Conceptual Design of CFETR

Blanket Design（I）： Solid Blanket

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What's Blanket Type is Suitable for CFETR?

- Tritium breeding blanket is a very complex component, work at very severe working condition. The concept of blanket will give the reactor's basic characteristics.
- It was assumed that CFETR should be steady state D-T operation, tritium self-sufficiency, and with net power output.
- Main design objectives will be:
  - to validate the tritium breeding performance , (TBR>1).
  - to realize the heat remove.
- Basic considerations for CFETR blanket selection:
  - Flexibility
  - Maintainability
  - Replaceability
  - Low-risk, and
  - Matured technology .

◆ **Based on current mission and Chinese ITER TBM development strategy, two kinds of blanket concept options can be considered:**

Option I: Helium-cooled ceramic tritium breeder with RAFM, HCCB ;

Option II: Liquid Li-Pb tritium breeder with RAFM, DCLL;

It is very important that exiting technology foundation and abundant data bases.

General Consideration of Solid Breeder Blanket

Option （I）： Solid Breeder Blanket

The ceramic breeder blanket with RAFM material concept might be primary option for CFETR design. General consideration of solid blanket as the following:

- It is easy to realize blanket flexibility，maintainability， replaceability, and multi-function based on the modularized structure design.
- Solid blanket concept is current main stream design in ITER TBM program.
  - good tritium breeding and release performance.
  - widely TBR design margin (TBR from 1.0 to 1.22 with Be, depend on the calculation model, nuclear data, and design element, etc).
- Widely technology foundation and R&D data base on around the world.
- Without MHD, material corrosion and compatibility issues.
- Matured technology on tritium extraction, recovery , purification and processing.

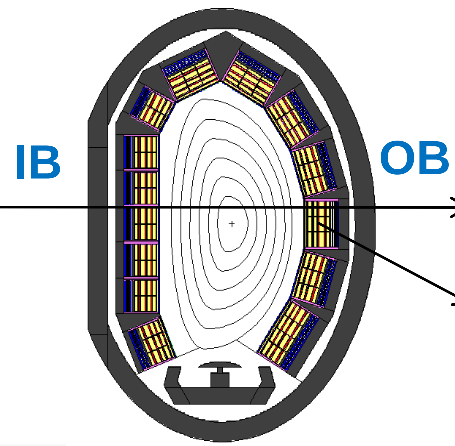
Basic futures of solid breeder blanket

- Structure material: Reduced-activation Ferritic/Martensitic steel (RAFM)
- Tritium breeder: Li_4SiO_4 or Li_2TiO_3, with pebble bed structure.
- Neutron Multiplier: Be, with pebble bed structure.
- Coolant: He gas with high pressure or supper-critical water coolant.
- Purge gas: He gas
- Tritium Breeding Rate: TBR >1.2

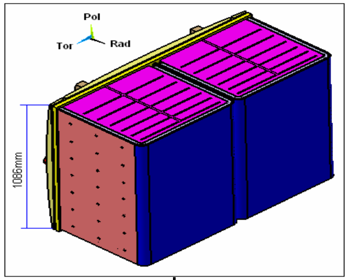
Parameter and Requirements

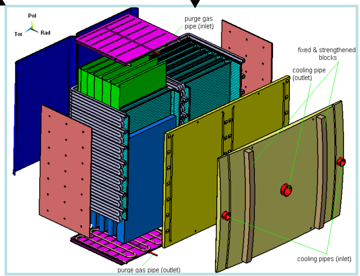
Assumed Pl. Parameter Range

- Major radius: 4.9m,
- Minor radius: 1.2-1.5m
- Elongation : 1.75
- Triangularity: 0.4
- Neutron wall loading: 0.4-0.8MW/m^2
- Fusion power : 200-400MW
- Operation duty : 0.3~0.5



3-D Model





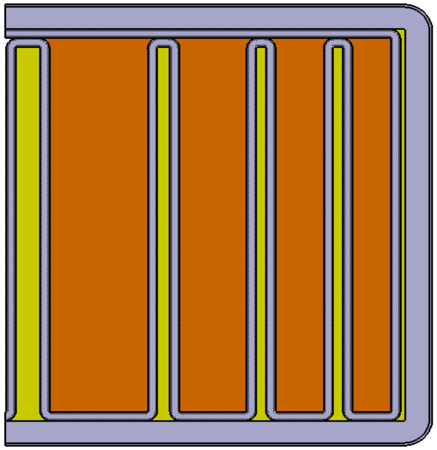
modularized blanket design

Basic Requirements

1. Tritium Breeder: Ceramic Breeder, Li_4SiO_4 or Li_2TiO_3
2. Tritium Self-sufficiency (TBR>1.2 , 3-D)
3. Blanket Thickness: Breeding + Shielding + VV < 1.0 m
4. Replace is easy

Requirement of Tritium Breeder

1. High enrichment of ^{6}LI: 80%-90%
2. High compatibility with structure materials and beryllium.
3. High heat, chemical, machinery and irradiation performance.
4. High tritium release performance.
5. Low tritium retention.
6. Tritium is easy to extract.

