Study on the Tritium Breeding Characteristics of Solid Blankets of Fusion Reactors

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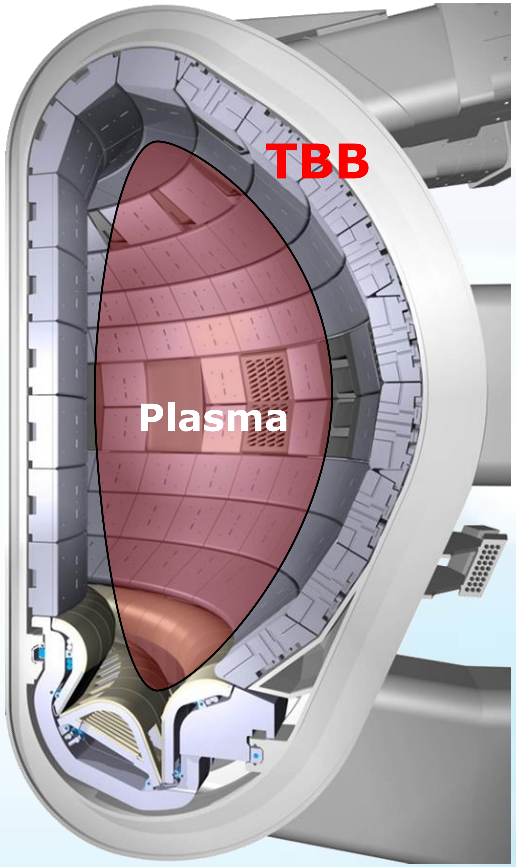
Background

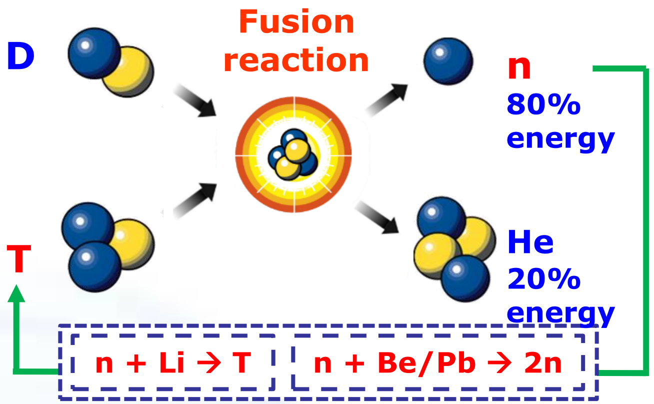
TBB (tritium breeding blanket): essential nuclear component for a magnet confinement fusion reactor

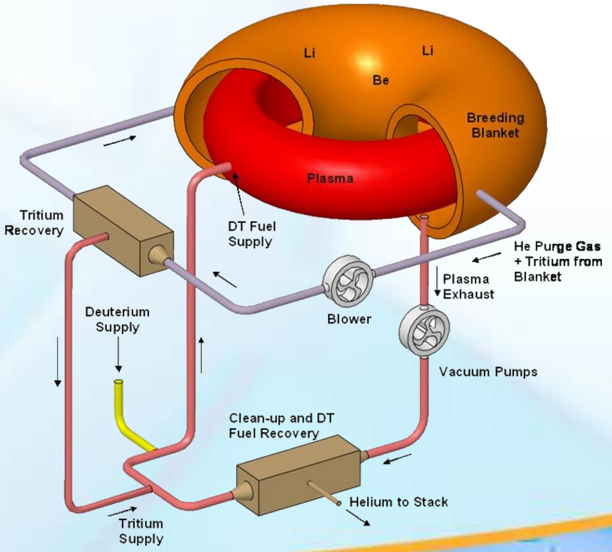


- **Tritium breeding → tritium self-sufficiency**
  Neutrons generated in the plasma contains 80% energy of the DT reaction. It can pass through the FW and tritium is produced by the nuclear reaction with the tritium breeder.

- **Heat generating → generate electricity**
  The use of coolants to extract heat from nuclear reactions（The kinetic energy of neutrons， Nuclear thermal deposition）and the heat radiation from the plasma. The heat is transferred by the coolant to generate electricity from the fusion reactor.

- **Nuclear shielding → protect people and environment**
  Structural materials, function materials and moderators could shield neutrons and γ rays, shielding is achieved with other tokamak components to protect external devices and the environment.



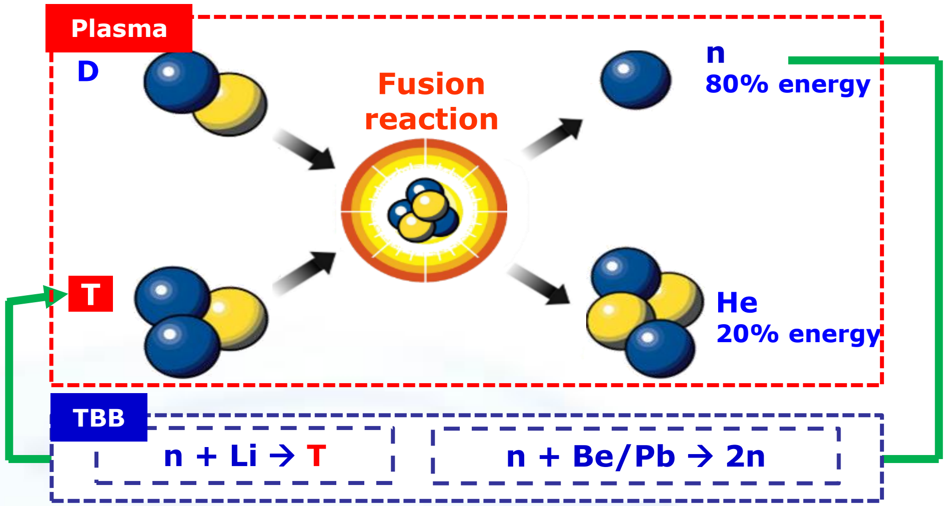


Background

➢ Tritium breeding ratio（TBR)

To evaluate whether the TBB can produce enough tritium to achieve the tritium self-sufficiency for fusion reactors

$$TBR = \frac{\text{Tritium generated in Breeder Blanket}}{\text{Tritium consumed in plasma}}$$



- The average atom number of the tritium produced in the TBB for every fusion neutron consumed

TBR	Function
Local-TBR	To evaluate the capacity of tritium breeding of a **typical module**.
Global-TBR	To evaluate whether the TBB can produce enough tritium to achieve the **tritium self-sufficiency** for fusion reactors

