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Application and Development of C&S in Manufacturing of Breeding Blanket

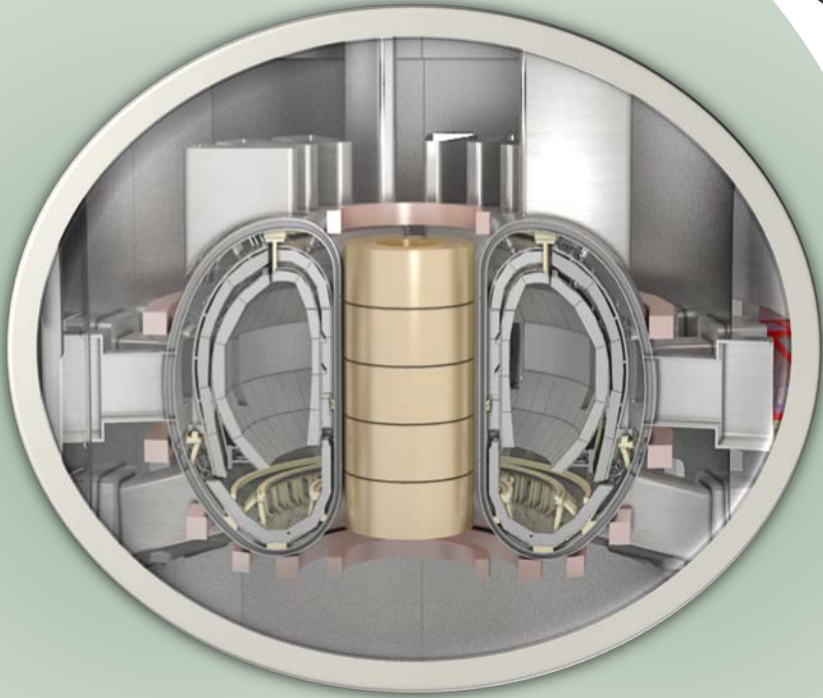
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Outline



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Introduction of Breeding Blanket

2

Application of C&S

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Development of Standards

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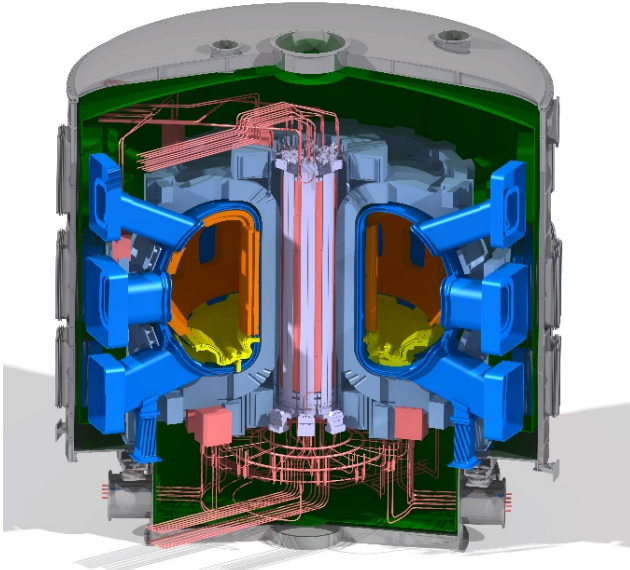
Issues and Challenges

5

Conclusion

1. Breeding Blanket-Devices

BEST and CFEDR have been designed to demonstrate tritium breeding technology.



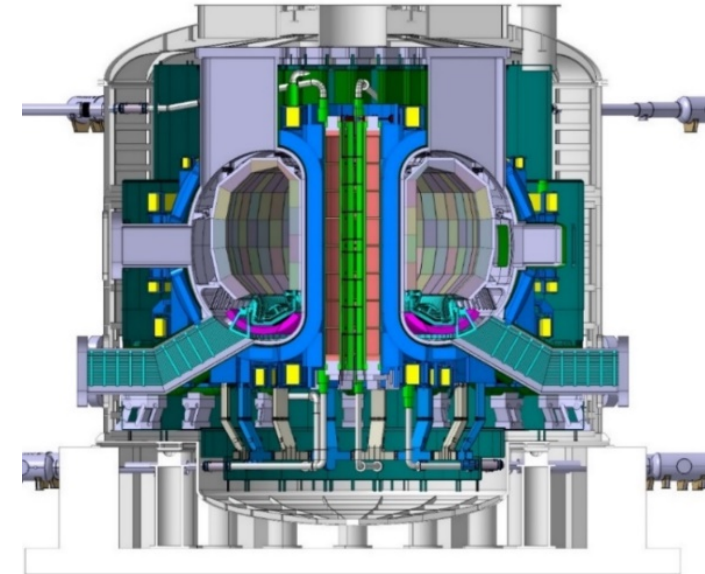
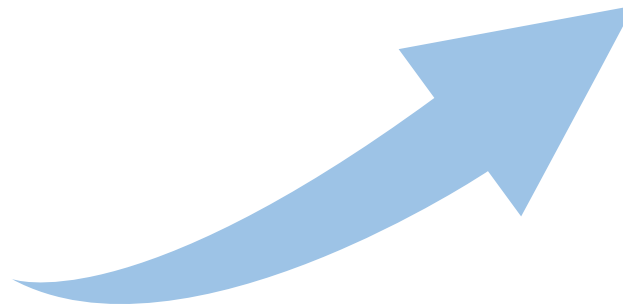
BEST configuration
($R=3.6\text{m}$, $a=1.1\text{m}$, 10-100MW)

❑ General objective:

Validate tritium breeding and energy extraction

❑ Test Blanket Module (TBM)

- Middle Port L: COOL-TBM
- Middle Port M: WCCB-TBM
- Module size: Tor.640mm×Pol.1000mm×Rad.800mm



CFEDR configuration
($R=7.8\text{m}$, $a=2.5\text{m}$, 0.2/0.5/1/1.5GW)

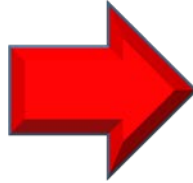
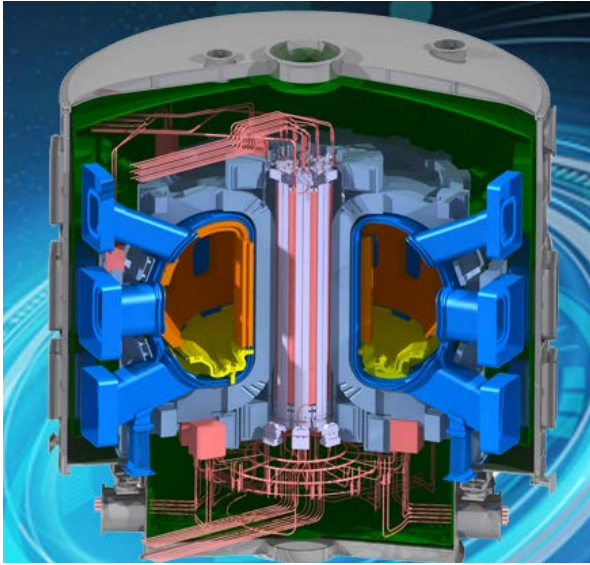
❑ D-T fusion reaction

- Power: 200-1500 MW
- SS operation: $Q=1-5$ @Phase I & $Q>10$ @Phase II

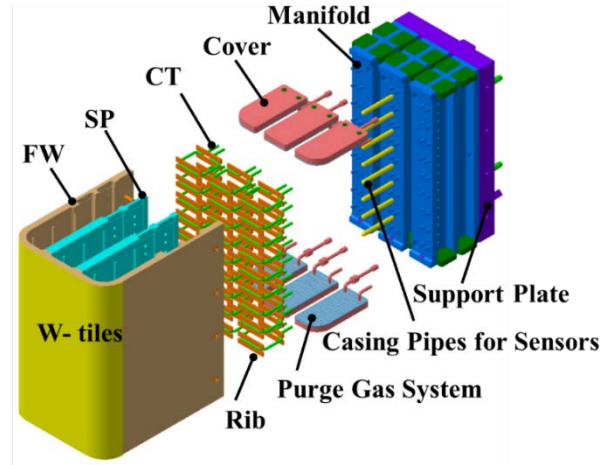
❑ Tritium Self-sufficiency (Real T-Breeding blanket)