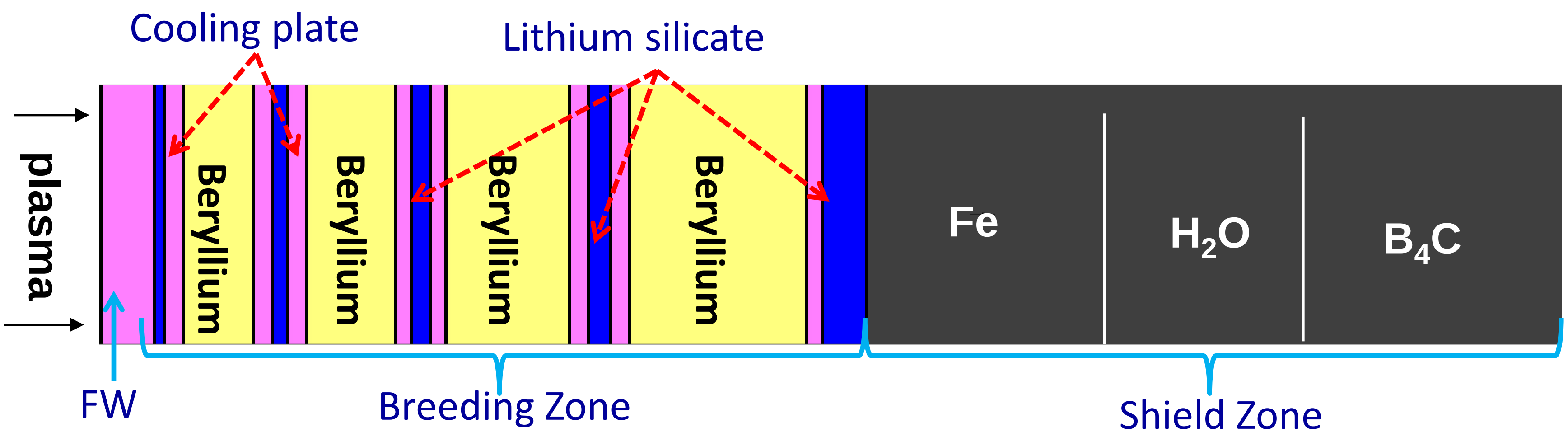


Structure and Materials of Blanket

- Single sized tritium breeder pebble Li_4SiO_4， D=1mm, packing rate is 60%, Concentration rate of ^6Li > 80%.
- Binary sized neutron mltiplier, Be pebble, D= 0.5-1.0mm, packing rate is 80%.

Thickness of each zones:

- First Wall: 3cm（structure material is RAFM).
- He cooling plate : 1cm.
- Shield zone : 30~50cm (depend on shield design).
- 5 lithium silicate zones: 6.4cm： 0.6、1.0、 1.0、1.3、2.5cm.
- 4 beryllium zones : 25.1cm：4.0、5.0、7.0、10.1cm.

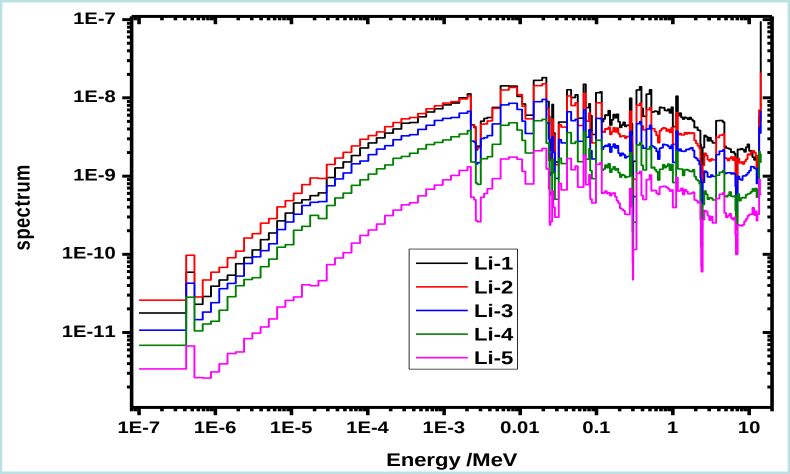


1-D Schematic of Outboard Blanket

Neutronics Analyses

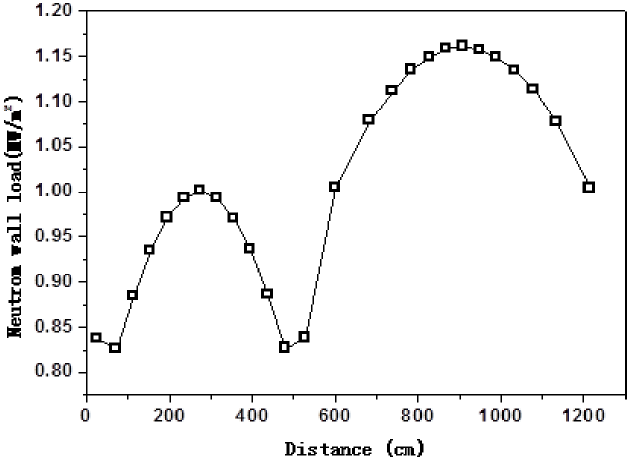
Neutron Wall Loading Distribution

- 1-D Neutronics Code:
  ONEDANT/ANISN
- 3-D Neutronics Code
  Neutronics： MCNP，MCNPX
  Shielding： MCNP+TORT, FISPACT
- Nuclear Data Library: FENDL21



Spectrum Distribution of OB Blanket

✓ Isotropic volume neutron source distribution ;
✓The maximum neutron wall load is about 1.4 times of the average wall loading ;
✓The outboard neutron wall loading is about 20% higher than the Inboard wall loading;
✓It should be considered for the variable of neutron wall loading distribution along radial direction.