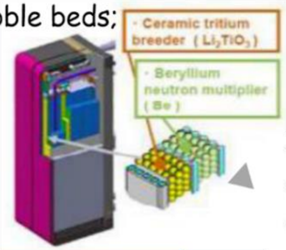
It is very necessary to study the global tritium breeding characteristics

Background

➢ Influencing factors for TBR

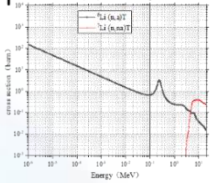
Materials

- Material types (tritium breeder, neutron multiplier, structure material);
- Packing factor (PF) of pebble beds;
- Density;
- Li enrichment;



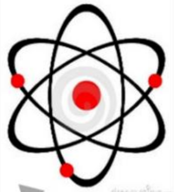
Nuclear Data

- Uncertainty;
- Doppler effect;



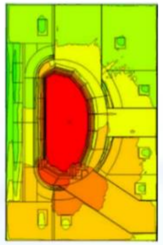
Neutronic Transport Code

- Uncertainty;



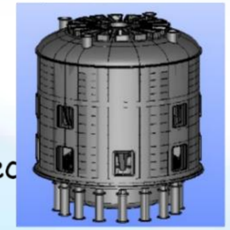
Neutron Source

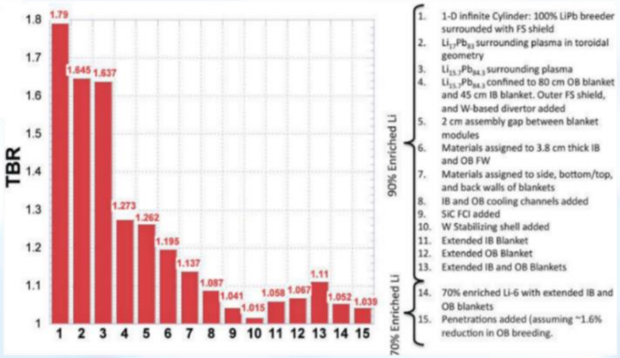
- Uncertainty of cross section of D-T reaction;
- Uncertainty of spatial and energy distributions;



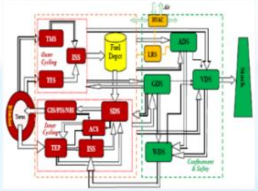
Geometry

- Port;
- Contour line;
- Heterogeneous;
- Space self-shielding effec
- W armor;





Tritium Loss



- Extraction;
- Recycling;
- Separation;

- Geometries (the opening ports to install the heating and diagnostic equipment , a heterogeneous model of the blanket , et al);
- Materials (type, density, enrichment).
- The uncertainties of nuclear libraries, neutron source, and the neutron transport codes could affect the TBR calculation results.
- The tritium losses occur during the fuel cycle because of the tritium decay, leakage, extraction, and retention which is a considerable challenge to achieve the tritium self-sufficiency.

Therefore, a TBR greater than 1 is required in the TBB design and it should be as large as possible to provide margins for other designs, such as the shielding design, the fuel cycle system design and etc.

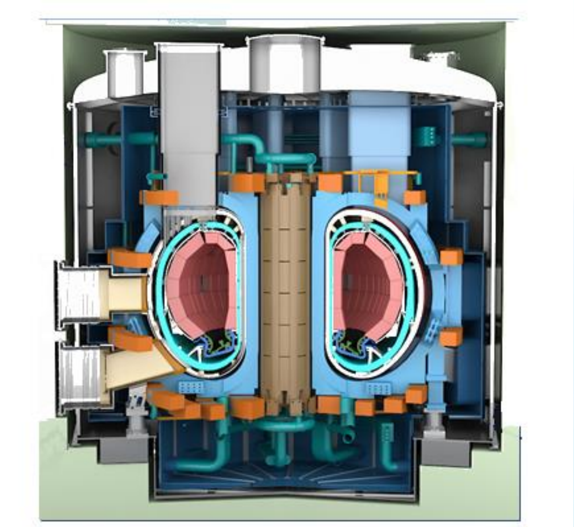
Background

➢ TBR enhancement

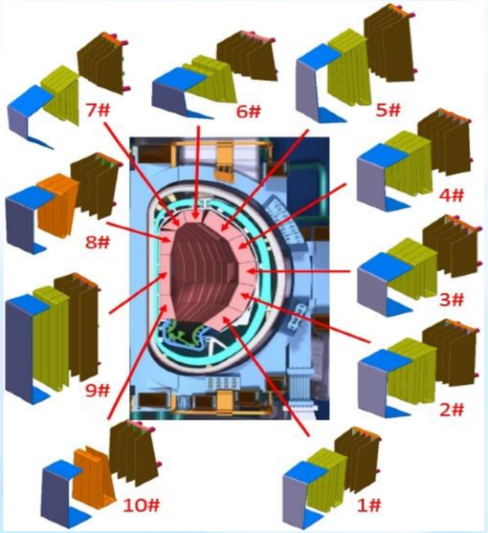
【Physics】 More thermal neutrons are produced for Li-6 to produce tritium

【Design】 Adjust the layout scheme, geometric parameters and material parameters (type, nuclide enrichment, packing fractions for pebble beds, etc.) inside the TBB.

Huge computational cost → **Local to global** →



Full-scale model



2-steps optimization

- The local tritium breeding characteristics of each typical module are analyzed and optimized, and the optimization schemes are obtained.
- Each optimization scheme is brought into the full-scale model for checking, and the optimized scheme for the full-scale model is obtained.

Method 1: iterative optimization (neutronic, thermal-hydraulic, thermal-mechanic, etc);

Method 2: TBR library is established, and a parametric formula for TBR based on machine learning is applied.

Background

➢ Problems and challenges

- Greedy algorithms are widely used in current codes.
  - In this way, only the TBB scheme with the TBR higher than the previous step will be accepted, and the schemes with the TBR lower than the previous step will be eliminated directly.
  - However, the neutronics optimization process is non-linear, non-smooth, time-consuming to evaluate, and in some way noisy.
  - In most cases, using a greedy algorithm could only find a local optimal value.
  - In addition, the algorithm greatly depends on the initial scheme and the selection of optimal step.
- In the TBR library, the TBR calculation results of the TBB under different geometric (layout, position et al.), material (type, density, enrichment, component et al.), and parameters are concluded. In this way, a high precision and resolution for the TBR calculation cannot be realized. This can only be adopted for a roughly or preliminary optimization.