- $TBR > 1$, T factory
- Licensing and safety

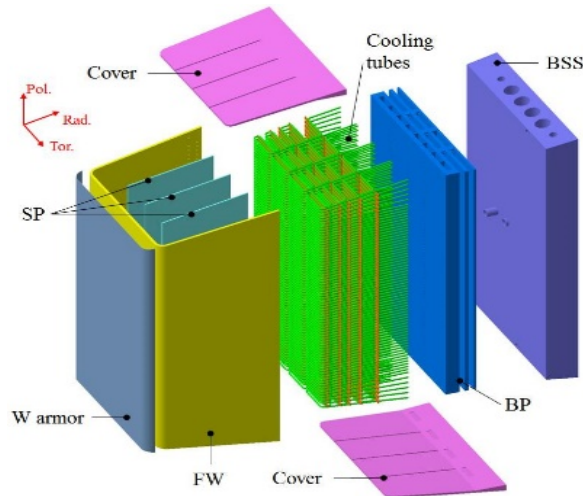
1. Breeding Blanket-Design



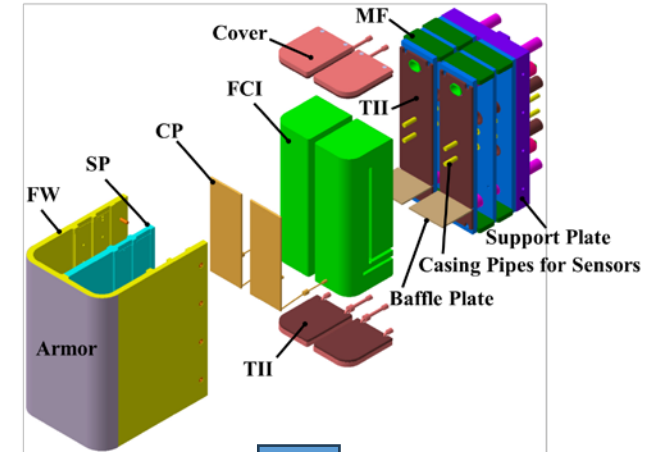
BEST-WCCB-TBM



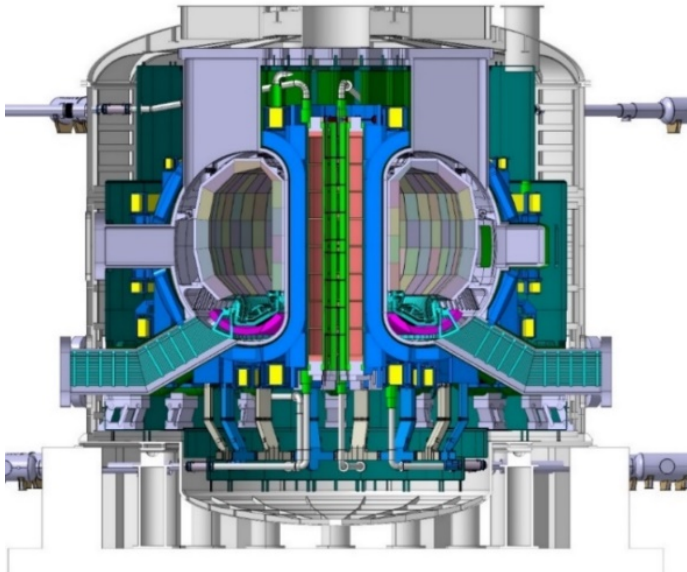
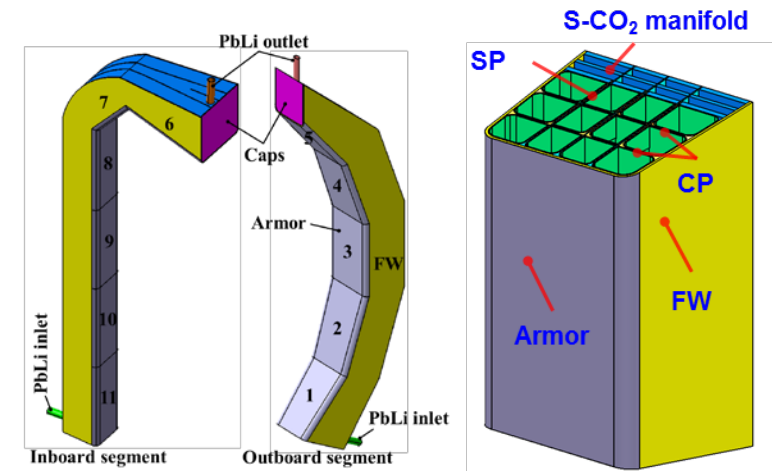
CFEDR-WCCB



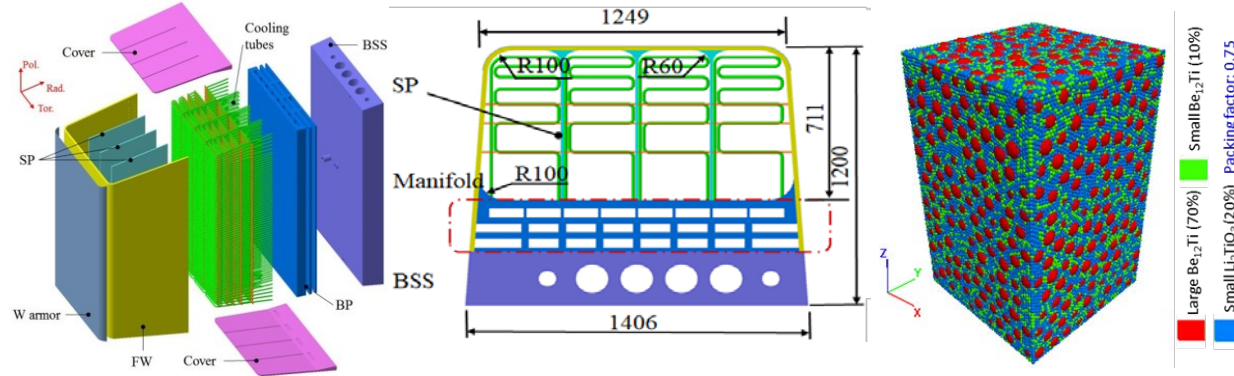
BEST-COOL-TBM



CFEDR-COOL

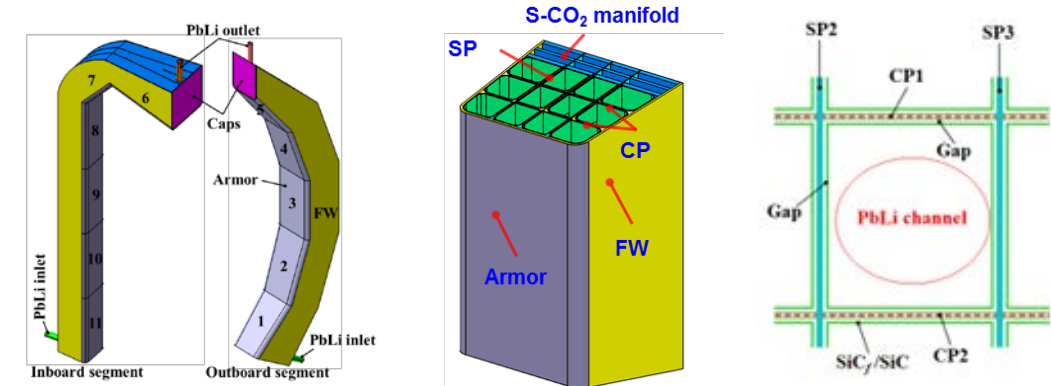


1. Breeding Blanket-Materials



Water-Coolant Ceramic Blanket (WCCB)

- **Coolant:** water at 15.5 MPa, 285 °C/325 °C
- **Structure materials:** RAFM steel
- **Plasma-facing Materials:** W--2mm
- **Breeder/multiplier:** $\text{Li}_2\text{TiO}_3/\text{Be}_{12}\text{Ti}$
- **Purge-gas:** 1-3 bar He + 0.1vol% H_2
- **Coefficient of thermal efficiency:** ~ 33%



S-CO₂ Cooled Lithium-Lead (sCO₂-COOL)

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

2. Application of codes and standards

During the development of the blanket module, we need to refer to many standards.

Here we will show some application experience of C&S in the manufacturing of WCCB module.

- **Funded: Chinese National Program for the Development of Magnetic Confinement Nuclear Fusion Energy (Fund Nos:2017YFE0300604, 10700000 RMB)**

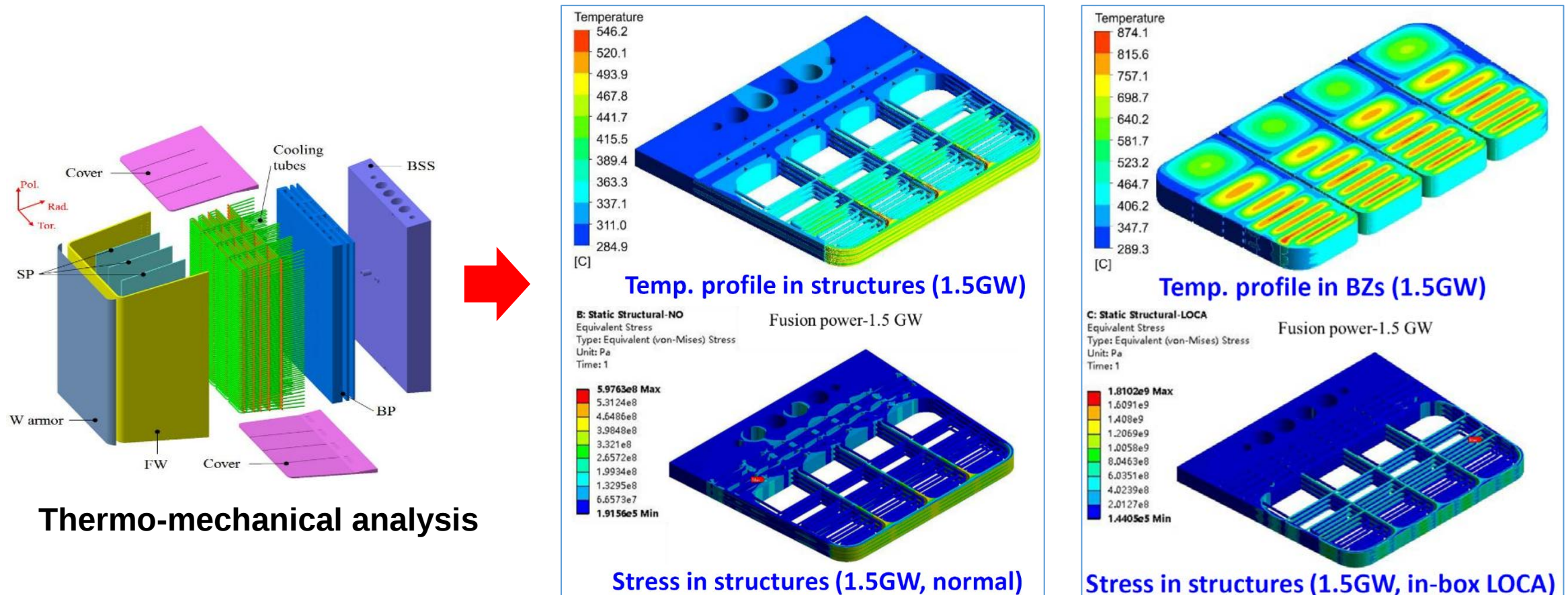
Main Task	Technical indicators*	Requirement value
❑ R&D of the key connection technologies for WCCB module. ❑ Complete the design, manufacturing and assembly of WCCB prototype module. ❑ Complete the prepare a full-scale WCCB prototype module.	Dimension of module	1.2 m (P)× 0.95 m (T) × 0.8 m (R)
	High heat flux loading of FW	1000 cycles @1 MW/m ²
	Pressure test of channel	≥18.6 MPa (1.25P @ GB/T 150)

Note: This project only sets three technical indicators.

