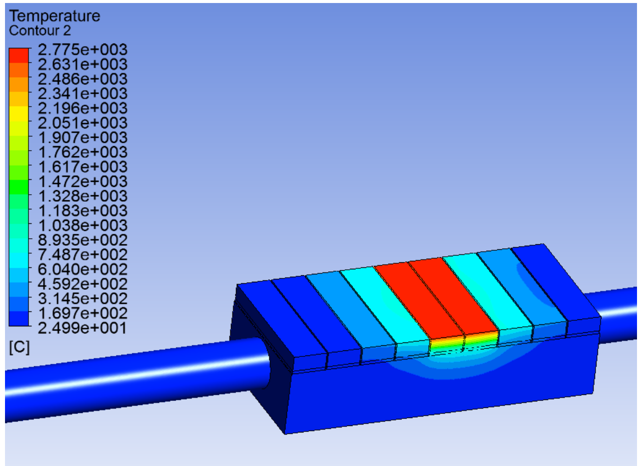
High heat load (20MW/m² , SS)

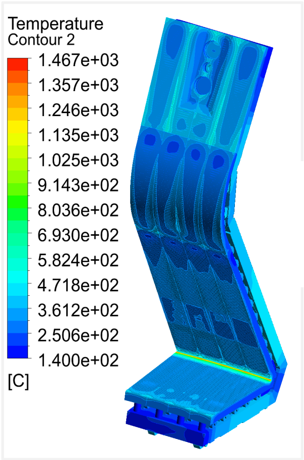




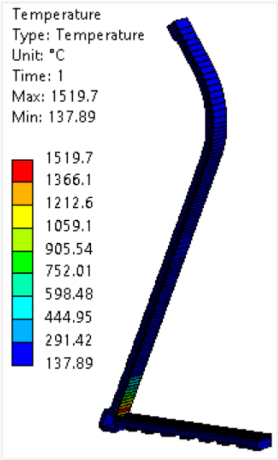
The variation parameters of the heat transfer enhanced structure such as height, width, thickness and spacing in each target were investigated using the **parameter optimization method**.



