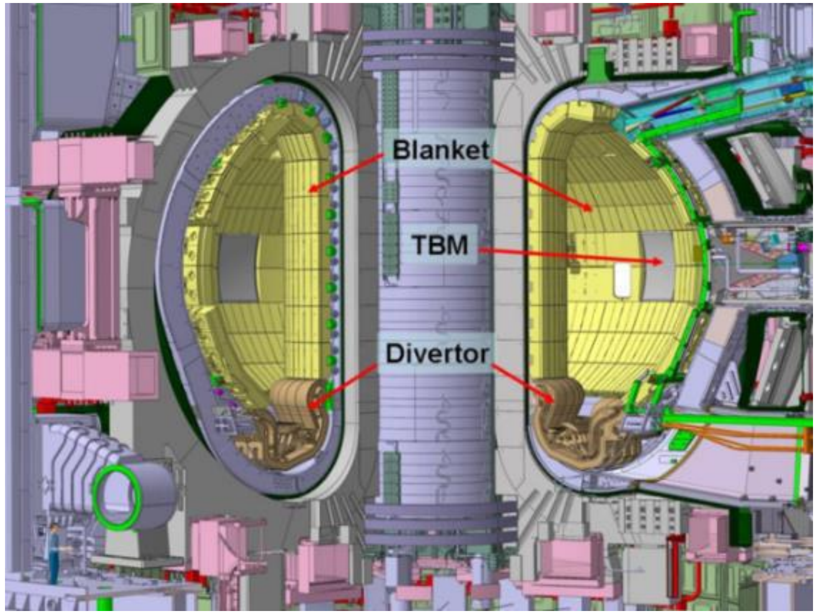

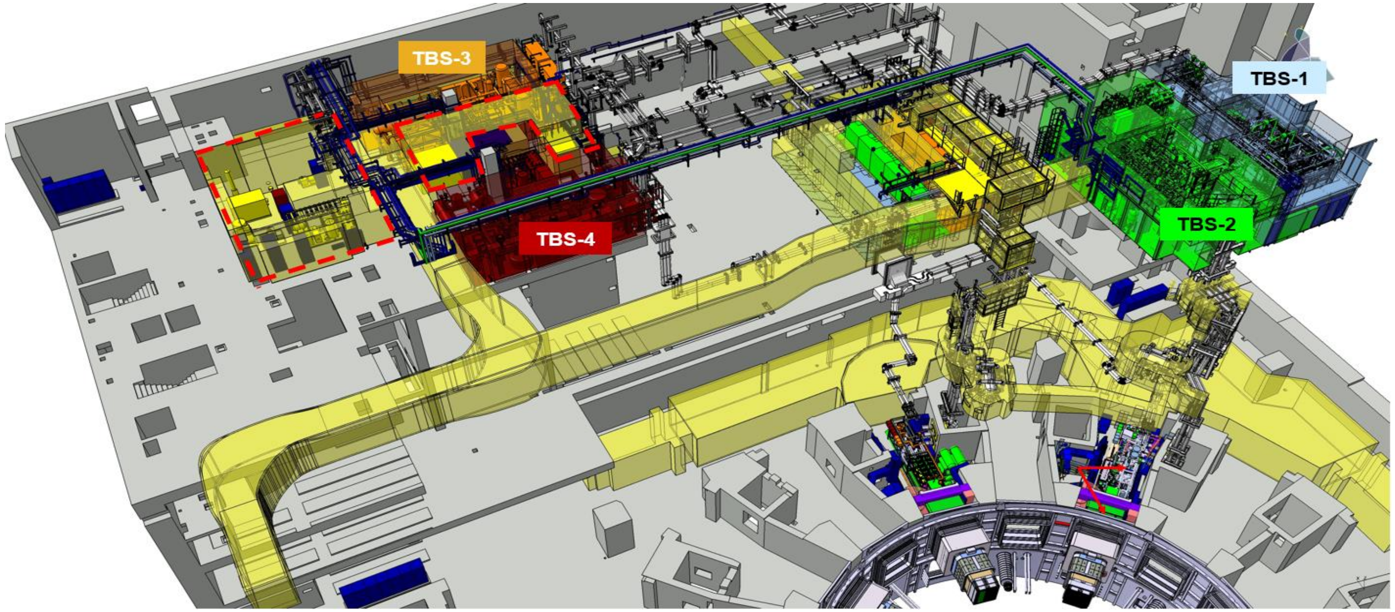

Technical Meeting on Tritium Breeding Blankets and Associated Neutronics
IAEA Headquarters, Vienna, Austria, 2-5 September 2025

The ITER TBM Program: a Pathway towards Tritium Breeding Blankets for D-T Power Reactors

Luciano Giancarli and the ITER TBM Project Team
TBM Project Team Leader, ITER Organization

➢ *Acknowledged contributions/pictures from the TBM Project Team, including ITER Members Laboratories*

Disclaimer
The views and opinions expressed herein do not necessarily reflect those of the ITER Organization

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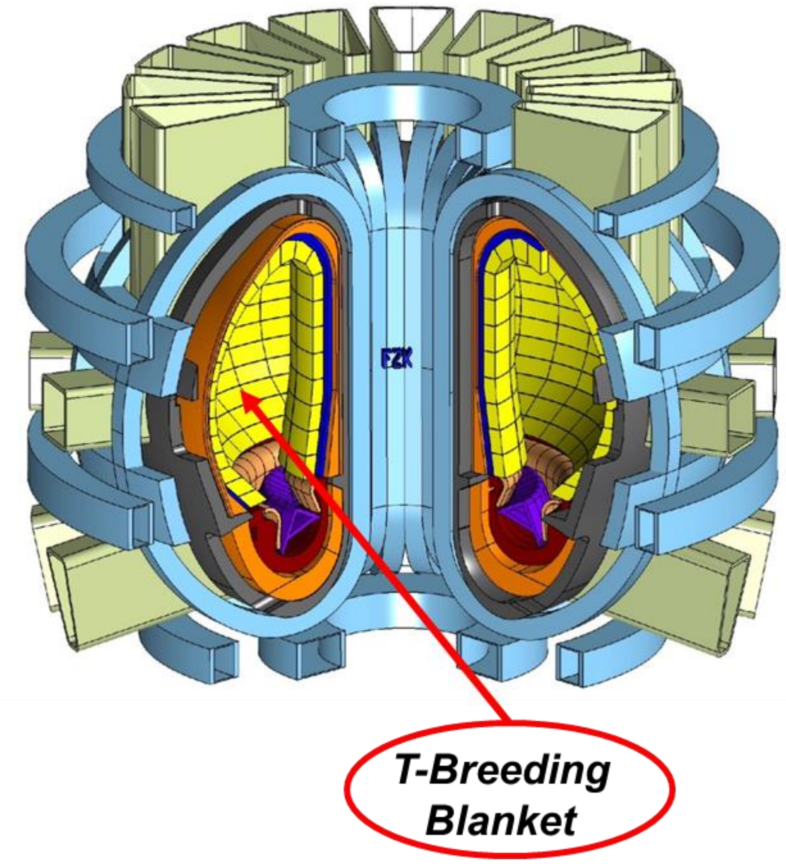
What is the ITER TBM Program ?

- A Fusion Power reactor needs to produce by itself all the Tritium that is needed as fuel for the D-T plasma (Tritium-breeding self-sufficiency) while ITER is using external Tritium source.

- To support this need, one of the ITER missions is the following (cf. Project Specifications):
  "***ITER should test tritium breeding module concepts that would lead in a future reactor to tritium self-sufficiency, the extraction of high-grade heat and electricity production.***"

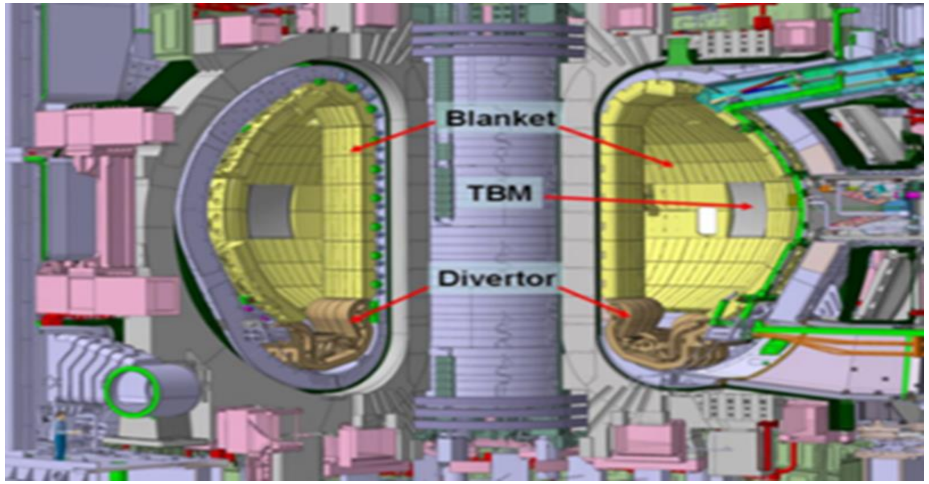


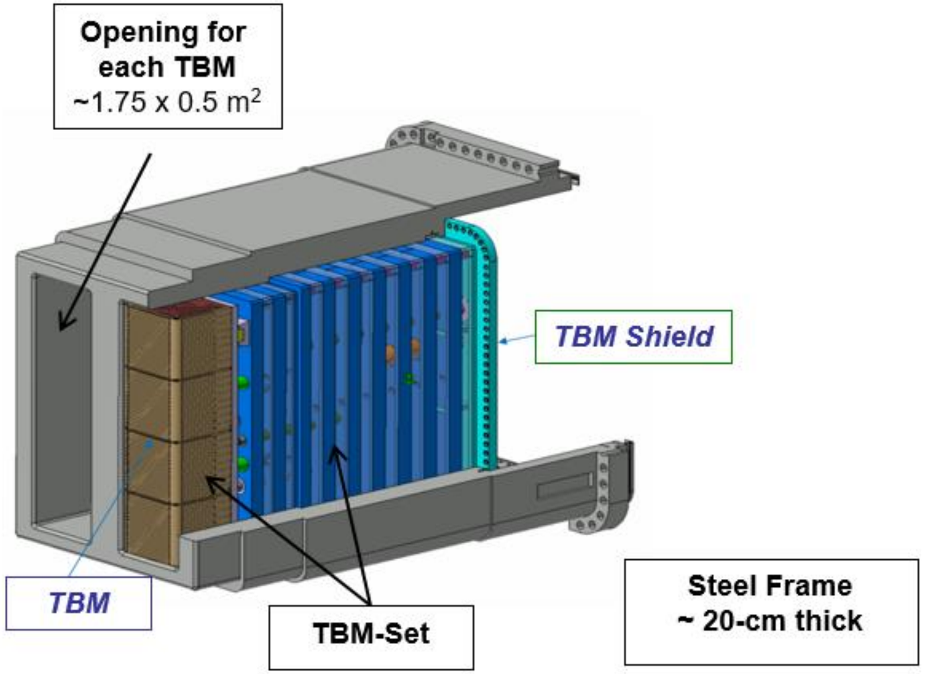
All the ITER Organization (IO) design and R&D activities related to this mission, both in IO Central Team and in the seven IO Domestic Agencies, form the so-called ITER TBM Program.