2. Application of codes and standards

■ In the structural design of the WCCB module, two codes were referred to.

- Structural Design Criteria-In-vessel Component (SDC-IC 222QGL) / RCC-MRx



The material temperature and stresses are all below limits under normal & LOCA, satisfying ITER SDC-IC code. 7

2. Application of codes and standards

■ Fabrication of RAFM steel in WCCB components

- Standards: GB/T 38875-2020 (CLAM), EJ/T 20242-2020 (CLF-1), (Certification is underway)

	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/°C	R _{p0.2} /MPa	R _m /MPa	A/%	KV ₂ /J	Strain/MPa	Cracking time
R.T	≥510	≥600	≥18	≥200		
450	≥400	≥450	≥18			
550	≥310	≥350	≥18		185	≥10000h
600	≥230	≥300	≥18		135	≥1000h

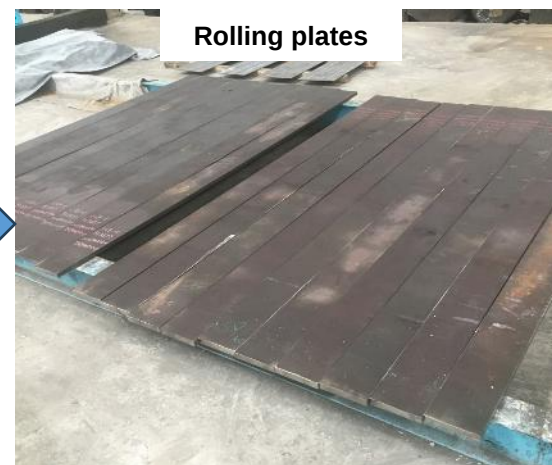
Vacuum consumable melting
Electroslag redissolution



Forge and press



Rolling plates

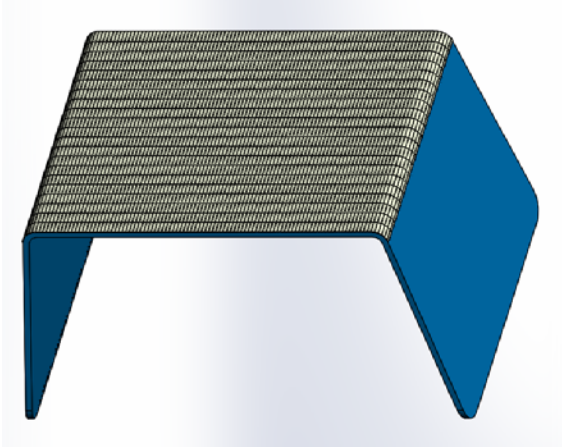


Rolling tubes



2. Application of codes and standards

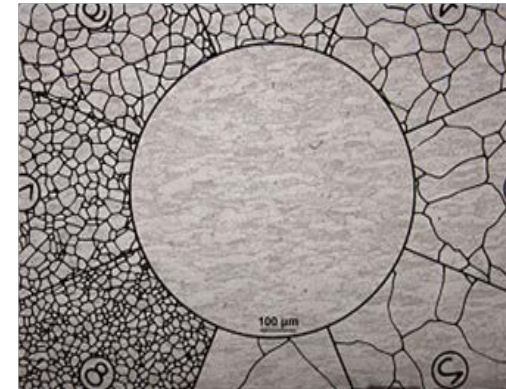
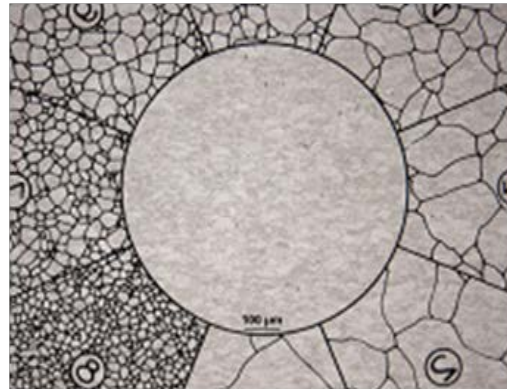
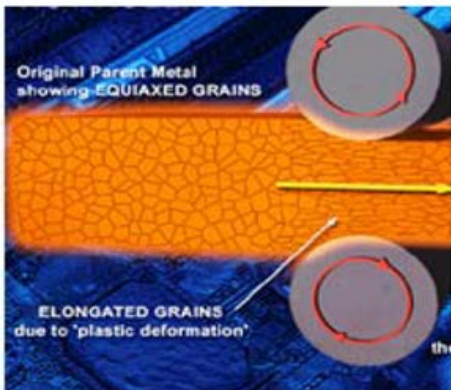
FW with W tiles



- ❑ **Technical Specification of W plates**
- ❑ Ref: ITER_D_2EDZJ4 v1.3, T/CITS 433
- Purity: 99.95 wt%
- Impurity content(C, O, N, Fe, Ni, Si): 0.01 wt%;
- Density(ASTM B311): $\geq 19.0 \text{ g/cm}^3$
- HV30(ASTM E92): ≥ 410
- Microstructure: Grade 3(ASTM E112)

❑ Preparation process

- ✓ Sintering: 2000°C
- ✓ Rolling: $1100\text{--}1300^\circ\text{C}$,
- ✓ Reduce rate: $\sim 70\%$
- ✓ Annealing: 1100°C



Warm rolling

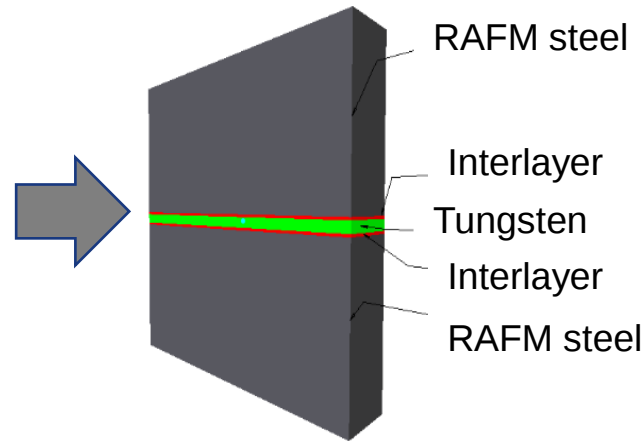
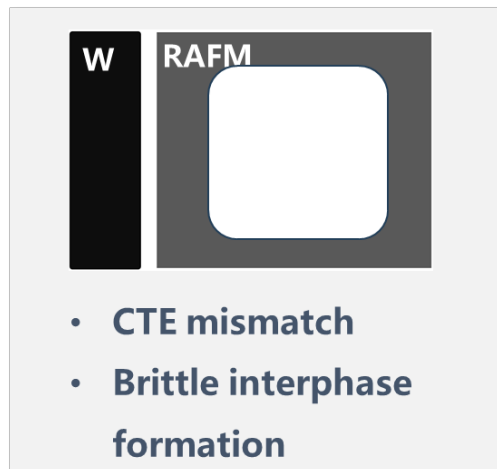
Microstructure: Anisotropic and better than grade 4

Mass production of W plates

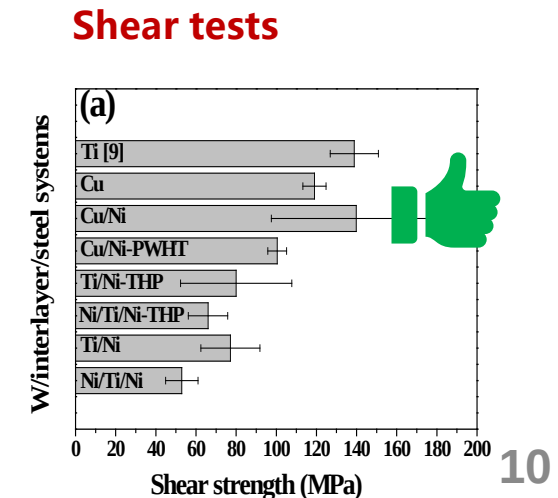
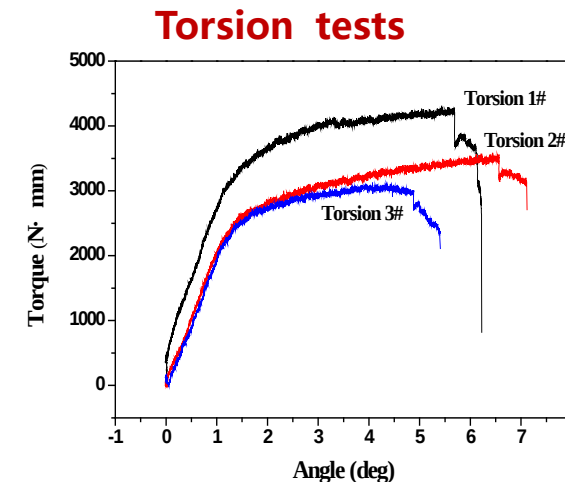
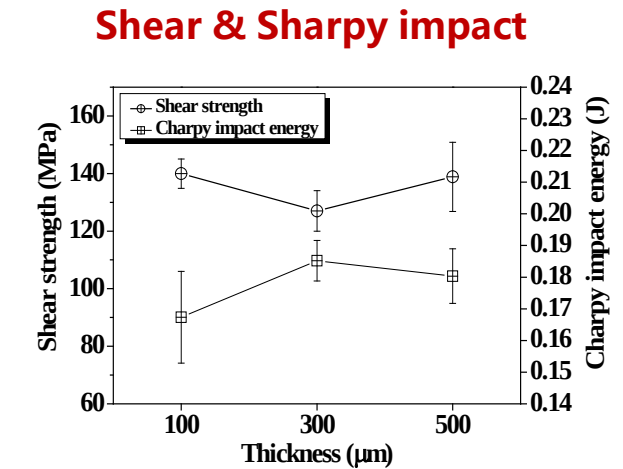
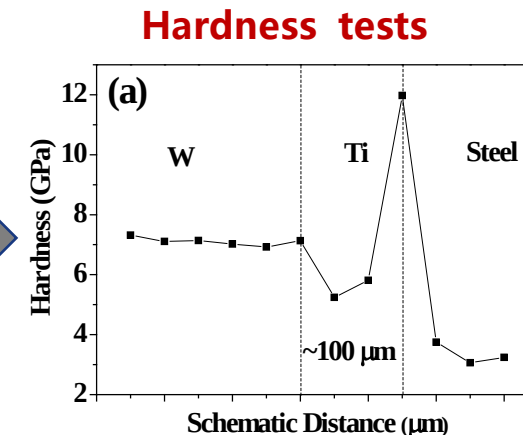
2. Application of codes and standards