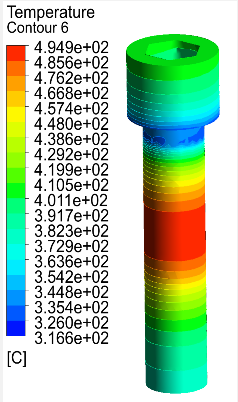


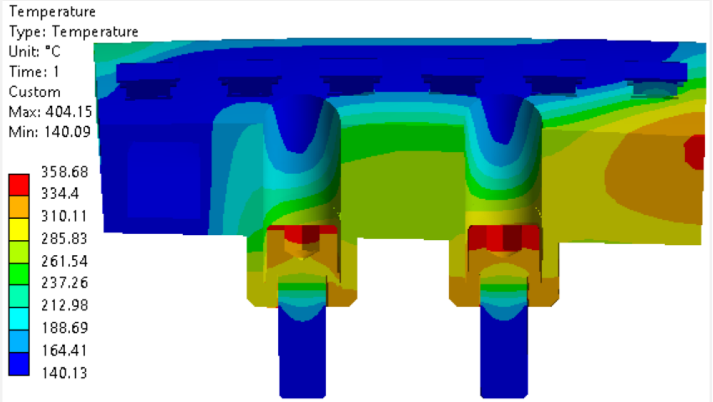


Outer Target



Inner Target

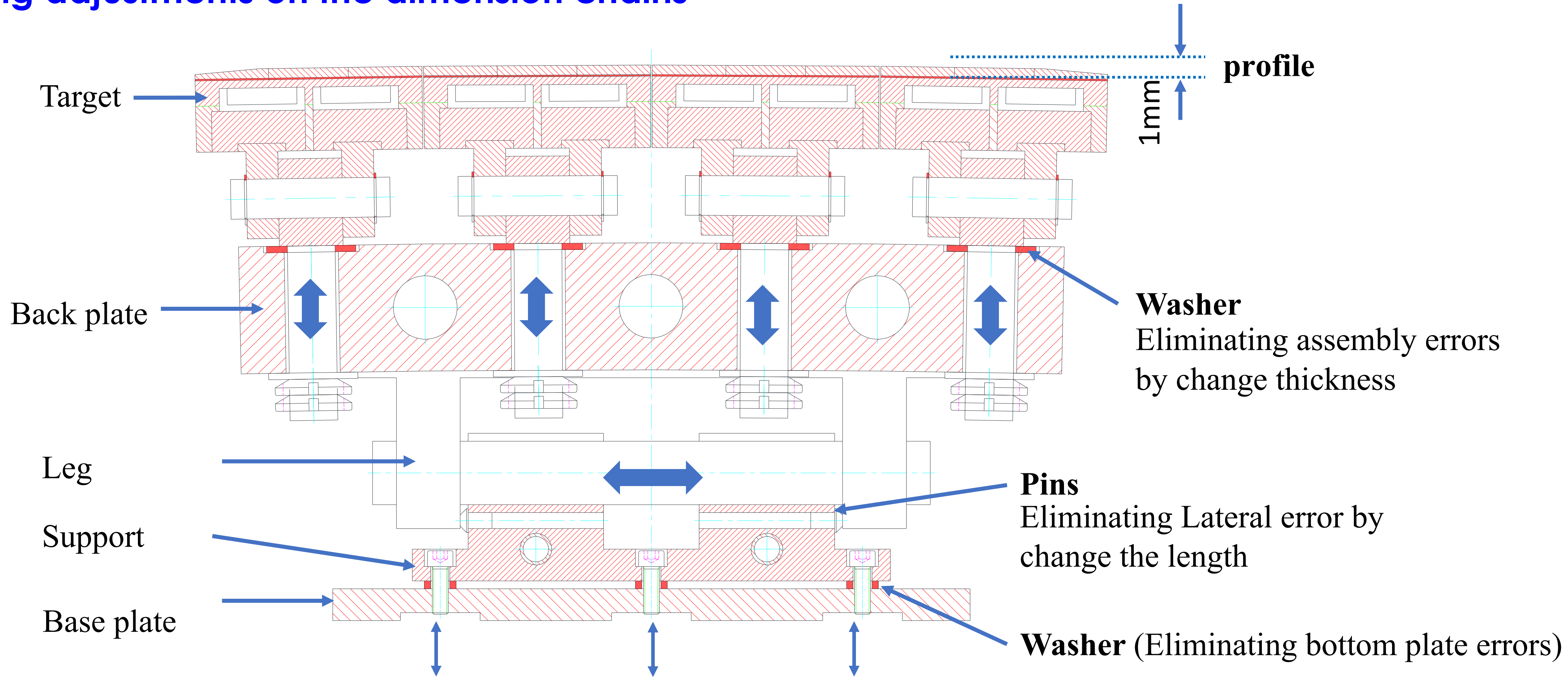




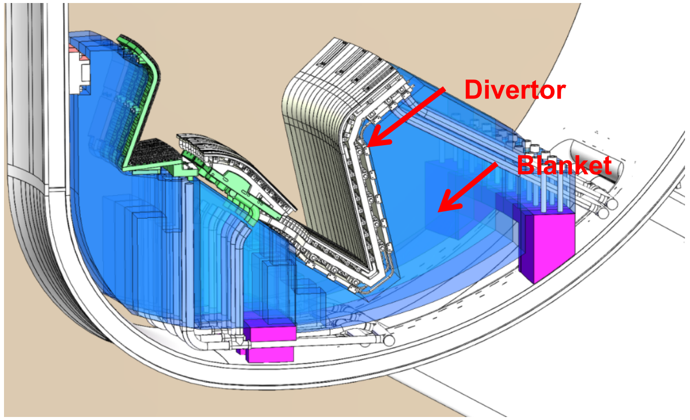
The maximum temperature of KW, ODS-Cu and RAFM is 1519 ℃, 646 ℃ and 542 ℃, below the allowable temperature of 1600 ℃, 650 ℃ and 550 ℃, respectively.

Profile error of PFCs (less than 1 mm)

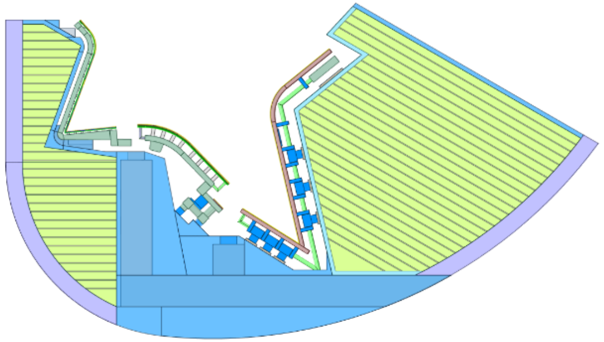
Setting adjustments on the dimension chains



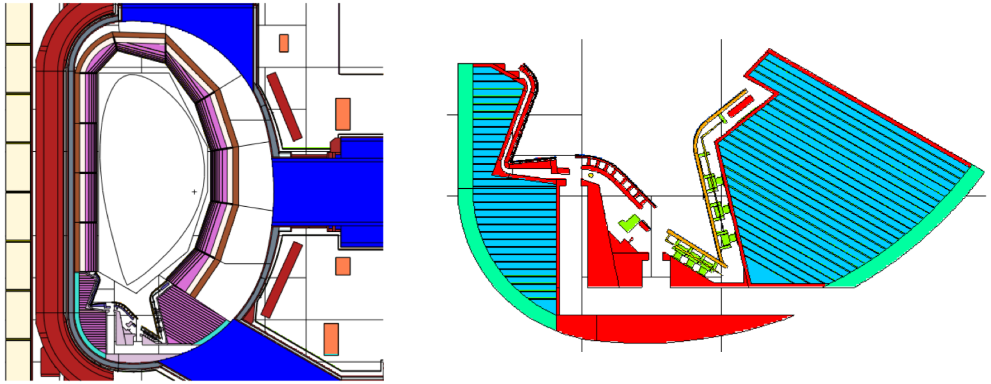
Hybrid divertor-blanket integration



Blanket (conceptual design) and divertor (enginnering design)



Simplified CAD model



Neutronics model

Blanket design	Ⅰ（Without any windows ）	Ⅱ（Ⅰ + Considering all the auxiliary systems ）	Ⅲ（Ⅱ+Hybrid divertor-blanket)
TBR	1.147	1.0285	1.1567

According to the neutronics analysis, the TBR is significantly increased from 1.0285 to 1.1567, meeting the TBR improvent requiremet of at least 0.04.

CFETR Divertor Material

Preliminary roadmap of divertor materials

Material	2020-	2030	2040
FW: W, W alloy	3-5dpa	10dpa, CFETR	20dpa, CFETR
Advanced W	1E25-1E28 PSI	CFETR	CFETR
ODS-Cu, Cu alloy	10dpa	50dpa, CFETR	100dpa, CFETR
RAFM steel	5dpa, 1000T	50dpa, CFETR	100dpa, CFETR
ODS-RAFM	10dpa，kg	50dpa, CFETR	100dpa, CFETR
Resistance tritium layer	5dpa	20dpa, CFETR	CFETR

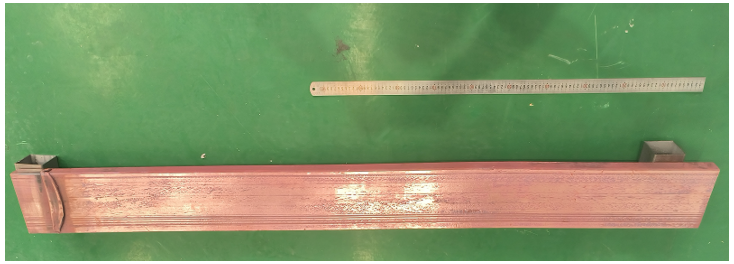
ODS RAFM steel could stand up to 100 dpa at final target, ODS-Cu and Cu alloy will be used for the heat sink with 20 dpa for the next 10 years and finally targeting 100 dpa for a possible solution.

Material is in initial R&D. Divertor material selection depends on China material development roadmap.

- PFM：Potassium-droped Tungsten (K-doped W) (W, ZrC W alloy)
- Interlayer：Oxygen-free Copper (OFC)
- Heat-sink：Oxide Dispersion Strengthened Copper (ODS-Cu) (CuCrZr)
- Structure material: Reduced Activation Ferritic/Martensitic (RAFM) steel (ODS RAFM, 316L)

Material Development and Chanllenge

CuCrZr-Y-Hf



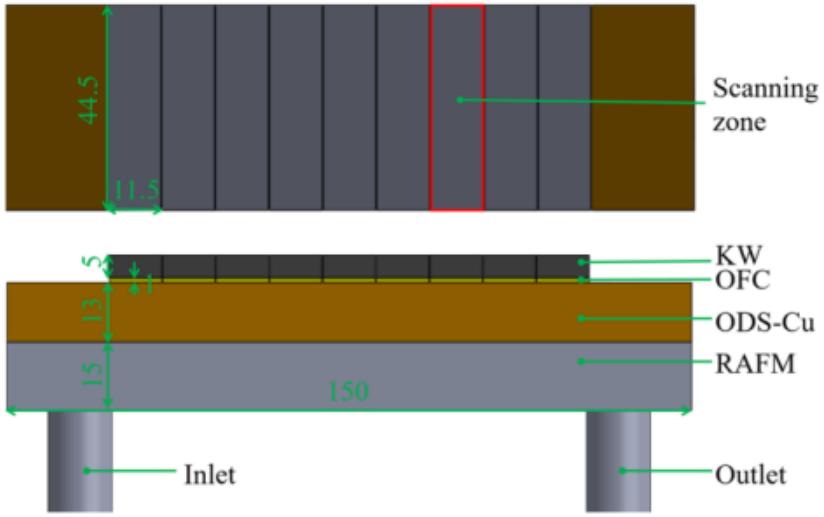
ODS-Cu (Domestic)