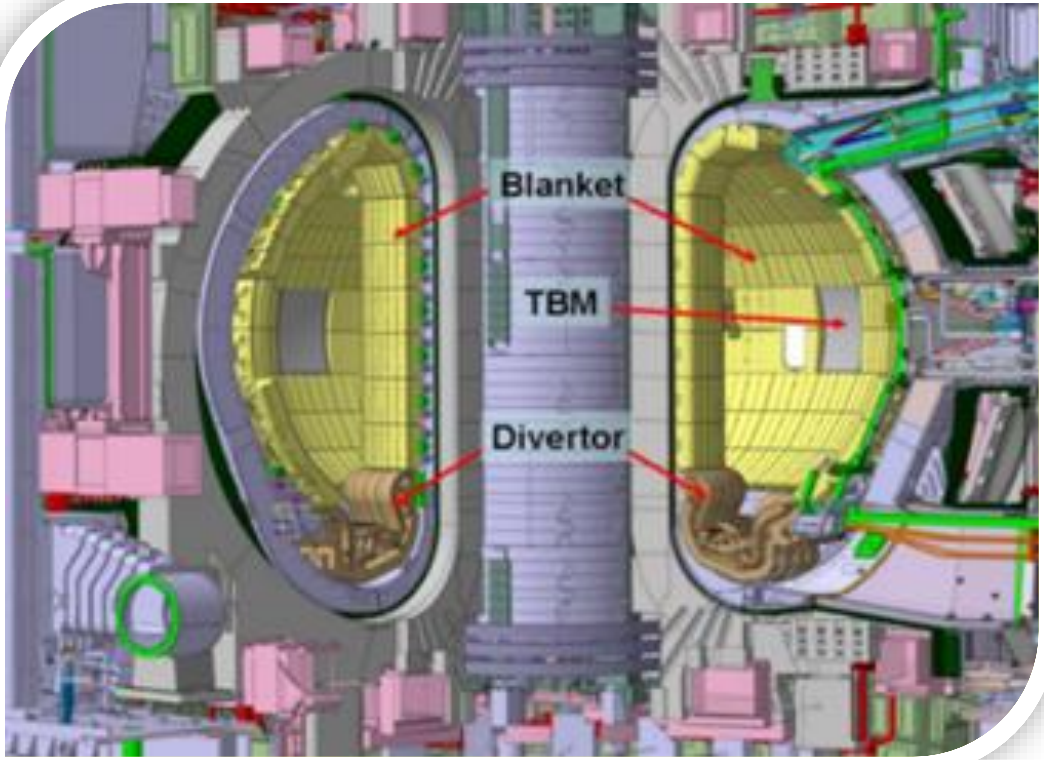
- The TBM Program is therefore a specific research activity run in ITER as part of the ITER Research Plan

Boundary Conditions in ITER for TBMs tests

- The "ITER TBM Program" foresees the installation of four Test Blanket Systems (TBSs) whose TBMs are located in the **2 ITER equatorial ports #16 and #18** (2 TBMs per port) inside the Vacuum Vessel.
- The TBMs are installed in a water-cooled steel frame (together with the associated shield).
- Each TBS is formed by a TBM and the associated ancillary systems (e.g., coolant, coolant purification, Tritium extraction, Tritium accountancy, Instrumentation & Control, maintenance tools and equipment) located in the Tokamak Complex. It is a complete mock of a whole DEMO Tritium Breeding Blanket Systems.
- It means that ITER is planning to simultaneously operate four independent Test Blanket Systems.







Main Characteristics of the Test Blanket Systems installed and operated in ITER for the TBS Initial Configuration (DT-1)

Port Allocation for the four Test Blanket Systems of the Initial Configuration (InCo) (DT-1)

Port Nº	First TBS	Second TBS
16 (F)	TBS-1: *Water-Cooled Lithium-Lead (EU)* ➔ *Eutectic: Li as breeder, Pb as n-multiplier* ➔ *Water at 15.5 MPa, 295-328ºC*	TBS-2: *Helium-Cooled Ceramic Pebble (joint KO & EU)* ➔ *Li-ceramic as breeder, Be as n-multiplier* ➔ *Helium at 8.0 MPa, 300-500ºC*
18 (S)	TBS-3: *Water-Cooled Ceramic Breeder (JA)* ➔ *Li-ceramic as breeder, Be as n-multiplier* ➔ *Water at 15.5 MPa, 280-325ºC*	TBS-4: *Helium-Cooled Ceramic Breeder (CN)* ➔ *Li-ceramic as breeder, Be as n-multiplier* ➔ *Helium at 8.0 MPa, 300-500ºC*

Note #1: The structures of the all the TBMs are made of Reduced Activation Ferritic /Martensitic (RAFM) steels, essential for reducing/eliminating long-lived radwaste (>100 years). They are ferromagnetic materials.

Note #2: Test Blanket Systems are designed & procured by the ITER Members that retain the TBSs ownership. IN, RF & US contributes to the TBM Program by performing supporting R&D.

Duration of the TBS operations

- The TBSs forming the Initial Configuration will be operated for several campaigns (DT-1) starting at FPO-1 until FPO-5 (~10y). The testing strategy is to test different TBM versions over DT-1, which implies several TBM replacements.
- **During DT-2** different TBSs (including those proposed by different ITER Members) could be installed and operated for some further campaigns.

Main Characteristics for the 4 InCo TBMs and associated Ancillary Systems

TBS-1 – **WCLL-TBM** (procured by EU)	TBS-2 – **HCCP-TBM** (jointly procured by KO/EU)
▪ Eurofer Steel (structure), **Pb16Li** (multiplier/breeder). ▪ Coolant: **H_2O at 15.5 MPa, 295 /328°C**. ▪ T-removal gas (from Pb16Li): He + 0.1% H_2 at 0.4 MPa. ▪ Maximum Tritium production (back-to-back pulses): 15-25 mg/day	▪ RAFM Steel (structure), Be pebbles (multiplier); **Li_4SiO_4 or Li_2TiO_3** pebbles (breeder). ▪ Coolant: **He at 8 MPa, 300/500°C**. ▪ Purge gas: Helium + 0.1% H_2 at 0.3 MPa. ▪ Maximum Tritium production (back-to-back pulses): 15-25 mg/day
TBS-3 – **WCCB-TBM** (procured by JA)	TBS-4 – **HCCB-TBM** (procured by CN)
▪ F82H Steel (struct.), Be pebbles (mult.), **Li_2TiO_3** pebbles (breeder). ▪ Coolant: **H_2O at 15.5 MPa, 280 /325°C**; ▪ Purge gas: He + 0.1% H_2 at 0.1 MPa. ▪ Maximum Tritium production (back-to-back pulses): 15-25 mg/day	▪ CLF-1 or CLAM RAFM Steel (structure), Be-pebbles (multiplier), **Li_4SiO_4** pebbles (breeder). ▪ Coolant: **He at 8 MPa, 300/500°C**. ▪ Purge gas: He + 0.1% H_2 at 0.3 MPa. ▪ Maximum Tritium production (back-to-back pulses): 15-25 mg/day

