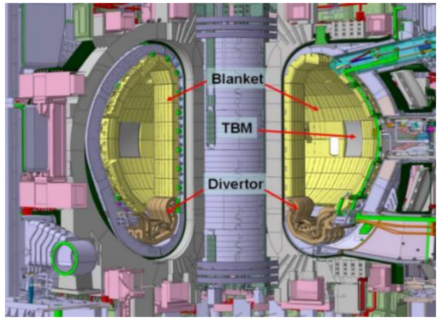

8th IAEA DEMO Programme Workshop (DPWS-8)
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Review of the ITER TBM Program Technical Targets and Progress

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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

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.***"

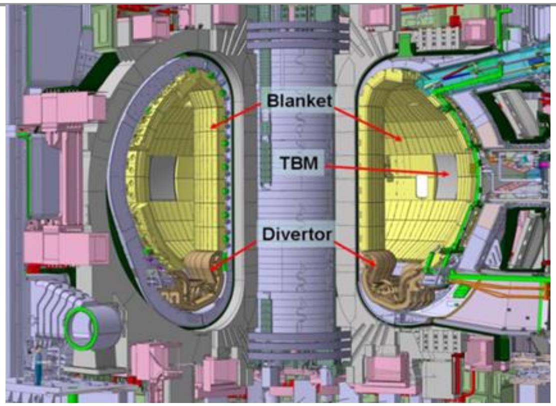
- All the ITER Organization (IO) activities related to this mission, both in IO-CT and in the seven IO Domestic Agencies, form the so-called **"ITER TBM Program"**.

- The TBM Program is therefore a research activity run in ITER in parallel to the main ITER Research Plan

➔ Next slides describe the TBM Program implementation in ITER and the expected achievements to support the DEMO breeding blankets design and manufacturing

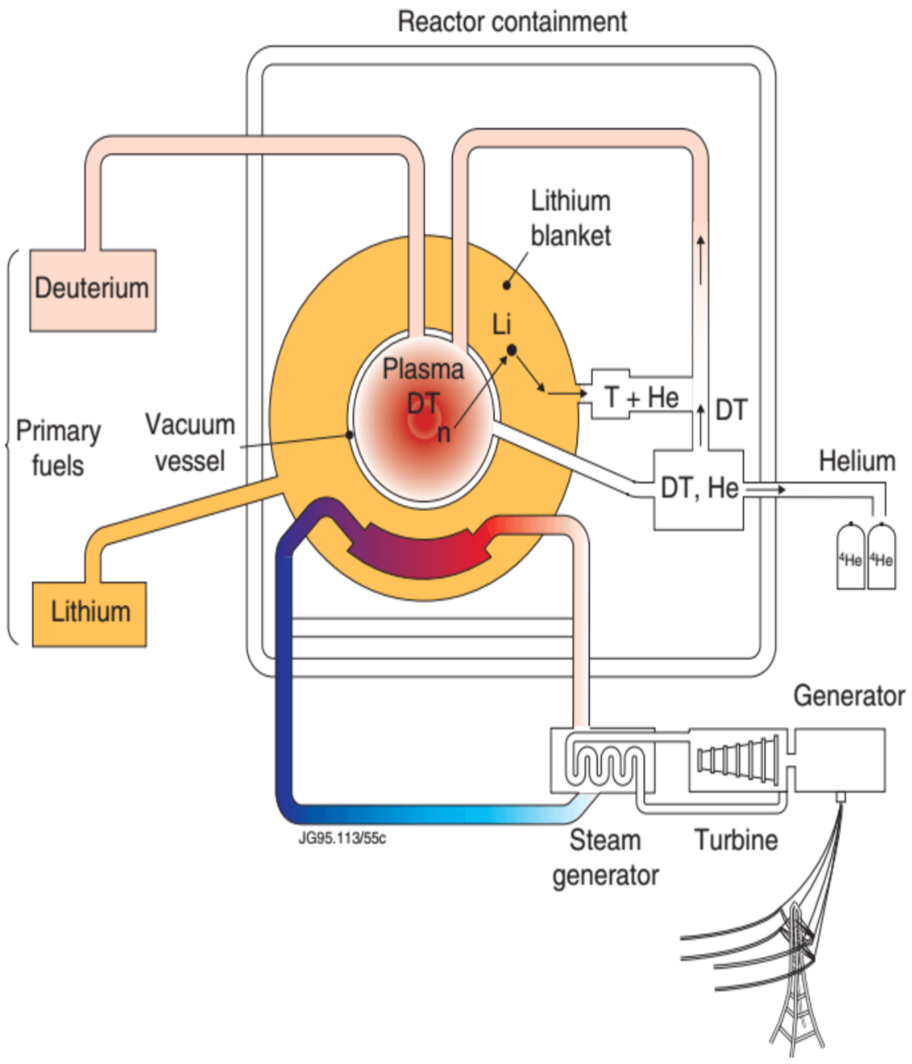
Outline of the presentation

1. Tritium Breeding Blankets (TBB) Functions in DEMO and potential associated designs
2. Rational of the ITER TBM Program and main features of the Test Blanket Systems
3. TBM Program Test Plan and Objectives
4. Activities carried out in IO in support of the Test Blanket Systems
5. Examples (not exhaustive) of on-going R&D on Test Blanket Systems carried out by the ITER Members
6. Further Considerations on the Achievements of the TBM Program in support the DEMO TBBs development
7. Conclusions



1 - Tritium Breeding Blankets (TBB) Functions in DEMO and potential associated designs

Tritium Breeding Blankets (TBB) Functions in a Fusion Power Reactor



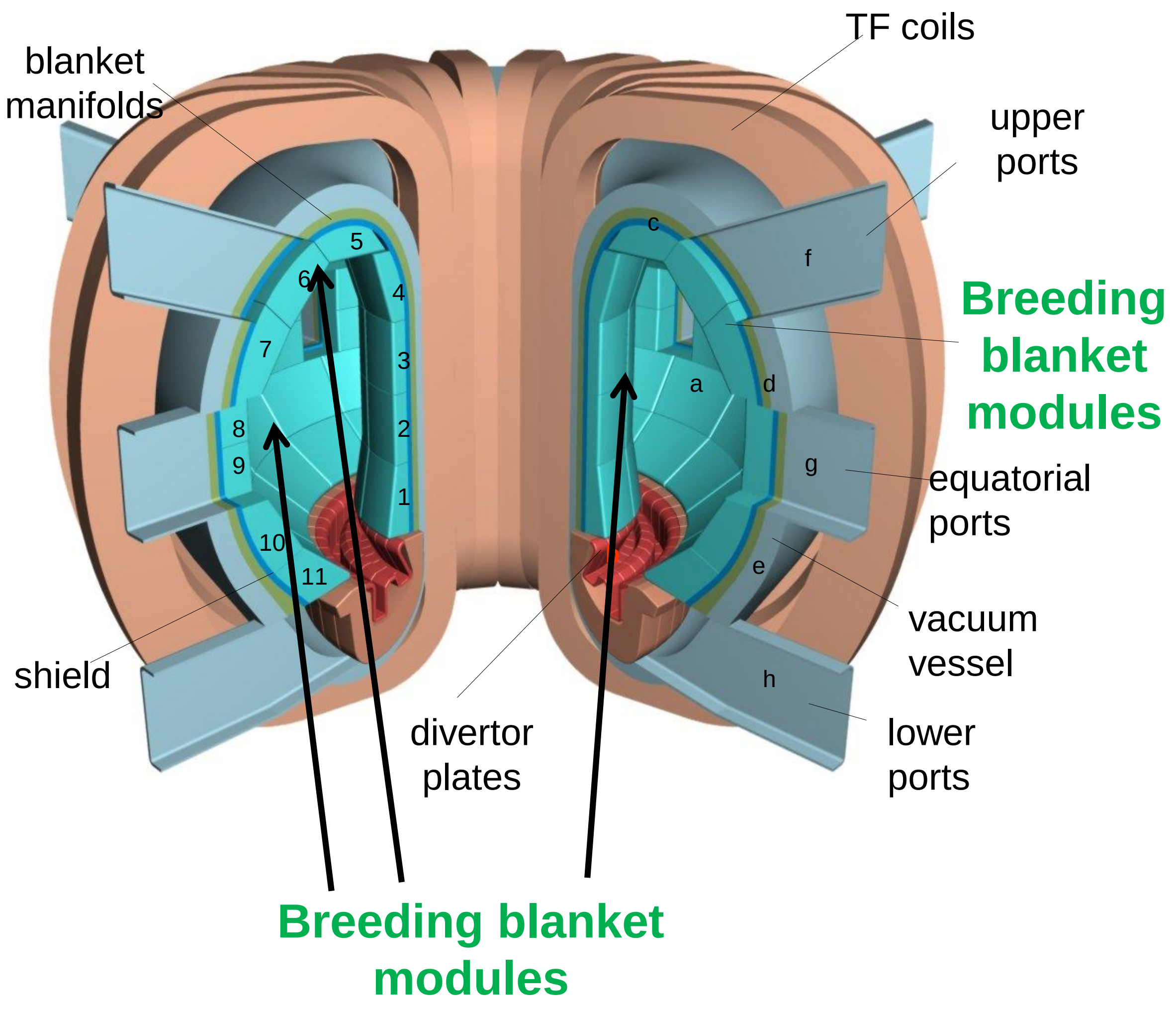
Three crucial functions

- **Convert** the neutron energy (80% of the fusion energy) in heat and collect it by mean of an high grade coolant to reach high conversion efficiency (>30%)
  ➔ equivalent to an in-pile heat exchanger

