Testing and nuclear qualification strategy for CFETR breeding blanket

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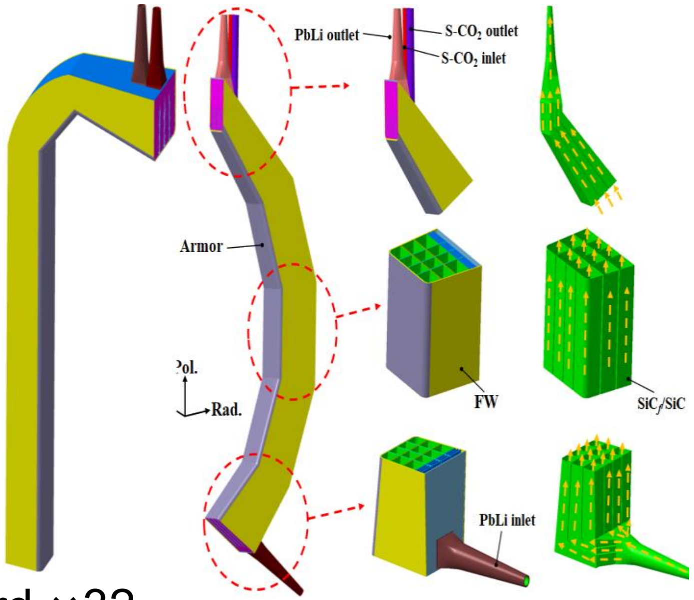
Technical meeting on tritium breeding blankets and associated neutronics, Viena, Sep. 2-4, 2025

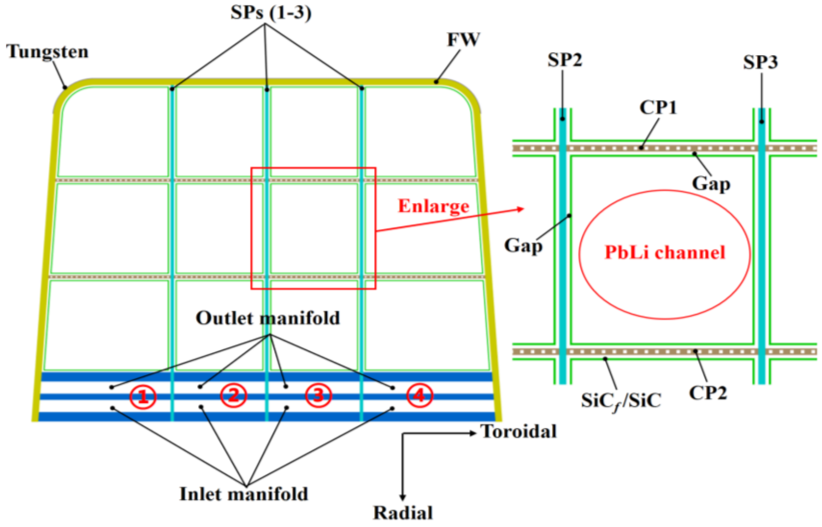
Outline

- Background
  - COOL blanket
  - WCCB blanket
- TH/MHD test facilities and experimental design
  - PbLi loop
  - S-CO_2 loop
  - Water loop & HFF test facility
  - In-VV LOCA facility
  - Pebble beds test facilities
- Nuclear measurements
- Concluding remarks

COOL blanket design



Inboard ×32 Outboard ×48



Structure design

Design features

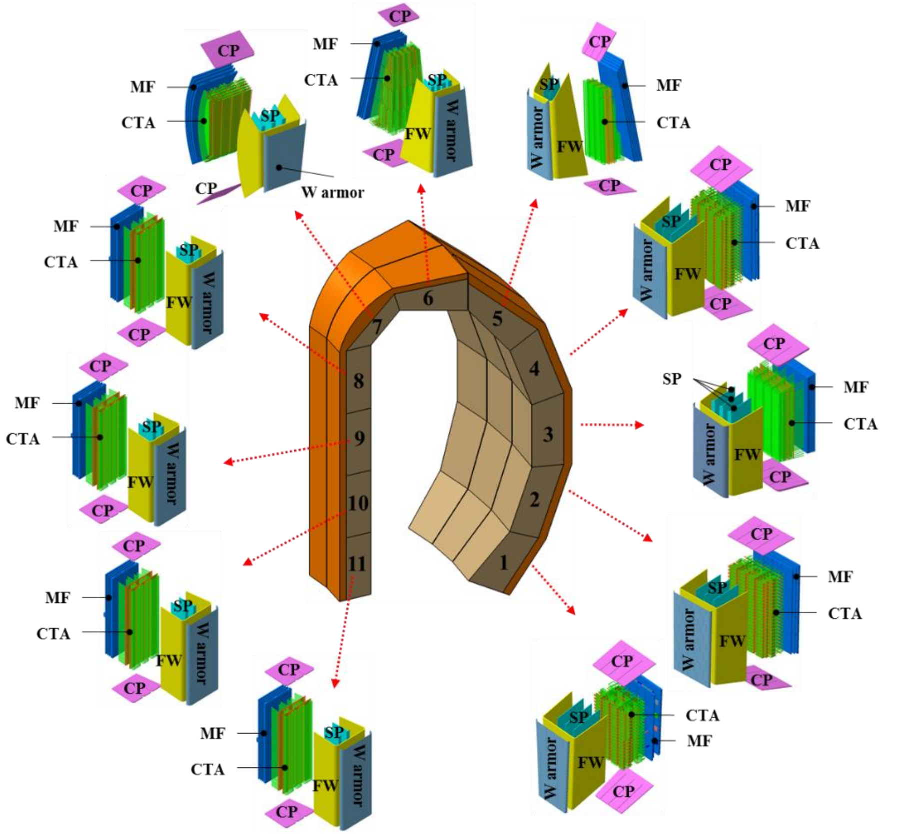
- Single Module Segment,
- RAFM steel as structural material
- S-CO_2: 8 MPa, 350 °C ~ 400 °C
- PbLi: 1~2 MPa, 460 °C ~ 700 °C
- FCIs to mitigate the MHD effect and corrosion
- PbLi “once-through” scheme
- Thermoelectric conversion efficiency: ≥42%

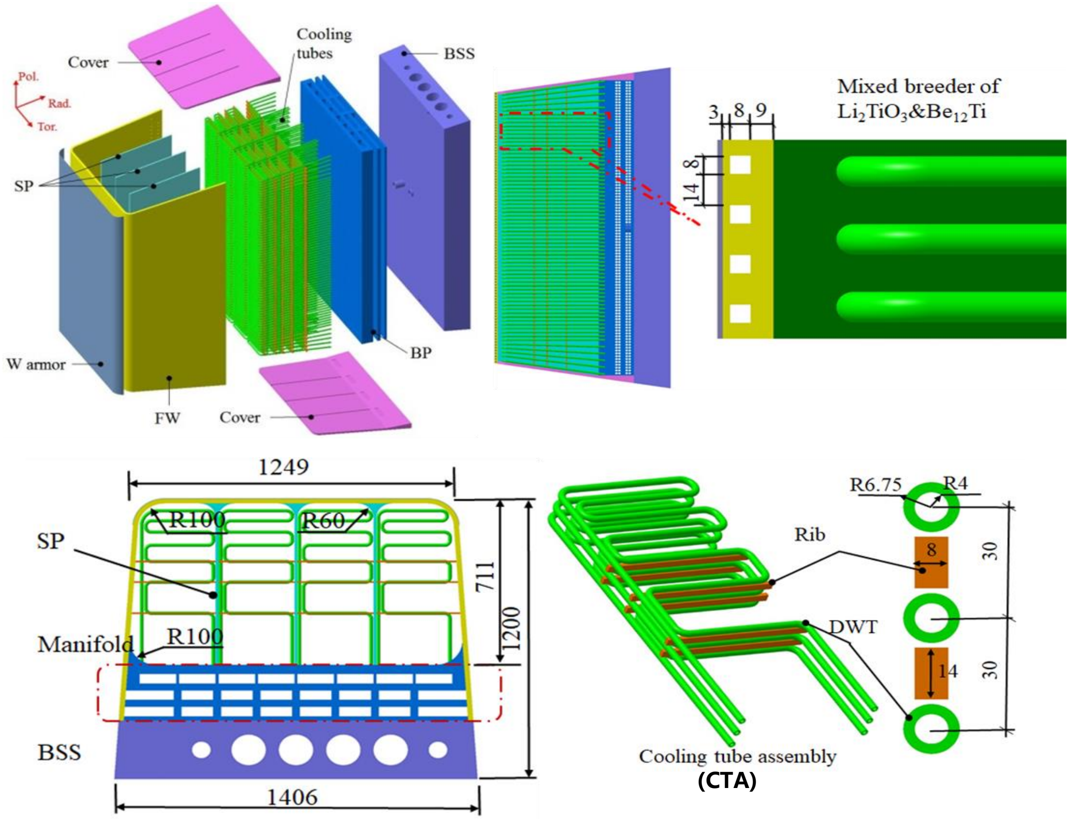
Main advantages

- Economic: Beryllium-based material is not used as the neutron multiplier
- Efficiency: Coolant outlet temperature can reach 700℃, thermoelectric conversion efficiency is high
- Online refueling and tritium extraction can be realized

Ref. Chen L., Jiang K., Ma X. and Wu. Q. 2021 Conceptual design of the supercritical CO_2 cooled lithium lead blanket for CFETR Fusion Eng. and Des. 173 112800

WCCB blanket design





◘ Material

- Coolant: pressurized water (15.5 MPa, 285 ℃/325 ℃)
- Structure: RAFM steel
- FW armor: 2 mm Tungsten
- Breeder/multiplier: Li_2TiO_3/$Be_{12}Ti$ mixed pebble beds
- Purge gas: He + 0.1vol% H_2 @1-3 bar

◘ Structure

- 8*8 mm^2 U shaped FW channels with horizontal counter flow
- Assemblies of Φ8 mm dual wall tubes with multi-bends

◘ Flow scheme

- FW and BZ cooled independently by water coolant
- Purge gas flow upwards

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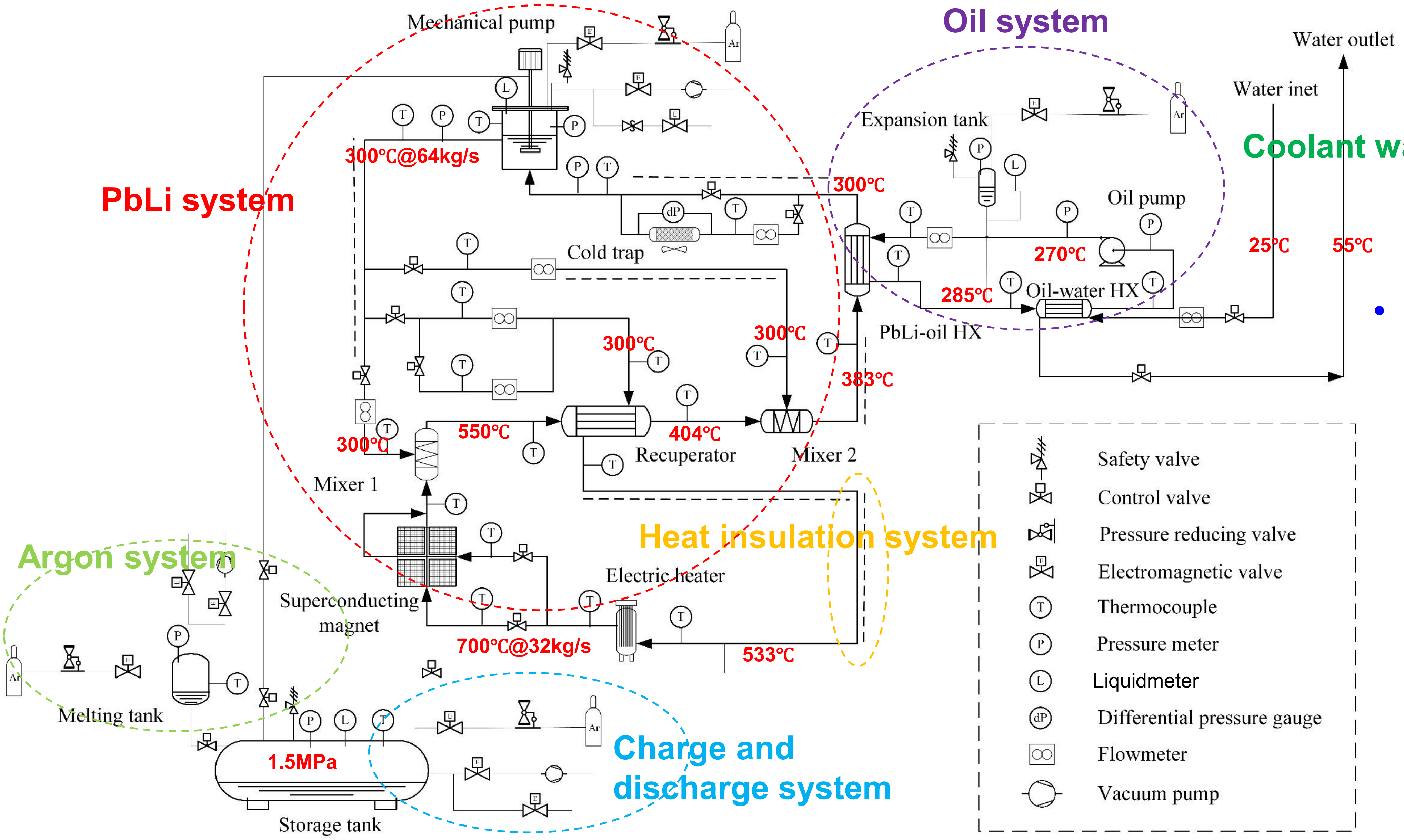
PbLi loop design