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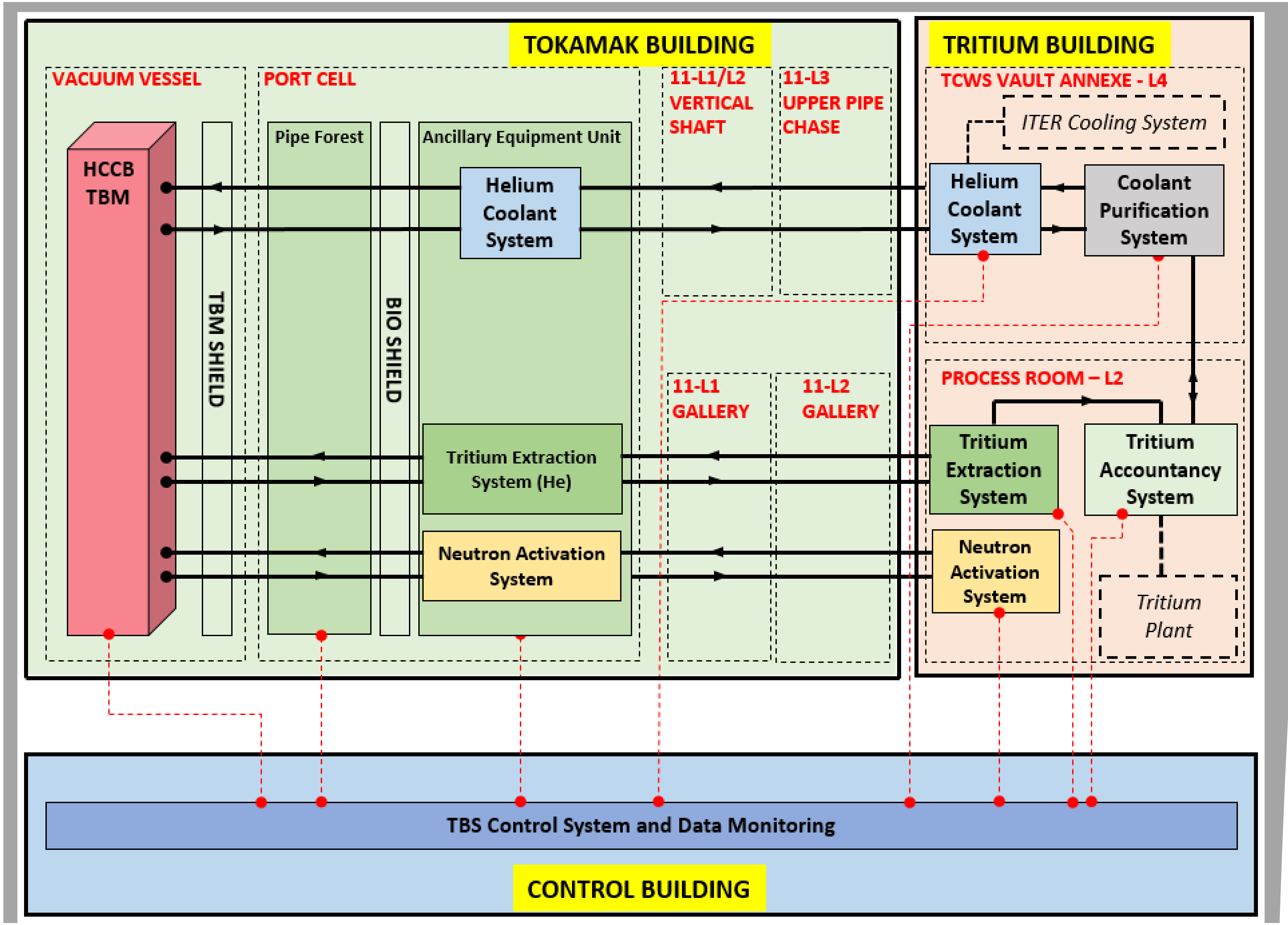
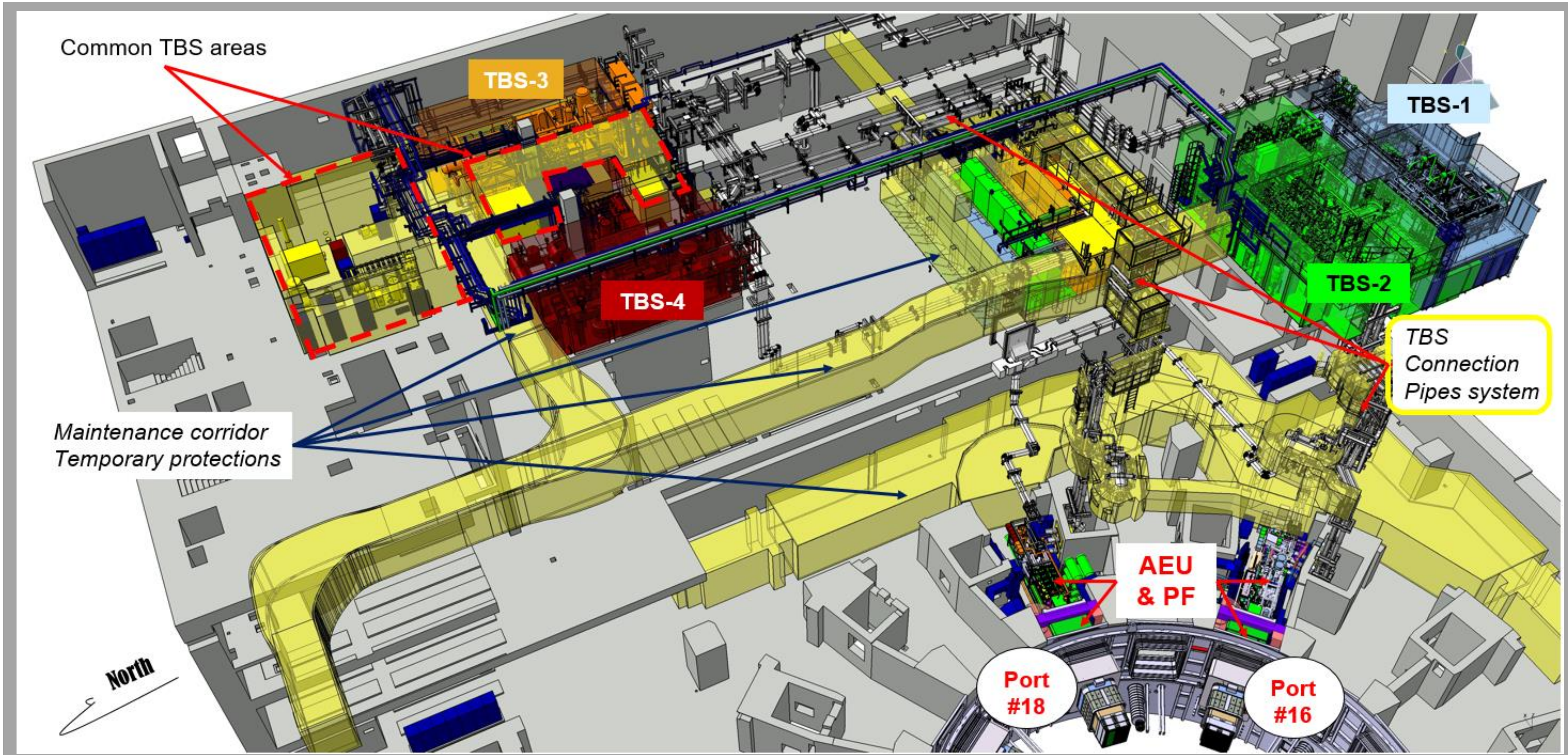


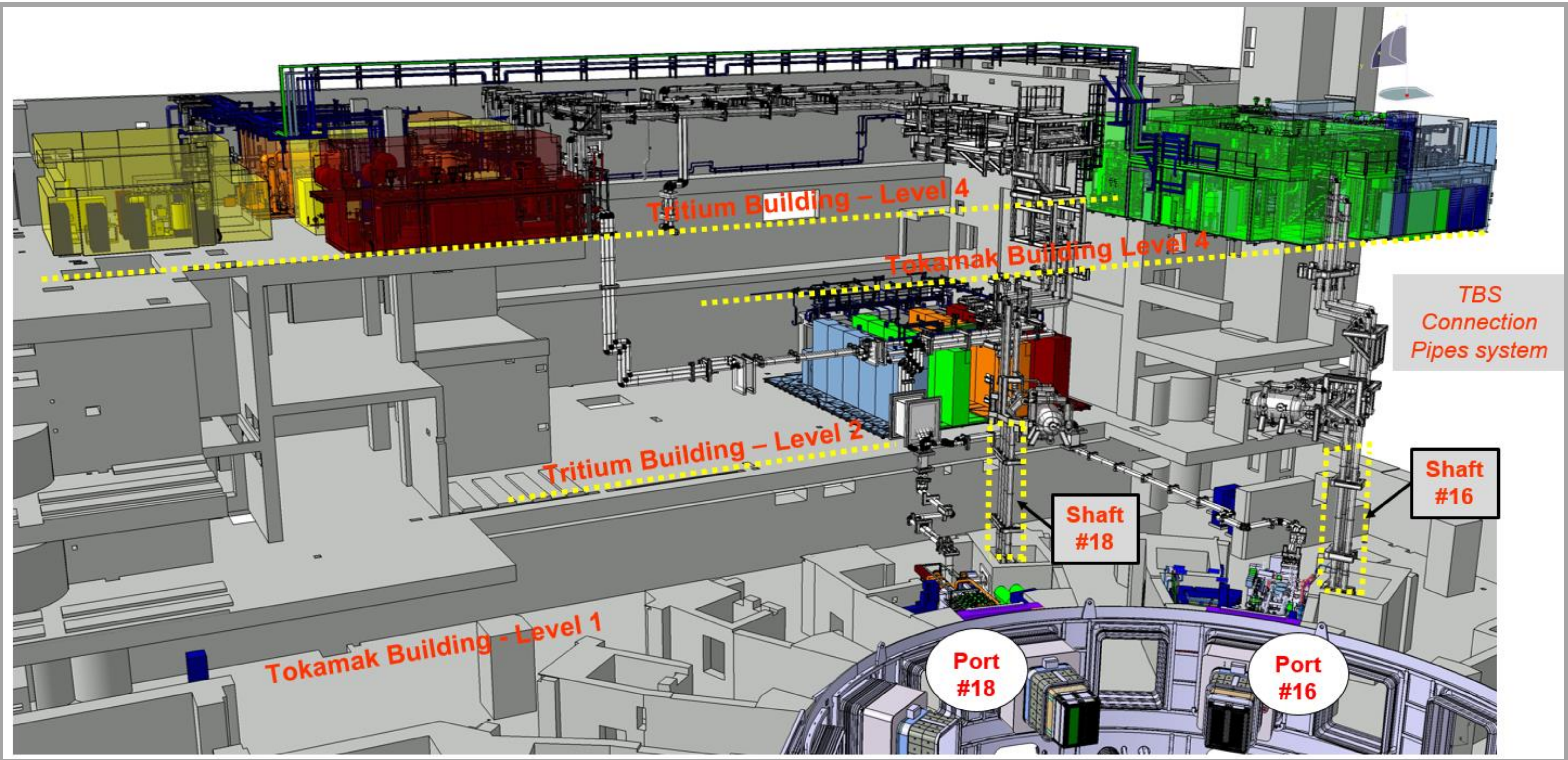
Scheme of a Helium-cooled TBS:

- ➔ Example of the HCCB-TBS
- ➔ Similar scheme for the other 3 TBSs

With indication of the main Locations in the various rooms of the ITER Tokamak Complex



3D-overview and location of the 4 Test Blanket Systems within the Tokamak Complex



Vertical View and location of the 4 Test Blanket Systems within the Tokamak Complex

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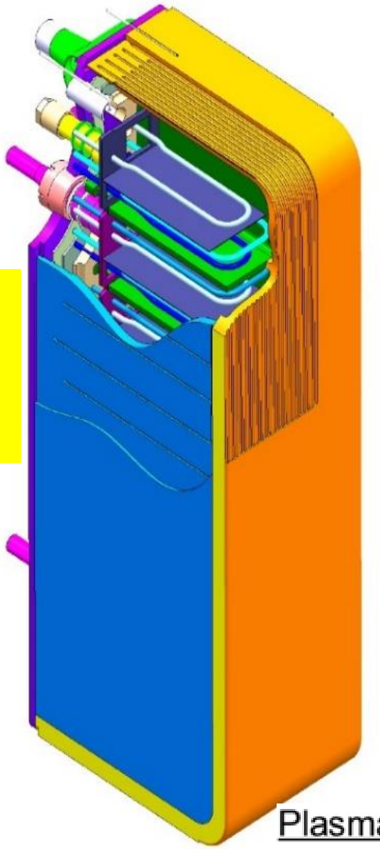
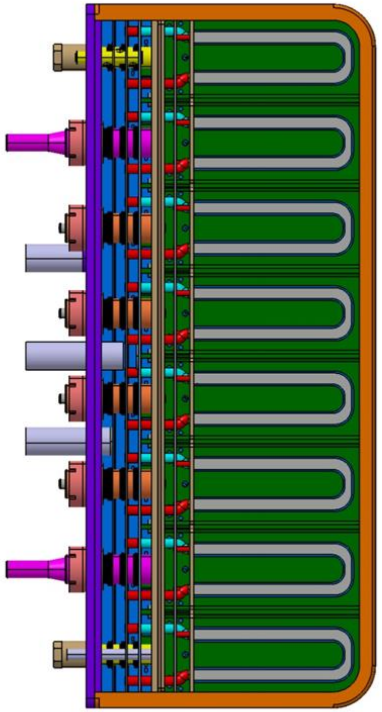
View of the internals of the four TBMs of the Initial Configuration

➔ The design (including materials) of each TBM is based on same structures and materials of the corresponding DEMO breeding blanket ➔ fully relevant mock-ups !!

