中核集团 CNNC
核工业西南物理研究院 Southwestern Institute of Physics

Design, Development and Safety Study of DEMO HCCB Breeding Blanket System

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Overview of HCCB TBB development

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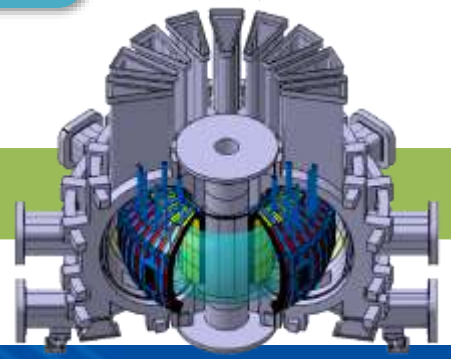
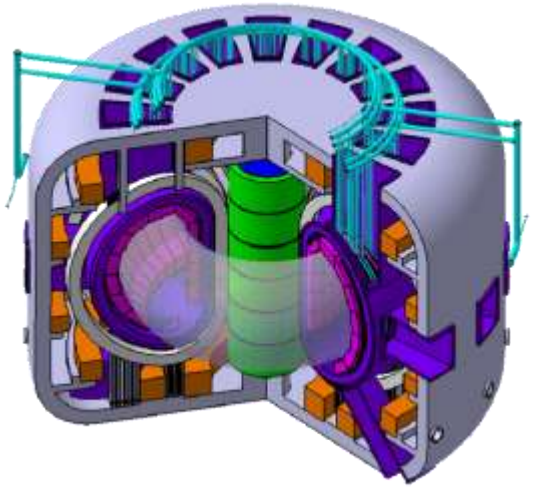
CFETR and DEMO HCCB TBB design

