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Breeding Blanket Modules testing in ITER: An international program on the way to DEMO

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Abstract

Testing of Breeding Blanket Modules is one of ITER's primary objectives. This paper discusses the major features and requirements of key tests to be performed in ITER for several DEMO-relevant Test Blanket Modules as proposed by the present six ITER Parties.

The content is focused on the assessment work recently performed by the ITER Test Blanket Working Group mostly devoted to the establishment of a testing strategy, to the presentation of the Test Blanket Modules proposals and to the definition of the necessary interfaces with the ITER machine and buildings.

Keywords: ITER; TBWG; Test Blanket Module; TBM; Breeding blanket

1. Introduction

Breeding blankets represent one of the major technological breakthroughs required from passing from ITER to the next step, usually called DEMO, a demonstration reactor able to furnish electricity power to

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the grid. In fact, a DEMO breeding blanket and associated systems have to ensure tritium breeding self-sufficiency, to show good power conversion efficiency and to withstand high neutron fluence. For this reason, among the technical objectives of ITER it is specifically stated that "*ITER should test tritium breeding module concepts that would lead in a future reactor to tritium self-sufficiency and to the extraction of high-grade heat and electricity production*" [1].

In order to comply with this mission, since the early stage of the ITER EDA, a working group, called ITER Test Blanket Working Group (TBWG), was officially established by the ITER Council, and charged to define and coordinate an appropriate breeding blanket testing program in ITER. The TBWG made a preliminary assessment of the testing capabilities of the present ITER machine in July 2001 at the end of the ITER EDA extension phase, and defined a set of Test Blanket Modules (TBMs) to be tested in the different operation phases of ITER in the framework of a coordinated testing program [2].

The TBWG has restarted its activity in October 2003 and its revised official membership includes representatives from the ITER Team and from the six ITER Parties (China, EU, Japan, Korea, Russian Federation, and USA). The TBWG charter is aiming to: (i) provide the Design Description Document (DDD) of the TBMs systems proposed by Parties including the description of the interfaces with the main ITER machine, (ii) promote co-operation among Parties on the associated R&D programs, (iii) verify the integration of TBM testing in ITER site safety and environmental evaluations, and finally (iv) develop and propose coordinated TBMs test programs taking into account ITER operation planning.

This paper reviews the activities performed by the TBWG so far and outlines the main achievements in term of TBM testing strategy and the corresponding requirements for integration, in ITER overall design and planned operations.

2. ITER boundary conditions and testing parameters

ITER as an experimental machine will have a rather broad domain of operation around $Q = 10$, with fusion powers between 300 and 600 MW, depending on achievable confinement, density and maximum pressure. The three equatorial ports no. 16, 18, and 2 (1.75 m wide × 2.2 m high) have been allocated for TBM testing.

2.1. TBM testing and design parameters

The ITER operational plan has been defined up to now for the first 10 years. It includes 1 year of integration of the sub-system level and in-vessel components baking, 2.5 years of initial H–H operation, a brief D–D phase and a long D–T phase (see Fig. 1). During the D–T phase, in the inductive mode of operation the reference operating conditions for TBMs include a surface heat flux up to 0.27 MW/m^2, a neutron wall load up to 0.78 MW/m^2, a pulse length of 400 s with a duty cycle up to 22%. Pulse lengths up to 3000 s, with a duty cycle up to 25%, could be possible in fully non-inductive operations, passing from the hybrid mode (inductive + partial current drive), capable of achieving a pulse lengths of about 1000 s. Longer burn times (>3000 s) could also become possible with some equipment up-grade [3]. The maximum disruption energy load will be of 0.55 MJ/m^2 (1–10 ms). In the first 10 years of operations, the expected available neutron fluence is of about 1.1 dpa (eq. Fe).

In fact, a recent ITER estimation shows that, because of possible magnetic field perturbations due to the TBM ferro-magnetic materials leading to a loss of fast particles and then to localized hot spots [3], the design value of the surface heat flux on the TBM First Wall (FW) has to be increased up to 0.5 MW/m^2 on 10% of the FW area. In the H–H phase this value should be up to 0.3 MW/m^2. This new specification has a strong impact on TBMs designs and needs a further detailed assessment.

The second 10-year period will be defined after the beginning of operation and its plan will be decided as a function of the obtained results. A tritium breeding blanket may be required for this operational phase taking into account the limited amount of tritium available from external sources.

2.2. Main interfaces with ITER machine

The schematic view of a TBM installed in an ITER test port is shown in Fig. 2.

