Survey of technological development for the European Test Blanket Systems in ITER

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EU Test Blanket Systems in ITER

The TBM project provides test blankets to test and validate design concepts of tritium breeding blankets relevant to a power-producing reactor

ITER Project Requirements
The mission of the TBM program is to **test and validate** during ITER operation tritium breeding blanket concepts for application to fusion energy systems, with focus on DEMO.

This is achieved by:

- Providing a **test environment** (= the TBM) that reproduces operating conditions foreseen in the DEMO Breeding Blanket (BB)
- Providing systems (Helium, Tritium, PbLi) to establish the conditions above that adopts technologies relevant to the DEMO BB, when compatible with ITER operational requirements
- Developing and validating **predictive modeling tools** that are essential for the design of the DEMO
- Contributing to the understanding of the **licensing process** for the construction and operation of a tritium breeding nuclear system involving a Nuclear Regulator
**Industrial and research suppliers**

F4E is contracting and managing specialized technical competences of Industrial and Research Partners over Europe

- **NRG**: Irradiation of TBM functional materials
- **Studsvik**: Irradiation/PIE of TBM structural materials
- **Kit**: Helium and Tritium Systems, Functional Materials, TBM Box fabrication development, modeling, etc.
- **Kit**: Helium turbo-circulators
- **Teledyne Doctors**: Irradiation of structural materials
- **Enel**: Helium and Tritium systems, Experimental tests

**European TBM Systems**

Europe has produced mock-ups of TBM sub-components with standardized welding procedure specifications and within TBM reference tolerances

Internal cooling channels are constructed using advanced fabrication processes (e.g., mixed laser + diffusion-bonding)

- **Stiffening Grid**: (fabrication: Laser + Diffusion Bonding)
- **Side Cap**: (fabrication: Laser + Diffusion Bonding)
- **Tritium Breeder Unit – HCLL-type**: (fabrication: Laser + Diffusion Bonding or 2-step Diffusion Bonding)
- **Tritium Breeder Unit – HCPB-type**: (fabrication: Spark Erosion + Bending)
The development of Helium Cooling and Tritium Systems is supported by detailed engineering studies and R&D support program.

Stress analysis of the Helium Cooling piping system according to European standards (EN-13480), calculated using Rohr2 software.

Development of a cold trap for removal of impurities in PbLi loop.

European TBM Systems

TBM box Mock-Up (standardization by Industry)
Performance characterization of the TBM Systems

- Characterization of Tritium getter (ZrCo)
- Characterization of isolation valve (Helium loop)
- MHD pressure drop (TBM mock-up)
- Operational domain of Helium Turbo-circulator (K300)

Status of TBM Systems

- Conceptual Design Review meeting (June 2015)
- Preparatory work to Preliminary Design ongoing
- Standardization of TBM box fabrication (Industry, support EFLs)
- EUROFER qualification and integration in Nuclear Construction Code
- Large scope of ongoing R&D for verification of Systems performance
- 2 members of the TBM team permanently on Cadarache site

→ more info in backup slides
Technologies for power extraction

- Plasma radiative and neutronic power (~1 MW in a TBM) is extracted by helium (8MPa) / water (15-25 MPa) circulating in box structures and cooling plates (/tubes)
- For Helium cooling, small rectangular channels (5-15 mm) are meandering in the thickness of structures
- Fabrication required the development of new fabrication processes, mostly based on Diffusion Welding (or combination of DW with laser/TIG welding)
- Since TBM is a nuclear component (ESPN), a full cycle of standardization & qualification is run in collaboration with Industry

Technologies for power extraction

**Standardization of Welding Procedures Specifications (WPS)**

- Welding process(es)
- Reference to materials
- Welding consumables
- Preparation (including cleaning)
- Pre/post-heating treatment
- Method and control of welding (e.g. NDE)
- Necessary equipment to be used
- Etc.

**Qualification**

- Endurance tests (thermal cycling)
- Standardized Qualification Mock-Up, e.g. EN 15613 (“Qualification based on a pre-production welding test”)

When relevant, this will be the basis for addition of new Welding Procedures in RCC-MRx/ASME construction code(s)
4 TBMs in sequence for each EU TBS

In order to perform a comprehensive experimental campaign under the different ITER operating conditions, 4 TBMs will be deployed for each of the two European systems (HCLL and HCPB)

- **Electro-Magnetic (EM) TBM** (plasma H-He phase)
- **Neutronic (NT) TBM** (plasma D and short-pulse DT phases)
- **Thermo-mechanic and Tritium control (TT) TBM** (DT phase)
- **Integral (IN) TBM** (DT phase)

