15th International Symposium on Fusion Nuclear Technology (ISFNT)

Progress in the Conceptual Design of the Supercritical CO_2 Cooled Lithium-Lead Blanket and the Power Conversion System for CFETR

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Topic: Blanket technology
Las Palmas de Gran Canaria, Spain, 10-15 September 2023

Outline

- Introduction
- COOL blanket analysis
- Power conversion system
- R&D progress
- Summary

Motivation (1/2)

➢Roadmap of nuclear energy development in China

Pressurized Water Reactor (1985 to ~2020)

Thermal efficiency: ~33%

- **1985-2015:** Qinshan Nuclear Power Station, 656MWe in total
- **~2000-2018:** EPR/AP1000/CAP1400…, ~1000MWe/~3000MWth
- **2021:** HPR-1000 (Hua-long Pressurized Reactor), 1150MWe/3190MWth

Fast Reactor (1992 to ~2030)

Thermal efficiency: ~40%

- **1992-2014:** CEFR (China Experimental Fast Reactor), 20MWe/65MWth
- **~2023:** CFR-600 (China Fast Reactor), 600MWe/1500MWth
- **~2030:** CFR-1000 (China Fast Reactor) 1000MWe/2500MWth

Fusion Reactor (~2035 to 2050)

Thermal efficiency: >40%?

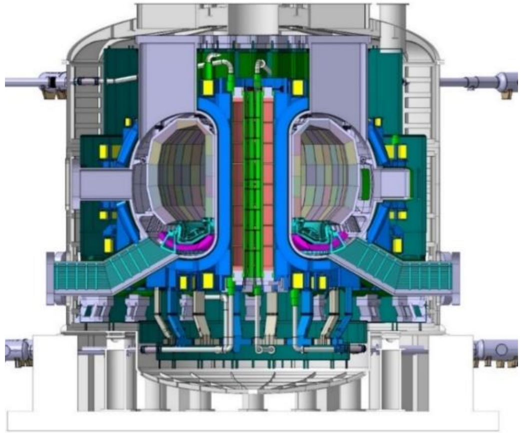
- **1984-:** HL-1/EAST/HL-2M/J-TEXT…, Physical experimental devices
- **2017-2035:** CFETR (China Fusion Engineering Test Reactor), fusion power up to 1500 MW
- **~2050:** Fusion Power Plant

Motivation (2/2)

➢CFETR Solid Blanket Candidates

◆ HCCB BLK option by SWIP

- **Coolant:** Helium @ **12 MPa**, 300 ℃/ 550 ℃
- **Structure:** RAFM/ODS steel
- **FW armor:** 2 mm Tungsten
- **Breeder/Multiplier:** Li_4SiO_4/**Be**
- **Purge gas:** He + 0.1vol% H_2 @1-3 bar
- **Thermal efficiency:** **~36%**

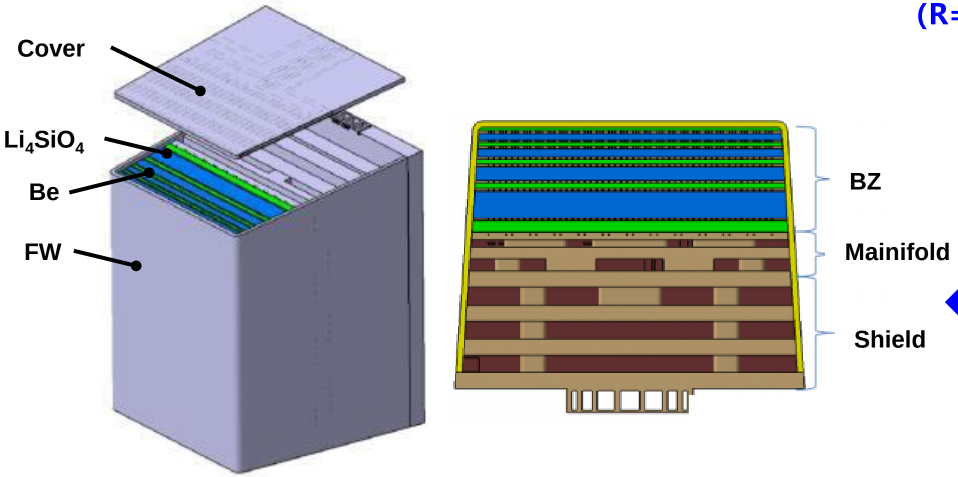


CFETR configuration

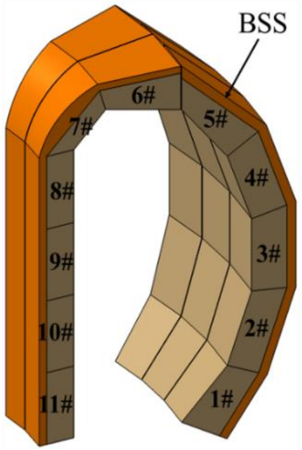
(R=7.2m, a=2.2m, FP200/500/1000/1500MW)

◆ WCCB BLK option by ASIPP

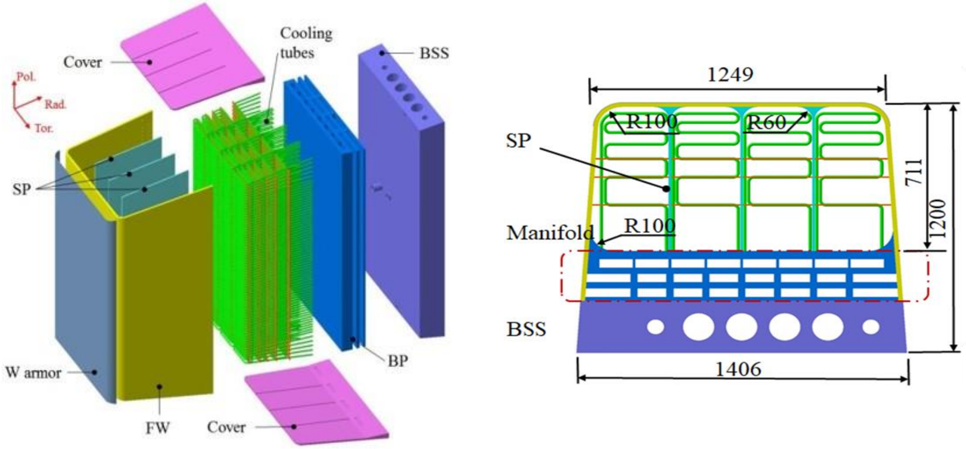
- **Coolant:** pressurized water of **15.5 MPa**, 285 ℃/325 ℃
- **Structure:** RAFM/ODS steel
- **FW armor:** 2 mm Tungsten
- **Breeder/Multiplier:** Li_2TiO_3/**$Be_{12}Ti$** mixed bed
- **Purge gas:** He + 0.1vol% H_2 @1-3 bar
- **Thermal efficiency:** **~33%**



Typical Helium Cooled Ceramic Breeder (HCCB) Blanket module 3#



Same blanket sector configuration (16 sectors, each including 3×5 outboard and 2×6 inboard blankets)

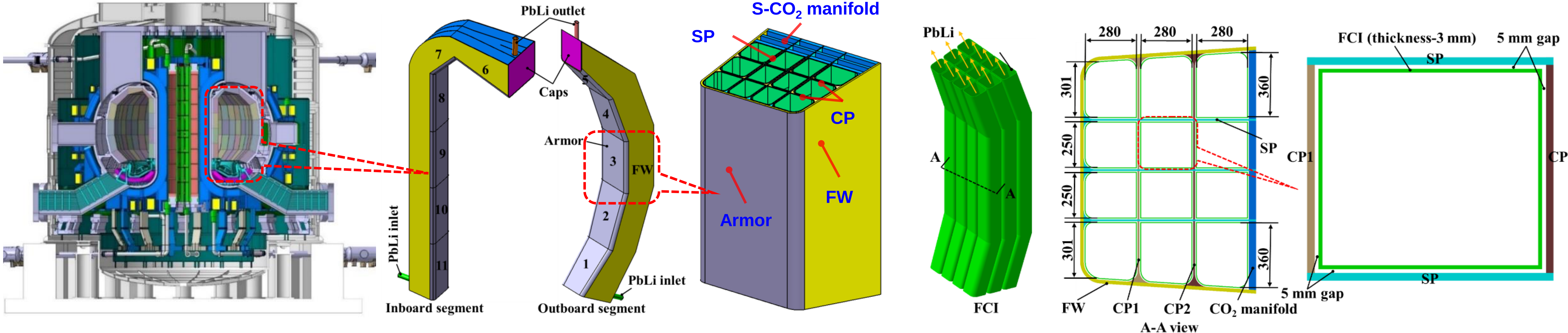


Typical Water Cooled Ceramic Breeder (WCCB) Blanket module 3#

High-efficient and safe fusion blanket with low construction cost is more competitive for fusion energy application

Supercritical CO_2 Cooled Lithium-lead (COOL) Blanket

➢COOL blanket (BLK): an advanced BLK option for CFETR in the long term



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

Typical COOL BLK segment

Typical COOL breeding unit

Cross section

➢Design features

- Single-module segment
- Dual coolant
  - 8 MPa S-CO_2 cooling structures, 350 °C ~390 °C
  - PbLi self-cooling BZ, outlet 600-700 °C
- RAFM steel as structural material
- Tungsten as armor material
- SiC_f/SiC composites as Flow Channel Inserts (FCI) material
- Thermoelectric conversion efficiency: 39~46%

➢Advantages and disadvantages

- **High thermal efficiency:** high PbLi outlet temp. and more suitable for efficient power conversion
- **Acceptable construction cost:** (1) cheaper neutron multiplier of Pb; (2) abundant CO_2 in natural world
- **Enhanced heat removal capacity of S-CO_2 for FW cooling:** larger density than helium (over 10 times @8MPa, 400℃)
- **MHD effect and metal corrosion problems:** mitigate by using electrical and thermal insulating Flow Channel Inserts (FCIs)

Outline

- Introduction
- COOL blanket analysis
  - Nuclear analysis
  - Thermal hydraulic analysis
  - MHD analysis
  - Thermo-mechanical analysis
  - Safety analysis
- Power conversion system
- R&D progress
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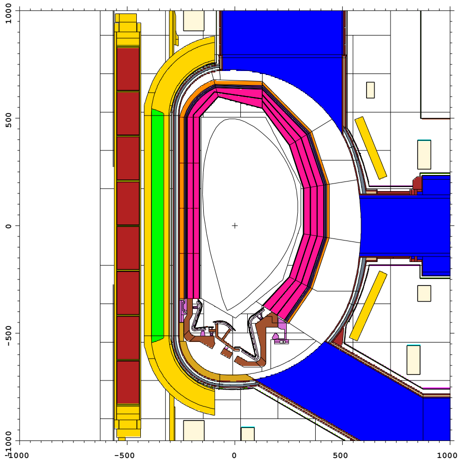
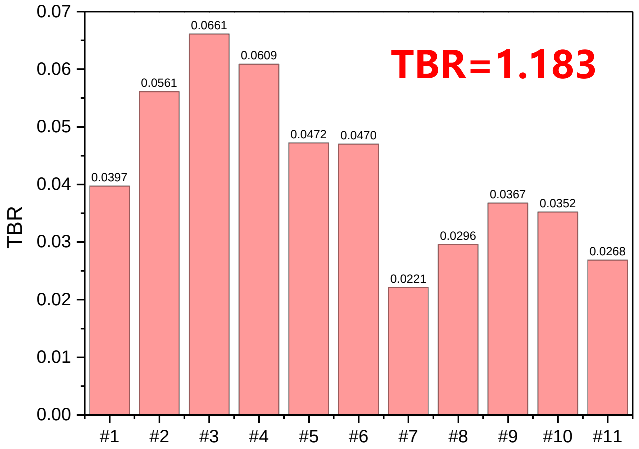
Nuclear Analysis (1/4)

➢Tritium breeding ratio (TBR)

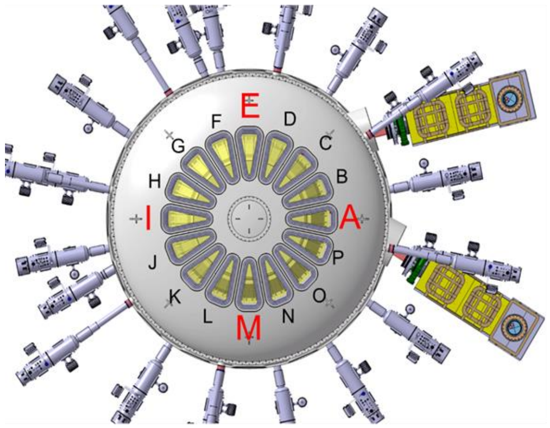
- **TBR=1.183** without considering port effects of heating and diagnostic systems of CFETR
- **TBR=1.113 considering port effects of CFETR**
- **TBR=1.166 considering port effects of CFETR and contribution of divertor blankets behand divertors**
- **Concept of the divertor blanket:** three sub-modules consisting of box structure and breeder zones, sharing water coolant with divertors



Neutronics Model

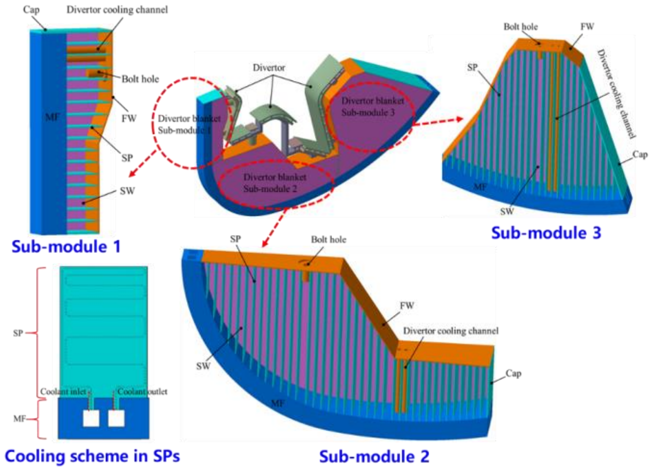


TBR



A:
B:
C:
D:
E: Diagnostics
F:
G:
H: ECRH
I: ECRH
J: ECRH
K: Diagnostics
L:
M: LHW
N: ICRH
O: ICRH
P: ICRH