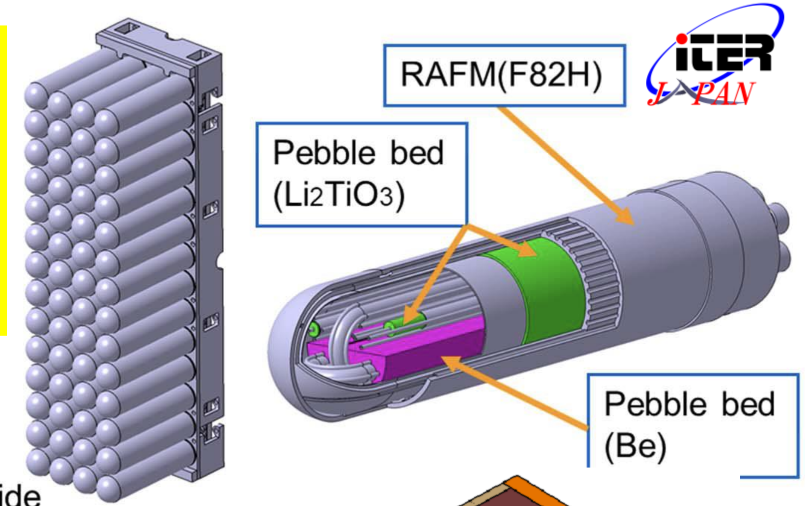
EU-WCLL
Water-cooled
Lithium-Lead



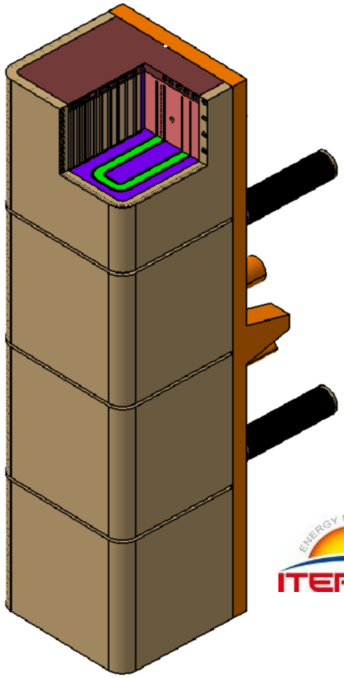
KO/EU-HCCP
Helium-cooled
Ceramic Pebble

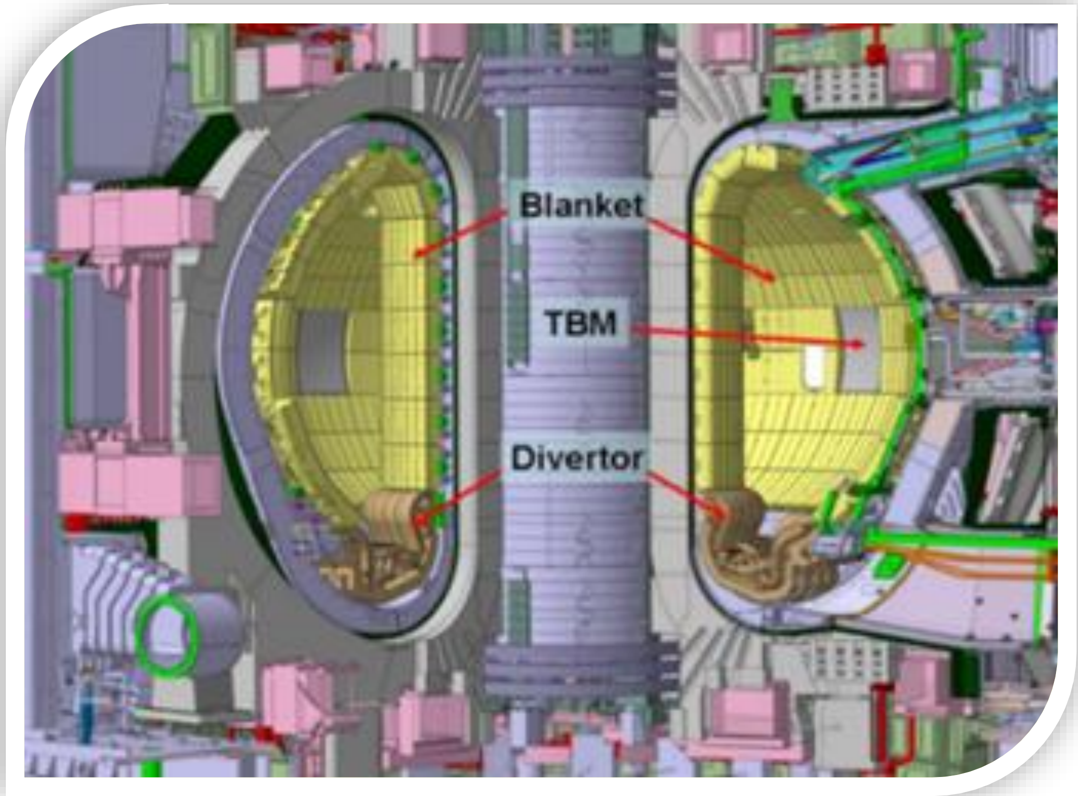


JA-WCCB
Water-cooled
Ceramic
Breeder



CN-HCCB
Helium-cooled
Ceramic Breeder

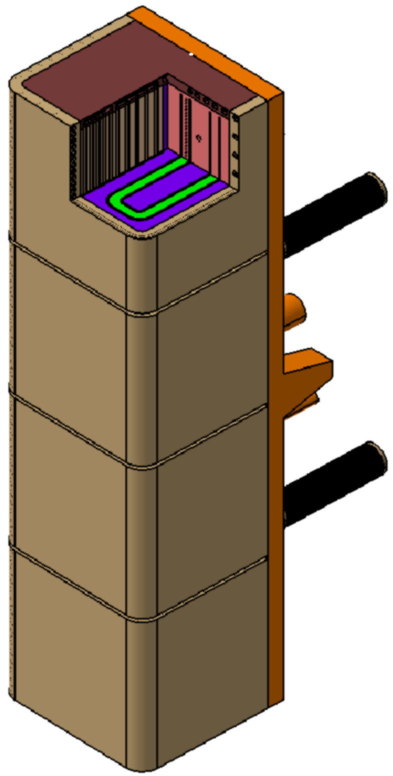




Examples of R&D Activities performed by the ITER Members during the Test Blanket Systems design & manufacturing phases and relevant for DEMO TBB development

TBMs structural materials

- ✓ **The TBMs are mock-ups** of the corresponding DEMO TBBs since they use the same structural materials: Reduced-Activation Ferritic/Martensic (RAFM) steels and relevant design architecture and manufacturing technologies.
- ✓ Therefore, **the RAFM steel manufacturing technologies** developed for TBMs have direct consequences on the choices to be made for TBBs. The potential material impurities obtained in the raw material fabrication process could increase the production of long-term radionuclides under neutron irradiation and shall be minimized.
- ✓ Each procuring ITER Member has developed a specific RAFM steel for its TBM and future TBB application: EUROFER-97 in EU, CLF-1 and CLAM in CN, F82H in JA and ARAA in KO. Their composition is relatively close to each other's.
- ✓ The manufacturing of RAFM steels products has already gained a **relevant industrial experience** (e.g., bars and plates up to 50mm-thick, few tens of tons), in particular in mastering the chemical composition (i.e., alloying elements and impurities control), the metallurgical state after heat treatment and the target tensile and impact properties.
- ✓ Typically, these products are currently delivered with an EN 10204 type 3.1 (EU), or even type 3.2 (CN) inspection **certificates**, which are required in EU for the manufacturing of (Nuclear) Pressure Equipment. It is a requirement of nuclear codes to get return on experience from several industrial batches.



R&D on Reduced Activation Ferritic/ Martensitic Steel Eurofer-97 (EU)

Manufacturing technologies using EUROFR-97

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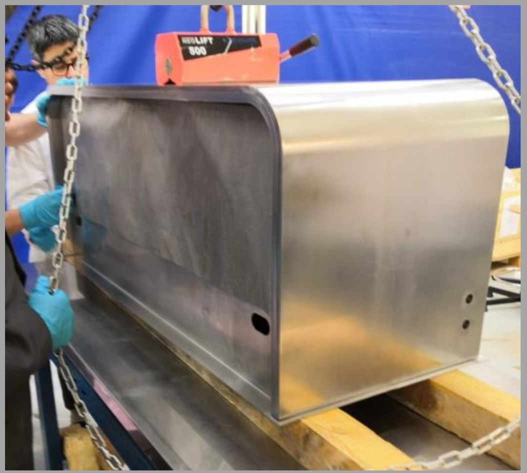

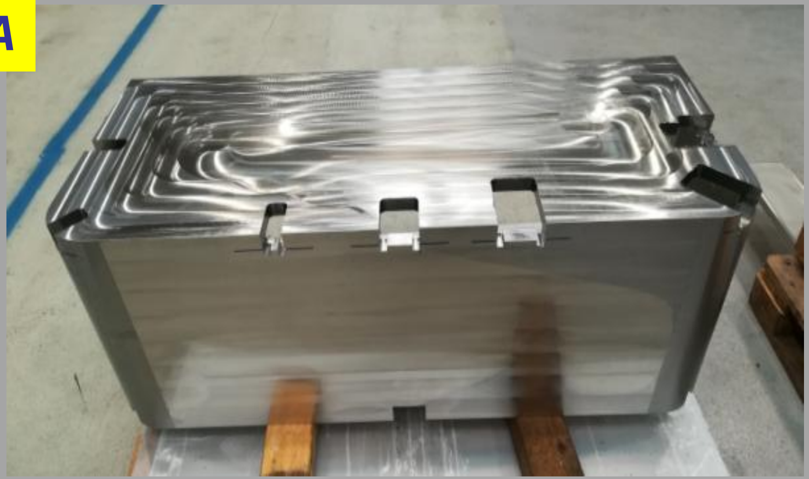

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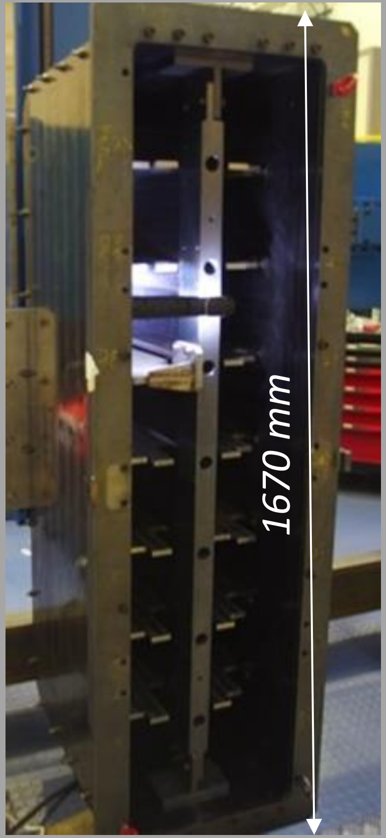

A - Welding external walls by HIPing : 2-step HIP process, NDT and DT completed

B - Welding TBM internals by robot : TIG welding robot assembling TBM mock-ups with narrow space accessibility

