IAEA Technical Meeting on Tritium Breeding Blankets and Associated Neutronics

Design and Multi-physical Performance Analysis of the WCCB and COOL Blanket for CFETR

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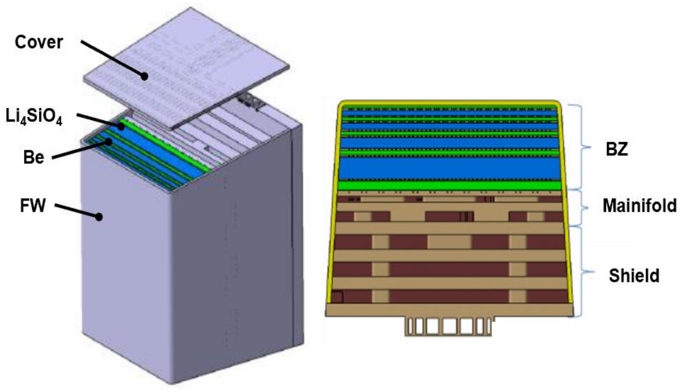
Outline

- Introduction
- WCCB blanket design
- COOL blanket design
- BEST TBS design and test plan
- Summary

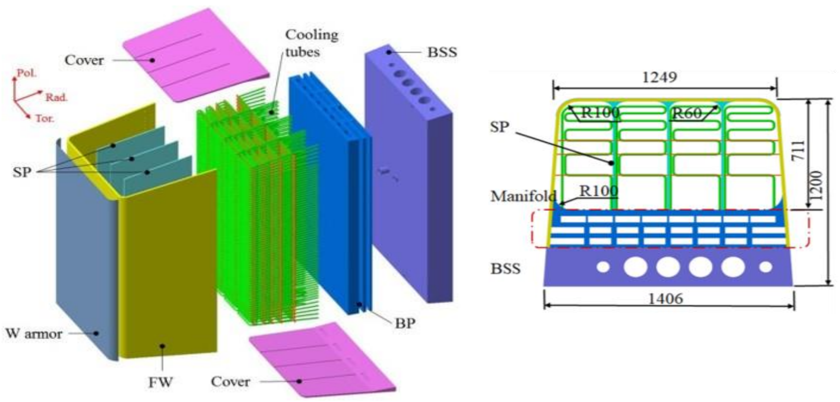
CFETR Blanket Candidates

Helium Cooled Ceramic Breeder (By SWIP)



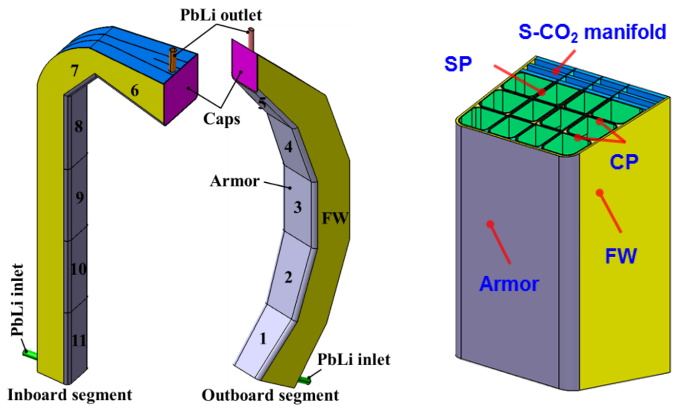
- **Coolant:** Helium @ **12 MPa**, 300/ 550 ℃
- **Structure:** RAFM/ODS steel
- **FW armor:** 2 mm Tungsten
- **Breeder/Multiplier:** Li_4SiO_4/**Be**
- **Purge gas:** He + 0.1vol% H_2 @1-3 bar
- **Thermal efficiency: ~36%**

Water Cooled Ceramic Breeder (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%**

S-CO_2 COoled Lithium-Lead (By ASIPP & UCAS)



- **Dual Coolant:**
  - 8-9 MPa **S-CO_2** cooling structures, 350 ℃ ~390 ℃
  - **PbLi** self-cooling BZ, outlet 600-700 ℃
- **Structure/ FW armor:** RAFM/ODS steel/ 2 mm
- **Breeder/Multiplier: PbLi**
- **Flow chanel Insert (FCI): SiC_f/SiC**
- **Thermal efficiency: ≥42%**

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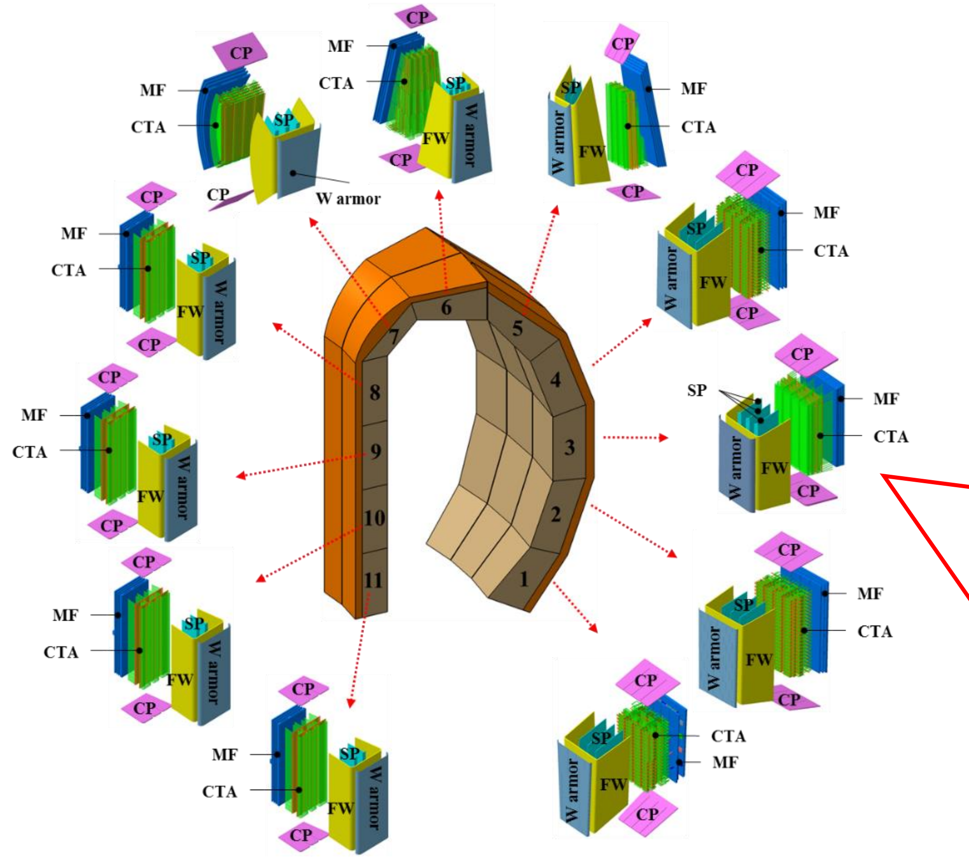
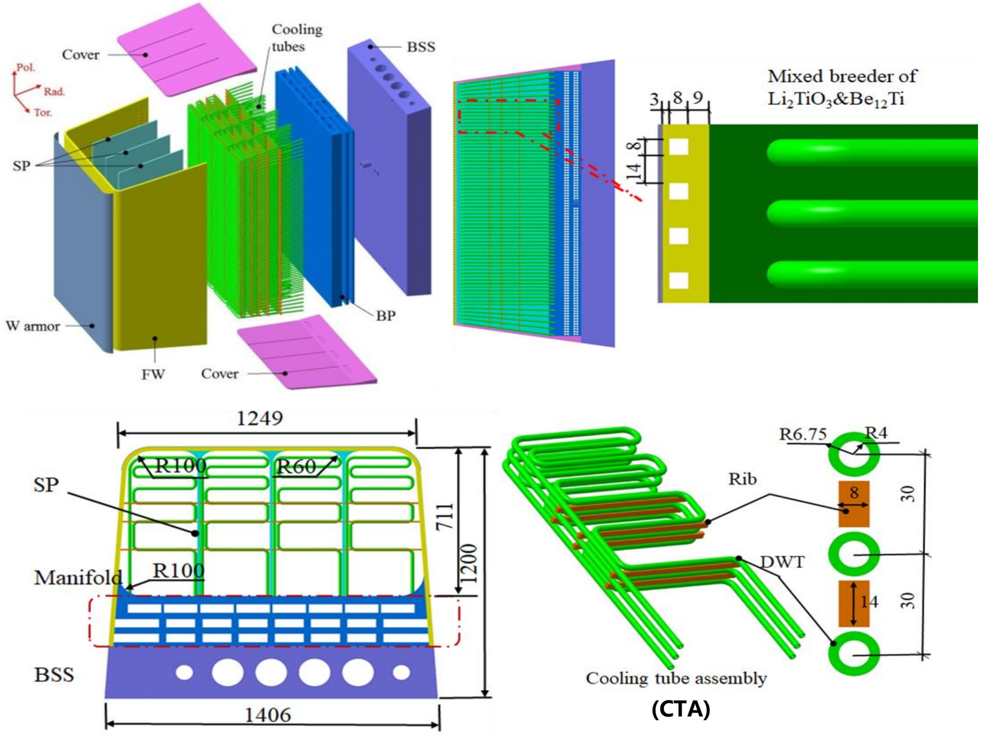
WCCB BLK design features

➢All 11 blanket modules were designed and share similar structural features





WCCB blanket module #3

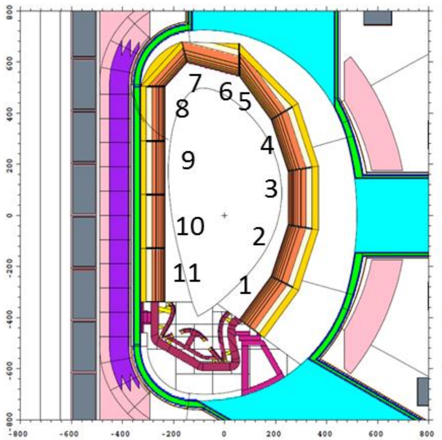
- ☐ Stiffening plates (SPs) divde the steel blanket box into several sub-zones to enhance the structure.
- ☐ The FW is a U-shaped plate bended in the radial-toroidal direction and cooled by water.
- ☐ Cooling tube assemblies (CTAs) are embedded in BZs filled with mixed pebble beds for heat removal.
- ☐ The ribs are bonded with SW/SP to enhance the blanket box structure.

- *Songlin Liu, et al. Design of the Water-Cooled Ceramic Breeder blanket for CFETR. FusionEngineeringandDesign177(2022)113059*

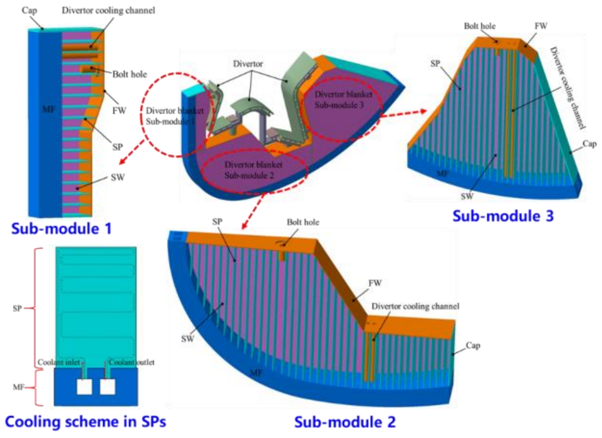
WCCB BLK nuclear performance (1/2)

➢Tritium breeding ratio (TBR)

- **TBR=1.165** without considering port effects of heating and diagnostic systems of CFETR
- **TBR=1.052** considering port effects of CFETR
- **TBR=1.123** considering port effects of CFETR and contribution of divertor blankets behind divertors



3D neutronic model of WCCB blanket

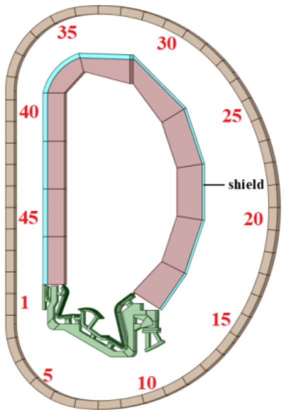


Divertor blanket

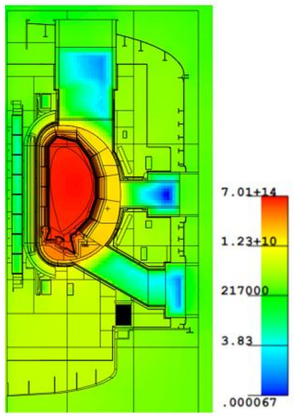
➢Neutron shielding capability

- **Fast neutron fluence/Nuclear heating is below ITER design limit for TF coils (TFC)**

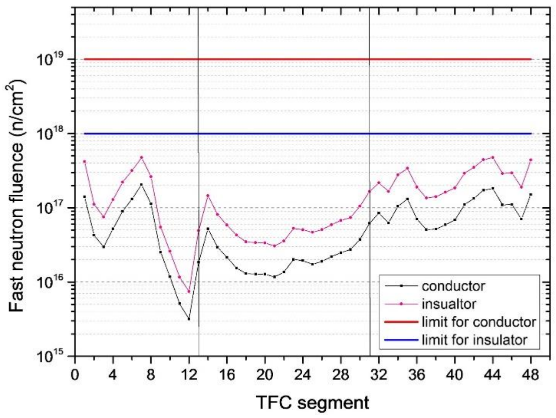
	Fast neutron fluence in magnet conductor (n/cm^2)	Fast neutron fluence in insulator (n/cm^2)	Nuclear heating in magnet steel case (W/cm^3)	Nuclear heating in magnet conductor (W/cm^3)
ITER Design Limit for TFC	1×10^{19} for 10 FPY	1×10^{18} for 10 FPY	2×10^{-3}	1×10^{-3}



