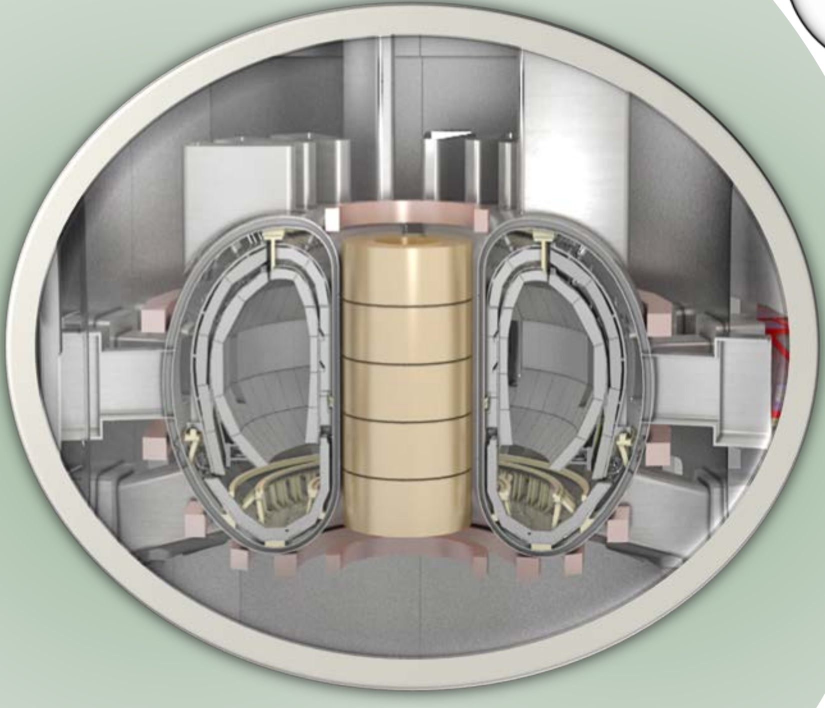
R&D status in manufacturing and assembly of Breeding blanket at ASIPP

Wanjing WANG and Blanket R&D Team

Institute of Plasma Physics, CAS(ASIPP)

E-mail: wjwang@ipp.ac.cn

Outline



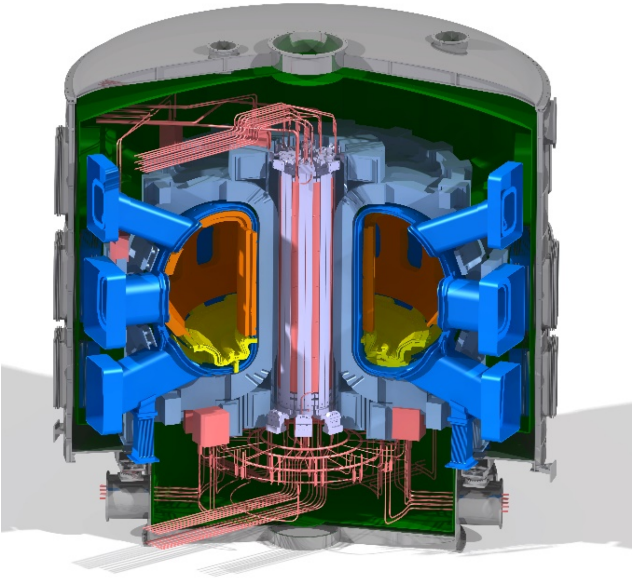
1 Introduction of Breeding Blanket

2 HIP Manufacturing

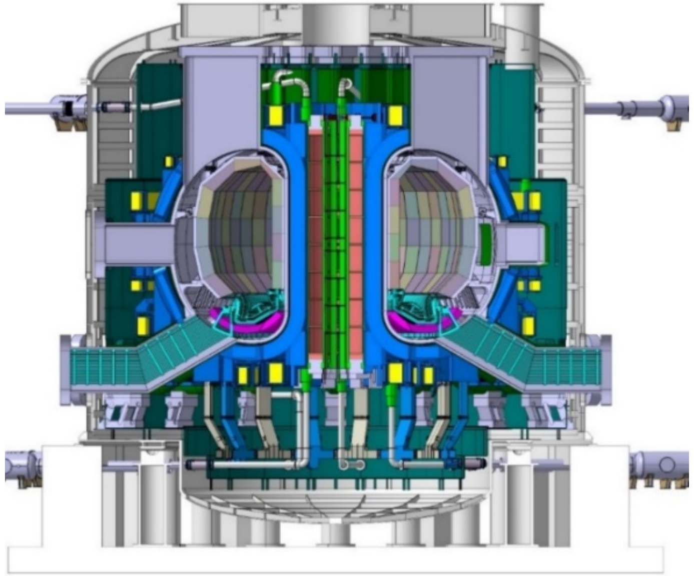
3 Additive Manufacturing

4 Conclusion and considerations

1. Breeding Blanket-Devices development



BEST configuration
(R=3.6m, a=1.1m, 10-100MW)

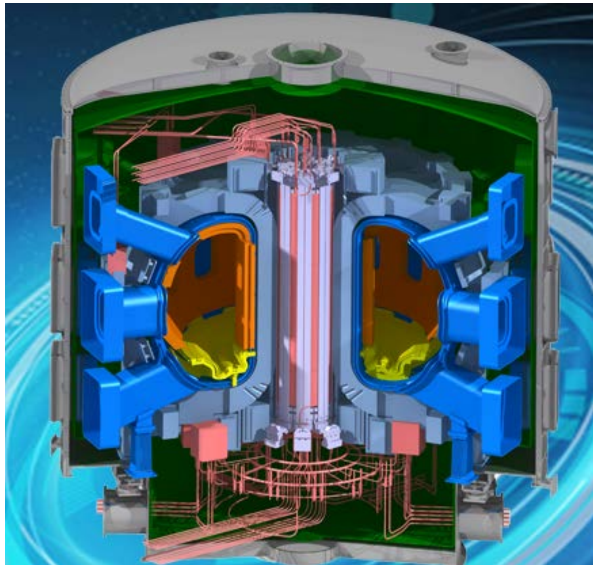


CFETR configuration
(R=7.2m, a=2.2m, 0.2/0.5/1/1.5GW)

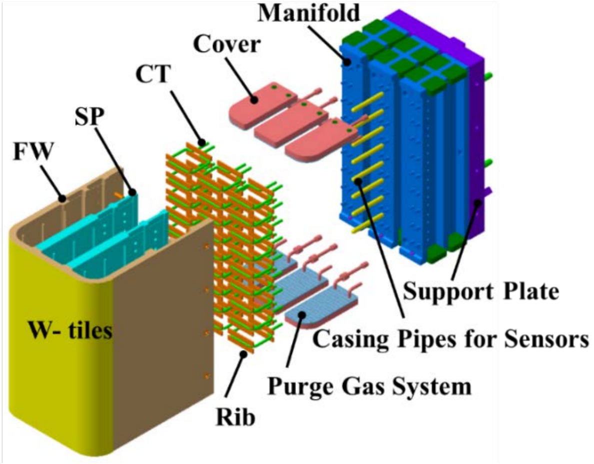
- Burning Plasma operation
  - **Fusion power:** 10-100 MW
  - **Operation:** Q≥1@10-20 MW & Q≥5@100 MW
  - High-model with α
- Test of materials and Blanket (TBM)
  - Licensing and safety
  - Test of breeding materials and breeding blanket

- D-T fusion reaction
  - **Power:** 200-1500 MW
  - **SS operation:** Q=1-5@Phase Ⅰ & Q>10@Phase Ⅱ
  - High-model with α
- Tritium Self-sufficiency (Breeding blanket)
  - TBR > 1
  - Licensing and safety
  - T factory, Remote handing