Challenge: how to achieve efficient 1-step optimization of global-TBR based on full-scale neutronic model with many variables.

Method

➢ TBR response function

neutron adjoint equation

$$-\frac{1}{v}\frac{\partial\phi^*}{\partial t}-\Omega\cdot\nabla\phi^*+\Sigma\phi^*-\int_0^\infty dE'\int_{\Omega'}\Sigma_s\left(r;E,\Omega\to E',\Omega'\right)\phi^*\left(r,E',\Omega',t\right)d\Omega'$$

$$=\frac{v\Sigma_f\left(r,E\right)}{4\pi}\int_0^\infty dE'\int_{\Omega'}\chi\left(E'\right)\phi^*\left(r',E',\Omega',t\right)d\Omega'$$

Sensitivity coefficient

$$\alpha_{(n,T)}(\vec{r},E)=\frac{\partial R_{(n,T)}(\vec{r},E)}{\partial\rho}=\frac{R^*_{(n,T)}(\vec{r},E)-R_{(n,T)}(\vec{r},E)}{\Delta\rho}$$

TBR response function

$$TBR_{global}=TBR_{global}(\boldsymbol{l},\boldsymbol{\rho})=TBR_{global}(l_1,l_2,\cdots,l_n,\rho_1,\rho_2,\cdots,\rho_m)$$

$$\approx TBR_{global}(\boldsymbol{l}^0,\boldsymbol{\rho}^0)+\sum_{i=1}^{n}\left(\frac{\partial TBR_{global}}{\partial l_i}\right)_{l^0}\delta l_i+\sum_{j=1}^{m}\left(\frac{\partial TBR_{global}}{\partial\rho_j}\right)_{\rho^0}\delta\rho_j$$

$$+\sum_{i=1}^{n}\left(\frac{\partial^2 TBR_{global}}{\partial l_i^2}\right)_{l^0}\delta l_i^2+\sum_{j=1}^{m}\left(\frac{\partial^2 TBR_{global}}{\partial\rho_j^2}\right)_{\rho^0}\delta\rho_j^2$$

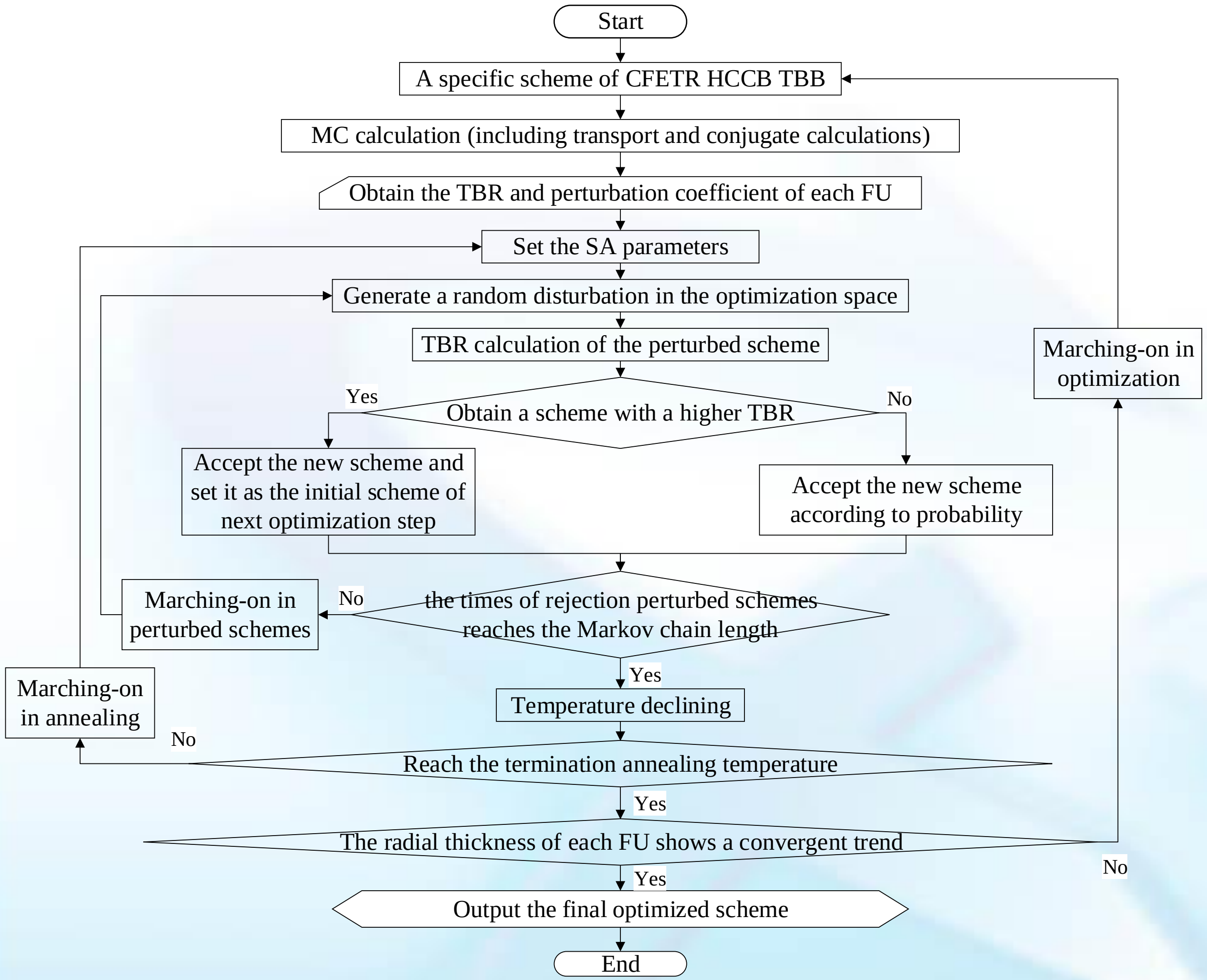
$$\approx TBR_{global}(\boldsymbol{l}^0,\boldsymbol{\rho}^0)+\sum_{i=1}^{n}\alpha_{TBR_{global},l_i}\delta l_i+\sum_{j=1}^{m}\alpha_{TBR_{global},\rho_j}\delta\rho_j+\sum_{i=1}^{n}\beta_{TBR_{global},l_i}\delta l_i^2+\sum_{j=1}^{m}\beta_{TBR_{global},\rho_j}\delta\rho_j^2$$

$$=TBR^0{}_{global}+\sum_{i=1}^{n}\sum_{j=1}^{g}\sum_{k=1}^{m}(\alpha^j{}_{TBR_{global},l_{i,k}}\delta l_{i,k}+\beta^j{}_{TBR_{global},l_{i,k}}\delta l^2{}_{i,k}+\alpha^j{}_{TBR_{global},\rho_{i,k}}\delta\rho_{i,k}+\beta^j{}_{TBR_{global},\rho_{i,k}}\delta\rho^2{}_{i,k})$$