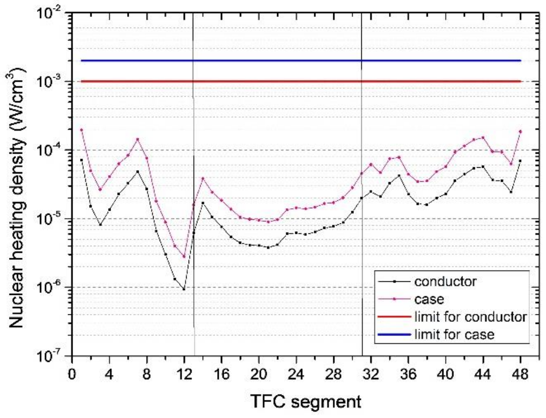
TFC segments



Neutron flux (n/cm^2/s)



Fast neutron fluence for TFC segments

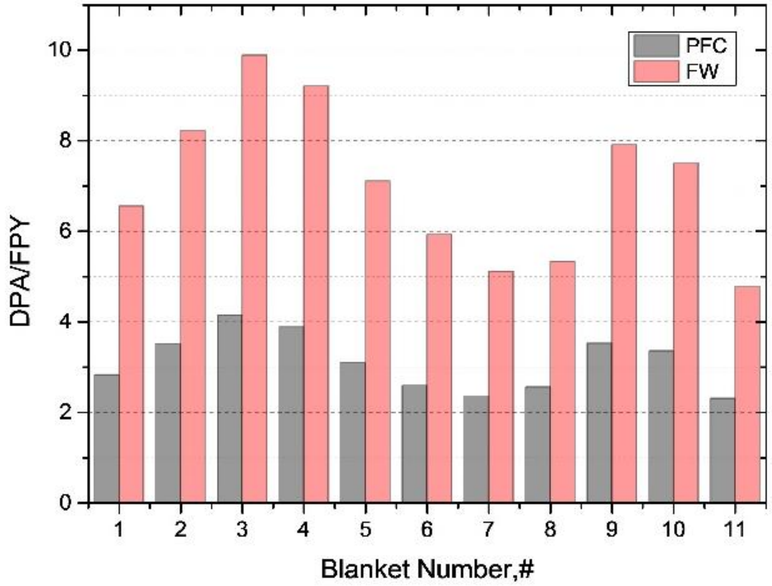


Nuclear heat density for TFC segments

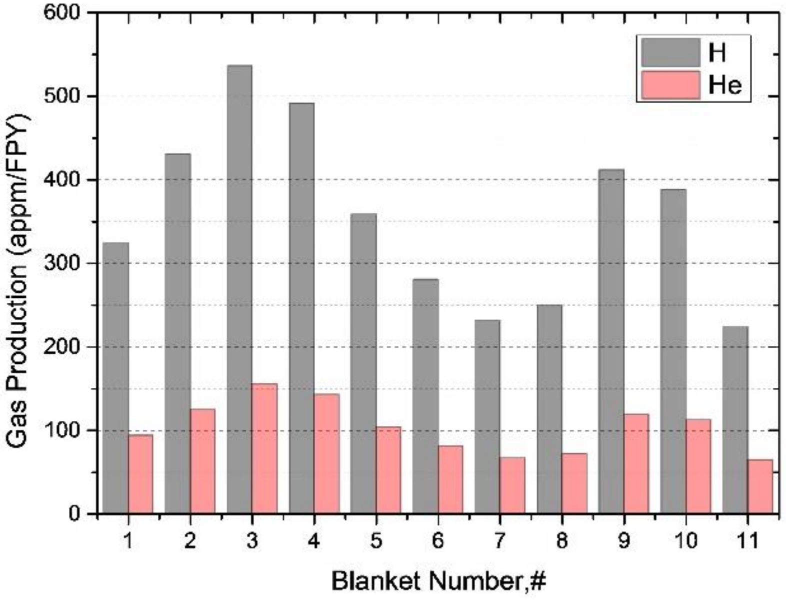
WCCB BLK nuclear performance (2/2)

➢Irradiation damage and gas production

- **BLK #3 has maximum DPA and gas (H/He) production due to high NWL**



DPA for BLK modules (1.5GW)



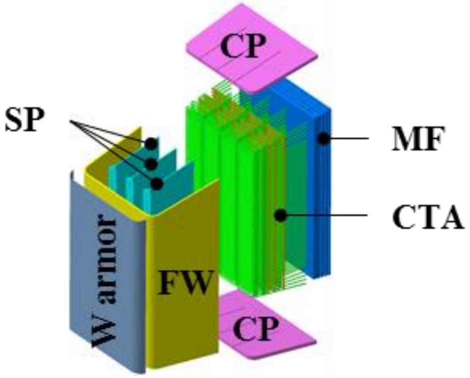
H/He production for BLK modules (1.5GW)

Item	**BLK #3**		**BLK #9**	
Component	PFC	FW	PFC	FW
DPA/FPY (@1.5GW)	4.15	9.20	3.52	7.91
He appm/FPY (@1.5GW)	7.84	142.82	6.60	119.41
H appm/FPY (@1.5GW)	19.13	491.67	16.10	411.67

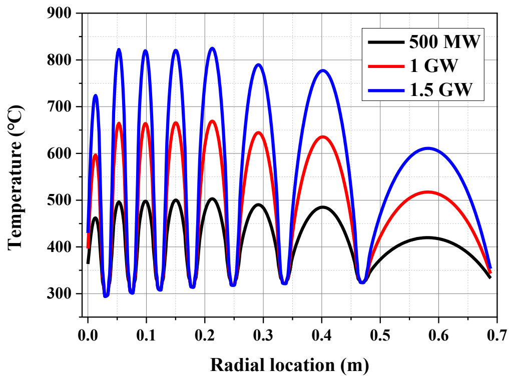
WCCB BLK thermo-mechanical analysis

➢Thermo-mechanical analyses performed for all 11 modules (#3/#9 as examples)

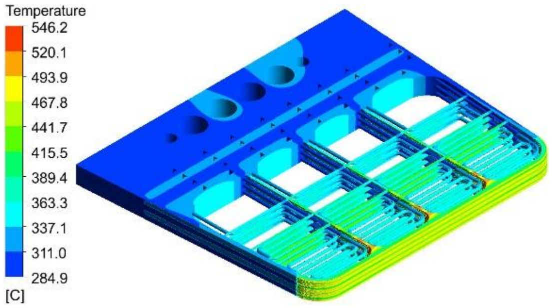
Equatorial outboard BLK #3



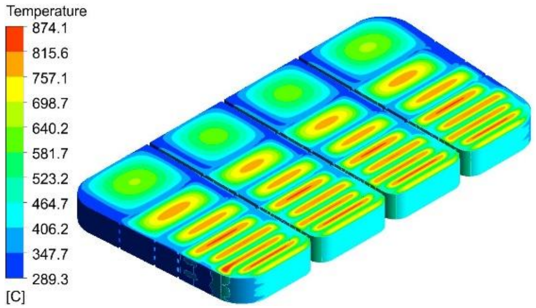
BLK #3



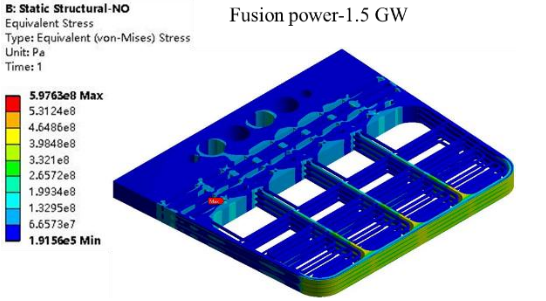
Temp. distribution in BZs



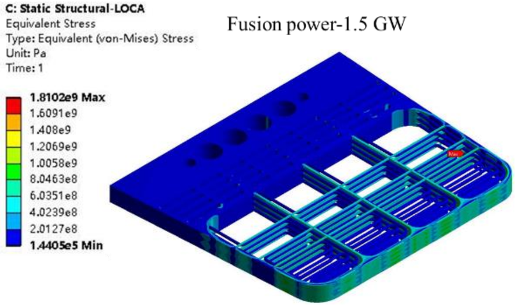
Temp. profile in structures (1.5GW)



Temp. profile in BZs (1.5GW)

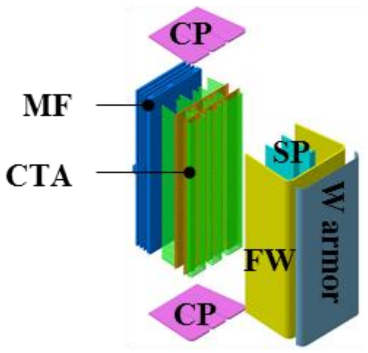


Stress in structures (1.5GW, normal)

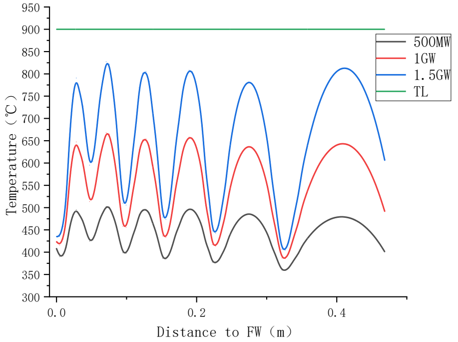


Stress in structures (1.5GW, in-box LOCA)

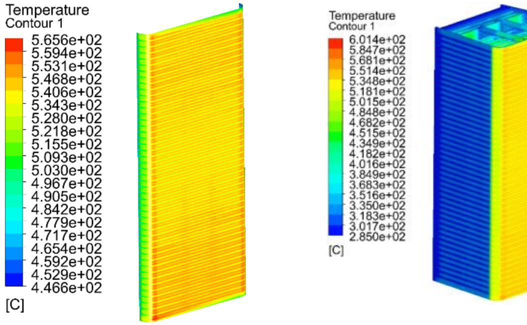
Inboard BLK #9



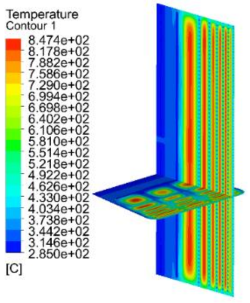
BLK #9



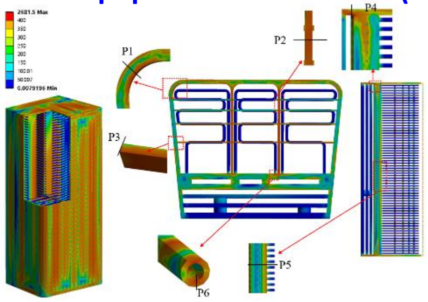
Temp. distribution in BZs



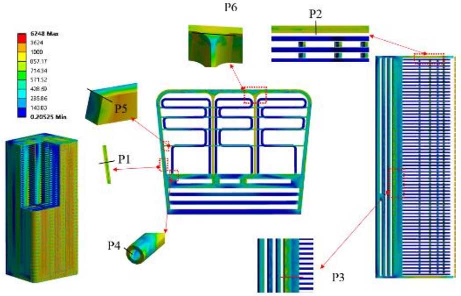
Temp. profile in structures (1.5GW)



Temp. profile in BZs (1.5GW)



Stress in structures (1.5GW, normal)

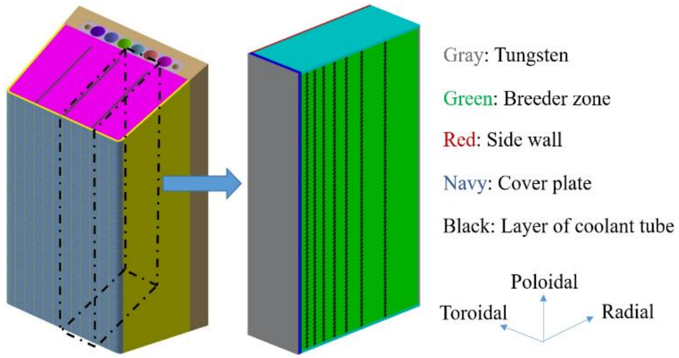


Stress in structures (1.5GW, in-box LOCA)

BLKs #3 and #9 are below material temperature limits and stresses under normal & in-box LOCA, satisfying ITER SDC-IC code

WCCB BLK tritium transport analysis (1/2)

➢Multi-physical tritium transport model for BLK #3



Simplified tritium transport model for BLK module #3

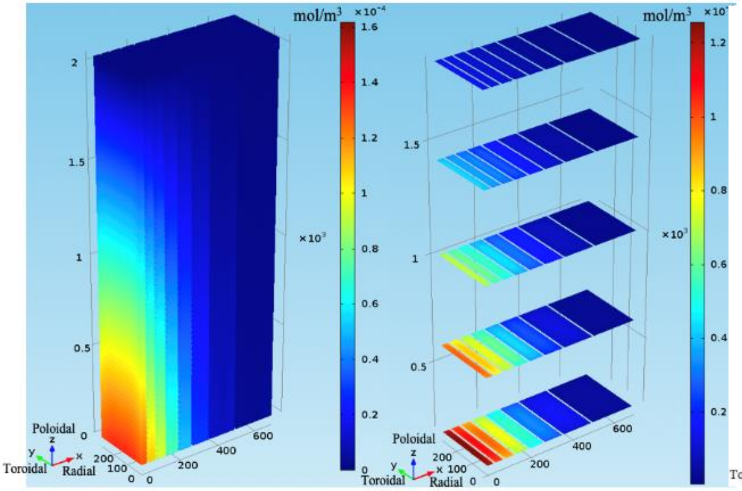
Mass conservation equation: $\rho\nabla\cdot(u)=Q_{br}$

Flow equation: $\nabla\cdot\left[-pI+\mu\frac{1}{\varepsilon_p}(\nabla u+(\nabla u)^T)\right]-\left(\mu\kappa^{-1}+\beta_F|u|+\frac{Q_{br}}{\varepsilon_p^2}\right)u+F=\rho\frac{\partial u}{\partial t}$