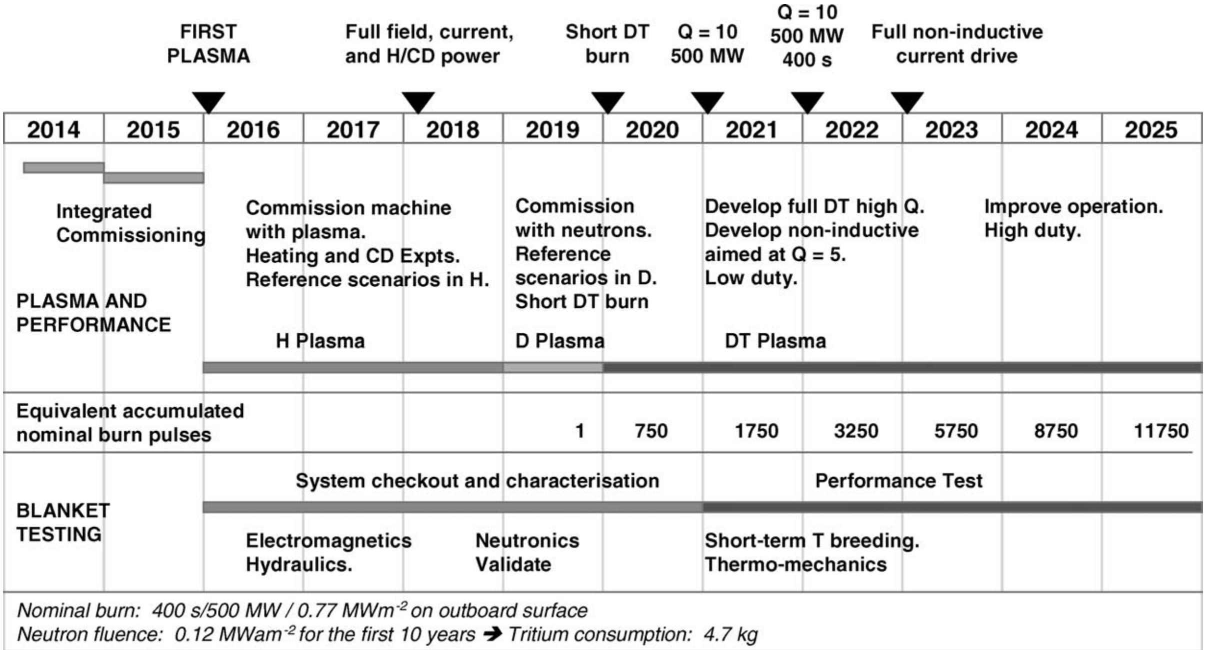

Fig. 1. First 10 years of operational plan of ITER and TBMs testing strategy.

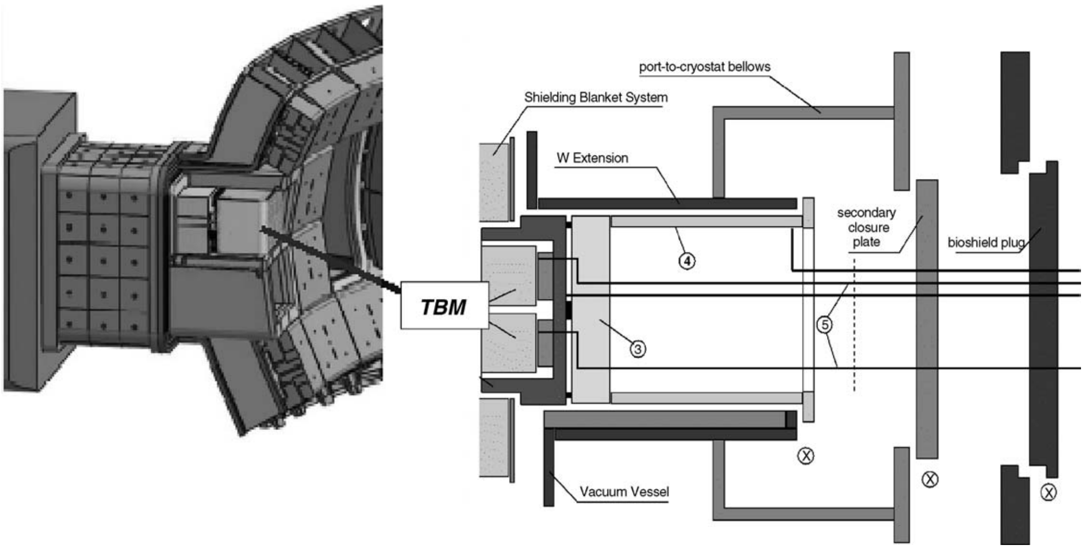

Fig. 2. Schematic view of TBMs installed in an ITER test port.

The TBMs inside a port must be contained in a water-cooled steel frame, 20-cm thick, which provides a standardized interface with the ITER basic structure, including thermal insulation of the basic machine. TBMs are mechanically connected to the back wall of the frame, acting also as neutron shield, through flexible supports.

To avoid the need of TBM alignment with the ITER shielding blanket, the TBM FW is recessed of 50 mm and may require a Be protection layer (1–2 mm) in order to limit sputtering and erosion issues.

The location of the circuits and components associated with the TBM is of extreme importance for testing. Outside the bioshield, behind of each port, there is a space (the port cell) available for placing a movable container (cask) with the interfacing equipment. Because of the limited amount of space available in the port cell, some components may be located in the Tokamak Cooling Water System (TCWS) vault and inside the tritium building.

TBM systems may use the ITER heat rejection system designed to supply cold water at 35 °C and to accept water at 75 °C. TBMs systems located in the port cells are subjected to magnetic fields up to one-tenth of tesla.

3. Testing capabilities and objectives

ITER may be the only opportunity for testing DEMO-relevant TBMs in a real fusion environment before the construction of a DEMO reactor ensuring: (i) in the initial H–H phase, relevant magnetic fields, surface heat fluxes, and disruption-induced loads, and (ii) in the following D–T phase, an additional relevant neutron flux, volumetric heat, and tritium production with corresponding T-management capabilities.

The most important restrictions for blanket testing are the magnitude of neutron flux, neutron fluence, and volumetric power density that in ITER are considerably lower than the expected corresponding DEMO values. As a consequence, for each selected blanket concept, several different TBMs have to be developed using different “engineering scaling” depending on the assessed performance, in order to achieve the corresponding DEMO-relevant working conditions in each dedicated TBM.

Maximum expected neutron damage is about 3 dpa (in ferritic steel) even after 20 years of operation, while dpa levels required for DEMO are greater than 70 dpa. Therefore, ITER cannot give answers to long-term irradiation effects on blanket performances, failures, functional, and structural materials, and interfaces, synergistic effects. These should be addressed in other facilities, e.g. fast-neutron fission reactors, fusion neutron sources.