CFETR ports for heating and diagnostic systems



Preliminary design of divertor blanket

TBR calculation considering heating/diagnostic systems

System	Configuration & BLK occupation	ΔTBR
ECRH	3 sets at upper port, 1 set uses 2 modules of BLK #4	-0.0146
ICRH	3 sets at upper port, 1 set uses 2 modules of BLK #5	-0.0174
LHW	1 set at upper port, 1 set uses 1 module of BLK #5	-0.0029
NBI	2 sets at middle port, 1 set uses 2 modules of BLK #2 and 2 modules of BLK #3	-0.005
Diagnostics	2 sets at middle port, 1 set uses 3 modules of BLK #2 and 3 modules of BLK #3	-0.021
limiter	3 sets at upper port, 1 set uses 1 module of BLK #6	-0.009
Divertor blanket	-	+0.053

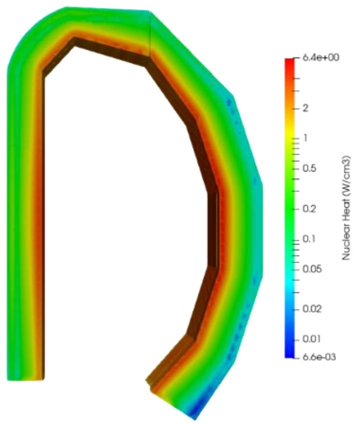
Nuclear Analysis (2/4)

➢Nuclear heating

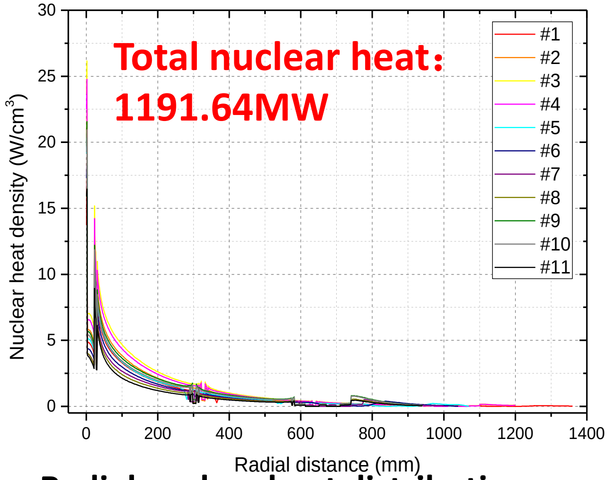
- **Total nuclear heat is 1.2 GW at the fusion power of 1.5 GW**
- **Exponential decay along the radial direction**

Nuclear heating in each breeding unit

Breeding unit	1	2	3	4	5	6	7	8	9	10	11
Nuclear heat (MW)	2.29	3.45	4.24	3.83	2.84	2.88	1.32	1.72	2.45	2.33	1.55



Nuclear heating in TFC

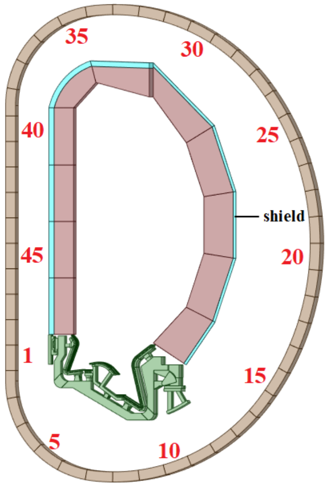


Radial nuclear heat distribution

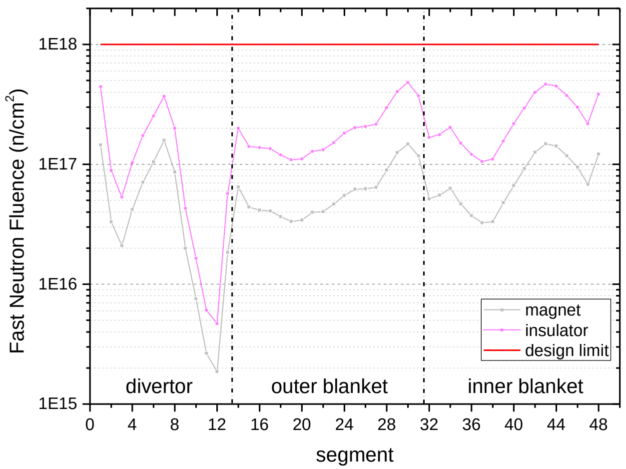
➢Shielding performance

- **Enough shielding for the magnet coils**

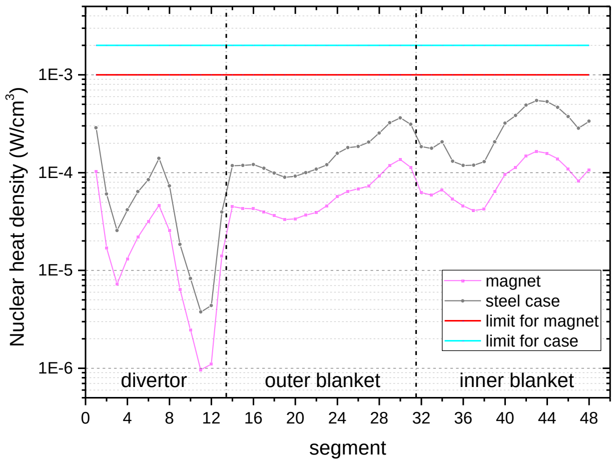
	ITER Design Limit
Fast neutron fluence in magnet conductor (n/cm2) （10 FPY）	1 × 10^{19}
Fast neutron fluence in insulator (n/cm2) （10 FPY）	1 × 10^{18}
Nuclear heating in magnet steel case (W/cm3)	2 × 10^{-3}
Nuclear heating in magnet conductor (W/cm3)	1 × 10^{-3}



TFC Neutronics Model



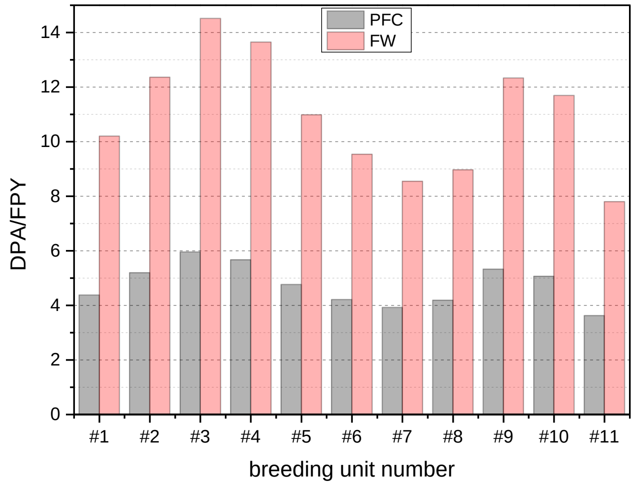
Fast neutron fluence in TFC

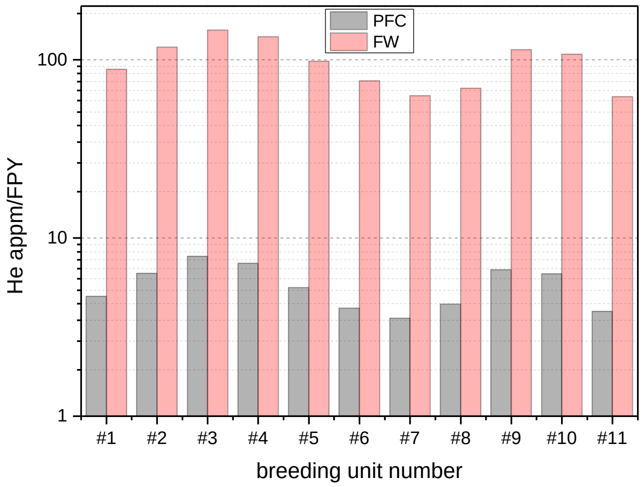


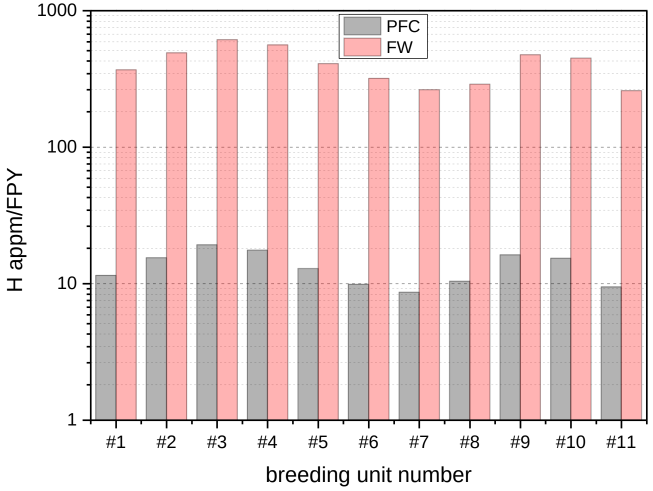
Nuclear heating in TFC

Nuclear Analysis (3/4)

➢Irradiation damage and gas(He/H) production rate in one FPY @1.5GW

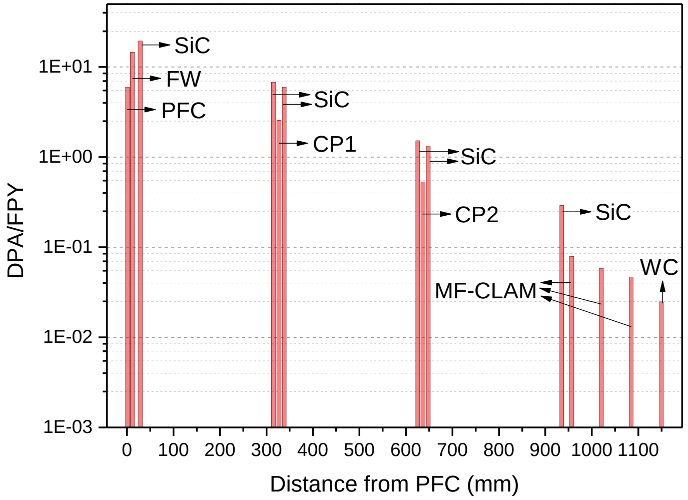




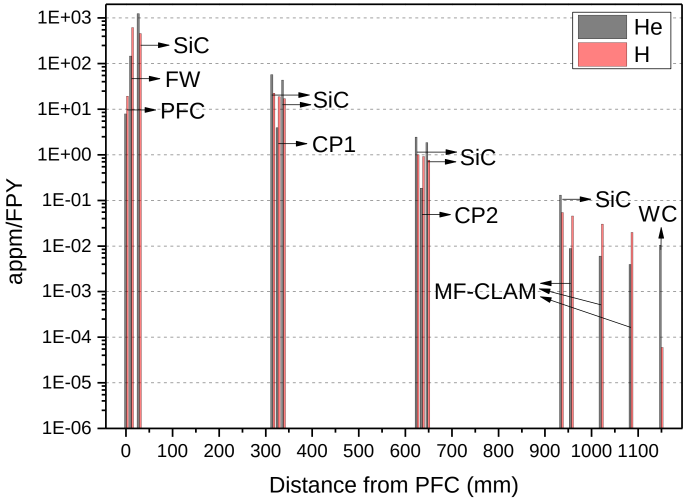


	3#		9#	
	PFC	FW	PFC	FW
DPA/FPY	5.96	14.52	5.33	12.33
He appm/FPY	7.86	146.80	6.62	113.64
H appm/FPY	19.26	612.76	16.21	475.12

Irradiation on PFC and FW for unit #1-11



SiC > SS > W



SiC/WC: He>H
SS/W: H>He

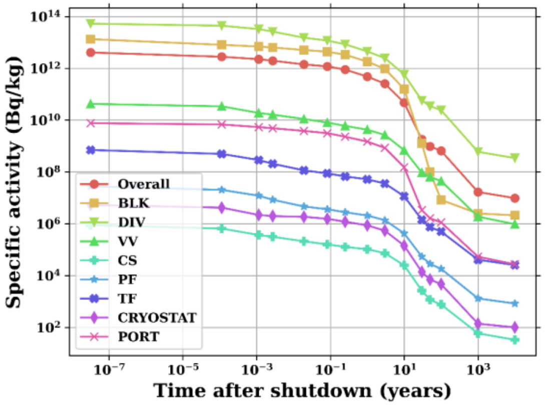
Irradiation on structural components for unit #3

Nuclear Analysis (4/4)

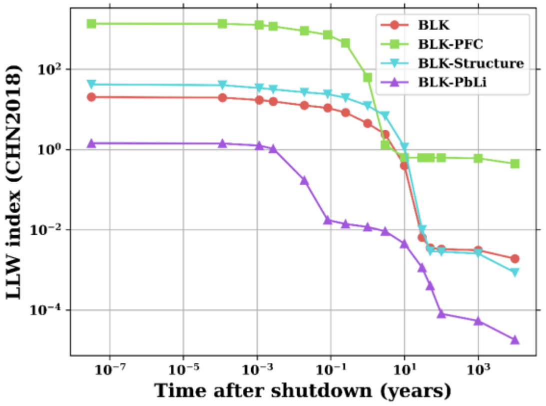
➢Activation and Hazardous Inventories

- **Operation scheme:** 200MW 2Y, 500MW 4 Y, 1GW 10 Y, 1.5GW 4 Y (duty factor=0.5);
- **COOL BLK radioactive waste:** 1150 m^3 and PbLi contributes 60%, but it can be recycled;
- **COOL BLK decays to a low level waste (LLW) after 10 years of shutdown and can be recycled.**