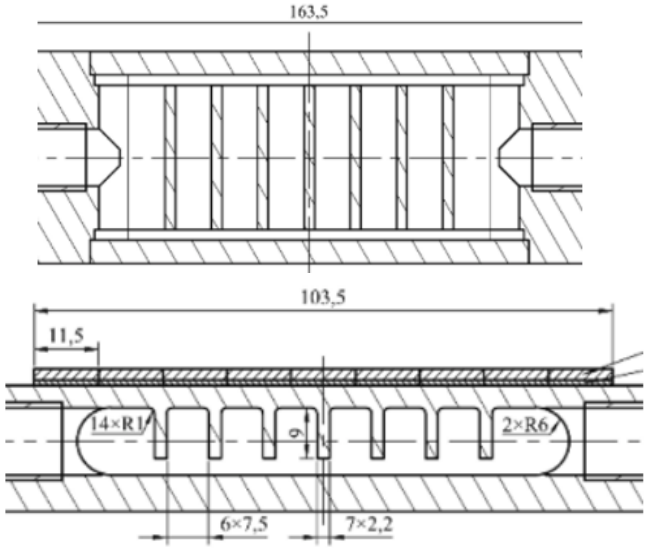
ODS-Cu (Overseas)

Temperature (℃)	Thermal conductivity (W/mK)					Tensile strength (MPa)				
	Lab data	CuCrZr-Y-Hf	ODS-Cu (O)	ODS-Cu (D)	Minimum required	Lab data	CuCrZr-Y-Hf	ODS-Cu (O)	ODS-Cu (D)	Minimum required
25	344	296	330	320	340	600	486	494	485	540
200	355		334		340	540				450
300	350				340	501	380			430
400	347	326	317	310	340	441	320	279	219	400
500	345				340	381	262	239		300
600	340	285	295		340	280	196	154		150
650					340	240				

There is still a gap of ODS-Cu material properties in the process of testing and developing large-size (1700 mm x 180 mm x 28 mm) commercially purchased products.

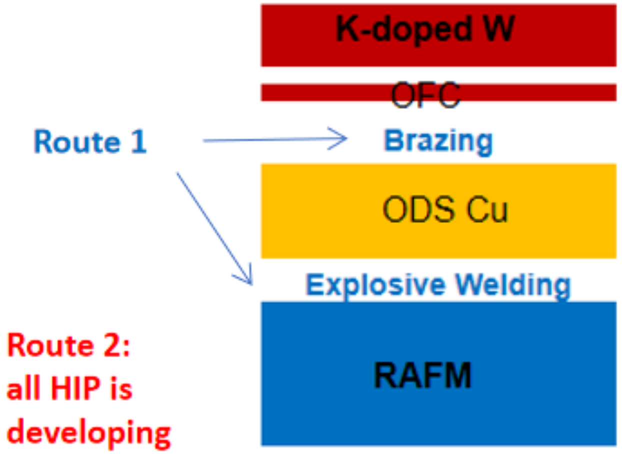
Small-sized Mock-up Tests





Typical size of a high heat flux unit

Small-sized mock-up tests were carried out to confirm technical parameter of steady-state heat flux of 20 MW/m^2.