3.1. Main test objectives for the D–T phases

Taking into account these limitations, the major overall testing objectives are the following:

- validation of structural integrity theoretical predictions under combined and relevant thermal, mechanical and electromagnetic loads, with consequent validation of the used fabrication techniques and processes;
- validation of tritium breeding predictions and their acceptability for the DEMO self-sufficiency proof;
- validation of mechanical, thermal, and thermo-mechanical predictions for strongly heterogeneous breeding blanket concepts with volumetric heat sources, including the maximum breeder material temperature and structural stability of the breeder elements, with the determination of safety factors to be included in DEMO designs development;
- validation of tritium recovery process efficiency and T-inventories in blanket materials, determination of the tritium permeability through breeding elements structure and of the efficiency of anti-permeation coatings;
- demonstration of the integral performance of the blankets systems.

Most of TBM sub-components thermal time constants are lower than 400 s, and therefore relevant temperatures can be achieved during a reference pulse length. On the other hand, most tests concerning tritium-related performances, because of the relatively long time constant [4], need long pulse (>1000 s) and an uninterrupted series of back-to-back cycles that will be available only in the last part of the D–T phase.

3.2. Main test objectives for the H–H phase

Important data can be obtained during the H–H phase which implies the installation of validated TBMs since the beginning of ITER operation. The main results expected in this phase are the following:

- demonstration of the structural integrity of the TBM structures, and attachment during disruption and vertical displacement events (VDE);
- assessment of the impact on ferritic/martensitic steel, used as a structure for most TBMs, on magnetic fields deformation in static conditions;
- verification of the need of Be-coating on the FW;
- functional check of the TBM system components before materials activation will restrict the hands-on intervention capability.

Moreover, in this phase, essential TBMs validation data can be obtained to be used in support of the TBM safety dossier to be prepared before starting the D–T phase.

For TBMs using liquid metals, additional data can be obtained for the validation of the MHD pressure drops estimations, and for the T-control and management simulated with addition of H/D in the flowing liquid.

3.3. Required instrumentation

In order to achieve the expected testing objectives, an important issue is the availability of appropriate instrumentation and measurement techniques. Most of the instrumentation available on the shelves are not compatible with the severe TBM environment which, since day-1, is characterized by high magnetic fields, high temperatures and pressures, materials compatibility issues, and finally, limited accessibility of the TBMs both for repair and for data acquisition. In the D–T phase, additional high neutron and gamma fields will be present, and direct access to TBMs will be no more possible.

4. Blanket development and Test Blanket Modules proposals

In order to give relevant information for developing breeding blankets for DEMO, ITER TBMs, and associated systems have to use the same blanket design, the same functionalities and the same technologies that are expected in DEMO. Moreover, the design of “act-alike” or “look-alike” mock-ups needs a direct reference to the DEMO design and performances. It is therefore essential to have a clear definition of the DEMO breeding blanket design before deriving the relevant TBMs to be tested.

4.1. Considerations on DEMO breeding blanket

DEMO reactor is likely to be defined in a different way from the different Parties and it may occur that most of the Parties will proceed to the construction of their own DEMO. Therefore, DEMO reactor parameters can vary from one design to another; however, some common requirements can be defined, such as tritium breeding self sufficiency, neutron wall loading above 2 MW/m^2, maximum FW heat flux between 0.5 and 1.0 MW/m^2, use of low-activation structural material and reasonable thermal efficiency (>30%).

Various breeding blanket concepts are proposed for DEMO and are used as basis for blanket R&D planning. They include both solid breeder and liquid breeder options. It is stressed that the selection of a given breeding blanket concept strongly characterizes the main features of the corresponding DEMO plant, and therefore, its definition should be considered as a priority in any DEMO plant study.

All ITER Parties consider helium-cooled ceramic breeder (HCCB) blankets [5–10]. This kind of blankets requires beryllium as neutron multiplier, and ferritic/martensitic steel (FMS) structures. The ceramic breeder is a Li-based compound, either Li_2TiO_3 or Li_4SiO_4, and is used in pebbles-bed form. Also Be is used in pebble-bed form with the exception of the RF design which uses porous Be blocks. In the Korea design, the rear part of the Be pebble bed are replaced by graphite pebble beds acting as neutron reflector. A water-cooled ceramic breeder (WCCB) blanket, corresponding to the water-cooled version of the HCCB blanket is also proposed by Japan.

Liquid lithium–lead (LL) blankets, using FMS structures, are considered by several Parties. EU has selected the helium-cooled (HCLL) version [5], while USA and China have selected the dual-coolant (DCLL) version, with He-cooling in FW and structures, and PbLi cooling the breeder zone [6,7].

Finally, liquid lithium blankets are considered by RF and Korea. RF has selected a self-cooled version (SCLi) with V-alloys structures and Be-multiplier [8], while Korea has selected a He-cooled version (HCLi) with FMS structures, making use of graphite pebble beds neutron reflector in the rear part of the blanket but no Be [9].

The Japanese DEMO program also includes more advanced designs, in case on-going R&D will be particularly successful [10]. In particular: dual-coolant molten salt (DCMS) blankets (in collaboration with USA), WCCB blanket using supercritical water as coolant, and very high temperature HCCB blankets using SiC/SiC structures.

It must be pointed out that significant R&D is still required for all the breeding blankets, although at a different level, before being able to demonstrate their feasibility, performances, and reliabilities. The corresponding tests in ITER represent therefore a significant part of the planned R&D. These uncertainties justify the tests of various blankets designs needing different TBM systems.

4.2. TBM testing strategy

Significant steps need to be performed prior to the TBMs installation in ITER, such as materials fabrication routes and irradiation resistance, out-of-pile tests of mock-ups and associated systems up to the test of prototypical TBM systems, and RH equipment validation.

Concerning the tests in ITER, some Parties envisage focusing on confirmation tests. For this kind of tests, TBM size of half a port appears to be the best compromise between obtaining sufficient measurement sensitivity and maximizing of the number of TBMs that can be tested simultaneously taking into account the space limitations and shield efficiency. Other Parties prefer to focus on parallel and sequential, functional tests, which require smaller size sub-modules, each of them designed using engineering scaling.