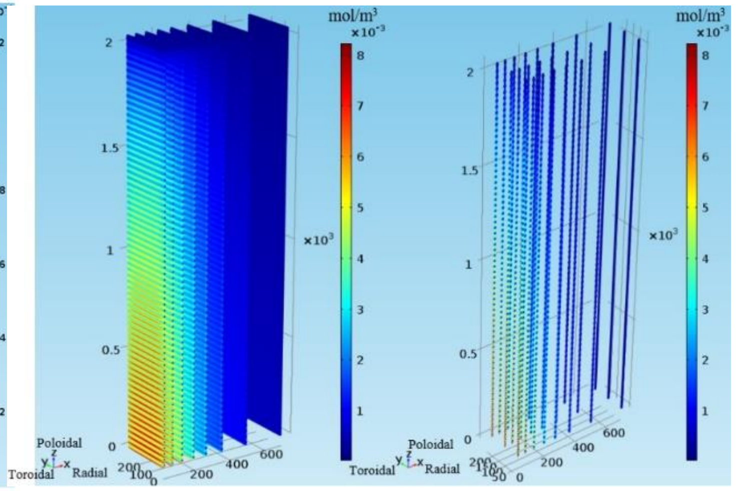
Heat transfer equation: $\rho C_p\frac{\partial T}{\partial t}+\rho C_p u\cdot\nabla T-\nabla\cdot(k\nabla T)=q$

Tritium transport equation: $\frac{\partial C}{\partial t}-D\nabla^2 C+u\cdot\nabla C=R,\ \frac{\partial C^{Br}}{\partial t}=G_T-\frac{C^{Br}}{\tau}$

➢Multi-physical analysis for BLK #3



Tritium distribution in BZs



Tritium distribution in structures

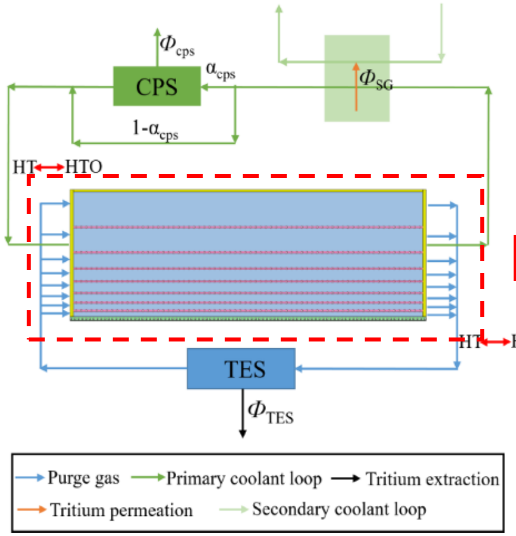
Tritum production, permeation, extraction and retention

	Tritium production (g/y)	Tritium permeation (g/y)	Tritium extraction (g/y)	Tritium retention in structures (g)
BLK #3	295	7.35	289.96	1.54×10^{-3}
All modules	99.7×10^3	2484	97.996×10^3	0.665

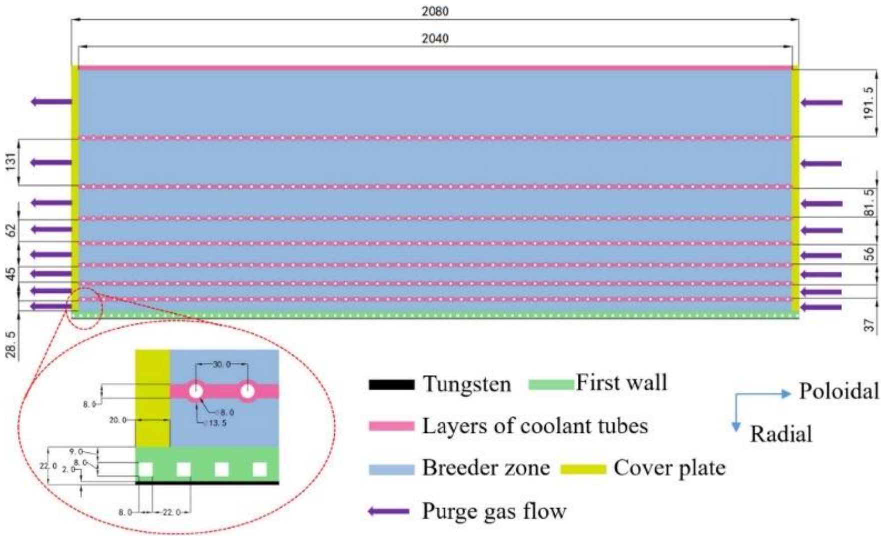
Tritium permeation into coolant is necessary to be extracted by CPS and reduced by tritium permeation barrier.

WCCB BLK tritium transport analysis (2/2)

➢Tritium transport model for BLKs and external fuel cycle



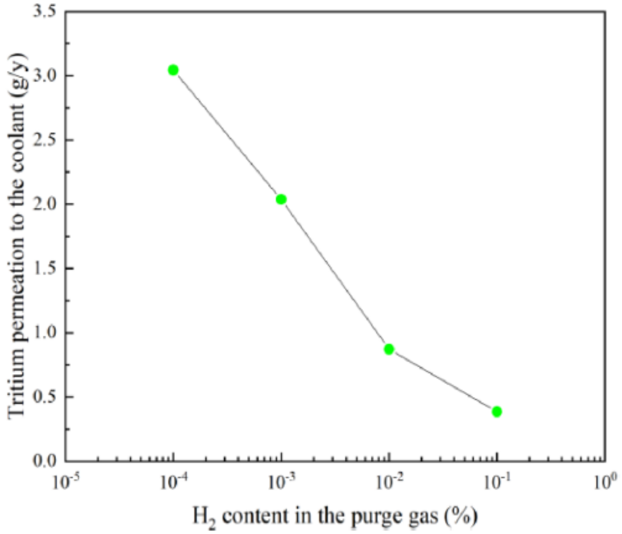
Model for external fuel circulating system



Simplified 2D model of typical BLK #3

Main parameters of tritium system of WCCB Blanket

Parameters	Value	Unit
Purge gas mass flow rate	8.86×10^{-1}	kg/s
Purge gas total mass	15	Kg
Primary Coolant mass flow rate	10,000	kg/s
Primary Coolant total mass	4.26×10^{5}	Kg
SG tubes wall average Temperature	554.76 [26]	K
SG permeation thickness	1.3×10^{-3} [26]	m
SG permeation area	3411.6 [26]	m^2
T permeability for SG	$5.19\times10^{-8}\cdot\exp(-0.43/(kT))$ [23]	mol/m/s/$\sqrt{Pa}$
Efficiency of TES	0.95	–
Percentage of coolant flowing into CPS	0.01	–



Tritium permeation under different H_2 contents

Items	Value (@FP1.5GW)
Tritium inventory in purge gas	9.85×10^{-2} g
Tritium inventory in coolant	8.57×10^{-4} g
Tritium extracted by TES	97.89 kg/y
Tritium purified by CPS	6.05 g/y
Tritium losses	2.85×10^{-5}g/y

- **Tritium extracted by TES is 97.89 kg/y, tritium purified by CPS is 6.05 g/y, and tritium losses is 0.285 Ci/y which satisfy the release limit of 20 Ci/d.**
- **H_2 in the purge gas can reduce tritium permeation to the coolant.**

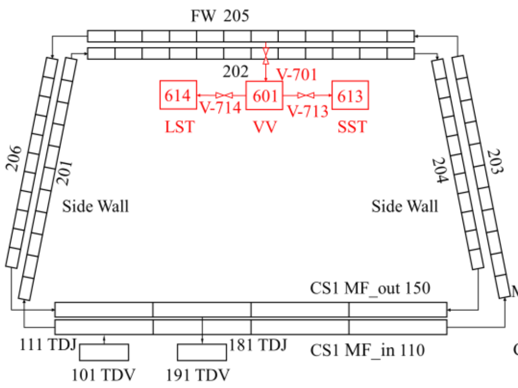
** X. Zhao, et al., Tritium transport code development based on COMSOL and MATLAB and its application to the WCCB blanket, Fusion Eng. Des. 173 (2021) 112929.*

WCCB BLK safety analysis

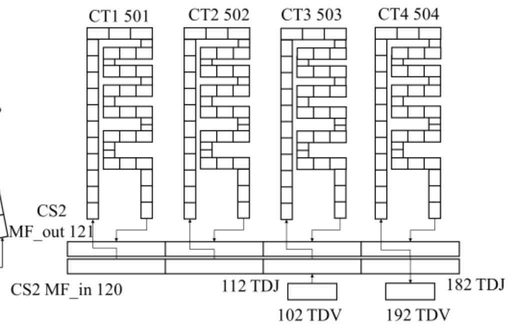
➢Thermo-hydraulic safety analysis for BLK #3

- **Temp. and pressure vary in allowable ranges under Steady /Transient /LOFA /In-Vessel LOCA condition**

RELAP5 nodalization for BLK #3



Nodalization for BLK #3 (CS1)

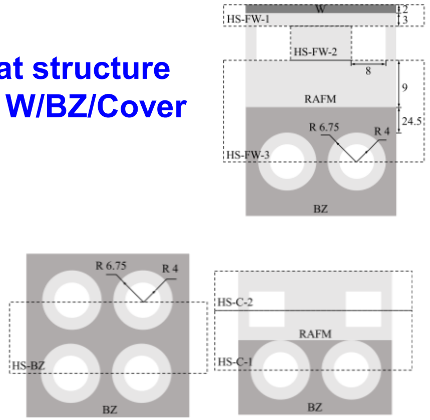


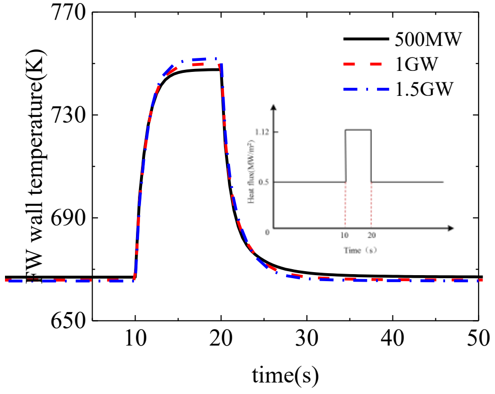
Nodalization for BLK #3 (CS2)

Thermo-hydraulic parameters at steady state (BLK 3#)

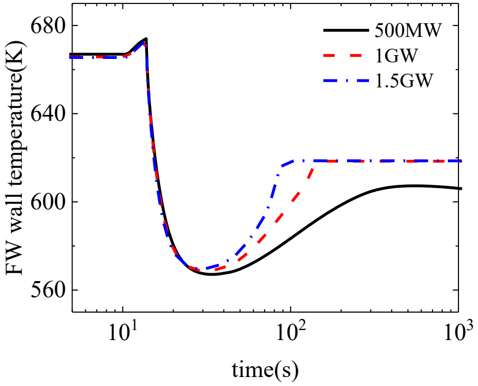
	500MW	1GW	1.5GW
Heat power（MW）			
Nuclear heat	1.739	3.479	5.218
Total heat	3.013	4.753	6.492
Mass flow rate（kg/s）			
CS1	8.2	10.2	12.3
CS2	5.9	11.7	17.34
Pressure drop（MPa）			
CS1	0.0117	0.018	0.0259
CS2	0.0017	0.0062	0.0132

Heat structure for W/BZ/Cover

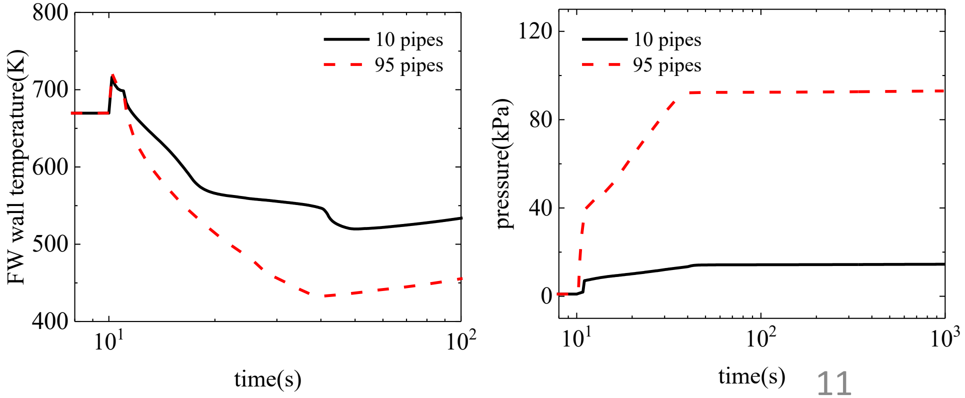




FW temp. (Transient operation)



FW temp. (LOFA)



FW temp. (left) and pressure drop in VV(right) (In-Vessel LOCA)

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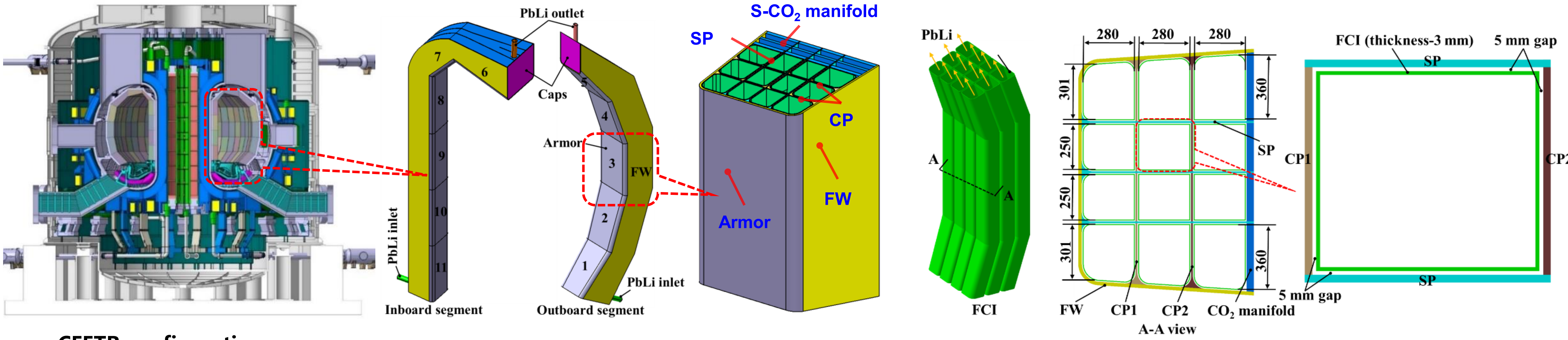
Supercritical CO_2 Cooled Lithium-lead (COOL) Blanket