■ Development of W/RAFM steel bonding process in WCCB-FW components

Referred Standards: ASTM E92 (hardness); GB/T 228.1(tensile), GB/T 229-2020 (Charpy impact)



HIP



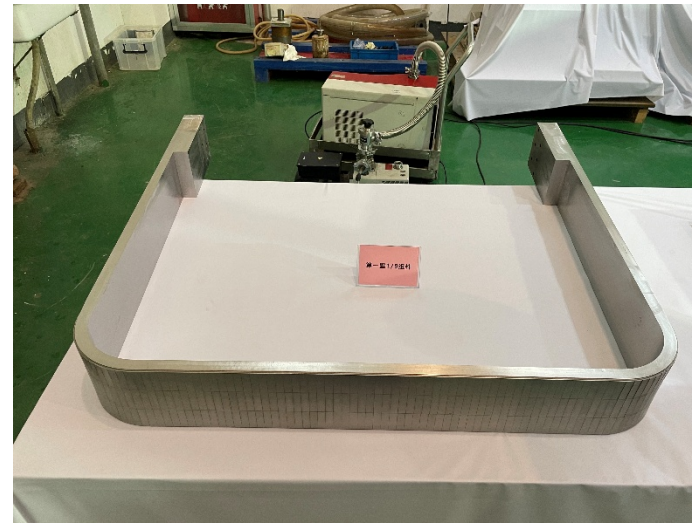
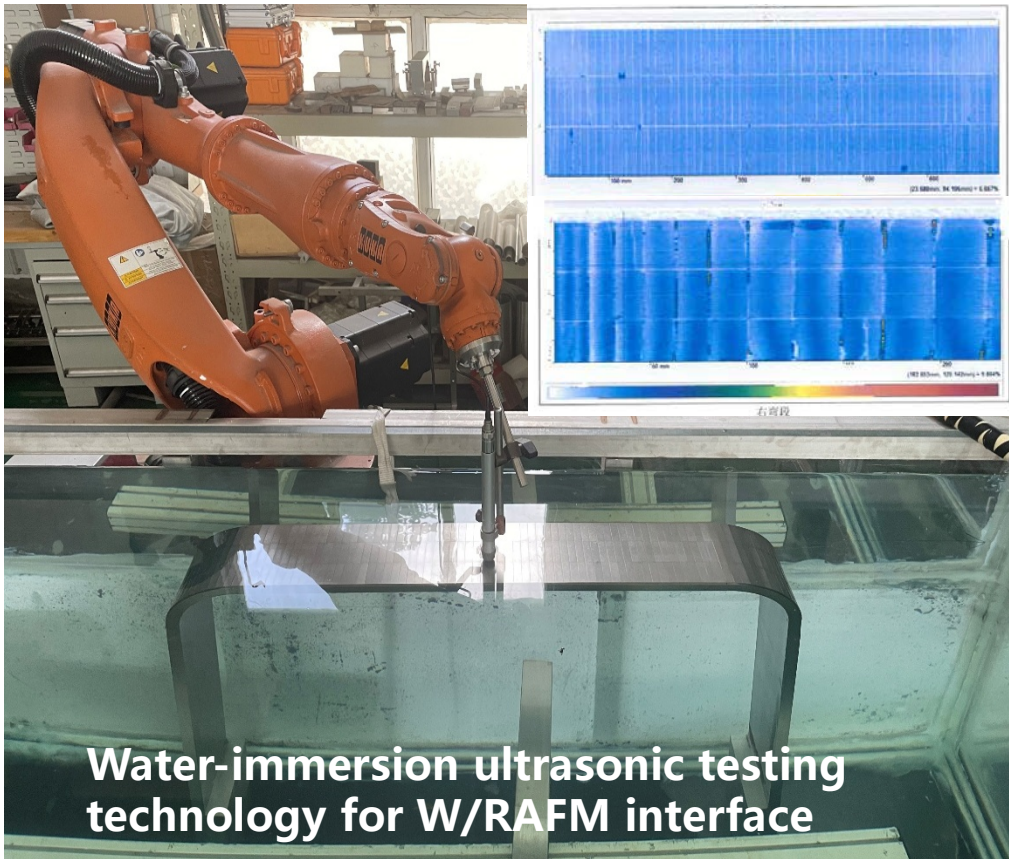
We achieved high-strength bonding of W-steel and fabricated multiple W/RAFM mockups.

2. Application of codes and standards

❑ Qualification control for W/RAFM and RAFM/RAFM bonding in manufacturing of FW

W/steel bonding quality: Ultrasonic test (GB/T 23912/ASTM E214-01, sensitive: $\phi 2\text{mm}$)

Pressure of cooling channel: Hydrostatic press test (GB/T 150.1-150.4, $P_t=1.25 P$)