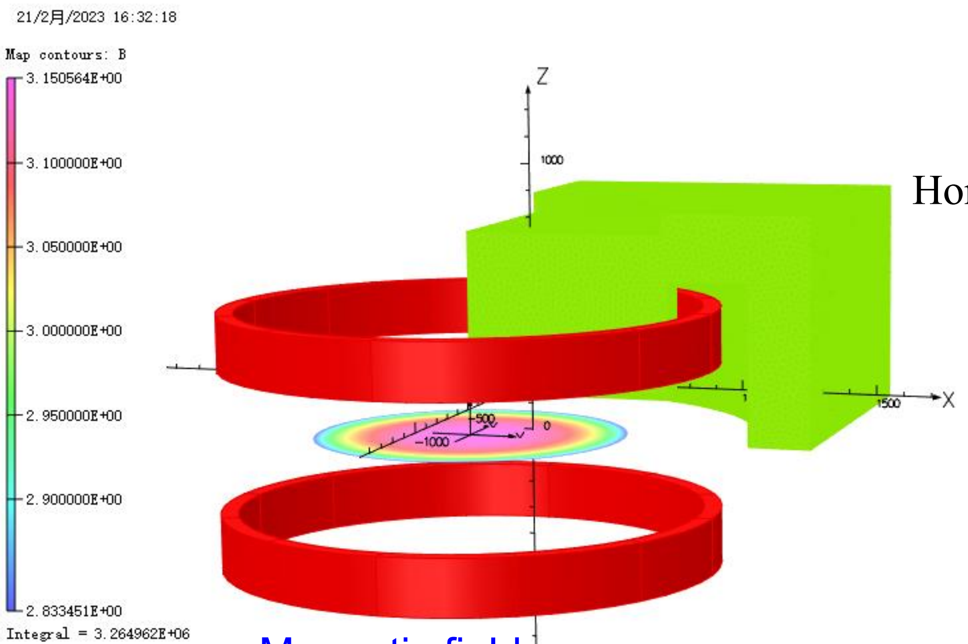


- Main components
  - Recuperator
  - Heater
  - Mechanic pump
  - Supermagnet
  - Storage tank
  - Mixer
  - Cold trap
  - Heat exchanger

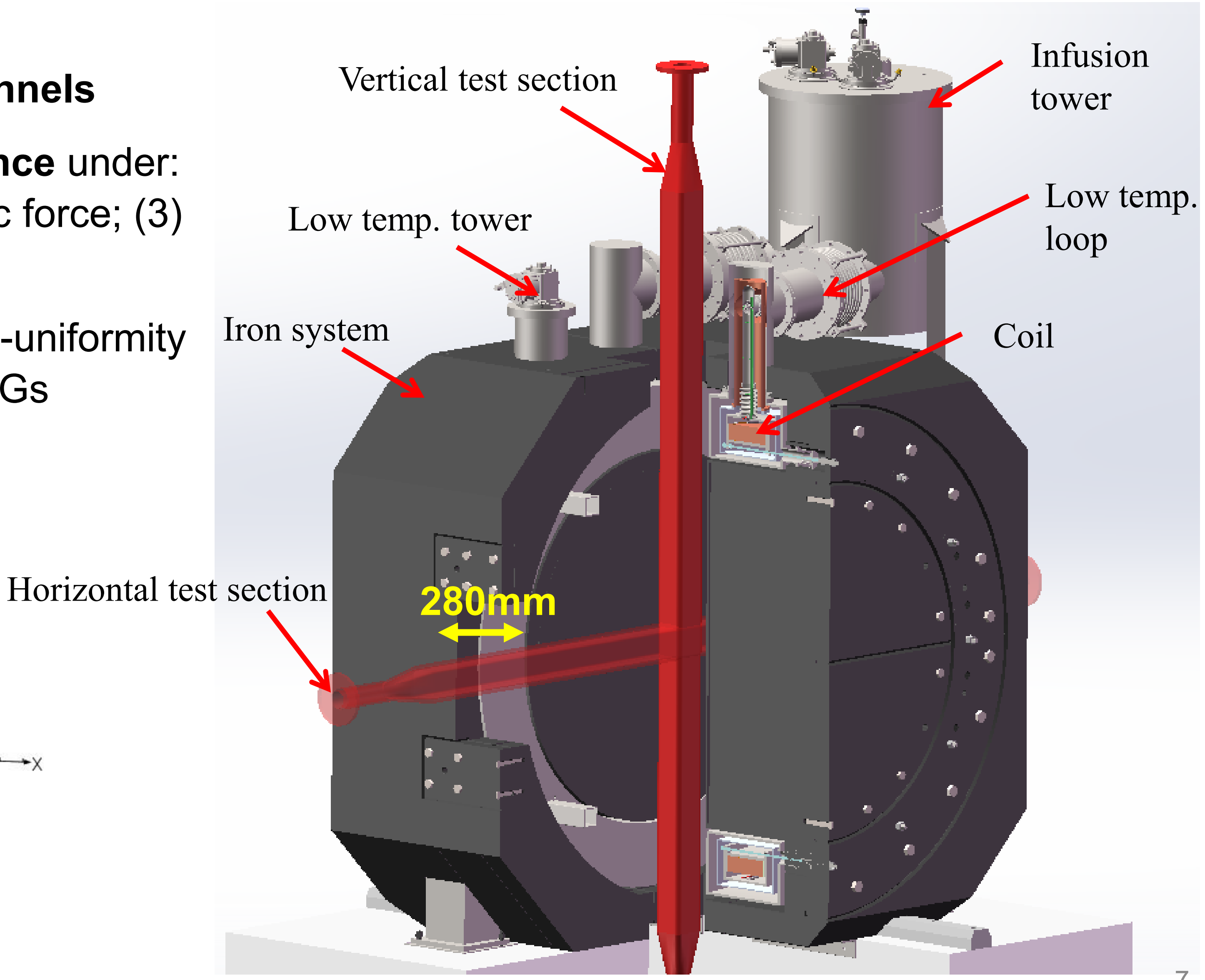
Main component

➢ Superconduct magnet

- Includes both **vertical and horizontal channels**
- Able to study the **Multi-physics performance** under: (1) Complex geometric; (2) Electromagnetic force; (3) Buoyancy effects
- Wide range uniform magnetic field, the non-uniformity is 8%; Surface magnetic leakage 1 m≤300 Gs



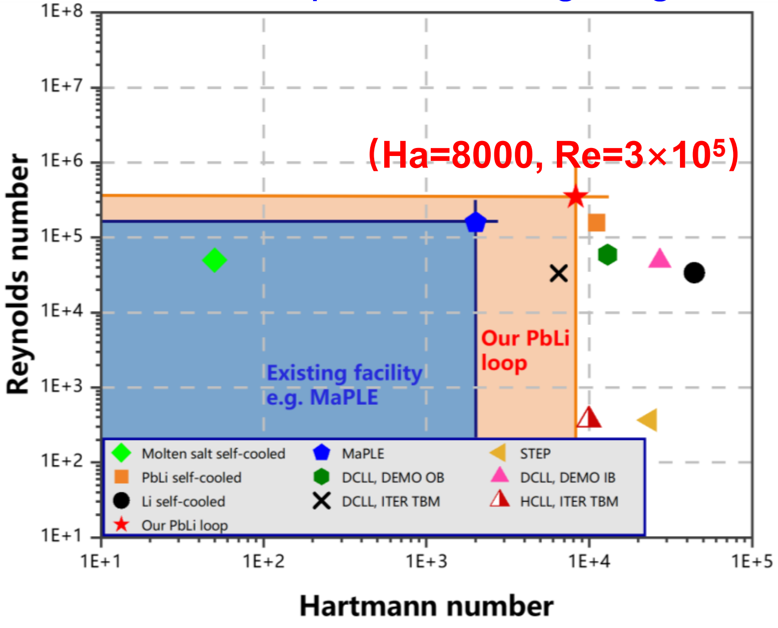
Magnetic field



3D layout

12 m (length)×9.5 m (width)×16 m (height)

3T superconducting magnet

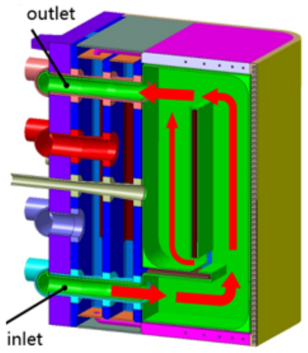


Comparison with existing facilities

Experimental plan

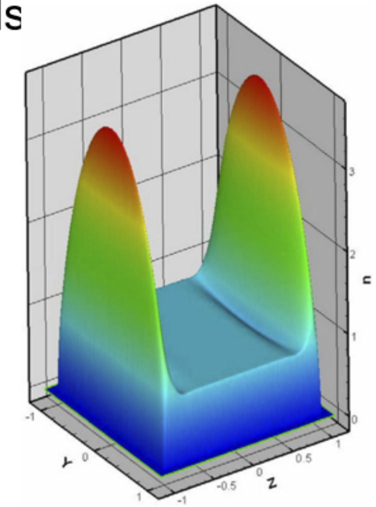
Mixed convection
- Straight channel
- Magneto-convection effects
- *U, f, Nu* under different *Re*, *Ha* and *Gr*

Out of pile mockup test
- Engineering feasibility



Complex geometry channel
- Electromagnetic coupling in multi parallel channels
- Sudden expansion/contraction channels

Flow channel insert effect (FCI)
- Straight and complex geometry channel
- Quantify the pressure drop reduction
- Effects of σ_{FCI} and wall conduction ratio C_w on ΔP