➢ COOL blanket (BLK): an advanced BLK option for CFETR/CFEDR



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 ℃ ~390 ℃
  - PbLi self-cooling BZ, outlet 600-700 ℃
- **RAFM steel as structural material**
- **Tungsten as armor material**
- **SiC_f/SiC composites as Flow Channel Inserts (FCI) material**
- **Thermoelectric conversion efficiency: ~42%**

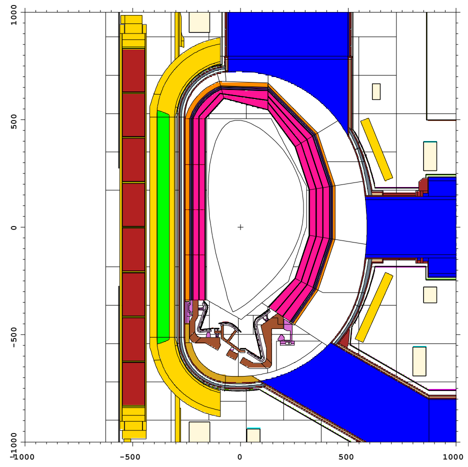
➢ Advantages and disadvantages

- **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)

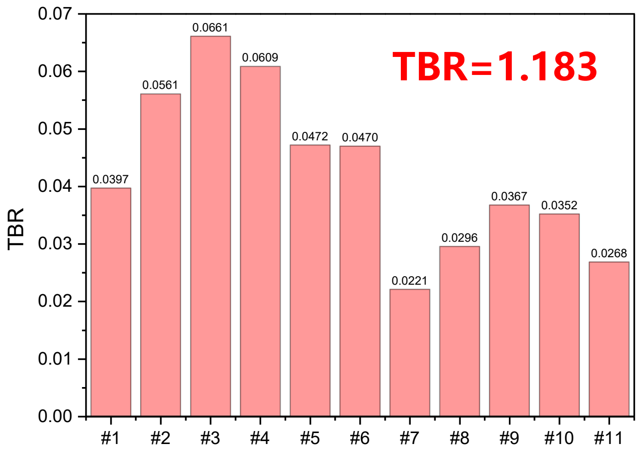
COOL BLK Nuclear performance (1/2)

➢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 behind divertors



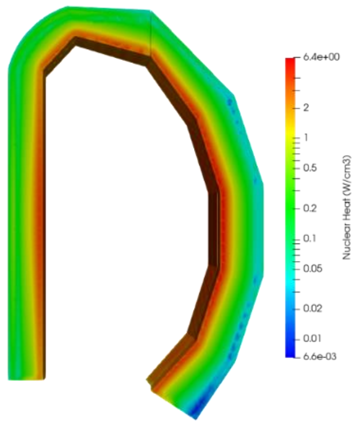
Neutronics Model



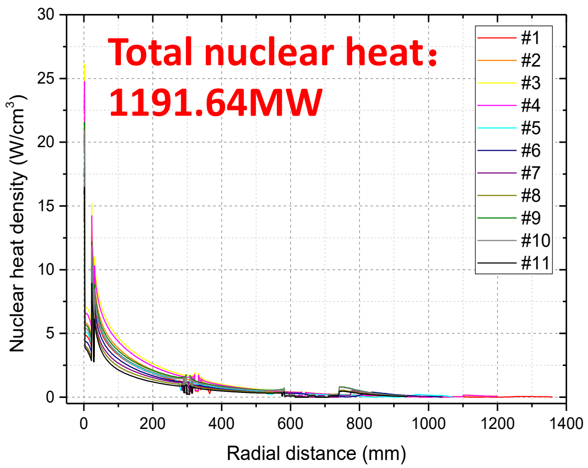
TBR

➢Nuclear heating

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



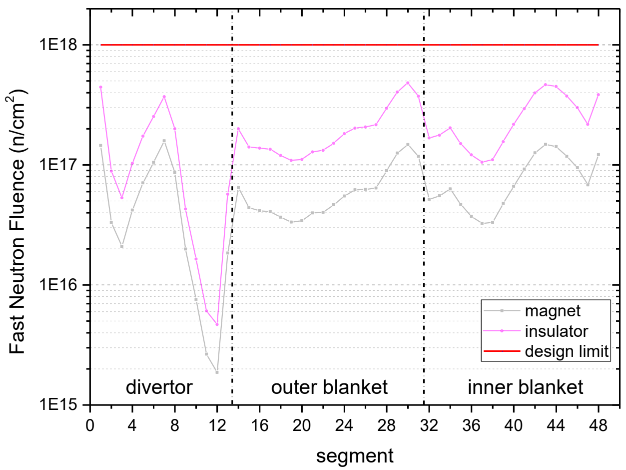
Nuclear heating in TFC



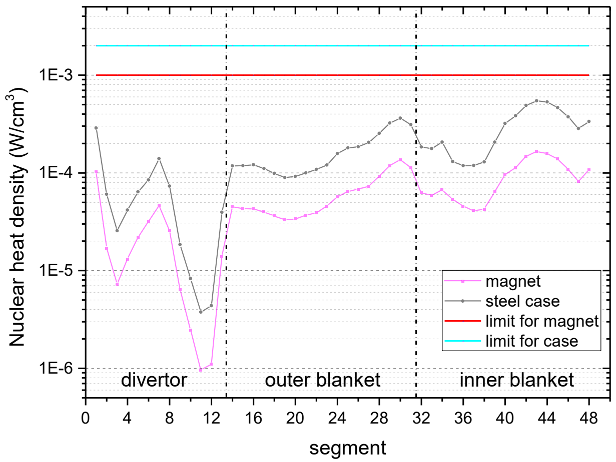
Radial nuclear heat distribution

➢Shielding performance

- Enough shielding for the magnet coils



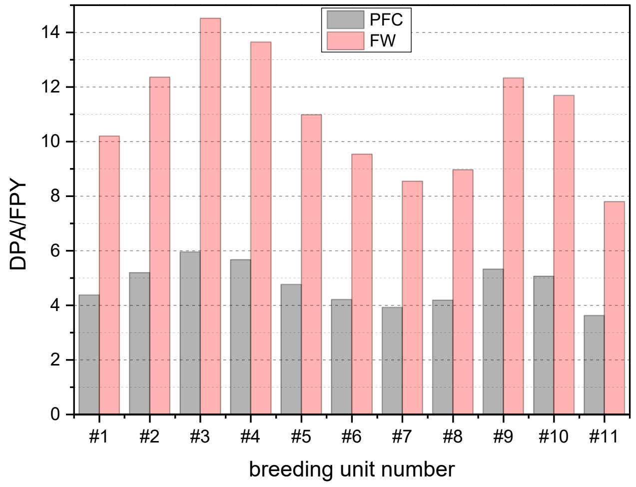
Fast neutron fluence in TFC

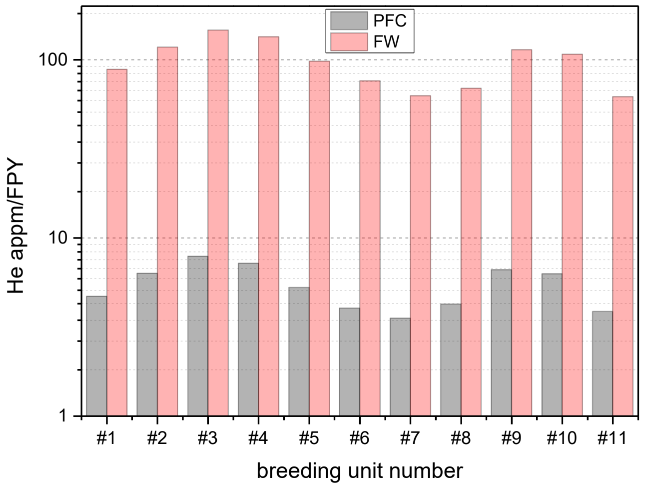


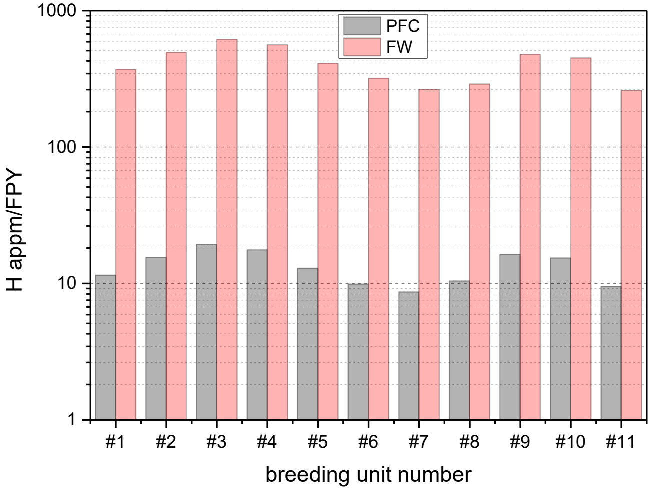
Nuclear heating in TFC

COOL BLK Nuclear performance (2/2)

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

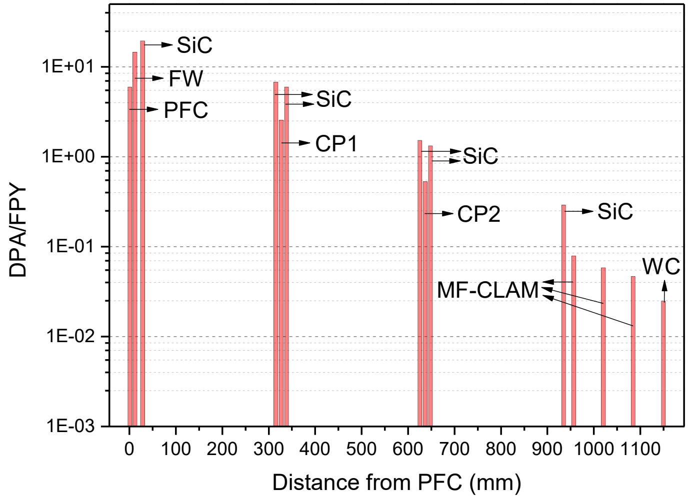




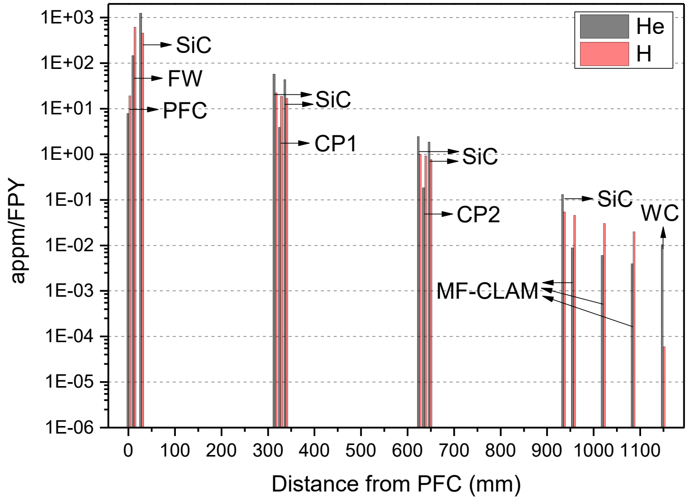


	3#		9#	
	PFC	FW	PFC	FW
DPA/FPY	5.96	14.52	5.33	12.33
He appm/FPY	7.86	146.80	6.62	113.64
H appm/FPY	19.26	612.76	16.21	475.12

Irradiation on PFC and FW for unit #1-11



SiC > SS > W



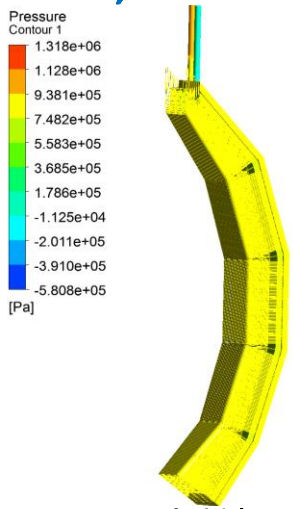
SiC/WC: He>H
SS/W: H>He

Irradiation on structural components for unit #3

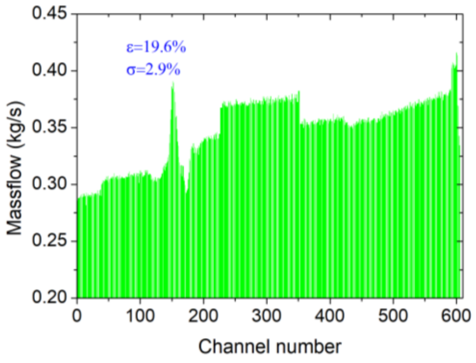
Q. Wu, P. Lu, X. Zhang, L. Chen, S. Liu, Neutronics analyses of COOL blanket for CFETR, Fusion Engineering and Design 179 (2022) 113130

COOL BLK thermal hydraulic & MHD analysis (1/2)

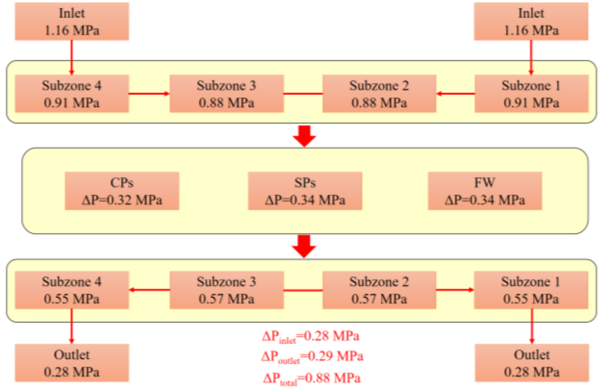
- 3D full banana model of PbLi and $S\text{-}CO_2$ is established independently to get the fields of flow and pressure.
- For $S\text{-}CO_2$, 82.3% of the total mass flow rate is distributed into the key component first wall.
- For PbLi, the distribution of mass flow rate decays radially, beneficial to cooling of BZs.