- All TBMs are designed with a common set of instruments for pressure, temperature, strain and the reconstruction of global forces on the attachments
- Additional sensors are deployed on each TBM to perform specific experiments (neutronics, thermo-mechanics, MHD, EM response, tritium control and management) tailored to ITER operating conditions
- Sub-system are fully instrumented at the initial installation

**Electro-Magnetic (EM) TBM**

**Neutronic (NT) TBM**

**EM TBM main test objectives:**
- Capability of heat extraction from the first wall
- Structural integrity of the box
- Effect of MHD phenomena and the operation of the PbLi loop (HCLL)
- Technologies and design of sub-system components, no related to tritium

**EM TBM sensors/instrum.:**
- Potential probes (induced currents)
- Ad-hoc thermocouples (reconstruction of the MHD velocity field)
- Resistive gauges (global force reconstruction)
- Distributed fiber optic arrays (T & strain)
- Hall sensors (magnetic field)

**NT TBM Main test objectives:**
- Operation and calibration of neutron sensors
- TBM neutronic response, including tritium production rate (TPR)
- Operation and calibration of tritium sensors & instruments to measure Pb-16Li composition

**NT TBM sensors/instrum.:**
- Capsule for activation foils
- 6LiF-diamond (SiC) detectors
- Miniaturized self-powered neutron detectors
**TT TBM Main test objectives:**
- Thermo-mechanical response of the TBM (including HCPB pebble beds) under DEMO relevant loads, including volumetric heat deposition
- Tritium control and recovery (preliminary validation)
- Breeder/multiplier materials measured during PIE activities (preliminary assessment)

**IN TBM Main test objectives:**
- Thermo-mechanical response of the TBM under DEMO relevant loads (with accumulated damages up to 3 dpa)
- Tritium control and recovery
- Technologies and design of sub-system components, extension of reliability and operational performance database
- Pb-16Li chemistry control and corrosion
- Performance of HCPB functional materials

**TT TBM sensors/instrum.:**
- Encapsulated resistive gauges on TBM structure (strain sensors)
- Direct contact piezo-electric resistive strain sensors (for pebble beds)
- Miniaturized fission chambers (mFC)

**IN TBM sensors/instrum. (rationale):**
- IN-TB sensors should: 1) maximize reliability & 2) minimize intrusiveness, e.g., i) FBG arrays to measure temperature and strain (stability under irradiation and ii) neutronic sensors are necessary to quantify source term

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**EU TBM Systems will test technological solutions**

DEMO concept studies and basic R&D are not sufficient to decide on selection/ranking of breeding blanket concept(s)

⇒ Need for RoX (Return on eXperience) from TBM Program in ITER

- Performances under tokamak actual and multi-loadings conditions (B, n, heat flux)
- Implementation of regulatory obligations (e.g. ESPN, waste disposal, etc.)
- Methodology for integration of new materials/fabrication in C&S
- Involvement of Industry, cost
- Availability (failures database)
RoX already gained through the EU TBM Program

- Introduction of EUROFER in RCC-MRx
- ESP(N) classification of TBM Systems
- Standardization of TBM box fabrication
- TBM Radwaste Management
- Design and performance validation
- Safety demonstration

→ more info in backup slides

RoX on design and licensing process

TBM Program is providing / will provide RoX on design, testing, commissioning and inspection of Breeding Blanket components covering the complete consultation cycle with an Agreed Notified Body and ASN (French Nuclear Regulator)

The EU TBM Systems:
- are pressurized nuclear equipment;
- feature a newly developed structural material (EUROFER) and advanced fabrication processes not referenced in nuclear construction codes (e.g. RCC-MRx);
- complex structures geometry and interconnected sub-systems exchanging Tritium.

“Development of a real technological object”
Overview of synergies areas

Impact of the technologies developed within the EU TBM program on the DEMO Blanket program

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Status of TBM Systems

- **Conceptual Design Review meeting (June 2015):** > 1500 pages of engineering reports; panel recognized high level of preparation and strategic vision; 2 category-1 chits currently under final resolution

- **Preparatory work to Preliminary Design ongoing:** 1) Consolidation of Requirements and their propagation, 2) Consulting with Agreed Notified Body (APAVE), 3) New location of Helium Cooling System in Tokamak building (11-L4-04), etc.

- **Standardization of TBM box fabrication (Industry, support EFLs):** 4 contracts achieved for TBM box sub-components; 1 new contract for sub-components assembly

- **EUROFER qualification and integration in Nuclear Construction Code:** 2 new contracts for irradiation (371 specimens); 2 new contracts for characterization and design rules development

- **Large scope of ongoing R&D for verification of Systems performance:** MHD, Helium turbo-circulators, isolation valves, instrumentation, Tritium getter, Tritium transport modelling, accidental analyses, etc.