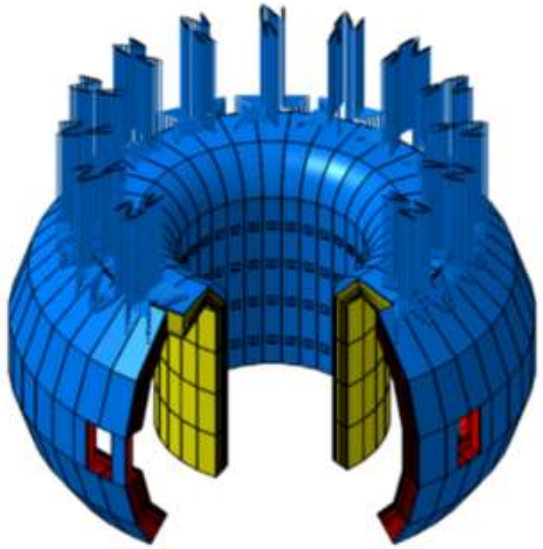


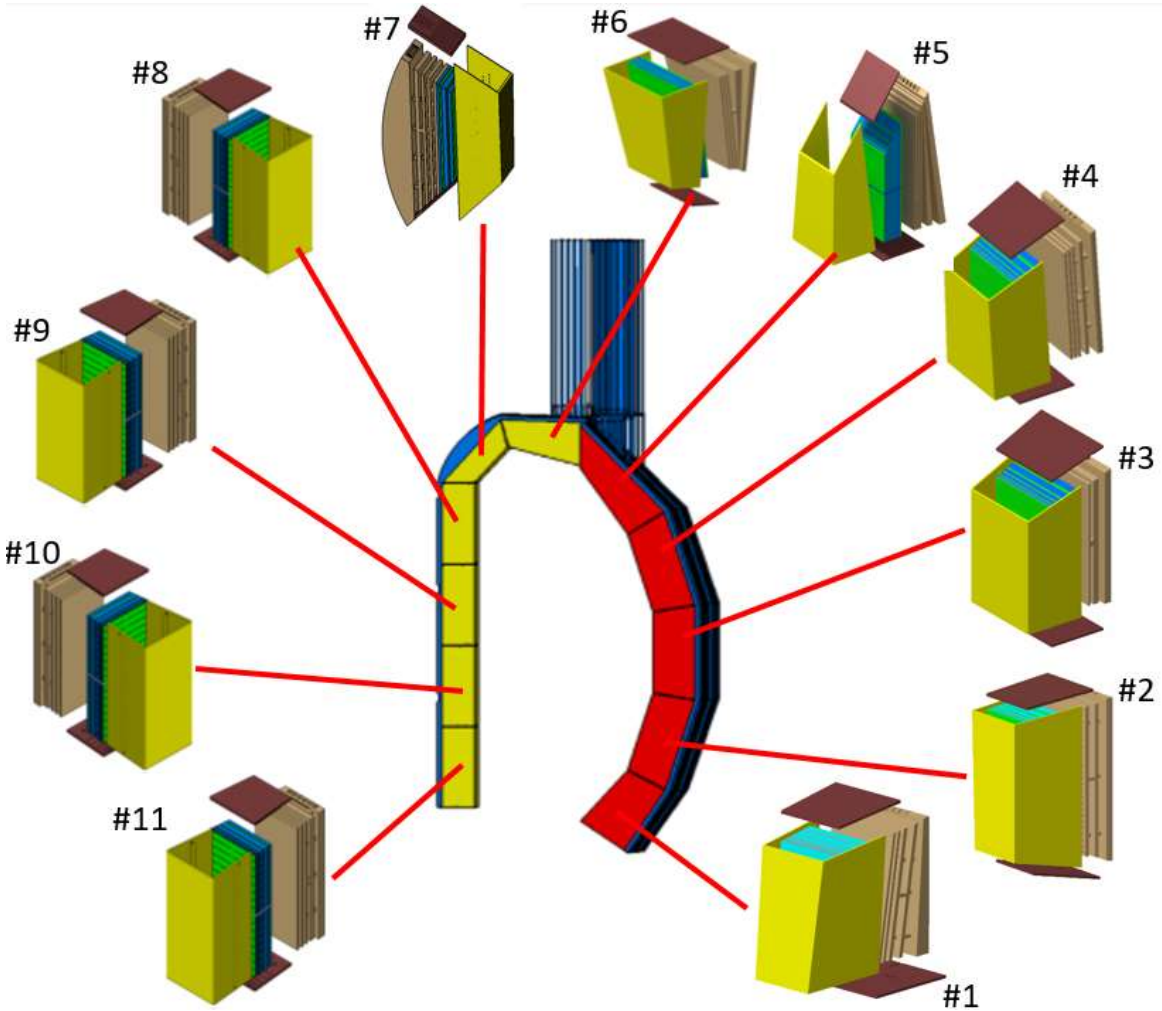


DEMO Realization

2 Design and safety Analysis of CFETR HCCB TBB

CFETR HCCB TBB Design





HCCB TBB configuration

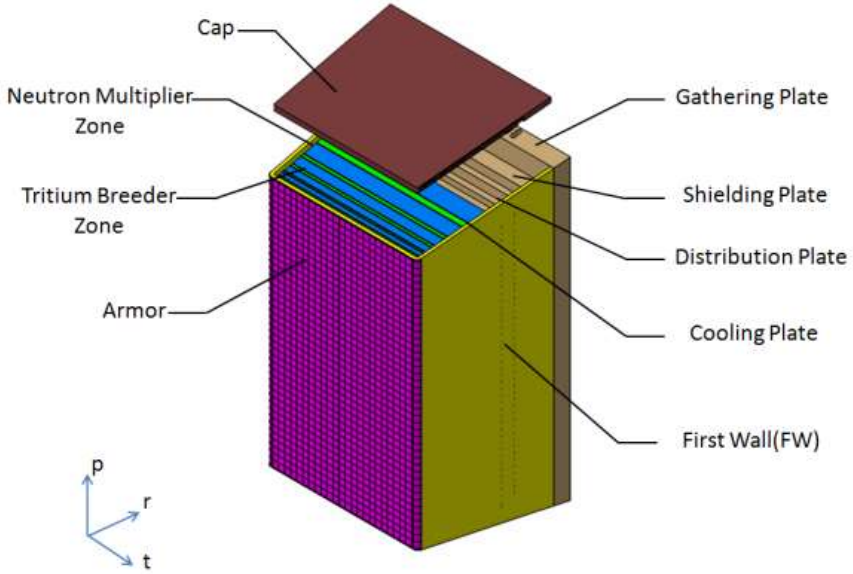
- “Banana” segment design compatible with RH
- 5 segments per sector: 2 for inboard,3 for outboard . Poloidal gap and toroidal gap: 20mm

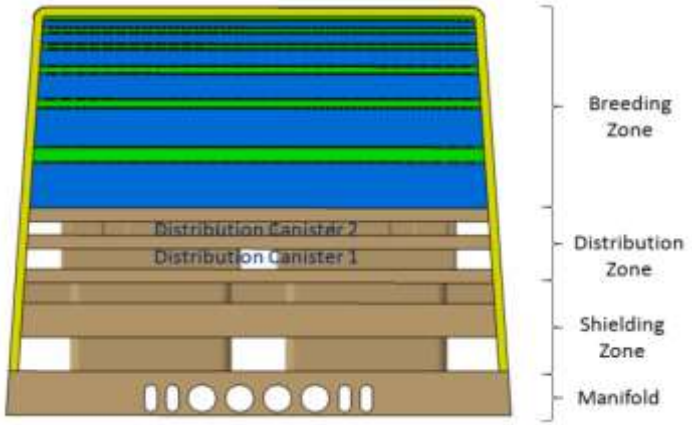
Total

- 16 sectors
- 80 segments
- 432 blanket modules
- ~5000 tons

CFETR HCCB TBB Design

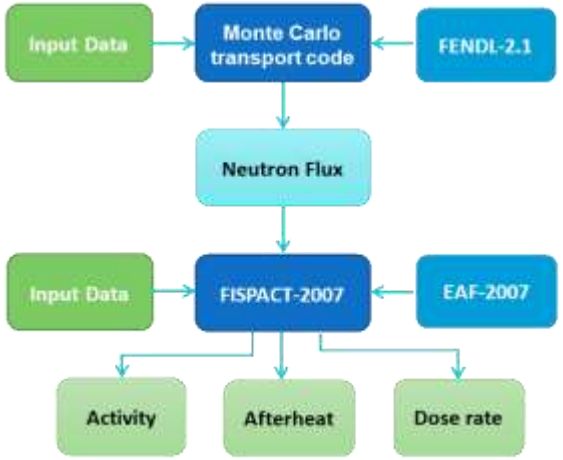
- **Basic design features:**
  - Blanket module consist breeding zone and shielding zone
  - Blanket modules connected at shielding zone or by back plate to form segment
  - Tritium breeder and neutron multiplier in alternation ranking
- **Material selection:**
  - FW armor: W / W alloy
  - Structural: CLF-1
  - Tritium Breeder: Li_4SiO_4
  - Neutron Multiplier: Be / Be alloy
- **Design parameters:**
  - Coolant: He@12MPa, 300-600°C
  - Purge gas: He(0.1%H_2)@0.3MPa

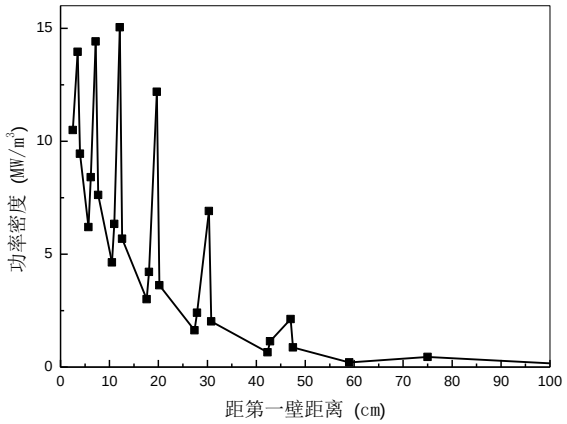




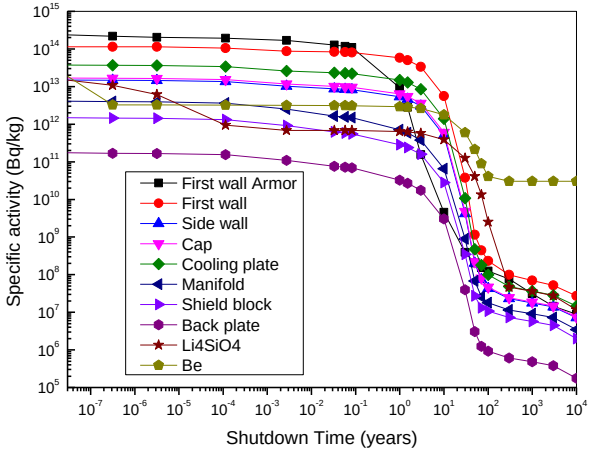
Neutronics analysis

- Detailed neutronics model for CFETR tokamak and HCCB TBBs are built for analysis.
- The layout of breeding and beryllium zone are optimized. Without Heating and Diagnostic ports, the overall TBR is 1.188. After consider NBI, ECRH, ICRH, LHW and Diagnostics, the TBR is 1.109.
- Nuclear heat, activation, decay heat are calculated and as input for other analysis.

