Current Status of Chinese Solid Tritium Breeder TBM

Improved Design and Analyses of CN HCCB TBM

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Outline

- **1. Introduction**
- 2. CN HCCB TBS Design Progress
- 3. CN HCCB TBS R&D Progress
- 4. Test Plan and Time Schedule
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Introduction

- ITER provides an unique opportunity to test tritium breeding blanket mockups in integrated Tokamak operating conditions.
- Helium-cooled ceramic breeder (HCCB) test blanket module is the primary option of the Chinese ITER TBM program.
- China as Port Master (PM) in port number 2 and the HCCB TBM concept Leader (TL) will test her own TBMs at different ITER operation phases.
- In order to reduce the effects of magnetic field ripple, the TBM design has been updated with reduced RAFM mass.
- Related R&D on key components, materials, fabrications and mock-up test have being implemented.
- China ITER DA have signed the HCCB TBS TBMA with ITER IO in February 2014.
- The Conceptual Design Review (CDR) for CN HCCB TBS was hold in July 2014

TBM Concepts and Port-Sharing

Six TBM systems to be installed in three ITER test ports

Port No. and PM	TBM Concept	TBM Concept
A (PM : EU)	HCLL (TL : EU)	HCPB (TL : EU)
B (PM : JA)	WCCB (TL : JA)	HCCR (TL: KO)
C (PM : CN)	HCCB (TL : CN)	LLCB (TL : IN)

PM : Port Master, **TL** : TBM Leader

HCLL : Helium-cooled Lithium Lead (Helium/LiPb)
HCPB : He-cooled Pebble Beds (Helium/Ceramic/Be)
WCCB : Water-cooled Ceramic Breeder (Water/Ceramic/Be)
HCCR: Helium Cooled Ceramic Reflector (Helium/Ceramic/Be/Gr.)
HCCB : Helium Cooled Ceramic Breeder (Helium/Ceramic/Be)
LLCB : Lithium-Lead Ceramic Breeder (LiPb & He, Dual-Coolant)



The signing ceremony of CN TBS

- CN HCCB TBM will demonstrate the required functions and technical feasibility for Chinese DEMO breeding blanket in ITER operation condition.
- The HCCB-TBS TBM Arrangement (TBMA)was signed on Feb. 13th in the ITER council chamber by ITER DG Motojima and Director Luo of the CN DA.
- This is a very fundamental step forward for the Chinese TBM Program.

General HCCB-TBS Testing Program Objectives



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CN HCCB TBM design - History

➤ A series of the Chinese HCCB TBM designs have been carried-out since 2004 within the port space limitation and technical requirements specified by ITER IO.





Original HCCB TBM Design

Original design of CN HCCB TBM (2X6 sub-modules arrangement) before 2009.

Basic design characteristics:

- TBM Box structure: 2X6 Sub-module arrangement
- Structure material: RAFM (CLF-1);
- Tritium breeder: Li₄SiO₄ pebble bed, 80%Li-6 ;
- Neutron multiplier: Be pebbles bed;
- Coolant and purge gas: Helium gas
- Coolant pressure: 8MPa
- Coolant temperature: 300 °C(inlet) -500 °C (outlet)
- Tritium production ratio (TPR): 0.0505g/d



Cross-section of Sub-module



TBM design – updated to current design

■ In order to simplify sub-module structure; reduce RAFM mass and increase TPR performance, the design of CN HCCB TBM in 2012.