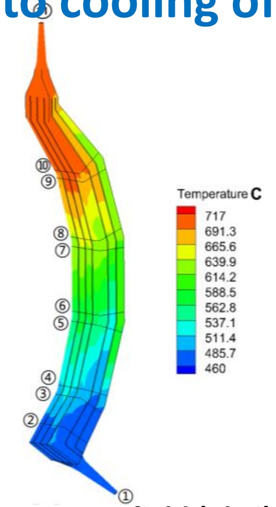
Pressure field ($S\text{-}CO_2$)



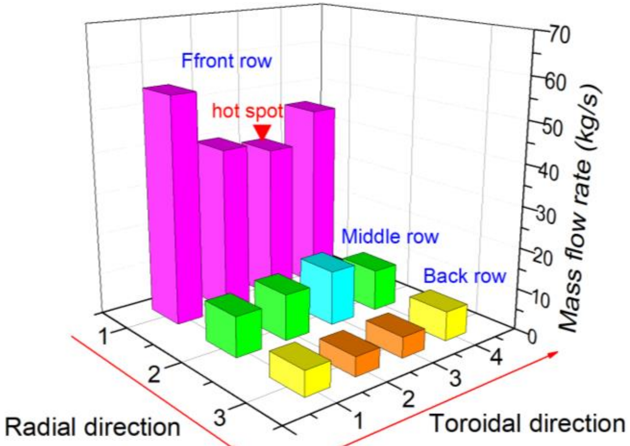
Mass flow rate in FW ($S\text{-}CO_2$)



Pressure flow path ($S\text{-}CO_2$)



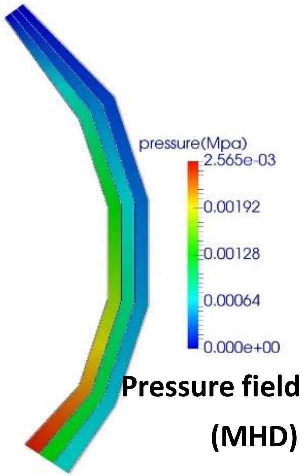
Tempeatrue field (PbLi)



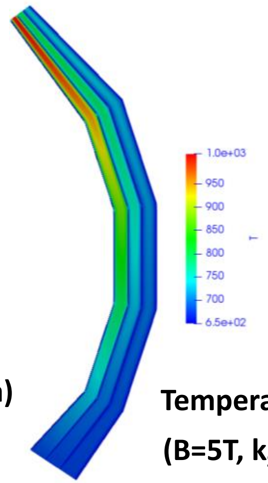
Mass flow rate distribution (PbLi)

2D MHD effect for outboard blanket segments

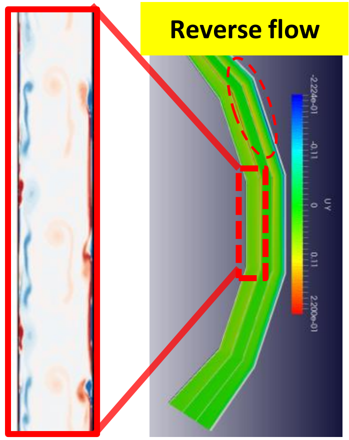
- Under the conditions of 5T magnetic field and electric insulation by SiC_f/SiC, the pressure drop decreases to ~10 kPa. The peak temperature is 740℃ neglecting the buoyancy effects.
- With the effects of MHD and buoyancy, there is reversed flow for PbLi and the high speed jet will induce flow instability near the channel wall.



Pressure field (MPa) (MHD)



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

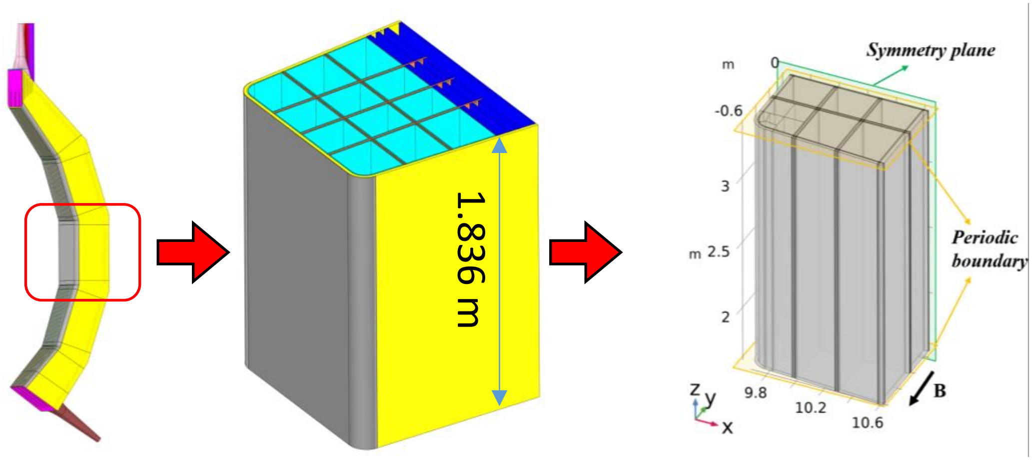


Velocity field (MHD)

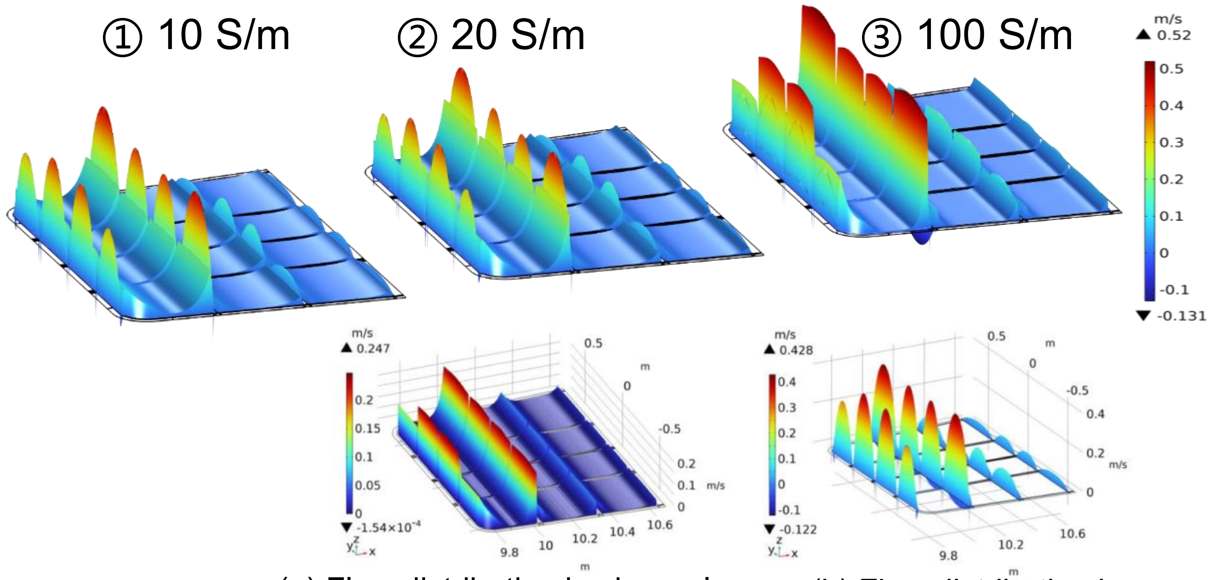
[1] K. Jiang, et al., Thermal hydraulic assessment on the full banana model of COOL blanket for CFETR, Nucl. Fusion 64 (2024) 046007.

COOL BLK thermal hydraulic & MHD analysis (2/2)

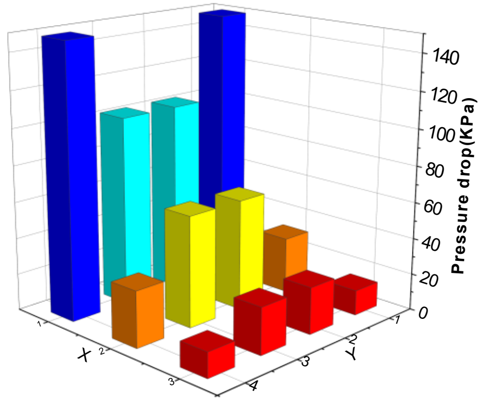
➤3D MHD analysis for typical outboard breeder unit (BU#3)



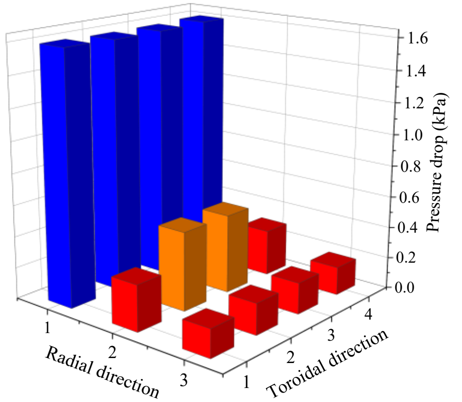
CFETR COOL MHD model for BU#3



(a) Flow distribution in channel (b) Flow distribution in gap



Case 1: MHD pressure drop (without FCI)



Case 2: MHD pressure drop (with FCI)

Influence of FCI on pressure drop of BU#3

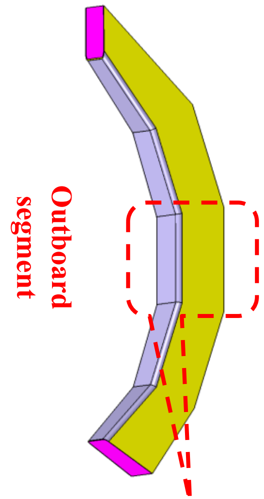
- **In case of conductive wall, the overall pressure drop of COOL segment reaches the order of ~1 MPa. FCI is needed to reduce the MHD pressure drop;**
- **FCI has strong effects on PbLi velocity and pressure field, insulating FCI with EC of ~10 S/m is helpful to decrease MHD pressure drop to below 2%.**

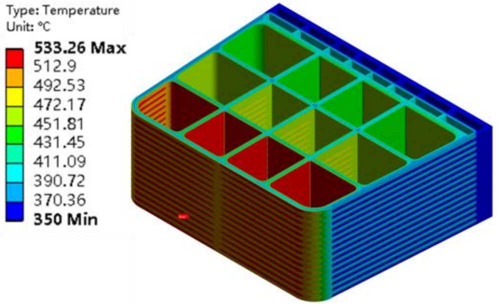
[1] P. Zhai, K. Jiang, L. Chen, S. Liu, Numerical simulation of MHD coupling effect relevant to COOL blanket for CFETR, Nucl. Fusion 65 (2025) 086047.

COOL BLK thermo-mechanical analysis

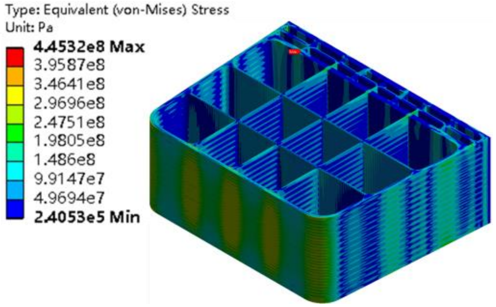
➢Thermo-mechanical analysis for typical outboard breeder unit (BU#3)

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

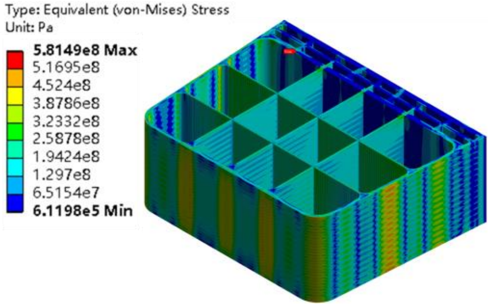




Temperature field of BU#3



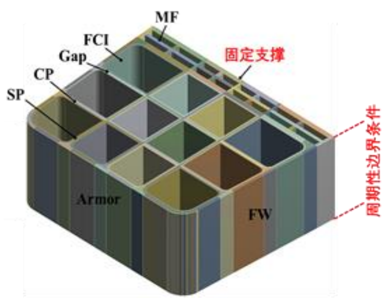
BU#3 stress field in normal condition



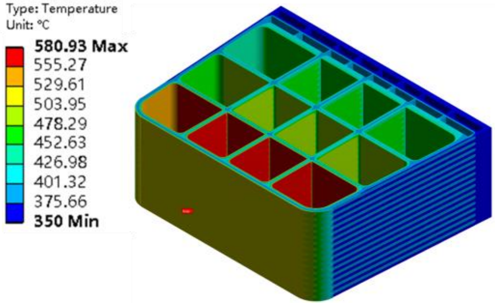
BU#3 stress field in in-box LOCA condition