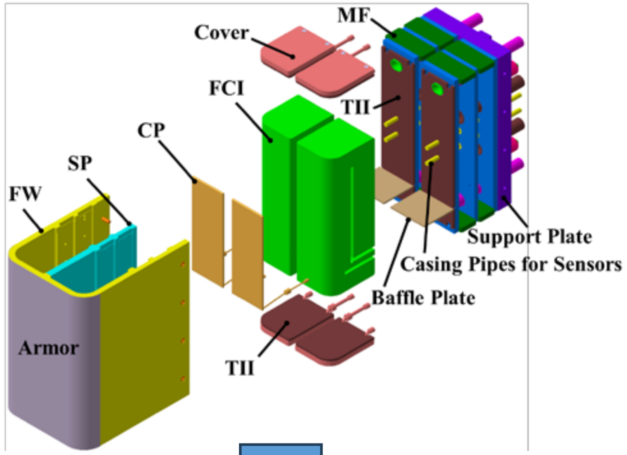
1. Breeding Blanket-Candidates

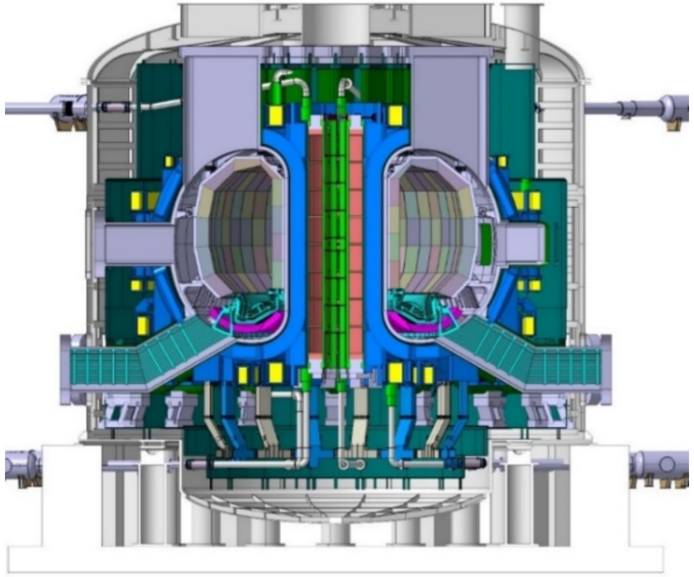


BEST-WCCB-TBM

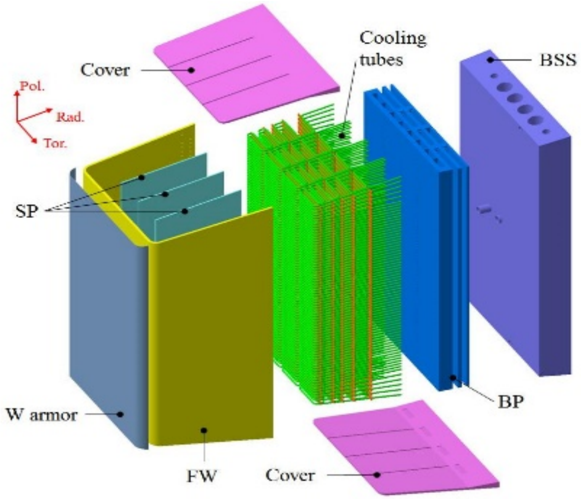


BEST-COOL-TBM

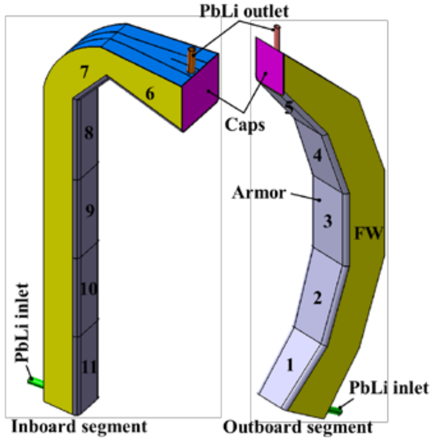


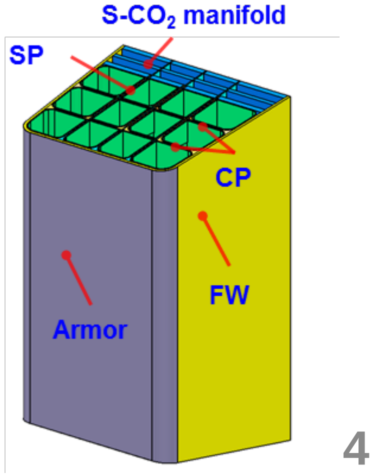


CFETR-WCCB

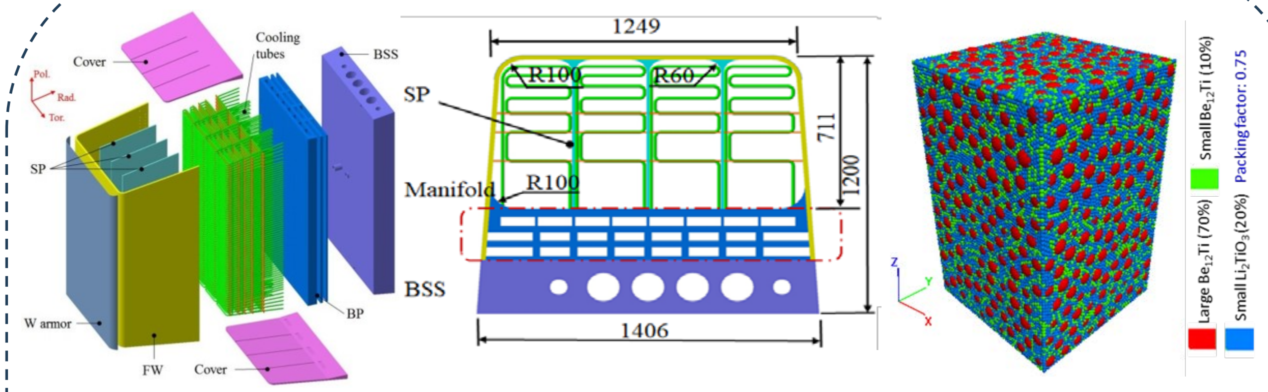


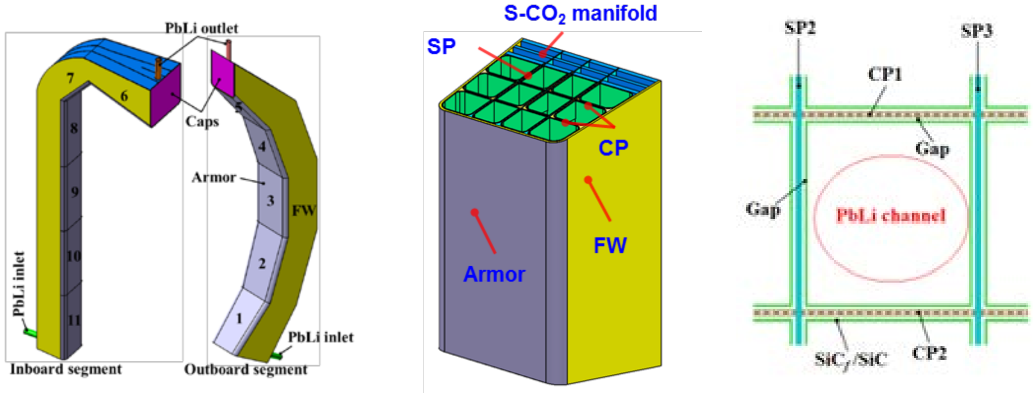
CFETR-COOL





1. Breeding Blanket-Material selection





Water-Coolant Ceremic Blanket (WCCB)

- **Coolant:** water at 15.5 MPa，285 ℃/325 ℃
- **Structure materials:** RAFM/ODS steel
- **Plasma-facing Materials:** W--2mm
- **Breeder/multiplier:** $Li_2TiO_3/Be_{12}Ti$
- **Purge-gas:** 1-3 bar He + 0.1vol% H_2
- **Coefficient of thermal efficiency:** ~ 33%

S-CO_2 Cooled Lithium–Lead (sCO_2-COOL)

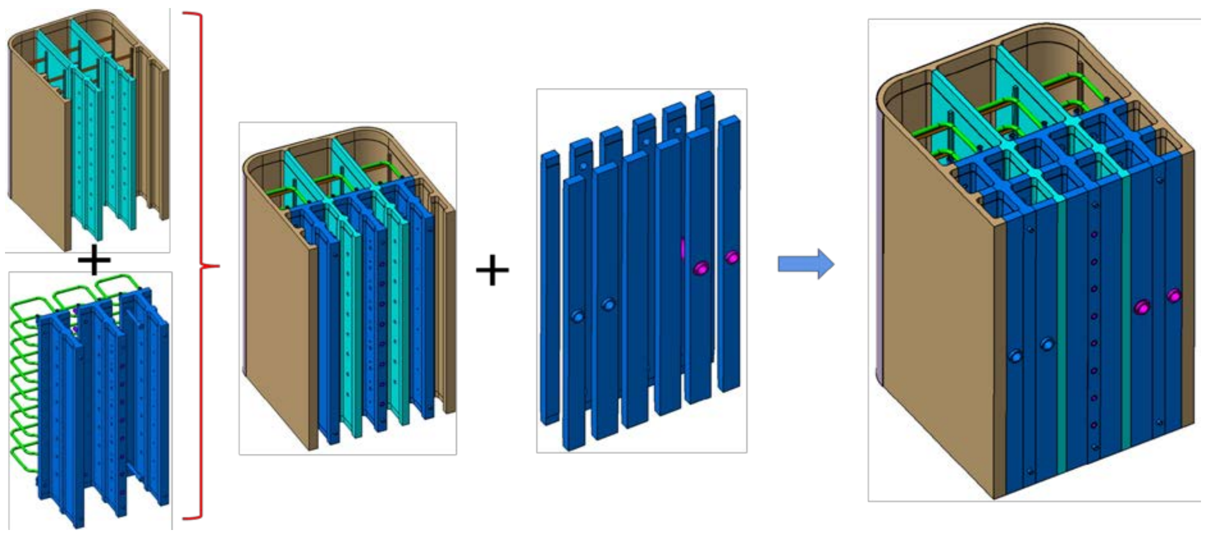
- **Dual Coolant:** 8-9 MPa CO_2，350 ℃/390-410 ℃; PbLi，460 ℃/600-700 ℃
- **Structure materials :** RAFM/ODS steel
- **Plasma-facing Materials :** W—2mm
- **Breeder/multiplier:** PbLi
- **Flow channel insert (FCI):** SiC_f/SiC
- **Coefficient of thermal efficiency:** ~ 42%

We will focus on the manufacturing of WCCB module.

1. Breeding blanket-Manufacturing routes

◻ HIP manufacturing route

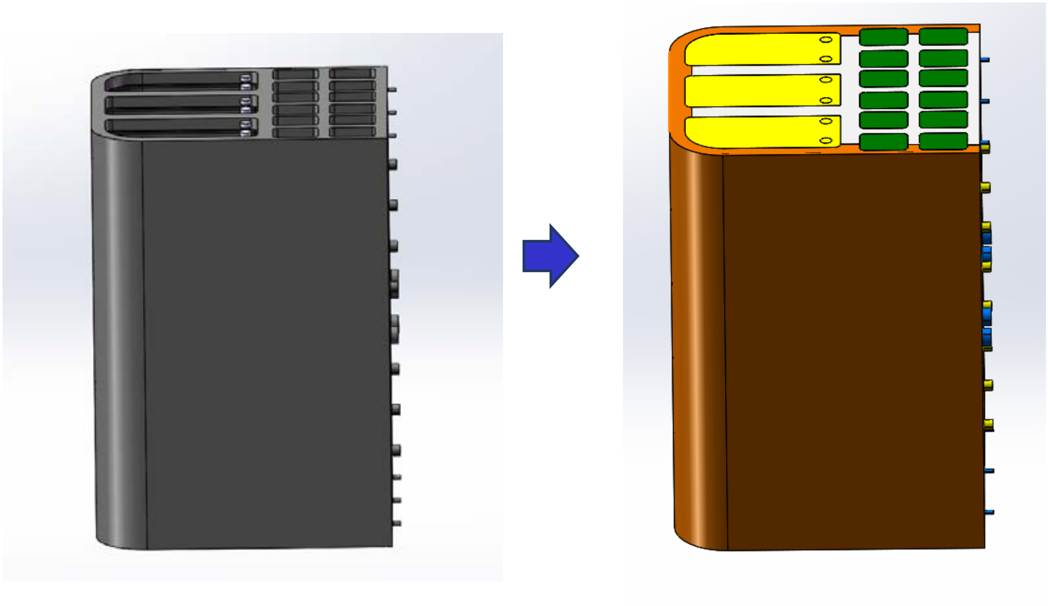
Two steps: Components manufacture+assembly



Technologies: HIP+LW/EBW+TIG

◻ Additive manufacturing route

Two steps: Integrated forming of steel components+W coating



Technologies: L/EB-PF+EBW+TIG

2. HIP manufacturing-Issues

Three issues to be solved in the HIP manufacturing route

1.Materials preparation

- Rolling W plates
- RAFM or ODS steel materials
- Breeding materials
- Shield materials

2. Bonding technology

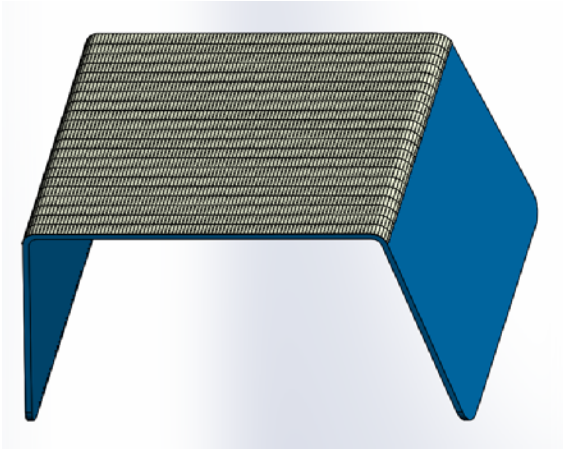
- W/RAFM bonding for First wall
- RAFM/RAFM bonding for FW, CP and DWT
- HIP, EBW, TIG and LW

3. Component Assembly

- TIG weld of DWT and manifold
- EB weld of FW and manifold
- EBW and TIG of cover plate and manifold

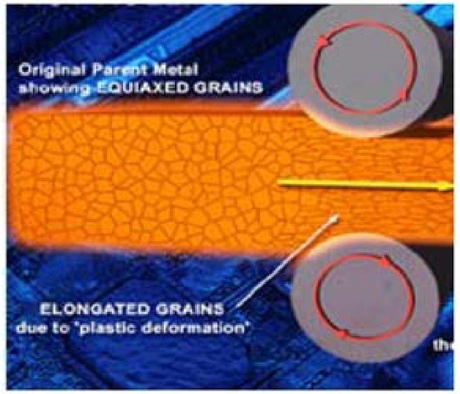
2. HIP manufacturing-W preparation

FW with W tiles

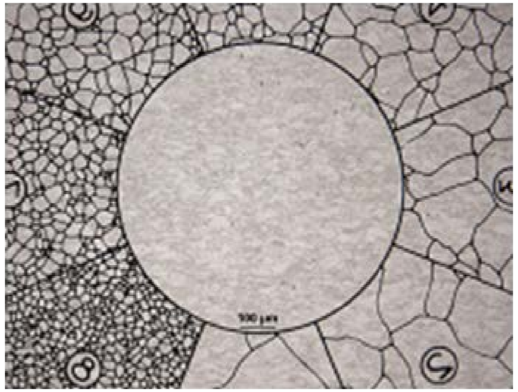


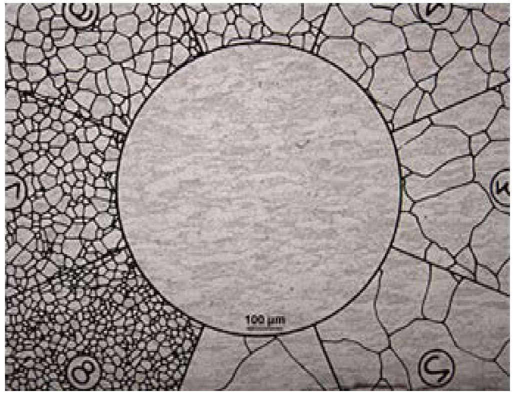
- ❑ **W plates for WCCB**
  - Ref: ITER_D_2EDZJ4 v1.3，T/CITS 433
  - Purity: 99.95 wt%
  - Impurity conten(C, O, N, Fe, Ni, Si): 0.01 wt%;
  - Density(ASTM B311): ≥ 19.0 g/cm^3
  - HV30(ASTM E92): ≥ 410
  - Microstructure: Grade 3(ASTM E112)

- ❑ **Preparation process**
  - ✓ Sintering：2000℃
  - ✓ Rolling:1100-1300℃,
  - ✓ Reduce rate：~70%
  - ✓ Annealing：1100℃



Warm rolling





Microstructure：Anisotropic and better than grade 4

Mass production of W plates

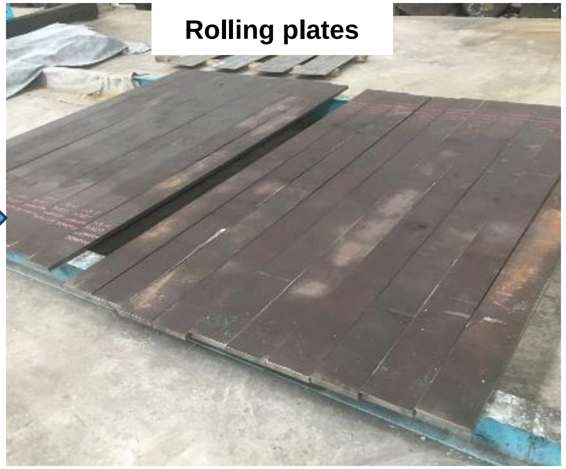
2. HIP manufacturing-RAFM steel

❑ RAFM steel for WCCB

Ref. standard: GB/T 38875-2020 (CLAM), EJ/T 20242-2020 (CLF-1)

