# Overview of Fusion Reactor Design and ITER TBM Program

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**Abstract:** In this paper, the progress and status of the research activities of fusion reactor design, ITER TBM design, and related TBM test and R&D at SWIP in 2007 are presented.

**Key words:** Fusion reactor；ITER；TBM；He experiment loop

## 1 Fusion DEMO study

It is assumed that DEMO is a next step after ITER machine. Therefore, according to China DEMO[1] development strategy, the basic features of DEMO[2～4] are:

（1）Fusion power in a range of 2500~3000 MW with an average neutron wall loading of 2.0~3.0 MW/m$^2$;

（2）Long burning time with inductive operation or steady-state operation with reverse shear plasma modes;

（3）NBI and RF system for current drive;

（4）Detached or semi-detached divertor operation modes.

Three cases of breeding blanket are selected: Case 1 has 4 zones of $Li_4SiO_4$ and 45.7 cm radial thick; Case 2 has 2 zones of $Li_4SiO_4$ and 51.5 cm radial thick; Case 3 has 3 zones of $Li_4SiO_4$ and 43.7 cm radial thick. 1-D neutronics results are given that for Case 1, 2 and 3, TBR are 1.22, 1.34 and 1.43, respectively and peak power density at the first $Li_4SiO_4$ zone are 6.94 MW/m$^3$, 20.58 MW/m$^3$ and 11.46 MW/m$^3$ with neutron wall loading of 0.78 MW/m$^2$. It is concluded that: （a）Case 1 can be taken into account as TBM-TM on ITER for the test of electrical-magnetic safety and thermal-hydraulics safety; （b）Case 2 is probably used to test the characterization of breeding materials and heat dissipation for DEMO blanket; （c）Case 3 can tend to be as DEMO blanket with tritium self-sufficiency.

By using MCNP code and non-uniform neutron source, 3-D neutronics calculation of optimized China HCSB DEMO blanket （Case 3 selected） has been completed. With fusion power of 2300 MW, inside blanket thickness of 63 cm and outside blanket thickness of 77.2 cm, 3-D neutronics results of China DEMO given are total power deposit on blankets of 1742.66 MW, averaged neutron wall loading on FW of 2.64 MW/m$^2$, peak power density at inside blanket of 3.52 MW/m$^3$ and TBR of 1.1.

In a word, it is concluded that:（1）Certain fold of engineering parameters of ITER TBM such as power density can approach to DEMO blanket by changing design; （2） Tritium breeding ratio（TBR）of 1.11 for a HCSB DEMO with tritium self-sufficiency is preliminarily obtained by adopting a new blanket concept of 3 breeding zones;（3）The effect of different boundary condition is so large that it need be further treated carefully.

## 2 ITER TBM design

### 2.1 Structure design

The Chinese HCSB-TBM is designed to check and validate the technologies of breeding tritium for Chinese DEMO Blanket Project. The revision of the HCSB-TBM has been carried out starting from January 2007, which is based on previous version （HCSB-06） of the HCSB-TBM. This version（HCSB-07）has been improved in its array of sub-modules and thermo-hydraulic configuration. Its 2×6 of sub-modules array is better than 3×6 in previous version in proportion between structure and breeder material. Decreasing structure material, at the same time increasing breeder material, will make for enhancing tritium breeding rate as well as reducing nuclear heat in HCSB-TBM. The new design considered RAFS as structural material, $Li_4SiO_4$ as tritium breeder, Beryllium pebble as neutron multiplier, helium as coolant and purge gas respectively.

The HCSB-TBM is located in vertical frame of the equatorial test port. Dimension of vertical frame is 1700 mm in poloidal direction, 524 mm in toroidal direction and 800 mm in radial direction. Taking into account 20 mm gap between TBM and frame, the dimension of HCSB-TBM is 1660 mm height and 484 mm width. Facing plasma side of HCSB-TBM is needed to be protected by beryllium layer of 2 mm. The radial dimension of the HCSB-TBM is 670 mm except for beryllium layer thickness.

### 2.2 Neutronics and activation calculation

A new 3-D MCNP module and calculation of 2×6 HCSB TBM, which had been optimized, have been completed in 2007. New work and method have been started to research, such as activation and afterheat analyses through code coupling of MCNP and FDKR, occupational radiation exposure and so on.

Based on the nuclear results of 3×6 HCSB TBM, disposal of material and structure have been optimized. To make the structure of TBM simpler, safer and trustier is the fundamental of optimization under the condition of assuring safety and increasing TBR. Improved HCSB TBM has 2×6 sub-model structure. Using MCNP/4c code, MCNP module and calculation have been completed. Total power deposit in TBM module is 0.587 MW, peak power density of 6.32 MW/m$^3$, Local TBR for is 0.57 and tritium production rate is 0.0123 g/d in 22% factor.