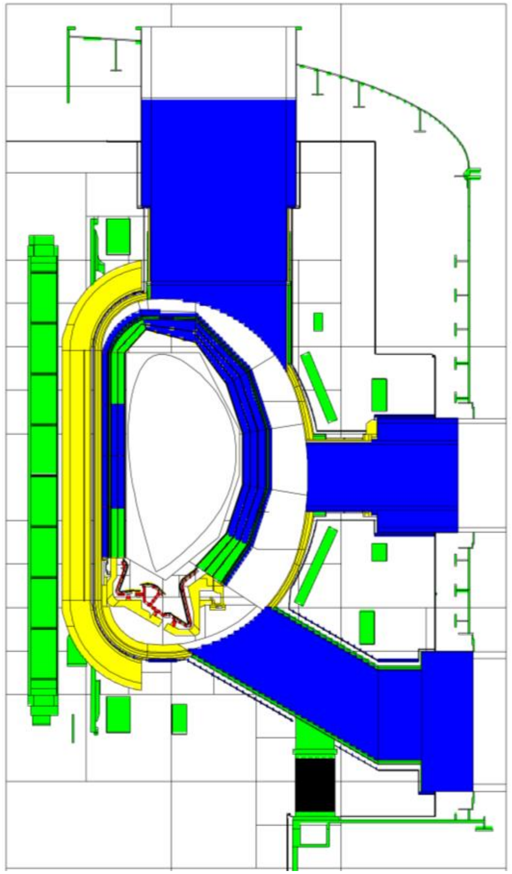
Components	radioactive waste volume(m^3)
BLK	1.15E3
BLK-RAFM	4.63E2
BLK-PFC	1.91E0
BLK-PbLi	6.99E2
DIV	2.25E2
VV	6.33E2
CS	2.25E2
PF	5.14E2
TF	1.45E3
Cryostat	6.89E2
Port	4.88E3
Total	1.02E4



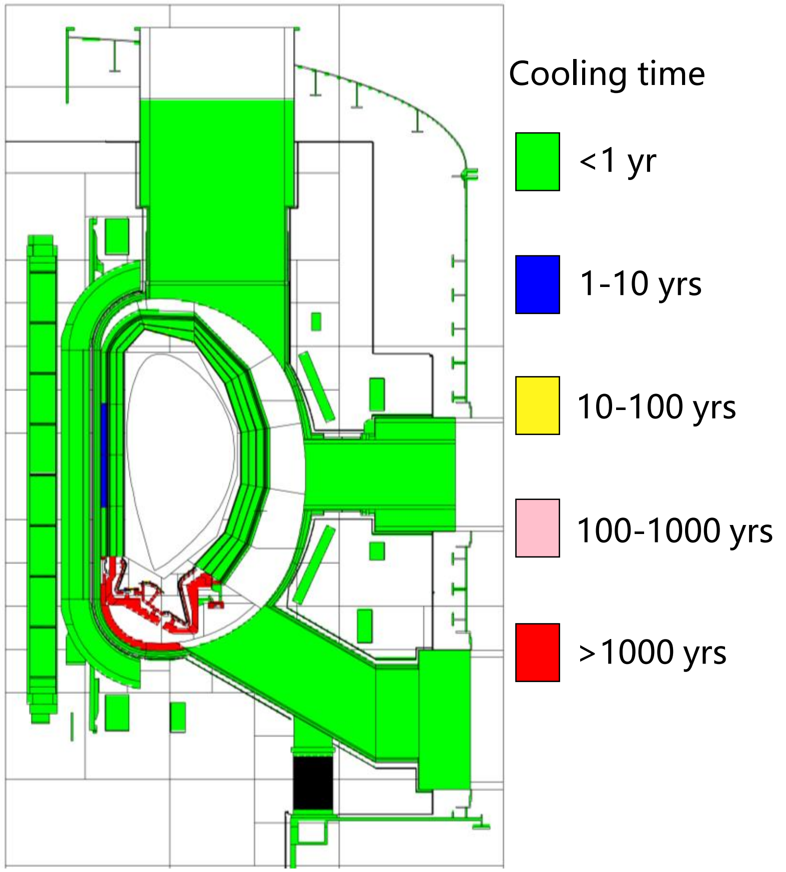
specific activity of CFETR machine



Index of low level waste variation



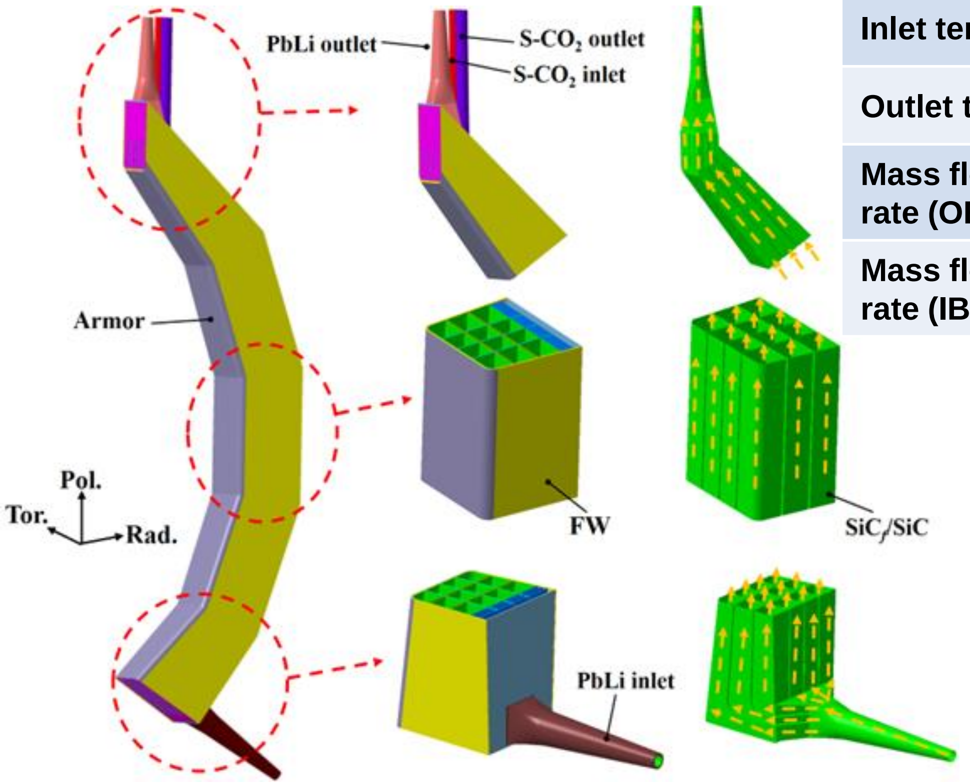
Time to recycling (<1E-2 Sv/hr)



Time to low level waste

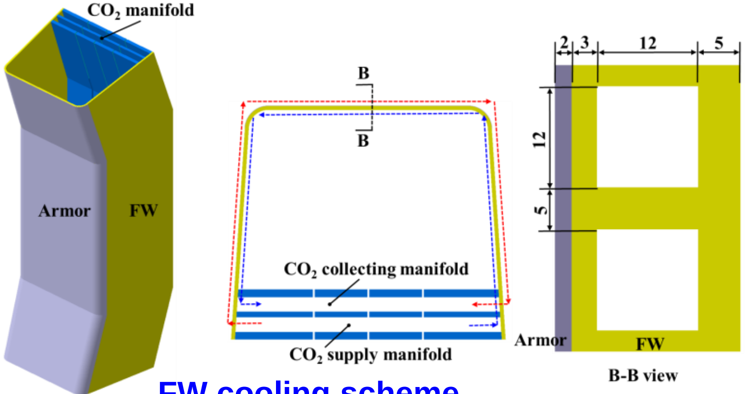
Thermal hydraulic analysis (1/2)

➢Coolant Flow Scheme



PbLi parameters

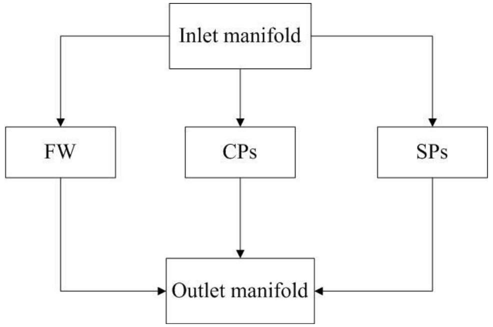
Inlet temp.	460 ℃
Outlet temp.	600/700 ℃
Mass flow rate (OB)	483/283 kg/s
Mass flow rate (IB)	332/195 kg/s



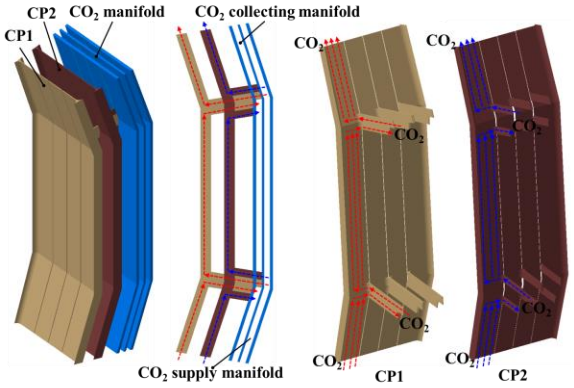
FW cooling scheme

S-CO$_2$ parameters

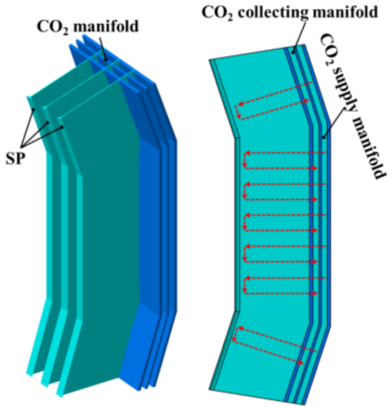
Inlet temp.	350 ℃
Outlet temp.	400 ℃
Mass flow rate (OB)	194 kg/s
Mass flow rate (IB)	185 kg/s



S-CO$_2$ Flow Scheme



CP cooling scheme



SP cooling scheme

☐ PbLi Inlet/Outlet Manifold

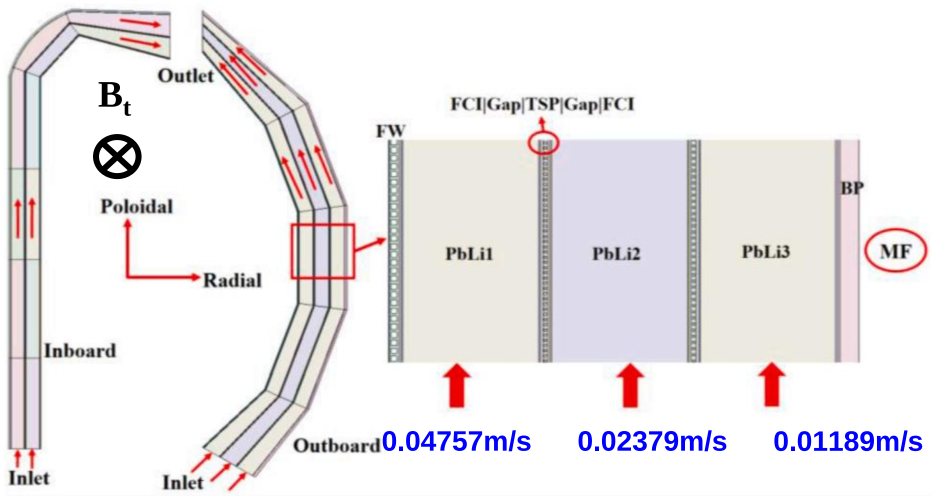
- FCIs to mitigate MHD effect and metal corrosion
- To mitigate severe MHD effect induced by sudden expanding/reducing duct, divergent/convergent tubes are used for the PbLi inlet/outlet manifold

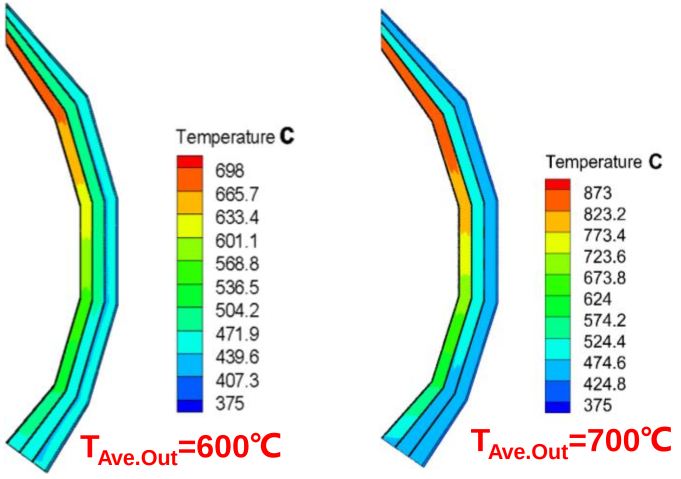
☐ S-CO$_2$ Flow Scheme

- CO$_2$ coolant is supplied by the SCO$_2$ feeding pipe from the upper ports of CFETR, then distributed to parallel built-in channels in FW/CP/SP structures, and finally collected by the SCO$_2$ outlet at the upper ports of CFETR.

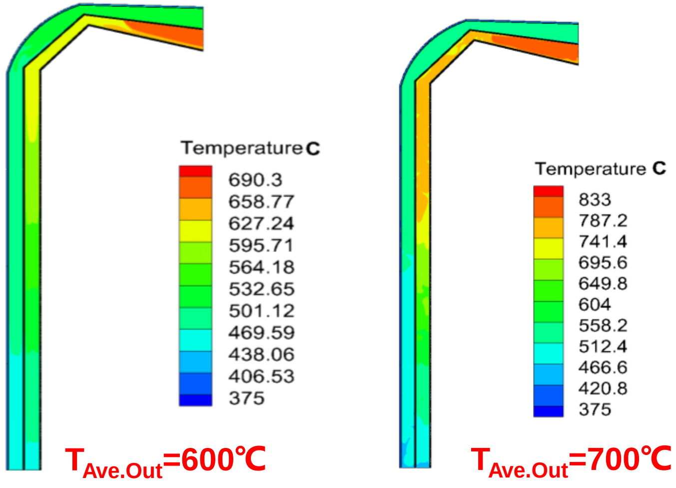
Thermal hydraulic analysis (2/2)

- ➢ PbLi outlet temp. at 600 ℃ and 700 ℃ is achievable by using thermal insulating SiC FCIs (k=3.5W/(m·K)). Meanwhile the RAFM-PbLi interface is below 480 ℃ (corrosion temp. limit for RAFM).
- ➢ The radial temp. gradient is high up to ~200-400 ℃ and the PbLi channel nearby FW has higher outlet temp.





