Development Status of ITER HCCB TBS and CFETR HCCB TBB

Xiaoyu WANG
On behalf of China HCCB TBB Team
Outline

- China MCF Roadmap & TBB Development Strategy
- CN HCCB TBS Design for ITER
- CFETR HCCB TBB System Design
- TBB R&D activities
- Summary
China MCF Development Roadmap

China Magnetic Confinement Fusion Development Roadmap

**TBB Technology**
Design, material, fabrication process, safety, etc.

**Experimental Facility**
HL-2M EAST J-TEXT

**ITER**
Validate technology feasibility of T production and heat removal

**ITER TBM**
Validate technology feasibility of T production and heat removal

**CFETR**

**CFETR TBB**
Verify engineering feasibility of T breeding and electricity generation

**PFPP TBB**
T self-sufficiency and electricity generation

**PFPP**

**TBB Development Strategy**
TBB Concepts and Application

HCCB TBB Concept (Helium Cooled Ceramic Breeder)
- ITER TBM
- CFETR HCCB TBB

WCCB TBB Concept (Water Cooled Ceramic Breeder)
- CFETR WCCB TBB

HCLL TBB Concept (Helium Cooled Lithium Lead)
- Advanced concept for future
CN HCCB TBS Design
(For ITER TBM)

**CN TBM program:** Helium Cooled Ceramic Breeder Test Blanket System (HCCB TBS)
**Led by CN DA**
**Supporting Institutes:**
1. Southwestern Institute of Physics (SWIP)
2. China Academy of Engineering Physics (CAEP)
3. Institute of Nuclear Energy Safety Technology (INESST)
The objectives of CN HCCB TBS is to test the feasibility of tritium breeding blanket technology in the tokamak operation conditions provided by ITER.
CN HCCB TBS schematic layout

- TBM set
- Pipe Forest (PF)
- Ancillary Equipment Unit
- Tritium Extraction System (TES)
- Helium Cooling System (HCS)
- Coolant Purification System (CPS)
### Main design parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutron wall load</td>
<td>0.78 MW/m²</td>
</tr>
<tr>
<td>Surface heat flux</td>
<td>0.3 MW/m²</td>
</tr>
<tr>
<td>Structural material</td>
<td>CLAM/CLF-1 ~1.2ton (&lt;550°C)</td>
</tr>
<tr>
<td>Tritium Breeder</td>
<td>Li₄SiO₄ pebble bed (&lt;900°C)</td>
</tr>
<tr>
<td>Neutron Multiplier</td>
<td>Beryllium pebble bed (&lt;650°C)</td>
</tr>
<tr>
<td>Coolant</td>
<td>Helium (8MPa) 1.04 kg/s (300°C/500°C)</td>
</tr>
<tr>
<td>Purge gas</td>
<td>Helium (0.3MPa) with 0.1% H₂</td>
</tr>
<tr>
<td>TPR</td>
<td>61mg/FPD</td>
</tr>
</tbody>
</table>
The design of all ancillary systems have been optimized considering the system performance, safety and interface requirements:

- Configuration update based on equipment investigation, PFD and PID diagrams
- System performance assessment, structural analysis, accident analysis

### Main design parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values (HCS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main structural material</td>
<td>SS316L</td>
</tr>
<tr>
<td>Supporting structure material</td>
<td>SS304</td>
</tr>
<tr>
<td><strong>Primary coolant circuit</strong></td>
<td></td>
</tr>
<tr>
<td>Pressure</td>
<td>Helium</td>
</tr>
<tr>
<td>Total flow rate</td>
<td>8 MPa</td>
</tr>
<tr>
<td>Pressure drop</td>
<td>1.04 kg/s</td>
</tr>
<tr>
<td>Inlet/outlet temperature</td>
<td>~0.5 MPa</td>
</tr>
<tr>
<td>Total flow rate</td>
<td>1.04 kg/s</td>
</tr>
<tr>
<td>Inlet/outlet temperature</td>
<td>500ºC/300ºC</td>
</tr>
<tr>
<td><strong>Interface with CCWS</strong></td>
<td></td>
</tr>
<tr>
<td>Pressure</td>
<td>Water</td>
</tr>
<tr>
<td>Total low rate</td>
<td>0.8 MPa</td>
</tr>
<tr>
<td>Total flow rate</td>
<td>21.3 kg/s</td>
</tr>
<tr>
<td>Inlet/outlet temperature</td>
<td>31ºC/43ºC</td>
</tr>
</tbody>
</table>