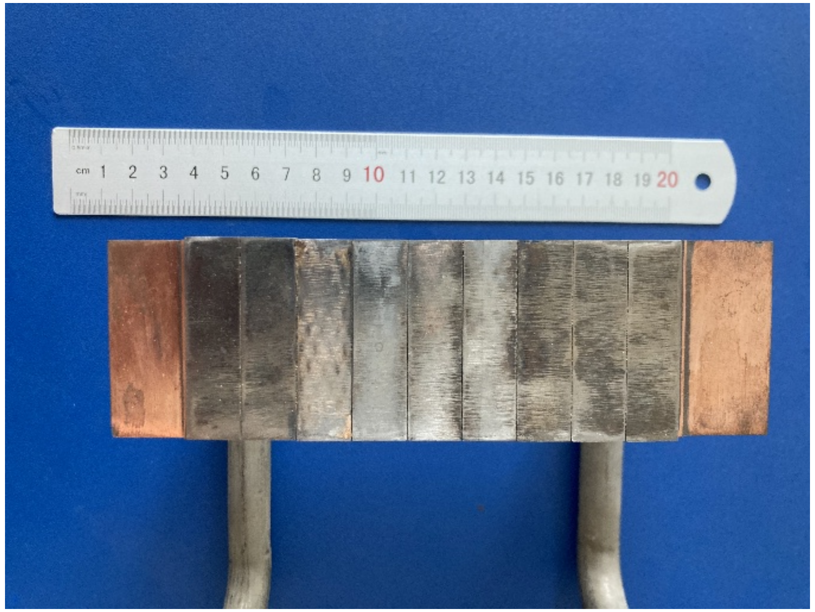


HHF test: SWIP
EMS-60, 5 m^3/h

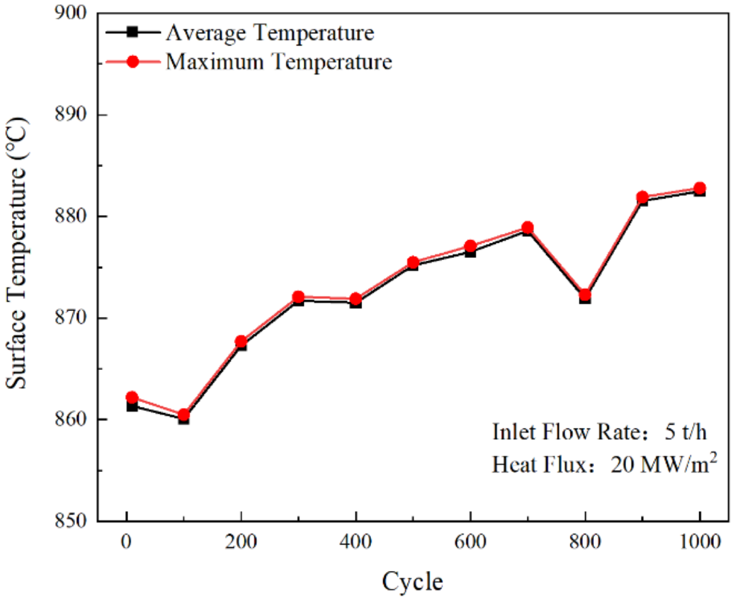
Small-sized Mock-up Tests

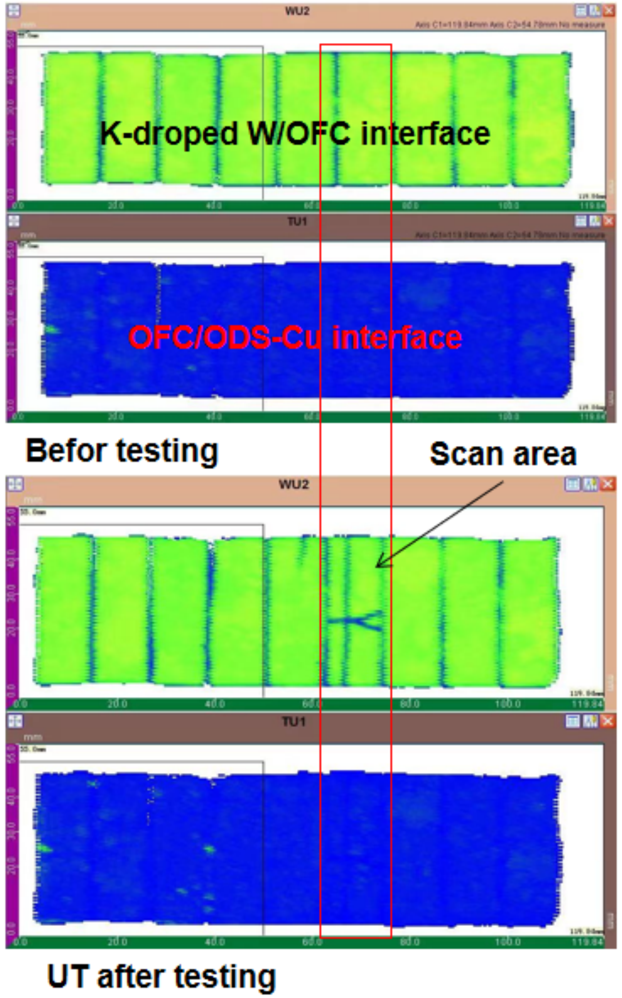
Number	Material	OFC/Heat sink connection	Test parameters	Interface results	Max. temperature of W surface (^oC)
1	W/OFC/CuCrZr/316L	Brazing	20 MW/m^2, 1000 cycle	W/Cu interface generates defects	1213
2	KW/OFC/CuCrZr/316L	Brazing		W/Cu interface generates defects	1191
3	KW/OFC/ODS-Cu/CLF (No.1)	Brazing	20 MW/m^2, 600 cycle	W/Cu interface generates defects	1286 (Temperature spikes after 600 cycle)
4	KW/OFC/ODS-Cu/CLF (No.1)	HIP	20 MW/m^2, 400 cycle	W/Cu interface generates defects	1050 (Temperature spikes after 400 cycle)
5	KW/OFC/ODS-Cu/CLF (No.2)	HIP	20 MW/m^2, 10 cycle	W/Cu interface detachment	/
6	KW/OFC/ODS-Cu/CLF (No.2)	Brazing	20 MW/m^2, 1000 cycle	No defects	882
7	KW/OFC/ODS-Cu/CLF	HIP	20 MW/m^2, 1000 cycle	No defects	1103
8	ZrC-W/OFC/ODS-Cu/CLF	HIP	20 MW/m^2, 1000 cycle	No defects	1085

Small-sized Mock-up Tests



Route 1

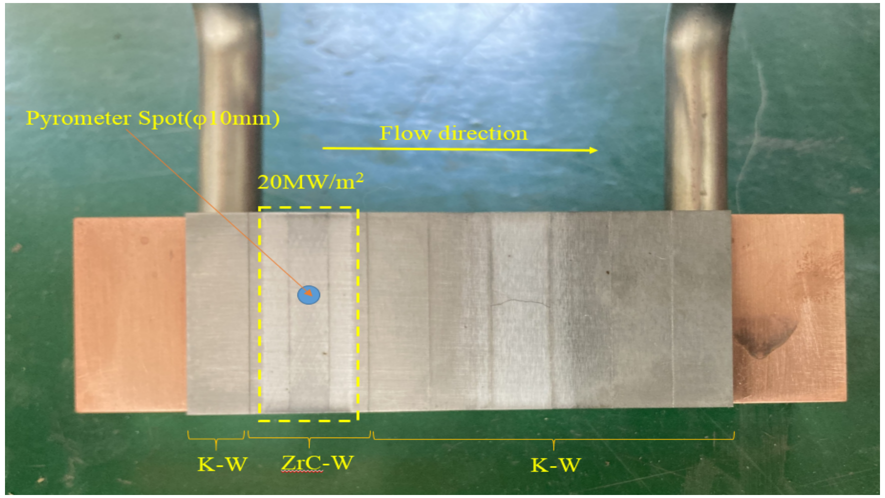




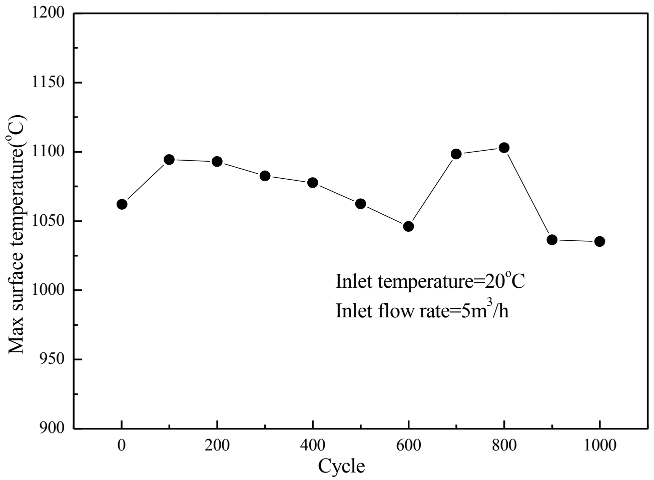
20 MW/m², 1000 cycle (15 s on ,15 off), HHF testing passed

- Temperature: Max. W surface is 882 °C, with a variation of 2.3%
- UT: no defects exceed Φ2 mm equivalent on each interface before/after testing
- No visual abnormalities on the surface and no detachment of tiles
- Pressure test after testing meets reqiured He leakage rate of 1 x 10^{-10} Pa·m^3/s