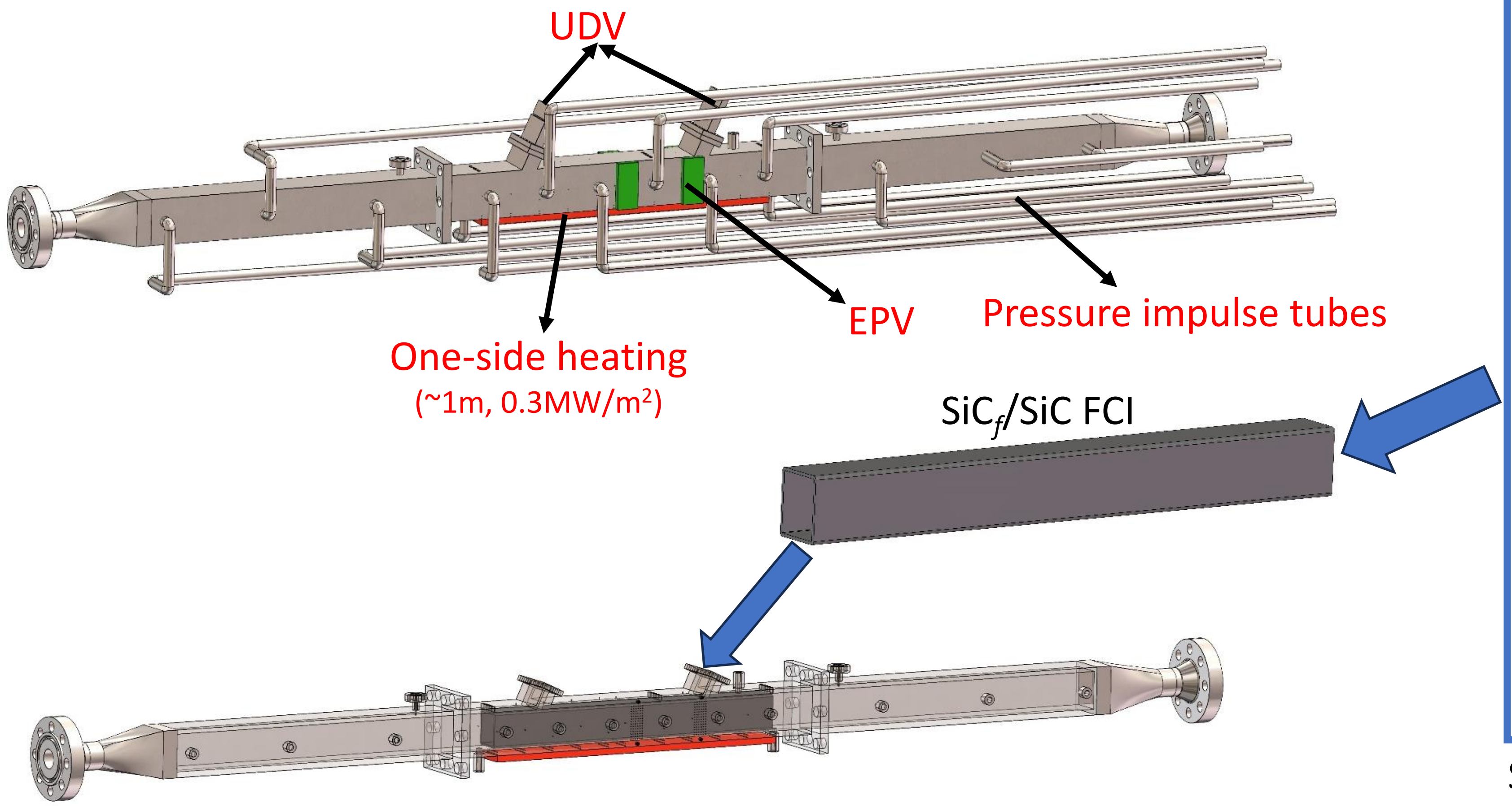


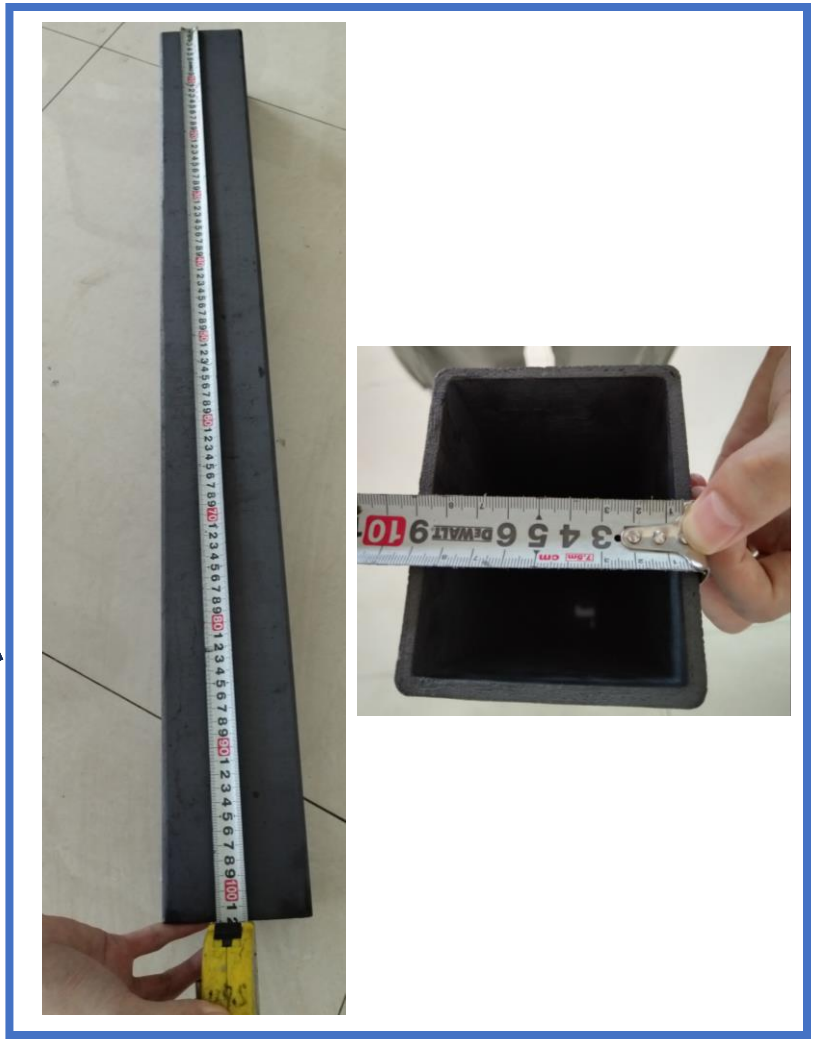
Flow phase diagram
- Straight channel
- Transition from laminar to Q2D and fully turbulent
- *U, f* under different *Re* and *Ha*

Pre-design on test section(1/2)

➢ MHD test section design

- MHD mixed convection under magnetic field and temperature difference
- Operating conditions: *Re*~10^5, *Ha*~10^4 and *Gr*~10^{10}

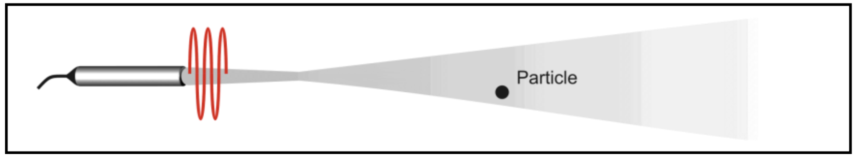


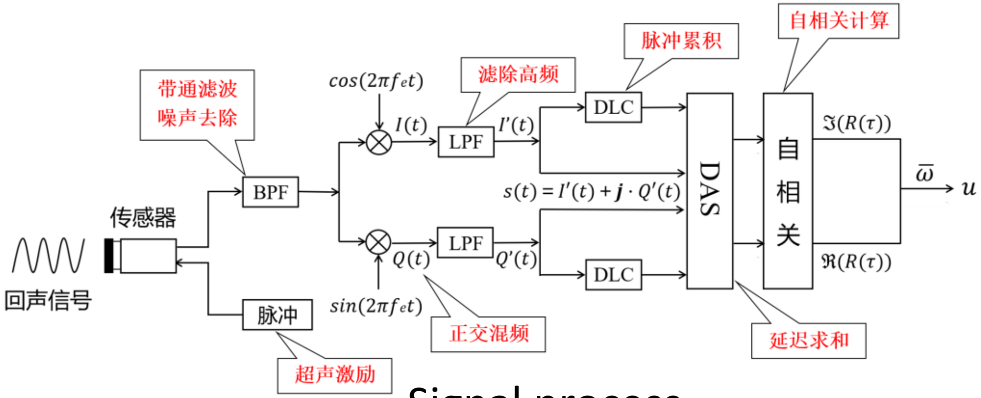


SiC$_f$/SiC FCI is successfully manufactured

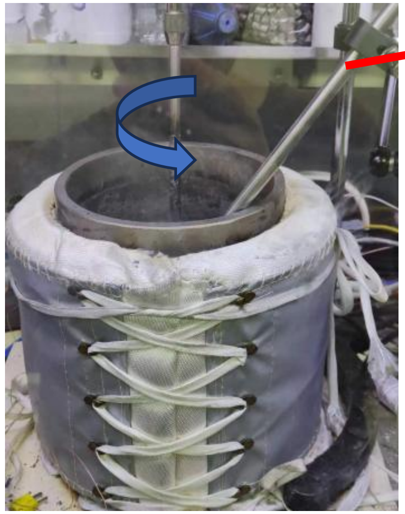
Pre-design on test section(2/2)

☐ Ultrasonic Doppler Velocimetry(UDV)

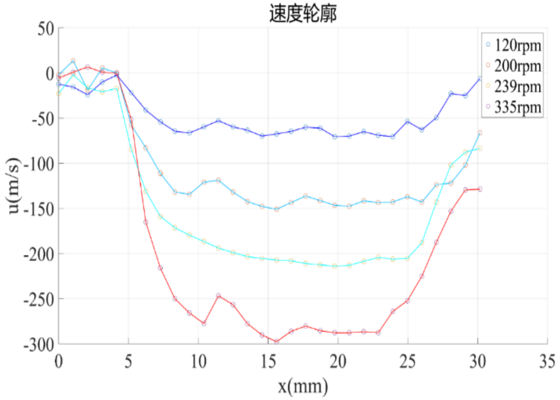




Signal process



Ultra-sound transformer



Velocity distribution

☐ Electrostatic Probe Velocimetry(EPV)

$$\rho\frac{\partial \boldsymbol{u}}{\partial t} + \rho(\boldsymbol{u}\cdot\nabla)\boldsymbol{u} = -\nabla p + \mu\nabla^2\boldsymbol{u} + \rho\boldsymbol{f}$$

$$\nabla\times\boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t} \quad \text{(Faraday's law)}$$

$$\nabla\cdot\boldsymbol{B} = 0 \quad \text{(Solenoidal nature of } B\text{)}$$

$$\nabla\times\boldsymbol{B} = \mu_0\boldsymbol{j} \quad \text{(Ampère-Maxwell equation)}$$

$$\nabla\cdot\boldsymbol{j} = 0 \quad \text{(charge conservation)}$$

$$\boldsymbol{j} = \sigma(\boldsymbol{E} + \boldsymbol{u}\times\boldsymbol{B}) \quad \text{(Ohm's law)}$$

$$\boldsymbol{f} = \boldsymbol{j}\times\boldsymbol{B} \quad \text{(Lorentz force)}$$

$$Re_m = \mu\sigma u L \ll 1 \quad \Rightarrow \quad \nabla^2\phi = \nabla\cdot(u\times B)$$