- **Produce all Tritium** required as fuel for D-T reactors in the Li-based breeding blanket and fully **RECOVER it** using, for instance, He purge-gas, for continuous re-injection in the plasma
  ➔ required Tritium breeding self-sufficiency

- Contribute to neutron and gamma **shielding** to protect the superconductive coils
  ➔ capability of resistance to neutron damages

Typical TBB Operating Conditions in a Fusion Power Plant



Picture: courtesy of KIT

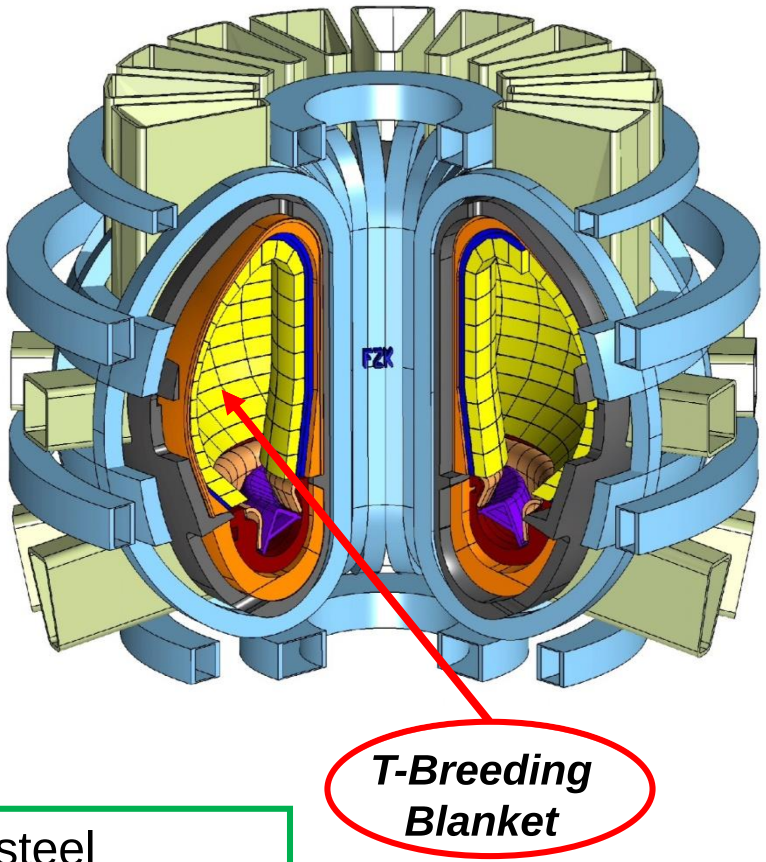
Need to have a breeding blanket, including the Fist Wall (FW), fully surrounding the plasma. It is therefore submitted to severe working conditions, in particular:

- ✓ High surface heat flux >0.5 MW/m^2 on FW
- ✓ High neutron wall loading ~2.5 MW/m^2
- ✓ Long irradiation time, at least 5 years: ~150 dpa(Fe) in FW
- ✓ Operation in vacuum (plasma) ➔ low coolant leakages
- ✓ High magnetic field (~7 Tesla) (high MHD effects)

DEMO TBBs considered within the ITER TBM Program (relatively short-term)

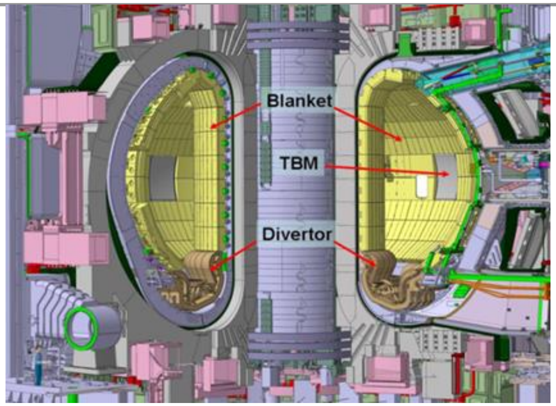
- ***Helium-Cooled Pebble Bed (HCPB)*** concept, using Reduced Activation Ferritic/Martensitic steel (RAFM steel) structures, He-coolant, Be-multiplier, and Li_2TiO_3 or Li_4SiO_4 ceramic breeder: *studied in EU*
- ***Water-Cooled Ceramic Breeder (WCCB)*** concept, using RAFM steel structures, water-coolant, Be-multiplier, and Li_2TiO_3 ceramic breeder: *studied in Japan*
- ***Helium-Cooled Ceramic Breeder (HCCB)*** concept, using RAFM steel structures, He-coolant, Be-multiplier, and Li_4SiO_4 ceramic breeder: *studied in China*
- ***Helium-Cooled Solid Breeder (HCSB)*** concept, using RAFM steel structures, He-coolant, Be-multiplier, and Li_2TiO_3 ceramic breeder: *studied in India*

SOLID Breeder Materials



- ***Water-Cooled Lithium-Lead (WCLL)*** concept, using RAFM steel structures, water-coolant, and Pb-16Li breeder & multiplier: *studied in EU*
- ***Dual-Coolant Lithium-Lead (DCLL)*** concepts using RAFM steel structures, He-coolant, Pb-16Li breeder & multiplier & coolant: *studied in US and in EU*

LIQUID Breeder Materials



2 - Rational of the ITER TBM Program and main features of the Test Blanket Systems

Testing of Tritium Breeding Blankets in ITER

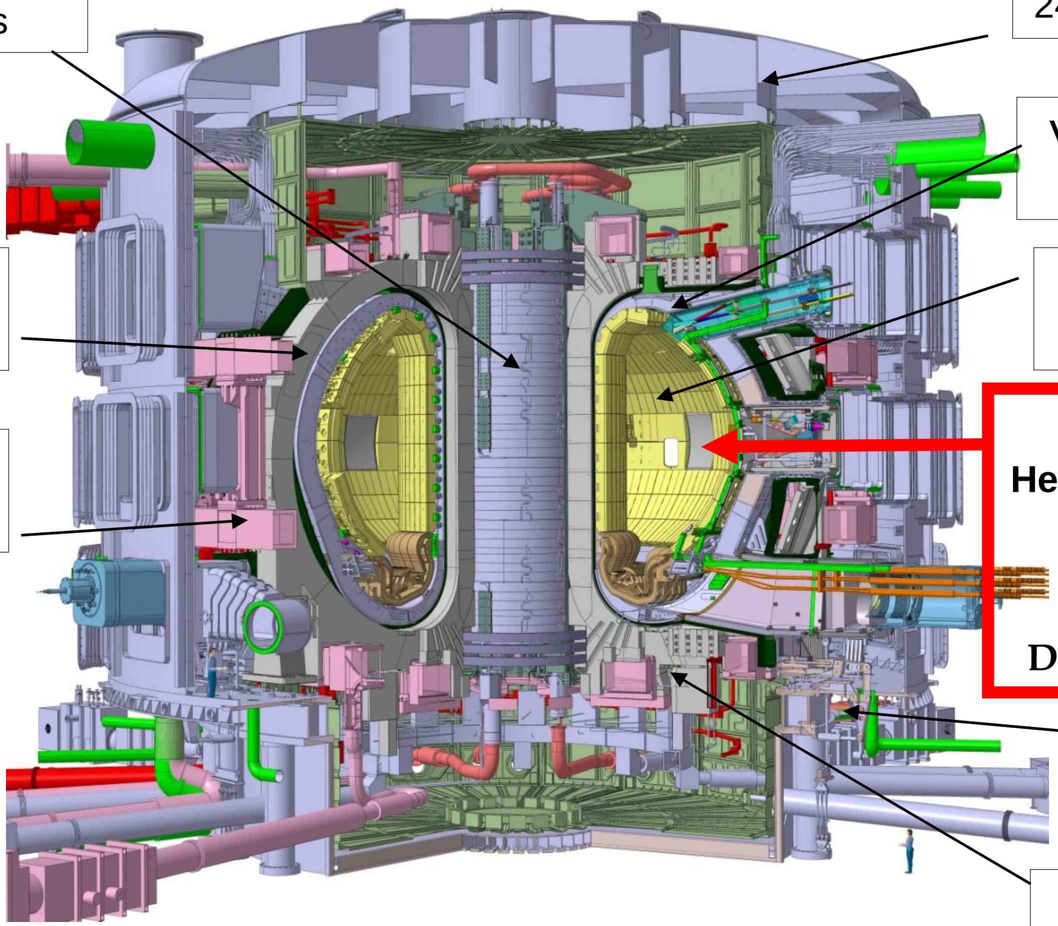
- Since the Tritium fuel is not available in nature, it is necessary to **entirely** produce it in the Tritium Breeding Blankets (TBBs). Therefore, TBBs are mandatory in DEMOnstration reactors while they are not present in ITER.