Main optimization results :

- All structure material RAFM
- Total mass of FAFM is reduced to ~1.3t from 1.8t
- TPR is increased to about 0.066g/d from 0.050g/d

Main design parameters

Parameters	Values
Neutron wall load	0.78 MW/m ²
Surface heat flux	0.3 MW/m ²
Structural material	CLAM/CLF-1 ~1.3ton (<550°C)
Tritium Breeder	Li ₄ SiO ₄ pebble bed (<900°C)
Neutron Multiplier	Beryllium pebble bed (<650°C)
Coolant	Helium (8MPa) 1.04 kg/s (Normal) FW(300°C/370°C) Breeding zone (370°C/500°C)
Purge gas	Helium with H ₂





Updated design with 1X4 SM

- Four sub-modules concept
 - Manufacturability
 - PIE/ transportation
 - U shape breeding zone
 - Reduce the structural material



TBM design - Current Design of sub-module

Sub-module

- A TBM contains 4 sub-modules.
- Each sub-module has one FW, two caps in top and bottom, middle rib, manifold.
- 4 inner cooling plates in U shape in the sub-module.
- Tritium breeder Li4SiO4 and neutron multiplier Be pebbles are distributed between these structure parts.





Explosive view of sub-module



TBM shield design

■ TBM shield is composed of the flange, plates, caps, pipes, etc.

■ There are totally 7 pipes passing through; double-wall pipes are considered for thermal isolation, and the area between walls will be pumped into vacuum.

Design parameters

Parameters	Values
Structural material	SS316LN-IG
Coolant	Water (4MPa) 0.1 kg/s (Normal) 70ºC/125ºC
Dead weight	~5 tons
Water volume	0.98 m3
Water fraction	~40%
Nuclear heating	20.3 kW

- Welded box structure concept
 - Manufacturability



Schematic diagram

Configuration Scheme of HCCB TBS



Auxiliary (HCS, TES, CPS) design

Based on requirements of heat removal, tritium extraction, coolant purification, and I&C from TBM module and the performance, the basic operation parameters of HCS, TES, CPS and I&C are proposed.

Design parameters

Main structural material

Primary coolant circuit

- Total flow rate

- Pressure drop

Interface with CCWS

Parameters

- Pressure





HCS Design

CPS Design

erface with CCWS	vvater	
- Pressure	0.8 MPa	
- Total low rate	21.3 kg/s	
- Inlet/outlet temperature	31°C/43°C	

- Values (TES, CPS) **Tritium related system** He - Purge gas - Tritium purification efficiency ≥ 95% - Impurity removal efficiency ≥ 90% ≥ 90%
 - Tritium extraction efficiency

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Design integration – with IO joint design

The sub-systems includes a Helium-cooled System (HCS), a Tritium Extraction System (TES), a Coolant Purification System (CPS), connection pipes, and the AEU and pipe forest (PF), etc.



Layout of ITER machine of the Ports for TBMs



Pipe Forest with IN TBM



Test Port Arrangement for CN HCCB TBM



Integration on Port Cell and AEU

Other interfaces/requirements including power, cooling water, signal process, maintenance strategy, et al. have been considered or are on-going.

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Related analyses

- In order to verify the design, related calculation and analyses have been performed.
 - Neutronics analyses
 - EM analyses
 - Hydraulic analyses
 - Seismic analyses
 - Thermal analyses
 - Structural analyses
 - Safety analyses



Equivalent stress distribution



Neutronics model



Temperature distribution



Neutron energy spectrum



Power density distribution



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R&D related to TBM set

RAFM steel - CLF-1 and CLAM

- Two RAFM steels CLF-1 and CLAM for Chinese TBM were produced by vacuum_induction melting method.
- Neutron irridiation test data up to 2.5 dpa was obtained by using the high flux test reactor in China.



CLF-1 Steel

MPT/P8-7: P. Wang

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CLAM Steel of vacuum smelting ingot

- Establishment of the material properties databases including mechanical, physical and neutron irradiation properties, have been completed.
- Welding performance was tested.
- Qualification as CN HCCB TBM stricture material is ongoing.

R&D related to TBM set

Tritium Breeder – Li4SiO4

MPT/P8-6: Y. Feng

- ✓ The ceramic breeder pebble of kg-class was fabricated by a melt spraying method.
- ✓ Related properties were tested.
- ✓ Main performance meets the requirement of HCCB TBM module design.