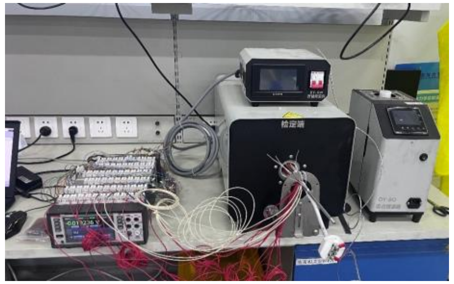
High $\vec{B}$

$$\mathbf{j}/\sigma = -\nabla\phi + \mathbf{u}\times\mathbf{B} \rightarrow 0$$

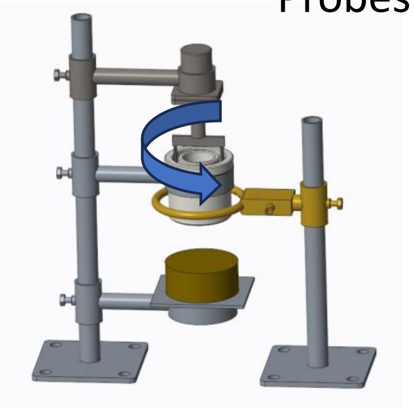
$$\Rightarrow \nabla\phi = u\times B$$

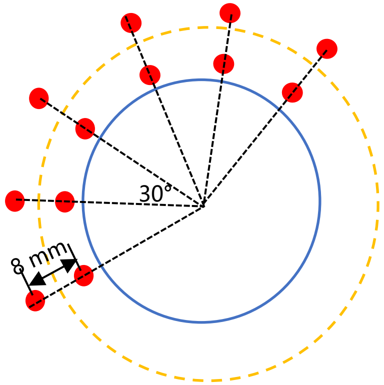
$$\Delta\phi = uB\Delta L,$$

Probes

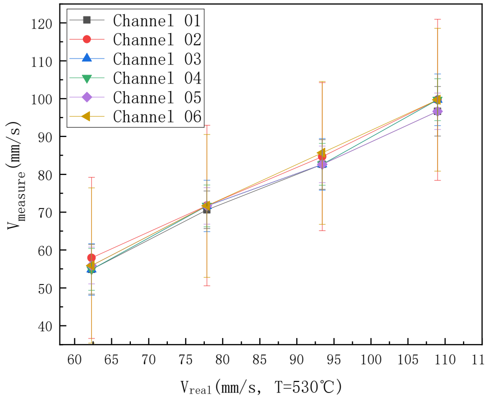


Calibration





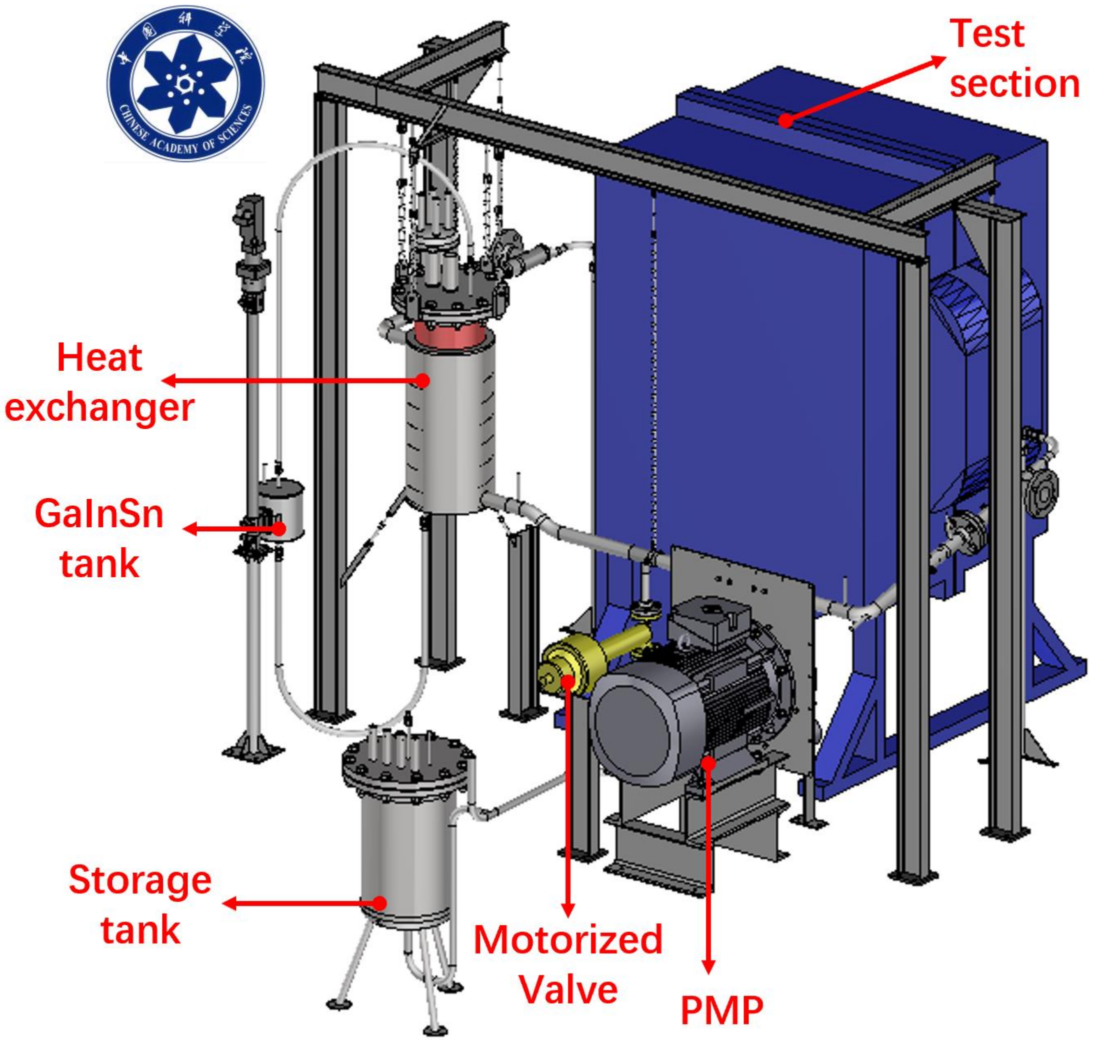
Probe arrangement

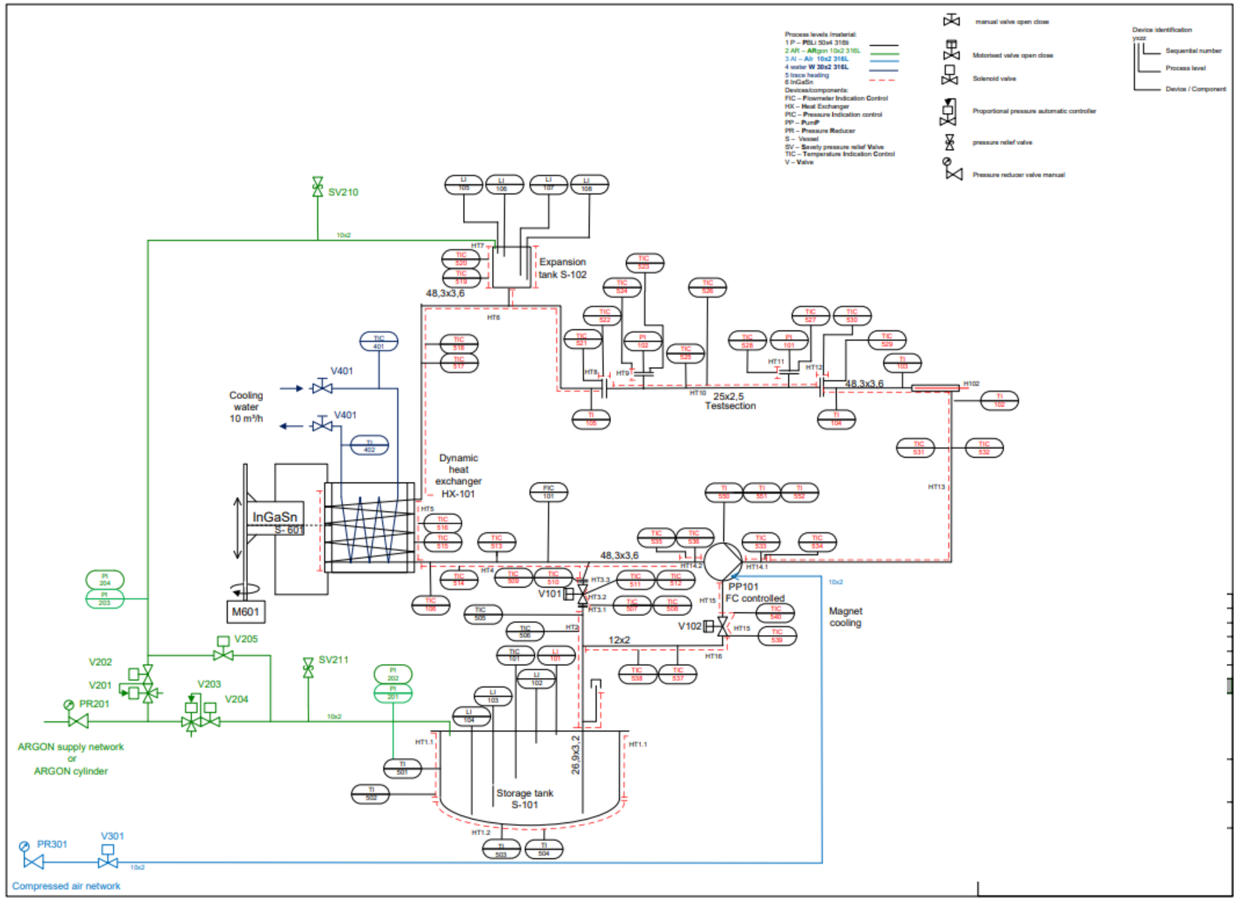


Velocity distribution

PbLi corrosion loop

- Liquid metal loop for corrosion in UCAS: 0.1-1.6 L/s, 450 ℃



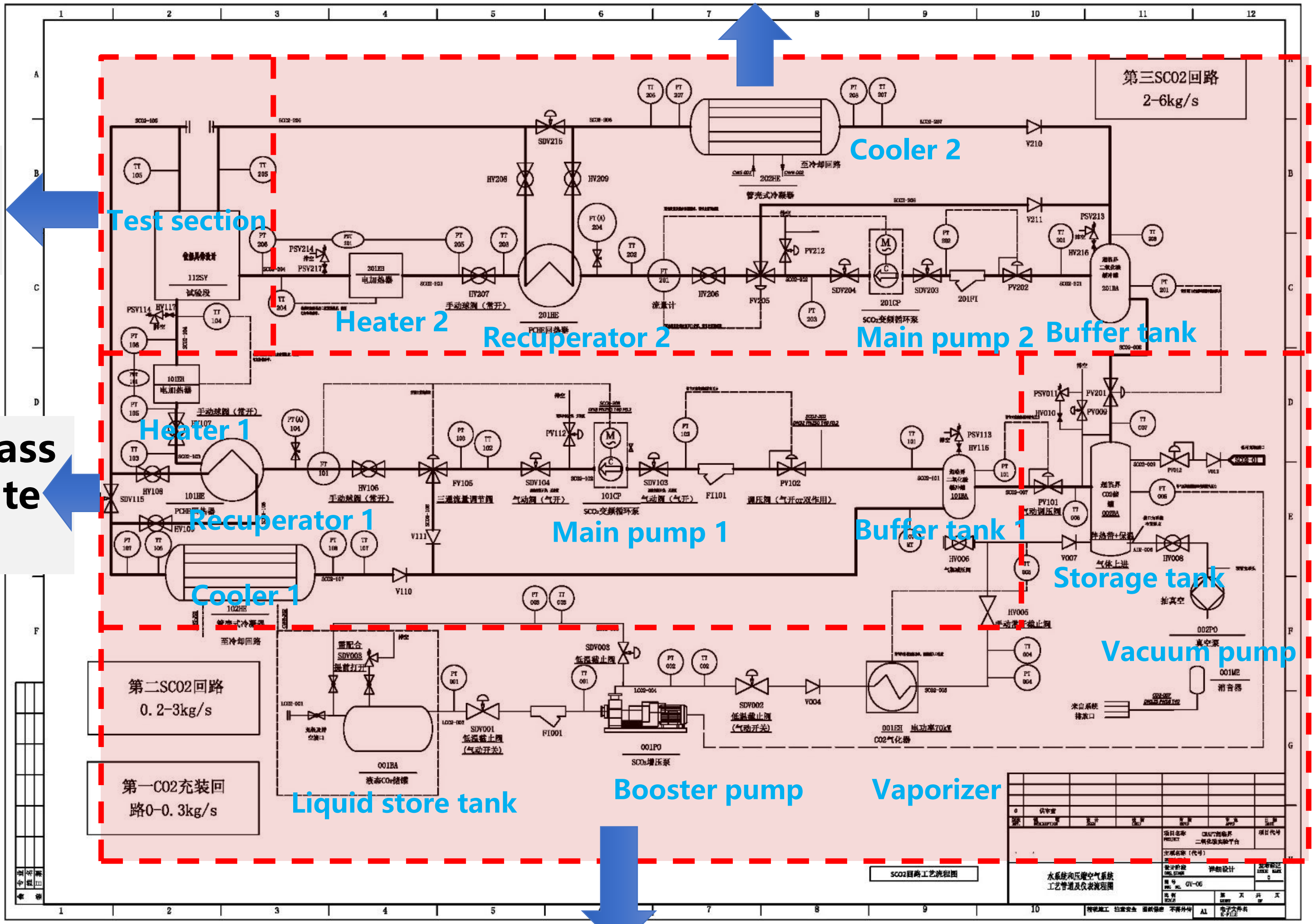


S-CO_2 loop design

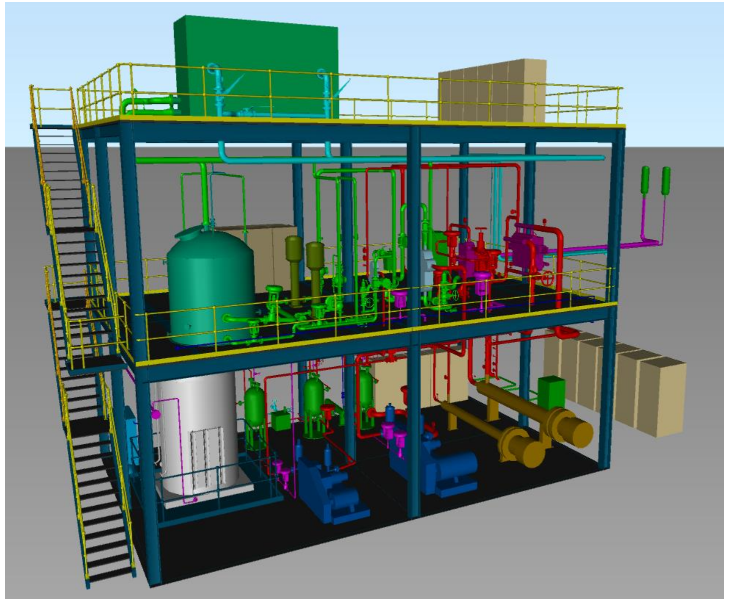
High mass flow rate loop

Test zone

Low mass flow rate loop



Charging loop



Charging loop（0-0.3 kg/s)

- **Function：** Store liquid CO_2、Gasified CO_2 to supercritical、pipeline vacuum、Charging/discharging CO_2 and pressure regulation.