	CLF-1 (wt.%)	CLAM (wt.%)
C	0.085-0.135	0.08-0.12
Cr	8.20-8.80	8.5-9.5
W	1.30-1.70	1.2-1.8
V	0.20-0.40	0.15-0.25
Ta	0.05-0.15	0.10-0.20
Mn	0.30-0.70	0.30-0.60
N	0.015-0.040	≤0.005
Fe	Balance	Balance
Others	＜0.01	＜0.01

	Tensile test			Impact test	Creep test	
T/℃	$R_{p0.2}$/MPa	R_m/MPa	A/%	KV_2/J	Strain/MPa	Cracking time/h
R.T	⩾510	⩾600	⩾18	⩾200		
450	⩾400	⩾450	⩾18			
550	⩾310	⩾350	⩾18		185	⩾10000
600	⩾230	⩾300	⩾18		135	⩾1000

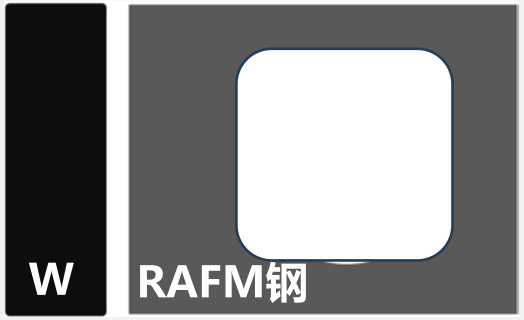


2. HIP manufacturing-W/RAFM bonding

◻ Manufacture of First-Wall (FW) component

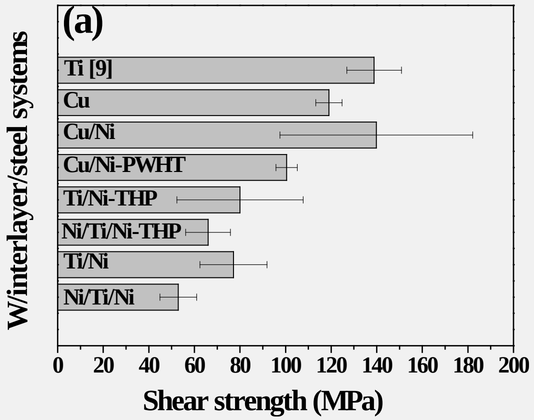
- **Key issue: Dissimilar materials bonding between W-RAFM**
- **Solution: HIP+interlayer optimization**

Issues

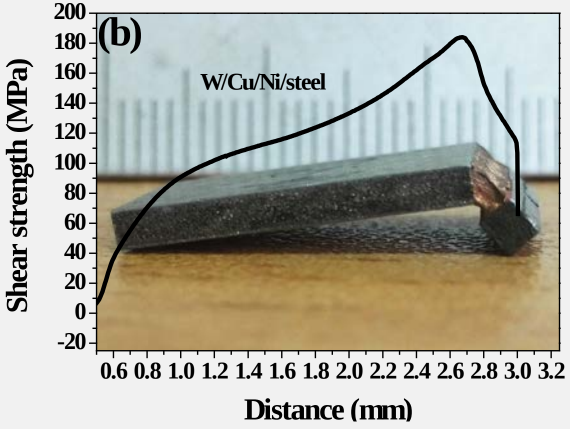


- CTE mismatch
- Brittle interphase formation

Interlayer optimization



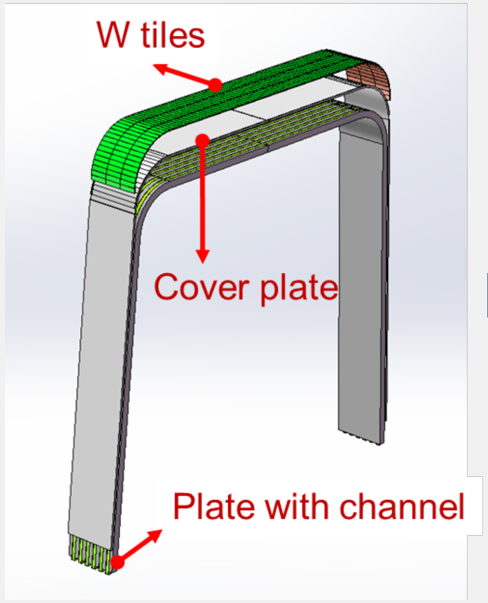
Compound interlayer



Optimal Interlayer

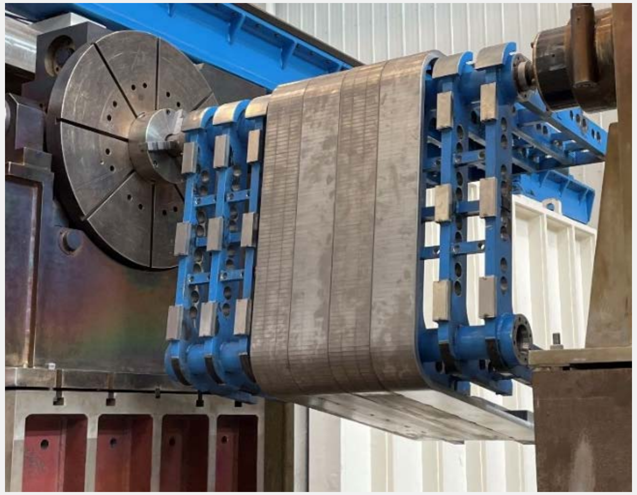
2. HIP Manufacturing--FW components

- **We have developed a one-step HIP technology to realize the W/RAFM connection and channel forming.**
- **Full-sized FW has been fabricated by two-step: HIP of 1/9 mockup and EBW assemblies**

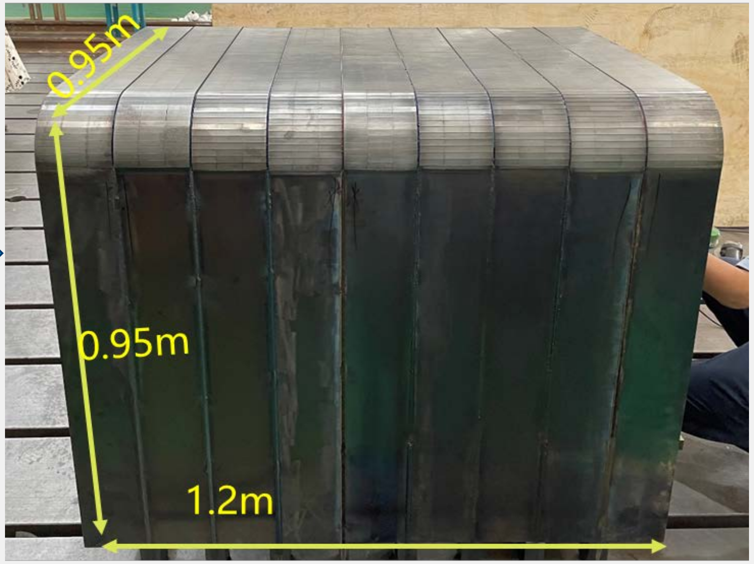


HIP

1/9 FW mockup



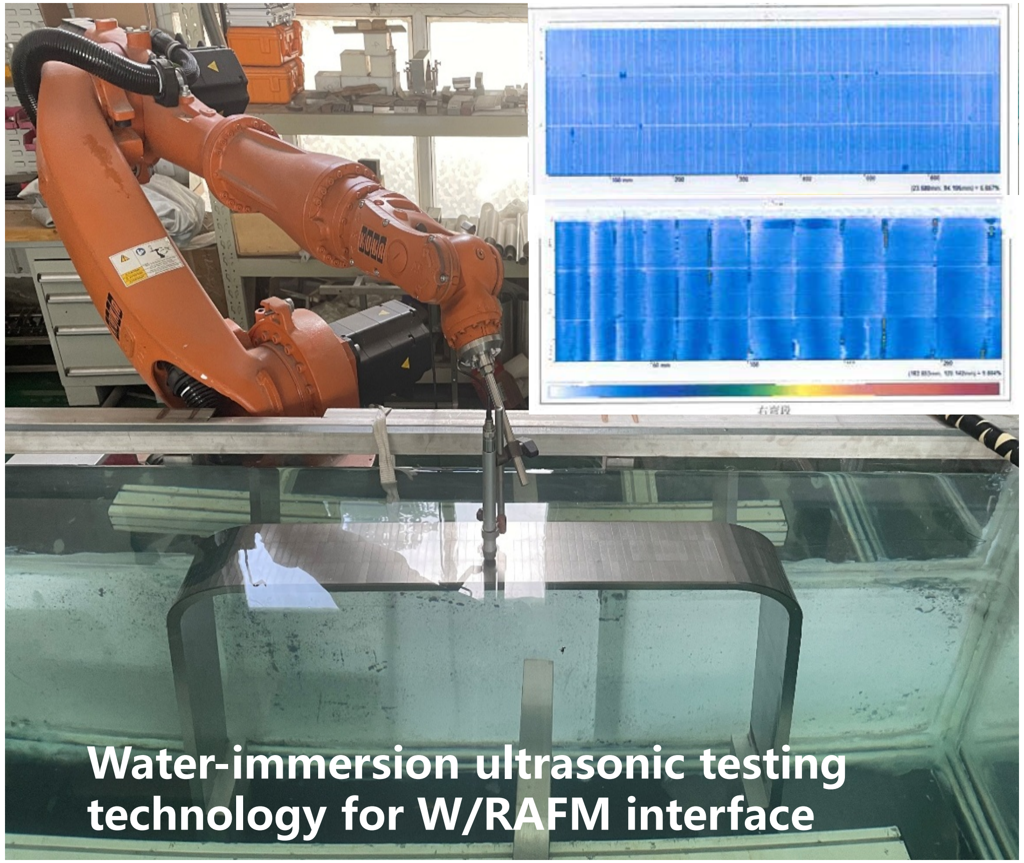
EBW



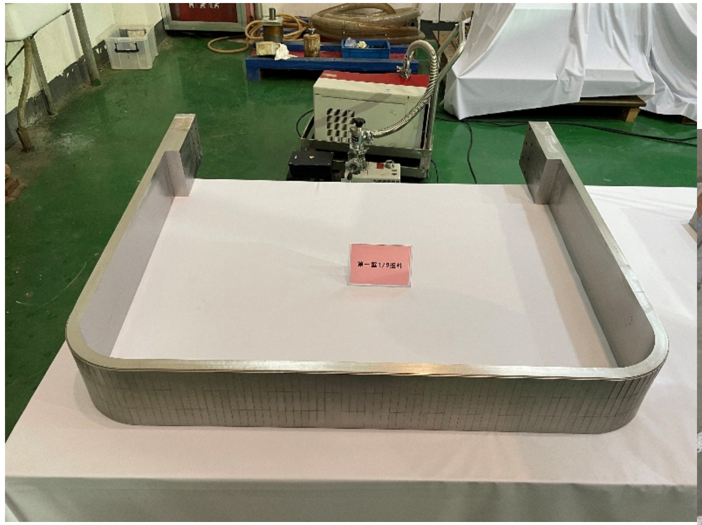
Full-sized FW

2.HIP Manufacturing-Qualification

□Water-immersion ultrasonic testing technology for W/RAFM interface and channel testing technology (hydrostatic pressure) have been developed for the welding quality of the first wall components.