$$p_T = 1.25 p \frac{[\sigma]}{[\sigma]_t}$$

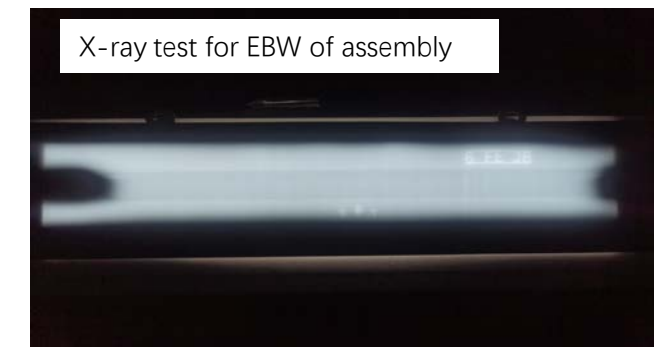
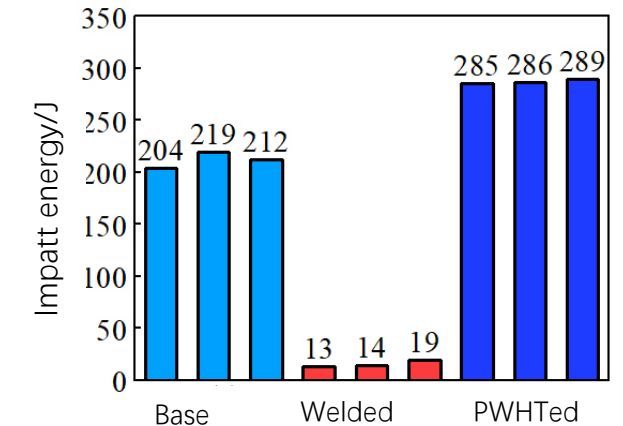
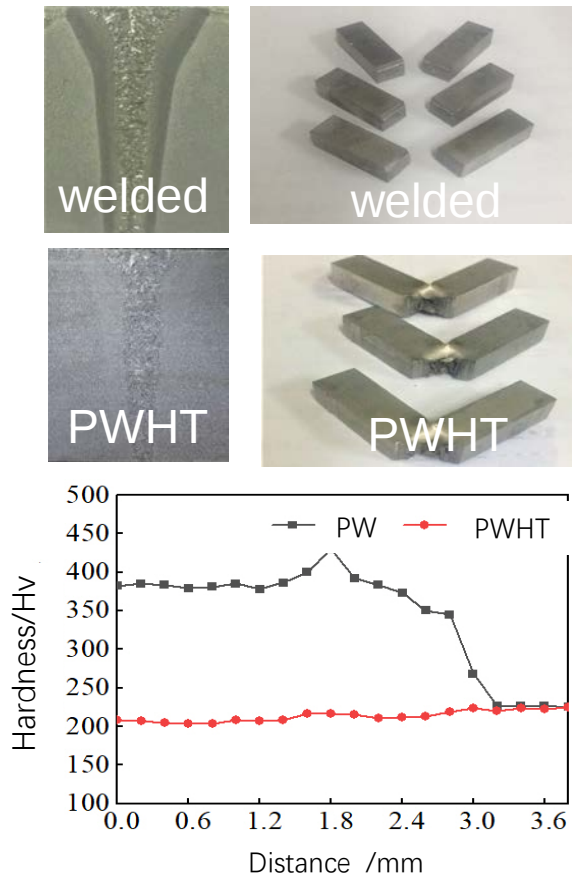
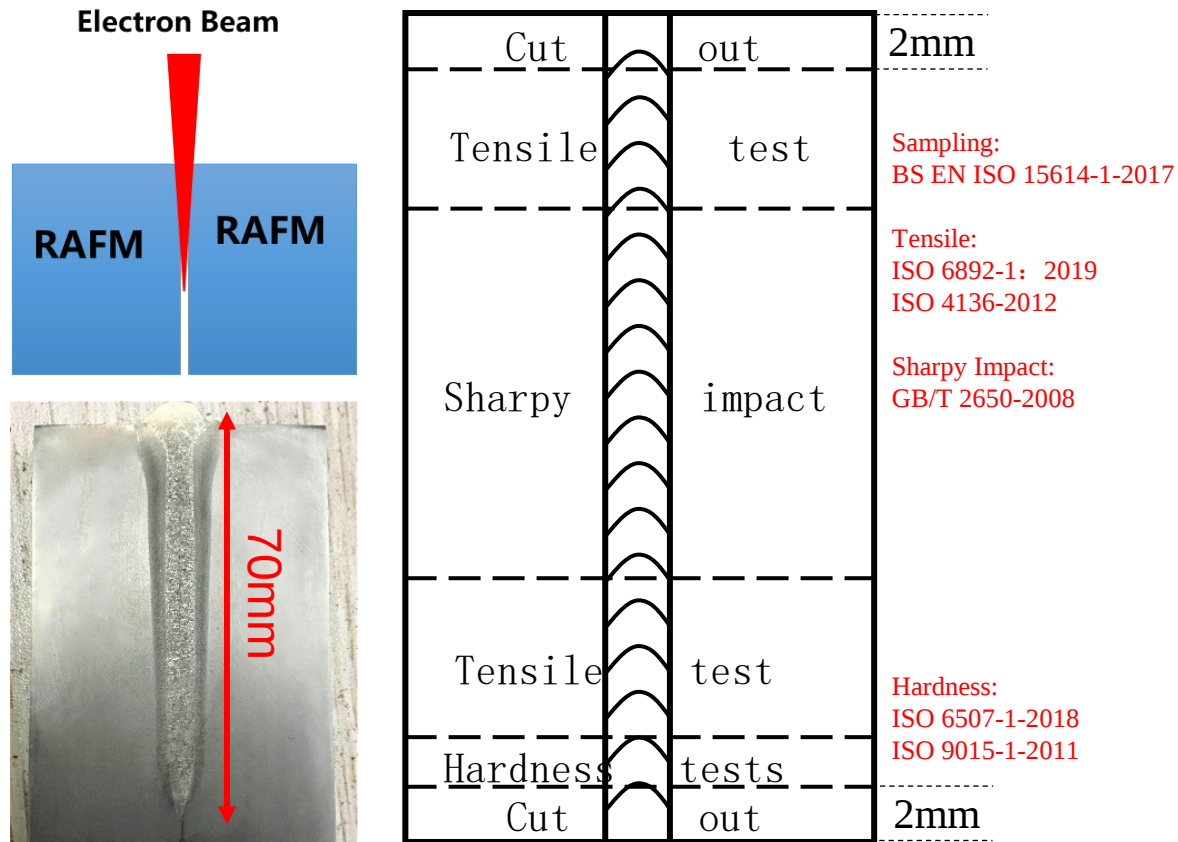
Hydrostatic pressure
@20MPa

Vacuum helium leak
detection



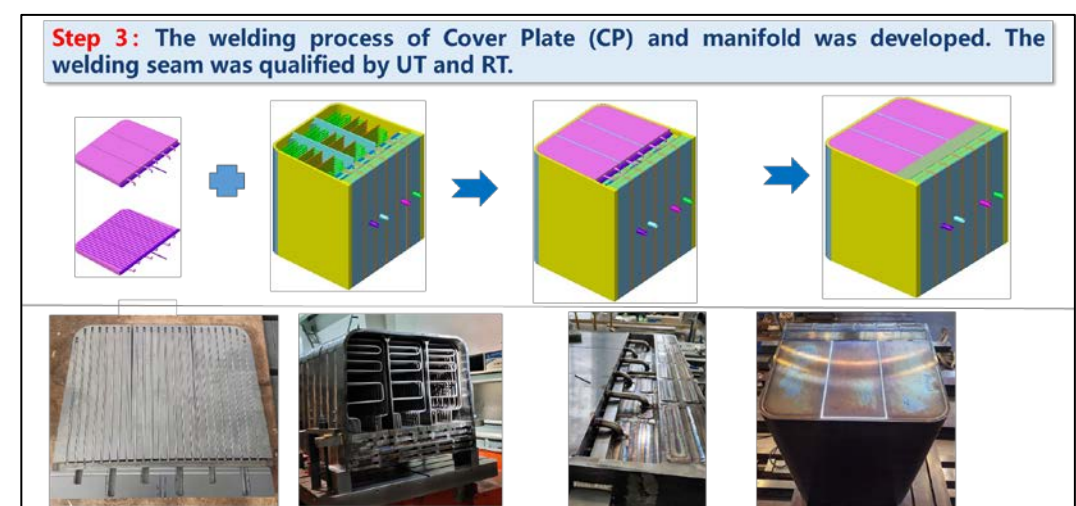
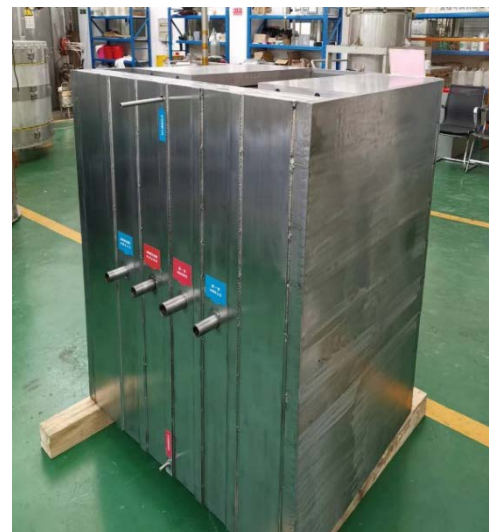
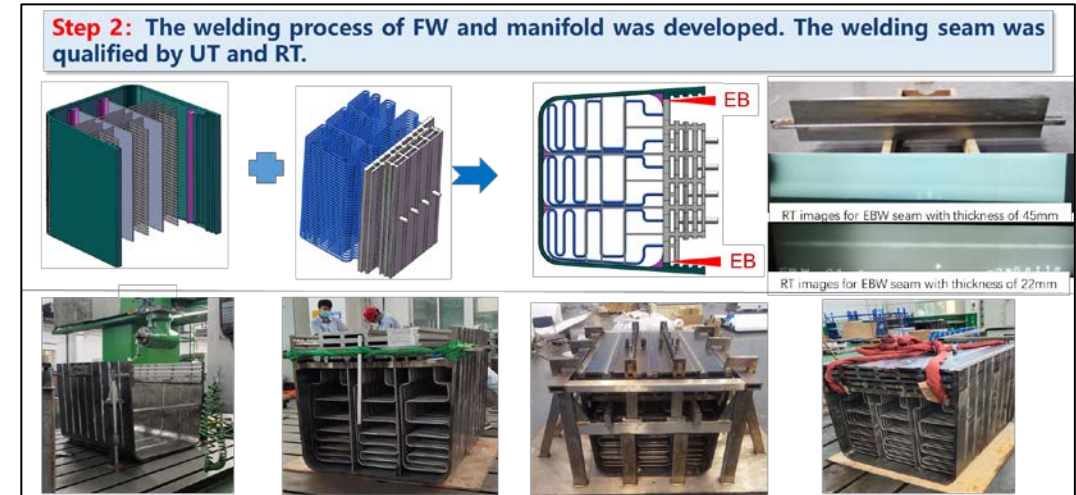
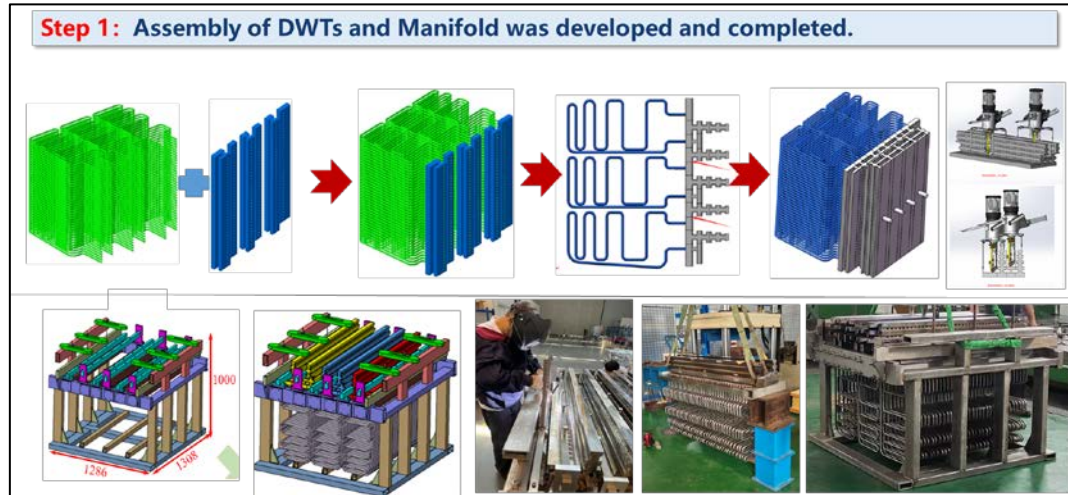
2. Application of codes and standards

- ❑ To qualify the weld process, some tests and studies were conducted according to the following standards.
- ❑ During the assembly stage, some non-destructive tests were carried out according to standards: GB/T 29710 and NB/T 47013.2.