Low mass flow rate loop（0.2-1.5 kg/s)

- **Function：** Provide test section with S-CO_2 at 0.2~1.5 kg/s、pressure 8-9MPa、Temperature 300-500℃。

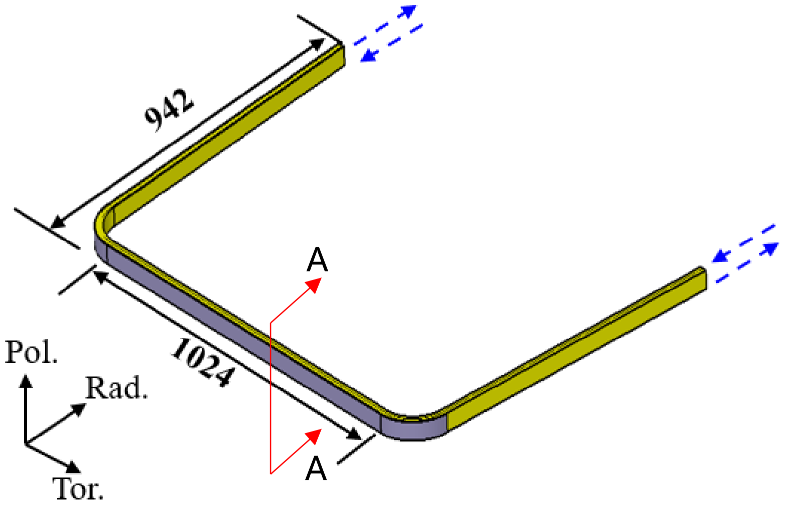
High mass flow rate loop（1-6 kg/s)

- **Function：** Provide test section with S-CO_2 at 1~6 kg/s、pressure 8-9MPa、Temperature 300-500℃。

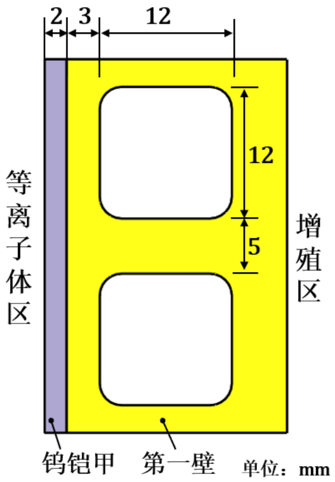
Experiments plan (1/3)

➢ High heat flux test on FW

- Cross area 12×12 mm^2;
- Heat flux at range of 0.5~1MW/m^2
- Parameters: 8-9 MPa, 350-400/375-450℃, mass flow rate 0.2~1.5 kg/s



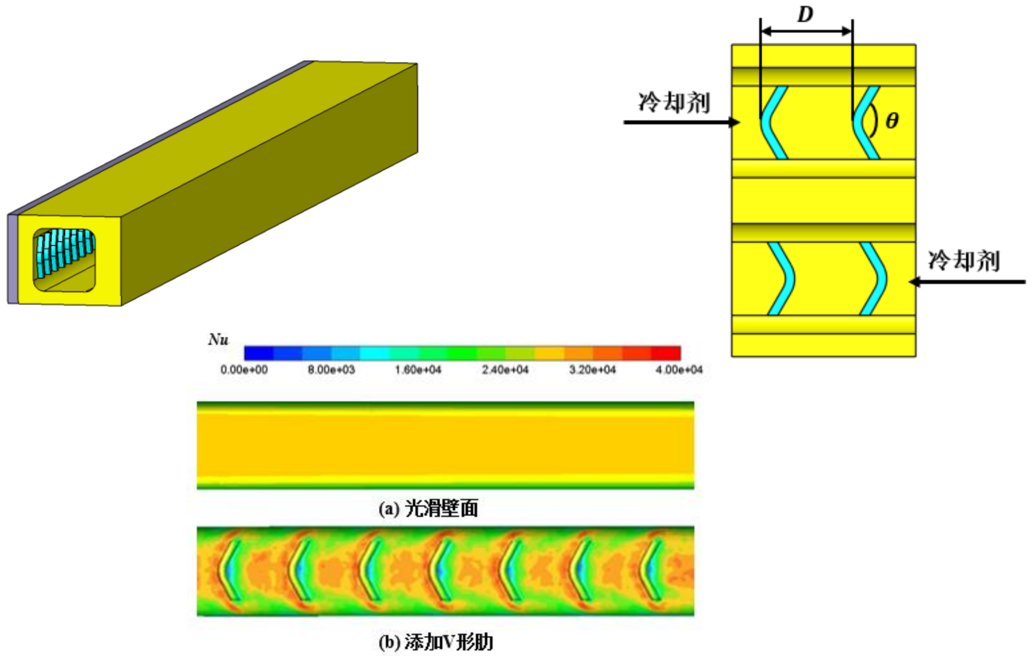
FW test section



A-A cross section

➢ Enhanced heat transfer study

- Cross area 12×12 mm^2;
- Heat flux at range of 0.5~1MW/m^2
- V-shaped rib on plasma facing side
- Parameters: 8-9 MPa, 350-400/375-450℃, mass flow rate 0.2~1.5 kg/s

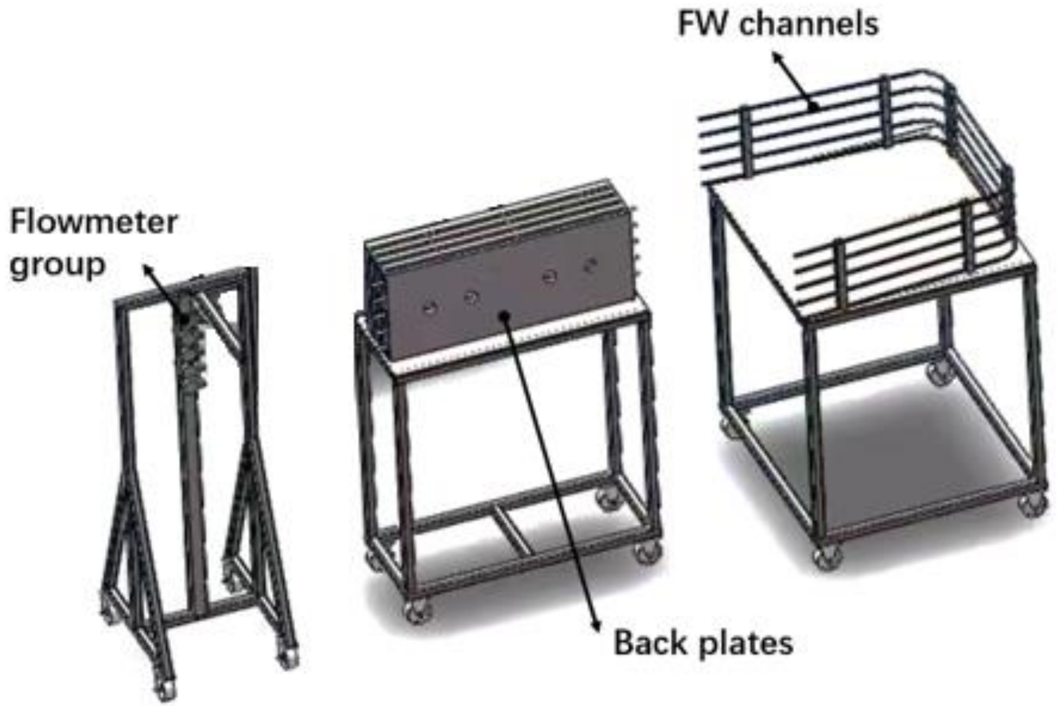


V-shaped rib

Experiments plan (2/3)

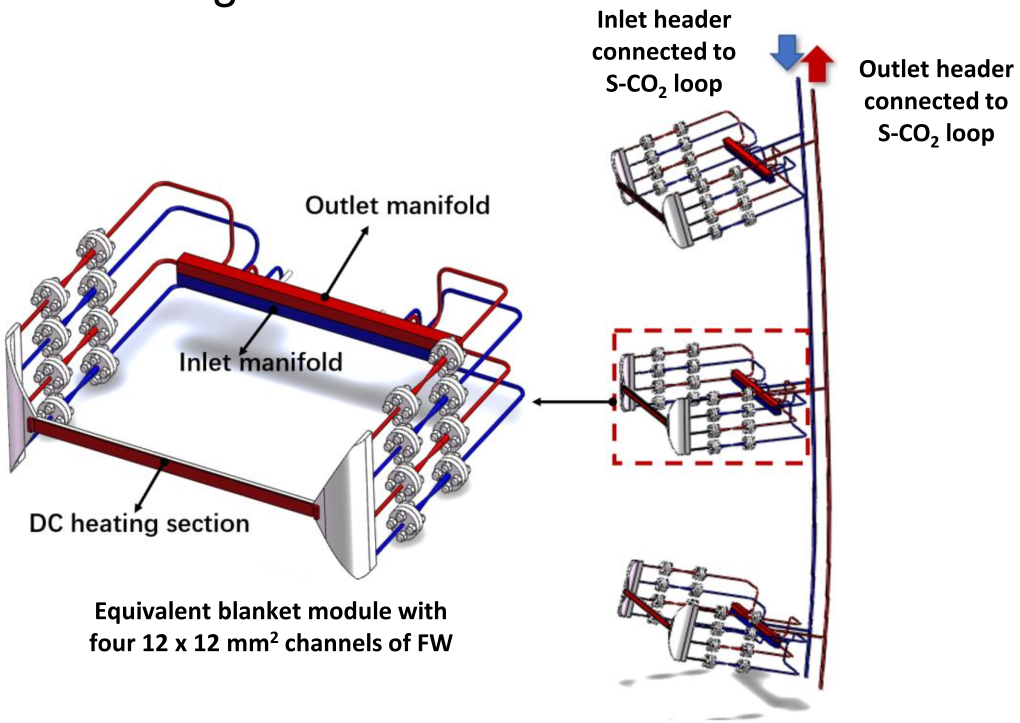
➢ Flow field and distribution

- FW/Manifold/Sector flow distribution in the parallel channels and visualization;
- Parameters: 8-9MPa, 350-500℃, mass flow rate ≤5kg/s.



➢ Flow instability in parallel channels

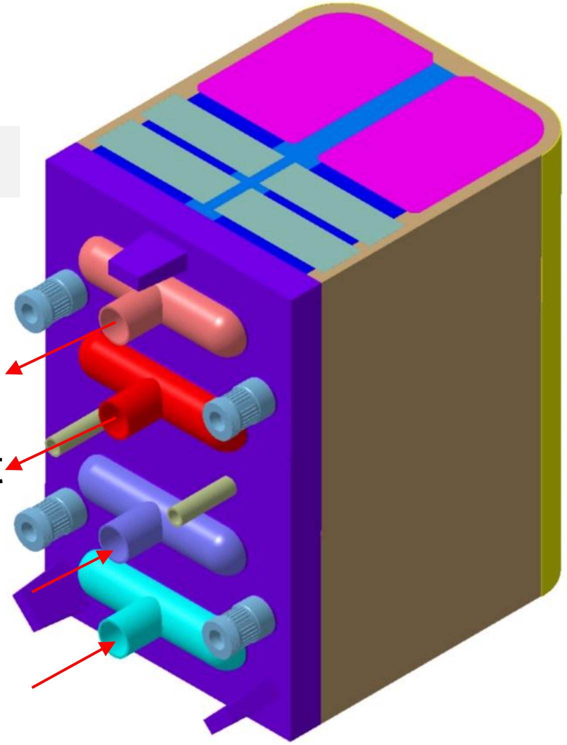
- Flow instability inside the same component or different blanket module;
- Heat flux at range of 0.5~1MW/m^2;
- Parameters: 8-9 MPa, 350-400/375-450℃, mass flow rate 0.8~3 kg/s



Experiments plan (3/3)