Water-immersion ultrasonic testing technology for W/RAFM interface

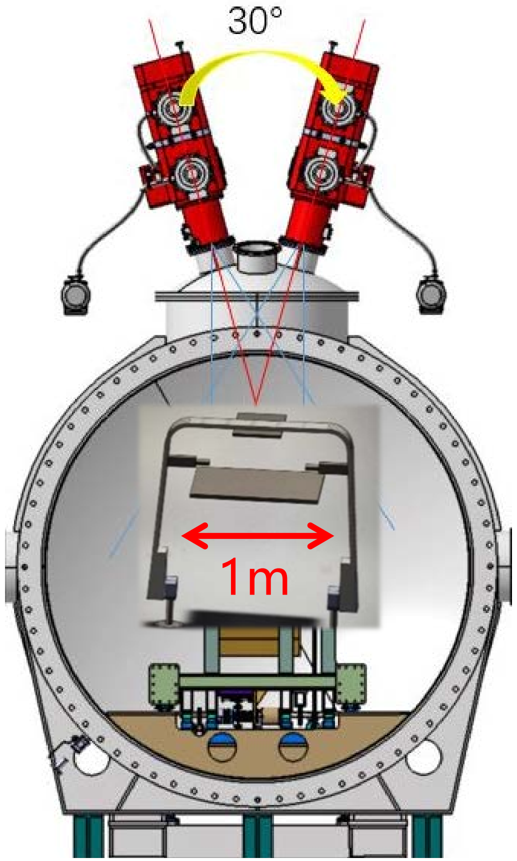


Hydrostatic pressure @20MPa

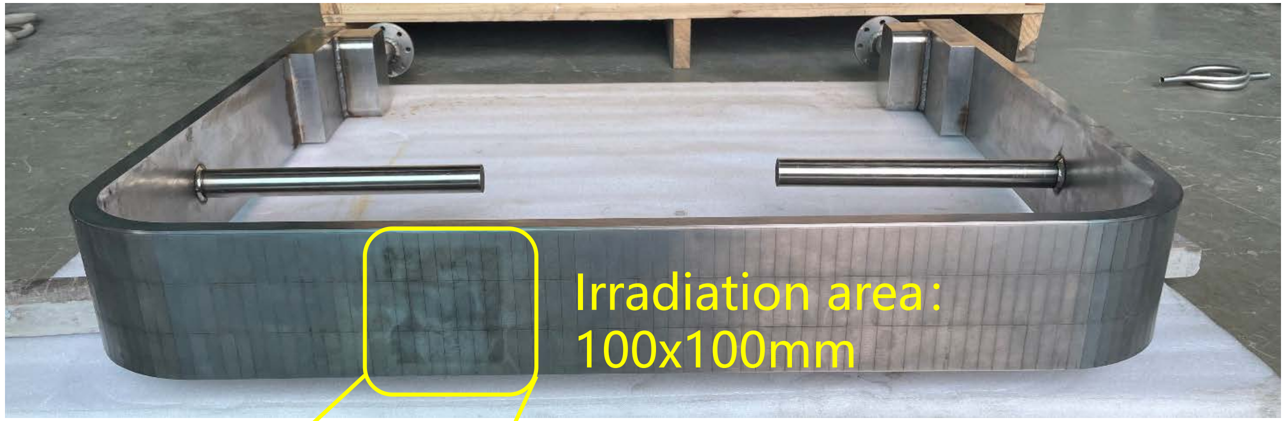
Vacuum helium leak detection

2.HIP Manufacturing-Qualification

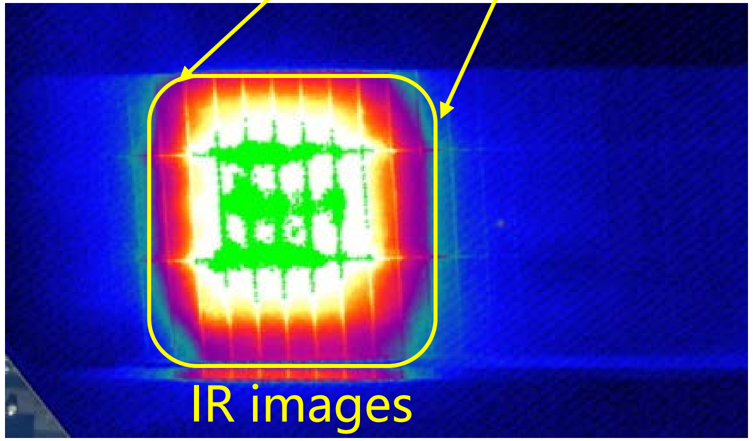
□A large-scale electron beam high heat flux test platform was designed and constructed, and was used to high heat flux tests of large-sized first wall components.

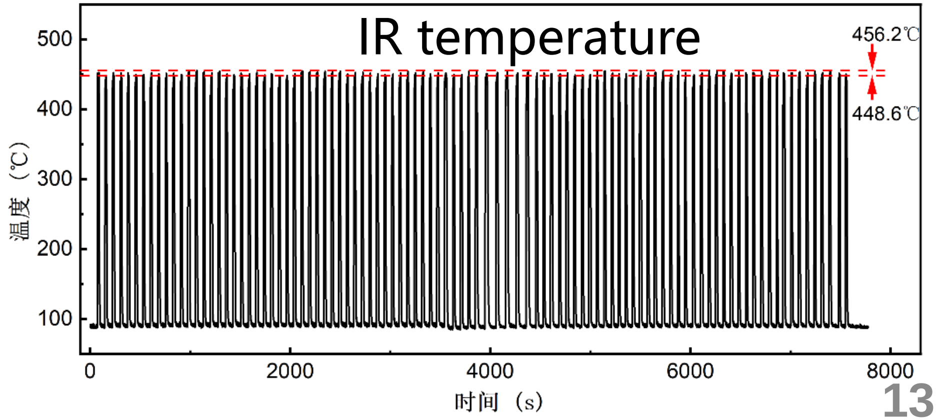


IR+TC+CCD+DIC



- HHFT@1 MW/m²
- Coolant：T-30℃，
  flow rate 0.096kg/s
- Max Temp.466℃



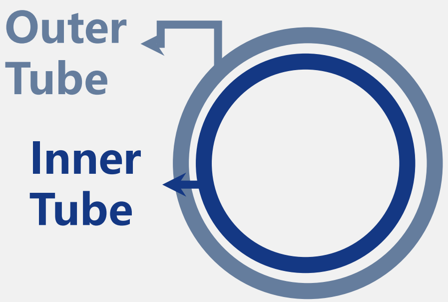


2.HIP Manufacturing-Double-wall tubes

- To prevent the crack from penetrating, it is proposed to adopt double-wall tubes to cool the breeding zone.

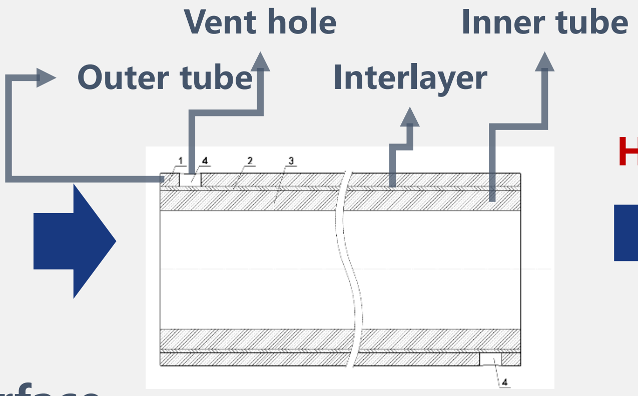
- **Key issue:** One-time welding of multi-bend, large-area interface in DWT
- **Solution:** Welding structure design + interlayer material selection.

Issue

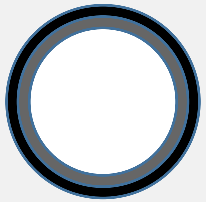


- Large welding interface
- Big gap
- Many bends

Solution



HIP



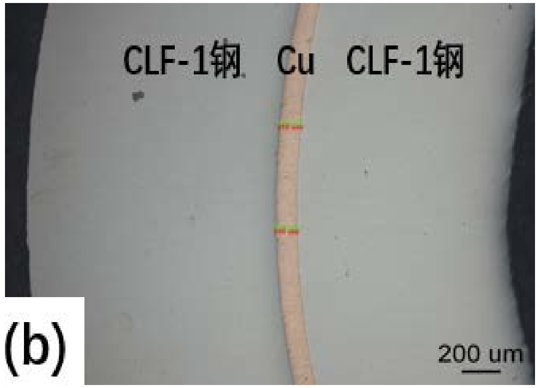
Functions: Heat dissipation + Anti-cracking + Tritium permeation barrier

Production

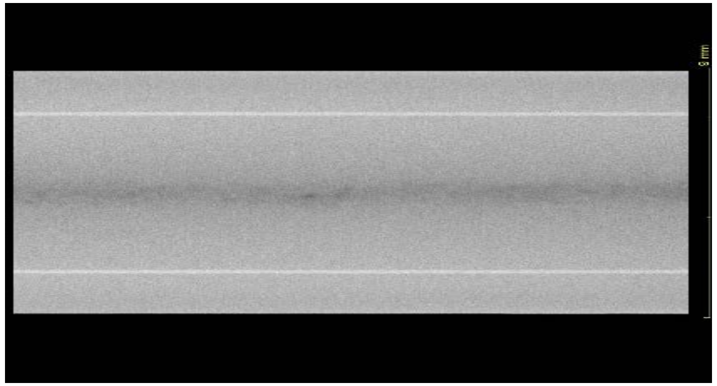
2.HIP Manufacturing-Qualification for DWT

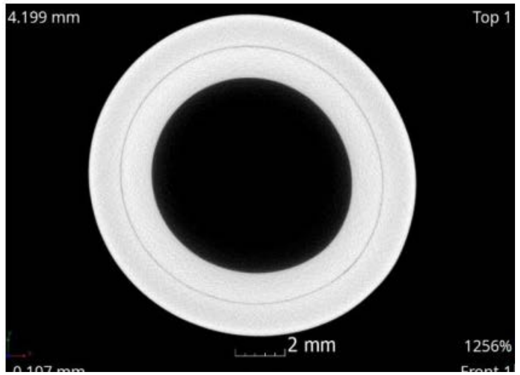
- The combination of metallographic and CT analysis indicates that a destructive + non-destructive testing technology for the interface welding quality of double-wall tubes has been developed.

Destructive testing:
Metallographic analysis



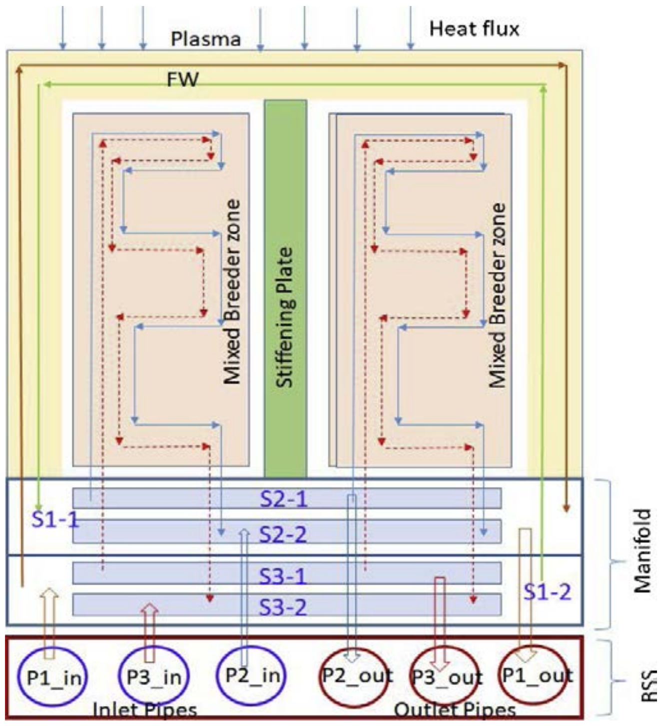
Non-Destructive testing:
CT analysis



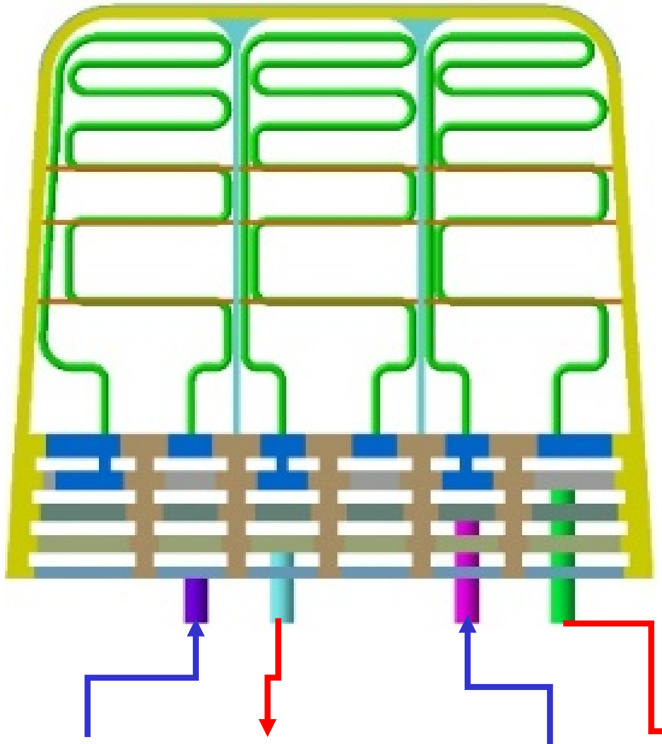


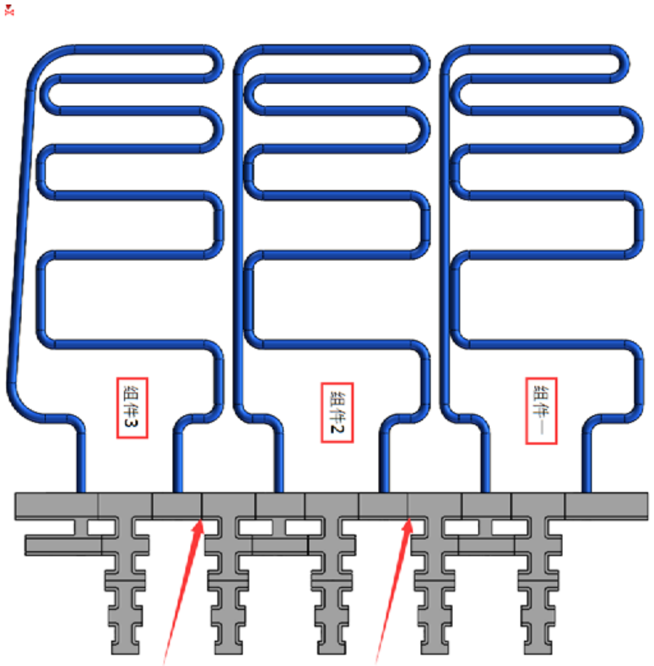
2. HIP Manufacturing--Assembly

Requirement: Cooling water of FW, DWTs and CP should be input and output by manifold.