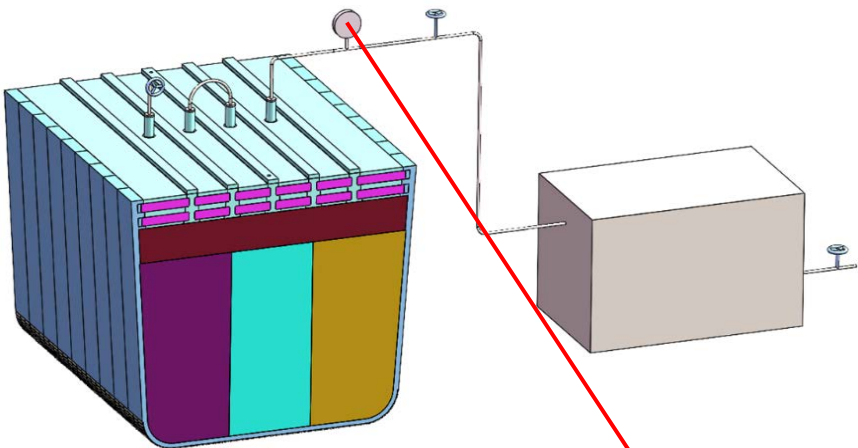
2. Application of codes and standards

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



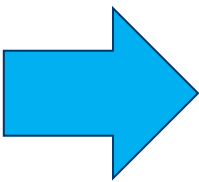
2. Application of codes and standards

□The final pressure tests have been carried out for pressure equipment (GB/T 150).



Test procedure:

- ① Negative pressure leak detection.
- ② Static water pressure test (all the channel),
- ③ Gradually increase the pressure step-by-step, maintaining the pressure for 5 minutes with step of 2 MPa increase.
- ④ At 18.6 MPa, maintain the pressure for 20 minutes.



Tests	Requirement	Measurement
Pressure	≥ 18.6 MPa	18.7 MPa

2. Application of codes and standards-summary

- Referred to some standards, we have explored the manufacturing and assembly techniques of full-scale WCCB prototype module.
- The successful manufacturing of the full-scale prototype module indicates the feasibility of the present technical route.
- There are still many issues to be solved to achieve the manufacturing of real tritium breeding blankets.
- Only a rough external dimension inspection and a pressure test for the coolant channels has performed..

Testing items	Present Requirements	Measurement results	Real Requirement
HHF test	1000cycles @1 MW/m ²	1.12 MW/m ²	10000cycles @1 MW/m ²
Pressure test	≥18.6 MPa	18.7 MPa	30 MPa
Dimension test	≥1.2 m×0.95m×1.0m	1.2 m×0.95m×1.1m	Error precision: mm
MPH, WPS, NDT.....			

- ❑ However, as a nuclear-grade pressure equipment, the tritium breeding blanket module requires more inspections to ensure it could be used in the fusion reactor.
- ❑ A set of inspection items should be set up according to the technical specifications and codes.

3. Development of standards

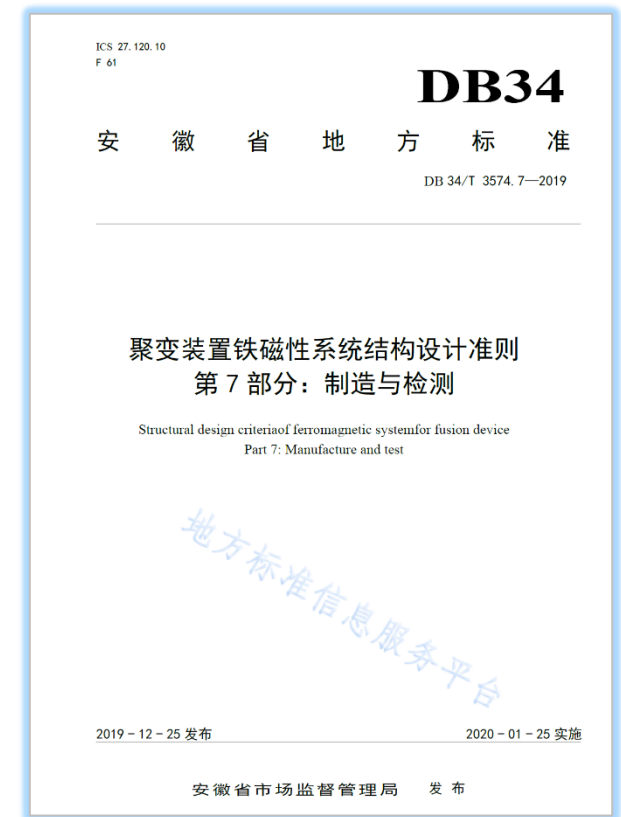
- During the manufacturing of WCCB prototype module, some national standards have been developed to control the quality of component.
- Firstly, a serial of local standards have been worked out for the designing based on some codes, including the ITER SDC-IC and RCC-MRx.

Local Standard Title:

DB34T 3574-2019 Structural design criteria of ferromagnetic system for fusion device

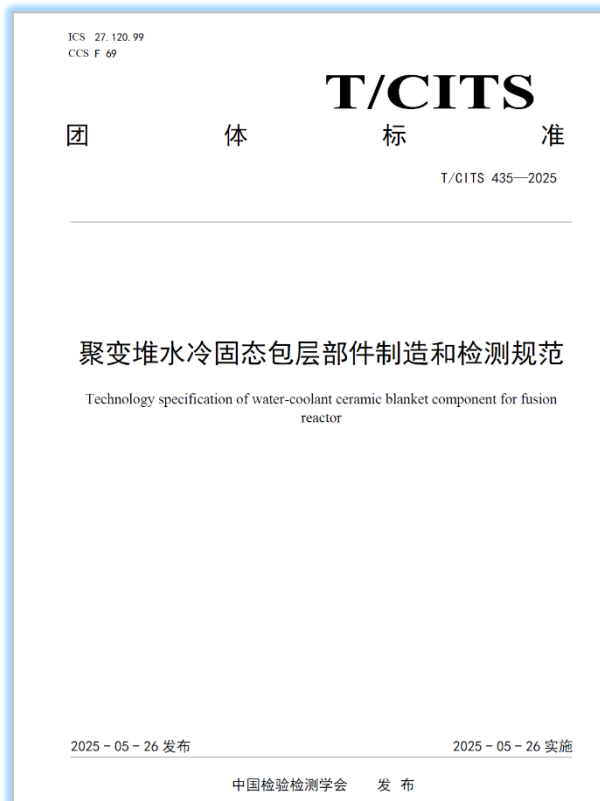
Standard contents:

Part 1: Intergrated design	Part 2: Blanket system
Part 3: Divertor system	Part 4: Pipeline system
Part 5: 3Sm regulation	Part 6: Fatigue life evaluation method
Part 7: Manufacture and test	Part 8: Irradiation shield



3. Development of standards

- In order to standardize the procurement and manufacturing technologies, we have developed a group standard for the WCCB prototype module.
- **Group Standard:** T/CITS 435-2025 Technical specification of water-coolant ceramic blanket components for fusion device



Standard contents:

- Structure design
- Manufacturing technology
- Technical requirement
- Inspection method
- Inspection regulation
- Inspection report and so on.

Contributions:

ASIPP、AT&M、Juneng、SCU、TBZH

3. Development of standards

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Standard contents:

- Structure design
- Manufacturing technology
- Technical requirement
- Inspection method
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- Inspection report and so on.

Contributions:

ASIPP、AT&M、Juneng、SCU、TBZH

5.1 The main manufacturing processes of the water-cooled blanket should meet the following requirements:

- a) First Wall: The tungsten tiles is welded to the steel material surface by hot isostatic pressing (HIP) or brazing technology.
- b) DWT: The inner and outer tubes are assembled together and the three materials are joined by HIP technology.
- c) Cover plate: First, the flow channels inside the cover plate are formed by HIP technology.
- d) Manifold: It is completed by mechanical processing combined with electron beam welding.
- e) Grid plate: It is completed by mechanical processing.
- f) Assembly: The parts are assembled in sequence and welded into a whole by electron beam welding and argon arc welding.

3. Development of standards

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Standard contents:

- Structure design
- Manufacturing technology
- Technical requirement
- Inspection method
- Inspection regulation
- Inspection report and so on.

Contributions:

ASIPP、AT&M、Juneng、SCU、TBZH

Parts	Join/Weld	Function	Weld Process	Grade
First wall	W/Cu	Heat transfer	HIP/Braze	I
	Cu/Steel	Heat transfer	HIP/Braze	I
	Steel/Steel	Heat transfer +Pressure	HIP	I
Cooling tube	Steel/Steel	Heat transfer +Pressure	HIP	I
Cover plate	Steel/Steel	Heat transfer +Pressure	HIP	I
Manifold	Steel/Steel	Pressure+support	EBW	II
FW/Manifold	Steel/Steel	Pressure+support	EBW	II
FW/CP	Steel/Steel	Pressure+support	EBW	II
MF/DWT	Steel/Steel	Pressure+support	TIG	II
FW/GP	Steel/Steel	Support	TIG	III
MF/GP	Steel/Steel	Support	TIG	III

According to the different functions of welds in the component, the welds have been classified and managed.