As said in chapter 3, in all cases, because of the reduced FW loads compared to DEMO, the agreed TBM testing approach requires to have for each blanket concept a series of different TBM designs, each one devoted to specific testing objectives, starting from the initial TBM in the H–H phase where no nuclear heat is present, to the one installed at the end of the D–T phase where pulse-length longer than 1000 s and a large number of back-to-back pulses could be expected.

At least two specific intermediate TBMs are required to focus either on neutronic performances, which can be partially tested and measured in the D–D phase and completed in the initial short pulse D–T phase, or on thermo-mechanical performances which can be tested and measured during the reference D–T pulses.

At the later stage of the D–T phase, ITER will operate with long pulse length and short repetition time, which will enable important types of tests, such as tritium management, to be performed. This last TBM, featuring all the functionalities of a DEMO blanket (TBM-In), could also be installed in the following 10-year operation to verify low-dose neutron irradiation effects and preliminary design reliability. A typical TBM test plan is recalled in Fig. 2 in relation with the various ITER phases.

4.3. Proposed Test Blanket Modules since the initial phase

Starting from the different envisaged DEMO concepts, the Parties have made several proposals of TBMs designs for installation in ITER since day 1 [5–10].

Within the HCCB blanket family, China, EU, Japan, and RF have made four independent TBM design proposals, while US and Korea propose to test sub-modules integrated to one of them. All TBMs use ceramic breeder under pebble-bed form, FMS structures and He coolant at 8 MPa with inlet temperature

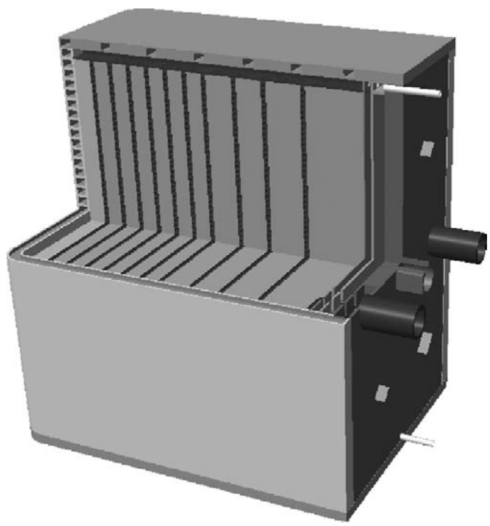

Fig. 3. View of the China HCCB TBM (1/4 port size).

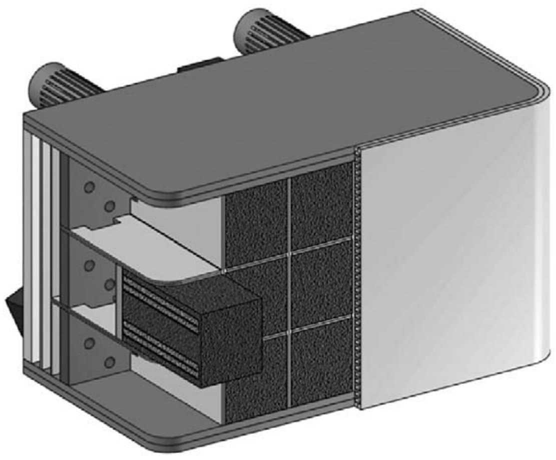

Fig. 4. View of the EU HCCB TBM (1/2 port size).

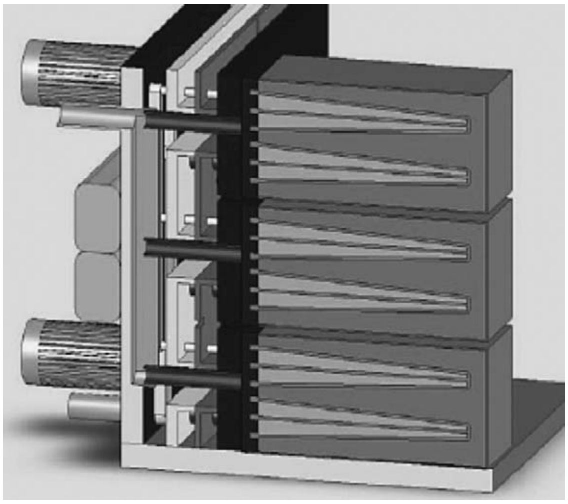

Fig. 5. View of the US HCCB breeder unit cells to be installed in another Party TBM.

of 300 °C and outlet up to 500 °C depending on operating conditions.

The China design (Fig. 3) is a single box, 1/4 port size, and uses Be and Li_4SiO_4 pebble-beds [7]. The EU design (Fig. 4) is a single box locating 18 unit breeder cells, 1/2 port size (horizontal), uses Li_4SiO_4 or Li_2TiO_3 and Be pebble beds [5]. Contribution from US [6] could be either to test a 1/4 port-size sub-module or to test 3 unit breeder cells inserted in the EU TBM (Fig. 5). The Japan design (Fig. 6) has a three sub-module structure with total 1/2 port size (horizontal), uses Li_2TiO_3 and Be pebble beds [10]. The RF design (Fig. 7) has a 2 sub-module structure with total 1/2 port size (vertical), uses Li_4SiO_4 pebble beds and porous Be-blocks [8]. Contribution from Korea [9] will be to test sub-modules, integrated in existing TBMs, using Li_4SiO_4 and Be pebble beds and, in the rear part of the blanket, graphite pebble bed acting as neutron reflector allowing therefore to reduce the required amount of Be.