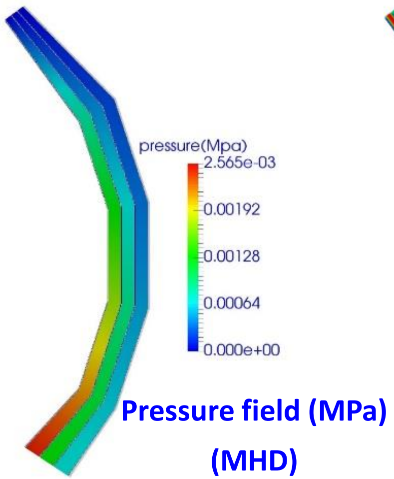
Outboard segment temp. (non-MHD)



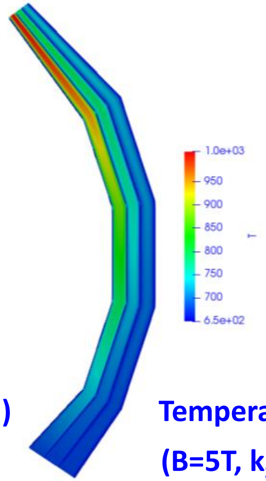
Inboard segment temp. (non-MHD)

2D MHD effect for outboard blanket segments

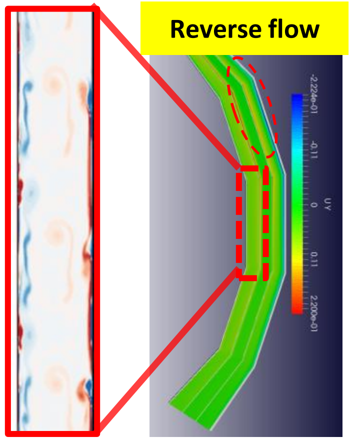
- Under the conditions of 5T magnetic field and electric insulation by SiC_f/SiC, the pressure drop is 2.5kPa. The peak temperature is 740 ℃ neglecting the buoyancy effects.
- With the effects of MHD and buoyancy, there is reversed flow for PbLi and the high speed jet will induce flow instability near the channel wall.



Pressure field (MPa)
(MHD)



Temperature field (MHD)
(B=5T, k_{SiC}= 3.5 W/(m·K))

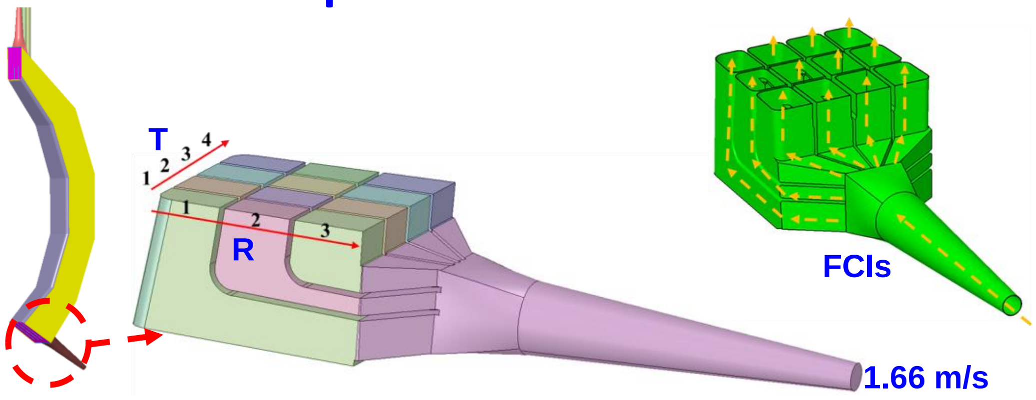


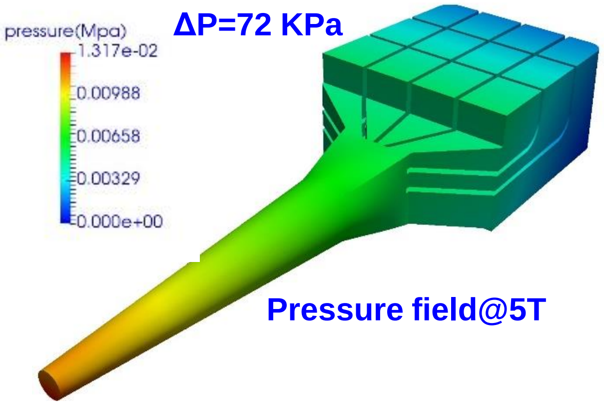
Velocity field (MHD)

MHD analysis for outboard segment inlet

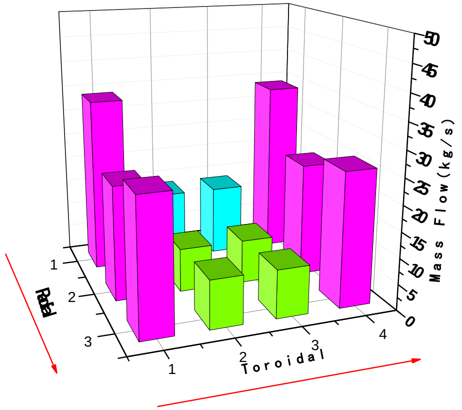
➢Present design & MHD analysis

- Inlet velovity of 1.66m/s (283 kg/s)
- ΔP=72 KPa for insulating FCI of SiCf/SiC
- Unreasonable distribution of inlet flow, further optimization is still needed



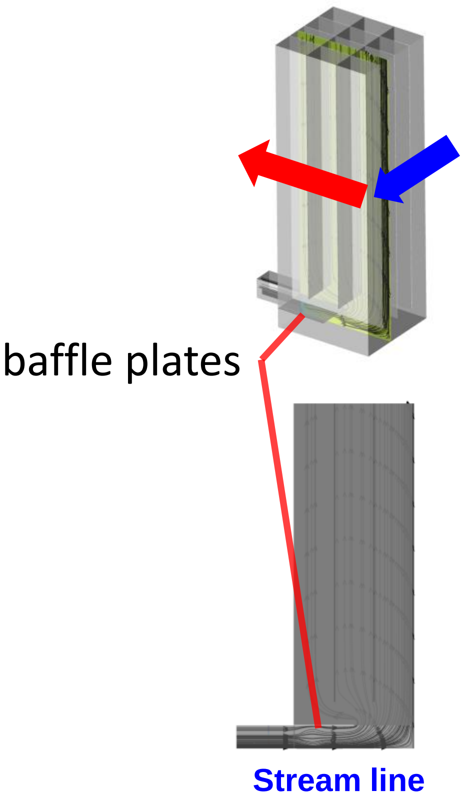


Pressure field@5T

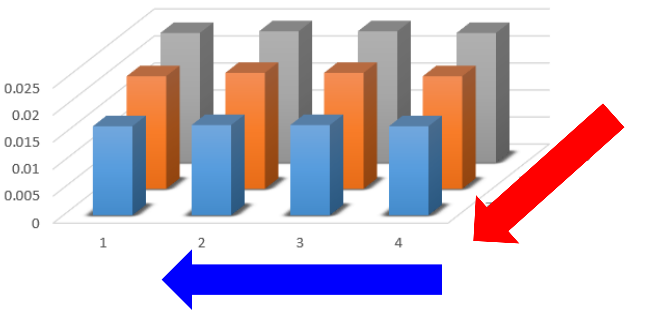


➢Possible modification for inlet

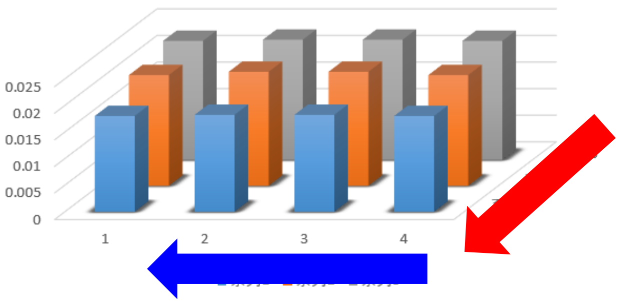
- Inserting baffle plates inside the inlet manifold for improving flow distribution
- PbLi flow distribution decreases radially, which is beneficial for FW side cooling
- $\Delta P_{insulating}$=0.09 MPa， $\Delta P_{conductive}$=0.75 MPa@2.4 m/s



Flow distribution (conductive FCI)



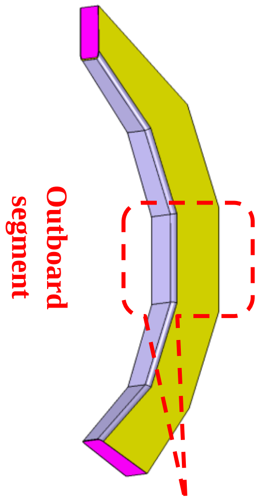
Flow distribution (insulating FCI)

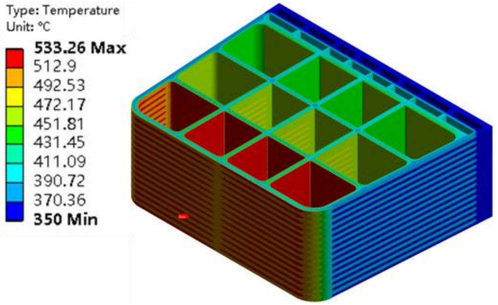


Thermo-mechanical analysis

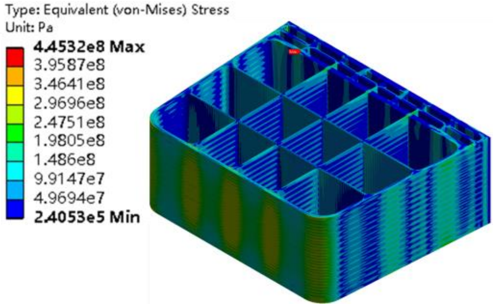
➢Thermo-mechanical analysis for typical outboard breeder unit (BU#3)

- **BU#3 is below material temperature limits and stresses under normal & in-box LOCA satisfy ITER SDC-IC code**

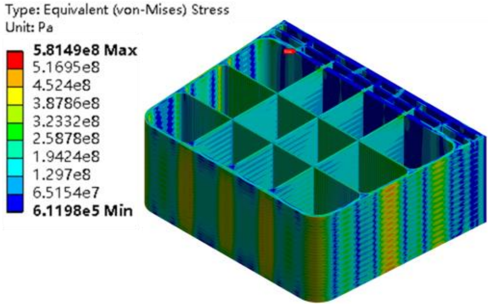




Temperature field of BU#3



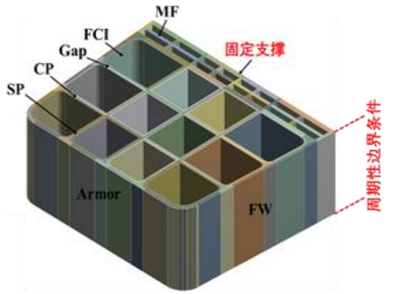
BU#3 stress field in normal condition



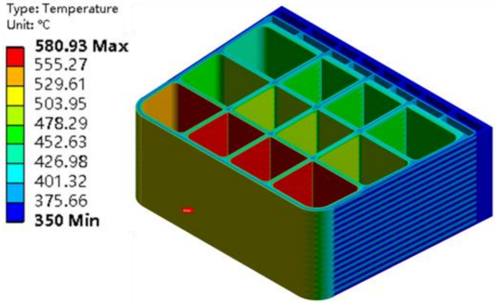
BU#3 stress field in in-box LOCA condition

PbLi outlet @600℃

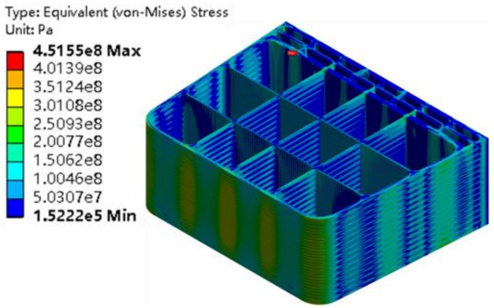
Components	Temp. (℃)	$SEQV \le 3S_m^D$		
		SEQV (MPa)	Design limit (MPa)	Margin
FW	358	504	1010	50%
CP	412	531	956	44%
SP	413	429	954	55%
MF	400	584	973	40%