The purpose of CH HCSB TBM safety design and analysis is to ensure TBM test safety to ITER. Activation analysis is one of the most important of CH HCSB TBM safety analysis. 1-D BISON code had been used in the past radiation activation analysis. Because of the localization of BISON code, it hasn't a better calculation result. A new activation analysis method has being developing in 2007, which is the coupling of MCNP code and FDKR code. Activation, Afterheat and BHP calculation have been completed and obtain some count results.

**2.3 Thermo-hydraulics**

For the CH HCSB TBM, the design scheme changed from the former 3×6 to the latest 2×6, and the square dimension of the FWs inner coolant channel was from 7×14 mm$^2$ to 15×14 mm$^2$ at the same time, so it's necessary newly to perform thermo-hydraulic design and calculation, as well as the thermal and mechanical analysis for the TBM. Table 1 is the summary of the thermal-hydraulic parameters of the TBM under the normal operation condition with the surface heat flux of 0.3 MW/m$^2$ and the extreme condition of 0.5 MW/m$^2$.

Based on the relational parameters listed in above table, the thermal and mechanical analysis results under the extreme operative condition show that: the maximum temperature of the first-wall, and of the $Li_4SiO_4$ pebble bed, Be pebble bed and structure material in the sub-module are 498℃, 687℃, 660℃ and 516 ℃, respectively, and the maximum stresses of the FW and sub-module are 295 and 402 MPa; which are to meet the design requirements of the TBM.

**Table 1 Thermo-hydraulic parameters of TBM**

| | Normal operation condition | Extreme condition |
|---|---|---|
| Neutron surface loading /MW/m$^2$ | 0.78 | 0.78 |
| Surface heat flux /MW/m$^2$ | 0.5 | 0.3 |
| Total power (includes surface heat flux)/MW | 0.95 | 0.79 |
| Helium pressure /MPa | 8 | 8 |
| Helium inlet/outlet /℃ | 300/500 | 300/500 |
| First wall | 300/360 | 300/388 |
| Sub-module | 360/500 | 388/500 |
| Mass flow rate of helium /kg/s | | |
| First wall | 1.34 | 0.71 |
| Sub-modules | 0.48 | 0.61 |
| Grid and caps | 0.86* | 0.10 |
| Equivalent diameter of flow channel /mm | | |
| First wall | 15.3 | 15.3 |
| Sub-modules | 6 | 6 |
| Velocity of helium /m/s | | |
| First wall | 37 | 20 |
| Sub-module | 11 | 14 |
| HTC /W/m$^2$/K** | | |
| First wall | 6349 | 3446 |
| Sub-module | 2132 | 2679 |
| Pressure drop of He /MPa | 0.08 | 0.034 |
| First wall | 0.071 | 0.021 |
| Sub-module | 0.008 | 0.013 |

* Here, the needed mass flow rate of grid and caps is only about 0.1 kg/s, and the rest will be by-passed

**Results are obtained under the considering of the inner surface with 0.2 mm roughness height

**2.4 Back-plate and manifold system**

Outside dimensions of the manifolds in coolant manifold system are set as 440×1580×20 mm$^3$. By controlling locations and dimensions of ribs and 29 holes and sub-boxes, helium can be distributed into first wall correctly. For first wall pipe 14×15 mm$^2$ （cross-section）, to 1.0 kg/s input flow rate, helium flow rate at output will vary between 0.0325 and 0.0364 kg/s. By the structure of manifold 2, error of flow rate into sub-modules is very low and flow rate to other components can be controlled. For total flow rate 1.0 kg/s, if flow rate coming from every first wall pipe is same, flow rate into sub-modules will vary between 0.062 and 0.066 kg/s. Manifold 3 is used to collect streams and send helium coolant to output of TBM. Ribs also go through this box to strengthen backplate. As manifold 2, coolant pipes connected to submodules will go through these ribs.

## 3 Safety analysis

The thermal-hydraulic safety analysis has to testify that the TBM and its helium cooling system (HCS) will not impact the safe operation of ITER under normal and accidental conditions. In order to simulate the transient accidents, TBM and HCS are modeled using system code Relap5/Mod3 [5]. The performance of the TBM and HCS during normal operation and accidents has been investigated [6, 7]. Steady State and three postulated initiating events are considered, and these are In-Vessel Loca, Ex-Vessel Loca and In-Box Loca.

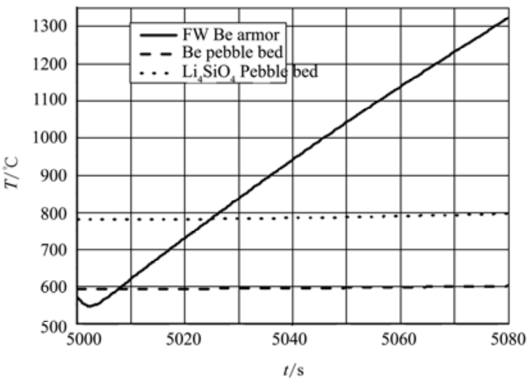


Fig.1. Temperature of FW Be armor/sub-module pebble bed for Ex-Vessel Loca.