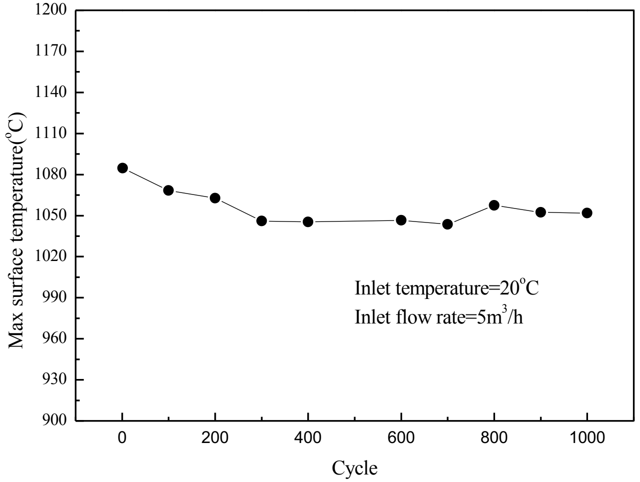
Small-sized Mock-up Tests



Route 2



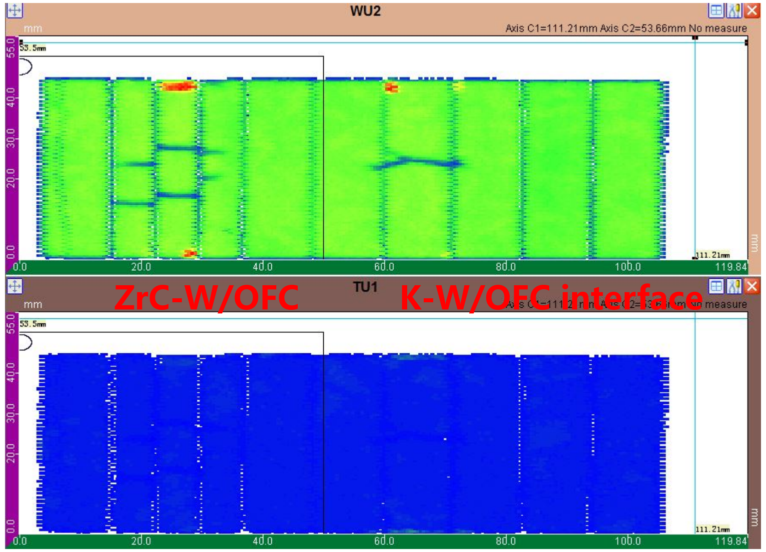
(KW/OFC/ODS-Cu/CLF-1)



(ZrC-W/OFC/ODS-Cu/CLF-1)

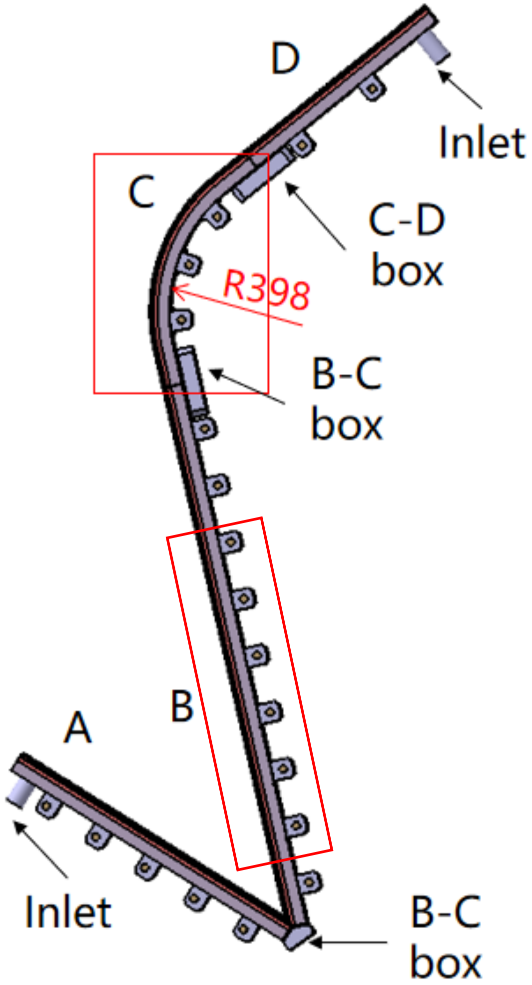
20 MW/m², 1000 cycle (15 s on ,15 off), HHF testing passed

- Temperature: Max. KW surface is 1103 °C; Max. ZrC-W surface is 1085 °C; variation less than 5%, meeting <20% between the initial and final.
- UT, visual inspection and pressure test meet the requirement.



OFC/ODS-Cu interface

Medium-sized Mock-up Tests



Medium-sized mock-up tests were carried out to confirm two technical parameters. Straight medium-sized mock-ups aims for testing the SS heat flux of 20 MW/m^2. Curved medium-sized mock-ups aims for validating the profile error of PFCs.

HHF test: ASIPP
EBG-II:60 kW; 20 t/h
VV: φ3 m x 4 m

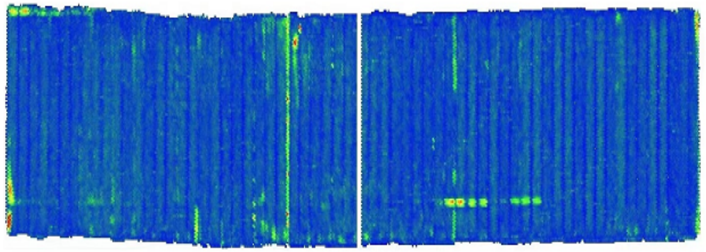
1. EBG-I: 800 kW; EBG-II: 60 kW

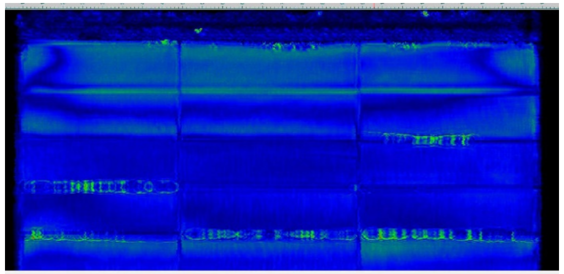
2. 0.2-15.5 MPa, RT-285℃, <10 t/h;
0.2-3 MPa, RT, <30 t/h.