### Tritium related system

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values (TES, CPS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Purge gas</td>
<td>He with 0.1% H₂</td>
</tr>
<tr>
<td>T purification efficiency</td>
<td>≥ 95%</td>
</tr>
<tr>
<td>Impurity removal efficiency</td>
<td>≥ 90%</td>
</tr>
<tr>
<td>T extraction efficiency</td>
<td>≥ 90%</td>
</tr>
</tbody>
</table>
CN HCCB TBS for ITER - Ancillary Systems

Configuration of HCS

Operation states and transition path

PFD and PID

Performance analysis model for HCS
The safety work covers the whole design activities of all subsystems.
- Design description and safety function
- Nuclear analysis
- Tritium analysis
- Accident analysis
- Other analysis

Example of tritium release results
Distance to TBM: 30cm

Example of accident analysis results

Example of dose rate results
Distance to TBM: 5cm

SDDR results for HCCB TBM (1d, Sv/h)

In collaboration with Dr. Brad Merrill, Idaho National Laboratory (INL), USA.
CFETR HCCB TBB System Design
(For CFETR)

CFETR program: Chinese Fusion Engineering Testing Reactor (CFETR)
Supported by MOST of China
Main Supporting Institutions:
1. University of Science and Technology of China (USTC)
2. Southwestern Institute of Physics (SWIP)
3. Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP)
4. China Academy of Engineering Physics (CAEP)
5. China Nuclear Power Engineering Co., LTD. (CNPE)
CFETR Mission

1. **Obtained Burning Plasma for fusion power**
   - P=200-2000MW
   - Q=1-10, SSO, hours
   - Q=20-30 hours-SSO
   - High energetic $\alpha$ heating

2. **Steady-state operation for fusion energy**
   - Hybrid (OH+BS+CD)
   - SSO (Ext H&CD +Higher $f_b$)
   - PSI on the first wall
   - Heat & particle exhaust on Div.

3. **Breeding Tritium for T self-sufficiency**
   - T-breeding by blanket
   - T-plant: extract & reprocessing
   - Materials & components
   - Reliable and quick RH
   - Licensing & safety
Design Objectives of CFETR HCCB TBBS

**Neutron shielding**
- Together with other CCSs to provide radiation protection

**Heating removal**
- High T, High P, Helium Cooling Loop
- Heat exchange with secondary Loop

**Structural integrity, compatibility and reliability**
- Withstand Load of Fusion environment
- Compatible with TOKAMAK and Remote Handling

**Safety**
- For normal and accidental condition
  - Confinement radioactive inventory;
  - Protect operator and equipment

**Tritium breeding**
- TBR≥1.1
- As Large As Reasonably Achievable
CFETR HCCB TBB system

- Tritium Breeding Blanket (HCCB TBB)
- Primary helium cooling system (HCS)
- TBBS I&C system

Interface with T-plant
Interface with CFETR I&C network
Interface with 2nd cooling loop and other services

TBBS I&C
TBB
HCS
CFETR HCCB TBB design features

**Basic design features**
- “Banana” segment design compatible with RH
- Several blanket modules in each segment
- Total
  - 16 sectors
  - 80 segments
  - 432 blanket modules
  - ~5000 tons

**Material selection**
- FW armor: W / W alloy
- Structural: ODS + RAFM steel
- Breeder: Li$_4$SiO$_4$ / Li$_2$TiO$_3$
- Multiplier: Beryllium / Beryllium alloy

**Design parameters**
- Coolant: Helium@12MPa
- Purge gas: Helium(0.1%H$_2$)@0.3MPa
Blanket module
- Integrated design for breeding and shielding functions
- Four zones
  - Breeding zone
    - Breeder pebble bed / porosint
    - Multiplier pebble bed / porosint
  - Distribution zone
  - Shielding zone
  - Manifold
- Cooling channel for breeding zone
- Cooling channel for shielding zone
- Purge channel for breeding zone

Design code: RCC-MR
Neutronics model and nuclear performance

Nuclear analysis model

Nuclear heating
(1.5GW Fusion power)

<table>
<thead>
<tr>
<th></th>
<th>Nuclear heating (MW)</th>
</tr>
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<tbody>
<tr>
<td>Inboard BLK</td>
<td>460</td>
</tr>
<tr>
<td>Outboard BLK</td>
<td>960</td>
</tr>
<tr>
<td>Total</td>
<td>1420</td>
</tr>
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</table>

NBI ports impact to TBR

<table>
<thead>
<tr>
<th>Number of NBI port (3m x 2m)</th>
<th>TBR</th>
</tr>
</thead>
<tbody>
<tr>
<td>No NBI port</td>
<td>1.16</td>
</tr>
<tr>
<td>Two NBI ports</td>
<td>1.13</td>
</tr>
<tr>
<td>Three NBI ports</td>
<td>1.11</td>
</tr>
</tbody>
</table>
LOFA accident analysis:
- Event sequence:
  \( t = 1800 \text{s} \), pump trip in HCS
  \( t = 1802 \text{s} \), terminate the plasma burn
- Results:
  Max. temperature FW: 656°C.
  Natural circulation flow rate: 8kg/s.