Neutron Wall Loading Distribution along radial direction

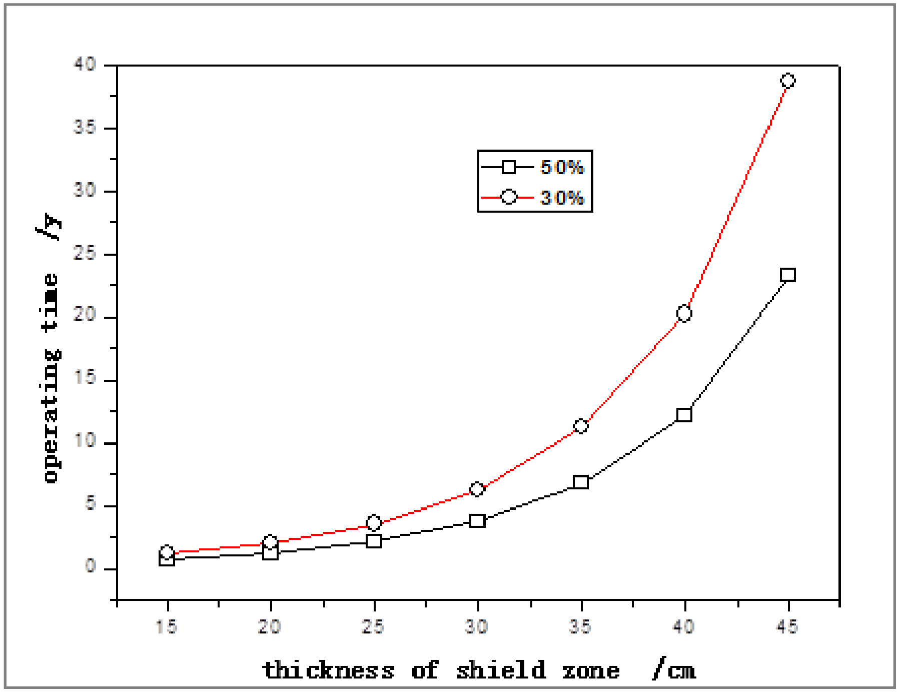
One-Dimensional Shielding Analysis

Shielding requirement

It was assumed that the change ratio of coil electric resistance will not exceed 10%， neutron fluence of coil less than $1\times10^{19}n/cm^2$。

Shielding thickness

If the operation duty is 30%, and the neutron wall loading is $0.8MW/m^2$ and the thickness of shield is 40cm， CFETR can operate 20 years 。

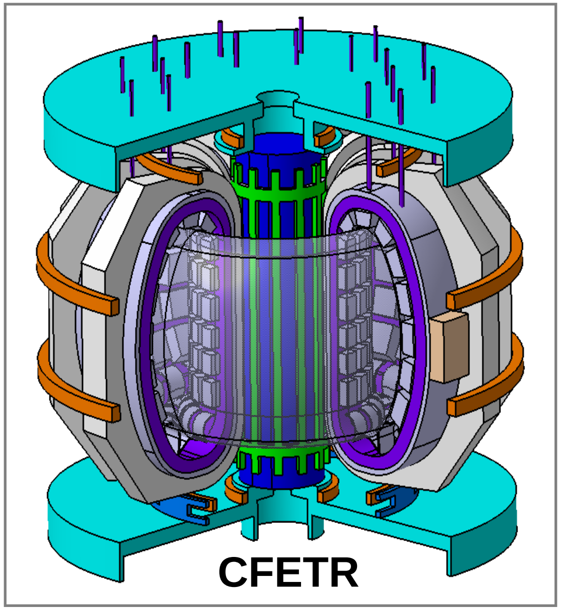


Shielding thickness VS. Operating time

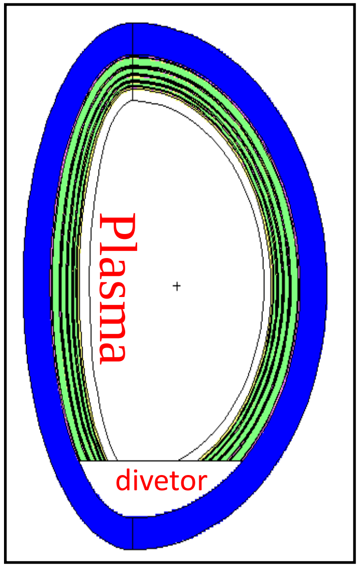
Simple 3-D Neutronics Analysis

Plasma parameter

parameter	unit	value
Major radius	m	5.3
Minor radius	m	1.2
Elongation	/	1.75
Triangularity	/	0.4
Neutron wall loading	MW/m2	0.5



- Calculation model
  - Blanket structure is same with 1-D model.
  - Arrangement of In-B and out-B is same.
  - 15 and 10cm scraping layer for IB and OB, respectively.
  - Space for divetor is taken in court.
  - Isotropic volume neutron source is used.