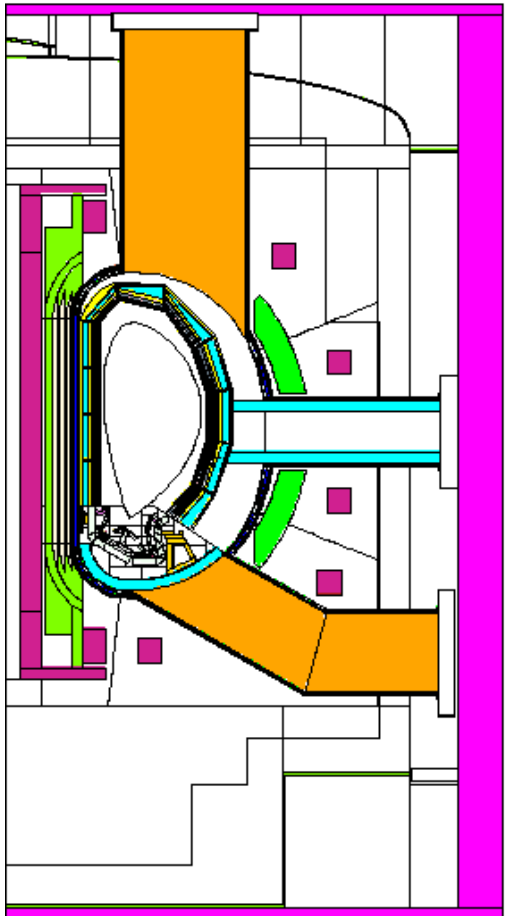




Nuclear heat

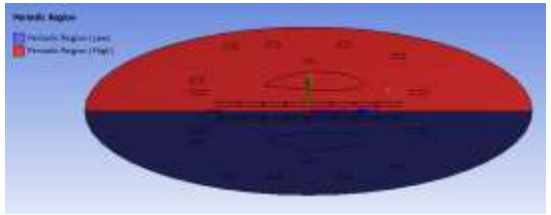


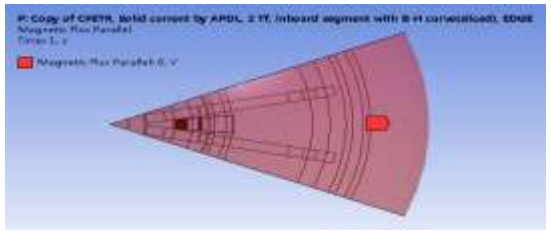
Activation

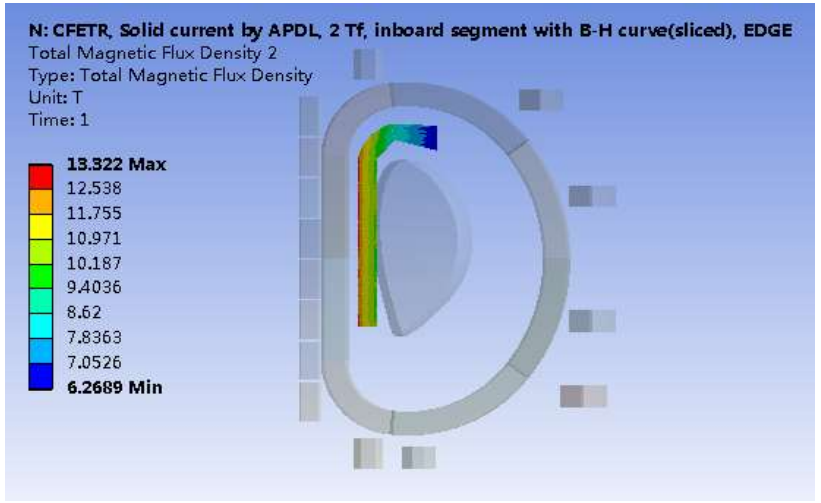


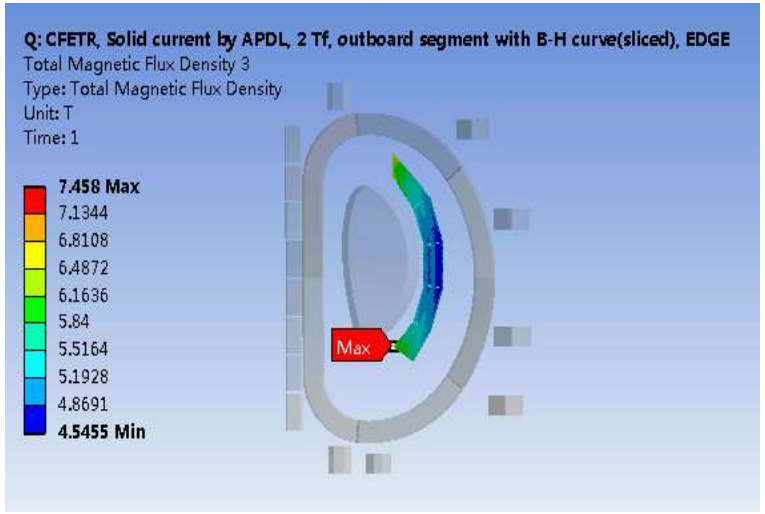
EM analysis

- EM analysis are performed using similar methods with ITER
- Magnetic property of CLF-1 steel is used as input.
- The Magnetization and eddy-current results are obtained.





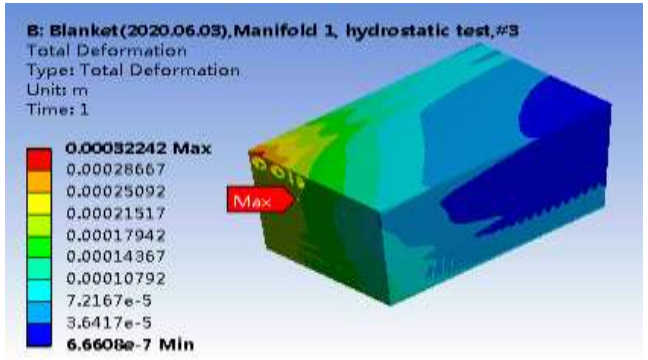


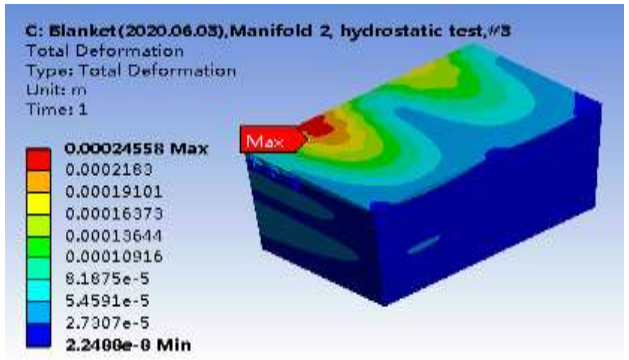


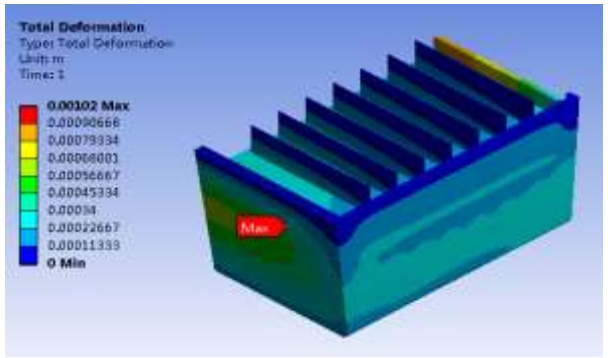
	Fr (N)	Ft (N)	Fp (N)	Mr (Nm)	Mt (Nm)	Mp (Nm)
高场侧(磁化)	-1.53e7	4.61e5	-4.52e5	-	-	-
高场侧(涡流)	-3.17e3	7.59e4	1.04e3	-1.76e5	-1.00e4	-7.49e4
低场侧(磁化)	-6.10e6	8.31e4	-3.32e5	-	-	-
低场侧(涡流)	-3.29e2	-4.14e4	-1.21e3	1.71e4	-1.52e4	-3.52e4