Each IM develops RAFM steels:
- ***AARA** by Korea*
- ***CLF-1** and **CLAM** by China*
- ***F82H** by Japan*

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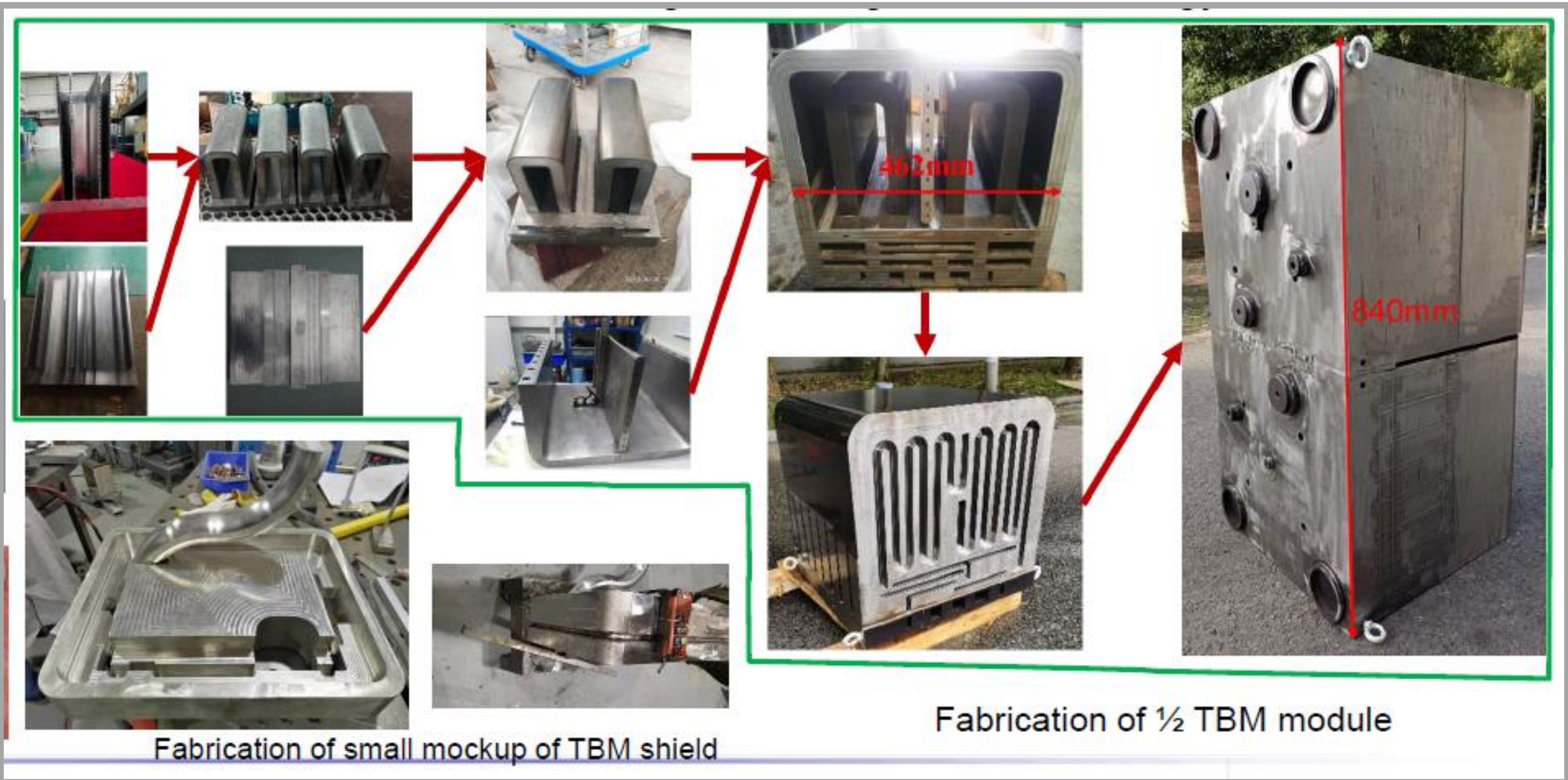
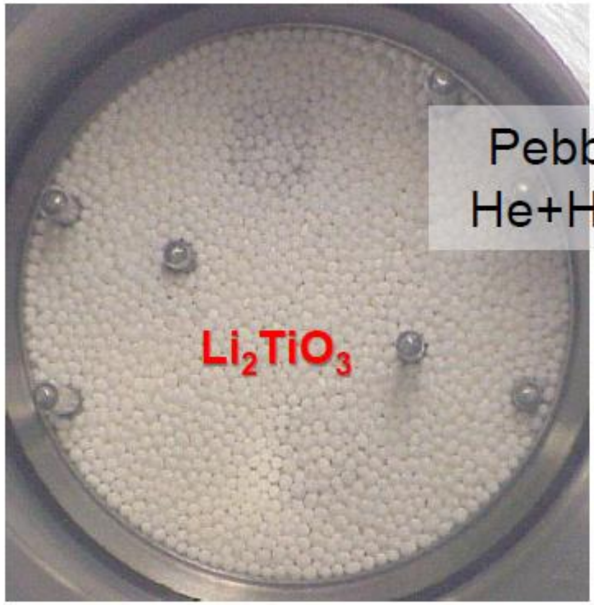


R&D on HCCB-TBM fabrication process and technology are on-going, developed and verified by making components mock -ups and semi–prototype of TBM box in CLF-1 (including NDT technology).

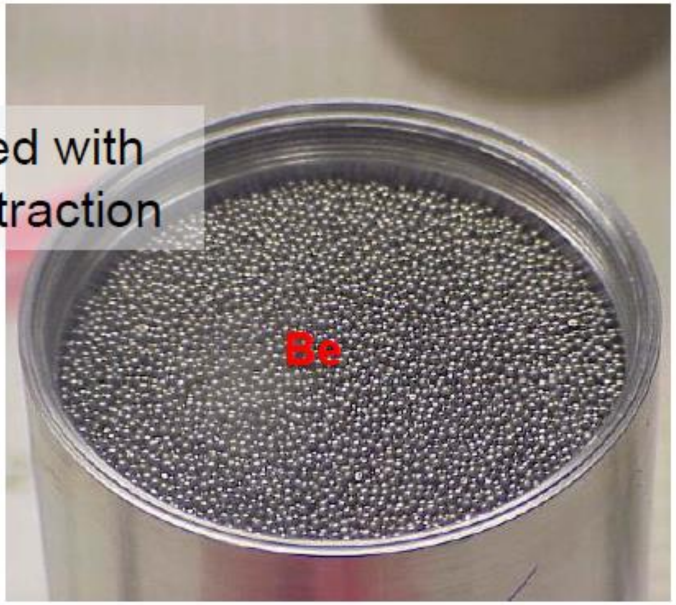
Development and industrial production of functional materials

- ✓ **Typical functional materials:** lithiated ceramics pebbles, low-impurity liquid lithium-lead (PbLi), beryllium pebble beds, beryllides.
- ✓ Manufacturing of these functional materials for TBMs open the way to develop new processes that will be directly applicable for future productions for TBBs.

- ❖ Ceramic Breeder: Ternary Lithium Oxides, based on Li_4SiO_4 and Li_2TiO_3
- ❖ T-production rate be raised by enrichment in ^6Li (typically 30–60%).
- ❖ Neutron multiplier: beryllium, beryllium alloys



Pebble-beds purged with $He+H_2$ gas for T-extraction



✓ Technology chosen for pebble production aims at low long term activation and the possibility to recycle (dissolution or remelting) of all the materials

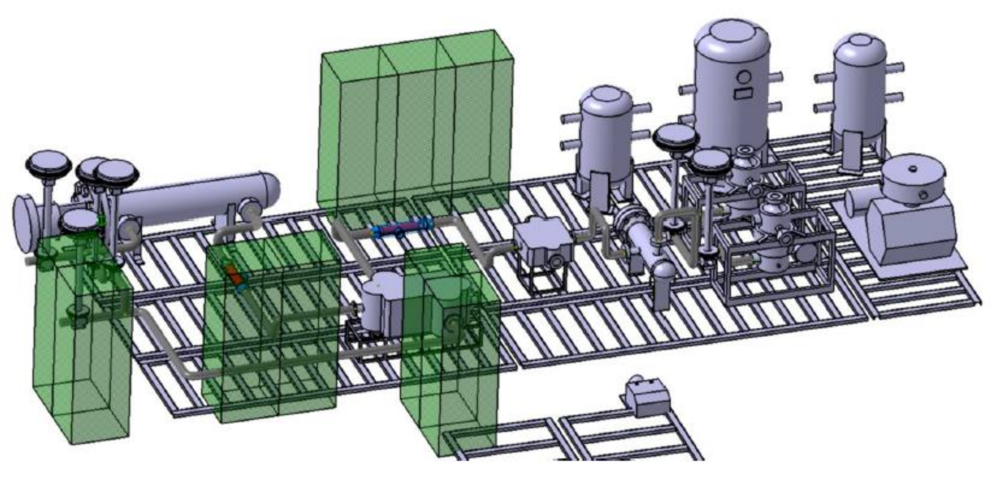
Development of specific TBS components and new technologies (coolant, tritium)

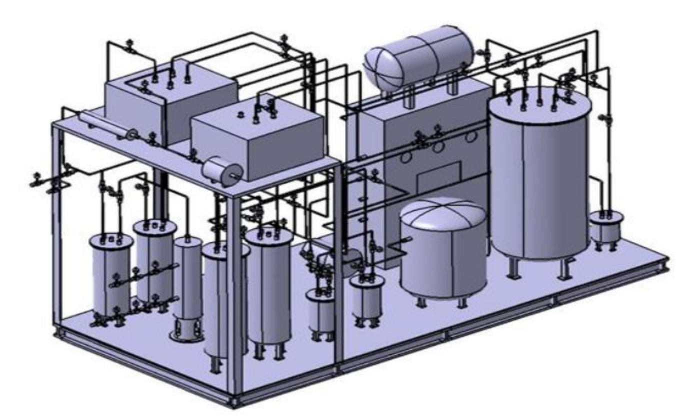
Coolant Systems components

- Most components are conventional components
- Example of Advanced PCHE (Printed Circuit type Heat Exchanger) = Compact HX with lower pressure drop (<50 kPa)

Tritium technologies

- Tritium managament is considered as one of the major issues for D-T fusion reactors since a long time. For this reason, a significant modelling efforts is made by the IMs since already several years. Examples are the development of EcoSimpro in EU, of modelling tool THETA-FR in KO, of simulation tool TriSim in China, of similar simulation tool in Japan, as well as COMSOL Multiphysics and TMAP (used by several IMs).
- For instance, EU EcoSimpro code is an advanced simulation tools able to predict the tritium migration as a function of tritium partial pressure and temperature in the various location of the TBS sub-systems with the implementation of all the knows phenomena governing these aspects, such as surface phenomena, material diffusion, impact of material defects.
- Tritium extraction, recovery and overall tritium management. Besides the tritium breeding ratio (TBR) aspects, the demonstration that tritium can be sufficiently “confined and recovered” is also of great importance for future D-T fusion reactor breeding blanket. It recalled that the amount of tritium to be produced and recovered in the DEMO TBBs is of the order of 350 g/day assuming a Fusion Power of about 2 GW. It is several orders of magnitude higher than the amount of tritium managed in present-day facilities.