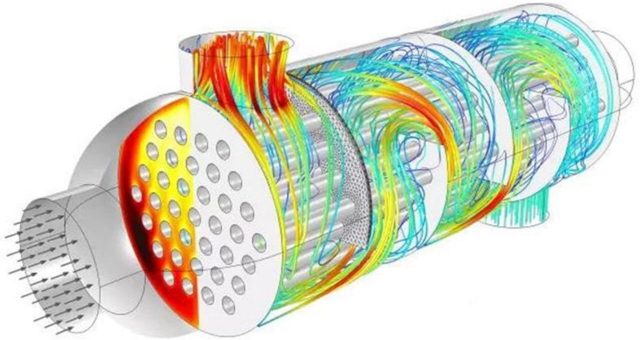
➢ COOL TBM test

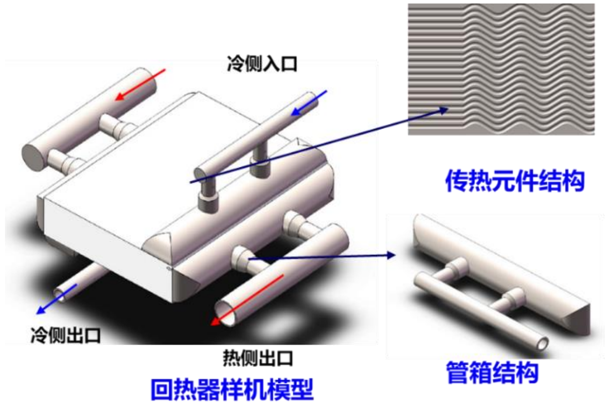
- Thermal power 50-100 kW;
- S-CO_2: 8-9MPa, 350-400℃/400-450℃, mass flow rate 1-2kg/s;
- PbLi: 400-460℃/600-700℃, mass flow rate ≤0.2-2kg/s



➢ Coupling heat transfer between primary and secondary system for BEST COOL TBS

- Thermal power 50-100 kW;
- S-CO_2: 8-9MPa, 350-400℃/400-450℃, mass flow rate ≤2kg/s;
- PbLi: 400-460℃/600-700℃, mass flow rate ≤2kg/s





Water loop & high heat flux test facility

800 kW Electron Beam Gun

- Max. accelerating voltage: 60 kV
- Deflection angle: ±15°
- Frequency: 10 kHz
- Min. spot diam.: 30 mm

60 kW Electron Beam Gun

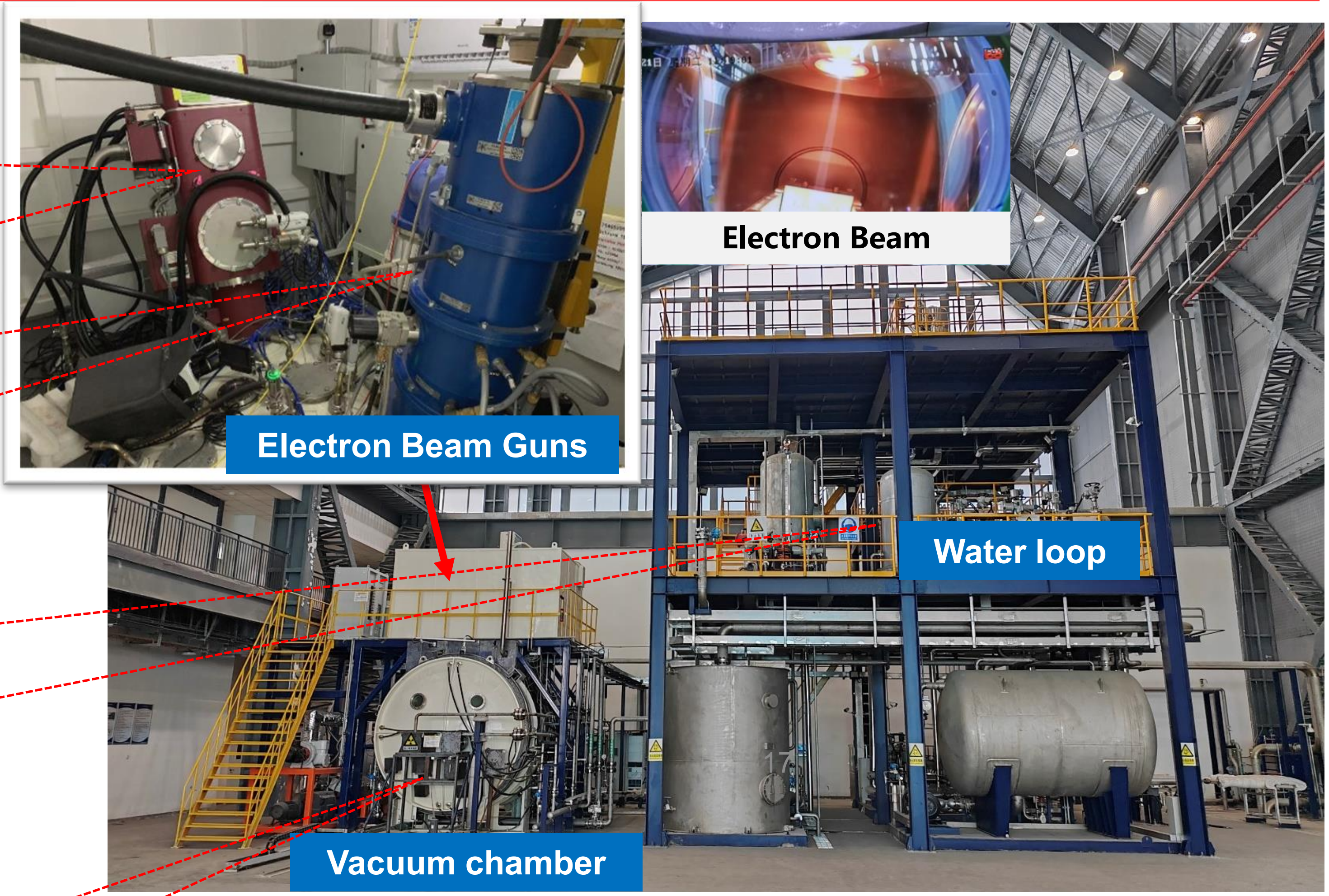
- Max. accelerating voltage: 120 kV
- Deflection angle: ±10°
- Frequency: 10 kHz
- Min. spot diam.: 1 mm

Water loop

- Operating pressure: 15.5 MPa
- Inlet/outlet temp. of the test section: 285 °C/325 °C
- Max. high pressure flow rate: 25 m^3/h
- Max. low pressure flow rate: 160 m^3/h

Vacuum chamber

- Inner diameter 3000 mm
- Length 4000 mm
- Vacuum: 10e-3 Pa

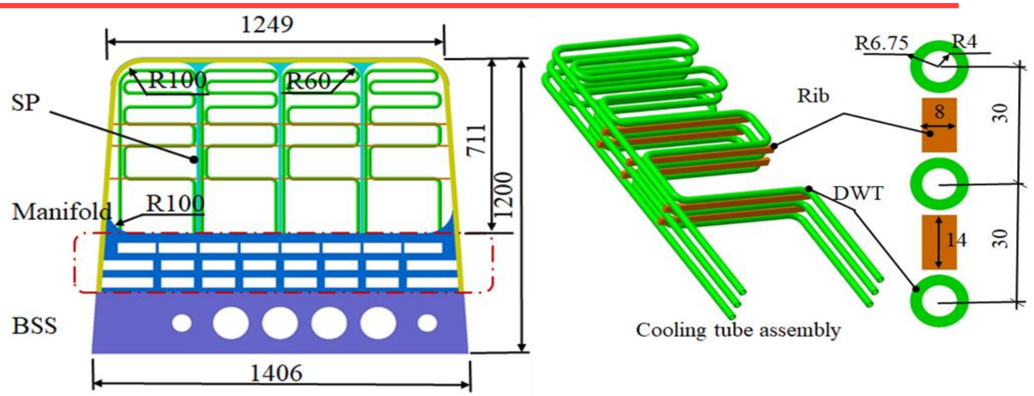


□ General objectives

- Provide non-nuclear high heat flux testing environment
- Validate thermal-hydraulic performance of fusion components
- Evaluate design and fabrication technology for fusion devices

Acrylic WCCB R&D for flow distribution

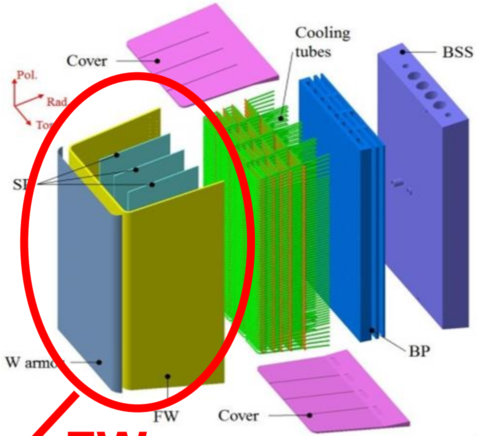
➤ **WCCB breeding zone cooling tubes**



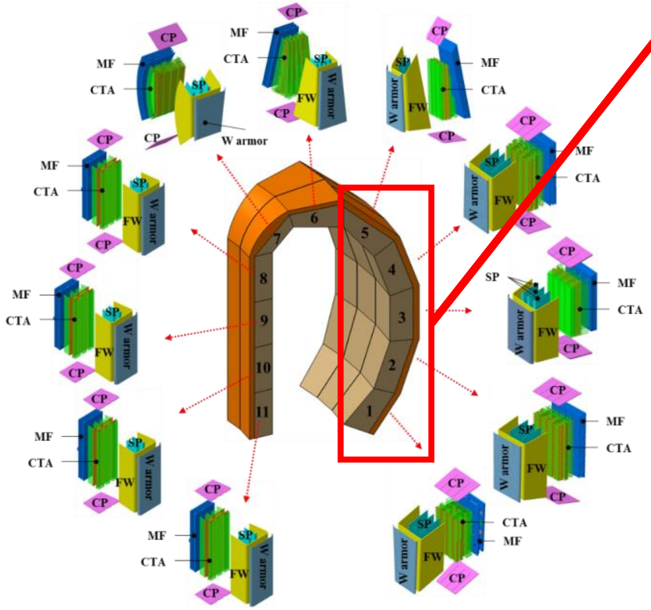
Completely the same with prototype

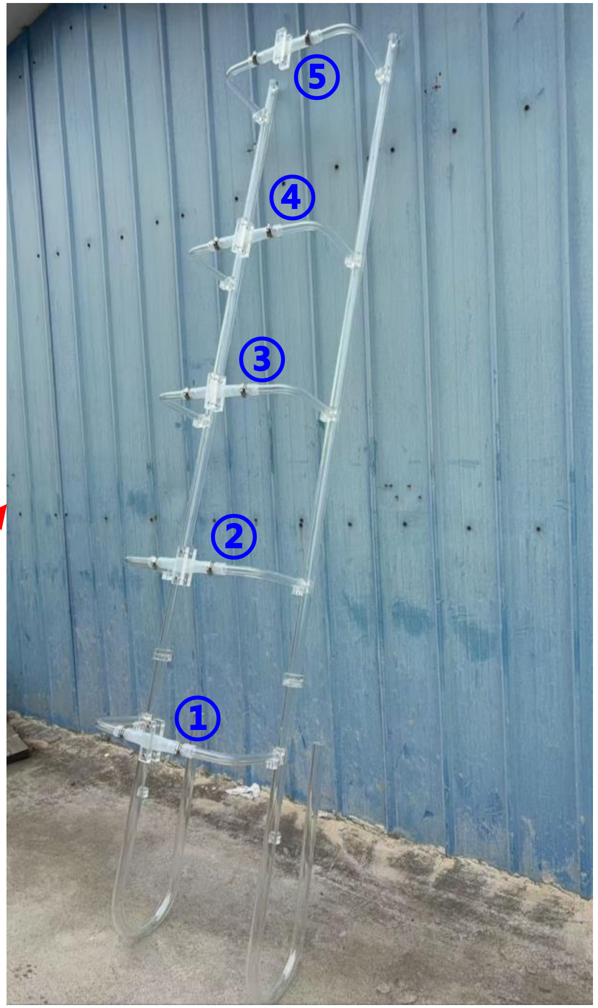
Acrylic WCCB R&D for flow distribution

➢ WCCB FW and segment cooling tubes



FW





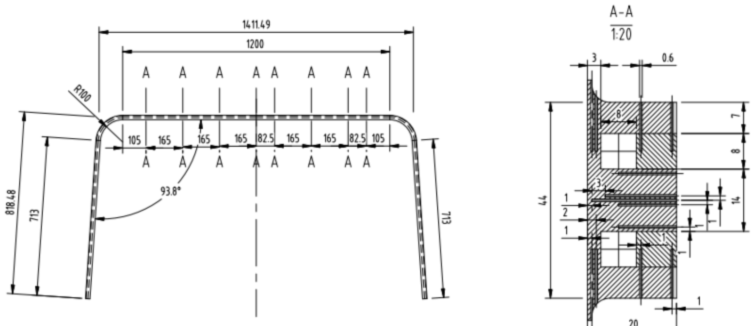
Segment

CHF and flow instability test section design

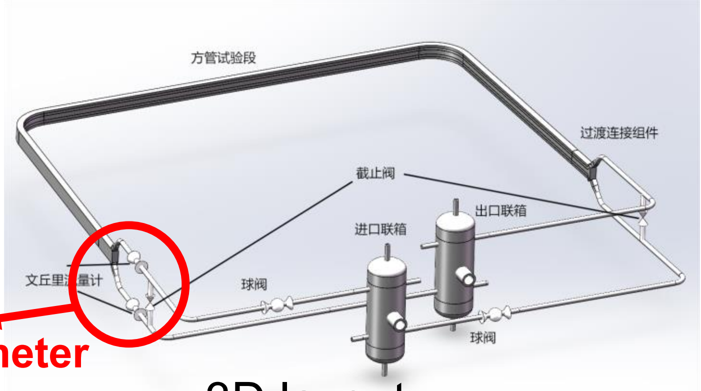
➢ Design on the FW test section

- Liquid-gas phase may occur under high plasma heating flux, inducing the CHF and flow instability.
- Connecting with the high pressure/temperature water loop (15.5MPa, 285/325℃).
- Changing heat flux, mass flow rate and pressure to identify these two phenomenon.