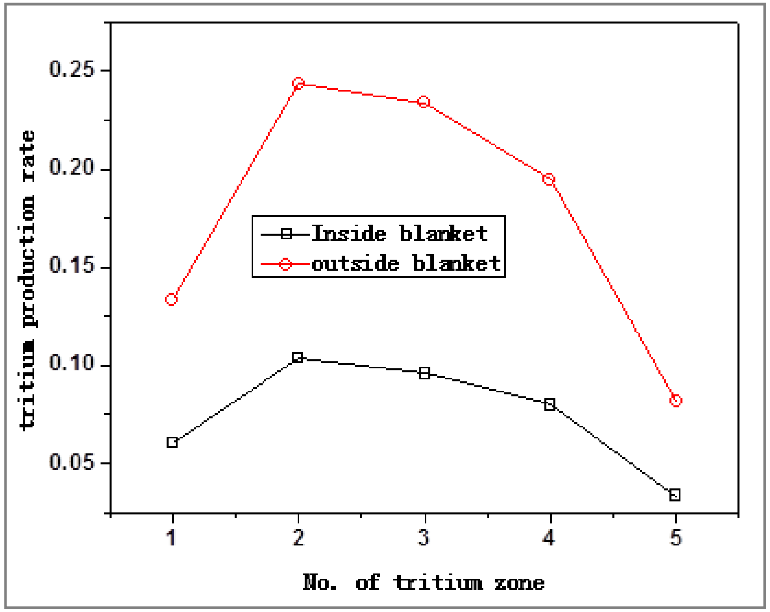


3-d analysis model

Tritium Breeding on IB and OB

- Based on calculation results of simple 3-D model, total tritium breeding rate (TBR) of the blanket is 1.26（IB+OB）
- Results are normalized to 1 D-T fusion neutron .

- About 70% of tritium breeding is contributed by outboard blanket, and 30% contribution from inboard blanket;
- Max. contribution of tritium breeding rate occurs in 2nd ceramic breeder zone.
- Installing In-board tritium breeding blanket is necessary for Self-sufficiency.

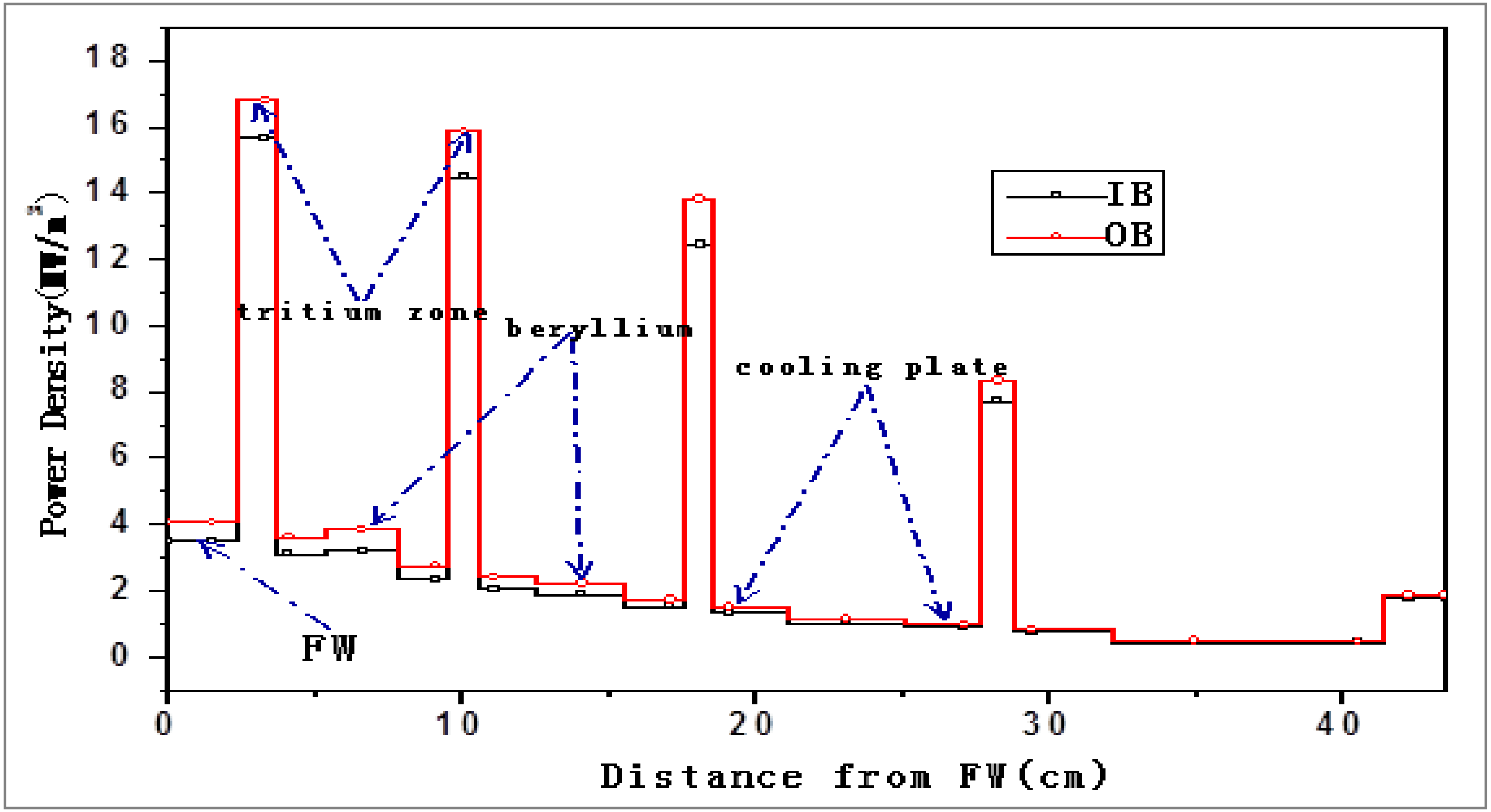


Tritium breeding distribution

Power Density Distribution

On along radial direction

- If average neutron wall loading is 0.8MW/m^2, the total fusion power will be 350MW。Max. power density is 17MW/m3 which occur at first tritium breeding zone.