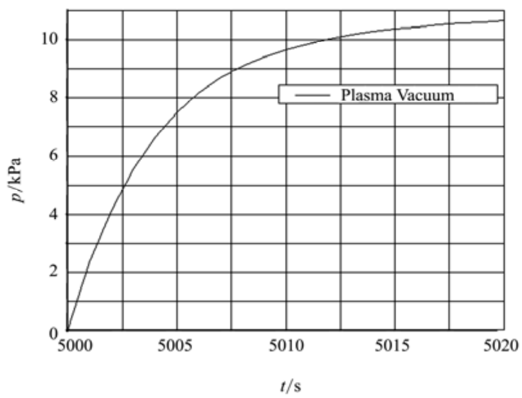


Fig.2. VV helium pressure for In-Vessel Loca.

The Ex-Vessel Loca will induce the melting of first wall beryllium armor after about 80 s of the Loca initiation and some controlling measures have to be taken before melting（See Fig.1）.The pressurization of vacuum vessel induced by In-Vessel Loca is about 10 kPa, and it’s within the allowable value of ITER design 200 kPa. The In-Box accident would lead to pressurization of the TBM box including all pebble beds, and the pressure of purge gas pipes to the system pressure of 8 MPa in about 2 s（See Fig.2）. So there must have a pressure relief for the blanket box, and at the same time the fast isolation of the TES from TBM has to be taken to keep the TES safety.

## 4 Helium experimental loop

In order to validate TBM design, especially regarding mass flow and heat transition processes in narrow cooling channels, it is indispensable to test mock-ups in a helium loop under realistic pressure and temperature profiles. According to TBM design parameters, requirements for the test section are summarized in table 2.

The loop includes the primary helium heat transport loop and the secondary water loop. Main components of the primary loop are, besides the test module, a heat exchanger, circulator, electrical heater, dust filter, control valves and pipe work. The primary loop is directly connected to the helium purification subsystem via small pipes by taking a small bypass flow. Another interface to the pressure control unit is needed for system evacuation, helium supply and protection against overpressure. Thermal stress has been calculated by software CAESAR Ⅱ. Corrugated pipe is not used. If it is used, the footprint will be smaller and the pipeline could be simpler.

## 5 Test and R&D

The R&D of CH HCSB TBM is undergoing. The foundational study on tritium behavior in solid breeder has been conducted with help of the Tokyo University and Shizuoka University in Japan. Deuterium instead of tritium is used to observe the existence states and desorption behaviors of hydrogen isotopes in various ternary lithium oxides, which is helpful to further understanding on diffusion and release mechanism of tritium from solid breeder.

In order to understand tritium trapping behavior in solid tritium breeding material $Li_2TiO_3$, the XPS and TDS measurements are carried out for $Li_2TiO_3$ and $TiO_2$ to elucidate the trapping behavior of energetic deuterium with the implantation of 3 keV $D_2^+$ with various fluences and the role of lithium in the breeding materials is discussed. The results indicate that the $Li_2TiO_3$ TDS spectrum consists of four peaks. The first and second peaks are assigned to be D adsorbed on the surface, third, D trapped by E’-center, and fourth, D bound to oxygen with forming O-D bond in bulk. From $TiO_2$ TDS spectrum, it is found that at high ion fluence and high temperature, the desorption rate of D for $TiO_2$ is lower than that for $Li_2TiO_3$. This result would be contributed to the role of lithium and the formation of Li-O-D.

The TDS measurement is also applied for the observation

**Table 2 Requirements for test sections**

| Test section | He mass flow rate /kg/s | Pressure /MPa | Pressure difference at test section /MPa | He inlet/outlet temperature /℃ | Power supply /MW |
|---|---|---|---|---|---|
| TBM | 0．13～1.3 | 8 | <0.3 | 100/300<br>300/500 | 1 |
| DEMO lanket | ～4 | 8 | <0.4 | 300/500 | 5 |

on the release behavior of deuterium from $Li_4SiO_4$ which is determined as tritium breeding material in CH HCSB TBM. It is observed that deuterium irradiated into $Li_4SiO_4$ powder can be desorbed as four chemical forms: $D_2$, HD, $D_2O$ and HDO. These release chemical forms can be divided into two groups, $D_2$/HD （termed as hydrogen molecular forms） and $D_2O$/HDO （termed as water forms）. The desorption temperature of deuterium as hydrogen molecular forms is higher than that as water forms in $Li_4SiO_4$.

The fabrication of beryllium pebbles has been investigated. Rotating electrode process developed by NGK co. in EU and Japan gas atomization method developed by Brush Wellman co. in USA are considered as candidate fabrication processes of beryllium pebbles for CH HCSB TBM.

The study on experimental technologies relative to pebble bed has also been started. We primarily investigated the influence of pebble bed dimensions and filling factor on pebble bed properties. In order to study the heat transfer in the blanket, the experimental apparatus will be planned to design and measure the effective thermal conductivity of pebble beds.

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