Solution: Pagoda type multi-layer structure manifold.





Input of FW

Output of FW

Input of DWT and CP

Output of DWT and CP

2. HIP Manufacturing--Assembly

Assembly route for WCCB

Based on the design of manifold, the assembly of the entire blanket module is divided into three steps:

① The assembly of the DWT and manifold

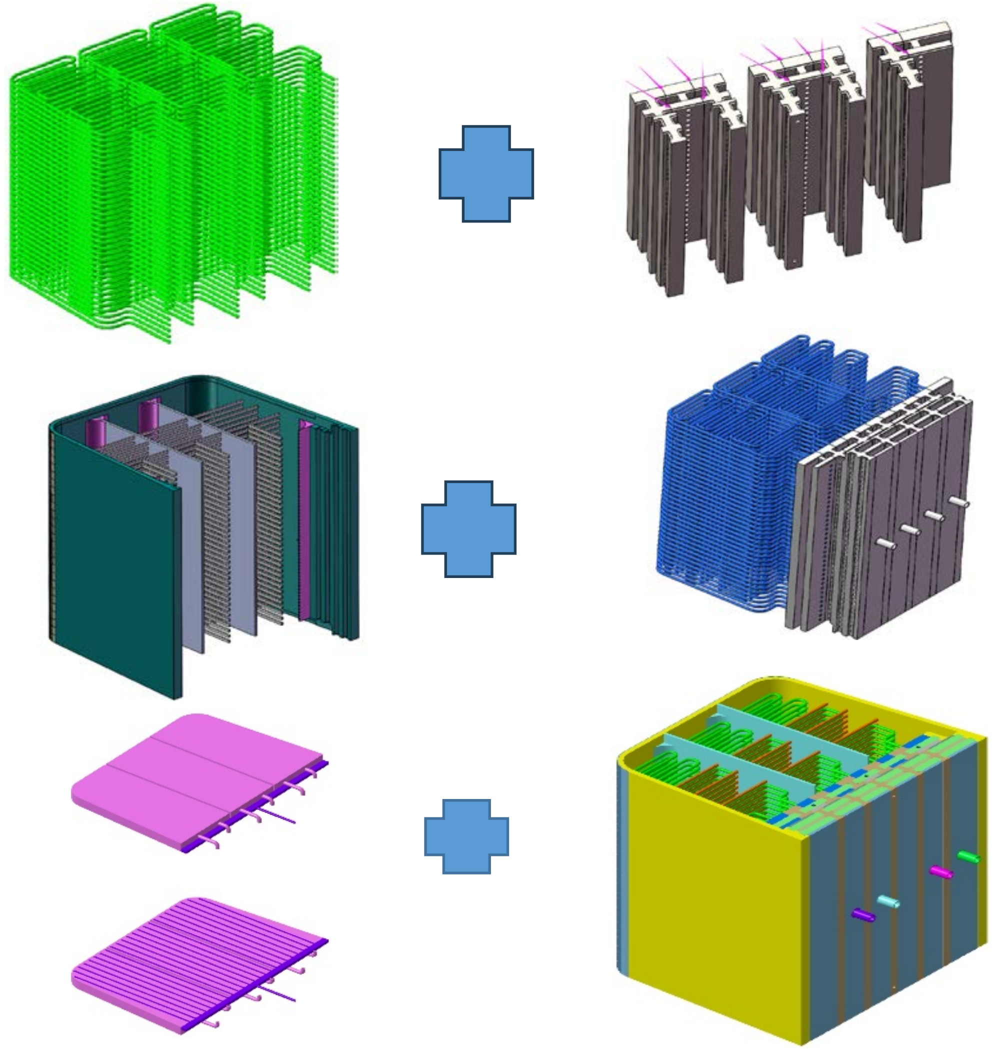
② The assembly of the FW and manifold,

③ The assembly of the CP and manifold. The following details the specific process route and implementation.

Step 1:

Step 2:

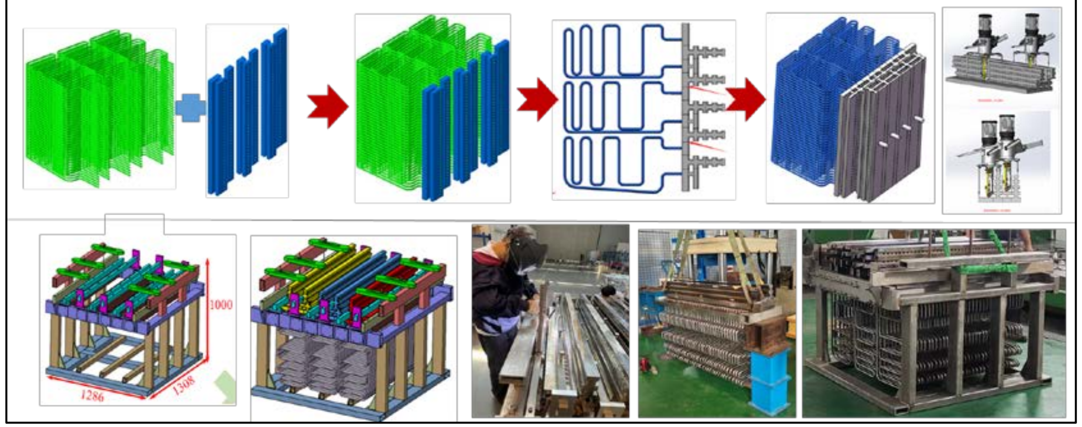
Step 3:



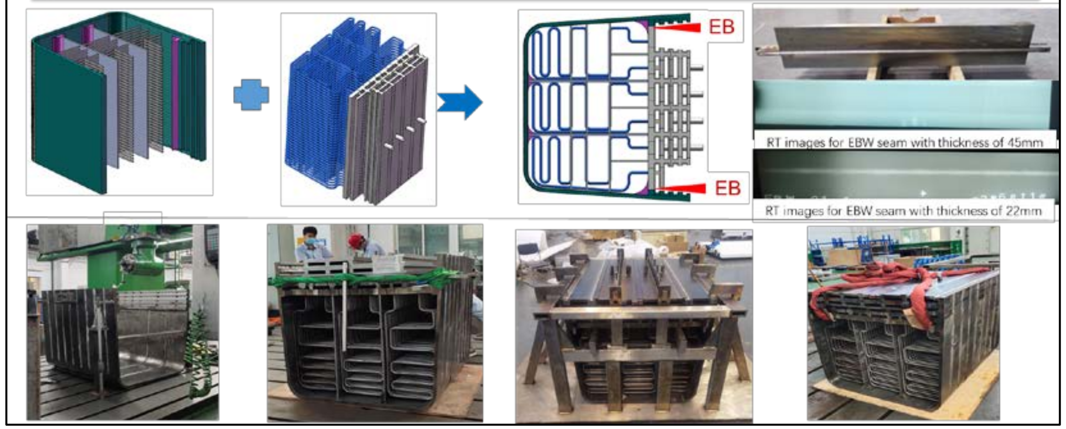
2. HIP Manufacturing--Assembly

□Full-sized WCCB blanket has been assemblied by TIG+EBW technology (Feasibility)

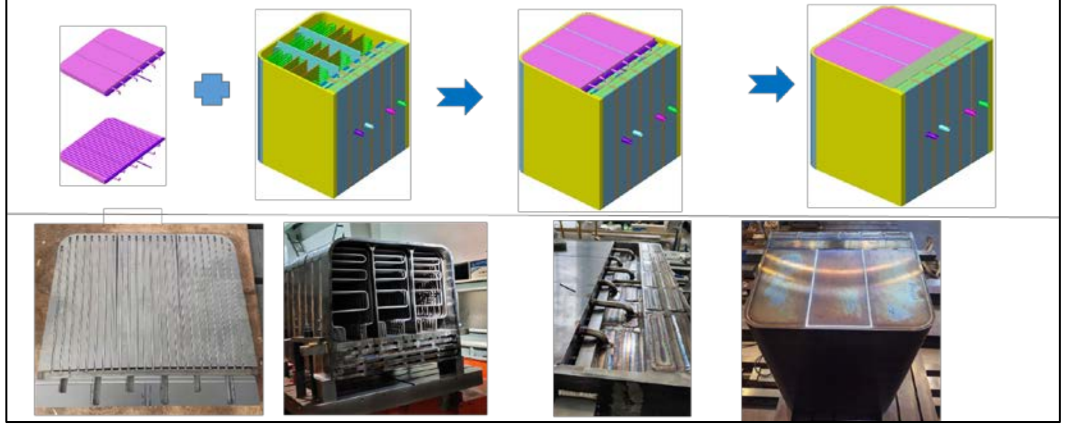
Step 1: Assembly of DWTs and Manifold was developed and completed.

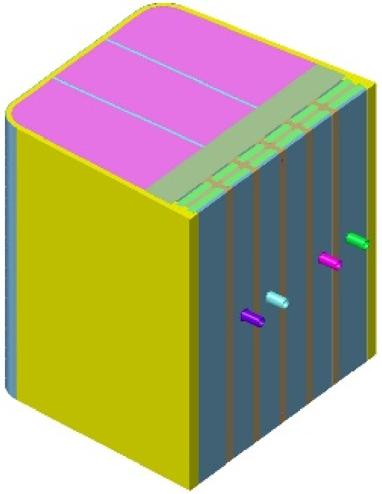


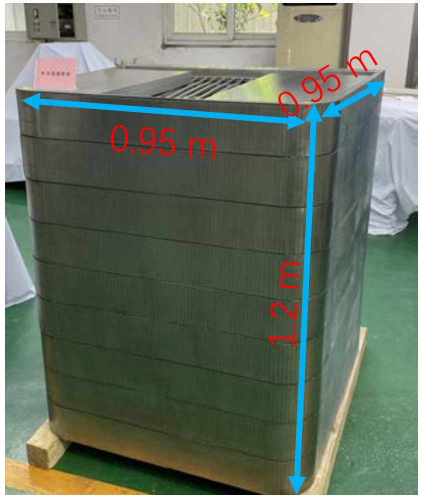
Step 2: The welding process of FW and manifold was developed. The welding seam was qualified by UT and RT.



Step 3: The welding process of Cover Plate (CP) and manifold was developed. The welding seam was qualified by UT and RT.