- Neutron transport calculation of the primary scheme;
- The neutronics perturbation theory is put to use for the adjoint neutron flux calculation to obtain the 1st +2nd order of the geometric and density sensitivity coefficients of each regions;
- TBR response function;
- The TBR of the perturbed scheme could be rapidly and directly calculated by the TBR and perturbation coefficients of the primary scheme

Method

➢ Efficient optimization algorithm



Flow chart of the TBR efficient optimization based on SA algorithm

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- Neutronics transport and perturbation calculations of the primary scheme
  - All the independent variables that impact the TBR are numbered, including the radial thickness of each region;
  - Then, the neutronics transport and perturbation calculations of the primary scheme needs to be performed.
  - Finally, the TBR and perturbation coefficient of each FU under the primary scheme is obtained.
- Simulated annealing algorithm
  - It is a kind of MC method, and there is a probability of jumping out of the local optimized solution;
- Both the local-TBR and the global-TBR optimization can use this method.

Method

- **MCINO**（**M**ulti-physics **C**oupling and **I**ntelligent **N**eutronic **O**ptimization code for TBB of fusion reactor）
  - MC transport code
    - 3D neutron transport calculation;
    - Neutronic performances（flux, TBR, sensitivity coefficients, nuclear heat, etc.）;
  - Optimization code
    - Control the operation of other codes;
    - Communicate with other codes through feedback data;
    - Hold the overall optimization direction;
  - Thermal feedback code
    - Input the nuclear heat results;
    - Update the temperature distribution in time;
    - Determine whether meet the thermal requirements;
  - Packing fraction feedback code
    - Input the geometry parameters;
    - Update the density field in time;
    - Modify thermal conductivity to the thermal feedback code.

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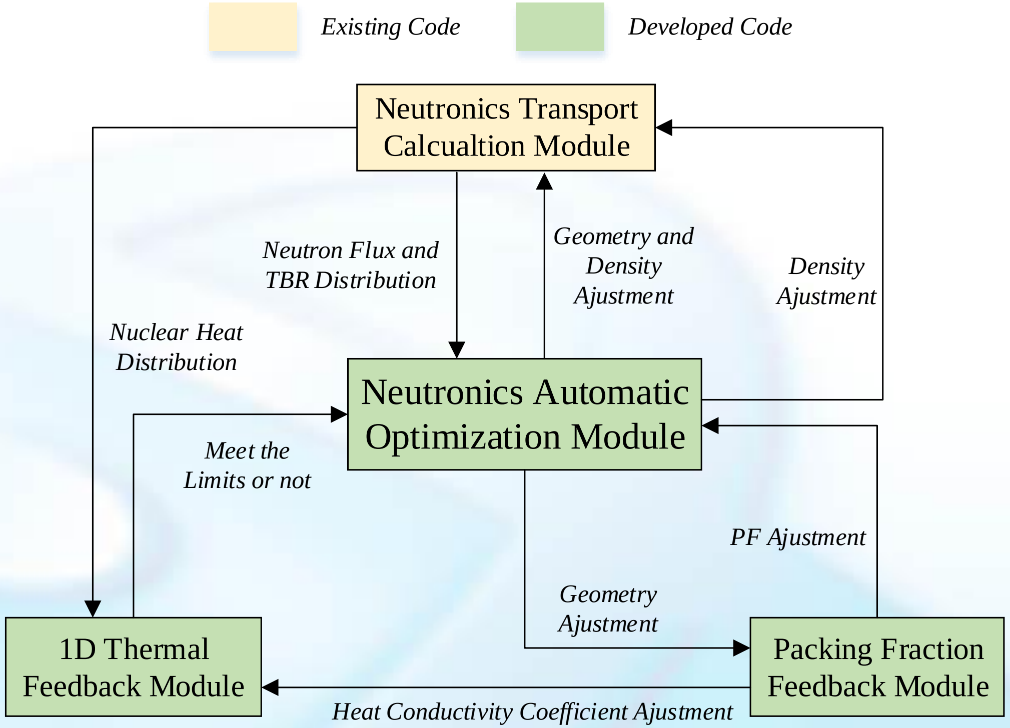
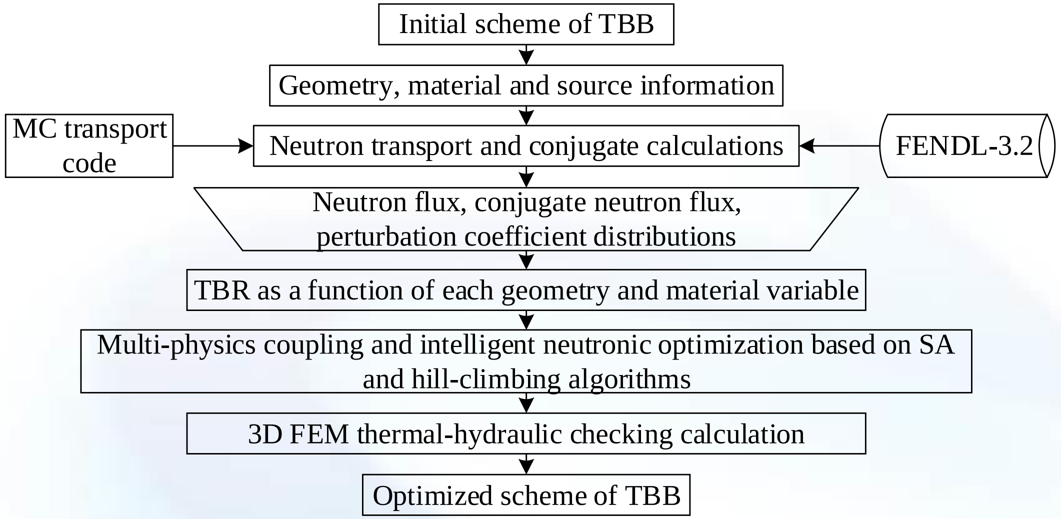


Flow chart of MCINO

Method

➢ **MCINO** （Multi-physics Coupling and Intelligent Neutronic Optimization code for TBB of fusion reactor）



A typical MCINO calculation flow chart

MCINO typical input and descriptions

Card	Description
“CONTROL”	Define the optimization mode and control parameters;
“FEEDBACK”	Define the feedback type: thermal feedback, density feedback;
“GEOMETRY”	Define the geometric parameters for breeding zone;
“METHOD”	Define the optimization algorithm
“OUTPUT”	Define the output information.