Medium-sized Mock-up Tests

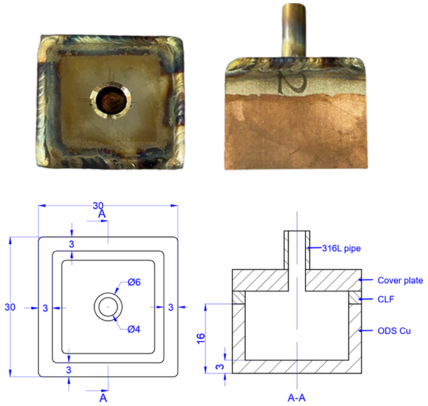
Route 1

Route 2





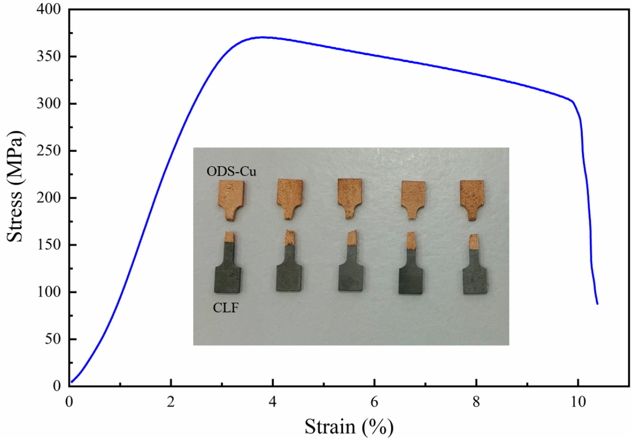
UT



UT

	Temperature (° C)	Holding time (min)	Helium pressure (MPa)	Dwell time (min)	He leakage rate (Pa·m³/s)	Required He leakage rate (Pa·m³/s)
(a)	RT.	--	6.3	30	4.0×10^{-11}	$\leq 1.0 \times 10^{-10}$
(b)	300	120	5	30	1.6×10^{-10}	$\leq 1.0 \times 10^{-8}$
	RT.	--	6.3	30	3.1×10^{-11}	$\leq 1.0 \times 10^{-10}$
(c)	300	120	5	30	1.6×10^{-10}	$\leq 1.0 \times 10^{-8}$
	RT.	--	6.3	30	2.6×10^{-11}	$\leq 1.0 \times 10^{-10}$

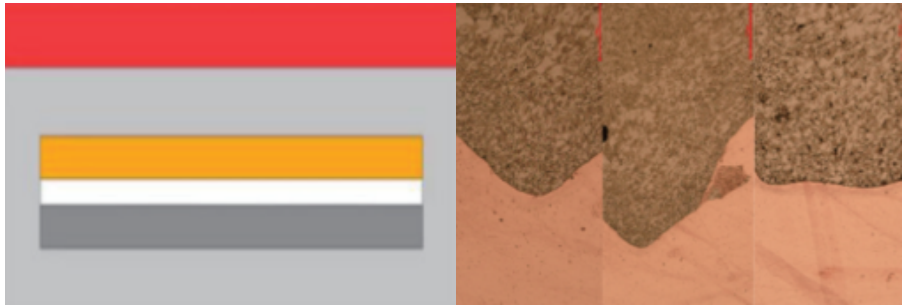
Pressure test

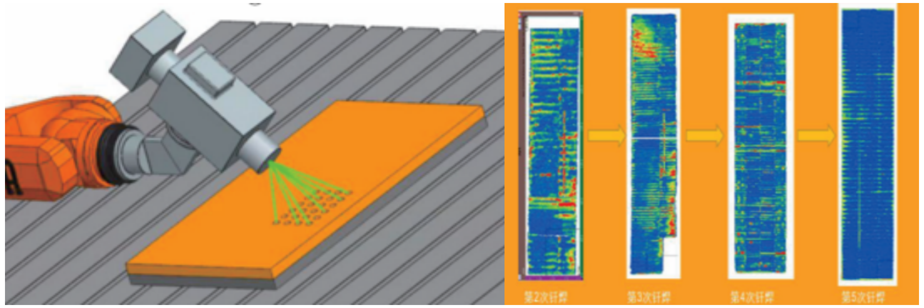


Tensile strength

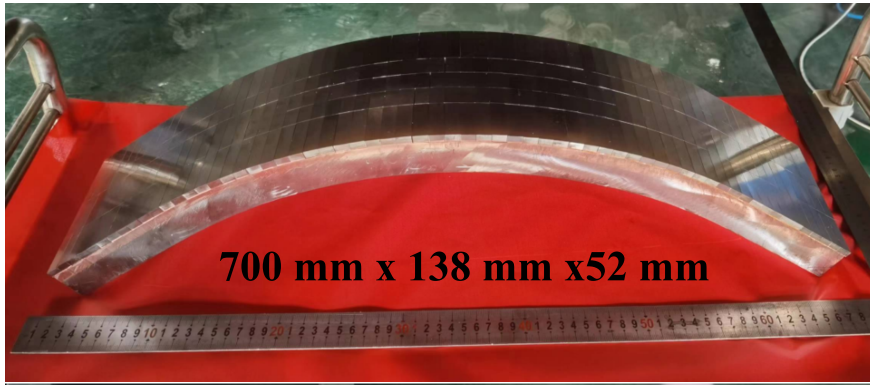
- UT: no defects exceeds Φ2 mm equivalent;
- Tensile strength of explosive welding joint: rupture place in ODS-Cu side;
- Pressure testing (wall thickness of 3mm): meets reqiured He leakage rate.

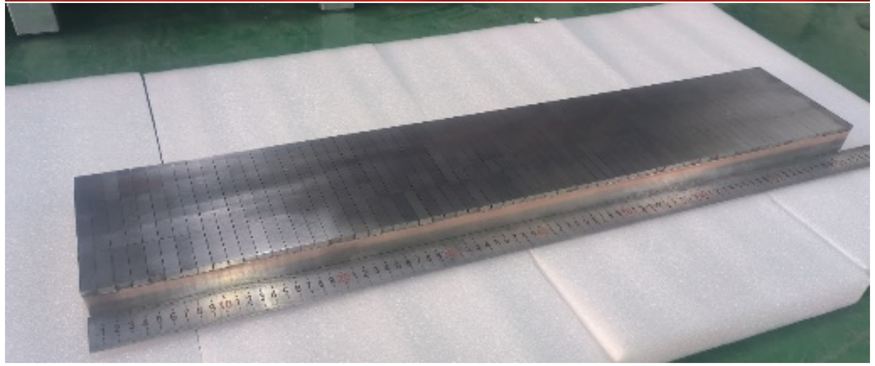
Medium-sized Mock-up Tests



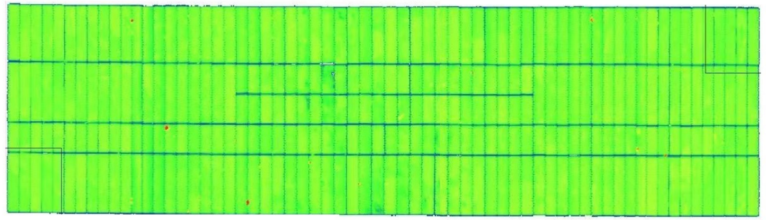


Development of specialised vacuum explosion welding process and laser array treatment process