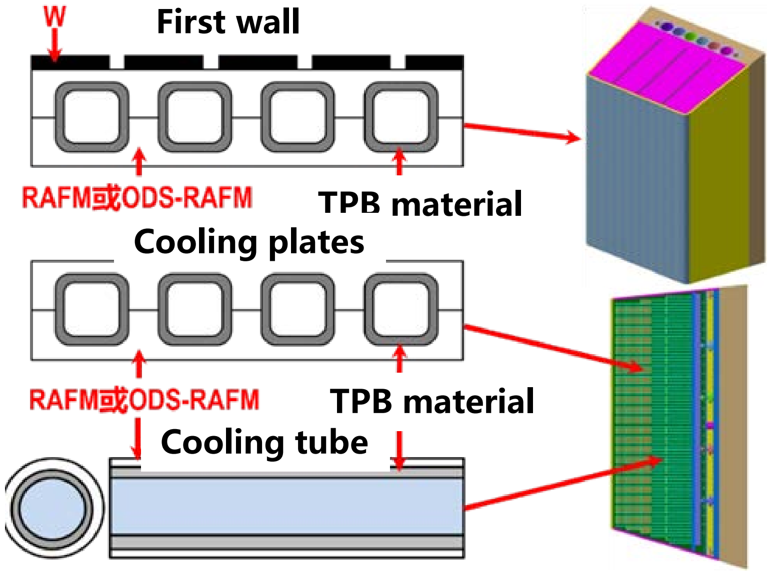




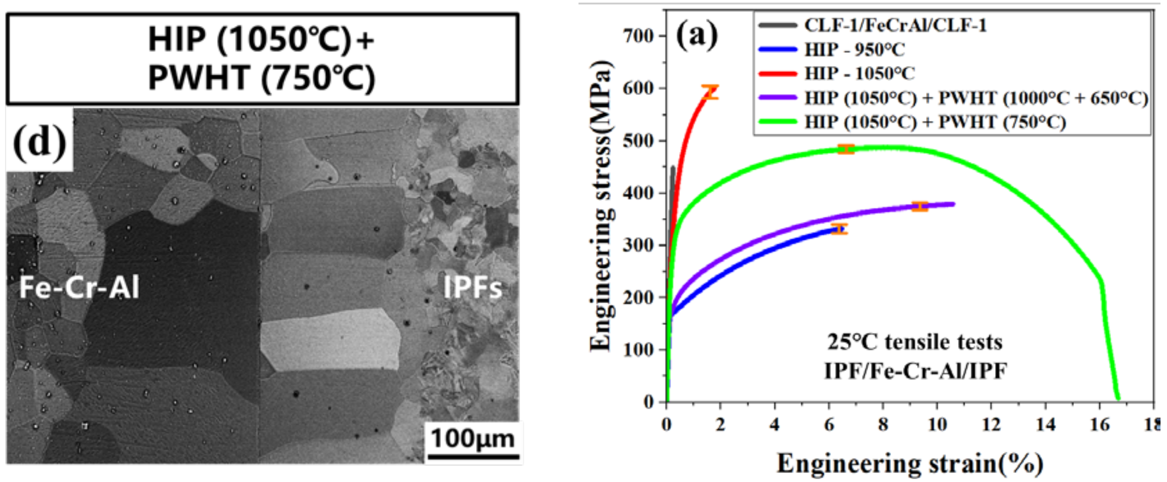
2. HIP Manufacturing—TPB mockup

- In response to the tritium permeation barrier (TPB) requirements of the blanket flow channel, a new HIP manufacturing process route for the blanket module was proposed based on the excellent tritium barrier effect of iron-based tritium barrier materials.
- The high toughness connection of FeCrAl-RAFM steel was achieved by optimizing the alloying elements of RAFM steel and the welding process.

New HIP manufacturing route for TPB

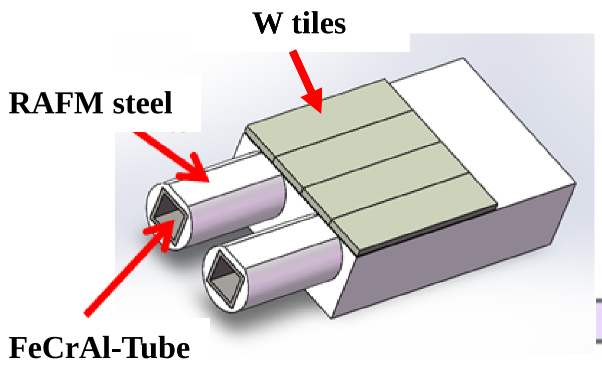


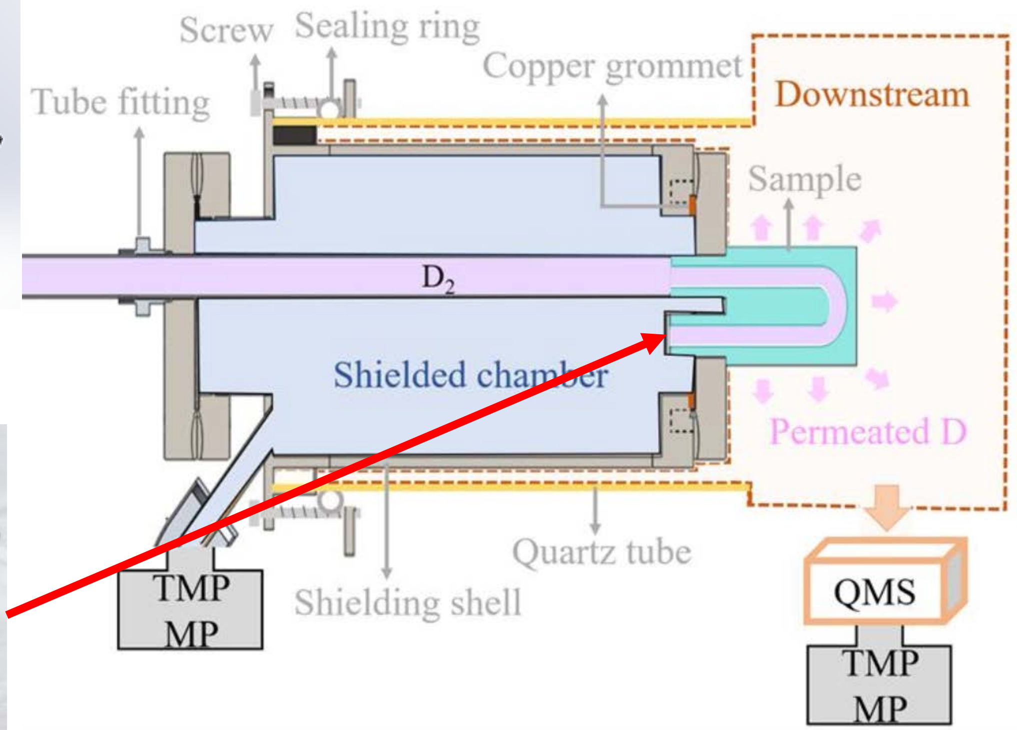
New bonding process of FeCrAl-RAFM

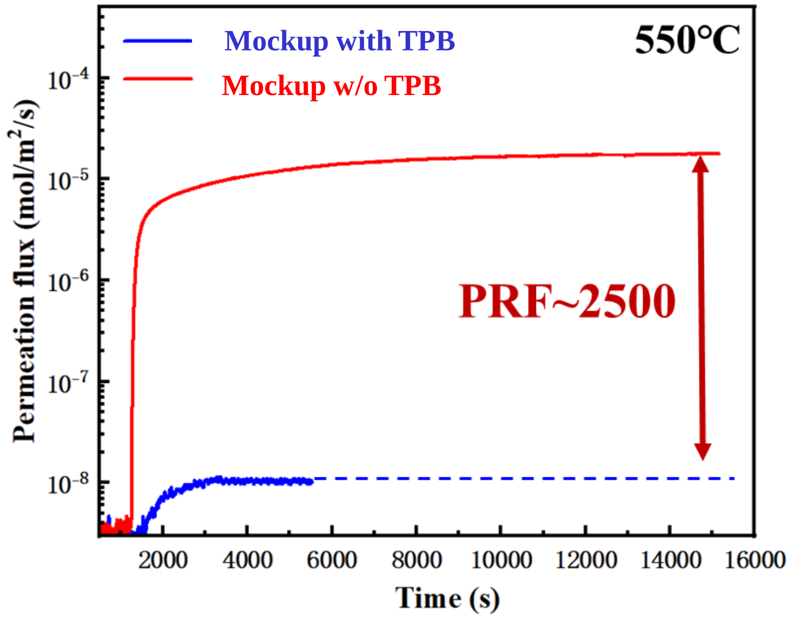


2. HIP Manufacturing—TPB mockup

- Optimized the process route, the integratation production of mockup with tritium permeation barrier in channel was achieved.
- Comprehensive hydrogen-barrier factor of mockup reaches 2500. (550℃)

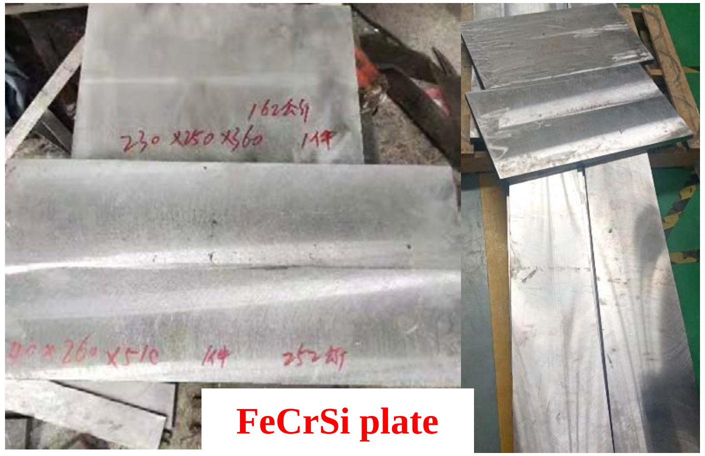




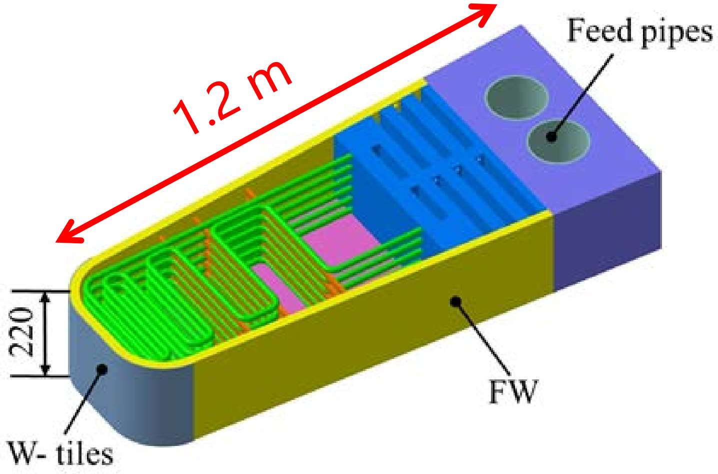


2. HIP Manufacturing—TPB mockup

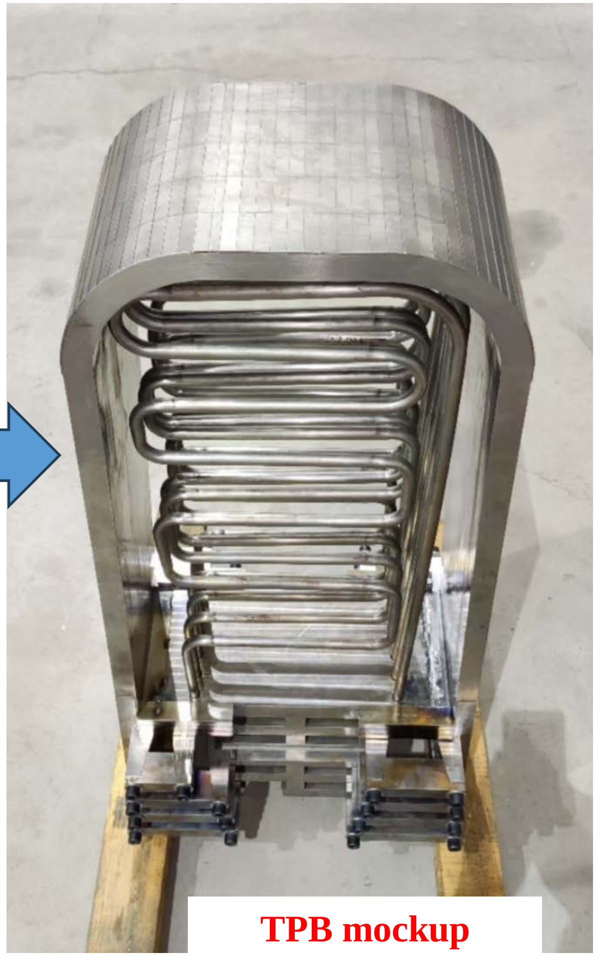
- Based on the development of new TPB material plates and tubes, a larger-scale TPB mockup was fabricated, verifying the feasibility of the process.