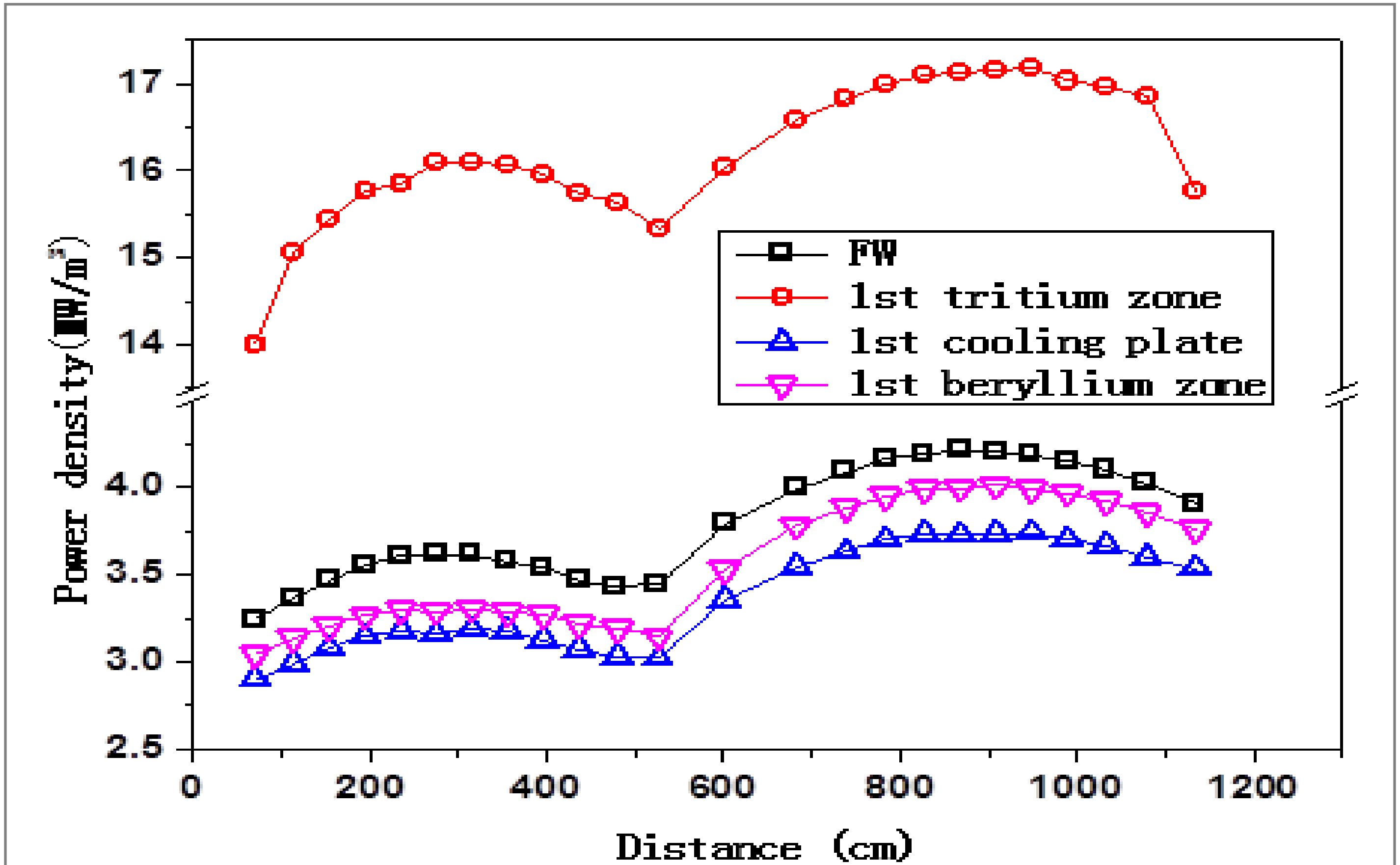


Radial power density distribution

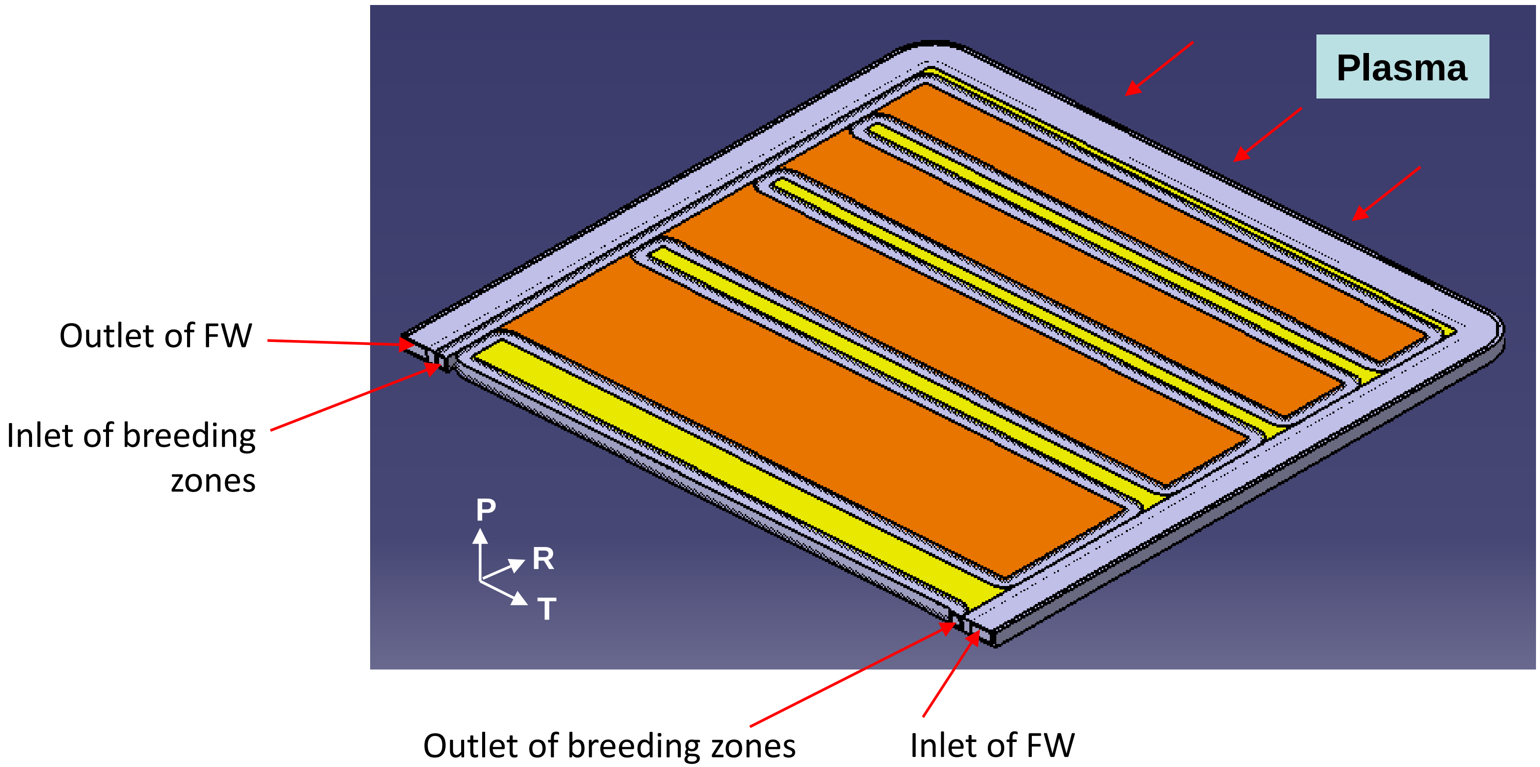
Power Density Distribution

On along Poloidal Direction

- Poloidal power density distribution of FW, first tritium , beryllium and cooling plate zone。
- Power density of tritium zone is much higher than the other zones.



Preliminary thermal-hydraulic analysis



Schematic view of a layer poloidal slice of outboard blanket module