- **2 members of the TBM team permanently on Cadarache site** (collaboration with IO-CT)

Tests on Electro-Magnetic (EM) TBM

**Main test objectives:**

- Validation of the capability of heat extraction from the first wall
- Validation of the structural integrity of the box and the response of the mechanical attachment
- Validation of the effect of magneto-hydrodynamic (MHD) phenomena on the TBM performance and the operation of the PbLi loop (HCLL)
- Verification technologies and design solution of sub-system components no related to tritium

**Sensors/instrumentation under development:**

- Measure induced current distribution by potential probes
- Measure temperature and electric potential with ad-hoc thermocouples (reconstruction of the MHD velocity field)
- Temperature & strain measurement with distributed fiber optic arrays
- Global force reconstruction with resistive gauges
- Magnetic field measurements with Hall sensors
Tests on Neutronic (NT) TBM

Main test objectives:
- Verify the operation and calibrate neutron sensors
- Preliminary validation of the TBM neutronic response, including tritium production rate (TPR)
- Verify the operation and calibrate tritium sensors (including TAS), and instruments to measure Pb-16Li composition

Sensors/instrumentation under development:

Passive sensors (activation foils)
Priority for D plasma operation:
- Can discriminate neutron energy (spectra)
- Can be optimized to measure low flux/fluence

Capsule for activation foils (processed by the Neutron Activation System, NAS)

Active sensors
Validate in pulse DT plasma operation:
- Low technological maturity
- Potential for high sensitivity

$^6$LiF-diamond (SiC) detectors
Under development: modified SCD and other Li-based sensor technology for TPR; main challenge is high temperature operation

Self-powered neutron detectors
Miniaturized SPND tested in ENEA

Tests on Thermo-mechanic & Tritium control (TT) TBM

Main test objectives:
- Validate the thermo-mechanical response of the TBM (including HCPB pebble beds) under DEMO relevant loads, including volumetric heat deposition
- Preliminary validation of tritium control and recovery
- Preliminary assessment of the activation of breeder/multiplier materials measured during PIE activities

Sensors/instrumentation under development:

Strain sensors for validation of PBTM numerical models:
- Encapsulated resistive gauges on TBM structure
- Direct contact piezoelectric (for pebble beds) resistive

Deployment of miniaturized fission chambers (mFC)
Tests on Integral (INT) TBM

Main test objectives:
- Validate the thermo-mechanical response of the TBM under DEMO relevant loads (with accumulated damages up to 3 dpa)
- Validate tritium control and recovery
- Validate technologies and design solution of sub-system components and extend the reliability and operational performance database
- Validate Pb-16Li chemistry control and corrosion
- Validate the performance of HCPB functional materials

Rationale for sensors/instrumentation:
IN-TBM sensors should: 1) maximize reliability & 2) minimize intrusiveness, in addition to control (basic) instrumentation:
- FBG arrays to measure temperature and strain, pending the assessment/validation of their stability under irradiation
- Neutronic sensors are necessary to quantify source term

Tests on Electro-Magnetic (EM) TBM

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Main test objectives:

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- Preliminary validation of tritium control and recovery
- Preliminary assessment of the activation of breeder/multiplier materials measured during PIE activities

Sensors/instrumentation under development:

Strain sensors for validation of PBTM numerical models:
- Encapsulated resistive gauges on TBM structure
- Direct contact piezo-electric (for pebble beds) resistive

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RoX already gained through the EU TBM Program

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<td>Introduction of EUROFER in RCC-MRx</td>
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<td>Conditions of acceptance of design limits and new design rules (statistics, justification documents, specific behaviors, etc.)</td>
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<td>TBM Radwaste Management</td>
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<td>Design and performance validation</td>
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<td>Safety demonstration</td>
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<td>R&amp;D verification of Systems components performance (He turbo-circulator, Tritium systems, etc.)</td>
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<td>Impact of Safety requirements on design</td>
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<td>Validation of the safety functions; consistent architecture of systems</td>
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<td>Development and validation of modeling tools</td>
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EU TBM Program will contribute to validate the DEMO BB safety approach thru:

- Definition of the TBS safety principles, functions and classifications
- Systematic determination and classification of accidental events
- Performance of safety analyses, the development of safety models (MELCOR, RELAP5) with DEMO relevant materials, design, components
- Estimation of radioactive inventory and analysis of radioactive waste
- Preparation of safety related documentation for licensing authorities (Preliminary, Provisional, Final Safety Reports)