PbLi outlet @600℃

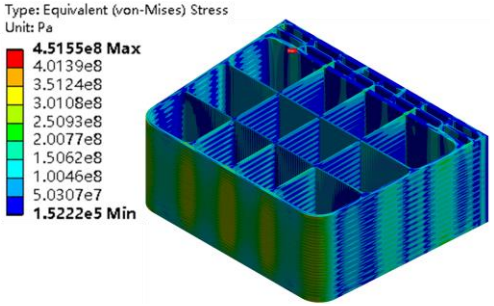
Components	Temp. (℃)	$SEQV \leq 3S_m^D$		
		SEQV (MPa)	Design limit (MPa)	Margin
FW	358	504	1010	50%
CP	412	531	956	44%
SP	413	429	954	55%
MF	400	584	973	40%



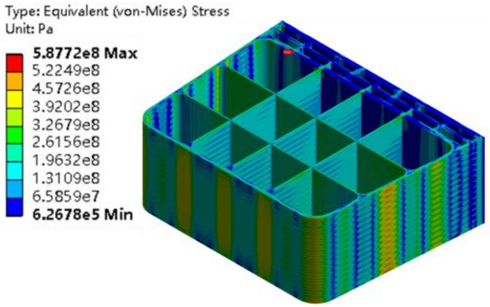
BU#3



Temperature field of BU#3



BU#3 stress field in normal condition



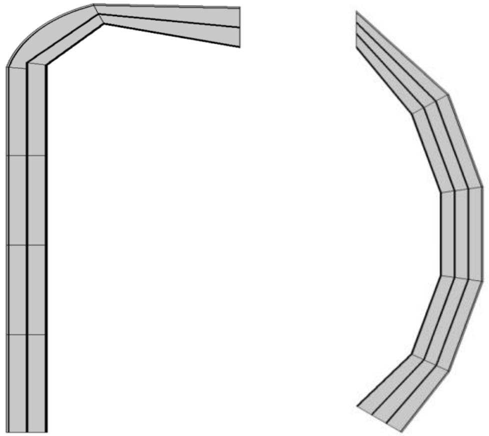
BU#3 stress field in in-box LOCA condition

Components	Temp. (℃)	$SEQV \leq 3S_m^D$		
		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%

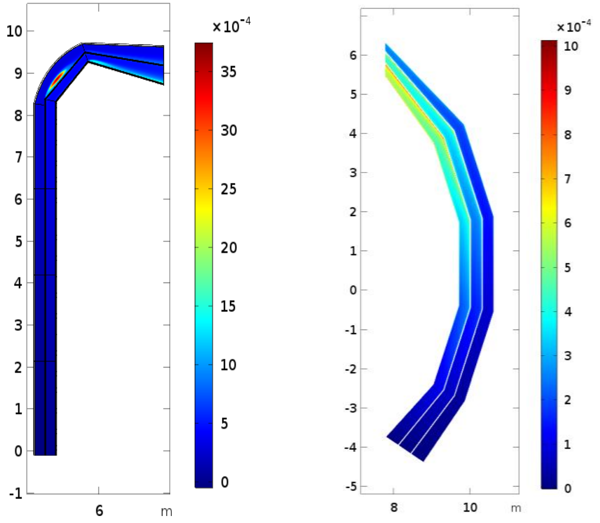
PbLi outlet @700℃

COOL BLK tritium transport analysis

➢2D Model



Geometry model of the blanket #1-#11



Tritium concentration in the breeder zone(@600℃ outlet)

➢ **Equations:**

- Equations for the breeder zone and structural

$$\frac{\partial C(x,y,t)}{\partial t} - D\nabla^2 C(x,y,t) + u\cdot\nabla C(x,y,t) = R$$

$$\frac{\partial C^{HT}(x,y,t)}{\partial t} = D\nabla^2 C^{HT}(x,y,t)$$

- energy equation

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p u\cdot\nabla T - \nabla\cdot(k\nabla T) = q$$

- N-S equations for the pure gas region in the blanket

$$\rho\frac{\partial \vec{u}}{\partial t} + \rho(\vec{u}\cdot\nabla\vec{u}) = -\nabla p + \nabla\cdot[\mu(\nabla\vec{u} + (\nabla\vec{u})^T] \qquad \rho\nabla\cdot\vec{u} = 0$$

➢ **Boundary conditions:**

PbLi-SiC: $C_{PbLi}/C_{SiC} = Ks_{PbLi}/Ks_{SiC}$ PbLi-RAFM: $C_{PbLi}/C_{RAFM} = Ks_{PbLi}/Ks_{RAFM}$

RAFM-SCO_2: $J_T = -2\cdot K_r\cdot C_{RAFM}\cdot C_{RAFM}$

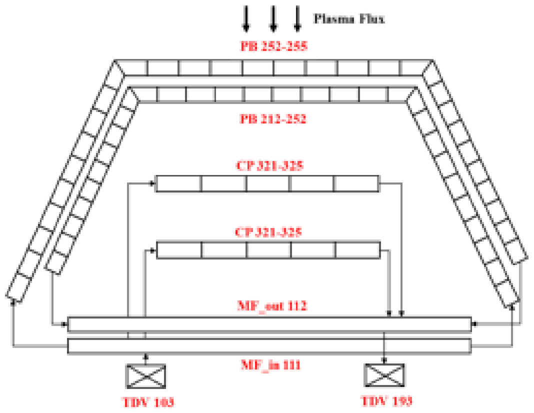
Item	Tritium inventory	Tritium permeation	Transported by the PbLi
Inboard segment	4.16×10^{-2}g	0.46 g/y	1.41×10^{3} g/y
Outboard segment	3.61×10^{-2} g	0.48 g/y	1.01×10^{3} g/y

Total tritium permeation is ~38g for all BLK segments if permeation barrier with a Permeation Reduce Factor (PRF) of 100 is assumed.

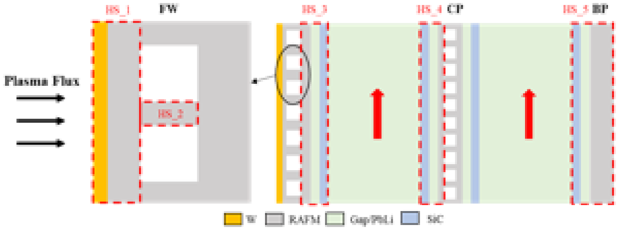
COOL BLK preliminary safety analysis

➢Safety analysis model of outboard segment

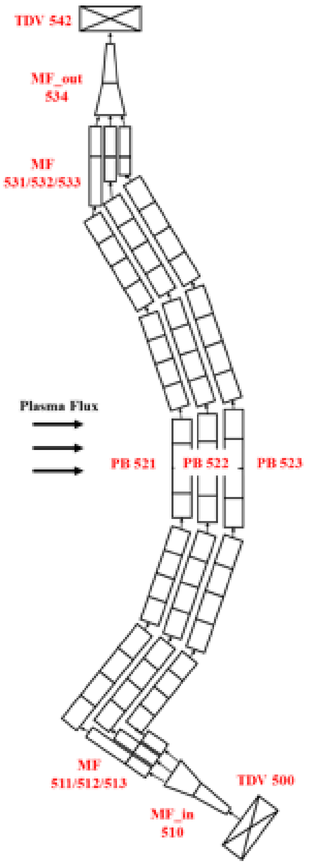
- Nuclear heat and FW heat flux considered



CO_2 coolant system nodalization



Blanket structure nodalization

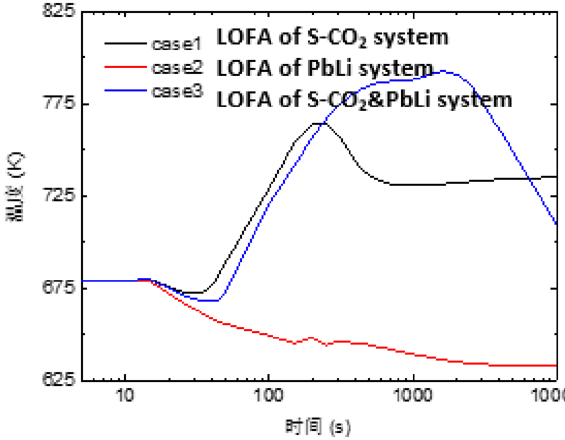


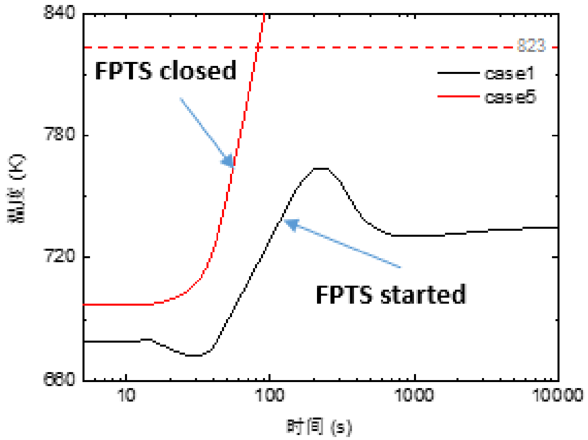
PbLi coolant system nodalization

➢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

- *W. Wang, et al., Fusion Engineering and Design 184 (2022) 113301.*
- *W. Wang,et al., Fusion Engineering and Design 199 (2024) 114138.*

Comparison between CFETR HCCB/WCCB/COOL

	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	~42% @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 S-CO_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

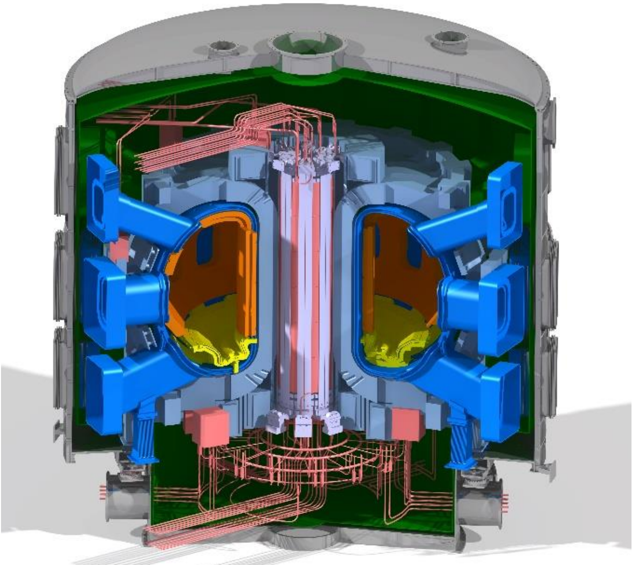
- COOL blanket has simple structure with high thermal efficiency, low coolant pressure, low construction cost, and is easy to extract tritium online, but MHD and corrosion are additional issues, yet controllable.
- Two-stage road map to mitigate corrosion and MHD effects: PbLi quasi-static flow for tritium extraction in first stage.

Outline

- Introduction
- WCCB blanket design
- COOL blanket design
- **BEST TBS design and test plan**
- Summary

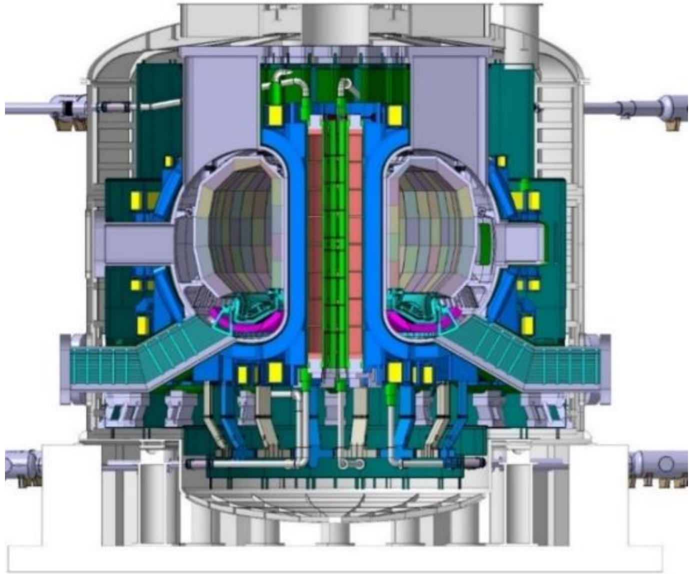
Burning plasma **E**xperimental **S**uperconducting **T**okamak (BEST)

BEST



BEST configuration
(R=3.6m, a=1.1m, 10-200MW)

CFETR



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

☐ To achieve burning plasma with lower cost

- **Fusion power:** 10-200 MW
- **Advanced DT operation:** Q≥1@20-40 MW & Q≥5@100-200 MW
- **High confinement mode for alpha particle heating**

☐ To develop key technologies for future reactors

- **Test materials and breeding blankets**
- **Tritium fuel cycle**
- **Licensing & safety**

☐ To demonstrate fusion energy production

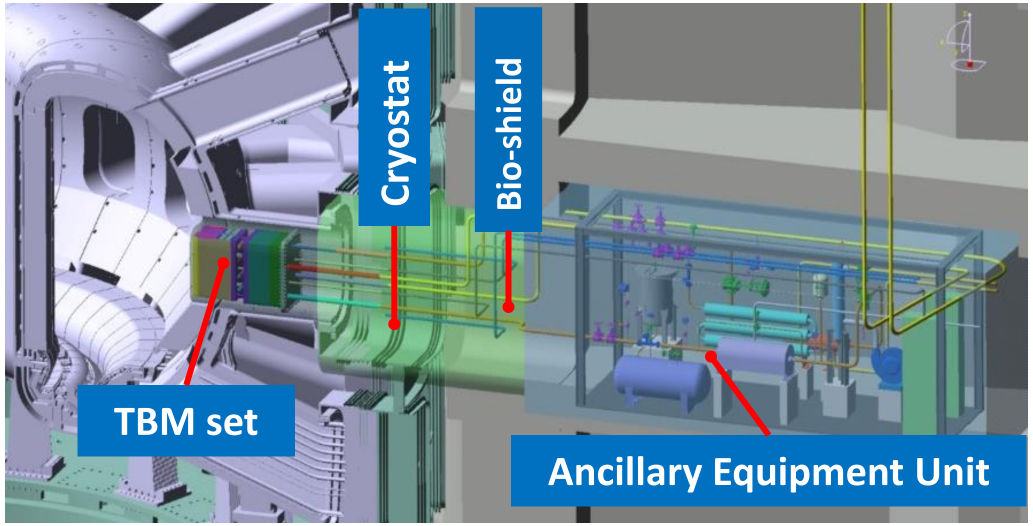
- **Fusion power:** 200-1500 MW
- **Phase I:** Q=1-5, Steady State Operation (SSO) of hours
- **Phase II:** Q>10, SSO of hours
- **High energetic α heating**