Example of the Helium-coolant system for HCCB-TBS (CN)

Main characteristics of the Helium Coolant System:

- Inlet/Outlet Temperature: 300/500 °C
- Operating Pressure: 8 MPa
- Flow-rate: 1.3 kg/s
- Total He inventory: ~40kg
- Temperature of the secondary water coolant: inlet/outlet 31/42 °C

Constructed He-coolant loop prototype: HeCEL-3 (2.5kg/s@8-12MPa & 550℃) with electromagnetic bearing circulator and Printed-Circuit Heat Exchanger (PCHE)

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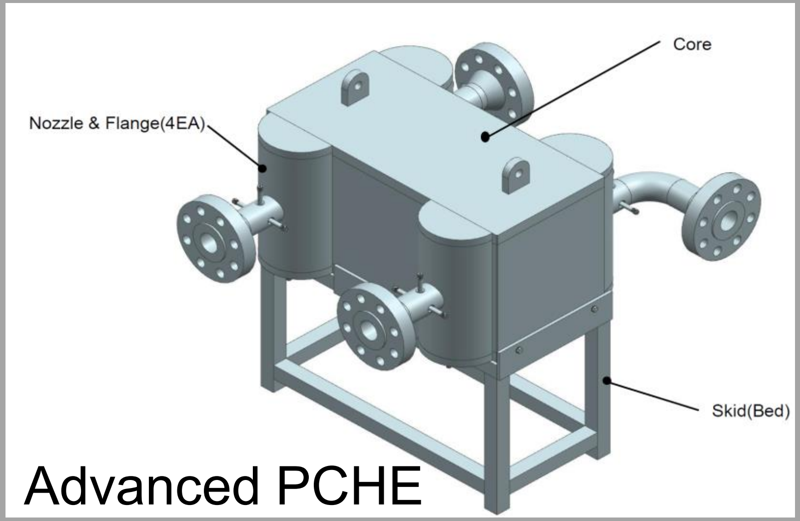
Example of the Helium-coolant system for HCCP-TBS (KO)

Helium Circulator



Advanced PCHE

Upgrade of HCS test facility named Helium Supply System (HeSS) (10 MPa, 550°C) for performance tests:

- Advanced PCHE (Printed Circuit type Heat Exchanger) = Compact HX with lower pressure drop (<50 kPa)
- Air bearing type circulator (ongoing R&D)

TRIEX-II experimental facility at ENEA-Brasimone

Operated since several years to determine the extraction efficiency of a gas liquid contactor for WCLL-TBS.

Experimental campaigns have been carried out using D_2 as dissolved gas in Pb16Li stripped by $He+H_2$ (0.1%vol.).

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High heat flux test

Flow accelerated corrosion test

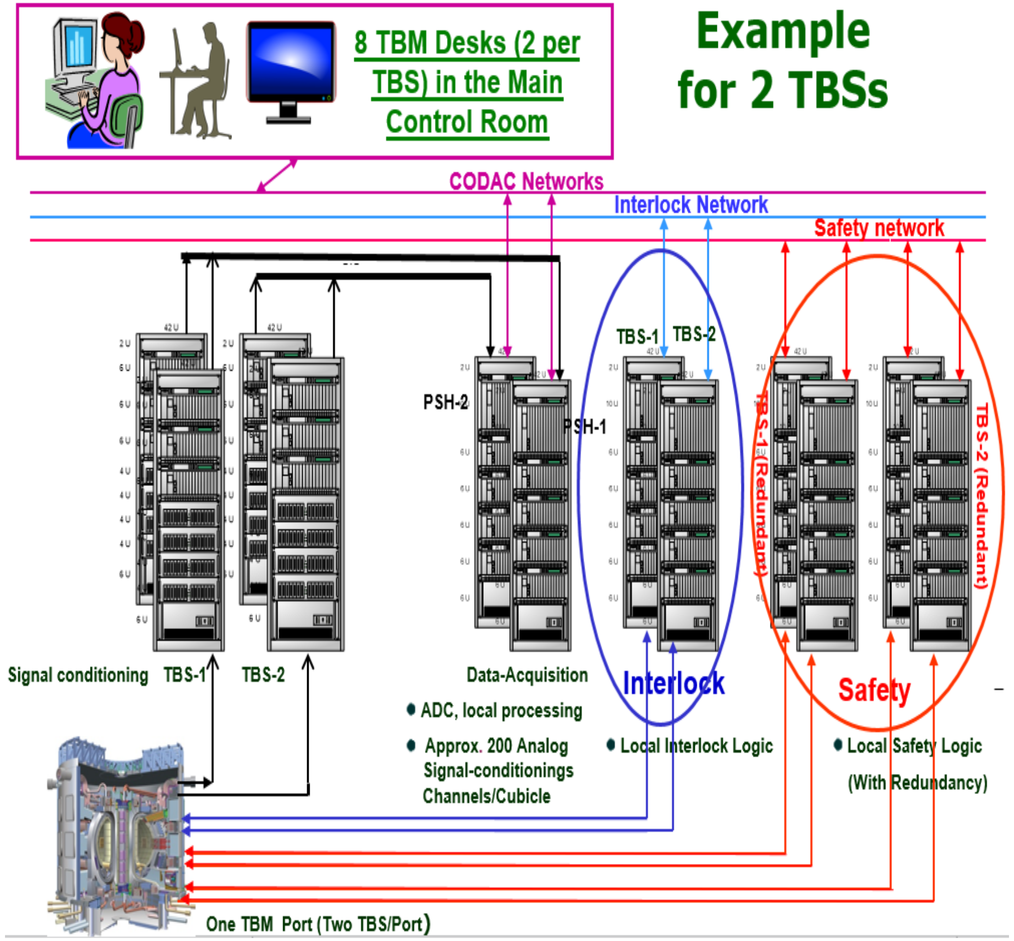
Coolant leakage propagation test

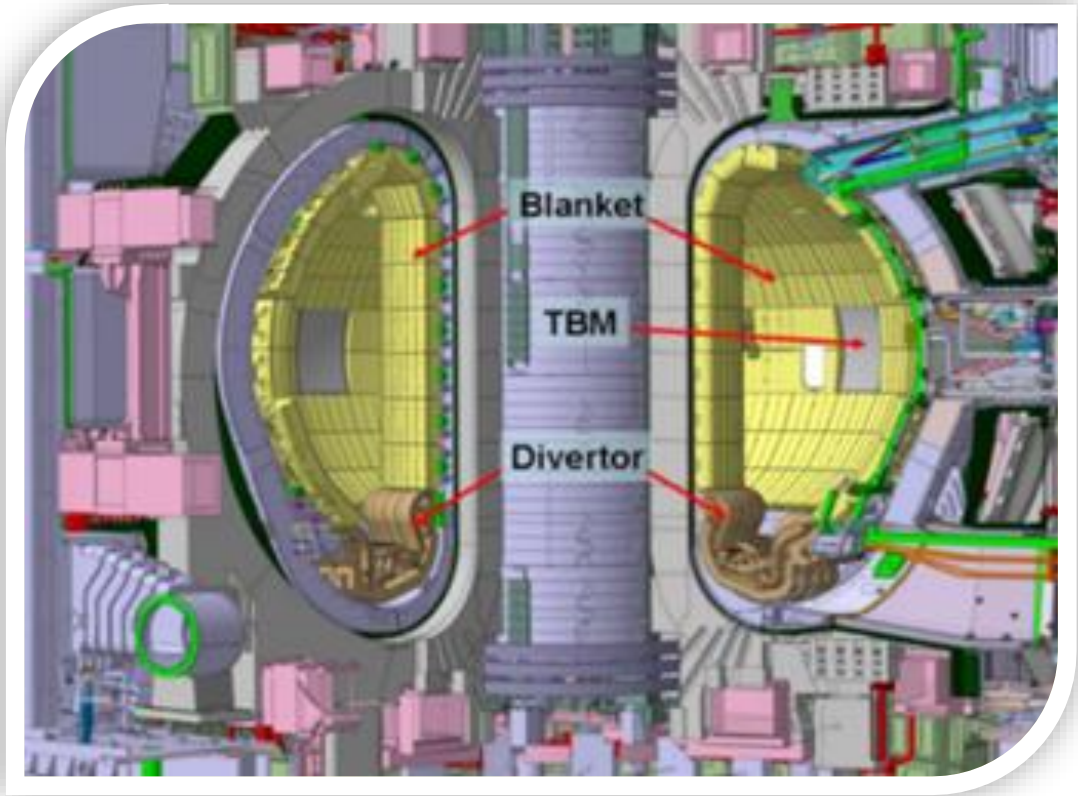
Be – Water reaction rate measurement

Test Facilities located in Rokkasho for physical mock-ups test related to the WCCB-TBS