- The development of TBBs is essential in view of a DEMO; therefore, this development is present in all Fusion Power R&D plans for all ITER Members .

- ITER is a unique opportunity to test complete TBB mock-ups in DEMO-relevant conditions in order to demonstrate that Tritium Breeding Self-sufficiency can be achieved.

- Therefore, the "ITER TBM Program" foresees to install and operate in ITER several Test Blanket Systems (TBSs) that include the **Test Blanket Modules** (TBMs) *(the in-vessel part)* and the **associated ancillary systems.**

Overview of ITER machine and locations of the TBMs



Central Solenoid
Nb_3Sn, 6 modules

Toroidal Field Coil
Nb_3Sn, 18, wedged

Poloidal Field Coil
Nb-Ti, 6

Cryostat
24 m high x 28 m dia.

Vacuum Vessel
9 sectors

Blanket
440 modules

Port Plug
Heating systems (EC, IC, NB) ,
Test Blankets Modules
Remote Handling
Diagnostics
Disruption Mitigation System

Torus
Cryopumps, 8

Divertor
54 cassettes

Major plasma radius 6.2 m

Plasma Volume: 840 m^3

Plasma Current: 15 MA

Typical Density: 10^{20} m^{-3}

Typical Temperature: 20 keV

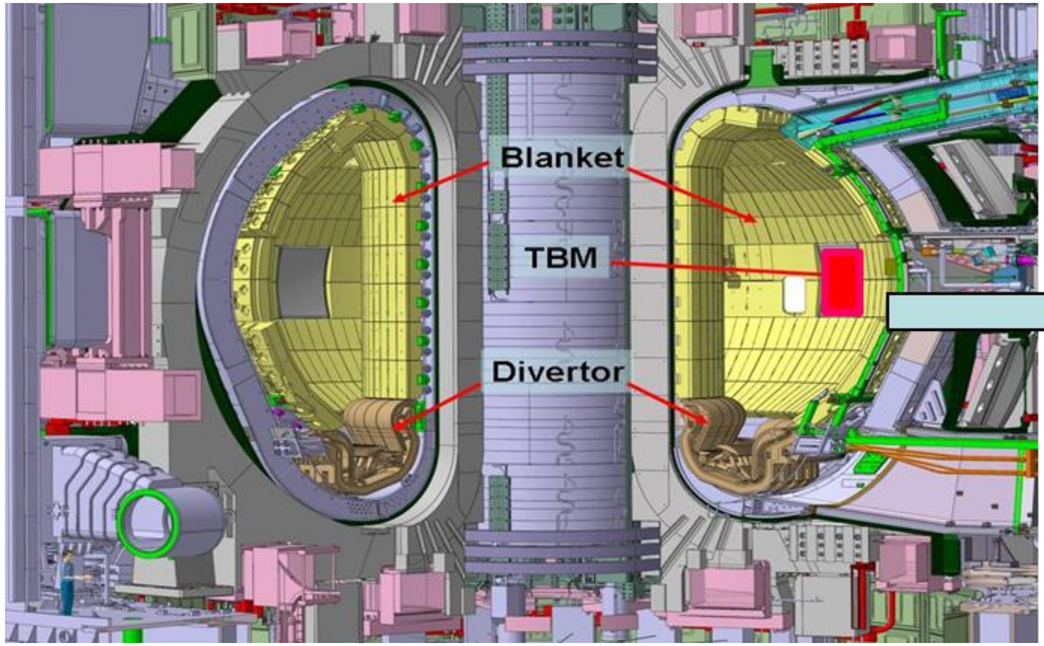
Fusion Power: 500 MW

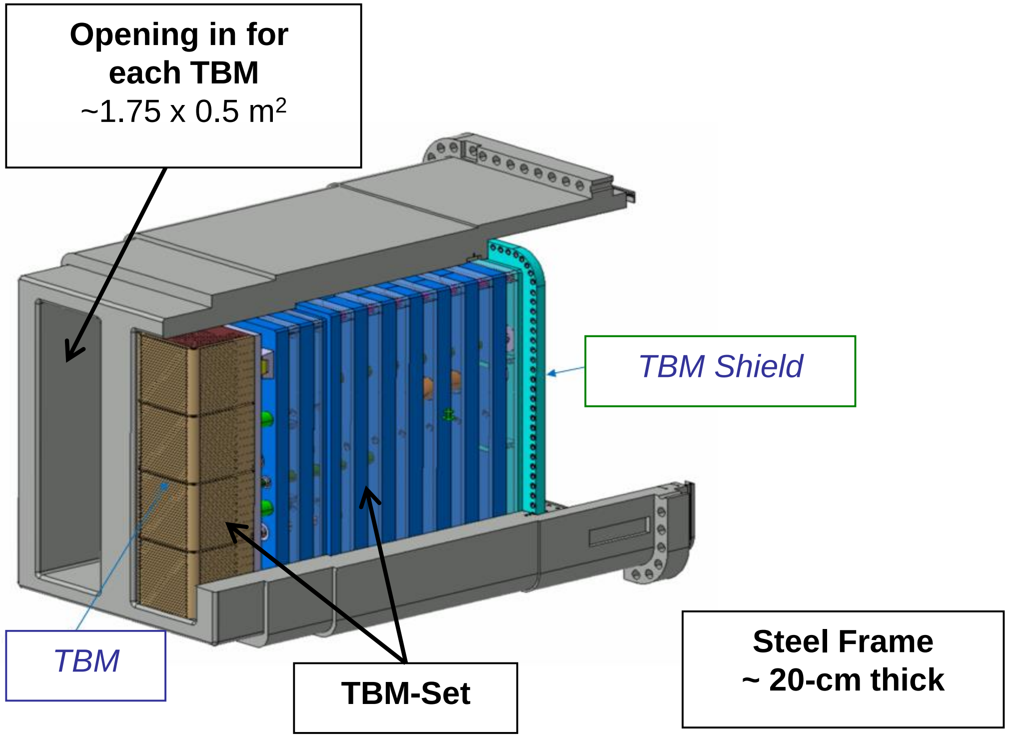
Max n-flux in FW: 0.78 MW/m^2

Boundary Conditions in ITER for TBMs testing

- The **"ITER TBM Program"** foresees the simultaneous operation of four TBSs whose TBMs are located in the 2 ITER equatorial ports #16 and #18 (2 TBMs per port).
- The TBMs are installed in a water-cooled steel frame (together with the associated shield).
- Each TBM has its own ancillary systems (e.g., coolant, Tritium extraction, Instrumentation & Control, maintenance tools and equipment) located in the Tokamak Complex

➔ Operation of **4 Test Blanket Systems**





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

Port Nº	First Concept	Second Concept
16 (F)	TBS-1: *Water-Cooled Lithium-Lead (EU)* ➔ *Water at 15.5 MPa, 280-325ºC*	TBS-2: *Helium-Cooled Ceramic Pebbles (joint KO & EU)* ➔ *Helium at 8.0 MPa, 300-500ºC*
18 (S)	TBS-3: *Water-Cooled Ceramic Breeder (JA)* ➔ *Water at 15.5 MPa, 280-325ºC*	TBS-4: *2nd Helium-Cooled Ceramic Breeder (CN)* ➔ *Helium at 8.0 MPa, 300-500ºC*

In the corresponding DEMO TBBs, the structures are made of Reduced-Activation Ferritic/Martensitic steel ➔ to be representative, the TBMs need to use the same structural material.

- These types of steels have been developed to avoid rad-waste with lifetime longer than 100 years. They are very important for the public acceptance of future of D-T fusion power !!! ☺
- They are ferromagnetic and, therefore, they could cause perturbations to the ITER magnetic field confining the plasma. Several experiments in DIII-D have been performed in the last decade obtaining promising results. The final check will be performed during the TBS operation in the non-nuclear phase of ITER.

Note: 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.