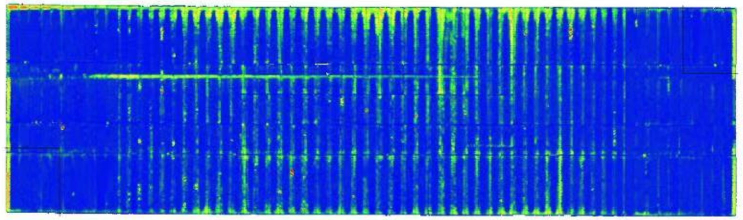




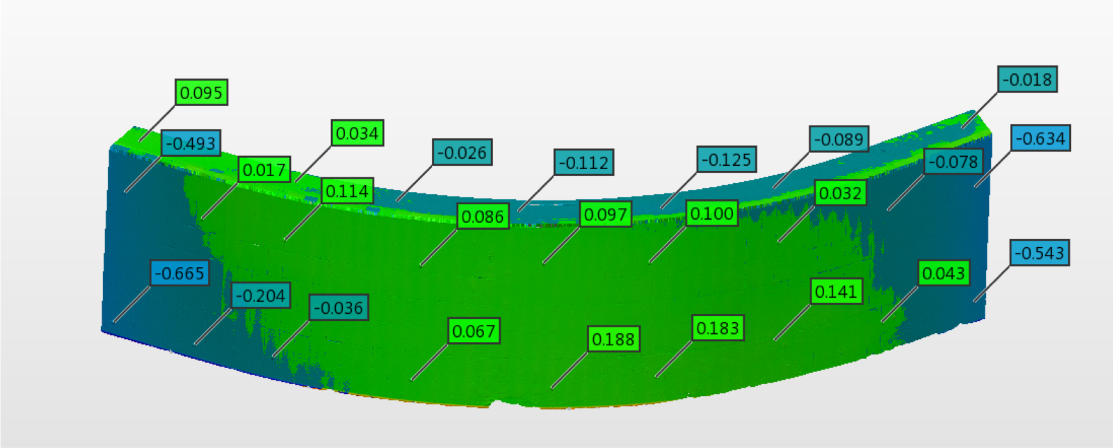
Route 1



K-doped/OFC interface

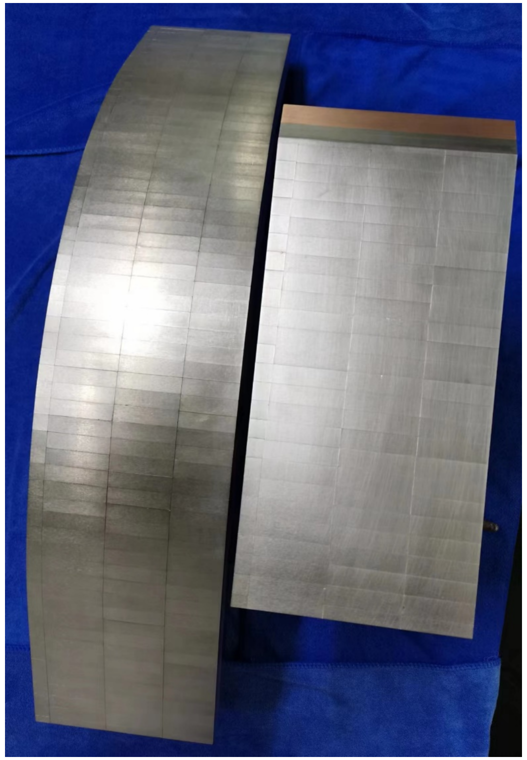


OFC/ODS-Cu interface

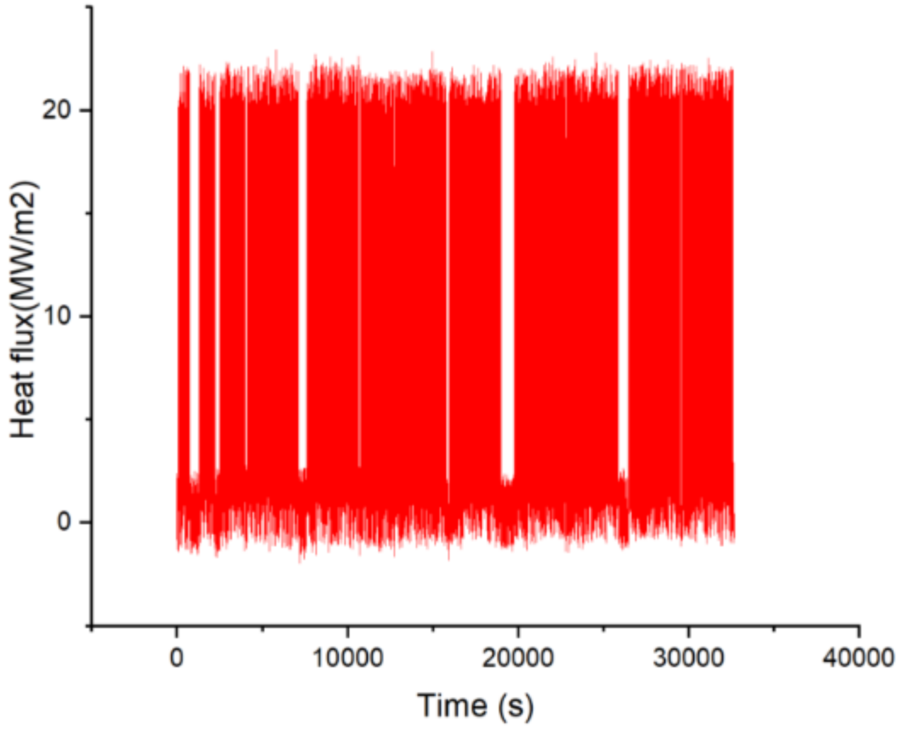


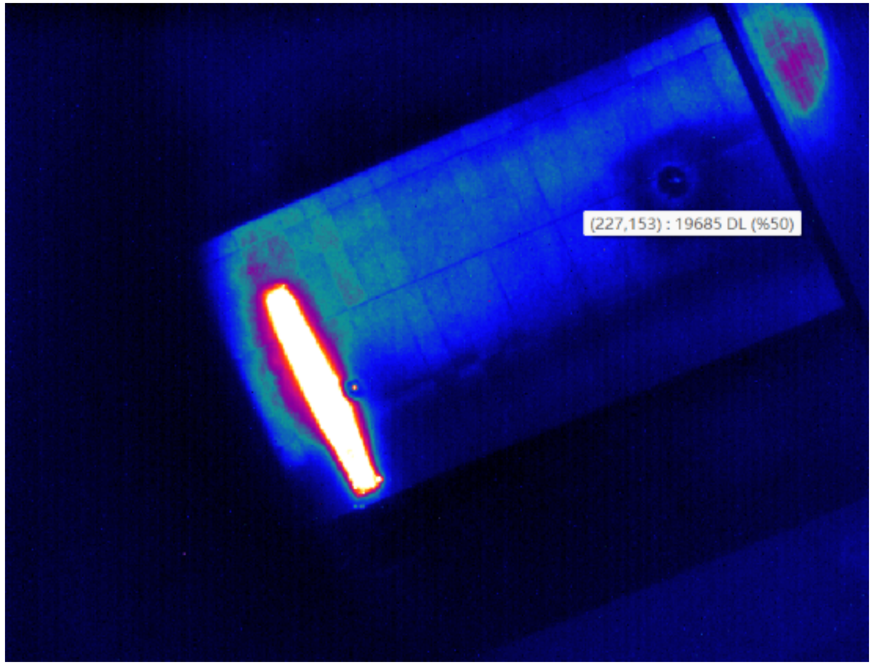
UT, Profile error of PFCs, 7 MPa pressure test meet the requirement.