- **Calculation model and Input data**

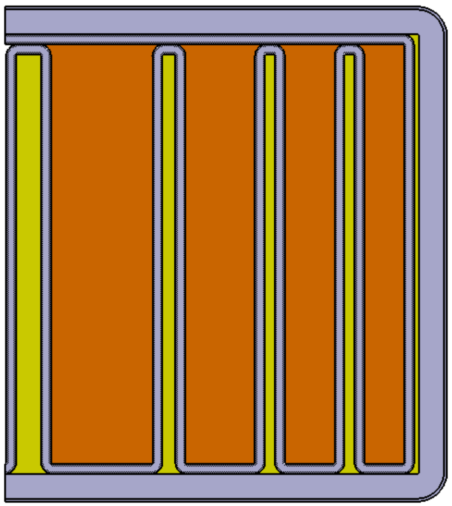
➢ Dimensions, 443mm(Radial)X500mm(Toroidal)X10mm (Poloidal);

➢ Including the FW of U-shape, breeding zones with 5 Li_4SiO_4 pebble beds and 4 Be pebble beds;

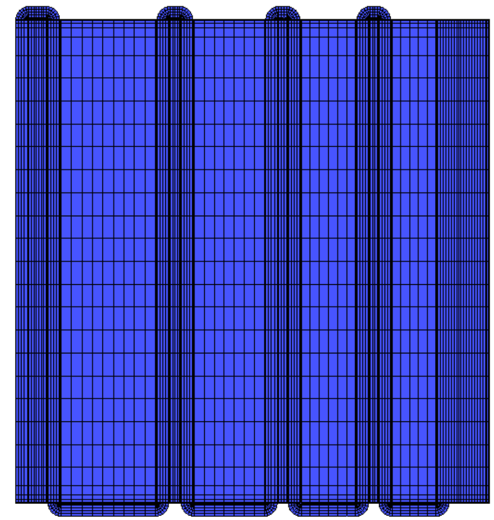
➢ Assumed to cool the FW and breeding zones independently;

➢ Coolant is the helium of 8 MPa, and inlet temperature is 300 ℃, outlet temperature is about 500 ℃ .