Measurements and control systems

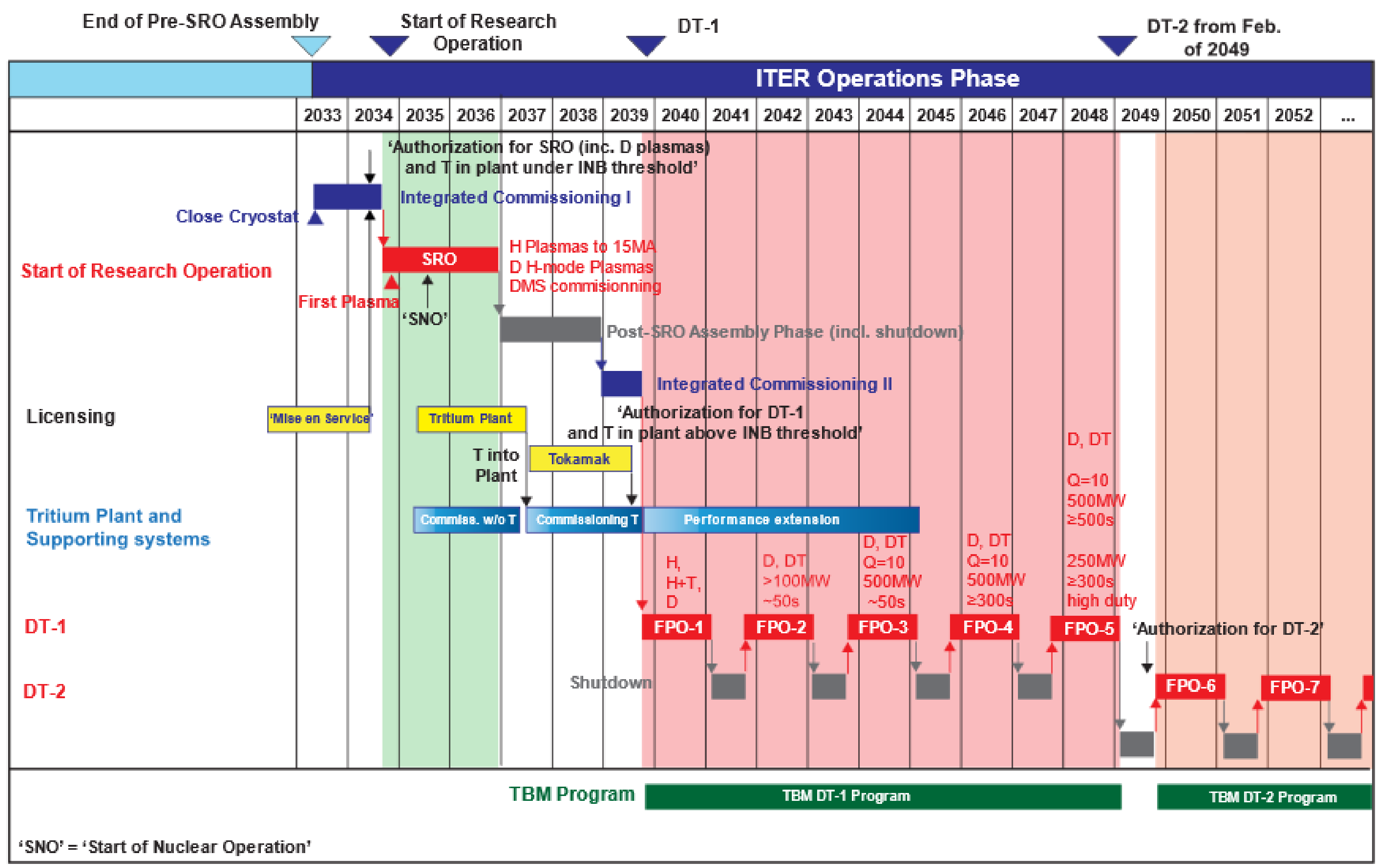
- A significant work is on-going within the ITER Members on the development of **appropriate detectors, instrumentation and measurement systems** able to measure the various TBSs operating parameters which are required to operate and to control the TBSs from the main Control Room.
- These detectors and instrumentations needs **to measure and transmit data** to be used by the Safety Systems (Central+Plant) to operate the defined safety functions, by the Interlock (Investement Protection) Systems (Central+Plant) and by the regular CODAC system for data acquisition. These systems need to be indipendent and the Safety system needs to be redundant (=2 systems).
- The instrumentation and cabling technologies developed and finally selected for the TBSs will be **directly applicable** to the DEMO TBB.
- The **whole network architecture** is specifically developped for the TBSs and can be used as the basis for the DEMO TBBs measurement systems.





ITER TBM Program Testing Plan and main overall objectives

The 2024 ITER Baseline – ITER Research Plan Level-1 & TBM Program



Duration of the TBS operations

The TBSs forming the Initial Configuration are expected to be operated during DT-1 starting FPO-1.

For DT-2, a Second TBS Configuration will be operated, with the possibility to include different TBSs

Phase	Duration (months)	Plasma scenarios	Heat flux on TBM FW (MW/m^2)	DT Neutron flux on TBM FW (MW/m^2)	Estimated Neutron Fluence ($x10^{24}$)
FPO-1	16	H, DD, H+T, T @ 7.5 MA/2.65 T	0.05-0.25 (peak)	Negligible	Negligible
FPO-2	16	DD, DT @ 7.5 MA/5.3T (~ 50 s burn ➔ attempts up to 300s) DD, DT @ 10 MA /5.3T (~ 50 s burn ➔ attempts up to 300s)	0.08-0.23 (peak) 0.09-0.24 (peak)	~ 0.18 (peak) ~ 0.30 (peak)	~0.27 ~1.66
FPO-3	16	DD, DT @ I_p ≥ 12.5 MA /5.3T (~ 50 s burn) Q=10 (attempts up to 300s at the end)	0.12 - 0.3 (peak)	~ 0.7 (peak)	~5.3
FPO-4 + FPO-5	16+16	DD, DT @ I_p ≥ 12.5 MA /5.3T (≥ 300 s burn)	0.12 - 0.3 (peak)	~ 0.7 (peak)	~13.87 + ~13.87
Total DT-1	*80*	-	-	-	*~35.0 [~0.035 dpa(Fe)]*
Total DT-2	*tbd*	-	-	-	*~3.0 dpa(Fe)*

Assumption for DT-1

For each TBS, 2 TBM replacements:

- 1st TBM covering FPO-1 & FPO-2
- 2nd TBM covering FPO-3
- 3rd TBM covering FPO-4 & FPO-5

Present estimation of the main characteristics of the expected DT-1 campaigns relevant for the TBM Program

Peak values mean values occurring during at least one pulse (=design values)

TBM Program Research Plan : DT-1 Top-Level Objectives

The TBM Research Plan is based on the following **Top-Level Objectives** (TLOs) for the DT-1 phase *(that are also valid for DT-2, for higher n-fluence & tritium production)*:

- **TLO-1**: *Validation of structural integrity theoretical predictions under combined and relevant thermal, mechanical and EM loads*
- **TLO-2**: *Validation of tritium breeding predictions*
- **TLO-3**: *Validation of tritium recovery process efficiency and T-inventories in the relevant TBS materials*
- **TLO-4**: *Validation of TBM thermal-hydraulic predictions, including volumetric heat sources*
- **TLO-5**: *Validation of technologies relevant for future fusion reactors*
- **TLO-6**: *Demonstration of the integral performance of the TBS sub-systems, including the achievement of coolant thermo-hydraulic parameters compatible with those required for high-efficiency electricity production*

Reminder: the effects of fusion-neutron irradiation on blanket materials (requiring high n-fluence of at least 50 dpa(Fe) or more) are not part of the ITER TBM Program objectives. They should be checked in other, more appropriate, facilities.

"The overall objective of the TBM Program is to demonstrate, in a relevant tokamak-fusion environment, the feasibility of the self-sufficiency of the Tritium production using relevant coolant temperature and pressure needed for the next tokamak generation (e.g., DEMO)"

How to achieve the Top-Level Objectives during the five DT-1 campaigns within the limit of the DT-1 neutron fluence?

➔ *Several Minimal Requirements have been defined and, then, implemented in the ITER Research Plan.*

➔ *Aside, two examples of essential Minimal Requirements*

1 - Minimal Requirement on plasma scenarios: it is planned to have some ITER operation days (in particular, during FPO-4 and FPO-5) fully dedicated to the TBM Program with the following main characteristics:

- A **Fusion Power of at least half of the maximum** (i.e., about 250 MW). It gives sufficient heat loads on the TBM FW and a sufficiently high neutron wall loading in order to have a sufficient tritium production rate.
- A pulse length with **a flat top of at least 300 seconds** in order to achieve the thermal quasi-steady state in TBMs.
- **A high repetition time**, for instance having around 32 “back-to-back” pulse for 16 hours (a day with 2 shifts), in order to achieve a pseudo equilibrium among the various tritium-related characteristics (i.e., production, extraction, permeation and coolant tritium purification).

2 - Minimal Requirements on TBM design: it is planned to add inside the TBMs (in particular, during FPO-1, FPO-2 and FPO-3) several **electrical heaters** to compensate the lack of volumetric heat deposited by neutrons and to operate the **coolant systems** in a way to keep relevant temperature level inside the TBM, in particular, in the breeding zone.

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Preparation of the Detailed TBM Program Research Plan

- Under the assumption that all Minimal Requirements have been implemented:
  Starting from the TLOs, for each FPO, several more detailed and measurable "general Campaign Testing Objectives (gCTOs)" have been identified for to each FPO and its associated plasma scenario. Most of them are applicable to all the TBSs.

- There are 11 gCTOs for FPO-1, 11 gCTOs for FPO-2, 9 gCTOs for FPO-3, and 15 gCTOs for FPO-4/FPO-5.

- The feasibility of each CTO has been assessed. The feasibility assessment for the various CTOs includes the following aspects:
  - *Definition of the parameters that need to be measured,*
  - *Identification of the possible instrumentation/sensors types that could be used and of their possible integration in the TBM/TBS designs,*
  - *Potential need of Post-Irradiation Examinations at IM premises on shipped TBMs,*
  - *Identification of some design changes that would be needed to comply with the plasma scenarios (for instance, the addition of electrical heaters to compensate the lack of neutron volumetric heat),*
  - ***Development of specific modeling to interpret the obtained measurements and to perform the extrapolation to DEMO.***

- Typical time-constants for main TBM/TBS parameters (to compare with the various plasma pulse length):
  - *TBM thermal responses: typical time constant in the range 80-100 seconds.*
  - *Tritium-related characteristics of TBSs (covering tritium inventory, extraction, permeation and purification): typical time constant in the range of few-thousands seconds.*

Examples of typical gCTOs and associated feasibility assessments over the 5 FPOs (1/3)

Examples of gCTOs *(=expected simulations & results from the TBS testing)*	**Main parameters to be measured ➔ examples of instrumentation & sensors + design aspects**
❶ [FPO-1, FPO-2] ☑ ***TLO-1*** • Capability of TBMs to withstand EM Loads, disruptions • Validation of structural analyses with combined EM and heat loads from TBM internal heaters	***Magnetic field***: some Hall sensors – TBM-Set and TBM frame *displacements*: several interferometers & accelerometers – ***Strains***: several strain gauges in different locations - ***Temperature***: thermo-couples (~50, in different locations). ***Post-Irradiation Examinations***
❷ [FPO-1, FPO-2] ☑ ***TLO-4*** • Validation of the heat removal capability from the First Wall under different coolant flowrates. • Validation of the heat extraction performance predictions from the TBM FW and TBM body	*Electrical heaters on.* *Temperatures*: several thermo-couples (in different TBM locations, including coolant inlet and outlet) ***Coolant flowrate***: several flowmeters in different locations, mass flowmeters for He, Coriolis flow sensor for H_2O
❸ [FPO-1] ☑ ***TLO-5*** Validation of the MHD predictions on PbLi pressure drop in the TBM and in PbLi loop in the PbLi operational domain	*Electrical heaters on.* ***PbLi pressure***: 4 membrane pressure gauges ***PbLi flowrate***: 2 thermal mass flowmeters
❹ [FPO-1, FPO-2] ☑ ***TLO-5*** Verification of I&C architecture performance. Performance assessment of implemented software and hardware (control algorithms, protocols, fast control cubicles, etc..) including efficiency	Hardware selected form the IO catalogue (PCDH). Verification of the ***performance assessment*** by monitoring the signals from all the TBS sub-systems. ***Check of responses*** in I&C integration through changing parameters of sub-systems