Main Characteristics for the 4 InCo TBMs and associated Ancillary Systems

TBS-1 – **WCLL-TBM** (proposed by EU) ▪ Eurofer Steel (structure), **Pb16Li** (multiplier/breeder). ▪ Coolant: **H_2O at 15.5 MPa, 280 /325°C**. ▪ T-removal gas (from Pb16Li): He at 0.4 MPa. ▪ Maximum Tritium production: 20-30 mg/day	TBS-2 – **HCCP-TBM** (joint KO/EU design) ▪ 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 at 0.1/0.4 MPa. ▪ Maximum Tritium production: 20-30 mg/day
TBS-3 – **WCCB-TBM** (proposed by JA) ▪ F82H Steel (struct.), Be pebbles (mult.), **Li_2TiO_3** pebbles (breeder). ▪ Coolant: **H_2O at 15.5 MPa, 280 /325°C**; ▪ Purge gas: He at 0.1 MPa. ▪ Maximum Tritium production: 20-30 mg/day	TBS-4 – **HCCB-TBM** (proposed by CN) ▪ RAFM Steel (structure), Be-pebbles (multiplier), **Li_4SiO_4** pebbles (breeder). ▪ Coolant: **He at 8 MPa, 300/500°C**. ▪ Purge gas: He at 0.1/0.4 MPa. ▪ Maximum Tritium production: 20-30 mg/day

- ***The TBS Initial Configuration is expected to be operated for three ITER phases**, namely the last non-nuclear phase (PFPO-2) and in the first two nuclear phases (FPO-1 and FPO-2).*
- ***After FPO-2**, different TBSs could be operated, for example, Dual-Coolant Lithium-Lead (DCLL) TBS proposed by US and Helium-Cooled Solid Breeder (HCSB) TBS proposed by India.*
- *A decision on the TBS Second Configuration is expected around 2030.*

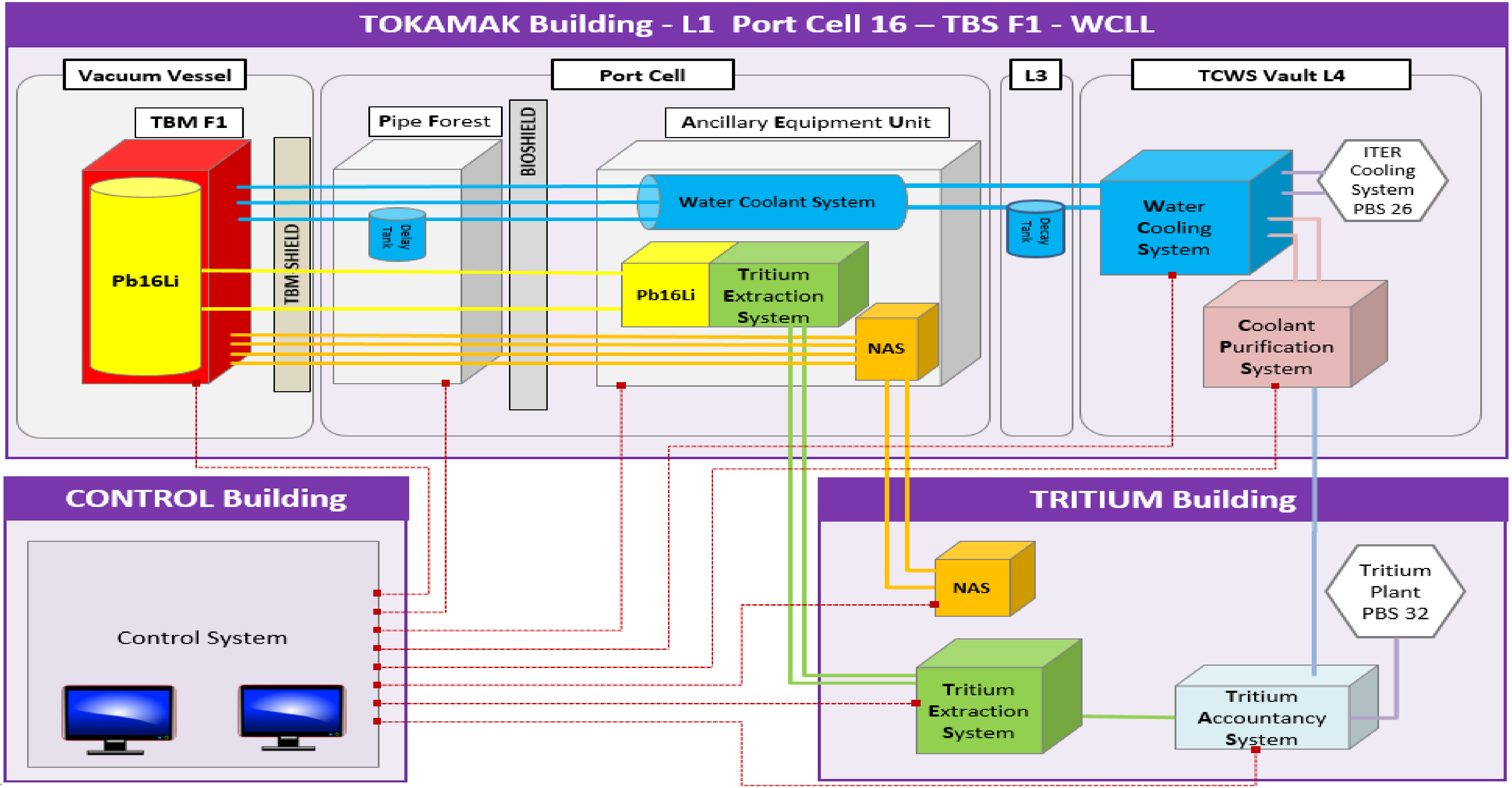
Main sub-systems present in each of the 4 InCo Test Blanket Systems which simultaneously operated (First-of-Kind)

TBS-1 – **WCLL-TBM** (proposed by EU) ✓ *Water Coolant System (primary, intermediate system ➔ secondary ITER CS) + CPS (Tritium)* ✓ *Lithium-Lead System (Tritium carrier in the Port Cell)* ✓ *Tritium Extraction System (He-purge of Pb-16Li)* ✓ *Tritium Accountancy System (➔ ITER Tritium Plant)* ✓ *Instrumentation & Operation Control Systems* ✓ *Neutron Activation System*	TBS-2 – **HCCP-TBM** (joint KO/EU design) ✓ *Helium Coolant System (primary ➔ secondary ITER CS) + Coolant Purification System (Tritium)* ✓ *Tritium Extraction System (= TBM He purge gas)* ✓ *Tritium Accountancy System (➔ ITER Tritium Plant)* ✓ *Instrumentation & Operation Control Systems* ✓ *Neutron Activation System*
TBS-3 – **WCCB-TBM** (proposed by JA) ✓ *Water Coolant System (primary, intermediate system ➔ secondary ITER CS)* ✓ *Tritium Extraction System (= TBM He purge gas)* ✓ *Tritium Accountancy System (➔ ITER Tritium Plant)* ✓ *Instrumentation & Operation Control Systems* ✓ *Neutron Activation System*	TBS-4 – **HCCB-TBM** (proposed by CN) ✓ *Helium Coolant System (primary ➔ secondary ITER CS) + Coolant Purification System (Tritium)* ✓ *Tritium Extraction System (= TBM He purge gas)* ✓ *Tritium Accountancy System (➔ ITER Tritium Plant)* ✓ *Instrumentation & Operation Control Systems* ✓ *Neutron Activation System*

➢ ***The TBMs are located within the Vacuum Vessel directly facing the plasma****, the various sub-systems components are located partially in the Port Cells, partially in the Level 4 of the Tokamak Building and partially in the Level 2 & Level 4 of the Tritium building. The I&C components are connected with the Control Room from where each TBS is independently operated.*