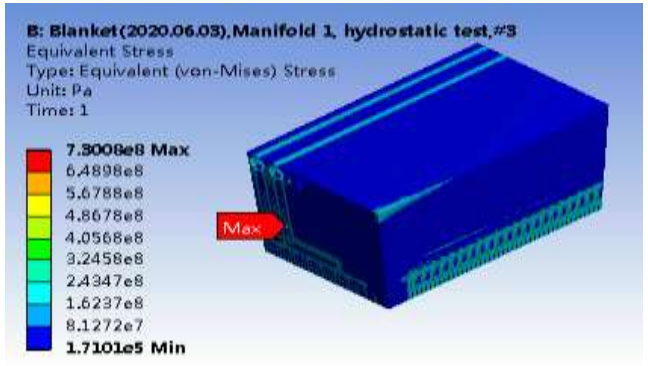
Structural analysis

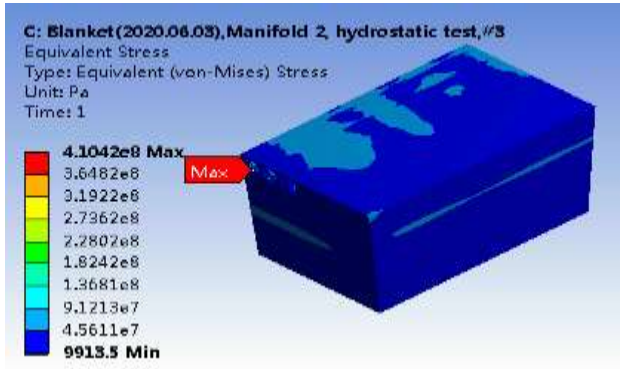
- Using RCC-MRx code, structural analysis has been performed and used for optimization of structure design .
- Different load combination are considered, including normal operation, baking, in-box LOCA etc.