Items	Unit	Parameters
Max. service temperature	℃	≥ 800
Operating pressure	MPa	15.5
Heating length	mm	1200
Inlet temperature	℃	≥285
Max. heat flux	MW/m^2	≥4
Mass flow rate	kg/s	0.36

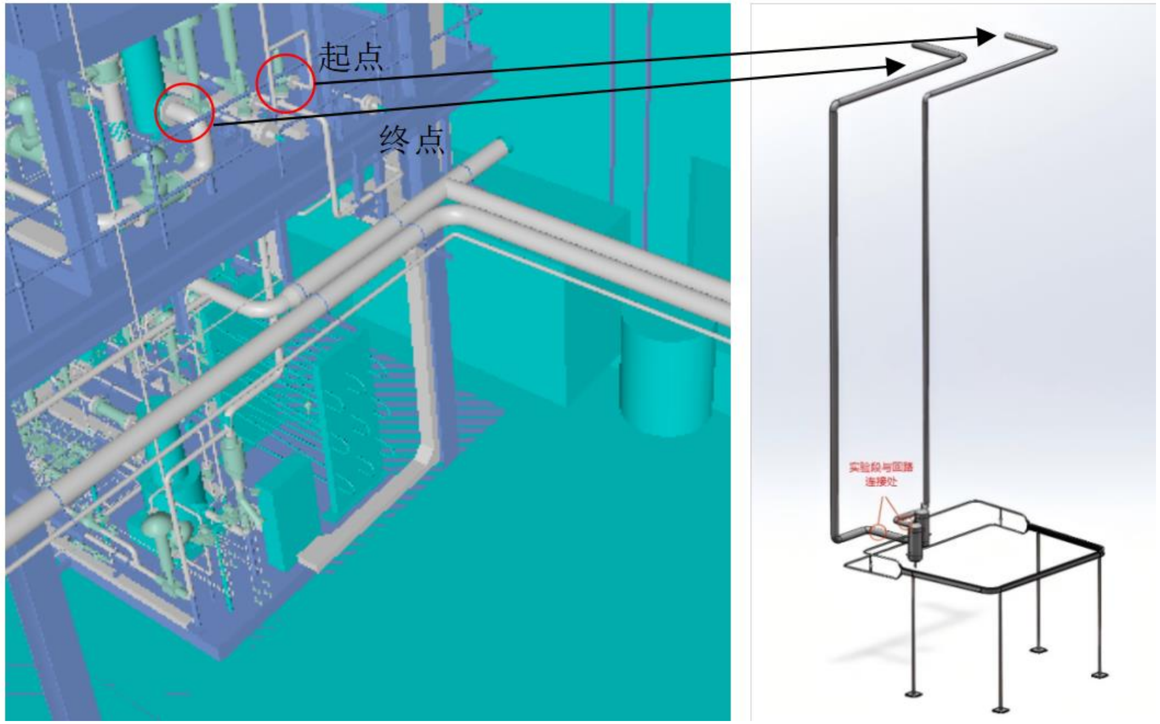


Thermocouple arrangement



Venturi flowmeter

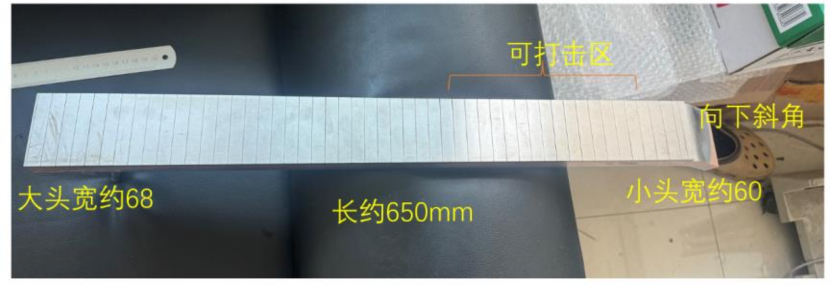
3D layout



Connecting with the water loop

HHF test on fusion components

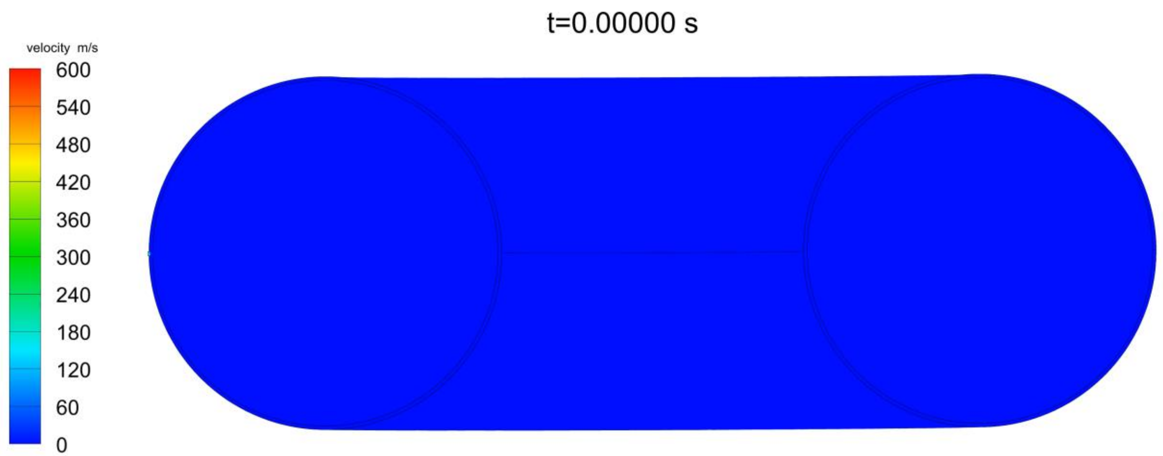
➢ Divertor HHF radiation test

Test samples	Radiation frequency	Radiation results
	**1000次** **(Two weeks)**	
	**1000次** **@20MW/m²** **(Two weeks)**	
	**5000次** **@15MW/m²** **(Two weeks)**	

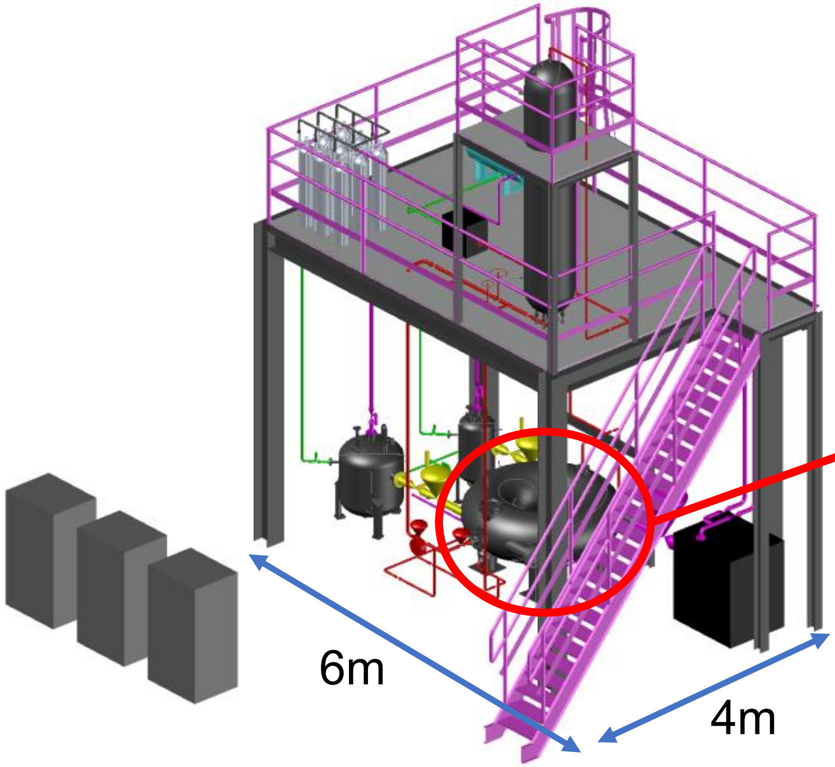
In-VV LOCA test facility

➢ Main objectives

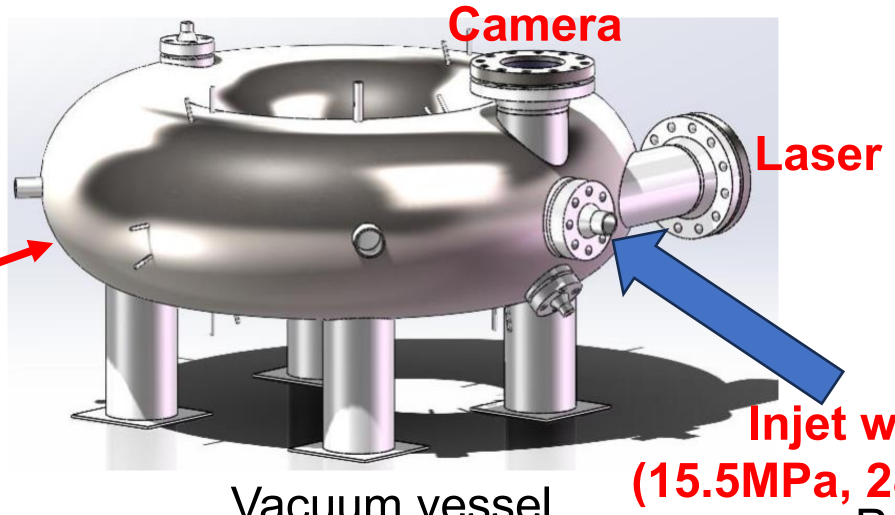
- Identify In-VV LOCA mechanism, and develop safety analysis model.
- Injet water conditions are consistent with WCCB coolant.
- PIV system is adopted to capture the transient velocity field.



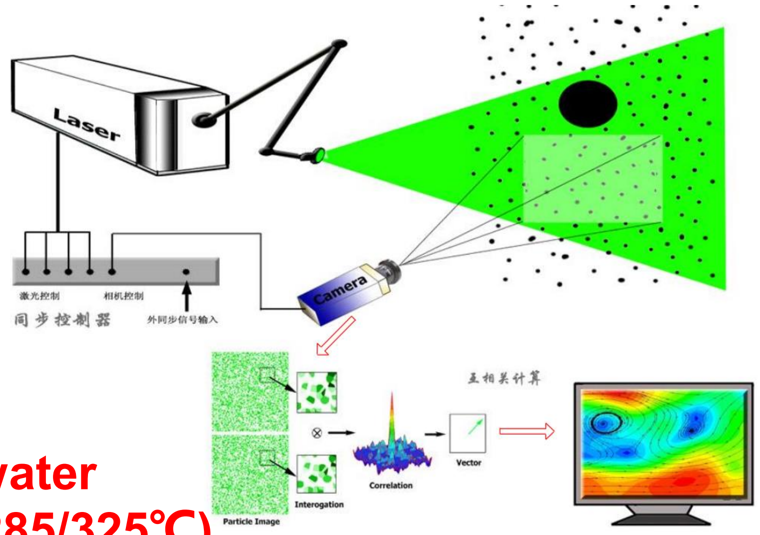
Velocity field by CFD simulation



3D layout

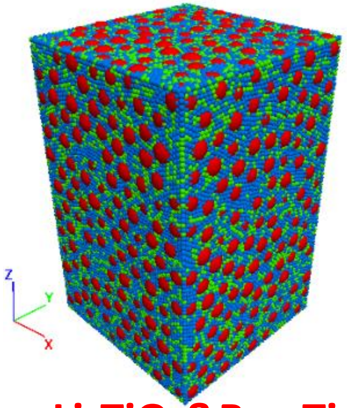


Vacuum vessel



Particle Image Velocity (PIV) system

Pebble bed test facilities



Li_2TiO_3&$Be_{12}Ti$ mixed pebble bed for tritium breeding

① Thermal hydraulic facility

- Flow and heat transfer characterization
- 0.1~2 MPa He, RT~500 ℃, 0~80 Nm^3/h

② Thermo-mechanical facility

- Thermo-mechanical characterization
- RT~800℃, 0.1~0.3 MPa helium, 0~10 MPa load