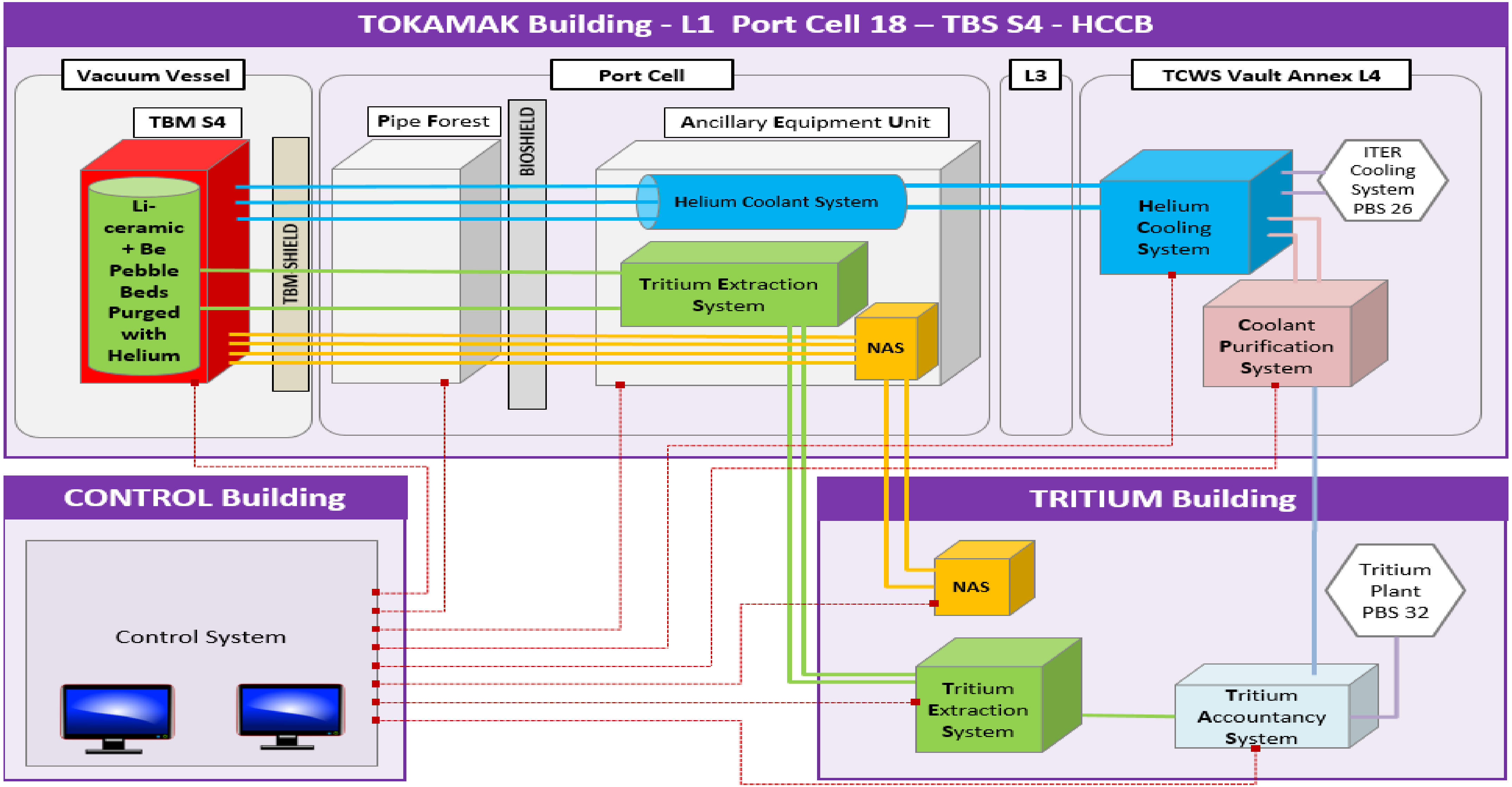
Scheme of a whole Test Blanket System *(e.g., Lithium-Lead breeder)*

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



Scheme of a whole Test Blanket System *(e.g., Solid Breeder)*

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



Location of the TBS Components in the Tokamak Complex (e.g., HCCB-TBS)