For all HCCB TBMs, the He-coolant system has to be located in the TCWS vault, therefore each TBM

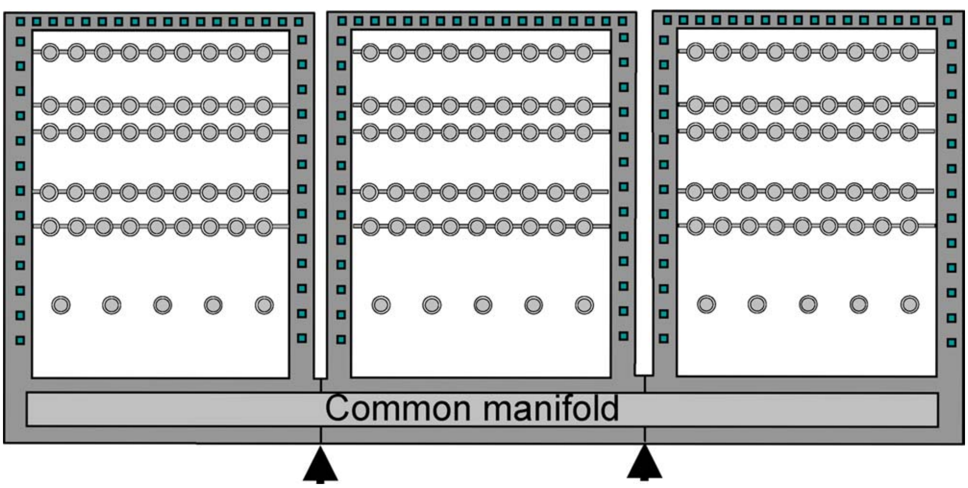

Fig. 6. Horizontal cross-section of the Japan HCCB TBM (1/2 port size).

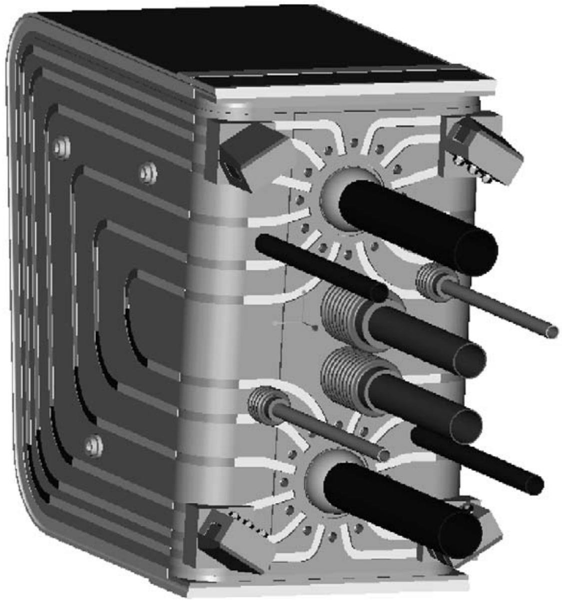

Fig. 7. View of the RF HCCB TBM (1/2 port size).

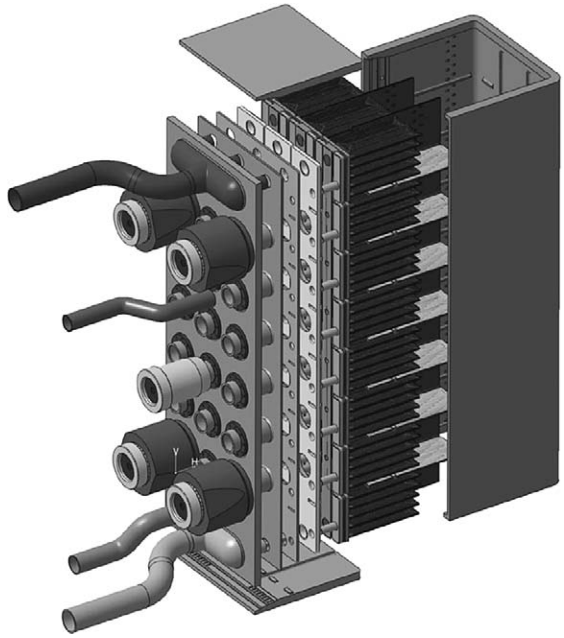

Fig. 8. Exploded view of the EU HCLL TBM (1/2 port size).

requires the connection of one coolant line (one inlet and one outlet pipes) between port cell and vault. Purge gas system components are located in the port cell, while recovered tritium is sent toward the ITER tritium plant in the tritium building.

Within the LL blankets family, there are three TBM proposals, all consisting in a single box, 1/2 port size (vertical), and use He at 8 MPa with T_{in} = 300 °C and T_{out} up to 500 °C. The EU design (Fig. 8) uses only He as coolant [5] while the US design (Fig. 9) uses He-coolant for the structures and PbLi as breeder-zone coolant with T_{in} of 460 °C and T_{out} up to 700 °C [6]. The China design (Fig. 10) has initially a single coolant (He) but can evolve to dual-coolant operations (DFLL, dual functional lithium–lead) [7]. HCLL TBM requires one He-coolant line connection with the TCWS vault. PbLi circuit components are located in the port cell, the recovered tritium is sent to the ITER tritium system. The DCLL TBM requires one additional He-line connection with the TCWS vault corresponding to the He secondary circuit of the PbLi primary coolant (heat exchanger located in the port cell).

For the WCCB blanket family a TBM design is proposed by Japan [10]. It has a two sub-module FMS structure with total 1/2 port size (vertical), and uses water coolant at PWR conditions and Be and Li_2TiO_3 pebble beds (Fig. 11). The WCCB TBM requires one water line connection to the TCWS vault, the tritium system being the same of HCCB TBM.