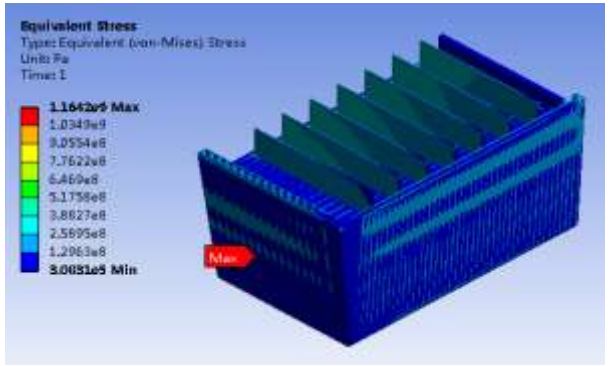






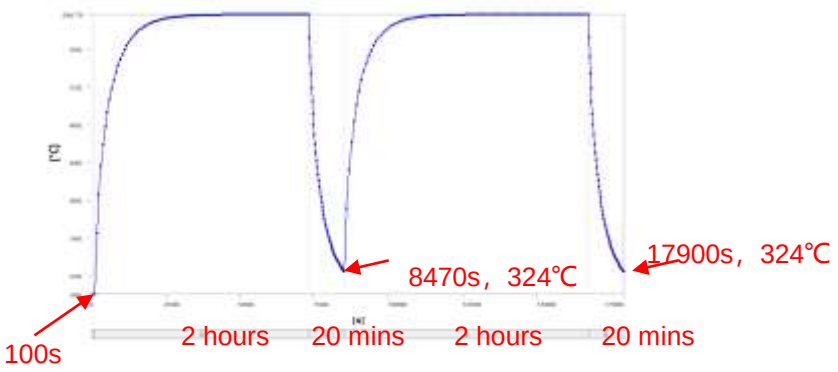


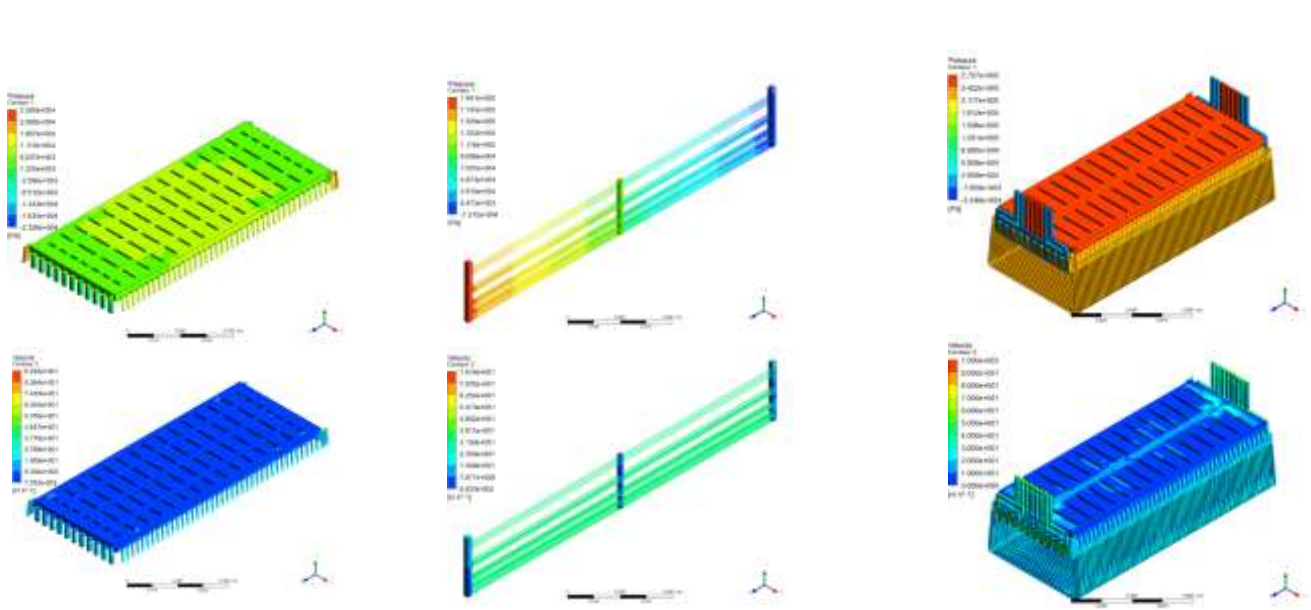


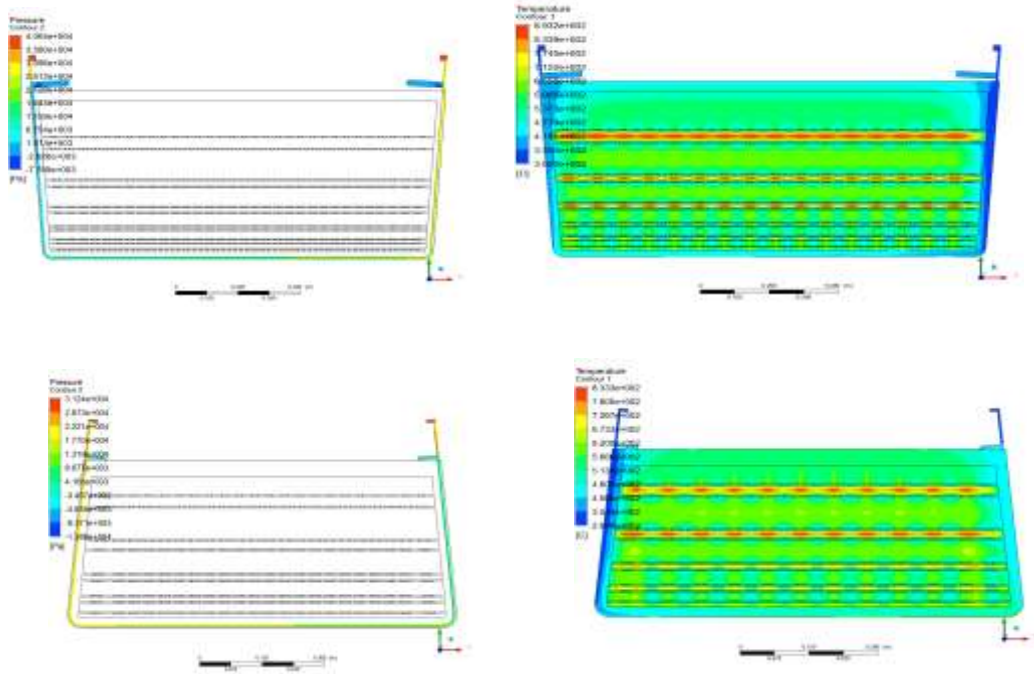


Thermal hydraulics analysis

- Detailed thermal hydraulics analysis had been performed to calculate flow distribution, temperature distribution, pressure drops, and used for optimization of flow channels.
- Simplified transient analysis were also performed for pulsed operations.

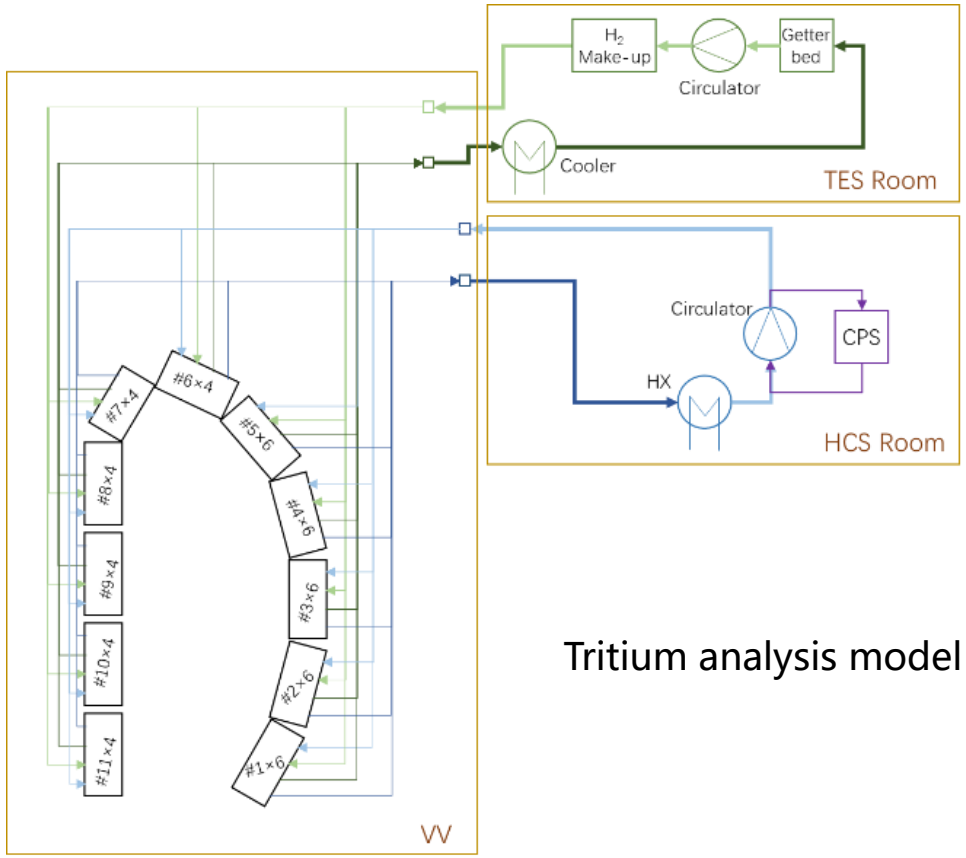




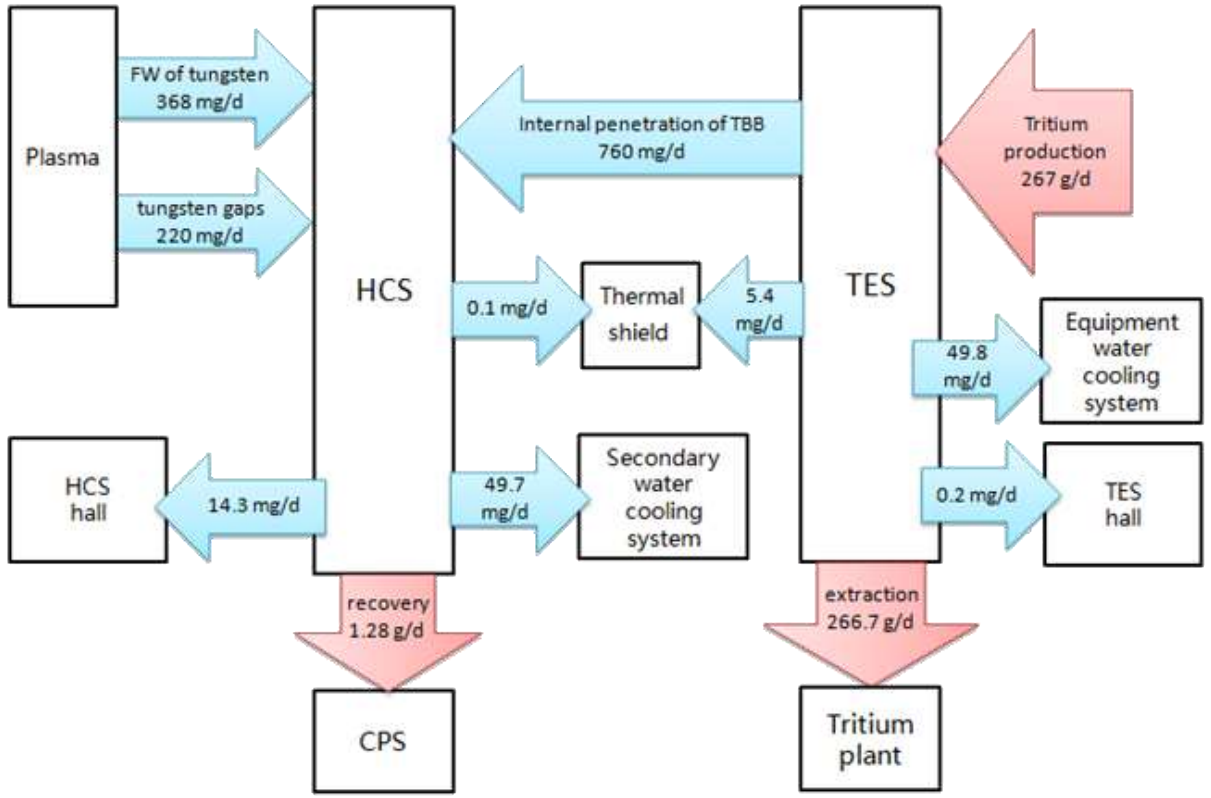


Tritium Analysis

- Using self-developed system level tritium analysis tool, the tritium transport had been analyzed.
- Permeation to coolant and to buildings had been analyzed.