MCINO typical input card

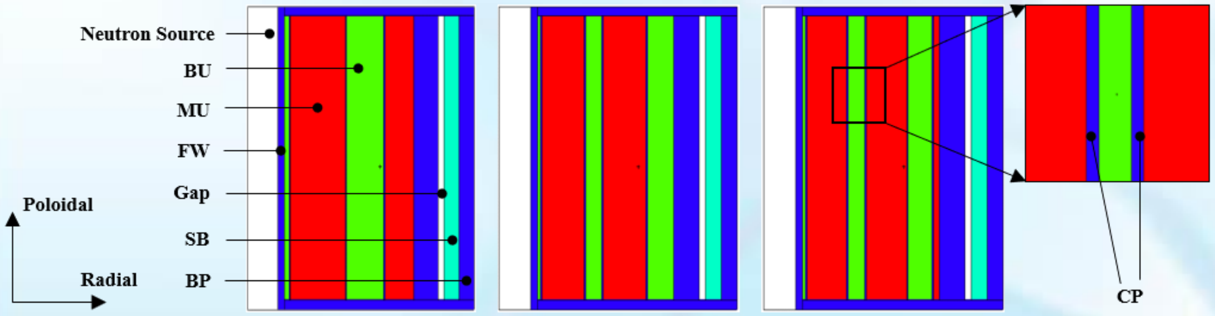
```
o------------------------ Optimization Card ------------------------------o
=== CONTROL ===
n_module     geo_mode     rho_mode
1            T            T
is_tb_rho_unify   is_nm_rho_unify   is_limit_thick_tb   is_limit_thick_nm
F                 F                 T                   T
layout_scheme     tb_flag       nm_flag       n_tb       n_nm       n_cp
sandwich          33            20            4          3          6
=== FEEDBACK ===
thermal_feedback   pf_feedback     nwl(MW/m^2)
F                  F               1.69
=== GEOMETRY ===
limit_thick_tb
2.5    4.5    6.0    10.0
limit_thick_nm
8.0    18.0   26.0
bz_layout
tb1   nm1   tb2   nm2   tb3   nm3   tb4
fw_rear      manifold_front      cp_thickness
2.0          45.0                0.5
suf_cp_1
8     9     PX
suf_cp_2
10    11    PX
suf_cp_3
12    13    PX
suf_cp_4
14    15    PX
suf_cp_5
16    17    PX
suf_cp_6
18    19    PX
=== METHOD ===
algorithm    sa_coe    sa_tf    sa_t0    step/cm    p_eff    total_opt_step
sa           0.95      5e-3     5e-8     0.1        0.02     20
pfu_tb    pfd_tb    pfu_nm    pfd_nm    rho_tb     rho_nm    Li6_enrichment
0.62      0.00      0.80      0.00      0.10065    -1.84     0.95
=== OUTPUT ===
is_optlist     is_graph
T              T
=== END ===
```

- MCINO is mainly written in Fortran;
- The input card mainly includes 5 keywords.
- The output card mainly includes all variables (geometric and material parameters) and TBR change information during the optimization process.

Verification and application

Code verification

- Referring to the latest design of the CFETR HCCB TBB developed in SWIP, three simplified homogeneous neutronics models with sandwich-like layouts were adopted for code verification;
- These mainly includes the FW, the BU and MU, CP, caps, manifold, and BP;
- Li_4SiO_4 with 90% of the enrichment of ^6Li was selected as the tritium breeder;
- Be as the neutron multiplier in the pebble bed regions;
- ODS steel as the structure material;
- The packing fraction for the Li_4SiO_4 and Be pebble beds were assumed to be 62% and 80%, respectively.



Model-1 Model-2 Model-3

Parameters for SA optimization

SA parameters	Value
Initial temp	500℃
Termination temp	1℃
SA coefficient	0.9
Markov length	100×variable numbers

3 random cases and corresponding local-TBR

Model-1

case	Li-1	Be-1	Li-2	Be-2	Initial local-TBR
1	8.0	14.5	4.5	14.5	1.090
2	2.0	6.0	4.0	29.5	1.060
3	7.0	20.5	3.5	10.5	1.067

Model-2

case	Li-1	Be-1	Li-2	Be-2	Li-3	Initial local-TBR
1	2.6	11.1	4.2	14.5	8.6	1.301
2	4.6	17.1	6.2	11.5	1.6	1.200
3	6.6	3.1	3.2	20.5	7.6	1.089

Model-3

case	Li-1	Be-1	Li-2	Be-2	Li-3	Be-3	Initial local-TBR
1	2.0	6.2	3.1	11.4	4.5	13.3	1.282
2	3.0	11.2	2.1	14.4	3.5	6.3	1.280
3	4.0	7.2	6.1	8.4	2.5	12.3	1.211

Verification and application

Code verification (2/2)