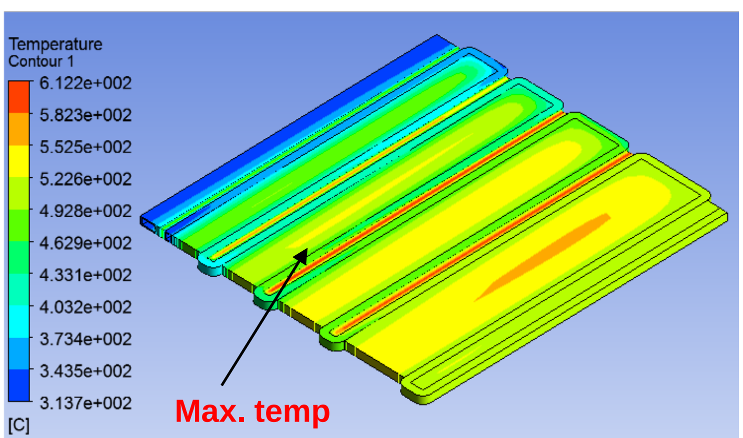
Preliminary thermal-hydraulic analysis



Thermal loading is based on the radial power density distribution



Analysis model and meshes



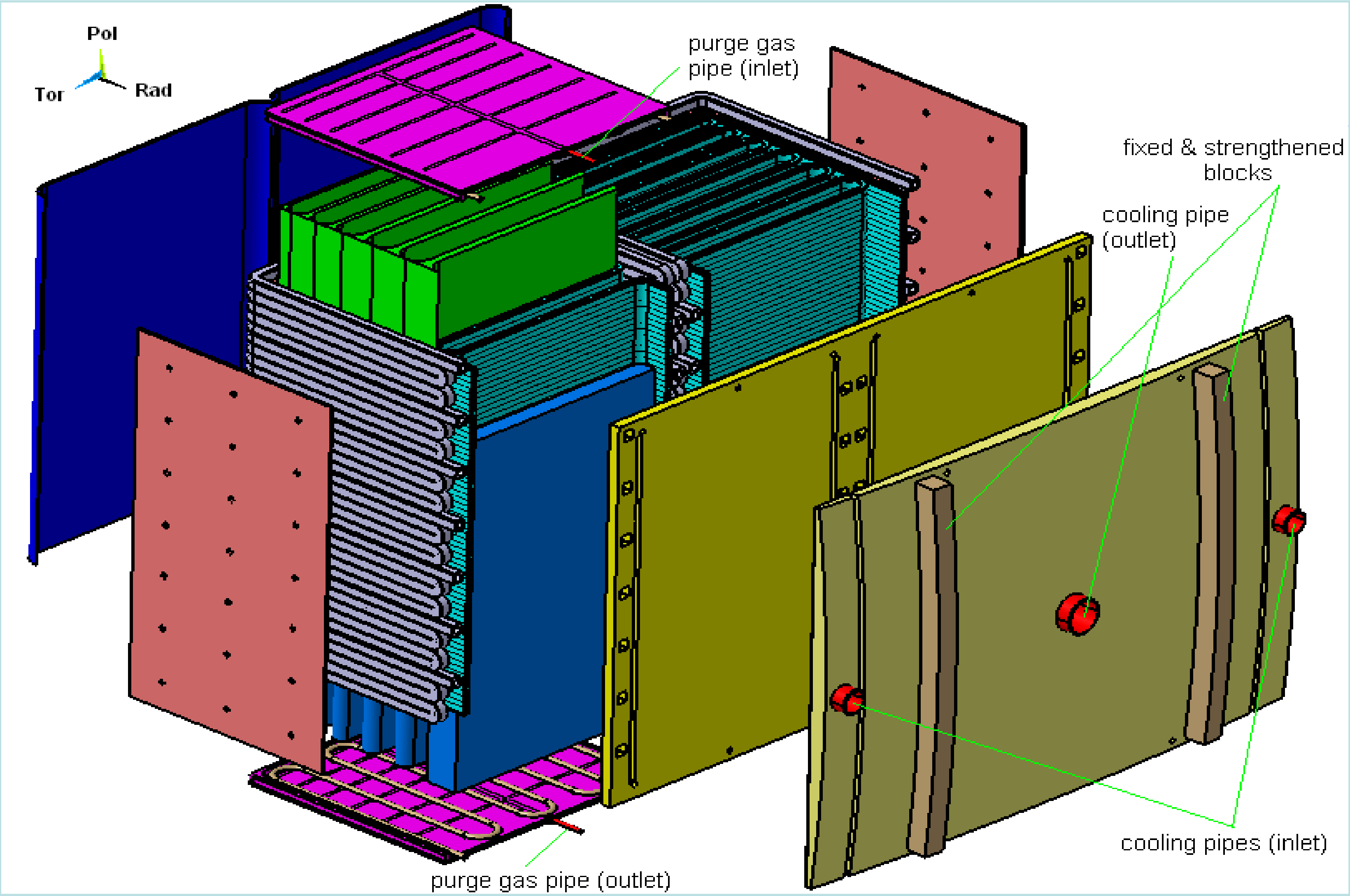
Global temperature distribution

Max. temperature for different materials

Materials	Max. Temp. [℃]	Allowable Temp. [℃]
First Wall RAFMs	522	550
Li_4SiO_4 pebble beds	613	920
Be pebble beds	554	650