4. Issues and challenges

Requirement For Breeding Blanket	Nuclear pressure equipment(RCC-MRx 2022 & GB/T 16702-2025 PWR)					
	Design	Materials			Bonding /welding	
		RAFM	Breeder	Others	Process/Tech	Qualitification
Technical Readiness Level	TRL-3/6: Engineering design	TRL-3/6: CLAM; CLF-1 (5 tons)	Li2TiO3 pebbles	Multiplier; Shield TP-Barrier	TRL-3/6: W/Steel-HIP; RAFM-EBW&TIG	TRL-3/6: UT,CT,RT, Pressure test.
Issues/ challenge	Codes-Fission Class 2?	MPH@ HT and n-irrad. PWHT Standardize	/	/	Mechanical properties; Multiple PWHT	Inspectable; Instruments; HHF test
To do	Code revision Final design review	HTM development Certification			WPS (weldability, inspectable)	Weld structure design
New progress	BEST-TBM	LA-IPF, AH steel			LPBF-AM	

The TRL assessment indicates that there are still many issues (technical and standardize) to be addressed for the manufacturing of the breeding blanket module as nuclear pressure equipment.

4. Issues and challenges-**BEST TBM**

BEST Construction Phase	2022				2023				2024				2025				2026				2027			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Conceptual Design																								
Engineering Design																								
R&D of Material /Components /Subsystems																								
System Fabrication & Testing																								
System Assembly																								

- ❑ In the BEST-TBM research and development plan, we aim to complete the manufacturing of Test breeding blanket module by next year.
- ❑ However, when we were formulating the technical specification document, we discovered that it is difficult to set specific requirements because of lack of materials property data.
- ❑ It will be very difficult to complete them within one year because of the lack of specific standard.

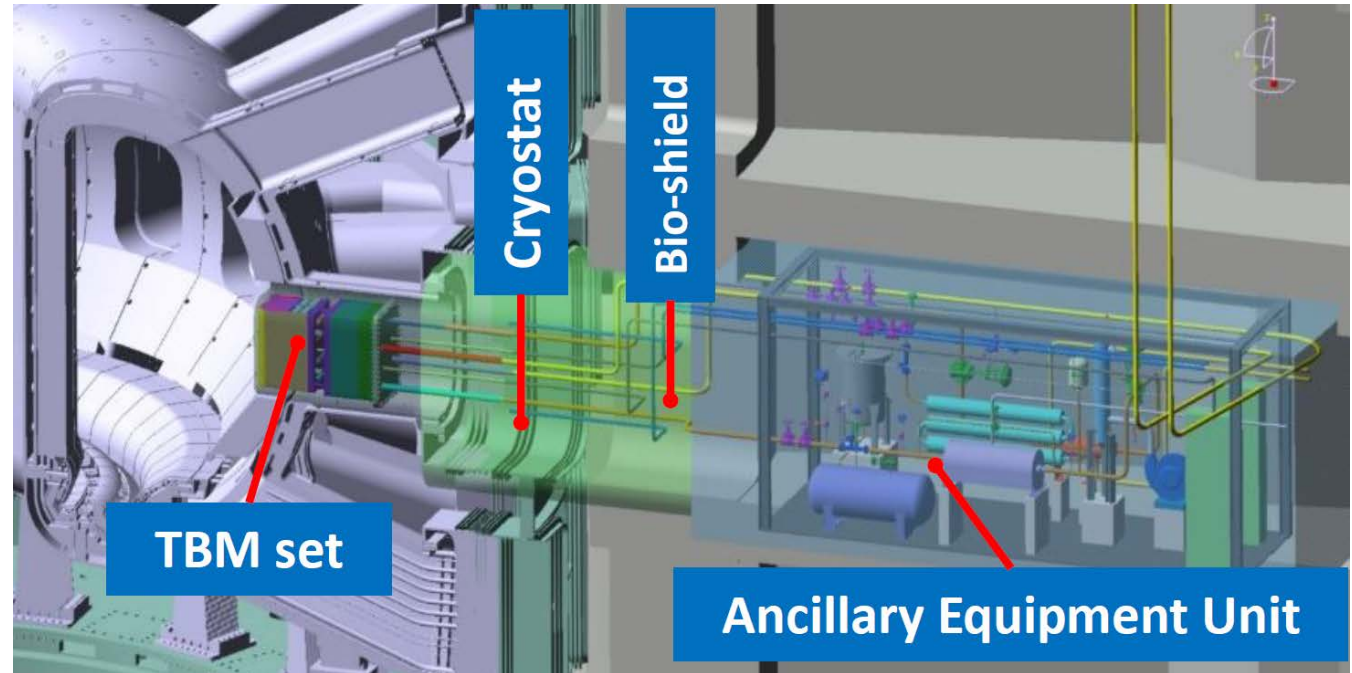
4. Issues and challenges-**BEST TBM**

Operation condition:

- DT fusion power: 10~40MW
- Burning time/cycle time: 1000s/pulse@40MW
- Neutron Wall Loading: 0.17MW/m^2 @40MW
- FW plasma heat flux: 0.3MW/m^2 @40MW

Test Plan:

- EM-Test: Electromagnetic Test
- N-Test: Neutronics Test
- T-Test: Tritium-operating Test
- TM-Test: Thermal Hydraulic/MHD Test

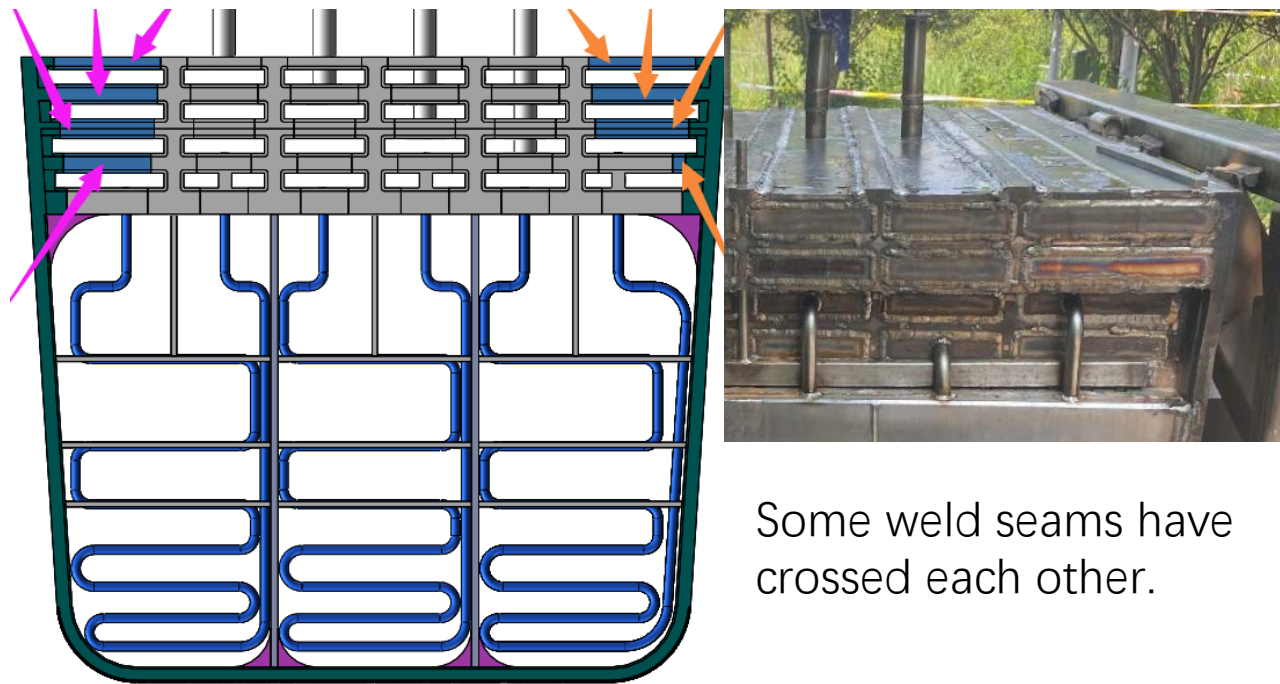


- ❑ **BEST is an experimental fusion device. So, does the TBM module need to be regulated according to the Codes of a nuclear-grade pressure vessel?**
- ❑ **Which class of pressure vessel should be followed? N2 @RCC-MRx, A2? @GB/T 16702-2025**
- ❑ **It is necessary to start the selection of RAFM steel as soon as possible: Industrial production, MPH and certification, then Weld structure design and validation**
- ❑ **Weldability of RAFM steel: Weld procedure specification, witness of certification**

4. Issues and challenges-Additive manufacturing

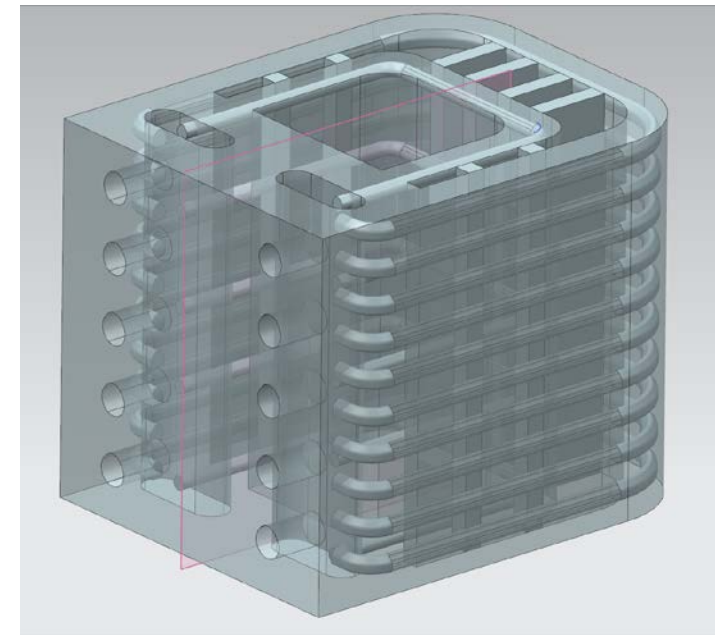
□ With respect to the difficulty and complexity of the conventional manufacturing technology route, the new additive manufacturing route has been proposed to simplify the structure design and manufacturing process, especially to reduce welding.