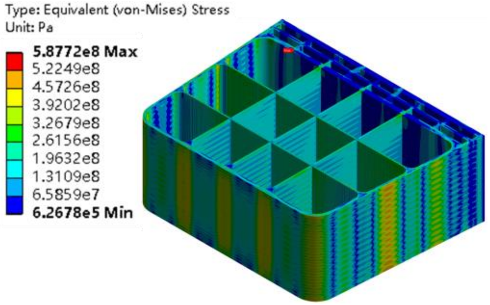
BU#3



Temperature field of BU#3



BU#3 stress field in normal condition



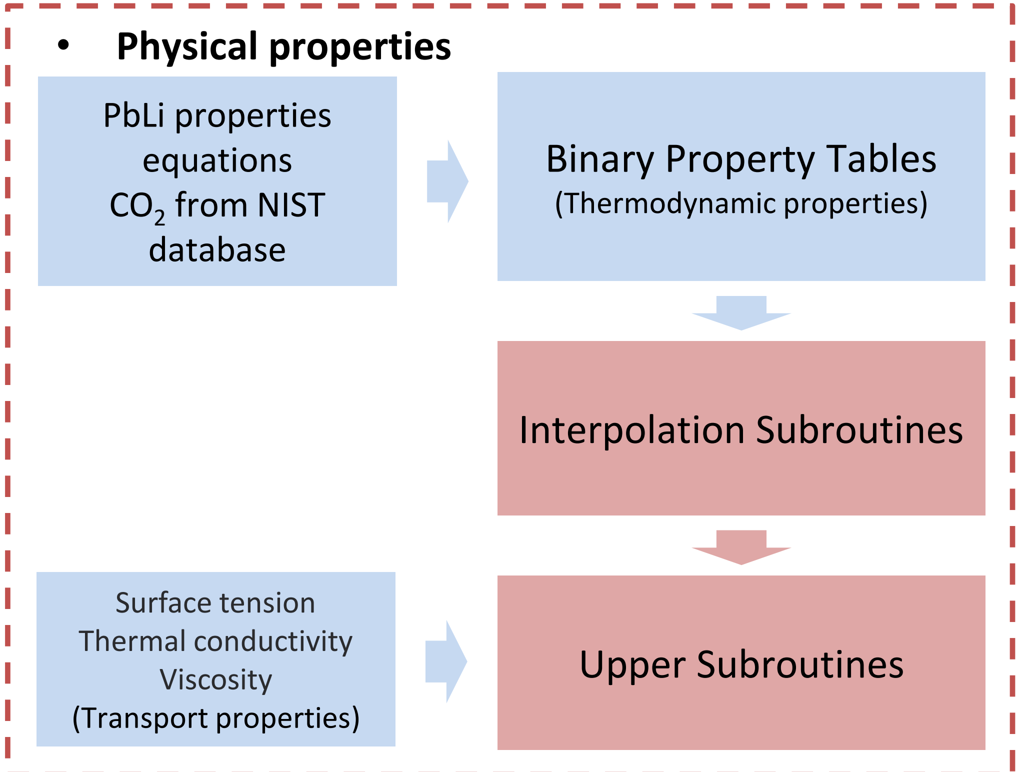
BU#3 stress field in in-box LOCA condition

PbLi outlet @700℃

Components	Temp. (℃)	$SEQV \le 3S_m^D$		
		SEQV (MPa)	Design limit (MPa)	Margin
FW	358	537	1010	47%
CP	418	560	948	41%
SP	417	411	949	57%
MF	400	588	973	40%

Safety analysis (1/2)

➢Model development: PbLi and CO$_2$ as working fluids in RELAP5



- **Physical properties**

PbLi properties equations
CO$_2$ from NIST database

Binary Property Tables
(Thermodynamic properties)

Interpolation Subroutines

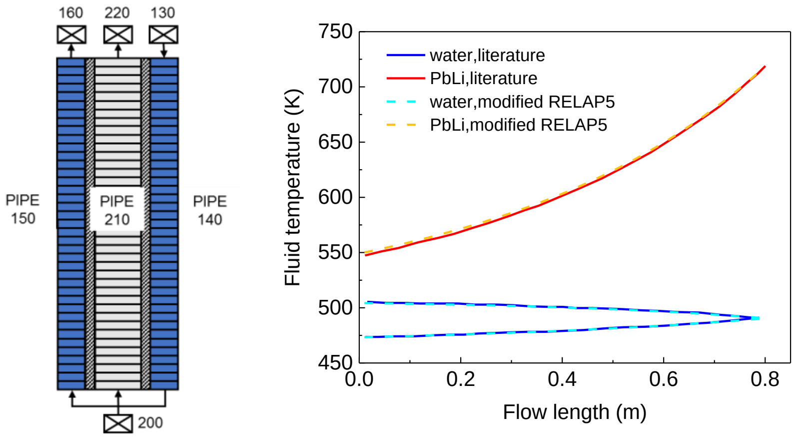
Surface tension
Thermal conductivity
Viscosity
(Transport properties)

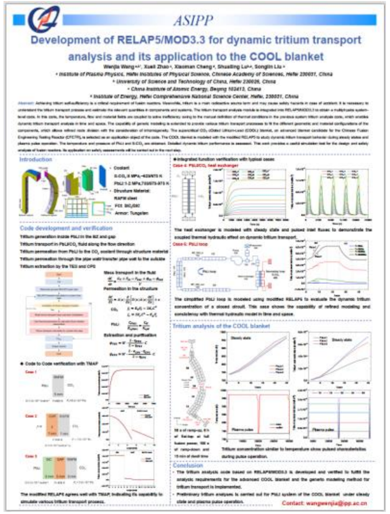
Upper Subroutines

- **Heat transfer equations**

Subroutine of heat transfer equations

☐Verification of PbLi



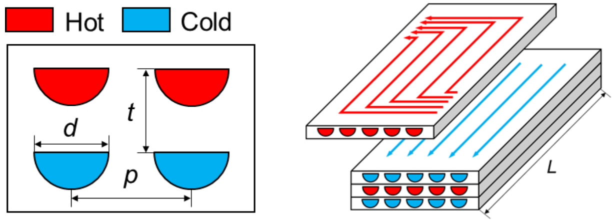


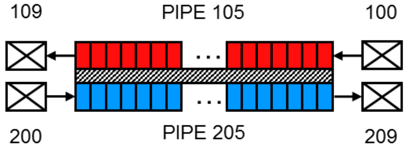
ASIPP

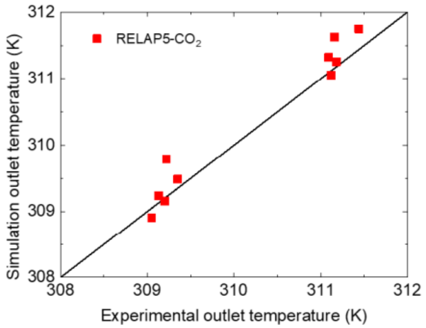
Development of RELAP5/MOD3.3 for dynamic tritium transport analysis and its application to the COOL blanket

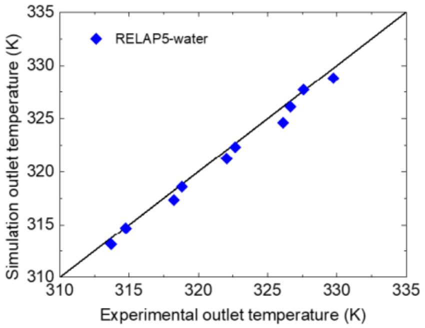
☐Verification of CO$_2$

Wenjia Wang, PS3-95, THURSDAY 14TH







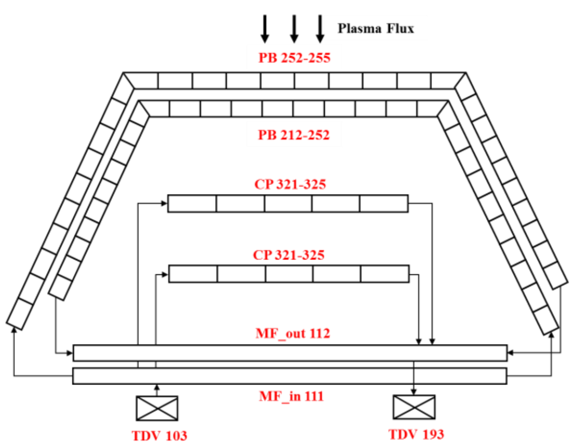


*Wenjia Wang, et al. Fusion Eng. Des. 184 (2022)113301

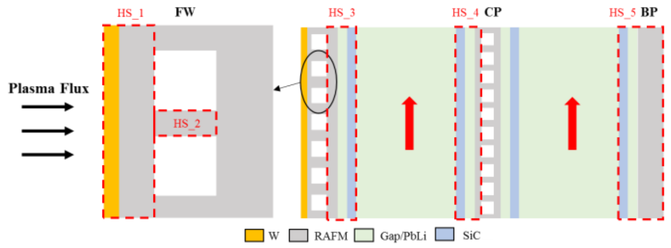
Safety analysis (2/2)

➢Safety analysis model of outboard segment

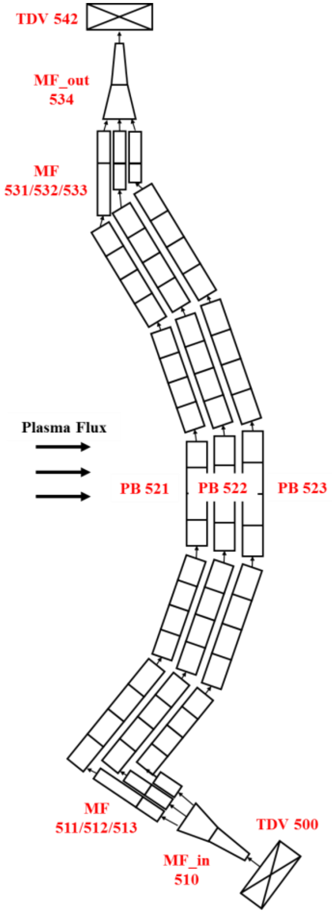
- **Nuclear heat and FW heat flux considered**



CO$_2$ coolant system nodalization



Blanket structure nodalization

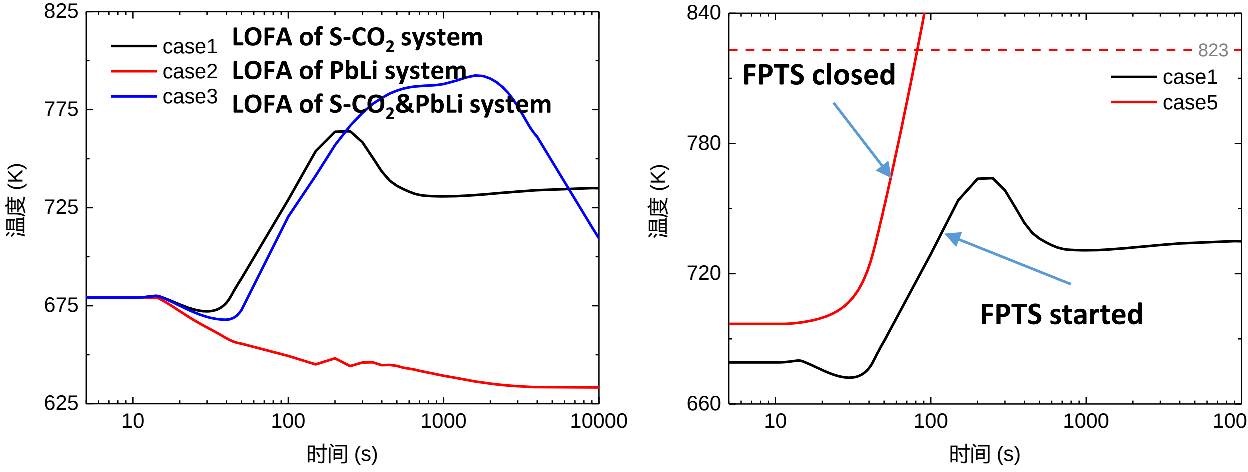


PbLi coolant system nodalization

➢LOFA accident analysis

- **Over heating is possible during LOFA (Loss of Flow Accident). It is necessary to start FPTS (Fusion Power Transport System) and restore coolant flow in time to mitigate LOFA.**

Time (s)	Case 1: LOFA without detection		Case 2: LOFA with plasma shutdown in time	
	Event	Heat load	Event	Heat load
t = 0	Steady state	100 % full heat load: nuclear heat + FW surface heat flux of 0.5 MW/m^2	Steady state	100 % full heat load: nuclear heat + FW surface heat flux of 0.5 MW/m^2
t = 10	Pump failure, coast down		Pump failure, coast down	
t = t_1	Mass flow decreased to 80% of normal level		Mass flow decreases to 80% of normal level, triggering FPTS	
t = $t_1 + 3$	Plasma burning		Plasma shutdown	Nuclear heat + Plasma disruption heat flux
t = 42	Pump coast down stopped, plasma burning		Pump coast down stopped	Decay heat
t = t_2	FW structure failure caused by overheating, plasma burning		Natural circulation established	



Temperature variation of FW

Outline

- Introduction
- COOL blanket analysis
- Power conversion system
  - Directly coupling BoP sheme
  - BoP sheme with IHTS
- R&D progress
- Summary

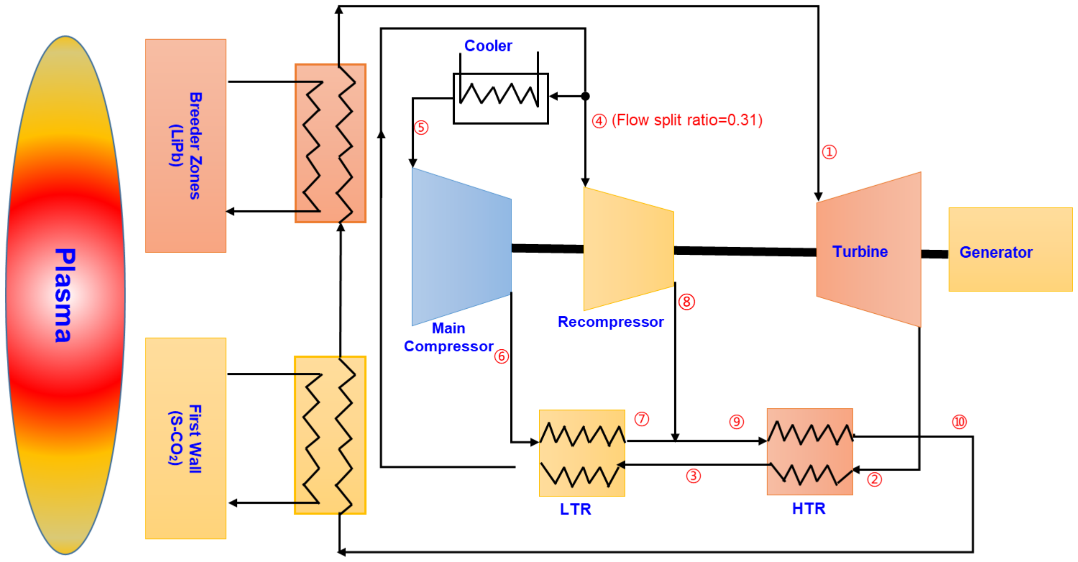
Directly coupling BoP sheme

➢Preliminary conceptual design for Balance of Plant (BoP)