Medium-sized Mock-up Tests



Route 2





- Adjustment temperature in heat treatment process.
- 20 MW/m^2, 1000 cycle (15 s on ,15 off), HHF testing is basiclly passed.
- UT, Profile error of PFCs and 7 MPa pressure test meet the requirement.

Summary and Outlook

Two main technical parameters are basicly met. Four key technologies are developing.

- The optimized small-sized mock-ups and the medium-sized mock-up of HIP route are successfully endured the 1000 cycles with 20 MW/m^2 SS heat load.
- The medium-sized mock-ups show the profile error of PFCs is less than 1 mm.
- Preliminary feasibility analysis meets the requirements. Three novel target designs show good RH compatibility.
- To improve the TBR, the hybrid divertor-blanket integration concept is being developed.
- Two material connection routes are feasible, including explosive welding and brazing, and HIP.
- UT, 7 MPa pressure test and HHF test meet the requirement, showing high heat load (20MW/m^2 , SS) handling technologies are initially satisfied.

Summary and Outlook

Three independent front-face RH targets are ready for prototype fabrication.

1. RH access damage prevention needs further evaluation.
2. Failure modes of HHF tests and verification of material connection are under detailed investigation.
3. RH tools for each step of maintenance procedure are developing. Soon, firstly, the targets prototype will be fabricated to meet technical parameters. Secondly, three targets will be verified and compared by RH test.
4. CFETR advanced divertor materials are in initial R&D. Especially, there is a gap of ODS-Cu material properties between those tested and required during the process of testing and developing large-sized commercially purchased products. At present, the purchased material meets the test requirements. But to meet the structural analysis requirements for off-normal events, material development or loads reduction will be necessary.

Preliminary Analysis

The preliminary results of hydraulic and SS thermal analysis meet the requirements.

Components	Analysis type	Loads/Loads combinations	Results	Accept criteria
Outer target	Hydraulic analysis	a) Hydraulic: Inlet P_{in}=5 MPa, T_{in}= 140 °C b) SS peaking heat flux: 20 MW/m^2 in outer/inner target and 10 MW/m^2 in Dome target c) Nuclear heat in the condition of CFETR fusion power of 1.5 GW	F=80 ton/h; ΔT=38 °C; V_{ave}=10 m/s; ΔP=1.09 MPa.	1) Flow rate: F < 100 ton/h 2) Water temperature rise: ΔT< 40 °C 3) Water average velocity in strike section: $V_{ave} \geq$ 10 m/s; 4) Pressure drop: ΔP < 1.5 MPa
DOME target			F=50 ton/h; ΔT=25.4 °C; V_{ave}=11.8 m/s; ΔP=0.4 MPa.	
Inner target			F=46 ton/h; ΔT=37 °C; V_{ave}=11 m/s; ΔP=0.96 MPa.	
Outer target	Steady state thermal analysis		Maximum temperature (°C): $T_{K\text{-}doped}$= 1467; $T_{ODS\text{-}Cu}$=646; T_{RAFM}=447	Allowable temperature (°C): 1) K-doped W: $T_{K\text{-}doped}$ < 1600 2) ODS-Cu: $T_{ODS\text{-}Cu}$ < 650 3) RAFM: T_{RAFM} < 550
DOME target			Maximum temperature (°C): $T_{K\text{-}doped}$=974; $T_{ODS\text{-}Cu}$ = 556; T_{RAFM}=542	
Inner target			Maximum temperature (°C): $T_{K\text{-}doped}$=1519; $T_{ODS\text{-}Cu}$=572; T_{RAFM} =358	

Preliminary Analysis

The preliminary results of structural analysis related of MD and VDE event meet the requirements.

Components	Analysis type	Loads/Loads combinations	Maximum equivalent stress (MPa)	Accept criteria
Outer target	MD event	a) Themal stress b) Halo current for EM load: 0.2x122.5 KA c) Maximum eddy current for EM torque load: Outer target (40 KA, B_T=7 T); Dome target (2.5 KA, B_T=8.5 T); Inner target (28.5 KA, B_T=7 T) d) Water pressure: 5 MPa	1) K-doped W: 670; 2) ODS-Cu: 472; 3) RAFM: 603	Allowable stress (MPa) 1) K-doped W: 714 (800 ℃) 2) ODS-Cu: 530 (300 ℃) 3) RAFM: 660 (500 ℃)
DOME target			1) K-doped W: 340; 2) ODS-Cu: 282; 3) RAFM: 538	
Inner target			P_L +Pb+Q 3) RAFM: 628	
Outer target	VDE event	a) Themal stress b) Halo current for EM load: 122.5 KA d) Water pressure: 5 MPa	1) K-doped W: 693; 2) ODS-Cu: 478; 3) RAFM: 612	
DOME target			1) K-doped W: 327; 2) ODS-Cu: 280; 3) RAFM: 633	
Inner target			P_L +Pb+Q 3) RAFM: 623	

Preliminary Analysis

The preliminary results of baking analysis and pump performance meet the requirements.

Components	Analysis type	Loads/Loads combinations	Maximum equivalent stress (MPa)	Accept criteria
Outer target	Baking	a) Temperature: 200 ℃ b) Pressure: 5 MPa	1) K-doped W: 522; 2) ODS-Cu: 465; 3) RAFM: 608	Allowable stress (MPa) 1) K-doped W: 1249 (200 ℃) 2) ODS-Cu: 560 (200 ℃) 3) RAFM: 700 (200 ℃)
DOME target			1) K-doped W: 335; 2) ODS-Cu: 221; 3) RAFM: 542	
Inner target			1) K-doped W: 336; 2) ODS-Cu: 428; 3) RAFM: 665	
DM x 80	Pump performance	a) Pressure P_{in}=1-5 Pa b) Single cryogenic pump pumping speed: S=55 m^3/s	1) P_{in} = 1 Pa, 8 units 2) P_{in} = 5 Pa, 2 units	>250 Pa·m^3/s