Design Parameters of Solid Blanket

Neutron Wall Loading, NWL [MW/m^2] Tritium Breeding Ratio, TBR	0.4-0.8 1.26
Coolant Inlet/Outlet Temperature, T [^oC] Pressure, P [MPa]	He 300/500 8
Tritium Breeder (single size) Li -6 Enrichment, % Filling ratio, % Max. Temperature, T [^oC]	Li_4SiO_4 Pebbles 80 60 613
Neutron Multiplier (binary size) Filling ratio, % Max. Temperature, T [^oC]	Be pebbles 80 554
Structure Material Max. Temperature, T [^oC]	RAFM 522



Proposed CFETR blanket module concept

Critical Issue for Solid Breeder Blanket

- Critical issues associated with solid breeder materials relate to the following

1. Fabrication consideration of the ceramic breeder,
2. Property data base: chemical stability, physical properties, compatibility, residual activation.
3. Tritium release from solid breeder，
   -- Temperature limits on breeder zone
   -- Tritium breeding capability
4. Radiation effects on properties (swelling),
5. Thermal conductivity of Lithium ceramic breeder，complexity of cooling tube layout；
6. Neutron multiplication issues (beryllium pebble fabrication).
7. Tritium extraction, recovery, coolant purification and tritium permeation barrier technology.

Potential tritium breeding materials

	Li_2O	$LiAlO_2$	Li_2ZrO_3	Li_4SiO_4	Li_2TiO_3
Melting Point / K	1696	1883	1888	1523	1808
Density / g cm^{-3}	2.02	2.55	4.15	2.4	3.43
Li at. density / g cm^{-3}	0.94	0.27	0.38	0.51	0.43
Thermal conductivity (773 K) /W m^{-1} K^{-1}	4.7	2.4	0.75	2.4	1.8
Reactivity with water	large	small	none	small	none
Tritium retention time (713 K) / h	8.0	50	1.1	7.0	2.0
Li Vaporization (in additional H_2)	> 600˚C	> 900˚C	> 800˚C	> 700˚C	> 800˚C
Long period use (2 years)	Instability (Li vaporization)	Stability	Instability (crack)	Instability (Li vaporization)	Instability (Reduction of Ti)
Tritium release (easy release)	> 400˚C	> 400˚C	> 400˚C	> 350˚C	> 300˚C
Optimum operating temp.	400 - 600˚C	400 - 900˚C	400 - 800˚C	350 - 700˚C	300 - 800˚C
Tritium breeding ratio (TBR)	High	Lower	Middle	Middle	Middle

- **Li_4SiO_4 is considered as reference material and Li_2TiO_3 as alternative material for Chinese CFETR.**

R&D Foundation for Solid Breeder Blanket

Structure Materials

- Two RAFM alloys have being developed in China; CLF-1 in SWIP and CLAM in ASIPP.
- Ton-class ingot of RAFM steel were recently produced

Tritium Breeder

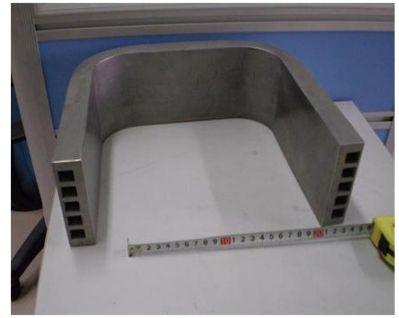
- Two kinds of ceramic breeders (Li_4SiO_4, Li_2TiO_3) are being developed at different institutions.
- Lithium orthosilicate (Li_4SiO_4) pebbles should be the primary option for FETR.

Neutron Multiplier

- Be metal of high performance has been developed in China.
- Be pebbles have been fabricated by Rotating Electrode Process (REP) method in China.

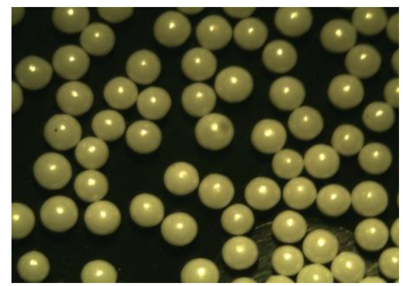
Test Facilities

- The construction of a small He Test Loop to validate circulator technology will be completed this year.



Mock-up of FW

500kg Ingot of CLF-1



Li_4SiO_4 Pebbles (D=1mm) by metl spraying method @SWIP

Sample of Be Pebbles(D=1mm)

High flux Test Reactor

REP Facility at HBSM Co.

Summary

- Based on mission and time schedule, the solid breeder blanket might be one of CFETR blanket options.
- TBR can achieve the tritium self-sufficiency (TBR >1.2) of based on current ceramic blanket model.
- Comprehensive consideration of breeding zone, shielding and vacuum chamber, the total thickness of blanket is not exceed 1.0 m.
- Preliminary thermal-hydraulic analysis shows that current blanket design parameters are feasible.

Thank you for your attention!