- **BLK and Primary Heat Transfer System (PHTS):** preheated by S-CO_2 to ~400 ℃ and reheated by PbLi to 600-700 ℃
- **Power Conversion System (PCS):** S-CO_2 recompressing cycle with turbine inlet conditions at 550-650 ℃, 25-30 MPa

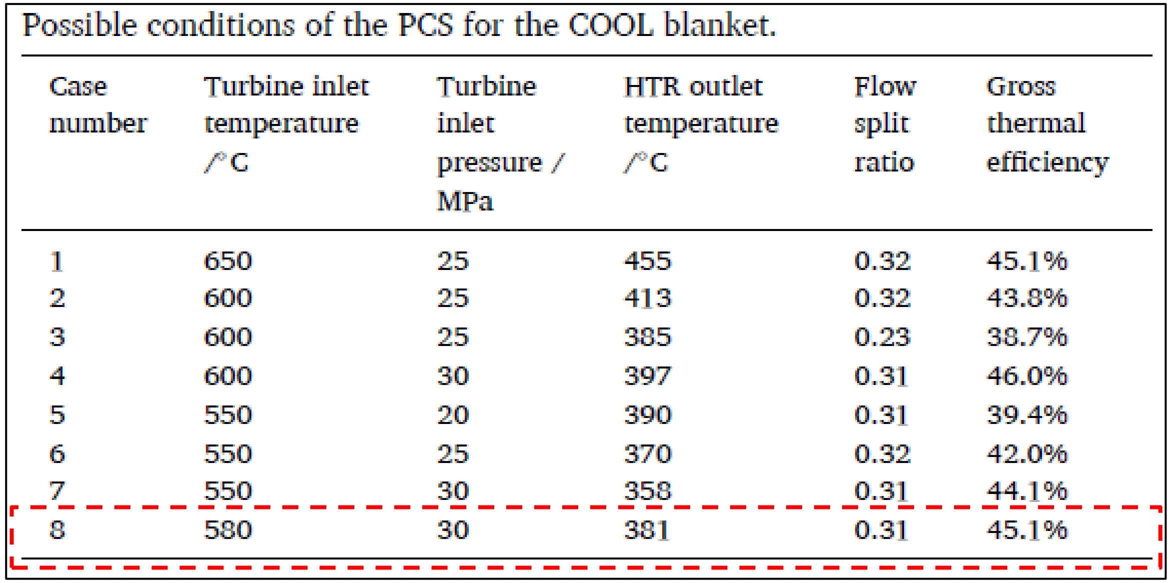
➢Gross thermal efficiency: 39%-46% (without consideration heat loss in PHTS)

- High turbine inlet temp. and pressure is beneficial for high efficiency, but increases the S-CO_2 inlet temp. in BLK
- Recommended operation condition for PCS: turbine inlet condition fixed at 580 ℃ and 30 MPa, and thermal efficiency estimated as 45%. The necessary BLK S-CO_2 inlet temp. is above 380 ℃, and the necessary PbLi outlet temp. could be 600 ℃.



PHTS

PCS (S-CO_2 recompressing cycle)



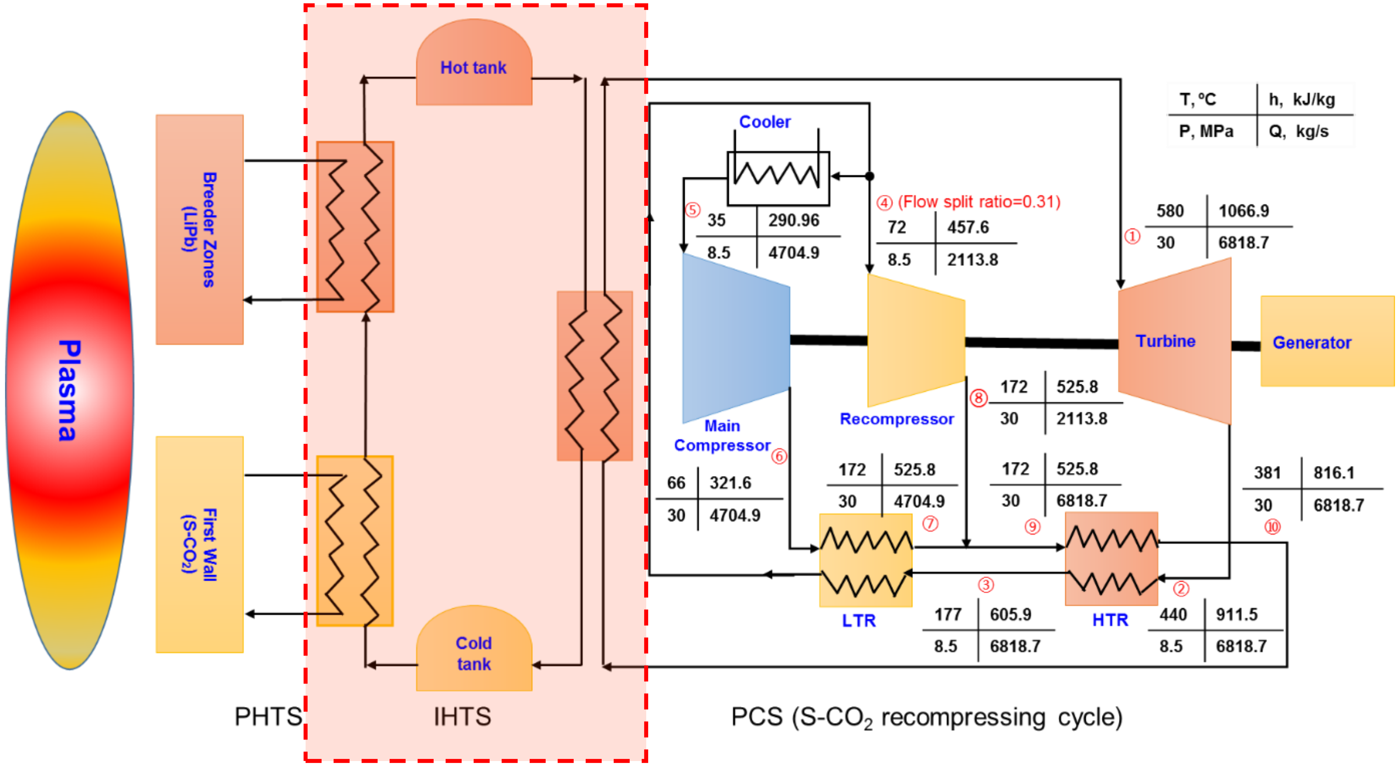
Possible conditions of the PCS for the COOL blanket.

Case number	Turbine inlet temperature /°C	Turbine inlet pressure / MPa	HTR outlet temperature /°C	Flow split ratio	Gross thermal efficiency
1	650	25	455	0.32	45.1%
2	600	25	413	0.32	43.8%
3	600	25	385	0.23	38.7%
4	600	30	397	0.31	46.0%
5	550	20	390	0.31	39.4%
6	550	25	370	0.32	42.0%
7	550	30	358	0.31	44.1%
8	580	30	381	0.31	45.1%

BoP sheme with IHTS

➢Intermediate Heat Transfer System (IHTS)

- Equipped with the Energy Storage System (ESS) to extract the pulsed plasma heat production to the PCS for steady energy output.
- Solar salt used as the working medium (60% sodium nitrate+ 40% potassium nitrate).
- Net thermal efficiency decays by ~2%-3% due to heat loss of IHTS.



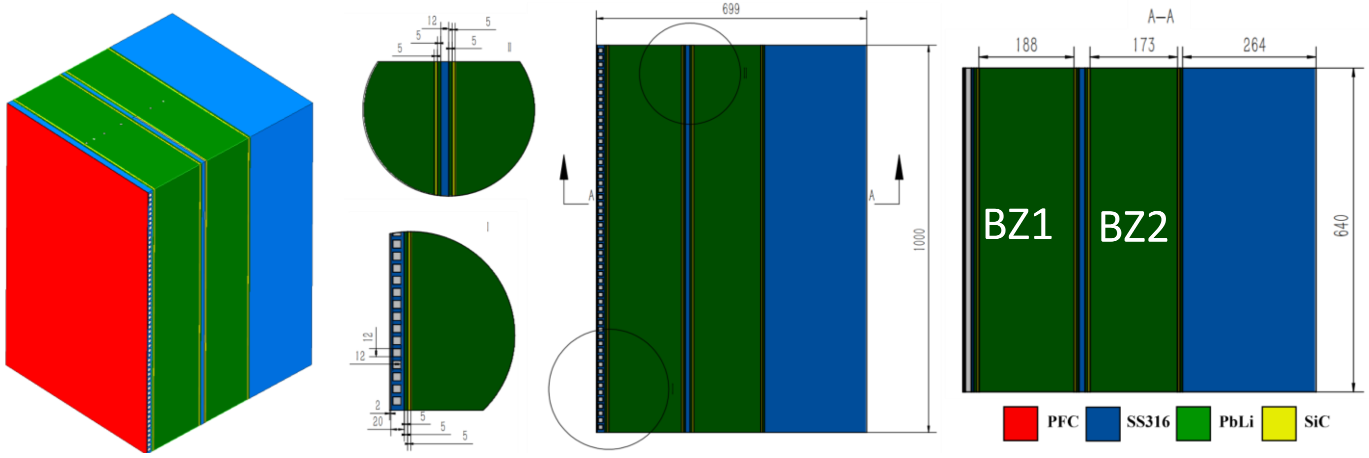
	Solar salt
Constituents (mass fraction)	60% $NaNO_3$ 40% KNO_3
Melting point (℃)	220
Max. temp. (℃)	585
Cp @300℃ (J/kg/K)	1495
Density @300℃ (kg/m³)	1899

Outline

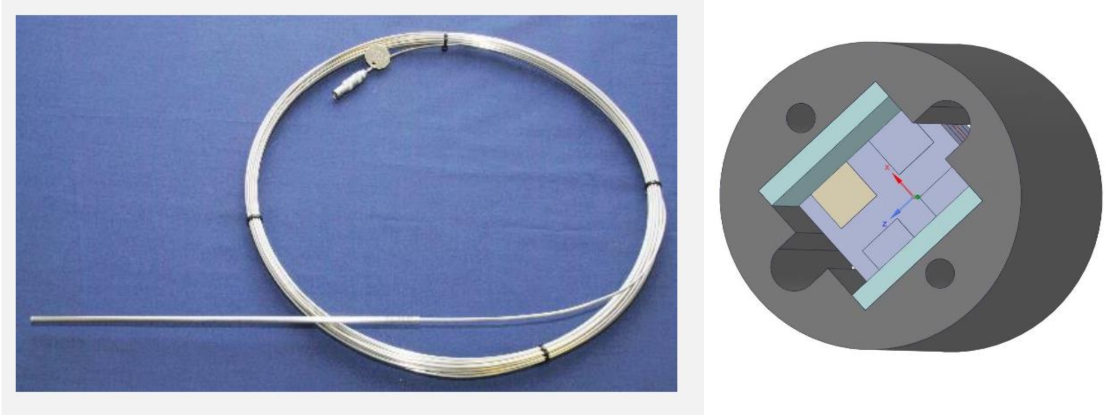
- Introduction
- COOL blanket analysis
- Power conversion system
- R&D progress
  - Design of neutronics experiments
  - Thermal hydraulic testing facilities
- Summary

Design of neutronics experiments

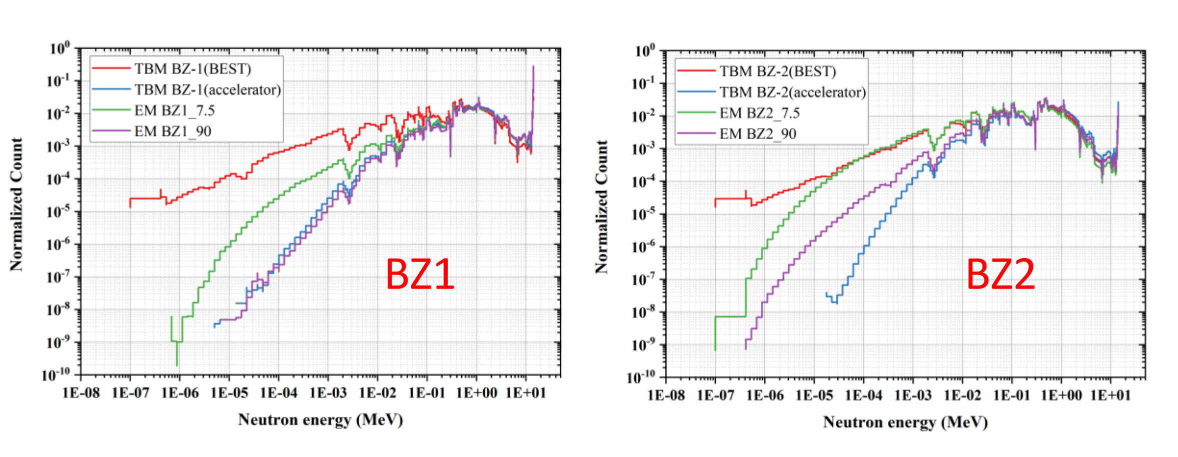
- **Neutronics experiments of COOL blanket mockup will be performed by using DT neutron source**



Design of experimental mockup



SPND detector (left) and Li-glass detector (right)



Comparsion of neutron energy spectrum

Parameters of DT neutron generator

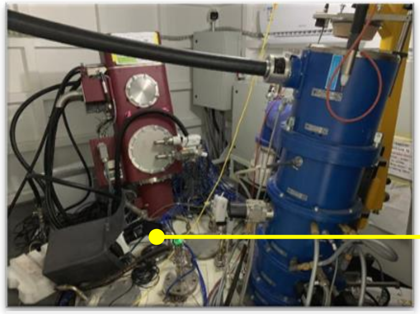
Mode	DC	Pulse
Beam Spot	<10mm	<6mm
D^+ Intensity	0~1.5 mA	0~40 μA
Neutron Intensity	0~ 3E11 /s	0~1.0E10 /s