Tritium analysis model

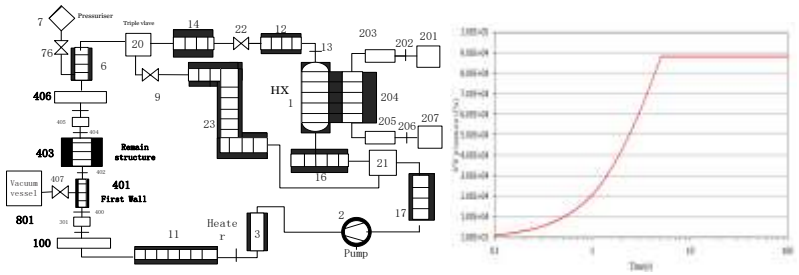


Tritium permeation results

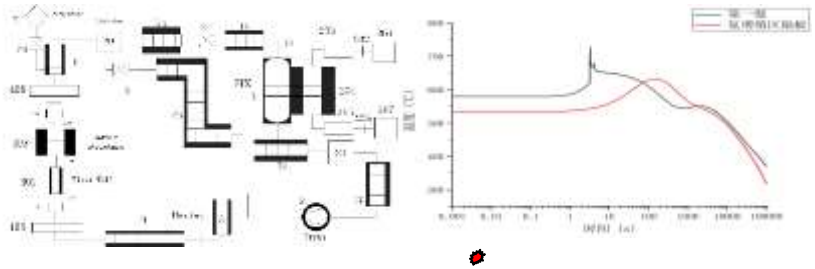
Accident Analysis

- Accident list and scenarios had been assessed.
- Representee accidents for HCCB TBB System, including LOFA, in-vessel LOCA, ex-vessel LOCA, in-box LOCA, TES line break had been analyzed.

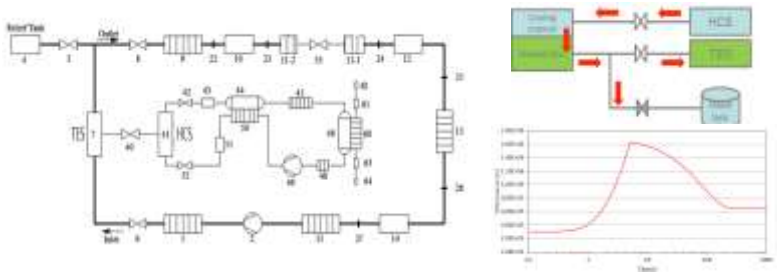
In-vessel LOCA



LOFA



In-box LOCA



In-vessel LOCA	Max FW temperature (℃)	VV pressure (KPa)	He leakage in VV (Kg)
Large break (80 FW pipes)	648	88	160

LOFA	Max FW temperature (℃)	HCS flow rate (Kg/s)	Max division plate temperature(℃)
Isolation valve open	656	5	615
Isolation valve closed	726	0	660

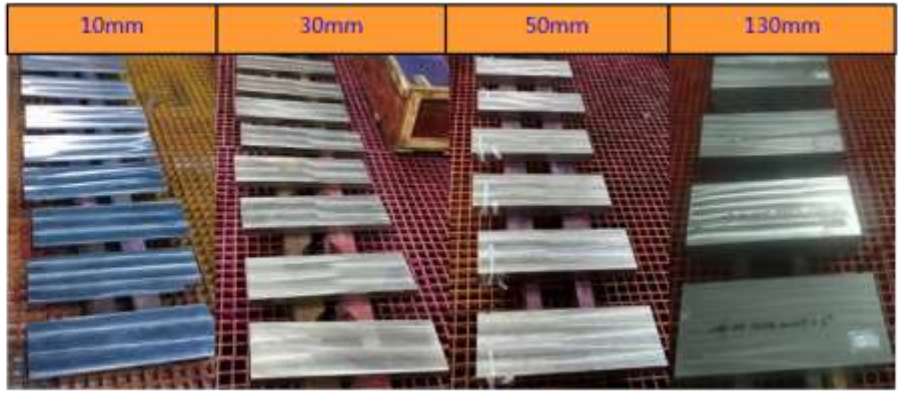
In-box LOCA	TES pressure (MPa)	TES Max temperature(℃)	Breeding zone pressure (MPa)
Large break (480pipes break in breeding zone)	1.6	530	10.5

3 Progress and plans for HCCB TBB R&Ds

Structural Material Development

- Three 5-tons ingots for CLF-1 RAFM Steel were produced, 10mm, 30mm, 50mm rolled plates and 130mm forgings were delivered.
- Welding (TIG, LBW and EBW) specimens are also under preparation and test.
- Tests of for microstructure, physical properties (RT~700℃), tensile properties (RT~700℃), impact properties (-120℃~RT) were performed, Tests for creep, fatigue, fracture toughness, aging, are ongoing.

Three 5-tons ingots of CLF-1



Different thicknesses plate of CLF-1

Test reports of CLF-1 engineering qualification tests

Creep tests of CLF-1

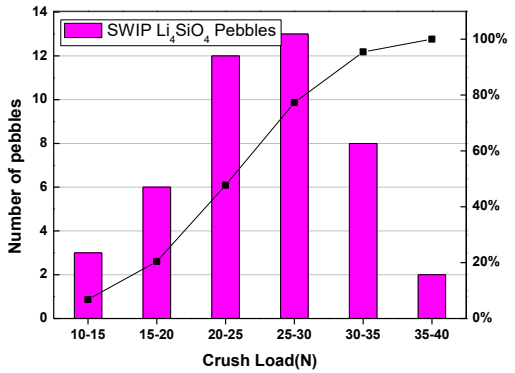
Aging test of CLF-1

TIG welding of CLF-1

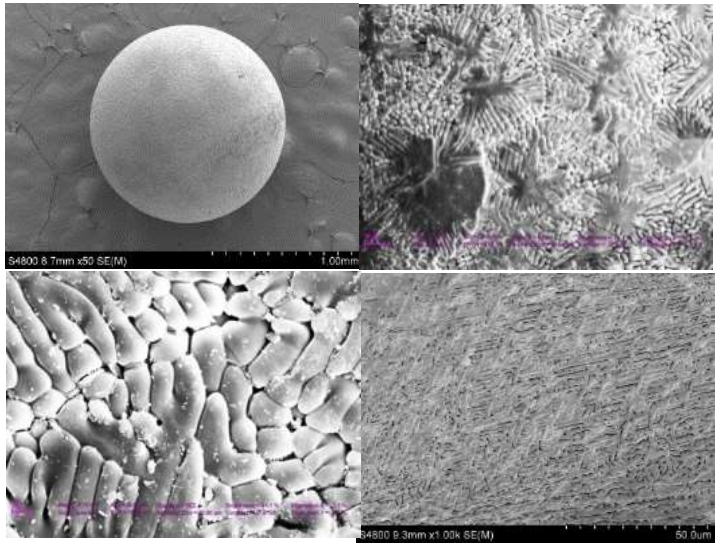
Tritium breeder Development

- Melt spray method had been developed, The facility will have the ability to produce 2~10 kg Li4SiO4 pebbles at a single batch.
- The large-scale fabrication technology of the advanced tritium breeder is being developed，such as bi-phase Li4SiO4-Li2TiO3 pebble, porous block ceramics.