☐ To realize tritium (T) self-sufficiency

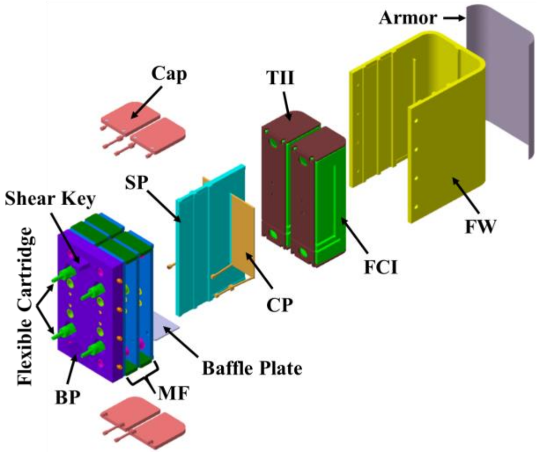
- **T-breeding by blanket:** Tritium Breeding Ratio (TBR) ≥ 1.1
- **T extract & reprocessing, Materials & components, Reliable and quick RH, Licensing & safety**

BEST Test Blanket Systems (TBS)

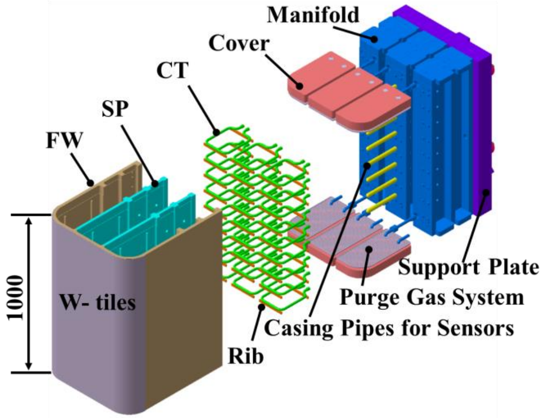
- **General objective:** validate tritium breeding and energy extraction
- **Strategies**
  - Keep relevancy to CFETR/DEMO to provide prediction for full size tritium breeding blanket designs
  - Select one solid blanket concept and one liquid concept to test
  - Start from low/near-term technology then move to high/long-term technology
  - Verify TBM thermal hydraulic performance out-of-pile before DT operation
- **Port Configuration**
  - Middle Port L: COOL TBM
  - Middle Port M: WCCB TBM
  - Module size: Tor.640mm×Pol.1000mm×Rad.800mm
- **Operation condition**
  - DT fusion power: 10~40 MW (40MW as the design basis condition)
  - Burning time/cycle time: 1000 s/pulse@40MW
  - Neutron Wall Loading: 0.17 MW/m^2 @ 40 MW
  - FW plasma heat flux: 0.3 MW/m^2 @ 40 MW



Port configuration in BEST



BEST COOL TBM



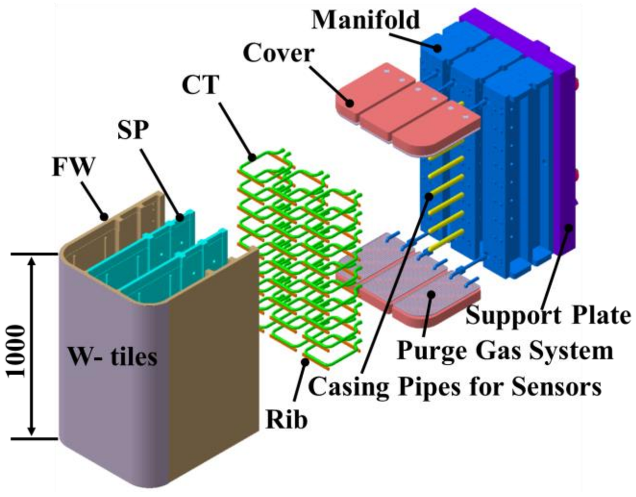
BEST WCCB TBM

Design of WCCB TBS

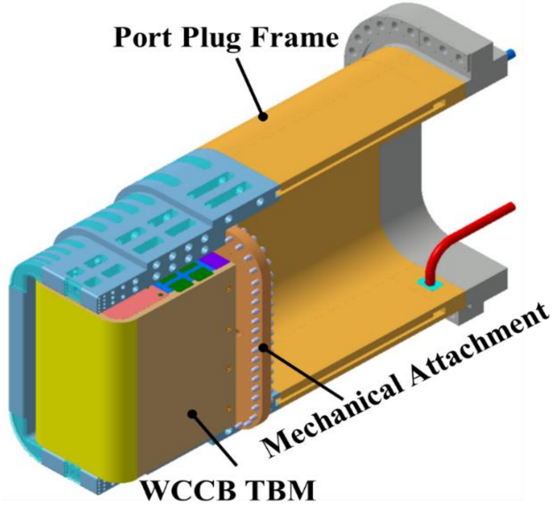
➤Main design features

- **CFETR/DEMO relevancy: same material/TH cond.**
- **Operation scheme starting from a low-power mode**
- **Out-of-pile test before operation in BEST**

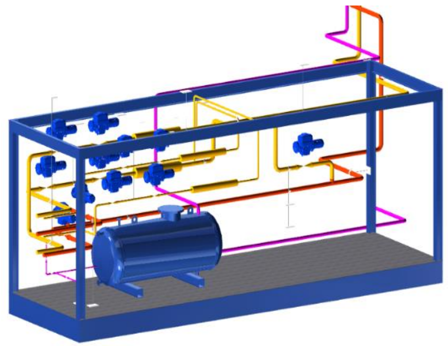
Mode	Item	Unit	Value
High FP	Operation P	MPa	15.5
	TBM inlet T	℃	285
	TBM outlet T	℃	325
	TBM flow	kg/s	1.27
	TBM total heat	kW	287
Low FP	Operation P	MPa	15.5
	TBM inlet T	℃	285
	TBM outlet T	℃	325
	TBM flow	kg/s	0.164
	TBM total heat	kW	37



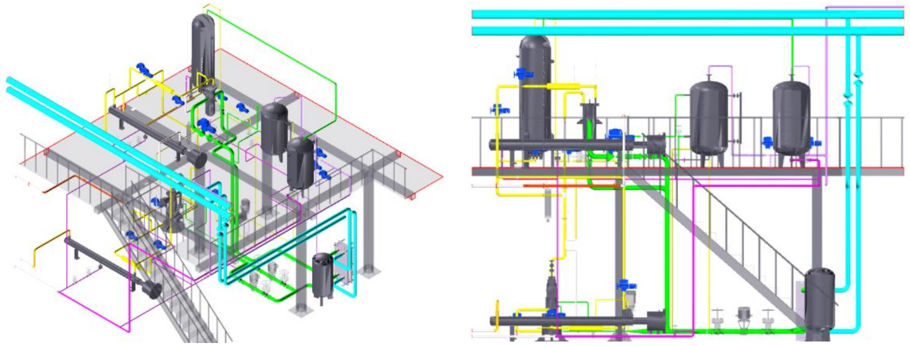
WCCB TBM



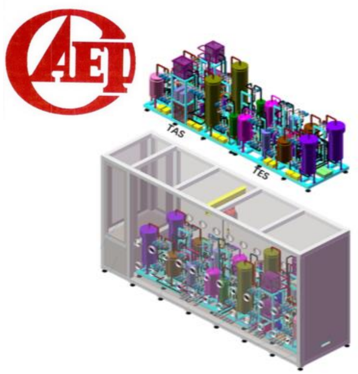
Port Plug



Ancillary Equipment Unit



Water Coolant System



TES/TAS

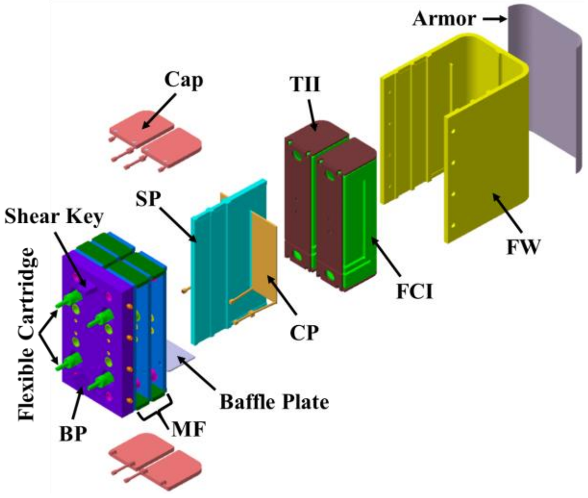
TES/TAS

- Purge gas: He+0.1% H_2, 0.3 MPa, 1~3 g/s, 300~500 ℃
- T extraction rate: ≥99%
- Ionization chamber:
  - Detection range: 10^7 ~10^{14} Bq/m^3, accuracy: ±5%
- Liquid scintillation analyser:
  - Detection range: >10 Bq/L, accuracy: ±1%

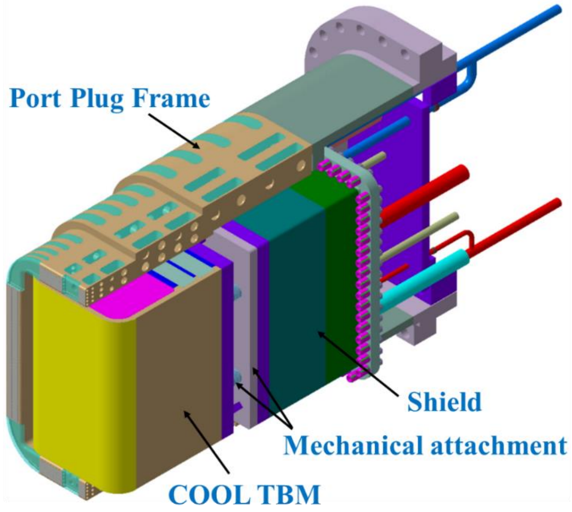
Design of COOL TBS

➢Main design features

- **CFETR/DEMO relevancy: same material/TH cond.**
- **SiC_f/SiC composites to mitigate MHD/corrosion**
- **Operation scheme starting from a low-temp. mode**
  - **Low-temp. mode: S-CO_2@8 MPa, 350/390 °C; PbLi@ 400/450 °C**
  - **High-temp. mode: S-CO_2@8 MPa, 350/410 °C; PbLi@460/600°C**
- **Out-of-pile test before operation in BEST**
- **Enriched lithium material will be used**



COOL TBM



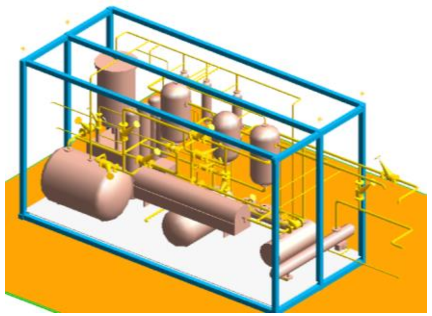
Port Plug

Coolant	Items	Unit	High mode	Low mode
PbLi	Power	kW	23	
	Inlet T	℃	460	400
	Outlet T	℃	600	450
	Mass flow	kg/s	0.2	1.41(<5)

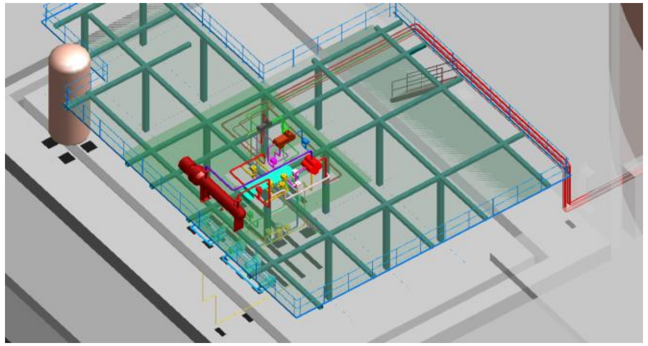
Coolant	Items	Unit	High mode	Low mode
S-CO_2	Power	kW	76	
	Inlet T	℃	350	350
	Outlet T	℃	410	390
	Mass flow	kg/s	1.1	1.88(<6)

Item	Value
PbLi volume	0.3 m^3
PbLi mass flow rate in PAV	Low/high temp. mode: 0.8/0.3 kg/s
Extraction temp. in PAV	535 °C
T at PAV inlet	Low/high temp. mode: <0.001/0.004 ppm
T extraction efficiency	≥ 90%
Vacuum of vacuum vessel	1×10^{-4} Pa