Within the Li-blanket family, RF has made a proposal of a SCLi TBM (Fig. 12). It is a single V-alloy

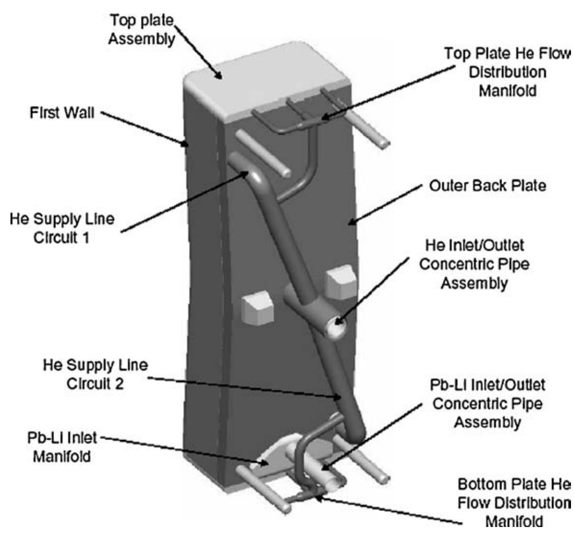

Fig. 9. View of the US DCLL TBM (1/2 port size).

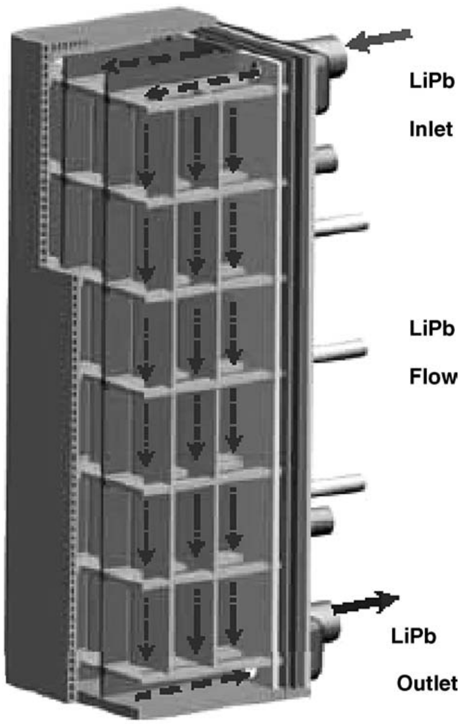

Fig. 10. View of the China DFLL TBM (1/2 port size).

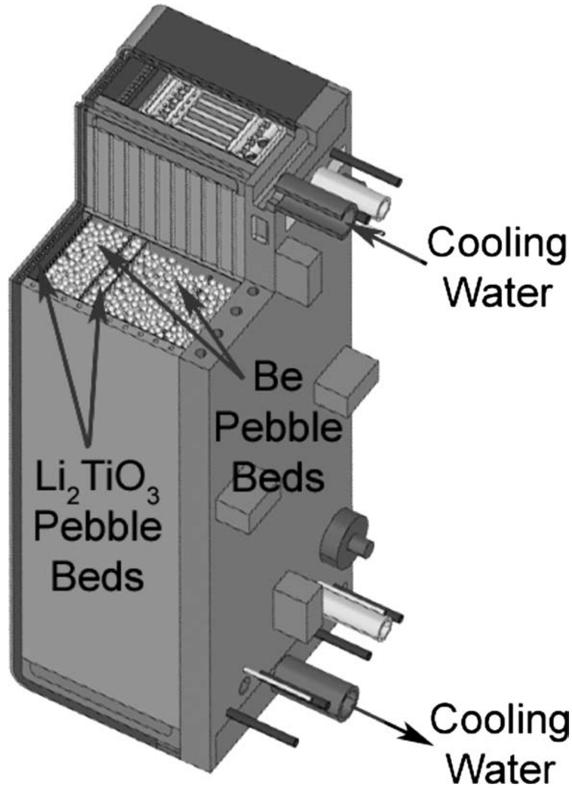

Fig. 11. View of the Japan WCCB TBM (1/2 port size).

box, 1/2 port size (vertical), it uses porous Be as n-multiplier and the Li coolant at T_{in} = 250–350 °C and T_{out} up to 550 °C [8]. Korea proposes to install a HCLi TBM (Fig. 13) using FMS structures and graphite neutron reflector. He-coolant has the same characteristics as in the other He-systems. For these TBMs, all Li systems are located in the VV port extension.

The initial TBMs for the H–H phase do not need to include all technology features required for the following TBMs (e.g., the quality of ceramic pebbles does not need to be optimized). However, because it has to be used for safety validation, the main structural and functional features have to be already present. It has to be stressed that for all proposed TBMs significant R&D has yet to be performed in order to ensure their installation on ITER day-1.

4.4. Additional proposals for later phases

Besides the TBMs already present since day 1, additional TBMs are proposed for testing in the ITER D–T phase.

First of all, US and Korea have proposed to install independent HCCB TBMs [6,9], whose design will be based on the results obtained on the sub-modules tested in the H–H phase.

An alternative liquid breeder concept is also proposed by Japan, in collaboration with US, based on the use of molten salts [10] and on the design of the DCLL (DCMS blanket). Moreover, TBMs using SiC/SiC structures could be envisaged at a later stage [10].

5. Definition of a coordinated TBMs test plan in ITER

At present, since the initial H–H phase, the port space required by the various TBM proposals is much larger than the space available in the three ITER ports devoted to TBM testing. Moreover, the situation becomes worst when looking at the available space in

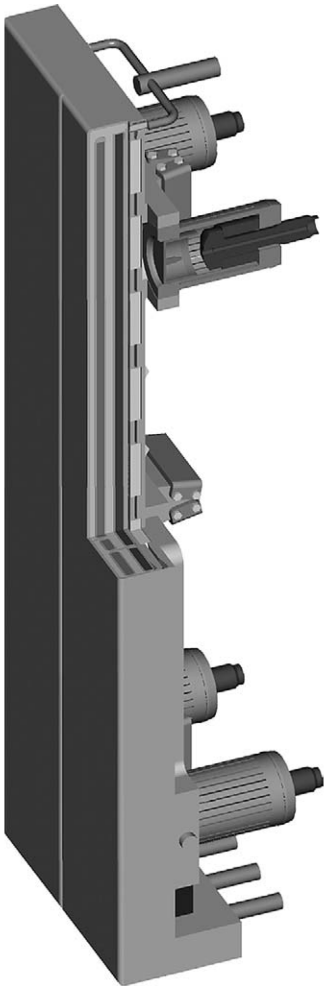

Fig. 12. View of the RF SCLi TBM (1/2 port size).