Conventional manufacturing route



Some weld seams have crossed each other.

Additive manufacturing route

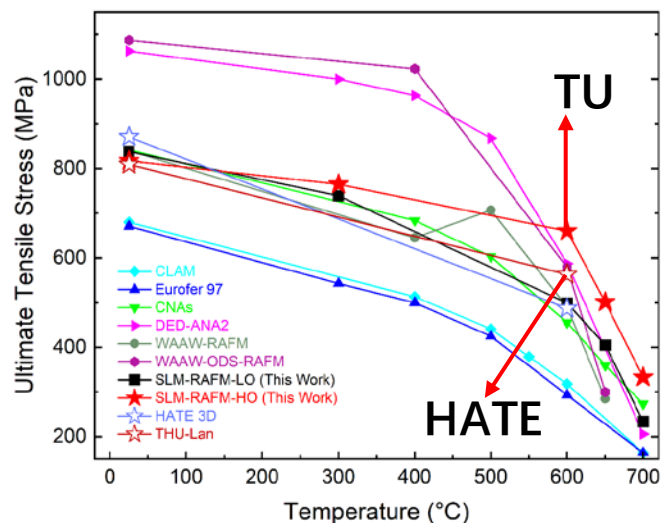


The application of additive manufacturing technology could greatly simplify the structural design and manufacturing process.

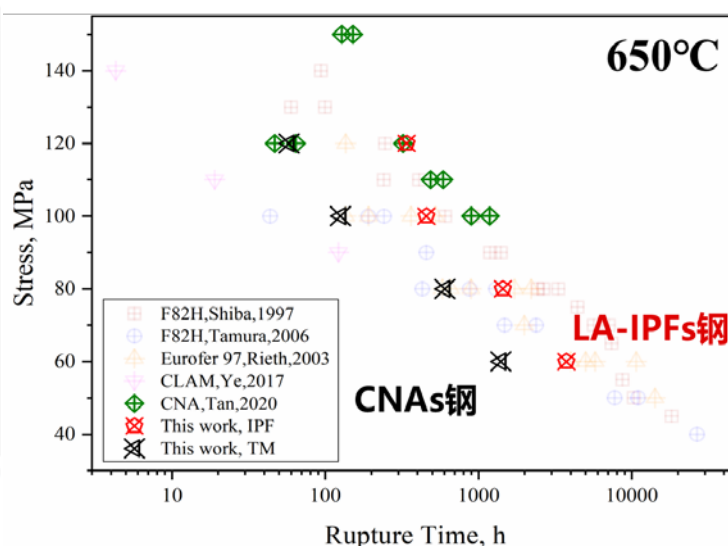
4. Issues and challenges-Additive manufacture

- ❑ The biggest problem is the lack of material qualification for the additive manufactured RAFM steel.
- ❑ To meet the requirements, the standardization of material composition design, preparation process, and performance test should be performed, including performance tests before and after irradiation and thermal stability.

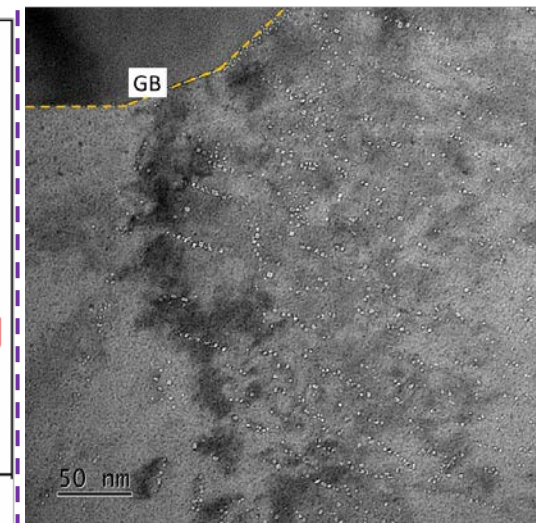
Tensile tests



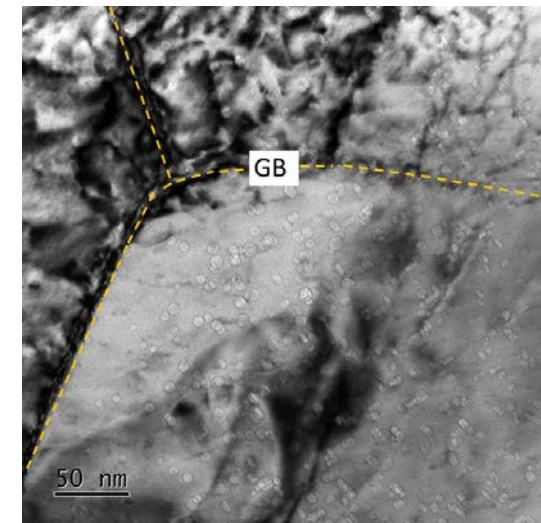
Creep tests



He-Irrad. @450°C



He-Irrad. @650°C

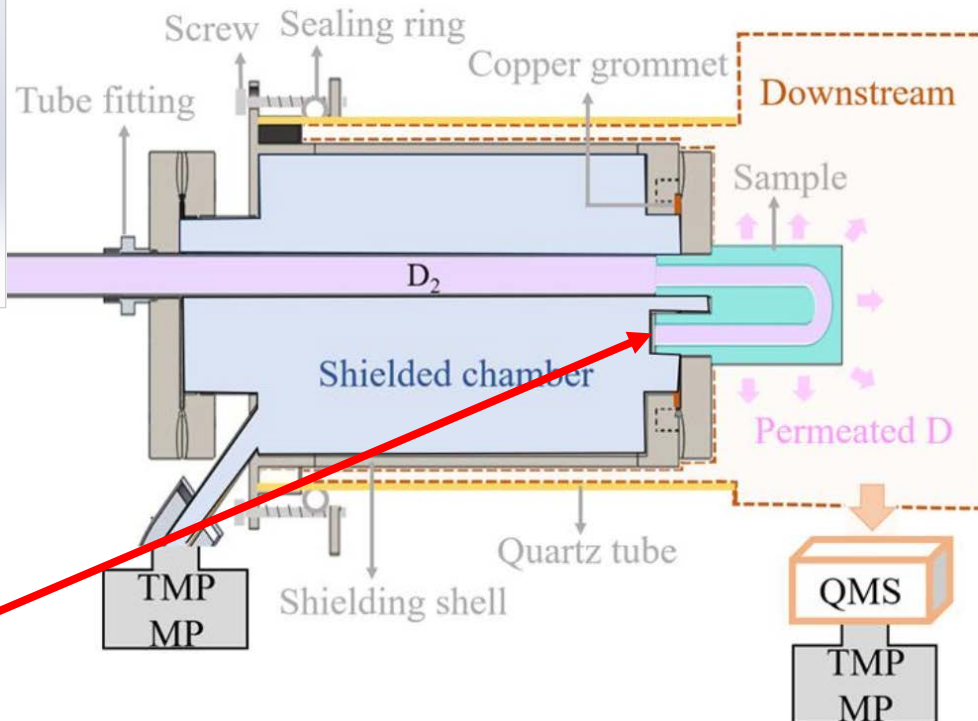
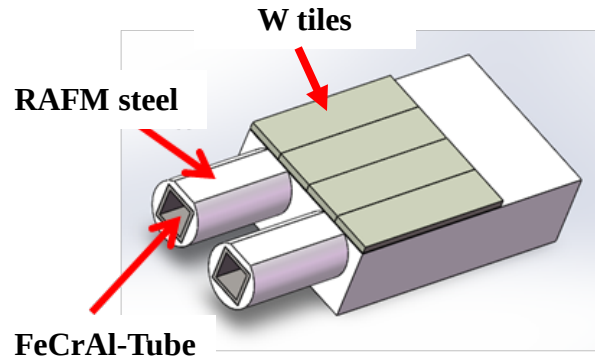


The strength properties have been reproduced on the different equipments in the factory, demonstrating the effectiveness of the material preparation process.

S. Zhang, et. al., Scripta Materialia 235 (2023) 115627)

4. Issues and challenges-Hydrogen permeation

- ❑ Preventing tritium from penetrating into the cooling water is a problem to the water-cooled blanket module, and it is also an important performance indicator that distinguishes it from the pressure vessel of a fission reactor.
- ❑ However, at present, there are still no corresponding standards and regulations to refer to.



Issues:

- ❑ Sample preparation
- ❑ Test method
- ❑ Test instrument
- ❑ Test pressure
- ❑ Water condition
(temperature\pressure)
- ❑ Requirements value

5. Conclusion and considerations

■ Conclusion:

Based on the application of multiple standards, we have successfully completed the manufacturing of full-scale WCCB prototype module to demonstrated the feasibility of these processes route.

However, it was also discovered that there are still many issues (technical and standardize) that need to be addressed. The development of the real tritium breeding blanket module is still at an early stage.

■ Considerations:

Technical Challenges

- Manufacturing route (HIP or Additive manufacture)
- MPH preparation of RAFM steel (no-irrad. &irrad.)
- Weld/Bonding (WPS, deformation control)
- NDT technology development (design inspectable)
- Larger facilities construction

Standardization issues

- Level of pressure equipment (Class 1 or 2)
- Class of Welding joint (pressure boundary)
- Test data and standard experiences
- Standards for New welding and manufacturing
- Standards of new test items (HHFT, TPB...)

Thank you for your attention !