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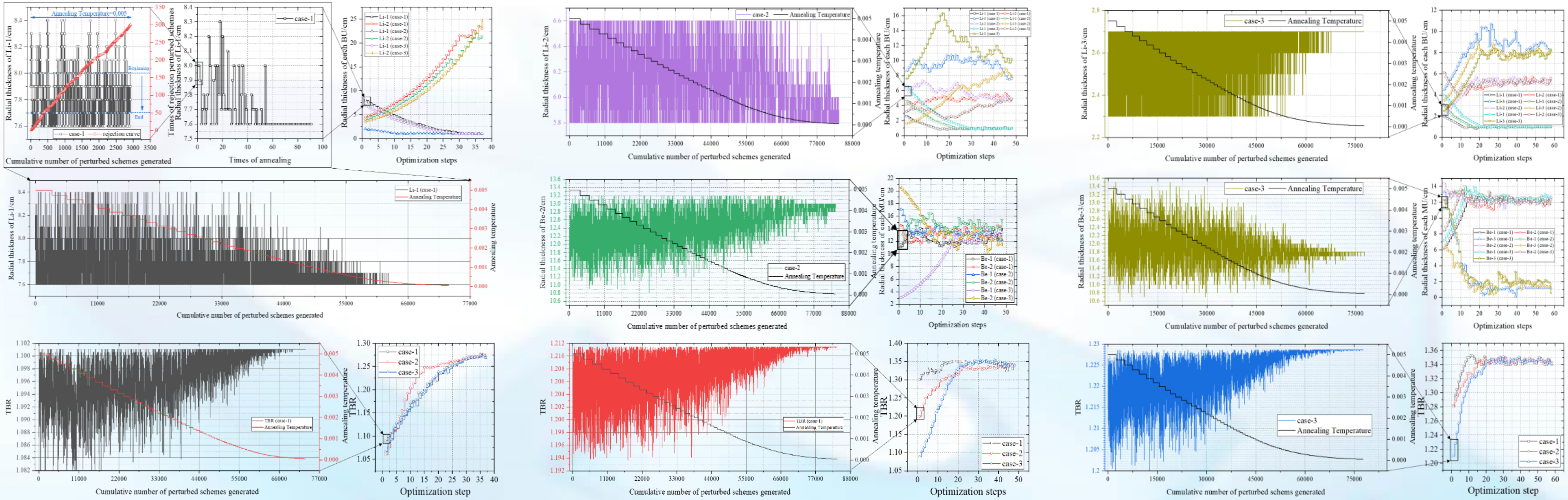
the SA curves of the radial thickness of each region are included. To show more details, curves of radial thickness vs the times of annealing and the optimization curve under the initial annealing temperature are also given below.



- The curve shows the trend of fluctuation first and then stability;
- Almost the same optimization scheme can be obtained after different initial random schemes are optimized;
- The developed code provides a good convergence property and stability, which is independent of selecting of the primary scheme;

Verification and application

➢ Application of MCINO

- **Local-TBR optimization**

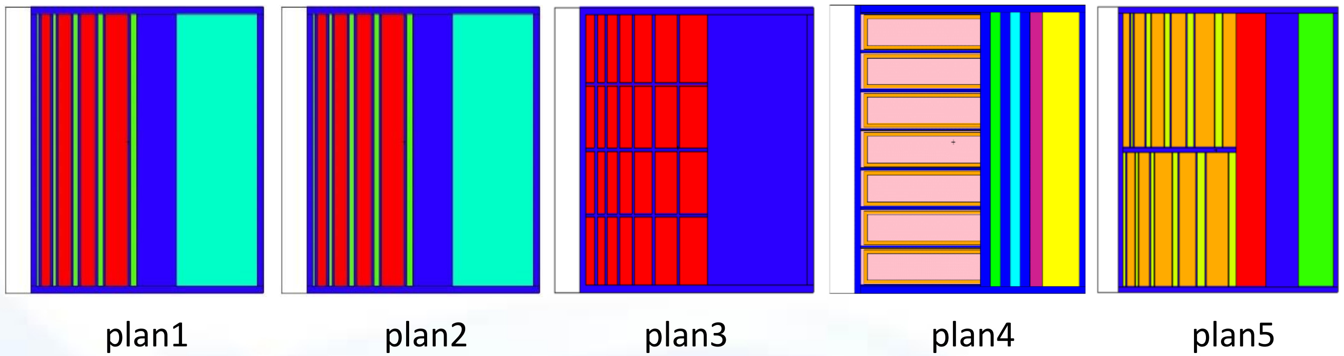
1. HCCB, Li_4SiO_4+Be, He（plan1）
2. HCCB, Li_4SiO_4+$Be_{12}Ti$, He（plan2）
3. WCCB, Li_2TiO_3+$Be_{12}Ti$, H_2O（plan3）
4. WCLL, LiPb, H_2O（plan4）
5. HCCB, Li_4SiO_4+Be, He（plan5）