SEM of pebble's surface



SEM micrographs of pebble

Main properties of Li4SiO4

Properties	Values
Density	2.32 g/cm ³
Open porosity (%)	~ 5.2
Closed porosity(%)	~ 1.78
Specific surface area (m ² /g)	0.4626
Pore Radius (nm)	3.674







Fabrication facility



Li4SiO4 pebble

R&D related to TBM set

Neutron Multiplier Beryllium

✓ The Be pebble of kg-class was fabricated by a REP method. Larger scaled fabrication of 10kg-class is progress.



SEM micrograph of pebble's surface



SEM micrographs



AFM micrograph

Main properties of Be pebble

Item	Value	
Pebble diameter, (mm)	~1.0mm	
Density, (% T. D.)	98	
Tap density, (g/cm3)	1.115	
Sphericity, (%)	99.7	
Specific surface area (m²/g)	0.5449	



Deformation of the Be pebbles for various applied mechanical loads





REP Facility



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Beryllium pebble (D:1mm)

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R&Ds related to TBM set

Manufacturing R&Ds for TBM module components have been investigated which include Hot press joining, EB welding, laser welding, tensile test and impact test, etc.



Hot press welding

Tensile test

EB welding



Impact test

- A medium-sized mock-up of U-shaped first wall is completed;
- Full scale first wall is under way.
- Different fabrication method (EBW, HIP, TIG) are used for FW and components joint.



U-shaped FW **MPT/1-2: X. Liu**

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Partition



Sub-module component



Sub-module

R&Ds of auxiliary systems



TES testing system



CPS testing loop

- Related tritium auxiliary systems and R&D performed in CAEP:
- Some test facilities are under construction.
 - A hot metal bed circulation loop
 - A MS adsorption loop
 - A hydrogen isotope separation sub-system
 - Experiments for Impurity absorber bed
 - Experiments for oxidation bed





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HCCB TBMA Milestones

- Current HCCB TBMA milestones is based on the current ITER construction, operation plan.
- CN HCCB TBS Milestones may be adjusted according to the update of ITER plan.

1. TBS Design activities

- HCCB TBS CDR approval (Oct.2014)
- HCCB TBS PDR approval (July 2016)
- HCCB TBS FDR approval (April, 2018)
- Amendment HCCB TBMA (July 2018)
- Contract signature for HCCB TBS (Oct. 2019)

2. TBS Qualification activities

- Materials qualification (Not in SMP milestone, but for FDR)
- Manufacturing process qualification (April 2019)

3. TBS delivery activities

- HCCB TBS delivery ITER site (Sep. 2021)
- HCCB TBS acceptance tests in ITER site (Jun, 2022)

Testing Strategy for the CN HCCB TBS

• At least four kinds of TBM modules will be tested in ITER different operating phases.

Operation Phase	Testing Description	TBM type
H-H	Safety, thermal load of surface, E-M load, disruption	EM-TBM
D-D	Neutron response data, Thermal behaviors	TN-TBM
D-T (Low duty)	Structure behaviours, Nuclear response for D-T neutron, Tritium production, Tritium procedure validation	TN-TBM
D-T (High duty)	Operational behaviours, Heat transfer, Tritium production and management. Overall reliability and operational performance	NT/TM INT-TBM



ITER Operation and TBM Test Schedule



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- The TBM program is an important part of China fusion development Strategy, for which HCCB concept is the primary option.
- The HCCB TBMA has been signed between ITER and CN DA. The CDR has been hold in 2014.
- The design of HCCB TBS is developing in details according to the schedule. R&D progress on structure material, function materials (ceramic tritium breeder, neutron multiplier Be pebble), mediumsized FW mock-up, others components of the sub-module.
- The R&D and test plan, delivery of CN HCCB TBS are scheduled.
 PD and FD design is under implementation.
- Chinese HCCB TBM test will be implemented with the cooperation of domestic and international institutions and industries.

Thanks for your Attention !