Properties	Values
Density	~96% TD
Open porosity	~ 5.2%
Closed porosity	~ 1.78%
Specific surface area	0.4626 m^2/g
Average pore radius	3.674 nm



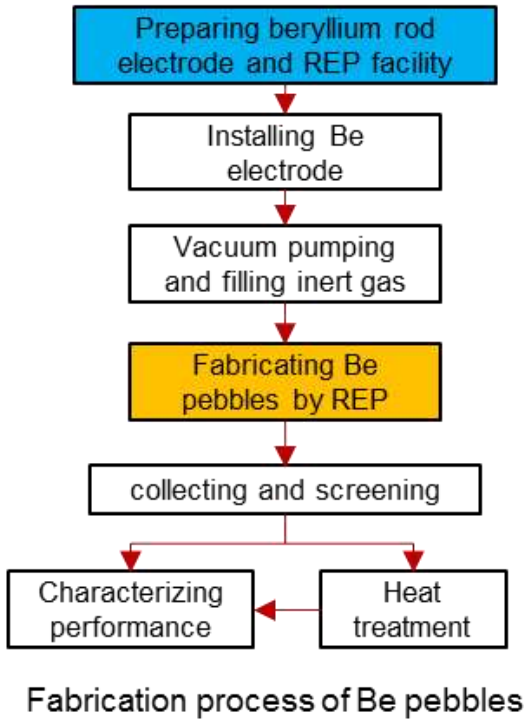
Crush load of Li_4SiO_4 pebbles



SEM of surface and cut section of Li_4SiO_4 pebble

Neutron multiplier Development

- The fabrication scale of beryllium pebbles has reached 10kg/batch after upgrade of the facility of Rotating Electrode Process (REP) method. The pebble formation is over 60%. Pebble size can be well controlled.
- The large-scale production technology of beryllium alloy is under development, such as, Be12Ti, Be13Zr, etc.



Fabrication process of Be pebbles

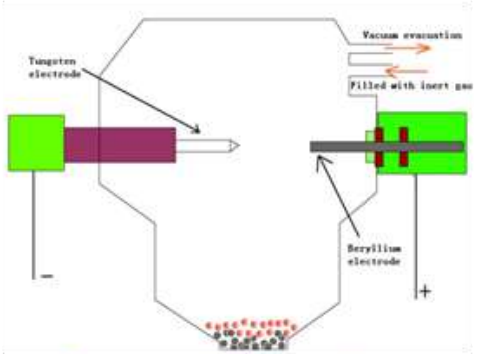
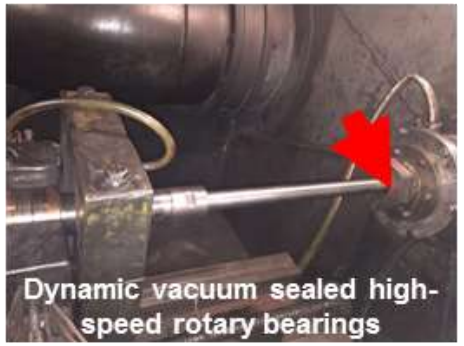


Diagram of REP method

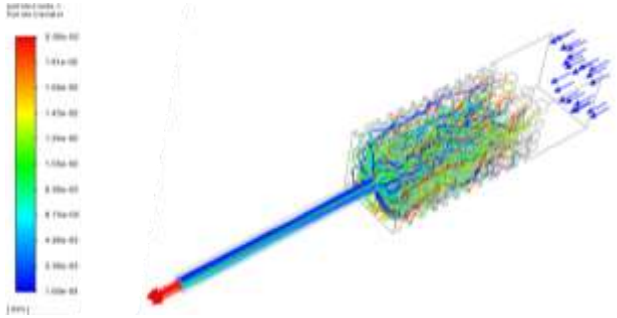


Be	> 98.5%
BeO	< 1.0%
U	1.27 ω(U)/10^{-6}, < 0.01%
Pebble size	0.3 mm ~ 1.2 mm
Sphericity	99.4%
Open porosity	1.32%
Surface area	0.5075m^2/g (a.v)
Density	98.89% T.D.
Packing factor	61.12%

Fabrication of Be pebbles based on rotating electrode method

Pebble Bed Technology Development

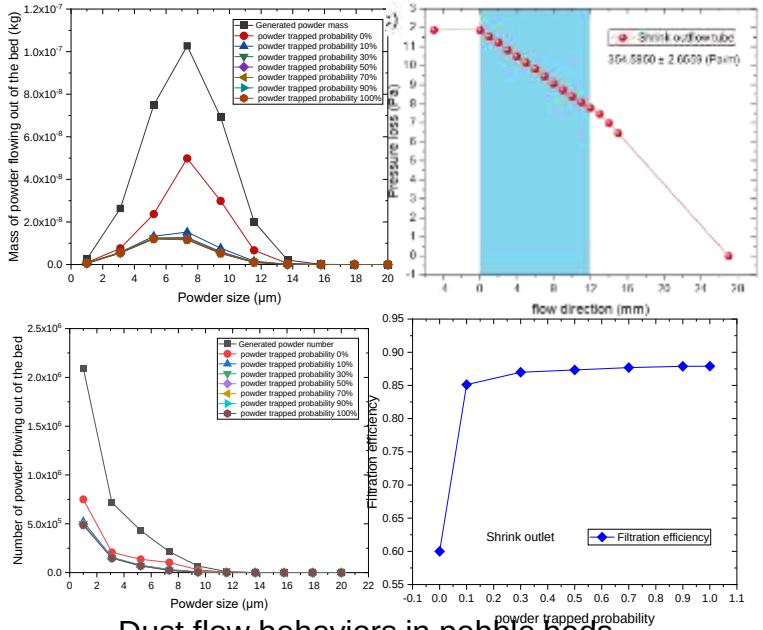
- A series of pebble bed experiment facility has been constructed, covering thermo-physical, thermal mechanical, multi-physics coupling, pressure drop, etc.
- Ceramic dust flow behaviors in pebble bed were investigated by DEM-CFD-DPM method.