HCS : He-coolant system

CPS : Coolant Purification System

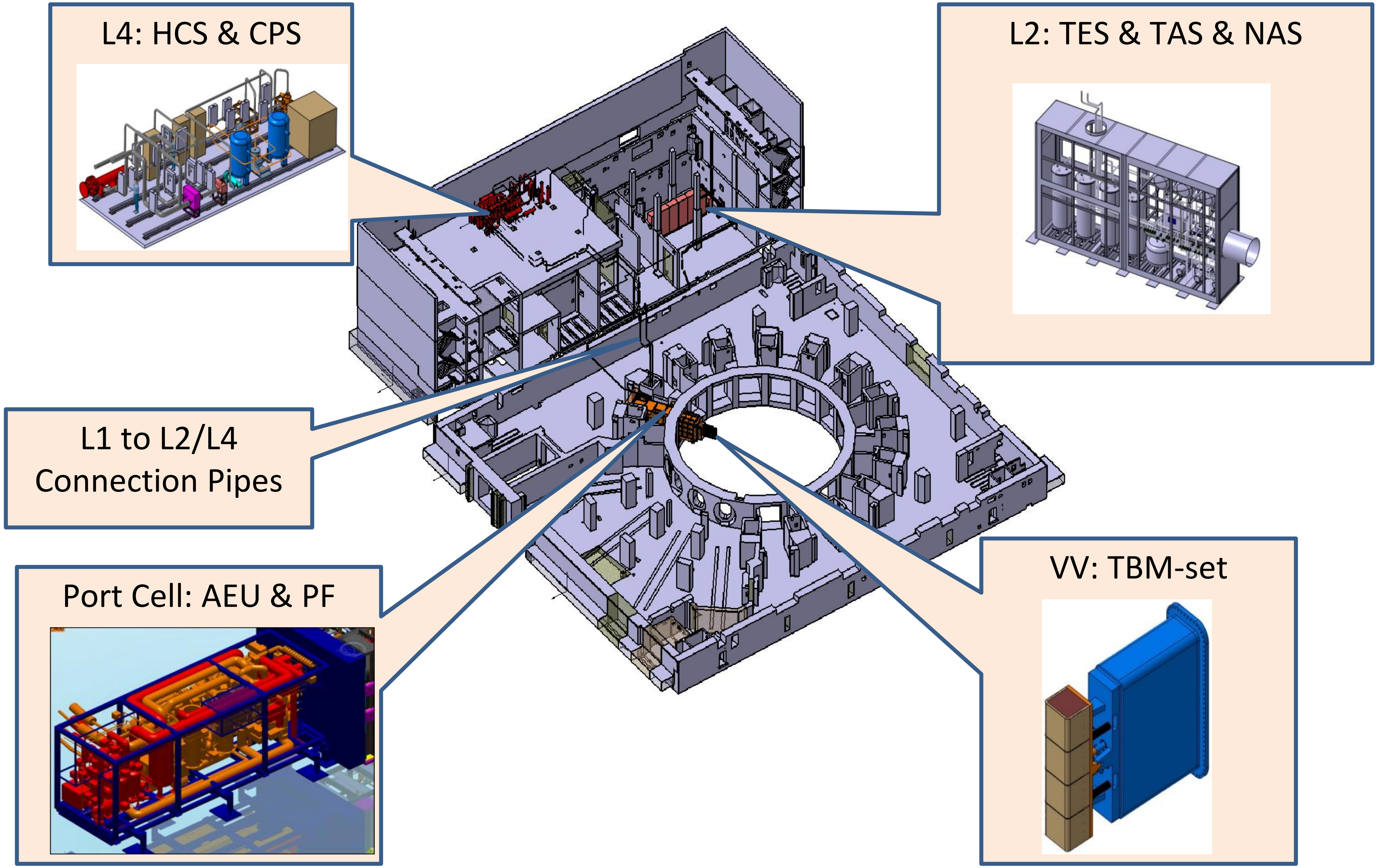
TES : Tritium Extraction System

TAS : Tritium Accountancy System

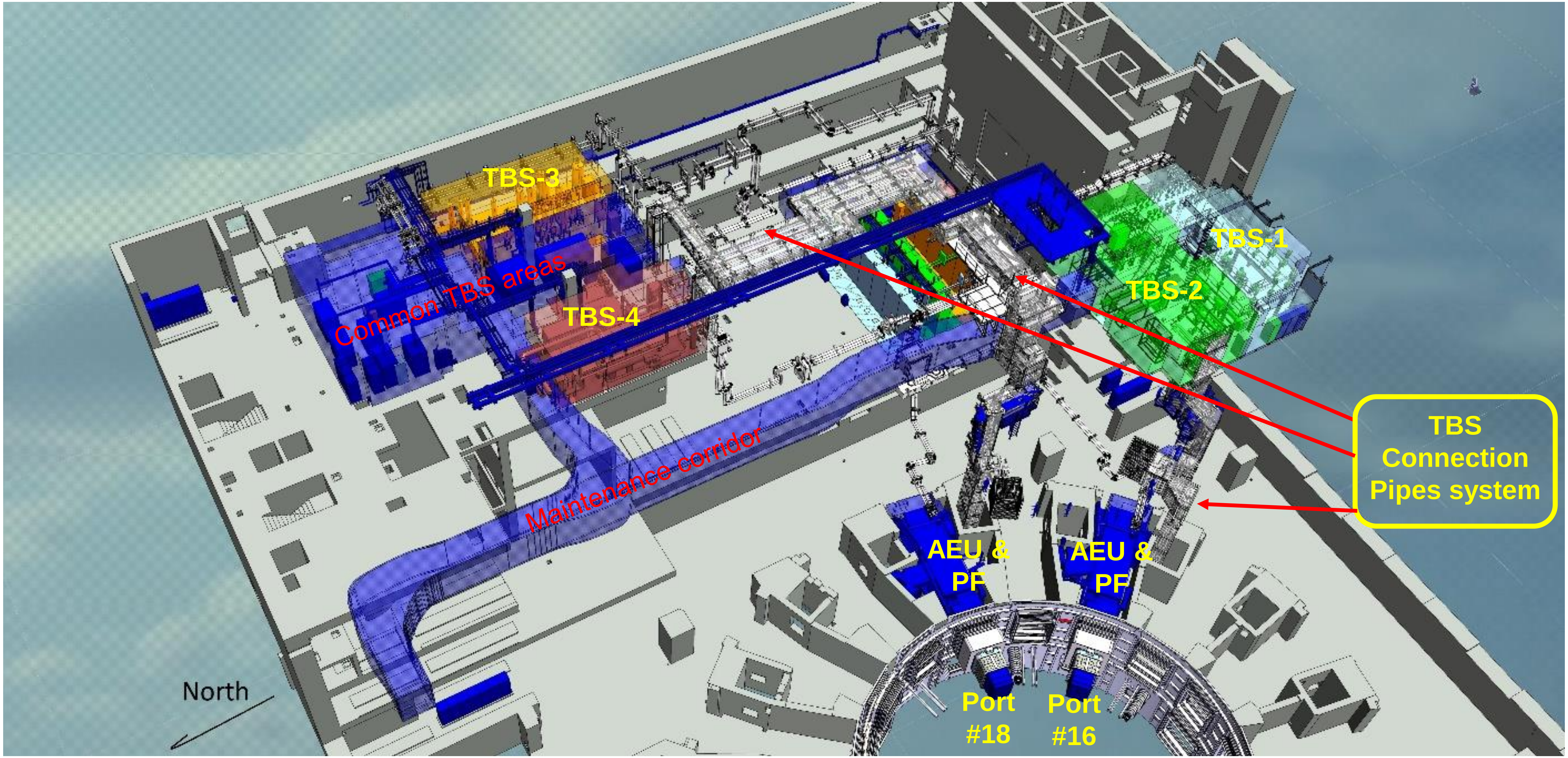
NAS : Neutron Activation System

AEU : Ancillary Equipment Unit

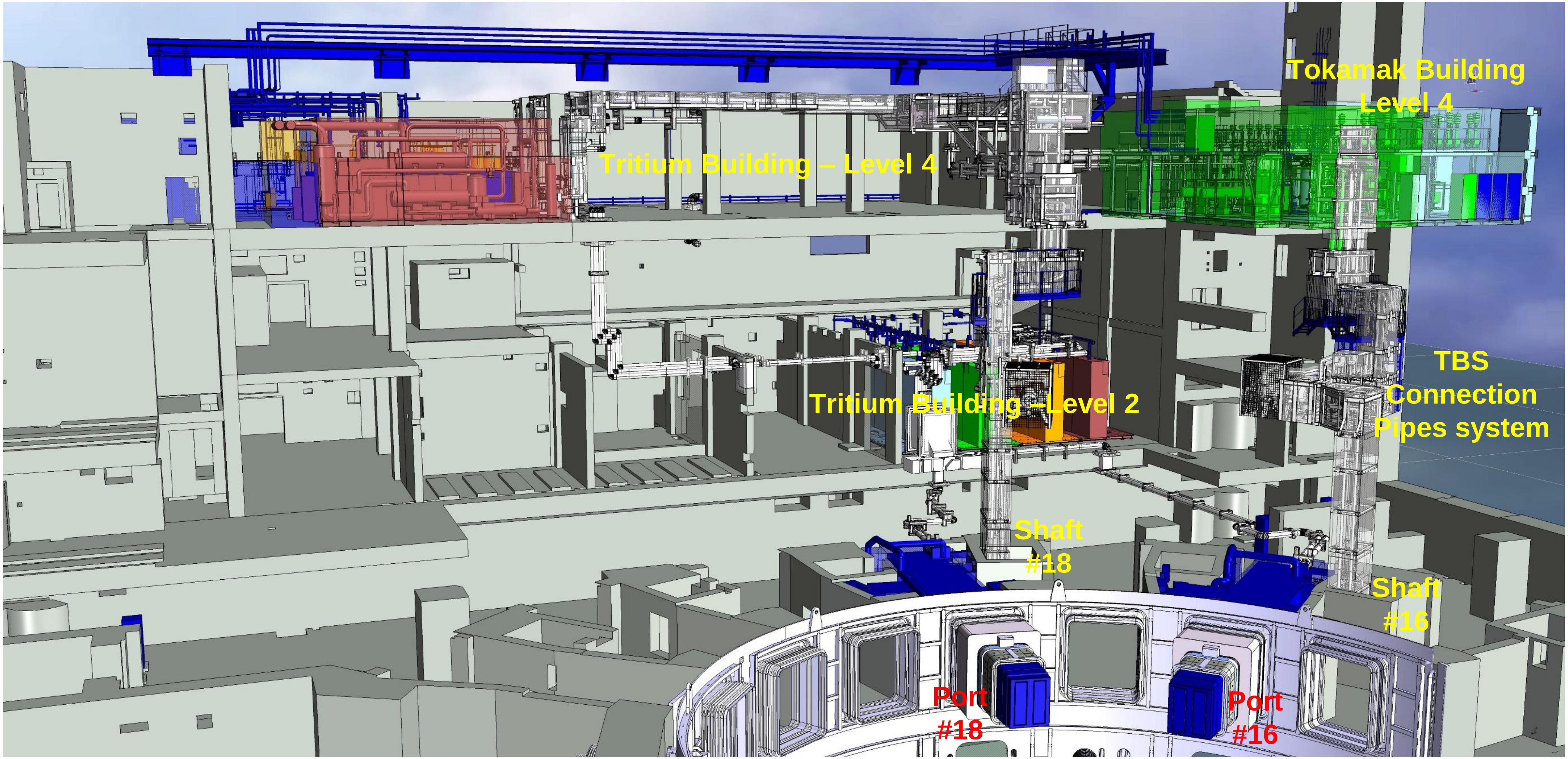
PF : Pipe Forest



Overall View of the 4 Test Blanket Systems within the Tokamak Complex



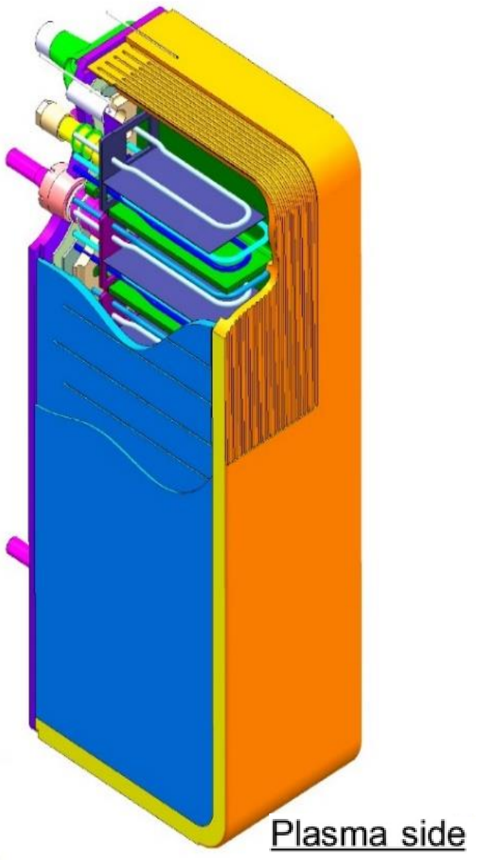
Location of the 4 Test Blanket Systems within the Tokamak Complex



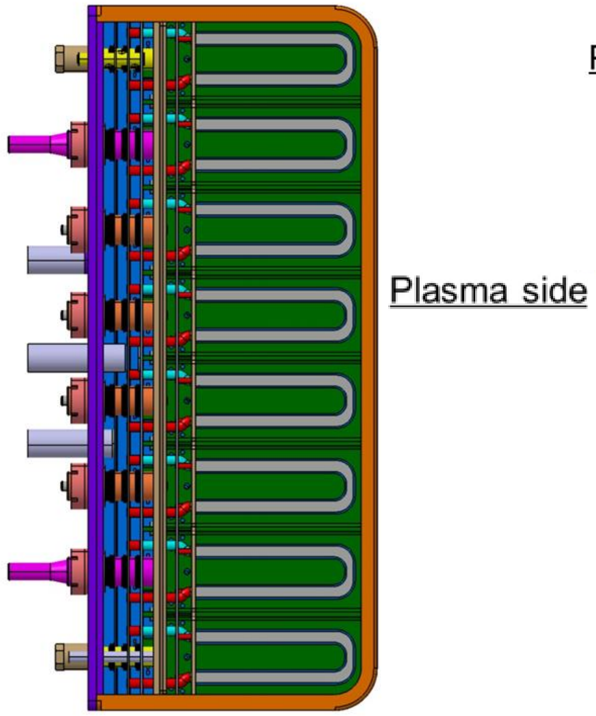
View of the internals of the four TBMs of the Initial Configuration