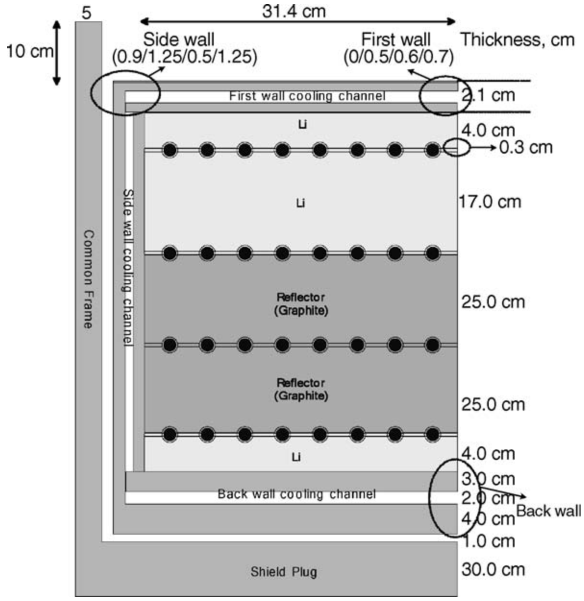

Fig. 13. Horizontal cross-section of the Korea HCLi TBM (1/2 port size).

the corresponding port cells and in the TCWS vault where most of the TBM systems will be located. A strong cooperation and coordination effort among the Parties is therefore essential for optimizing the available space without reducing the TBM test objectives.

In fact, it would be desirable to select the final TBMs installation plan when all essential R&D results will be known, probably in some years from now. At the same time, it is necessary to have all information required for integration of the TBMs systems in the design of the ITER machine and buildings, and this since the ITER components procurement phase that will occur immediately after the decision on ITER construction [11].

5.1. Proposed approach and port allocation

In order to allow the required flexibility without impact on ITER construction phase, it is necessary to fix, for each port, the number and the dimension of the connection lines crossing the vertical shaft between port cells and TCWS vault, and other ITER buildings. A limited space is available in the vertical shaft, therefore the number of connecting lines has to be minimized.

Taking into account the various proposals, it appears that most TBM need He-coolant lines. After optimization on the use of the available space, the TBWG has decided to have two He-lines for port no. 16, one water line and two He-lines for port no. 18, and three He-lines for port no. 2 [11]. Pipes characteristics have been standardized (same diameter, operating pressure, and material). Other services lines are also required. The details of all connecting lines for each port are given in Table 1.

5.2. Arrangement of the TBM systems

For each TBM, the associated systems include the primary coolant circuits and components (two circuits for dual-coolant TBMs), the secondary coolant circuits

Table 1
Number and type of connection lines in each port (one line = one inlet pipe + one outlet pipe)

System type	Test port no. 16	Test port no. 18	Test port no. 2
He-coolant	Two lines	Two lines	Three lines
H_2O-coolant	–	One line	–
ITER heat rejection system	Available	Available	Available
He purge gas	Four lines	Four lines	Four lines
ITER component cooling system	One line	One line	One line

and components, the tritium management components (including He purge-gas loop for solid breeder TBMs and liquid breeder loop for the others), the instrumentation packaging and control system, safety-relevant detection systems and valves.

In order to maximize measurements efficiency, it is extremely important to have tritium-related measurements as close as possible to the TBM, therefore all T-relevant components will be located in the port cell. In particular, tritium extraction, either from He or liquid breeders, is performed in the port cell and the extracted tritium is then directed toward the ITER tritium system located in the tritium building.

Assuming two TBMs present in each port, the remaining space available in the port cell is mostly used for piping and is not sufficient for hosting the heat extraction components from He-cooled TBMs, which will then be located in the TCWS vault. On the contrary, because of their relatively limited dimension, it is possible to locate in port cell the liquid breeder heat exchangers.

As shown in Section 2, the space available in the TCWS vault is common to all the TBMs installed in the three ports and it is relatively small. It appears that it may not be possible to locate there six independent heat extraction systems, therefore, depending on the final selection of the type of TBMs tested simultaneously, a share of some components may be required.

5.3. TBM acceptance tests

Test modules must neither interfere with ITER operational plans nor jeopardize the machine availability. TBMs reliability is therefore of extreme importance, and therefore complete functional tests of TBMs should be successfully performed prior to installation in ITER. The ITER quality assurance and quality control program should be applied to TBMs systems in all stages of the engineering design, fabrication, and testing.

Final acceptance tests for TBMs and associated circuits components will be done at the ITER site after transportation, and will include pressure tests and leak tightness tests.

5.4. Conclusions on TBMs test plan

At present, the ITER Parties have proposed several independent DEMO-relevant TBMs that cannot all be tested simultaneously on day-1. Space limitation is not only due to the space available in the test ports but also to the limited space available in the port cells, in the vertical shafts, and in the TCWS vault. The situation will become even more difficult during the D–T phase because additional TBMs are proposed.

However, although at different levels, all proposed TBMs need further specific R&D before proving their acceptability for installation in ITER at the beginning of the H–H operation. It can be expected that not all the present proposals will be finalized and, therefore, it is important to have some flexibility on the final choice of the TBMs concepts to be installed in each port. On the other hand, to allow TBM systems integration in ITER, it is essential to know the number and the type of pipe connections required at each port. TBWG has therefore fixed this item that becomes a constraint for future decision on TBMs test planning.