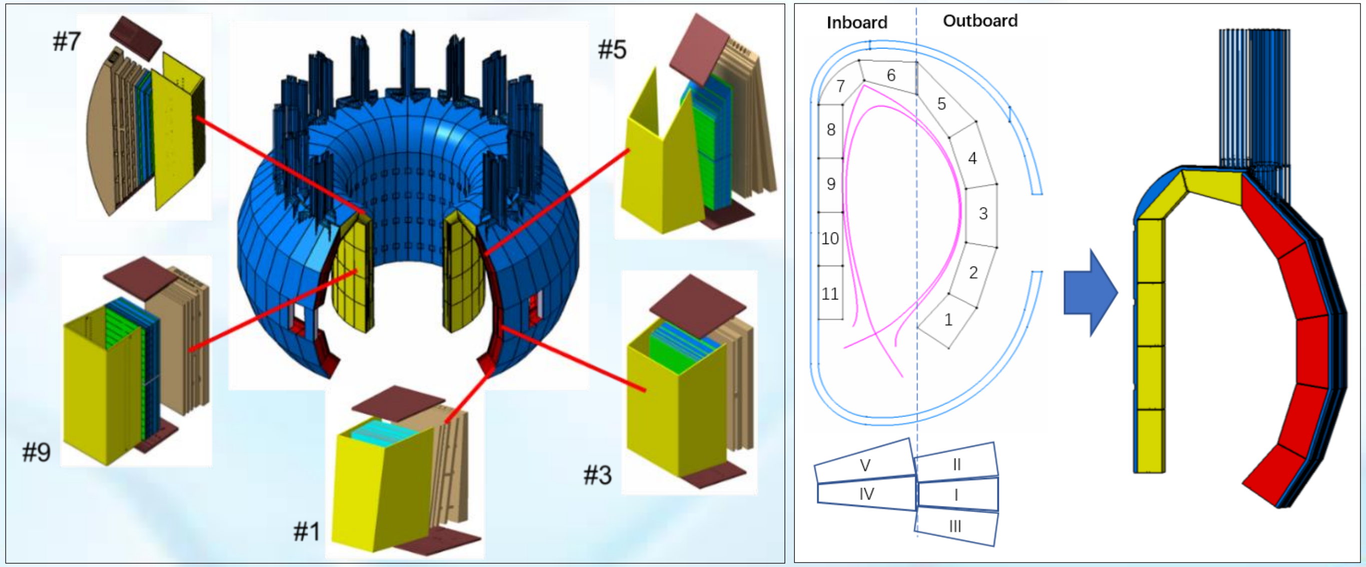
- **Global-TBR optimization（2-steps）**

6. plan1+CFETR layout

- **Global-TBR optimization（1-step）**

7. plan1+CFETR layout



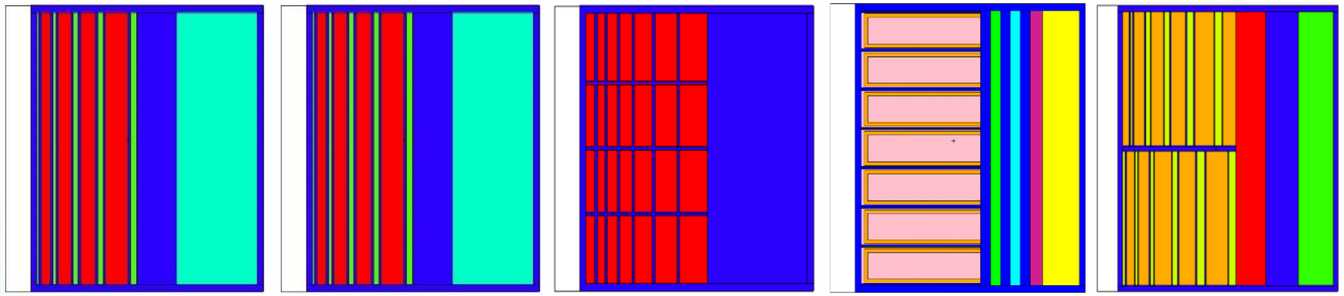


Layout configuration of CFETR TBB

Verification and application

➢ Local-TBR optimization

- 5% - 6% enhancement for local-TBR;
- Convergence is achieved in only 10-15 times of MC transport calculations;
- Applicable to different blanket concept;
- the developed code exhibits good effects for the optimization of neutronics.



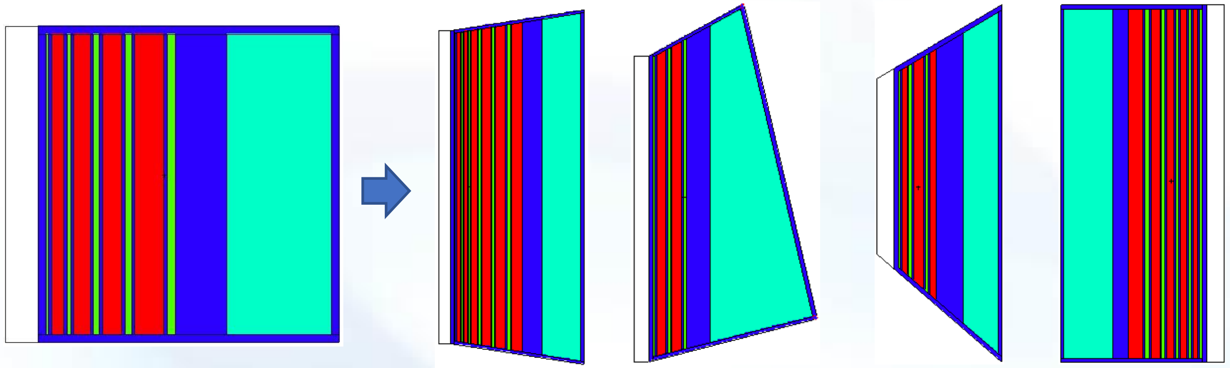
plan1 plan2 plan3 plan4 plan5

Results comparison

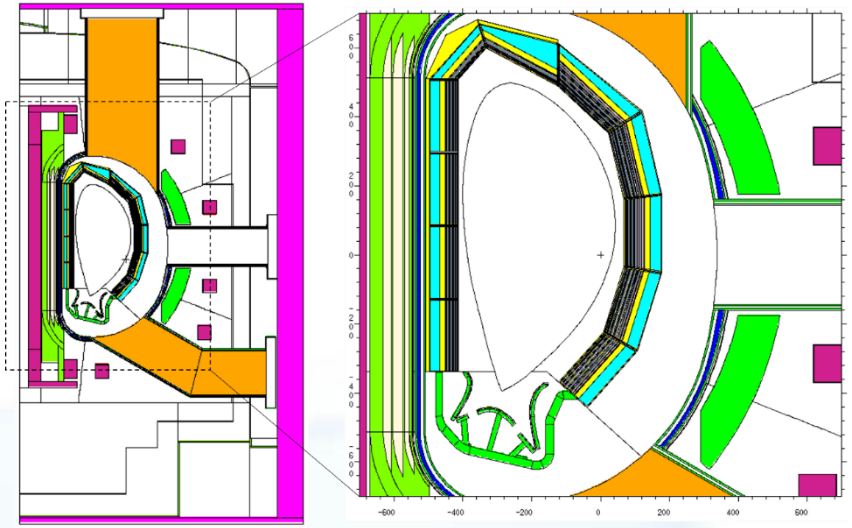
case	concept	Tritium breeder	Neutron multiplier	Structure material	coolant	variables	Local-TBR			Times of transport calculation
							initial	optimized	enhancement	
1	HCCB	Li_4SiO_4	Be	CLF-1	He	11	1.264	1.323	4.7%	10~15
2	HCCB	Li_4SiO_4	$Be_{12}Ti$	CLF-1	He	11	1.177	1.246	5.9%	
3	WCCB	Li_2TiO_3	$Be_{12}Ti$	CLF-1	H_2O	6	1.201	1.277	6.3%	
4	WCLL	LiPb		CLF-1	H_2O	2	1.081	1.148	6.2%	
5	HCCB	Li_4SiO_4	Be	CLF-1	He	44	1.301	1.383	6.3%	

Verification and application

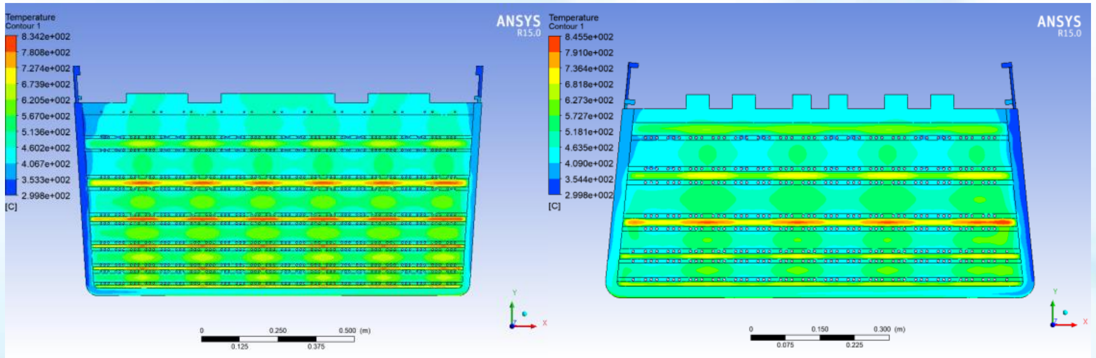
- **Global-TBR optimization: case-6**
  - Global-TBR increase from 1.101 to 1.178；
  - meet certain thermal-hydraulic requirements.