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

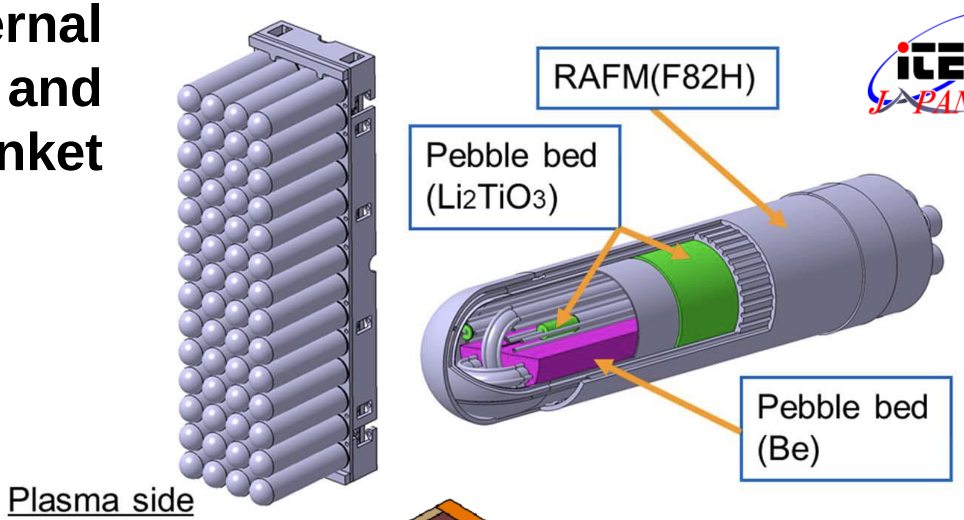
EU-WCLL



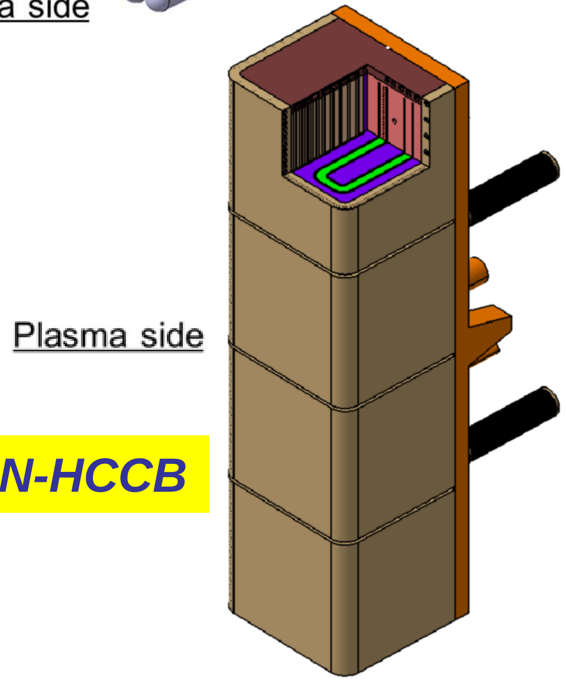
EU/KO-HCCP



JA-WCCB



CN-HCCB



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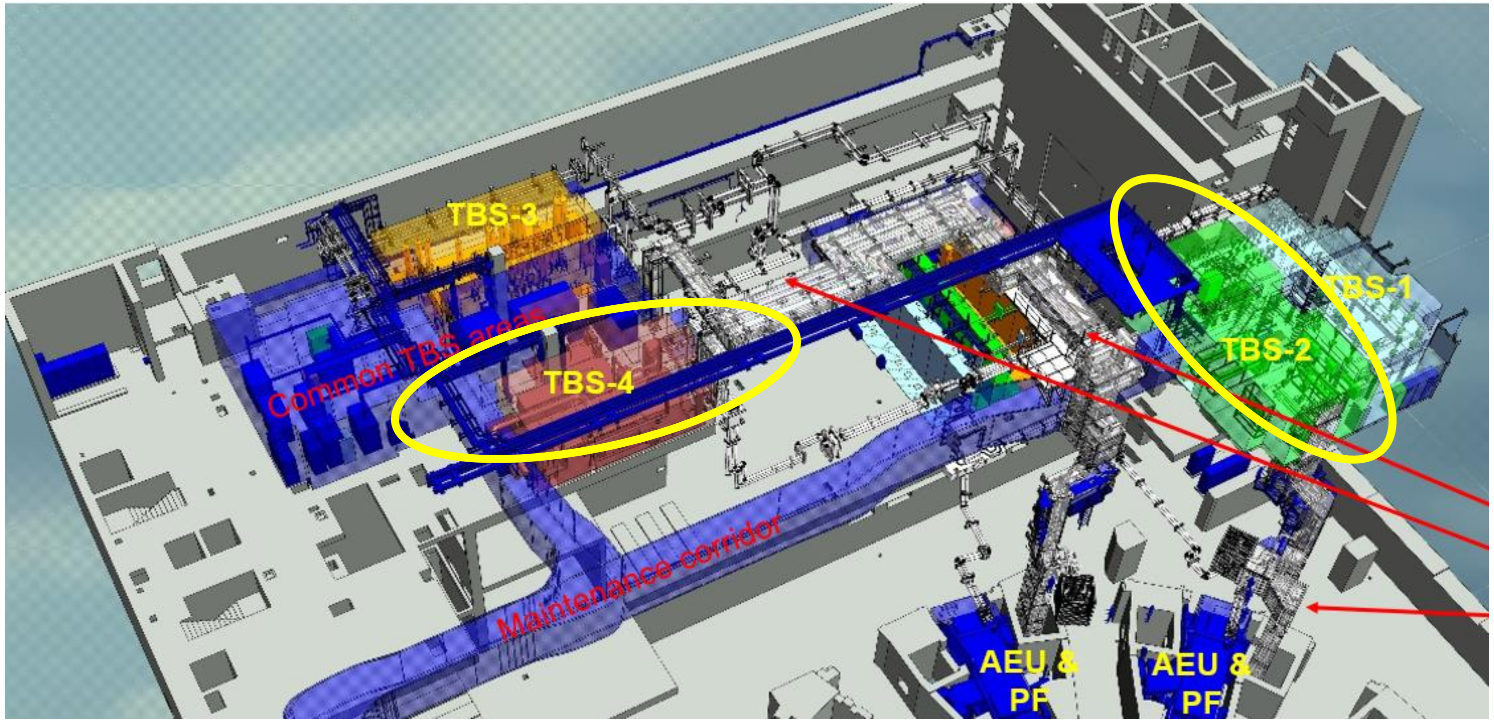
Example of a typical Helium Cooling System (+CPS)

For each of the two He-coolant system + CPS in ITER:
Footprint : ~80 m²
Height ~7 m

Main characteristics of the Helium Coolant Systems:

- 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

Need of an electrical heater of ~400 kW at 400 Vac to increase the He-temperature at inlet value.