Examples of typical gCTOs and associated feasibility assessments over the 5 FPOs (2/3)

Examples of gCTOs [=expected simulations & results from the TBS testing]	**Main parameters to be measured** **➔ planned instrumentation/sensors + design aspects**
❺ [FPO-1 & beyond] ☑ ***TLO-5*** Determination of coolant (He, water) corrosion/erosion rate in TBM RAFMs and validation of modelling predictions - Dust production in Be and Ceramic pebbles	Post-Irradiation Examinations: corrosion/erosion rate, dust product. Use of γ-detector for Activated Corrosion Products Comparison with numerical simulation. Measurement of dusts generated in Be and ceramic pebbles during PIE; measurement and analysis dust in HCS/TES/CPS filters.
❻ [FPO-2 & beyond] ☑ ***TLO-2*** • Preliminary analysis of the TBM nuclear responses and calibration of the nuclear instrumentation (e.g., NAS operation) • Neutronic analysis and tritium generation rate prediction validation against measures. • Reconstruction of achievable TBR	Neutron flux and spectrum in TBM: some SPND, some fission chambers, at least 2 NAS irradiation ends. Neutron fluence: NAS/Activation foils, 2 capsules in TBM Gamma flux: SPGD in various locations, γ-ray of activation foil Nuclear volumetric heat: several thermo-couples Measurements of total tritium content (Tritium calorimeter) compared with modelling
❼ [FPO-1, FPO-2] ☑ ***TLO-3*** Assessment and verification H/D permeation prediction from plasma to FW and then to coolant	Hydrogen isotopes concentration in coolant (mass spectrometers in HCS & CPS or other types of gas analysers) + tritium detectors
❽ [FPO-2 & beyond] ☑ ***TLO-5*** Thermo-mechanical characterization of the Li-based ceramic breeder and Be-based neutron multiplier (compatible temperature distribution only with heaters)	*Electrical heaters on.* Characteristics of pebble bed thermo-mechanics behavior, pebble failure rate and powderization characteristics PIE for damage accumulation assessment, dimensional stability evaluation and characterization of functional materials

Examples of typical gCTOs and associated feasibility assessments over the 5 FPOs (3/3)

Examples of gCTOs [=expected simulations & results from the TBS testing]	**Main parameters to be measured** **➔ planned instrumentation/sensors + design aspects**
❾ [FPO-1, FPO-2] ☑ ***TLO-3*** Preliminary performance characterization of the tritium processing technologies (using D2-addition)	*Electrical heaters on.* **Concentration** of H, D & T: Demonstration of T extraction technology by adding D2 in TES (measurement of D2 concentration by spectrometer or H-sensors, gas-chromatography, mass spectrometer **Temperature**: thermocouples
❿ [FPO-3, FPO-4/FPO-5] ☑ ***TLO-4, TLO-6*** Demonstration of achievement of coolant thermo-hydraulics conditions (both water and Helium) relevant for electricity production.	*Electrical heaters partially on.* **Temperature**s: several thermo-couples, including coolant inlet/outlet. **Coolant pressure and mass flowrate**: differential pressure flowmeters at inlet/outlet WCS/HCS inside Port Cella area.
❶❶ [FPO-3, FPO-4/FPO-5] ☑ ***TLO-3, TLO-6*** • Collection of experimental data for the validation of the predictions of the tritium transport models with particular focus on the tritium permeation into the primary coolant. • Performance characterization of the tritium processing technologies • Determination of the ratio between the generated tritium and the tritium accounted in the TAS in a given period of time	**Tritium concentration**: - in He-purge gas: beta rays (ionization chambers in TES, TAS & CPS), tritium chemical forms under different purge gas conditions - in PbLi: permeation-based sensors in various locations - in water: scintillation counter (batchwise) - in He-coolant: Gas Chromatography, Mass Spectrometers. - Appropriate activation foil, ionization chambers, fission chambers. **Tritium concentration** in getter beds, Q2O columns, reducing beds… **Total tritium content** (one T-calorimeter) **Beta rays**: e.g., 4 ion chambers, 2 for TES, 2 for CPS

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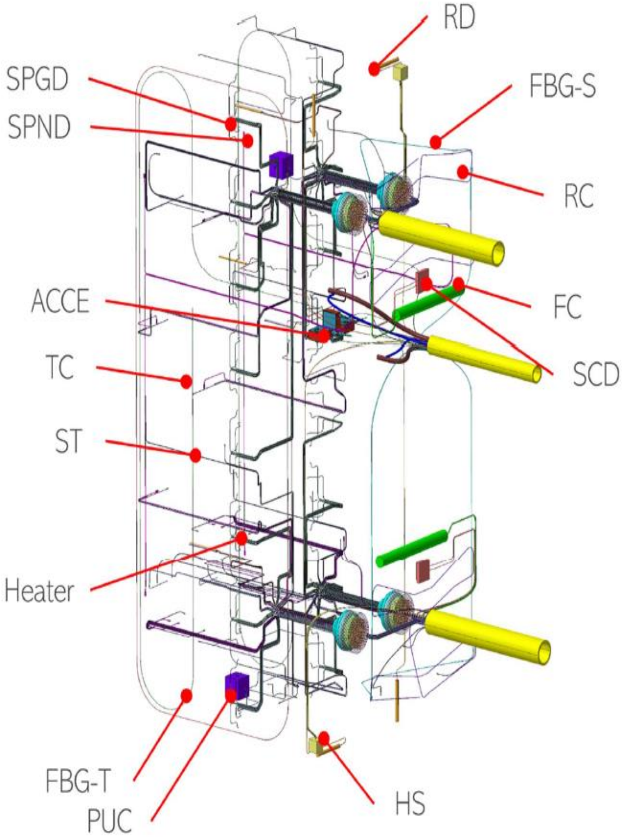
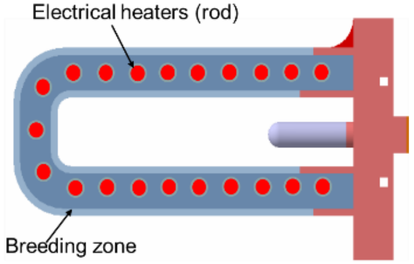
Design Integration and Modelling Aspects

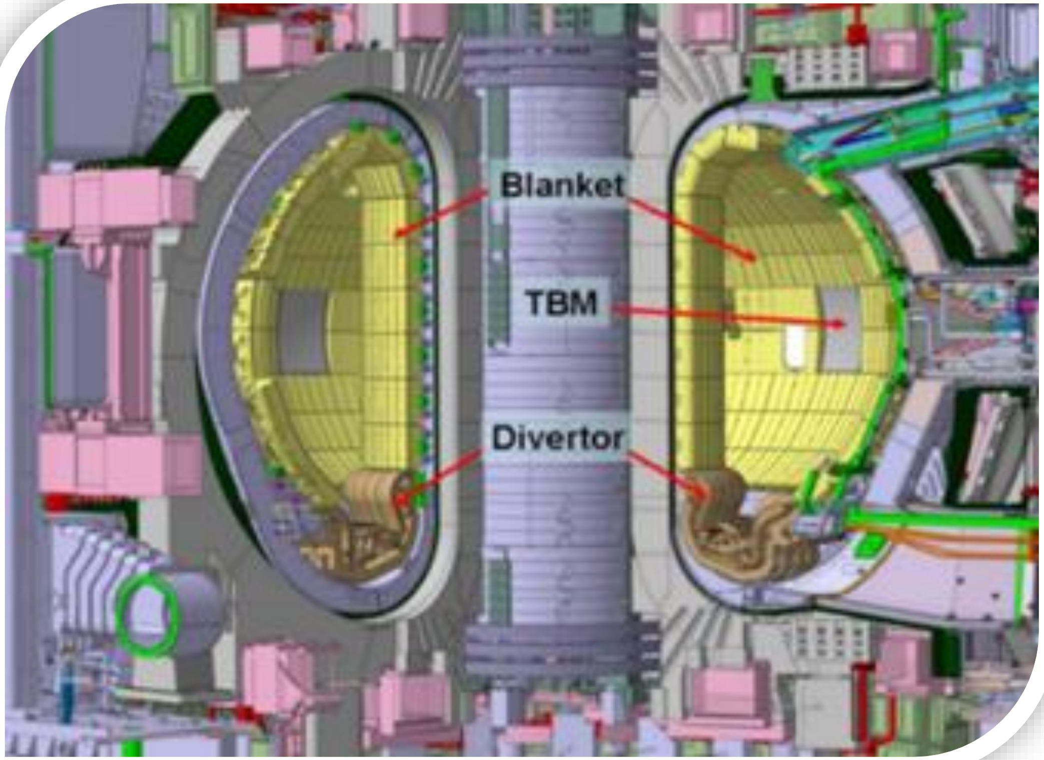
- Electrical heaters are added in most TBMs.
- Many sensors and instrumentation are needed inside the TBMs (up to 100 sensors).
- Variation of operational parameters is needed to measure the TBS sub-systems responses several measurements in whole TBSs).
  - Design integration becomes a key aspect of the TBS design, in particular fo the TBM designs.
- The achievement of most gCTOs requires a *significant effort in term of modelling and codes developments* that become essential in the implementation of the operational conditions expected in DT-1 (e.g., pulses length, fusion power, pulse repetition times, fluence limits). It involves various fields (*e.g., thermal-hydraulics, mechanics and thermal-mechanics, neutronics, Tritium behavior*).



Schematic view of possible location of the sensors in the HCCP- TBM and of the cable routing



Electrical heaters in HCCB-TBM: example of rod-type heaters



Final Considerations and Conclusions

Final Considerations and Conclusions

- The TBM Program has the objective to install and simultaneously operate in ITER four Test Blanket Systems (=mock-ups of the corresponding DEMO TBB), starting from the beginning of the ITER DT-1 phase (i.e., the TBS Initial Configuration).
- All the four TBSs are in the Preliminary Design Phase (PDRs planned in 2026).
- The design of the various TBMs is progressively improving taking into account fabrication process and R&D results. Many R&D activities are on-going within the ITER Members laboratories, in particular on manufacturing technologies and on experimental loops. They are all directly applicable for the development of Tritium Breeding Blankets for DEMO.
- It has been found that the main objectives of the TBM Program can be achieved in DT-1 phase even considering that the reduced neutron fluence in the 2024 ITER baseline compared to the previous ITER baseline (2016).
- The development of modelling in various fields (e.g., thermal-hydraulics, mechanics and thermal-mechanics, neutronics, Tritium behavior) is essential for the results interpretation and extrapolation to DEMO TBB.
- Important observation: even during the TBS design and manufacturing phases, several results and experimental data concerning the TBSs are of significant benefit for the development of the breeding blankets systems of the next generation of the fusion power reactors (such as DEMO).
- *<u>Remark</u>: obtained results will be applicable/useful to other types of TBSs and corresponding TBBs.*

Thank you!

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