In-vessel LOCA accident analysis:
- Event sequence:
  \( t = 0 \text{s} \), break in FW, plasma breaks down
  \( t = 6 \text{s} \), HCS is isolated
- Results:
  Max. temperature FW: 648°C.
  Max. pressure VV: 88KPa.
  Max. helium leakage VV: 160kg.
TBB R&D activities
Functional materials and pebble bed technology

Based on the CN HCCB TBM program, the fabrication technology of Li$_4$SiO$_4$ and beryllium pebble have been developed, the database is under establishment.

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**Compositions of Be Pebbles**

<table>
<thead>
<tr>
<th>Element</th>
<th>Composition</th>
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<tr>
<td>Be</td>
<td>98.7</td>
</tr>
<tr>
<td>BeO</td>
<td>0.3</td>
</tr>
<tr>
<td>Fe</td>
<td>0.070</td>
</tr>
<tr>
<td>Al</td>
<td>0.0252</td>
</tr>
<tr>
<td>Si</td>
<td>0.0097</td>
</tr>
<tr>
<td>Mg</td>
<td>0.0139</td>
</tr>
<tr>
<td>Cr</td>
<td>0.0099</td>
</tr>
<tr>
<td>Cu</td>
<td>0.0018</td>
</tr>
<tr>
<td>Mn</td>
<td>0.0124</td>
</tr>
<tr>
<td>Ni</td>
<td>0.0092</td>
</tr>
<tr>
<td>Pb</td>
<td>0.00017</td>
</tr>
</tbody>
</table>

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In collaboration with Dr. Alice Ying, UCLA, USA.
Structural material development

- **RAFM steel**
  - Two kinds of RAFM steel: CLF-1 & CLAM
  - Fabrication procedure for >5 tons ingot
  - 3.2 certificate based on RCC-MR
  - Material database
  - Irradiation experiment
  - Environment compatibility experiment

- **ODS steel**
  - Ton-scale casting
  - High performance:

![RAFM steel scale-up diagram](image)

- China Low-activation Ferrite steel (CLF-1)
- Scale-up with impurity control
  - 5 ton x 3
  - 1 ton
  - 350 kg
  - 50 kg
  - 10 kg

![CLAM diagram](image)

- CLAM 10-55mm Plates
- Forging
- Forged Bars

![Chemical composition chart](image)

- CLF-1 vs. CLAM
- Metal composition:
  - Mn
  - V
  - W
  - Ta
  - N

![Absorbed energy chart](image)

- 1 ton scale RAFM steel vs. CLF-1 & CLAM
- DBTT: -72°C
- DBTT: -40°C

![Irradiation test results](image)

- Material properties vs. temperature and radiation exposure
- Room temperature
- 773 K
- Irradiation test results
- Number of cycles to failure
Fabrication processes

Fabrication processes development for HCCB TBM, whose experience can by use for CFETR TBB

FW sample
CP sample
Breeding unit sample
Prototype mockup of double-layer pipe for shield
FW mockup
Cooling plate (CP) mockup
Submodule mockup welding
Back plate mockup
Cover plate mockup
Fabrication processes – CFETR TBB

Deep drilling hole

W armor
Helium cooling technology

HHFT facility EMS-60

Control system and ITER Mini-CODAC

Hydraulic testing

HeCEL-1 (0.1kg/s, 8MPa, 400°C)

High heat flux testing

HeCEL-3 (under design) (>2kg/s, 12MPa, >500°C)
Several testing facilities/loops have been constructed by CAEP to verify the tritium technology.

In-pile irradiation of lithium ceramic and tritium extraction experiment in both CIAE and CAEP.
Summary

The development of HCCB TBB is one of the most important part of China fusion development roadmap toward DEMO.

In order to support the design validation, a lot of design and R&D activities have been implemented. It will be an key step for the technology development of HCCB TBB and also it is providing the indispensable experience.

The development of CFETR HCCB TBB is one of the most important activities of CFETR, which is learning from the CN HCCB TBS and ITER. Its preliminary design has been started based on the latest CFETR design. But some technology challenges have been identified and will be developed in the future.
# Collaboration

<table>
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<tr>
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<th>Universities</th>
<th>Industries</th>
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Thank you very much for your attention!