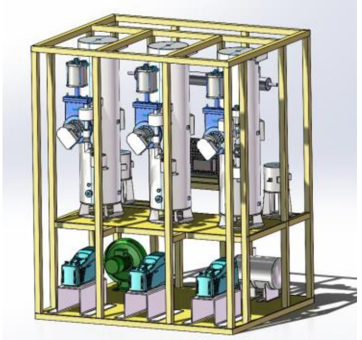
PbLi loop



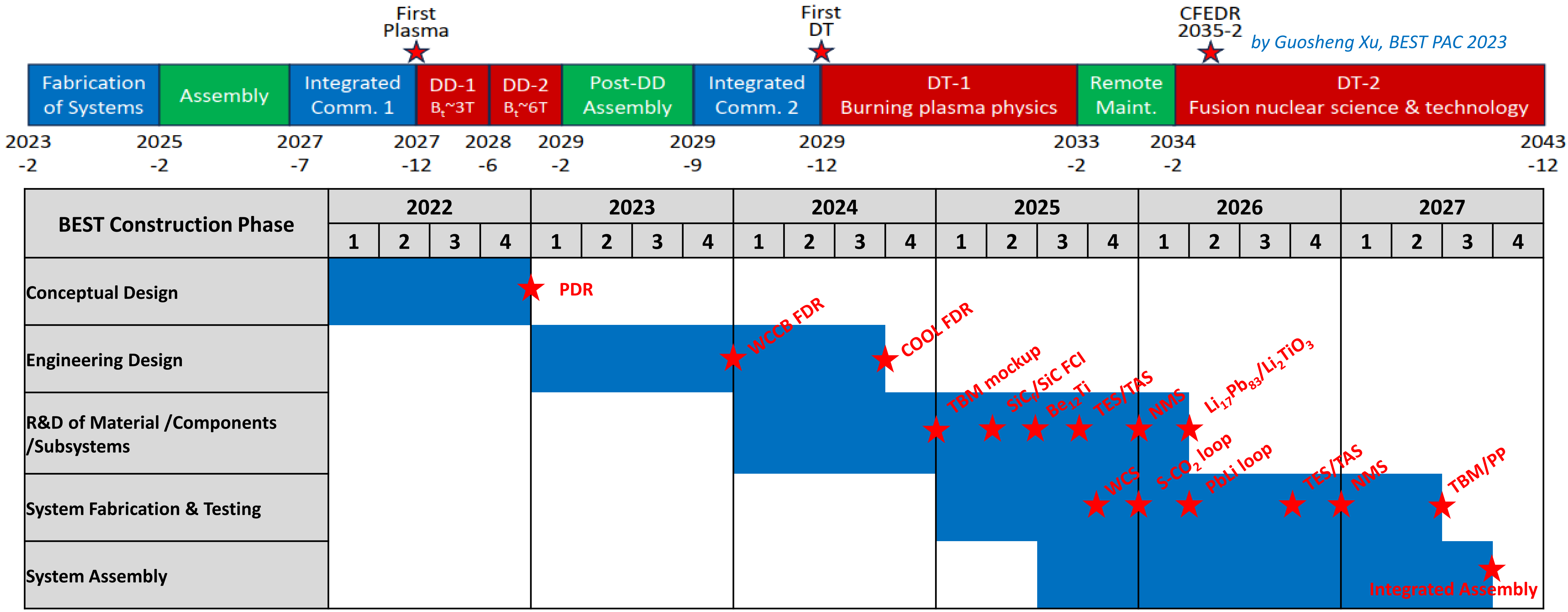
S-CO_2 loop



TES/TAS



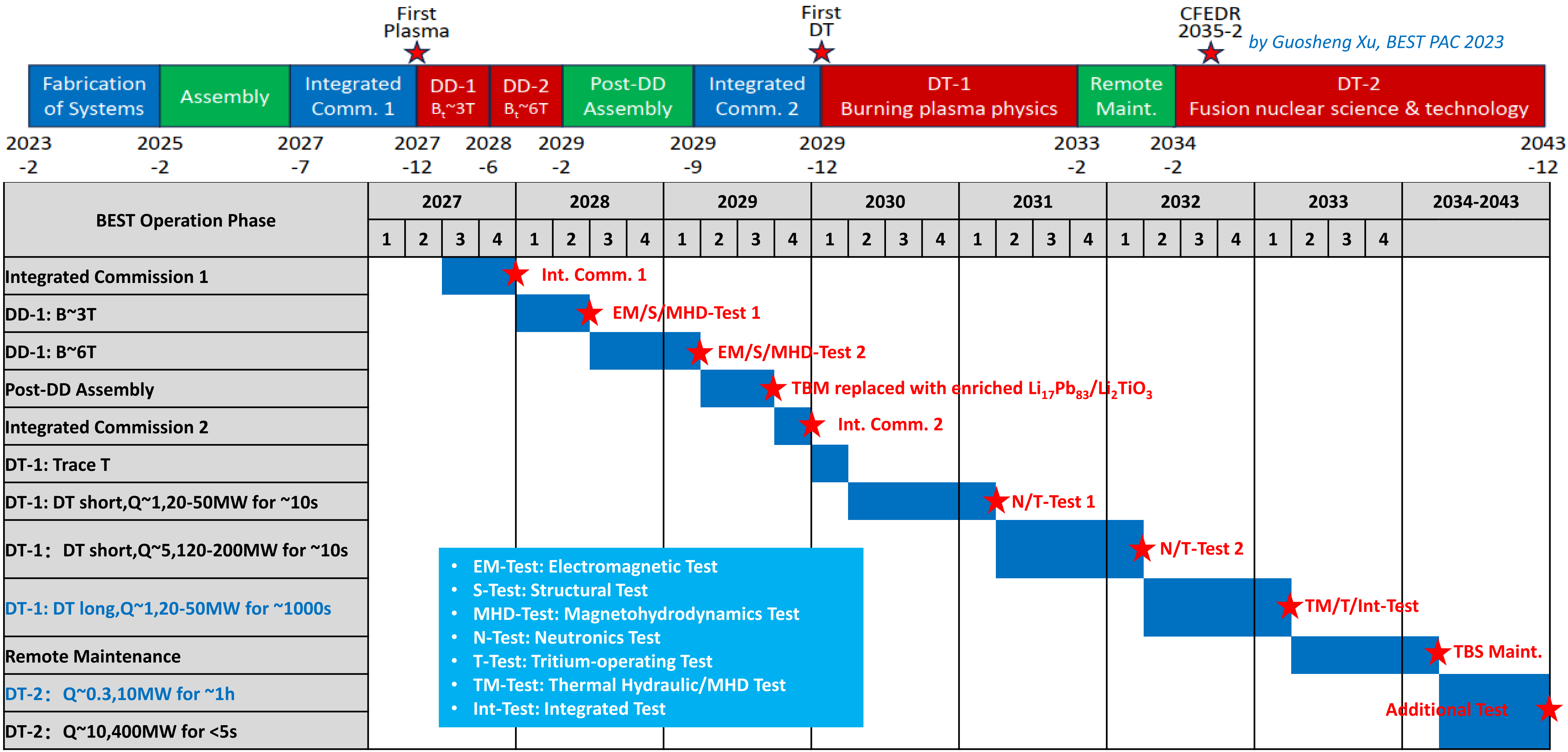
Design, R&D, Fabrication, Assembly Plan of BEST TBS



*Both WCCB/COOL TBM plan included

Preliminary Test Plan of BEST TBM

by Guosheng Xu, BEST PAC 2023



Test Plan of BEST TBM during DT-1 and DT-2

- **DT-1: DT long pluse, Q~1, 20-50MW for ~1000s**
  - **N-yield during DT-1:** ~1E24
  - **Tritium production during DT-1:** ~105mg by COOL TBM & ~165mg by WCCB TBM
  - **Testing Plan:**
    - **Thermal Hydraulic Test at high temp. for high-grade energy extraction**
    - **MHD Test at low/high temp. mode**
    - **Tritium-operating Test periodically for tritium extraction and accountancy**
    - **Integrated Test of the whole TBS including all sub-systems**
- **DT-2: DT long pluse, Q~0.3, 10MW for ~1h**
  - **N-yield during DT-2:** ~2.5E25
  - **Tritium production during DT-2:** ~2600mg by COOL TBM & ~4100mg by WCCB TBM
  - **Testing Plan:**
    - **Thermal Hydraulic Test at steady state for high-grade energy extraction**
    - **Tritium-operating Test periodically for tritium extraction and accountancy**
    - **Integrated Test for an extended period of time in order to obtain initial reliability data**

BEST WCCB TBM compared with ITER/CFETR

	BEST WCCB TBM	ITER WCCB TBM	CFETR WCCB (BLK #3)
FP	40 MW	500 MW	1500 MW
NWL	0.17 MW/m^2	0.78 MW/m^2	1.82 MW/m^2
FW heat flux	Average ≤0.3 MW/m^2	Average 0.3 MW/m^2	Average 0.5 MW/m^2
Burning time	1000s/pulse	400s per 2000s	8h running &15min dwell
Size (Rad.×Tor.×Pol.)	700×640×1000	600×680×1940	948×1249×2090
Total power	≤284 kW	1.55 MW	6.57 MW
Nuclear heat	92 kW	1.15 MW	5.25 MW
Irradiation damage	Max. ~0.02 dpa/life	~<0.2 dpa/DT-1 & ~<0.5 dpa/DT-2	Max. ~10 dpa/FPY
TPR	0.147 mg/pulse (12.7 mg/FPD) (1000s/pulse, 1 pulse/day)	~0.42 mg/pulse (~80 mg/FPD) (450s/pulse, 48 pulses/day, duty factor=0.25)	15.7 g/FPD

Technology ready: Pressurized water loop, EBG for high heat flux, Preparation of Li_2TiO_3 of nature abundance, FW mock up fabrication, out-of-pile neutronics experiments

R&D needs: Key components fabrication & module assembly, production of $Be_{12}Ti$ and enriched Li_2TiO_3, R&D for TES/TAS/NMS, out-of-pile thermal hydraulic test

BEST COOL TBM compared with ITER/CFETR

- NWL of BEST is ~20% of that of ITER and the maximum irradiation damage is ~0.02 DPA in BEST TBM. Therefore, the material irradiation effect cannot be tested in BEST.
- Neutron yield of BEST is 2.5E25, close to that of ITER in DT-1 operation stage (3E25), which indicates BEST will have a comparable tritium production with ITER in DT-1 by similar FW size of TBM.
- Similar systems (PHTS/TES/TAS/NMS) and technologies (BLK fabrication, BLK test facilities) will be tested by BEST TBS, which are also beneficial and applicable to ITER.
- BEST probably starts the TBM testing and acquire data before ITER, which should be able to provide a reference for ITER.
- The concept of dual coolant blanket will be demonstrated for the first time in the world by BEST COOL TBS under relevant fusion environment, which is an important supplement to ITER TBM.

	BEST COOL TBM	ITER WCLL TBM	CFETR COOL (BU #3)
FP of plant	40 MW	500 MW	1500 MW
NWL	0.17 MW/m^2	0.78 MW/m^2	1.82 MW/m^2
FW heat flux	Average ≤0.3 MW/m^2	Average 0.3 MW/m^2	Average 0.5 MW/m^2
Burning time	1000s/pulse	450s/pulse per 1800s	8h running &15min dwell
Size (Rad.×Tor.×Pol.)	780×640×1000	685×462×1670	948×1249×2090
Total power	≤262 kW	722 kW	5.56 MW
Nuclear heat	70 kW	488 kW	4.24 MW
Irradiation damage	Max. ~0.02 dpa/life	~<0.2 dpa/DT-1 & ~<0.5 dpa/DT-2	Max. ~14.5 dpa/FPY
TPR (Tritium Production Rate)	0.094 mg/pulse (8.1 mg/FPD) (1000s/pulse, 1 pulse/day)	0.35 mg/pulse (66.4 mg/FPD) (450s/pulse, 48 pulses/day, duty factor=0.25)	15.2 g/FPD

What can be tested by BEST TBM?

➢Most effects & interactions in BB can be partially validated by BEST TBM

BLK concepts	Nuclear effects	Electromagnetic effects	Thermal hydraulic effects	Thermo-mechanical effects	Tritium interactions	Nuclear safety
CFETR /BEST WCCB	• Irradiation damage: ≥50/~0.01 dpa; • Tritium breeding in one module: ~5/~3-5E-3 kg/FPY; • Material activation: ~4E20 /~3E16 Bq	• Static magnetic force: 4-8/3-6 T • Transient electromagnetic force in plasma disruption events: 14/7.4 MA disruption	• High heat flux removal from FW: 0.3~0.5/<0.1-0.3 MW/m²; • Coolant leakage: 300℃, 15.5 MPa; • Structure/Pebble bed thermal hydraulics: 300-900/300-600℃;	• Static/Transient load; • Thermal stress: ΔT~600/300℃; • Structure/Pebble bed thermo-mechanics: T_{max}~900/600℃; • Fatigue and failure	• Tritium permeation; • Tritium rention; • Tritium extraction and isotopic exchange:~0.3/~1E-3 Ci/kg@BZ	• LOCA accidents; • Radioactive substance release and migration: LLW/ILW or HLW @decommissioning. • License
CFETR /BEST COOL		• Static magnetic force in 4-8/3-6 T • Transient electromagnetic force in plasma disruption events: 14/7.4 MA disruption • MHD effects: Re=1E5/2E3, Ha=1E4/1E4, Gr=1E11/1-4E10	• High heat flux removal from FW: 0.3~0.5/<0.1-0.3 MW/m²; • Coolant leakage: 350-500℃, 8 MPa; • Structure/liquid metal thermal hydraulics: 400-700/300-600℃;	• Static/Transient load; • Thermal stress: ΔT~300/200℃; • Structure/FCI thermo-mechanics: T_{max}~700/600℃; • Fatigue and failure	• Tritium permeation; • Tritium rention; • Tritium extraction and transport in liquid metal: ~1E-3/~1E-4 Ci/kg@BZ	

Can not be validated **Can be nearly validated** **Can be partially validated**

Outline

- Introduction
- WCCB blanket design
- COOL blanket design
- BEST TBS design and test plan
- **Summary**

Summary

- **WCCB/COOL blankets are proposed as BLK candidates for CFETR in ASIPP and related N /TH /TM /T /safety analyses prove feasibility of the BLK concept.**
- **Both WCCB and COOL TBM will be tested in the BEST machine for validating tritium breeding and energy extraction technology. TBM system design has been updated, and test plan will start from 2027.**

Thank you for your attention!