③ Mixing and sieving facility

- Breeder loading/ unloading testing
- Flow rate ≥ 360 kg/h, Mixing uniformity ≥ 0.9

④ Computer Tomography (CT)

- Packing structure testing/crack analysis
- Sample < 200×200×200 mm^3, Max. resolution < 20 μm

⑤ Vibration testing facility

- Packing structure stability testing
- He flow, 0~5 MPa load, 0~10 g, 1~100 Hz

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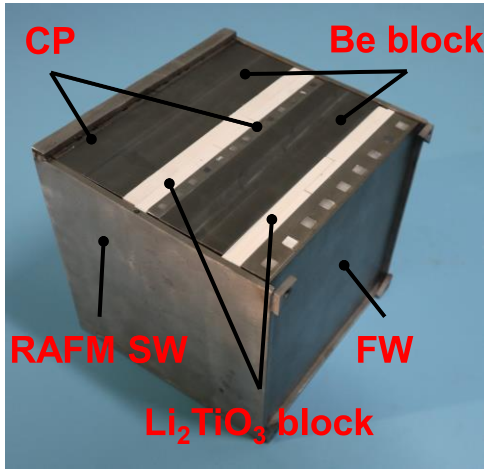
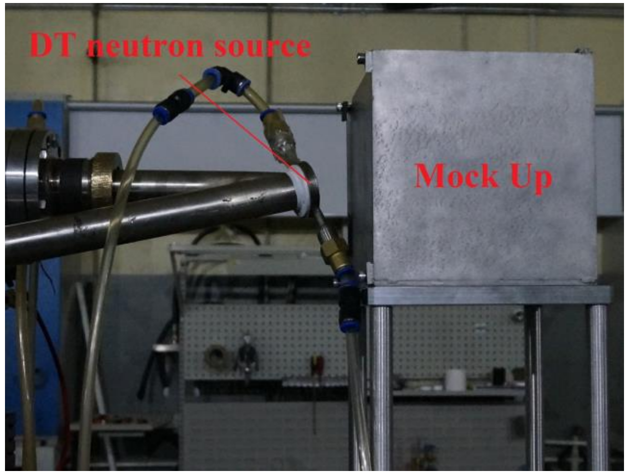
  - Pebble beds test facilities
- **Nuclear measurements**
- Concluding remarks

Neutronics experiments for WCCB mockup

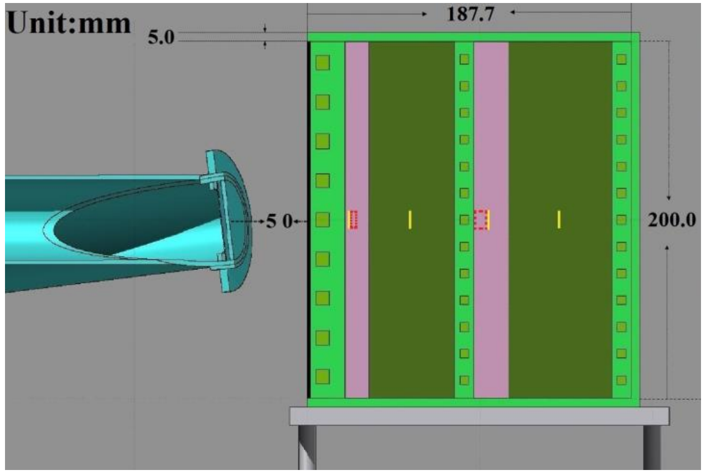
□ Tritium Production Rate (TPR) measurement by DT neutron source

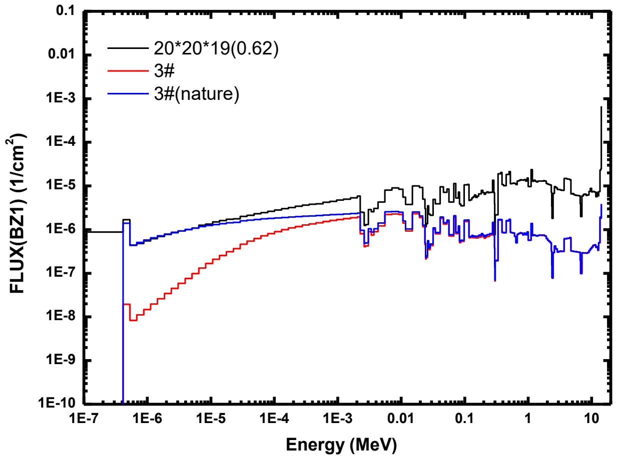


WCCB Mockup (20×20×19 cm)
(scaled module #3 of WCCB V2013)

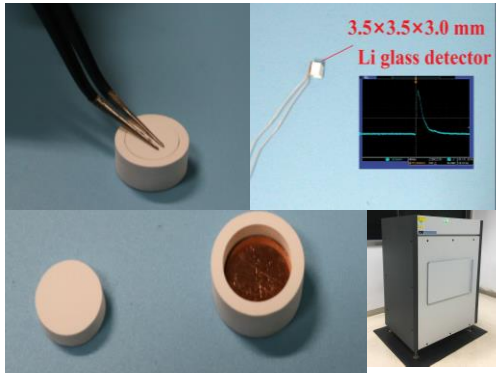


Experiment setup

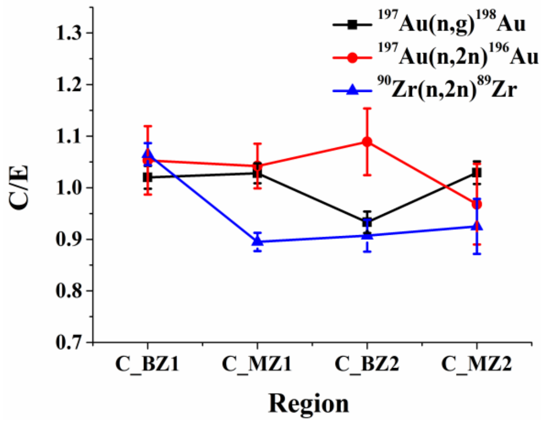




Monte Carlo model and neutron flux comparison between WCCB blanket module #3 and the scaled mockup



Detector



C/E of activation foils

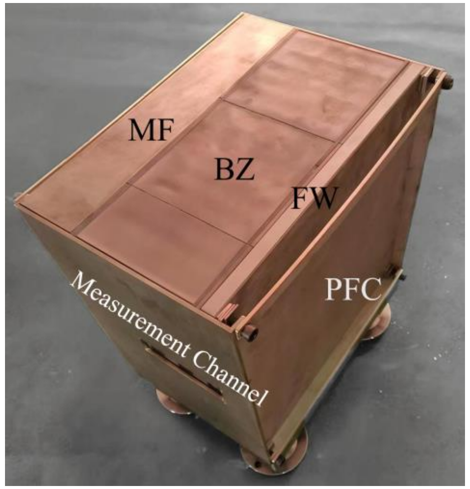
Calculated/Experimental results of TPR

Position	Calculation	Experiment	C/E
TPR in Li_2TiO_3 off-line measurement			
C_BZ1	1.220E-05	1.062E-05	1.06
C_BZ2	8.030E-06	7.609E-06	0.97
TPR in ^{6}Li glass on-line measurement			
C_BZ1	3.492E-05	3.773E-05	1.08
C_BZ2	4.069E-05	4.245E-05	1.04

- **DT neutron source** at CIAE (China Institute of Atomic Energy)
- **TPR measurement by** online lithium glass detector and offline liquid scintillator
- **Calculated/Experimental results of TPR are consistent**

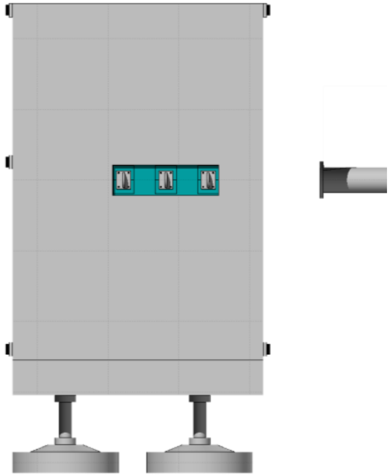
Neutronics experiments for COOL mockup

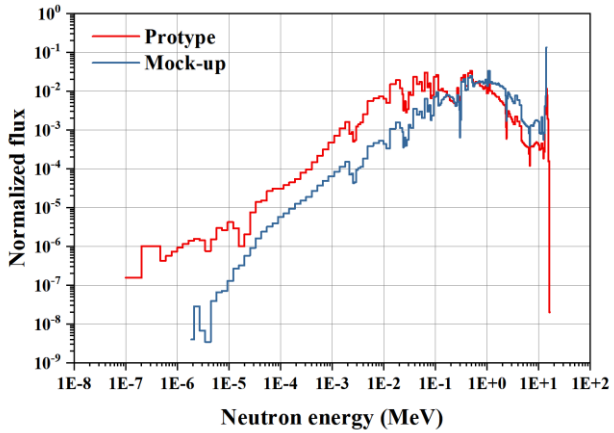
□ Tritium Production Rate (TPR) measurement by DT neutron source



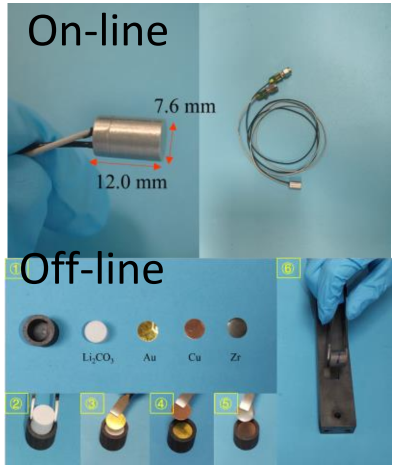
COOL Mockup (50×50×33 cm)
(scaled module #3 of COOL V2021)

Experiment setup





Monte Carlo model and neutron flux comparison between COOL blanket module #3 and the scaled mockup



Detector

Calculated/Experimental results of TPR

Radial (mm)	Toroidal (mm)	Experiment (atoms/cm3/sn)	Calculation (atoms/cm3/sn)	On-line C/E ratio	Experiment (atoms/cm3/sn)	Calculation (atoms/cm3/sn)	Off-line C/E ratio
21.4	0	4.25E-06	4.32E-06	0.99±4.91%	3.00E-06	2.76E-06	1.09±4.05%
21.4	100	2.41E-06	2.31E-06	1.04±5.92%	2.15E-06	2.16E-06	1.00±3.66%
21.4	200	1.26E-06	1.23E-06	1.02±5.88%	9.80E-07	1.08E-06	0.91±3.42%
81.3	0	3.61E-06	3.45E-06	1.05±5.17%	1.48E-06	1.35E-06	1.09±4.05%
81.3	100	2.97E-06	3.02E-06	0.98±4.76%	1.16E-06	1.10E-06	1.05±4.00%
81.3	200	1.58E-06	1.64E-06	0.96±5.66%	6.09E-07	5.66E-07	1.08±4.02%
141.3	0	2.86E-06	3.01E-06	0.95±4.63%	8.59E-07	8.10E-07	1.06±3.89%
141.3	100	2.46E-06	2.23E-06	1.10±5.61%	6.96E-07	6.83E-07	1.02±3.76%
141.3	200	1.34E-06	1.37E-06	0.98±4.66%	3.89E-07	3.96E-07	0.98±3.66%

- **DT neutron source** at CIAE (China Institute of Atomic Energy)
- **TPR measurement by** online lithium glass detector and offline liquid scintillator
- **Calculated/Experimental results of TPR are consistent**

Concluding remarks

- **TH/MHD test facilities and experimental design are ongoing to support the COOL and WCCB blanket design, mainly including:**
  - Turbulent heat transfer, MHD effects and mixed convection under large heating source and magnetic fields
  - High heat flux test, enhanced heat transfer technology development, flow distribution and instability
  - Moreover, the out-pile of Mockup will be fully tested before its installation into the fusion reactor
  - Identify In-VV LOCA mechanism, and develop safety analysis model.
  - TH, TM, Mixing and sieving and vibration test for pebble beds
- **Nuclear measurements on TPR have been carried out for COOL and WCCB mock-up**
  - TPR measurement by online lithium glass detector and offline liquid scintillator
  - Calculated/Experimental results of TPR are consistent

Thank you for your attention!