Multiphysics coupling pebble bed performance test platform

Pebble bed gas pressure drop testing

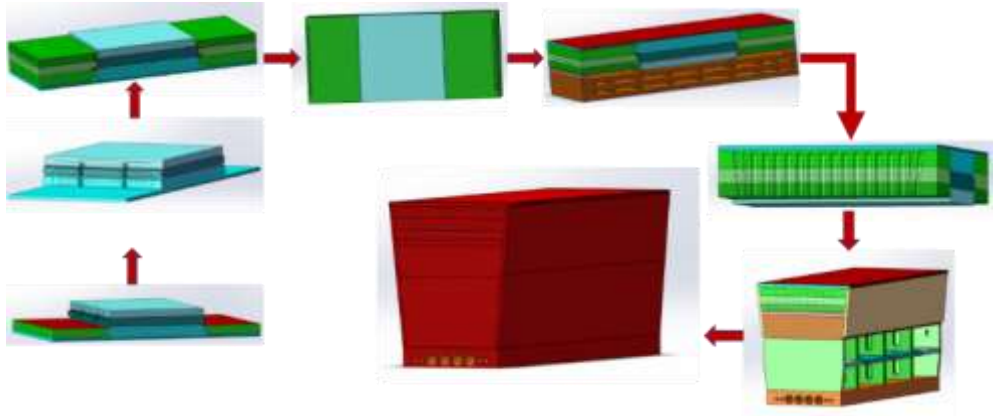
Thermal mechanical testing with compress load



Dust flow behaviors in pebble beds

Blanket Fabrication Technology

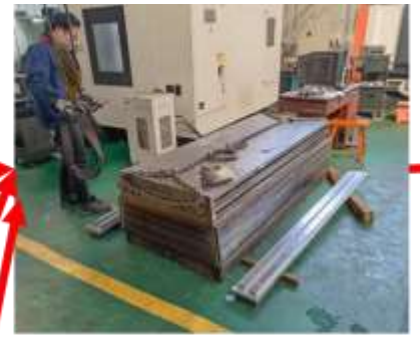
- Based on design of CFETR HCCB blanket, the fabrication and assembly procedure had been studied
- A full size mockup of inboard blanket module had been fabricated。
- The mock-up passed 30MPa pressure test and helium leakage test (<1x10^{-7}Pa·m^3/s@RT).

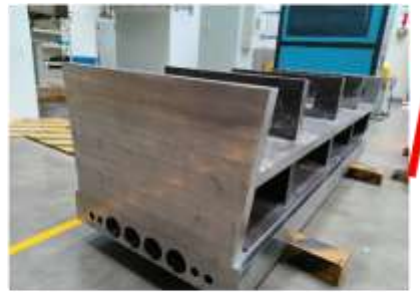


FW

Cooling plate

Distribution plate



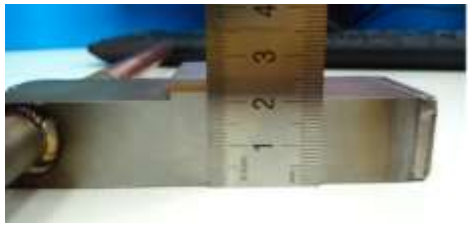


Shielding plate

W FW armor technology

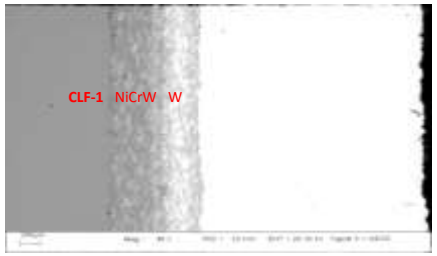
- Regarding blanket FW armor technology, SWIP performed test for different bonding technologies, and finally chose HIP bonding for large-size FW mockup fabrication,.
- The mock-up has passed 1MW/m^2, 1000 cycles test using water coolant, further test with be performed using helium coolant.

HIP welding sample

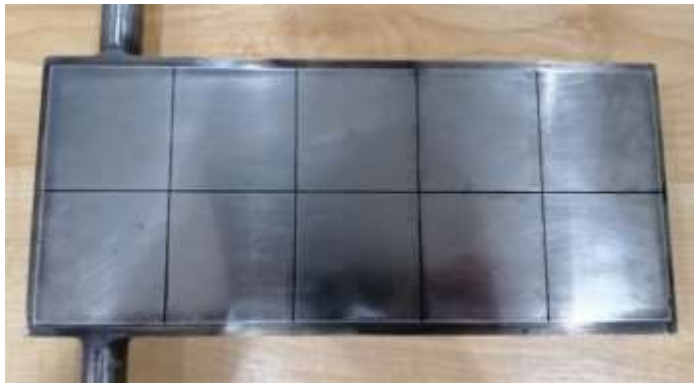


Vacuum brazing sample

Laser spraying sample

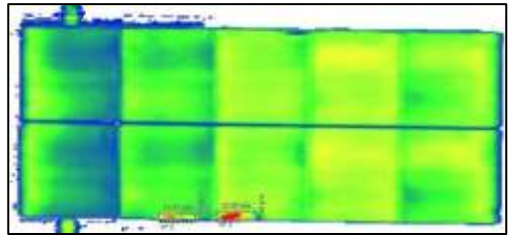


Vacuum plasma coating sample

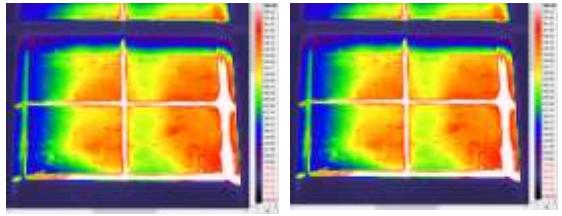


High heat flux test-heat power	Test area	Test cycle	Water velocity	Water inlet temp.
1MW/m^2	100mmx150mm	30s(15s on, 15s off), 1000 cycles	0.75m^3/h	RT

Surface status after high heat flux test



UT after high heat flux test



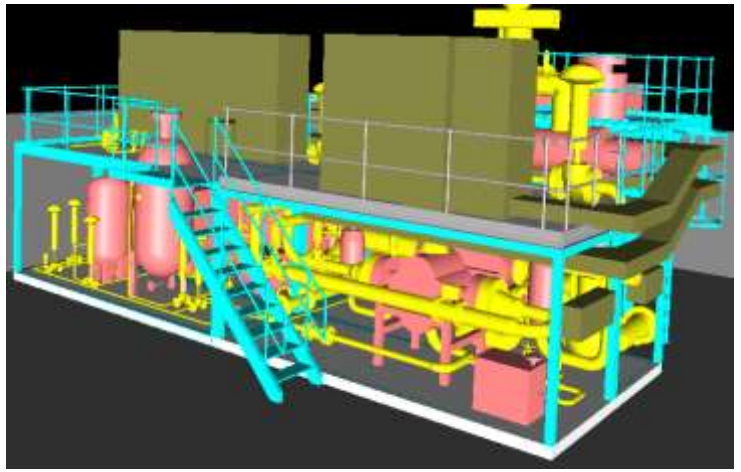
Thermal image before and after high heat flux test

Helium cooling technology

- Helium cooling experiment loop HeCEL-3 was constructed for the thermohydraulic testing HCCB Blanket mock-ups.
- HeCEL-3 is planned to be upgraded after moving to new blanket research center and connect to 400/800kW high heat flux facility.

HeCEL-3 (2.5kg/s, 12MPa, 550℃)

Test of CFETR HCCB Blanket Mock-up



Design for upgrade

SWIP Blanket research center

A blanket engineering research center (~9600m^2) is under construction and will be put to use summer 2024.

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Thank you for your attention!