- **Experimental mockup has been designed and will be tested by using neutron source.**
- **Tritium production rate will be measured by SPND and Li-glass detectors.**

High heat flux testing facility

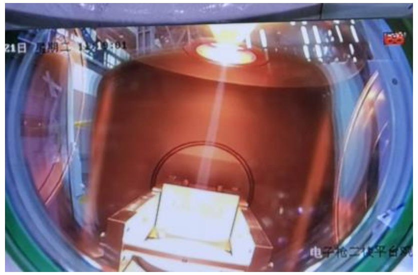
➢Objectives

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



Electron Beam Gun

Electron Beam



High heat flux testing facility & High pressure and temp. water loop

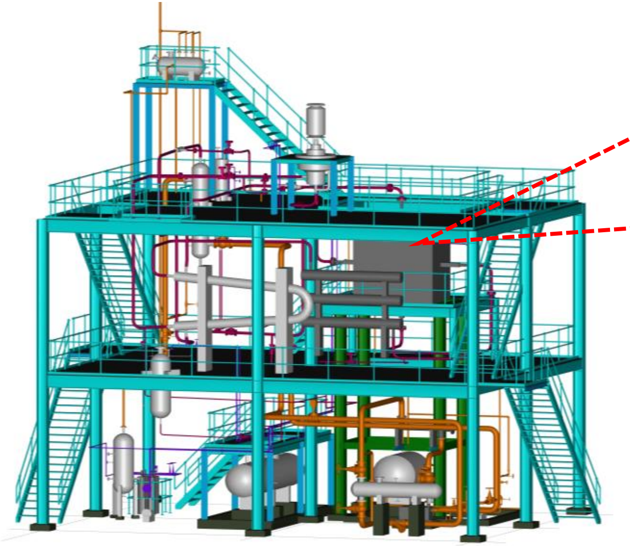
Electron Beam Gun (EBG) for high heat flux test of FW

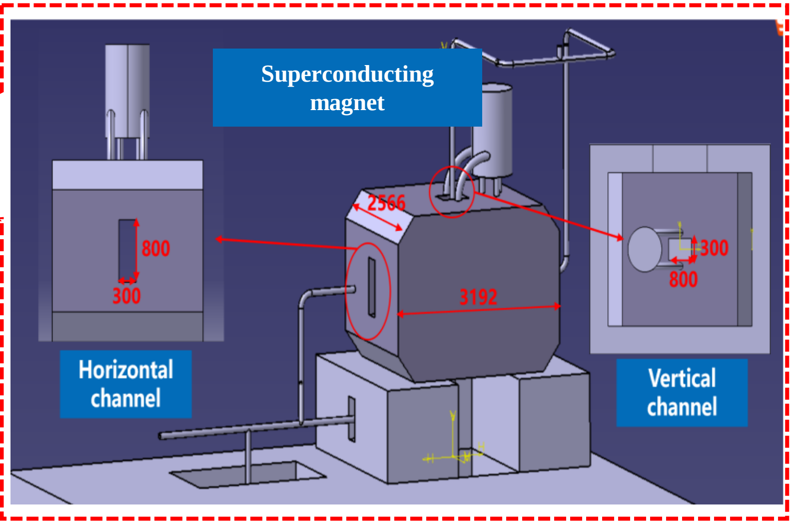
- 800 kW + 60 kW to simulate steady/transient flux
- Maximum flux: up to 20 MW/m^2
- Vacuum chamber diameter: 3.0 m
- Sweep frequency: 10 kHz
- Max. accelerating voltage: 60/120 kV
- Minimum spot diameter: 30 mm/1 mm
- Deflection angle: ±15°/±10°
- Water coolant： 4-15.5MPa, 285/325℃, 25 m^3/h

Cheng Xiaoman et al., A Water Loop Design for the CRAFT Project towards the Testing of CFETR Water-Cooled Blanket and Divertor, Energies,* ***14* *7354*

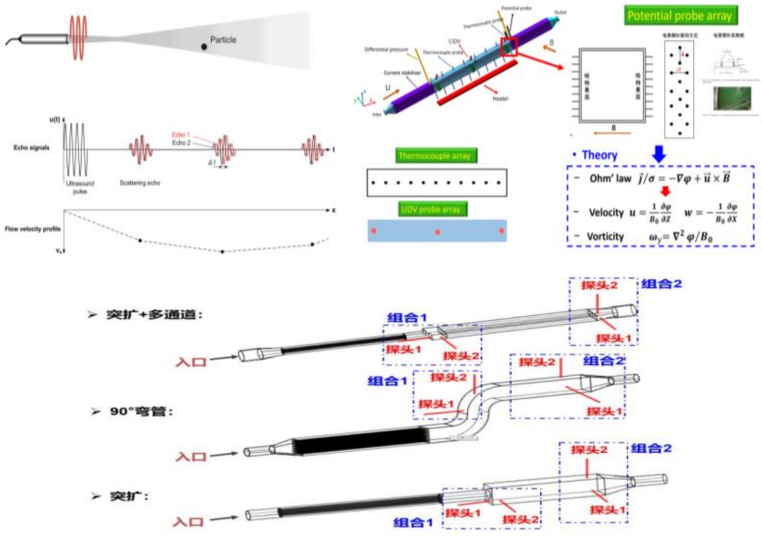
***Qiang Li, et al., Fusion Engineering and Design, 183 113276*

High temp. LiPb loop with 3T magnet





The construction will start in 2023



Main parameters	
Operating pressure	1.5 MPa
Design temperature	High temp. section (310s) 750 ℃ Low temp. section (316L) 550 ℃
PbLi operation temperature	270-700 ℃
PbLi flow rate	30 m^3/h
PbLi inventory	10 t
Magnetic field	0~3 T, uniformity of 8% in 0.25 m*0.6 m*1.0 m region
Oil design parameter	1.6 MPa, 350 ℃, 130 m^3/h
Water design parameter	0.5 MPa, 80 ℃
Heating power	1.5 MW

Key experiments

- **Turbulent heat transfer**

– Thermal boundary layer flow on forced convection

– PbLi flow in complex geometry channel

- **MHD effects**

– Phase diagram and turbulent transition mechanism under different Re/Ha

– The effects of FCI on the flow and heat transfer

– MHD flow in complex geometry channel

– Multi channel under electromagnetic coupling effect

- **Mixed convection**

– One-side heat flux conditions

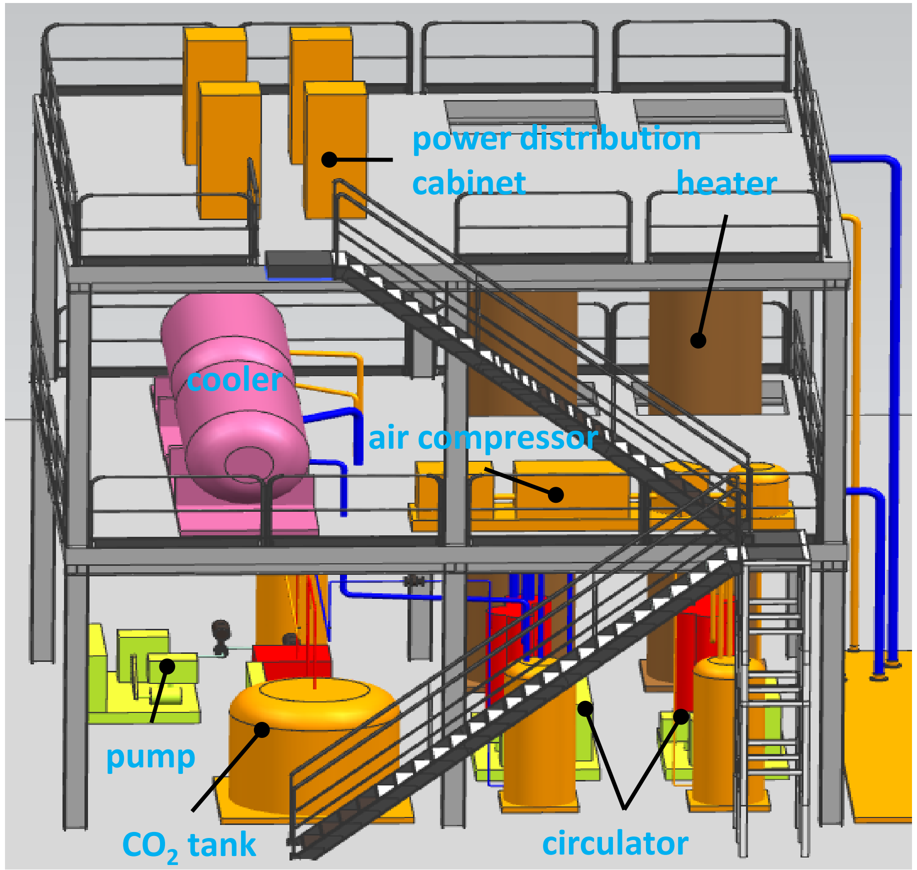
– Large magnetic/heat source

Kecheng Jiang, et al. Development of the high temperature PbLi experimental loop for CFETR, ISFNT15 Blanket technology session, Monday, 11th Sept. 2023.

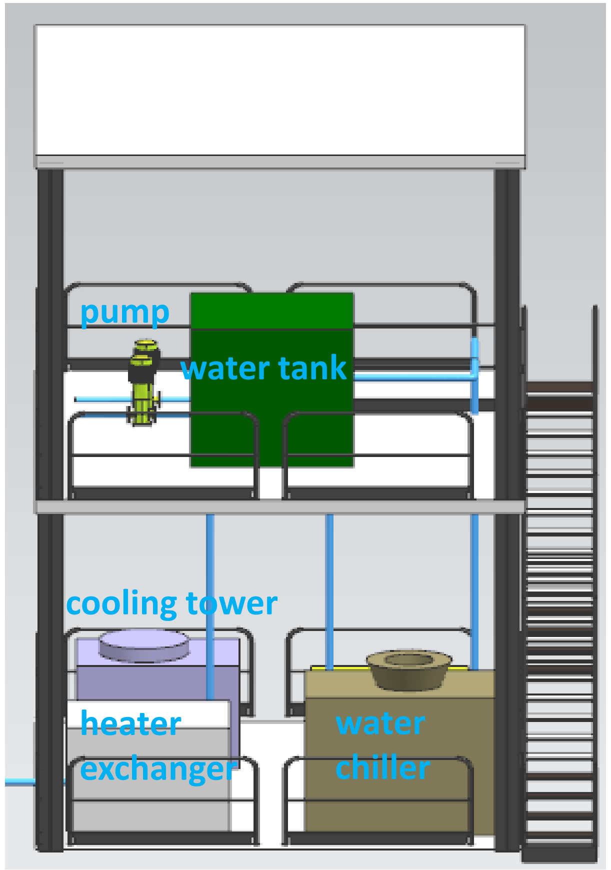
High temp. S-CO_2 loop

➢Objectives

- **Provide thermal-hydraulic testing environment of COOL blankets**
- **Validate the design codes/methods/models**



S-CO_2 loop (10×10×10 m^3)



Outside auxiliary cooling loop (7×6×10 m^3)

Main parameters	
Operating pressure	8-9 MPa
Operating temperature	300-500 ℃
Flow rate	0.2-6 kg/s
Heating power	1.7 MW

● **Key experiments**

- Heat removal capability of S-CO_2 with one-side high heat flux
- Coupling heat transfer performance with PbLi
- Flow characteristics of S-CO_2 in complex channels of blanket and heat exchangers

Outline

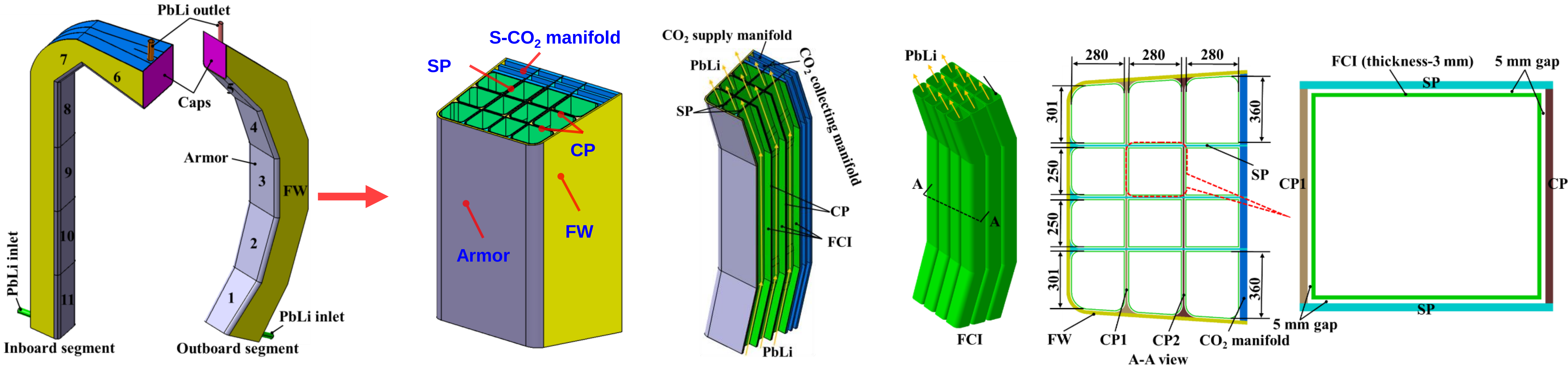
- Introduction
- COOL blanket analysis
- Power conversion system
- R&D progress
- **Summary**