FeCrSi plate


FeCrAl tube



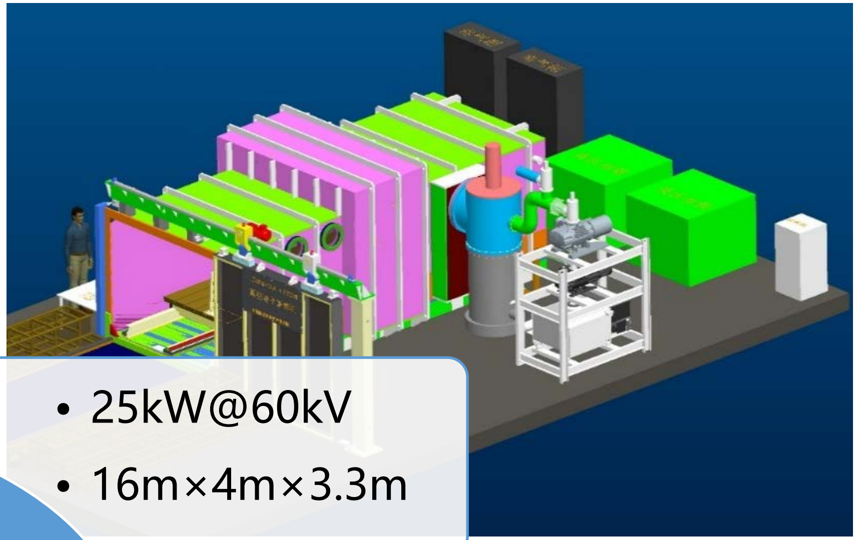

FW with TPB in channel


TPB mockup

2. HIP Manufacturing—Facilities

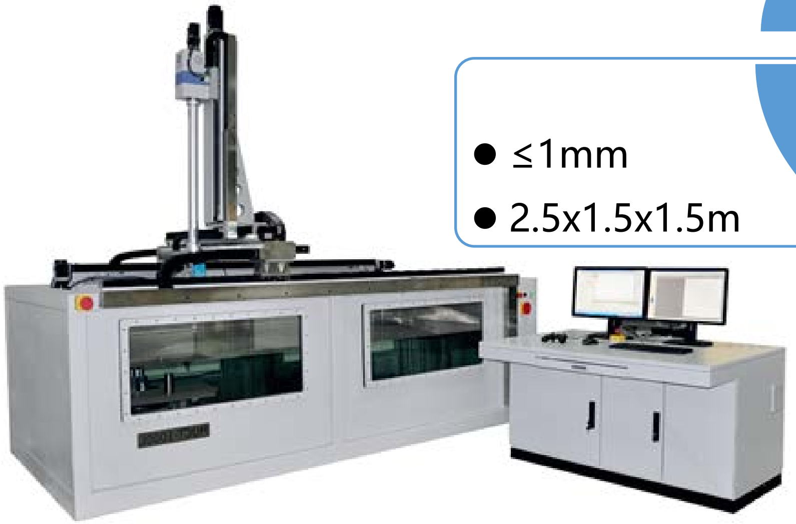
- Φ1850×2500
- 200MPa×1400℃

HIP



- 25kW@60kV
- 16m×4m×3.3m

EBW

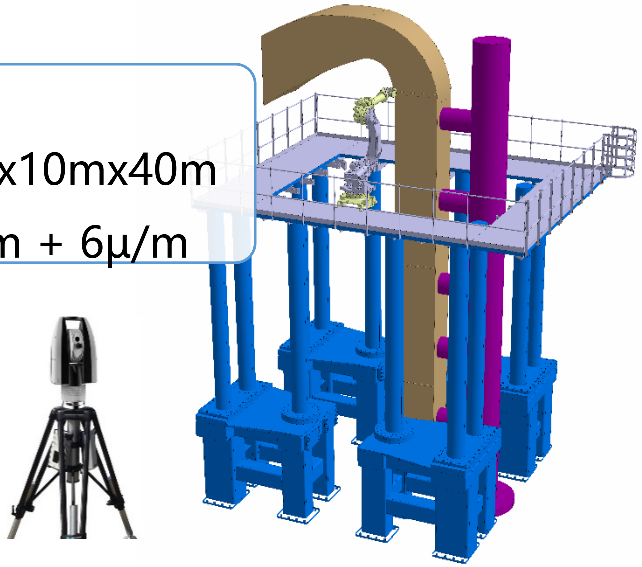


- ≤1mm
- 2.5x1.5x1.5m

NDT

Assembly Platform

- 10mx10mx40m
- 15μm + 6μ/m



3. Additive manufacturing-Issues

□There are also three issues to be solved in the development of additive manufacturing technology route。

1.Materials issues

- Chemical element for RAFM or ODS steel
- Mechanical properties
- Radiation resistance

2. Scale magnification issues

- Thermal strain and cracking
- Support free in channel
- Homogeneity

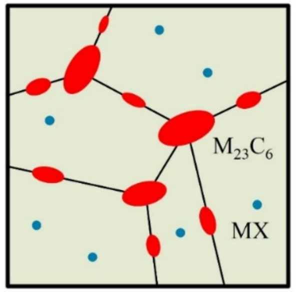
3. Component intergratation

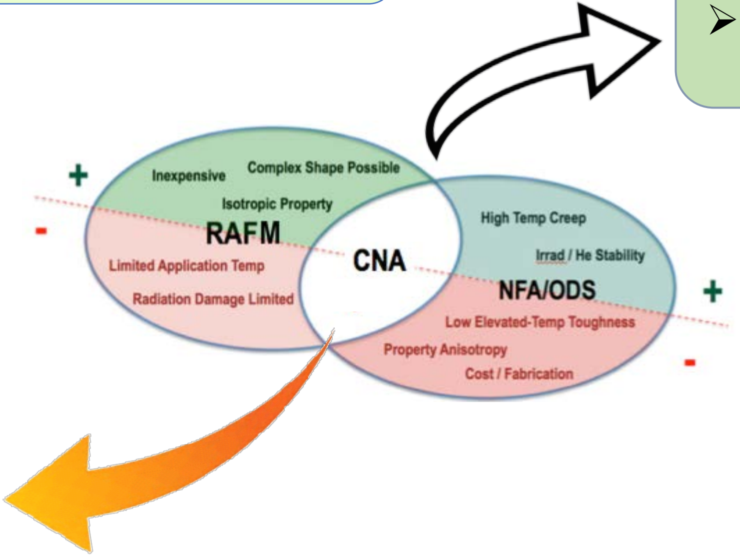
- W coating on RAFM steel
- RAFM/RAFM bonding for cover plates

3. Additive Manufacturing--Alloy design

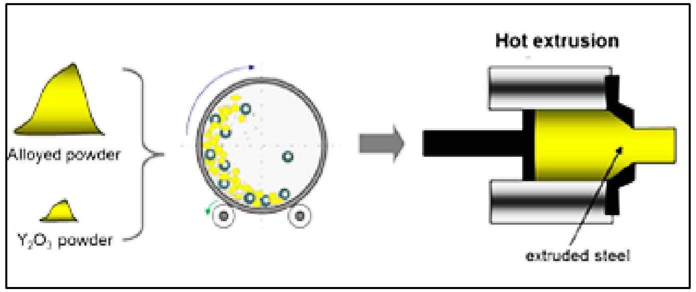
Alloy design scheme based on additive manufacturing

RAFM steel:
- ■ The preparation process is mature.
- □ The precipitation and coarsening are severe.

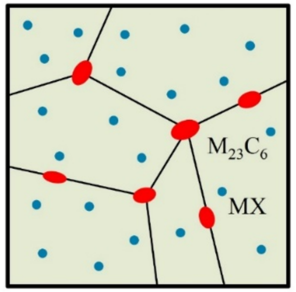




New route (LA-IPS @Tsinghua U.) ：
- ➢ Further increase the density of MX phase.
- ➢ Completely eliminate the coarse precipitated phase at grain boundaries



ODS:
- ■ Excellent performance
- □ It is difficult to prepare on a large scale.



CNA:
- ■ The density of the MX phase has increased somewhat.
- ■ The coarse phase in GB has not yet been eliminated.

Castable Nanostructured Alloys (CNAs)

OAK RIDGE National Laboratory

Lizhen Tan

3. Additive Manufacturing--Alloy design

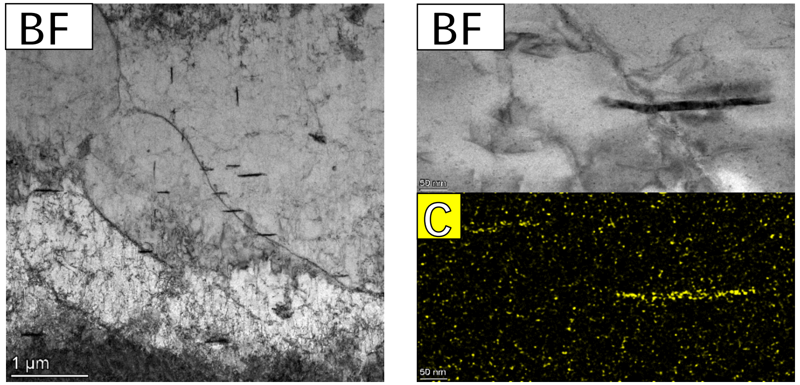
□Design:Addition of high Ti elements

□Results: a low-activation Interphase precipitation strengthen steel（LA-IPS）.

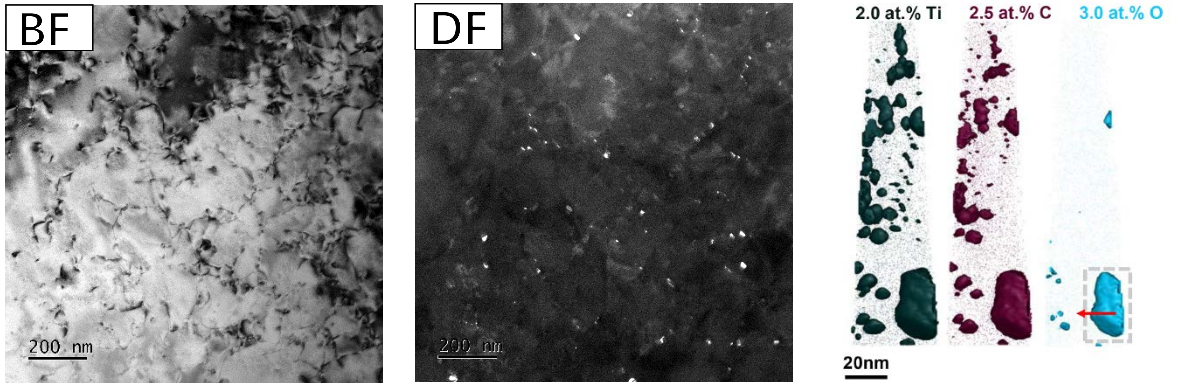
	C	Cr	Ti	W	Si	Fe
0.12Ti	0.056	9.14	**0.12**	0.94	0.16	Bal.
0.27Ti	0.075	8.90	**0.27**	0.82	0.086	Bal.
0.46Ti	0.076	9.16	**0.46**	0.96	0.088	Bal.
0.74Ti	0.069	9.13	**0.74**	1.03	0.093	Bal.

MX phase charaterization

	9Cr RAFMs	9Cr CNAs	**0.05C IPF**
Size, nm	~10-50	~3-20	**~3-5**
Density, m^{-3}	10^{19}-10^{20}	10^{21}-10^{22}	**10^{22}-10^{23}**



0.12Ti样品



0.27Ti样品

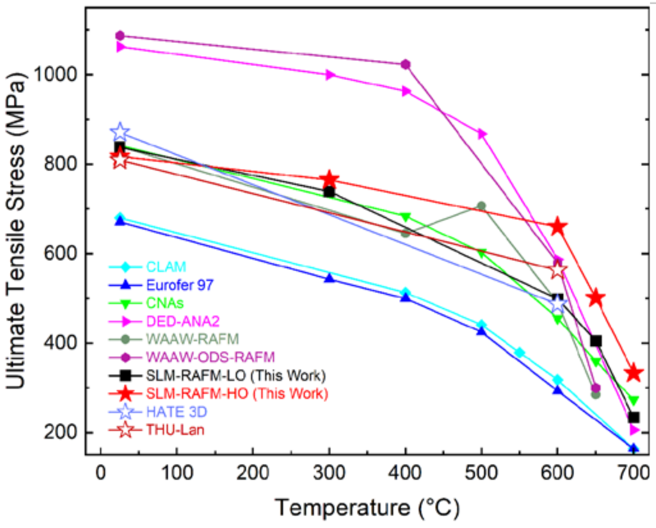
- A large amount of rod-shaped iron-rich carbides precipitated in the matrix.

- Fine MX phase (TiC) precipitated in the matrix, but no rod-shaped carbides precipitated.

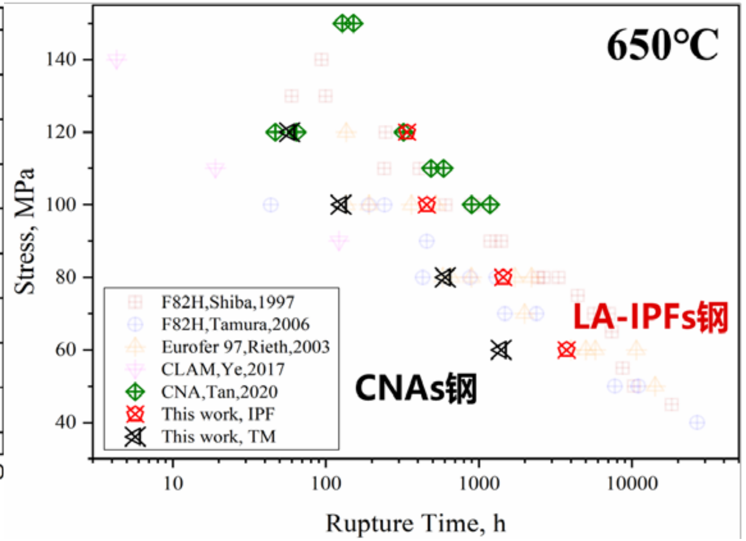
3. Additive Manufacturing—Properties data

- High-temperature tensile、creep and irradiation data of this material have already been obtained.
- LA-IPS steel has excellent high-temperature mechanical properties and radiation resistance.