In order to facilitate the final selection and to define a fully coordinated test program, a strong collaboration between Parties is required. This collaboration should be stronger than in the past and should aim not only to agree on space sharing or time sharing for testing, but also to promote technical convergence to similar TBM design, and even whenever possible, to common TBMs to tests.

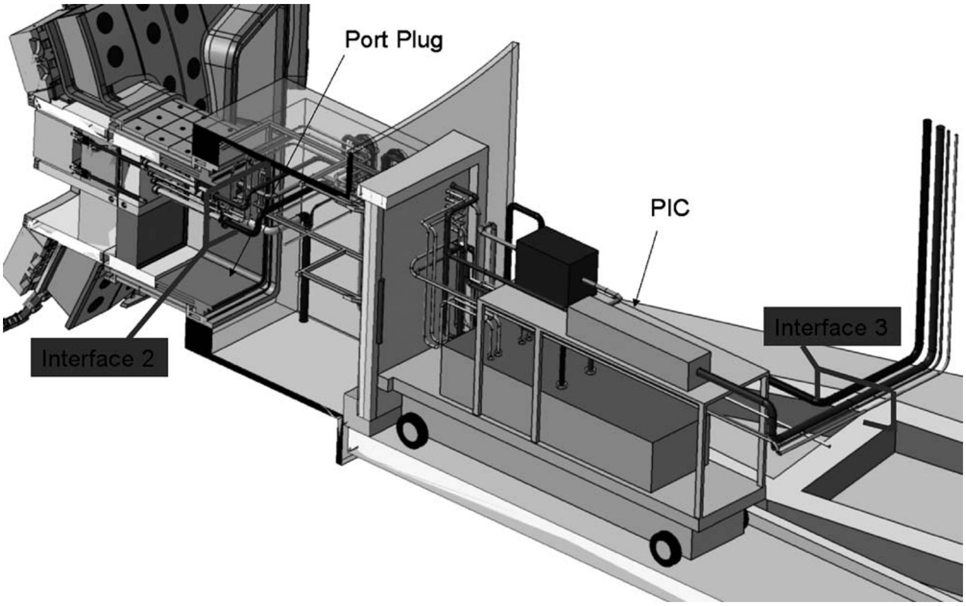

Fig. 14. View of a possible port cell arrangement for one TBM (EU HCCB TBM).

6. Remote handling, maintenance, and safety considerations

The general assumed rule is that the testing of TBMs must not spoil ITER operational safety. The present strategy is to consider that all accidental sequences that could involve TBMs remain within the envelope cases assessed for ITER.

Each TBM system has to be checked against specific accidental sequences, in particular in case of LOCA inside the VV (in-vessel loss-of-coolant accident), inside the TBM (in-box LOCA) or outside the vacuum vessel (ex-vessel LOCA). Failure of a TBM system should have no impact in the overall safety of ITER in term of VV and vault pressurization, tritium and hydrogen release, and long-term temperature transient.

The safety analyses performed so far [11] do not show any major difficulties. However, as the port cells form a containment volume, some overpressure events in this region, such as the rupture of a cooling pipe, have yet to be assessed.

TBM replacement occurs in the ITER hot cell, where the whole TBMs/shield plug system is remotely transported in a standard ITER transport cask. Because of the large number of TBM system components present in the port cell, parking spaces need to be added in order to allow RH operation with the transport cask. A view of a possible port cell volume occupation is shown in Fig. 14.

Either the addition of a hot cell port or the modification of the TBM replacement procedure might be required if the simultaneous replacement of the three test-port plugs has to be possible during a ITER planned shut down (1 month/year). The ITER hot cell may be used to replace irradiated TBMs, but it is not designed to allow TBM repair and/or post-irradiation examinations. Current ITER hot cell scheme considers the irradiated TBMs as a waste object. The presence of hot cell facilities on the site selected for construction has also to be taken into account and should help to solve this issue. Storage needs shall also be re-evaluated.

7. Conclusions, recommendations, and further work

After successful ITER operations, breeding blankets development will become one of the most challenging issues that will remain to be addressed for designing and constructing a DEMO reactor.

The tests of DEMO-relevant TBMs in ITER will give essential information to accomplish such a development, although a part of the required R&D results will have to be obtained in other facilities, namely the high dose irradiation effects on blanket materials, materials interactions, and synergistic effects.

The work of the TBWG has shown that for all TBMs significant R&D is still required and that it is technically premature to select now the best performing candidates. It is therefore recommended to focus the blanket R&D programs on TBMs R&D, and to focus the design effort on the TBM engineering designs, and on their integration on the ITER machine and buildings.

Besides the need of checking TBM compatibility with ITER operations, TBM testing in the initial H–H phase is essential both to demonstrate structural integrity and safety-related performances of TBMs before starting the D–T operations and to validate remote operations on the on the TBM systems.

The preliminary TBM integration work in ITER has shown that blanket testing in ITER will be very complex and very lengthy. It is therefore required to make most of the performance tests, if feasible, in dedicated out-of-pile facilities prior to the installation in ITER.

Present TBM designs are dictated by testing objectives and are performed to assess the TBM behavior under ITER operating conditions. However, to recover the required data, the development of appropriate instrumentation and data acquisition systems is necessary with high priority.

Finally, in order to maximize the information obtained by TBM testing in ITER, it is essential to develop and improve the corresponding DEMO blanket designs in order to have a coherent basis of comparison and interpretation for the obtained TBM results, and to have the possibility to evaluate the impact on the DEMO blanket designs of the observed TBM performances. The difficulty of the task suggests to optimize the design of the DEMO reactor plant with respect to the need of the breeding blankets performances.

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