Summary

- **Supercritical CO_2 cooled Lithium-Lead (COOL) blanket is proposed as an advanced BLK option for high thermal efficiency.**
  - **Nuclear analyses by a 3D neutronic model show that the current design can achieve a global TBR of 1.183 and is able to provide enough shielding for TFC.**
  - **MHD analysis shows that coupling effect of magnetic field and convection has a non-negligible influence on the flow and temperature field of PbLi. Inlet pressure drop & flow distribution are estimated and the inlet structure is modified accordingly.**
  - **Thermo-mechanical analysis for typical Breeding Unit #3 & #9 proves that all components do not exceed their allowable temp. limit and the structure stress meets the ITER SDC-IC standard.**
  - **Safety model has been developed based on RELAP5 and preliminary safety analysis proved that starting FPTS and restore coolant flow in time are helpful to mitigate the effect of LOFA.**
  - **Preliminary scheme of the PCS based on the S-CO_2 recompressing cycle is proposed for the blanket and the gross thermal efficiency is estimated to be 39%-46% at a turbine outlet temperature of 550-650 ℃.**
  - **Preliminary R&Ds such as design of neutronics experiments and construction of thermal hydraulic facilities are ongoing.**
- **More work is needed to be done in the future.**
  - **More detailed analysis regards to thermo-hydraulics and thermo-mechanics.**
  - **3D MHD analysis will be updated for both PbLi inlet and outlet manifold to optimize their structural design. Coupling effects of MHD and convection will be studied particularly.**
  - **Safety program regards to the S-CO_2 and PbLi analysis will be developed and applied for the safety analysis of in-vessel LOCA/ ex-vessel LOCA.**
  - **Evaluation of tritium permeation and inventory will be improved by considering the convection and MHD effects.**
  - **Development of key fabrication technologies and key functional material needs to be performed.**

Thank you for your attention！

Structural design



☐ Single-Module Segment

- 16 sectors with each including 3 outboard and 2 inboard segments
- Outboard segment: 1-5 breeding unit
- Inboard segment: 6-11 breeding unit

☐ Box-shaped Breeding Unit

- U shaped FW coated with Tungsten armor of 2 mm
- S-CO_2 manifold configured in the back
- SPs and CPs divide breeding unit into several PbLi breeder zones

☐ Once-through PbLi flow channels

- PbLi flows through parallel channels from segment bottom to top
- FCIs to mitigate the MHD effect and corrosion
- 5 mm gap between FCIs and structures for preventing thermal stress

Comparison with CFETR HCCB/WCCB

	CFETR HCCB (1.5GW)	CFETR WCCB (1.5GW)	CFETR COOL (1.5GW)
TBR (neglecting port effect)	1.17	1.15	1.18
Thermal efficiency	~36%@550 ℃ outlet	~33%@325 ℃ outlet	~45% @600 ℃ outlet
Shielding capability	✓(water moderator needed)	✓	✓
Irradiation damage (1 FPY)	Max. 14.5 dpa @ BLK #3 FW	Max. 10 dpa @ BLK #3 FW	Max. 14.5 dpa @ BLK #3 FW
Safety	12 MPa helium	15.5 MPa water	8-9 MPa SCO_2
Tritium extraction	• Tritium permeation: 39g/y (PRF=100) • Difficult to extract online	• Tritium permeation: 25g/y (PRF=100) • Difficult to extract online	• Tritium permeation:38g/y(PRF=100) • Easy to extract online
Economical efficiency	Costly Be and helium	Costly $Be_{12}Ti$	Cheap Pb and CO_2
Material compatibility	Inert helium	Weak $Be_{12}Ti$-water reaction	Corrosion
Heat removal capacity of FW	limited	excellent	moderate
Technical risk	moderate (huge PHTS)	Low (mature water technology)	high (MHD and corrosion, SiC FCIs)
Maintainability	Complex structure	Complex structure	Simple steel structure

COOL blanket has simple structure with high TBR, high thermal efficiency, low coolant pressure, low construction cost, and is easy to extract tritium online, but MHD and corrosion are additional issues, yet controllable.

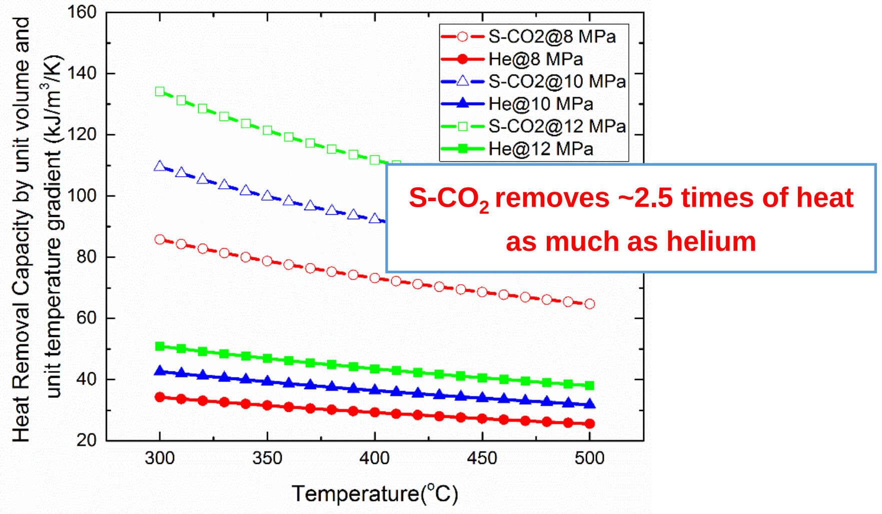
Advantages of S-CO_2

➢For BLK

- Higher heat removal capacity at FWs due to larger density than helium
- Higher TBR than WCCB due to weak neutron moderation
- Lower coolant pressure of 8 MPa than HCCB(12MPa He) and WCCB(15.5 MPa water)

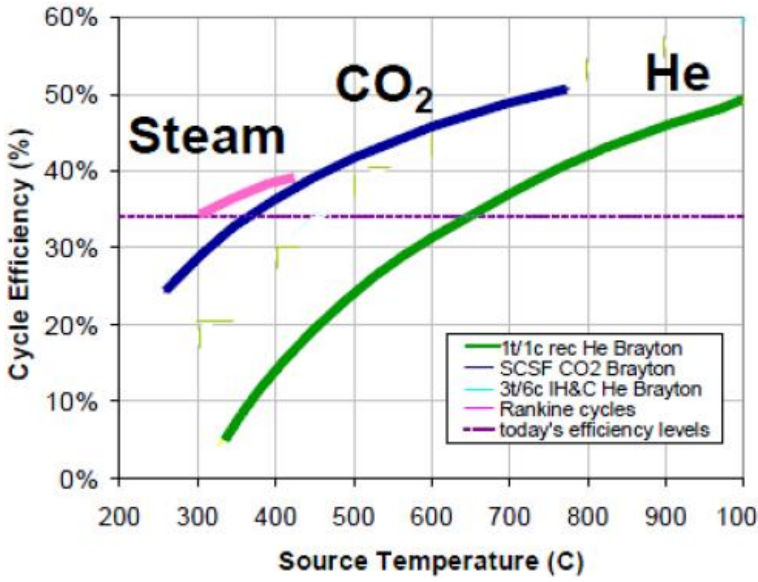
➢For PCS

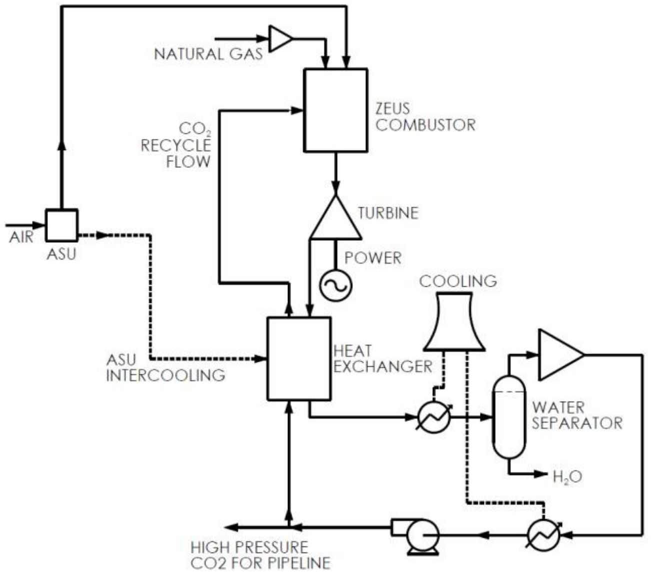
- Higher thermal efficiency in the medium temperature regime of 500-700 ℃
- Small volume of PCS (~1/10-1/7 of steam cycle) and low construction cost
- More extensible for high thermal efficiency up to ~60% (by Allam cycle)



S-CO_2 removes ~2.5 times of heat as much as helium

Comparison of heat removal capacity of helium and supercritical CO_2



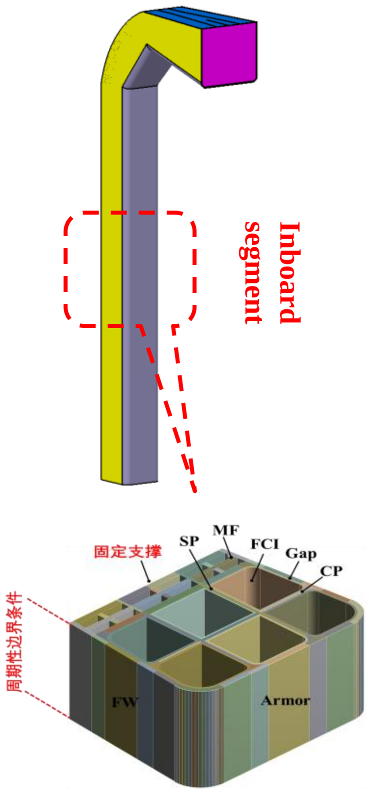


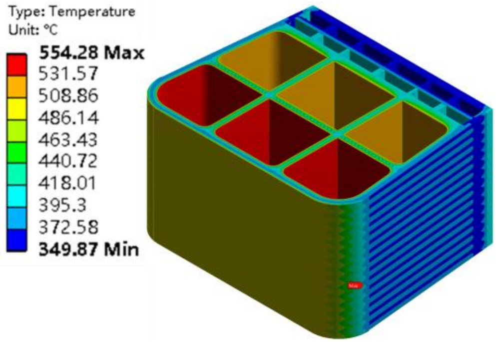
Allam cycle (efficiency up to ~60%)

Thermo-mechanical analysis

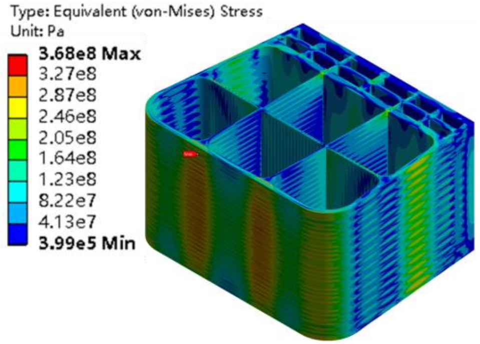
➢Thermo-mechanical analysis for typical inboard breeder unit (BU#9)

- **BU#9 is below material temperature limits and stresses under normal & in-box LOCA satisfy ITER SDC-IC code**

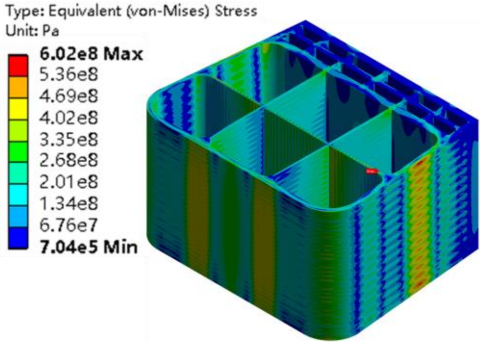




Temperature field of BU#3



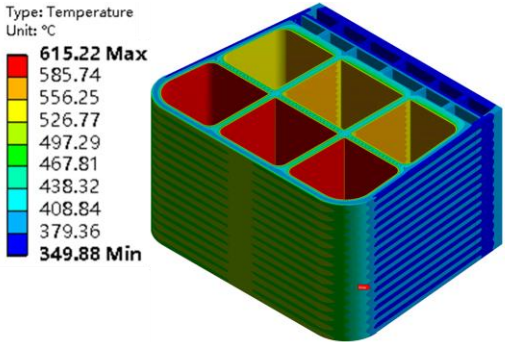
BU#3 stress field in normal condition



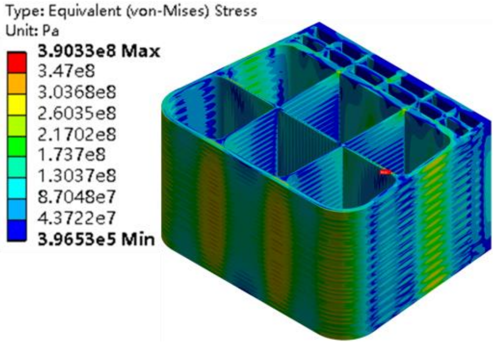
BU#3 stress field in in-box LOCA condition

PbLi outlet @600℃

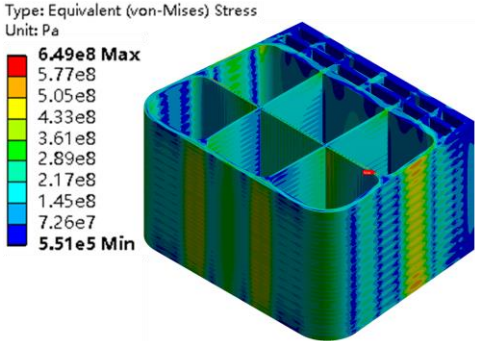
Components	Temp. (℃)	$SEQV \leq 3S_m^D$		
		SEQV (MPa)	Design limit (MPa)	Margin
FW	367	555	1002	45%
CP	437	602	921	35%
SP	406	417	964	57%
MF	405	426	966	56%



Temperature field of BU#3



BU#3 stress field in normal condition



BU#3 stress field in in-box LOCA condition

Components	Temp. (℃)	$SEQV \leq 3S_m^D$		
		SEQV (MPa)	Design limit (MPa)	Margin
FW	384	545	987	45%
CP	448	587	906	35%
SP	418	417	948	56%
MF	413	479	954	50%

PbLi outlet @700℃