Each typical TBB module of plan-1（#3#5#6#9）



Sector neutronic model



3D thermal FEM checking（#3#9）

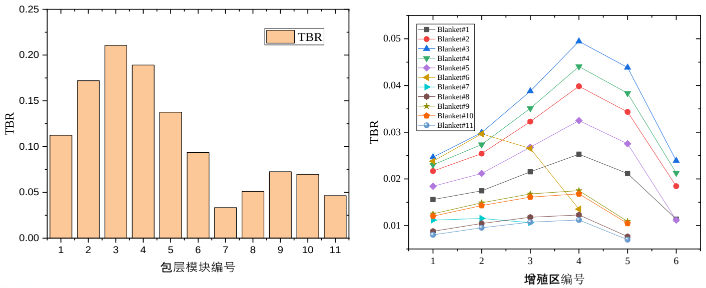
Geometric parameters before and after optimization

FU	Radial thickness/cm				FU	Radial thickness/cm			
	#1-#5	#6	#7	#9		#1-#5	#6	#7	#9
Li-1	1.0	1.2	1.0	1.0	Li -4	1.8	--	--	2.0
Be-1	2.9	5.8	4.8	3.0	Be-4	7.5	--	--	5.7
Li-2	1.1	1.9	1.8	1.1	Li -5	2.8	--	--	2.8
Be-2	4.1	7.0	5.7	3.9	Be-5	7.8	--	--	--
Li -3	1.2	2.3	2.0	1.8	Li -6	3.2	--	--	--
Be-3	5.3	--	2.9	6.2	Be-6	6.8	--	--	--

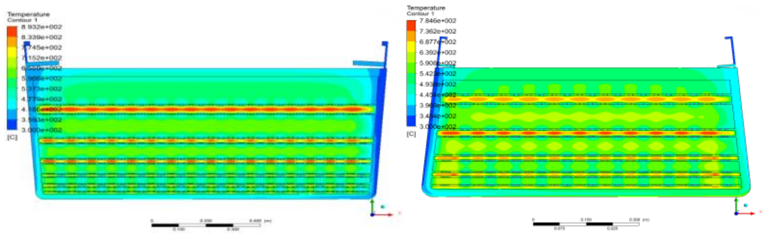
Verification and application

➢ Global-TBR optimization: case-7

- 1-step optimization
  - Different typical modules use different geometric parameters;
  - The global-TBR could be improved to 1.193；

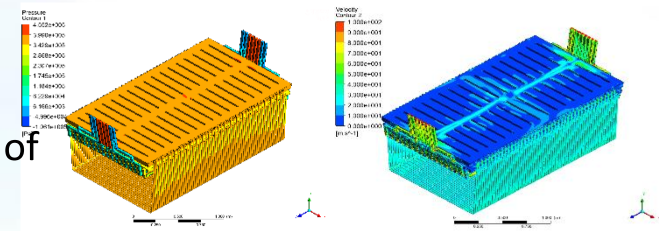


TBR results

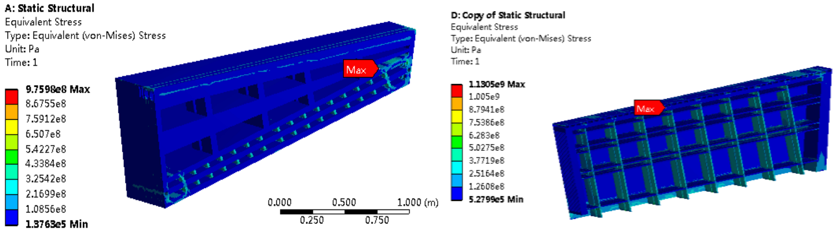


3D Thermal FEM checking

- 3D FEM checking calculation
  - The optimized scheme meet the requirements of thermal-hydraulic and thermal-mechanic.



Hydraulic checking results



Thermal-mechanic checking result

NWL of each module under 1.5GW

number	NWL/ $MW\cdot m^{-2}$	number	NWL/ $MW\cdot m^{-2}$
1	1.00	7	0.64
2	1.33	8	0.58
3	1.69	9	1.17
4	1.51	10	1.09
5	1.23	11	0.52
6	0.87		

Thermal FEM checking results of each module

number	ODS steel/K		Li_4SiO_4/K		Be /K	
	Max	requirement	Max	requirement	Max	requirement
1	910	923	1145	1173	911	923
2	914	923	1096	1173	919	923
3	894	923	1151	1173	918	923
4	879	923	1120	1173	921	923
5	895	923	1020	1173	920	923
6	918	923	1160	1173	921	923
7	901	923	1120	1173	918	923
9	891	923	1106	1173	903	923

Verification and application

➢ Comparison

Results comparison

Items		2-steps optimization	1-step optimization
Manual assistance	modeling	~10min/module	-
	Data processing	~10min/module	~10min/sector
	Source calculation	~10min	-
Each MC transport calculation cost		~0.05cpu.h	~0.5cpu.h
Each optimization cost		~0.02cpu.h	~0.25cpu.h
Iterative times		5-8 times	5-8times
Optimization coset		**~18.0cpu.h**	**~6.0cpu.h**
Optimized global-TBR		1.178	1.193
enhancement		**7.90%**	**8.36%**

- Compared with the 2-steps optimization method, the 1-step optimization method shows a better effect and higher efficiency;
- The whole optimization process is highly automatic and intelligent;

Conclusions

Conclusions

- The developed code based on the SA algorithm and perturbation theory provides an innovative method for efficient optimization of the tritium breeding performance;
- The developed code provides good convergence property and stability, which is independent of selecting of the primary scheme;
- Compared with the efficiency of the automatic optimization code, the SA algorithm based on the perturbation calculations demonstrates lower computational costs and higher optimization efficiency.

Future plan

- Each step of SA optimization could only be performed within ±15% of geometry perturbation, which constrains the search for the global optimum. For these weaknesses, an enhanced neutronics optimization algorithm study based on the neutronics perturbation calculation will be performed in future.
- A deeper neutronics optimization work both considering the adjustment of geometry and density of each FU will be presented.

Thank you for your attention

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