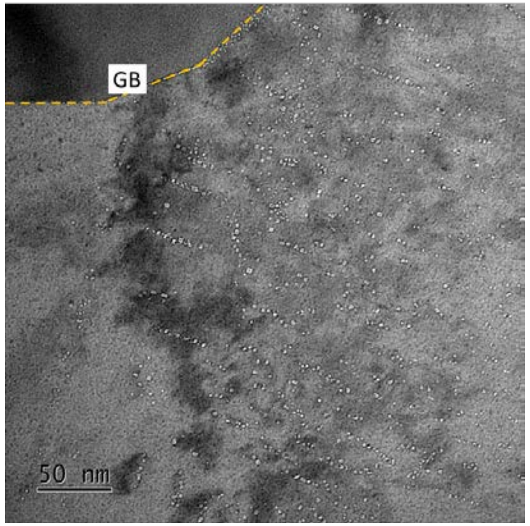
Tensile tests



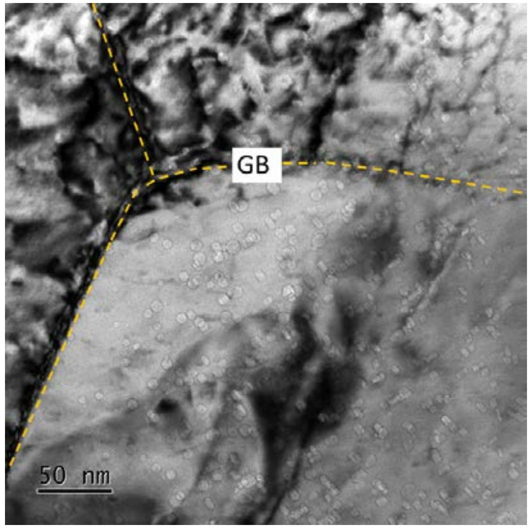
Creep tests



He-Irrad. @450℃

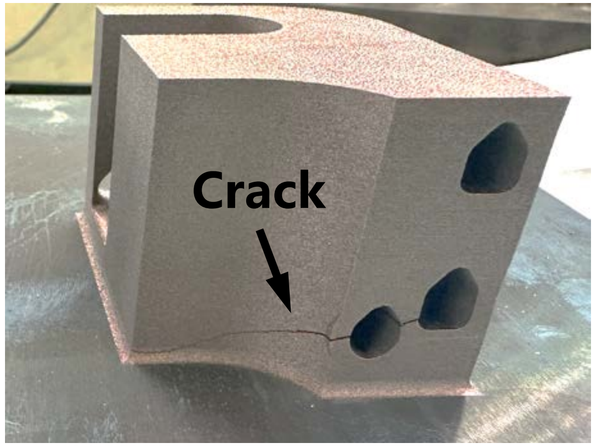


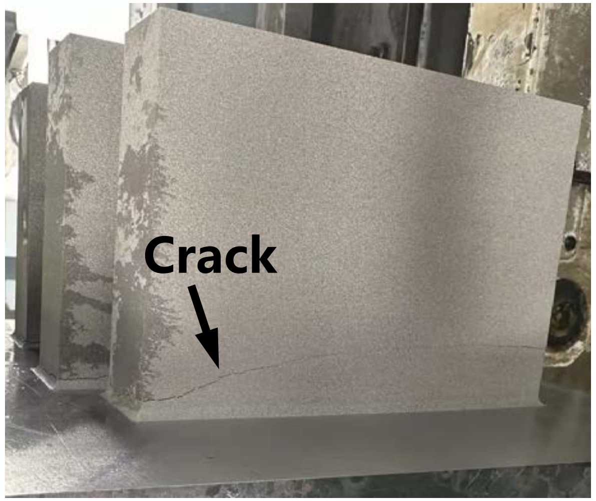
He-Irrad. @650℃



3. Additive manufacturing-Crack

□Based on laboratory research, trial research was conducted on the prevention of cracking during and after the additive manufacturing of large-scale LA-IPS steel parts.



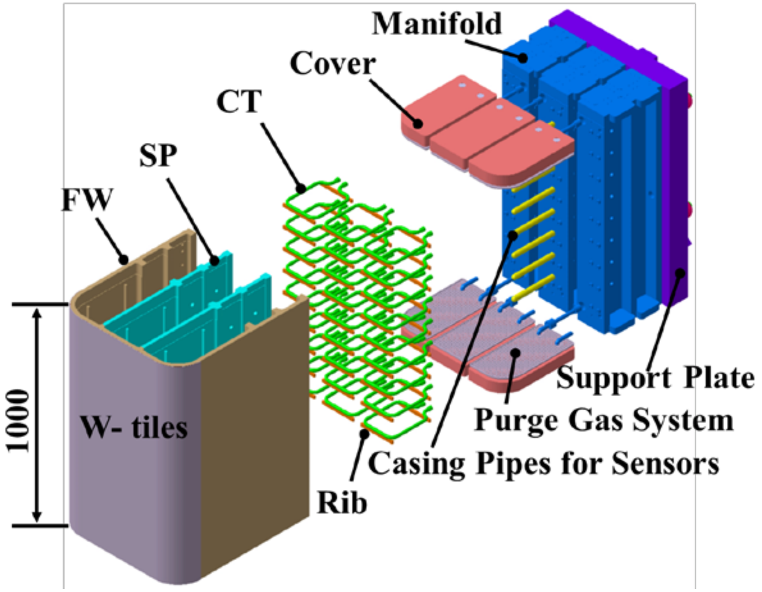


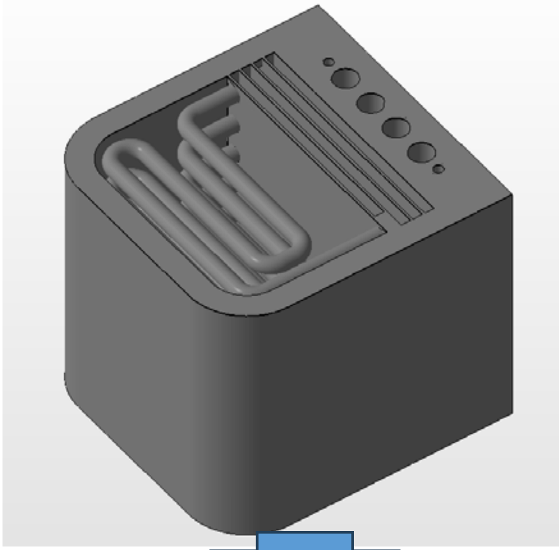
Solution:

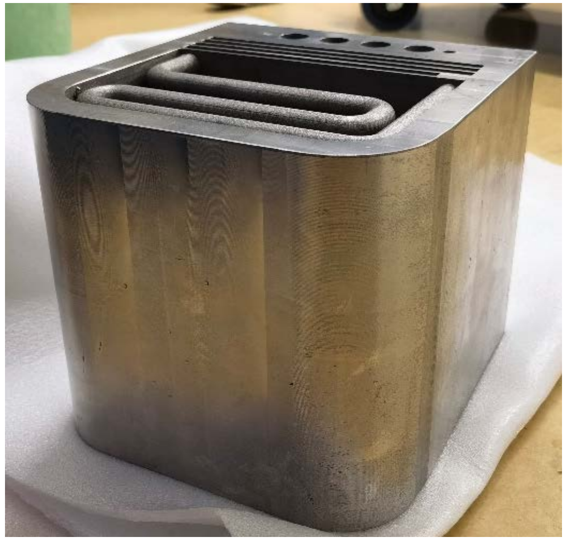
Substrate heating
+Post fusion heat treatment

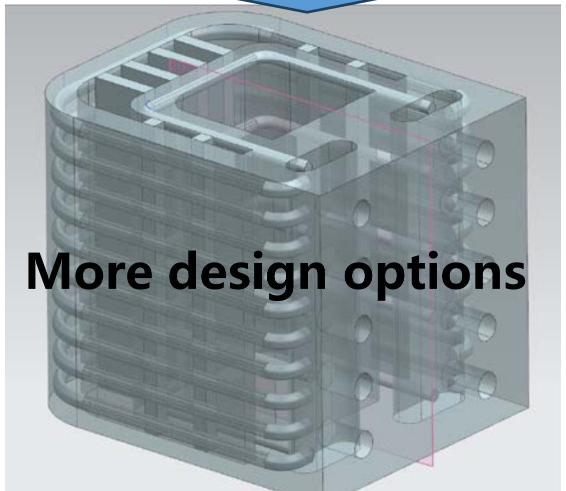
3. Additive manufacturing—small-scale mockup

□The additive manufacturing of the small-scale mockup was carried out with optimized process.



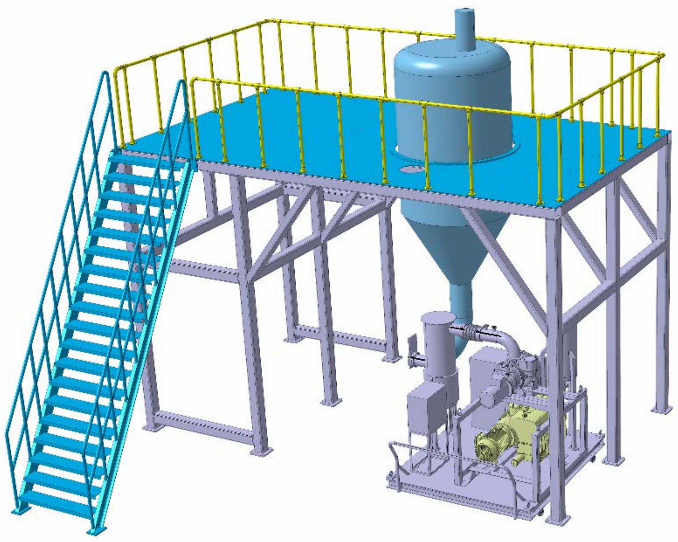






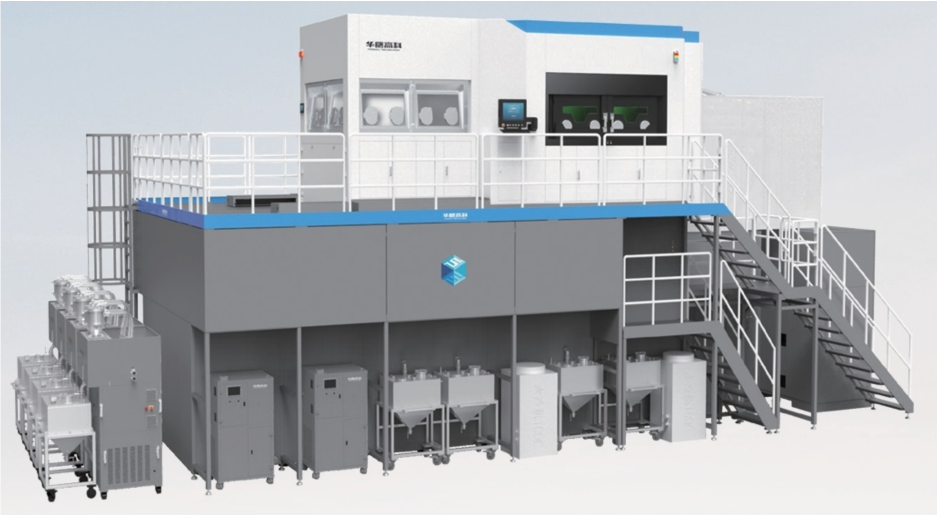
3. Additive Manufacturing—Facilities

VIGA (100kg)



Provide alloy powders with high purity and element design for additive manufacturing platforms.

L-PBF (2mx2mx2.5m)



Additive manufacturing of large-sized and complex-structured blanket RAFM steel components

EB-PBF (2mx2mx0.5m)

Additive manufacturing of first wall tungsten coating on the surface of steel components.

4. Conclusion and considerations

■ Conclusion:

Two manufacturing technology routes for breeding blanket modules were proposed, and the manufacturing technology, assembly technology and detection technology was researched and developed..

I. The full-scale WCCB module was successfully developed based on HIP technology.

II. Research on the integral forming technology of advanced steel components for small-scale blanket modules based on additive manufacturing technology has been carried out.

□ Considerations:

1. Materials issues (New structure materials, breeding materials,…)
2. Manufacturing issues (Deformation control, Larger scale facilities such as HIP furnace, 3D printer …)
3. Assembly issues (Qualification of weld, injecting of breeding materials…)
4. Standards for the HIP manufacturing technologies and additive manufacture (Pressurized vessel, Nuclear reactor...)

ASIPP

Thank you for your attention !