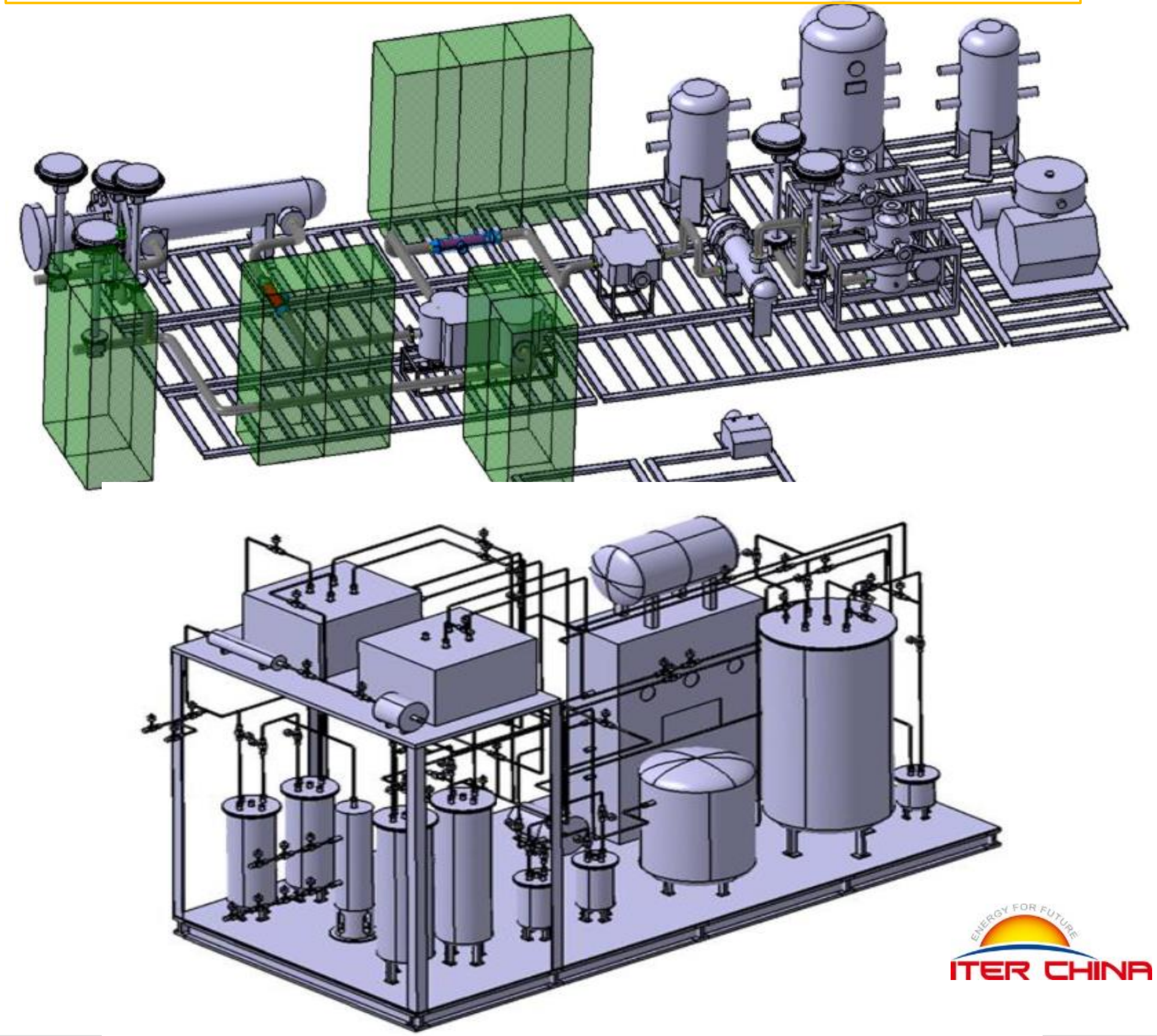


Typically, need of two circulators per system in order to improve reliability (redundancy).

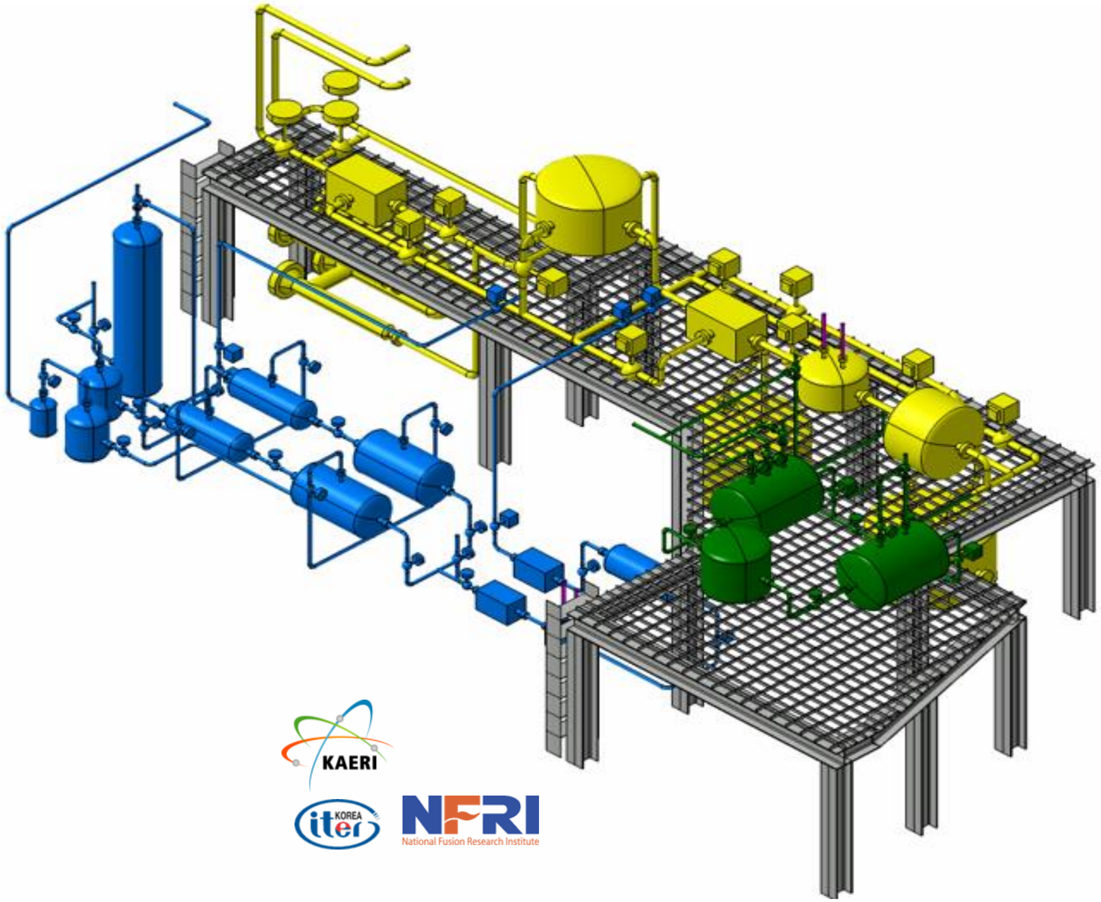
- Cooled by chilled water (inlet ~6 °C), operating with He at low temperature (<100 °C)
- Power supply: ~300 kW at 400 Vac (potential need of adding a transformer since the power is supplied is at 6.6 kV).

Examples of Conceptual Design of HCCB-HCS and of HCCR-HCS

Layout & components of the HCCB HCS (above) and CPS (below)

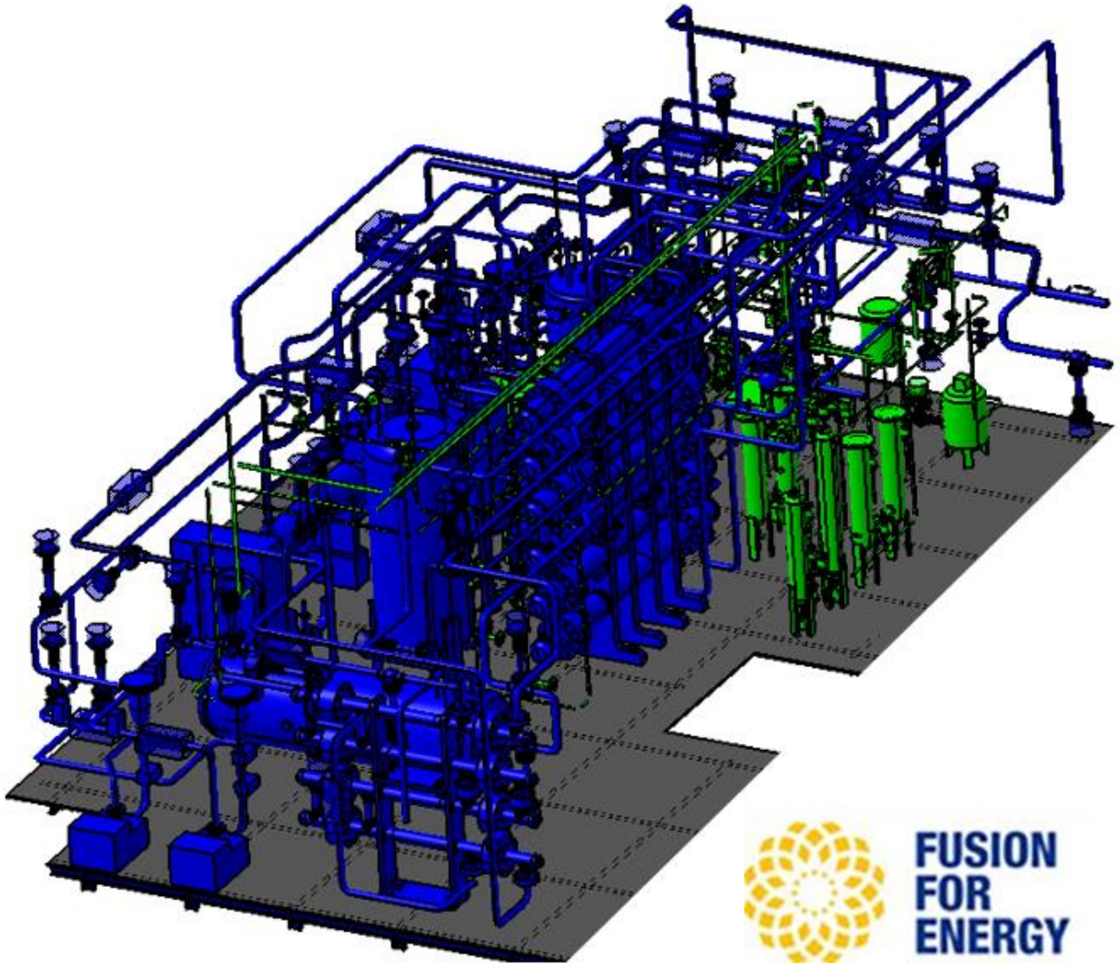


Layout & components of the HCCR HCS + CPS



Examples of Conceptual Design of WCLL-WCS and of WCCB-WCS

Layout & components of the WCLL WCS



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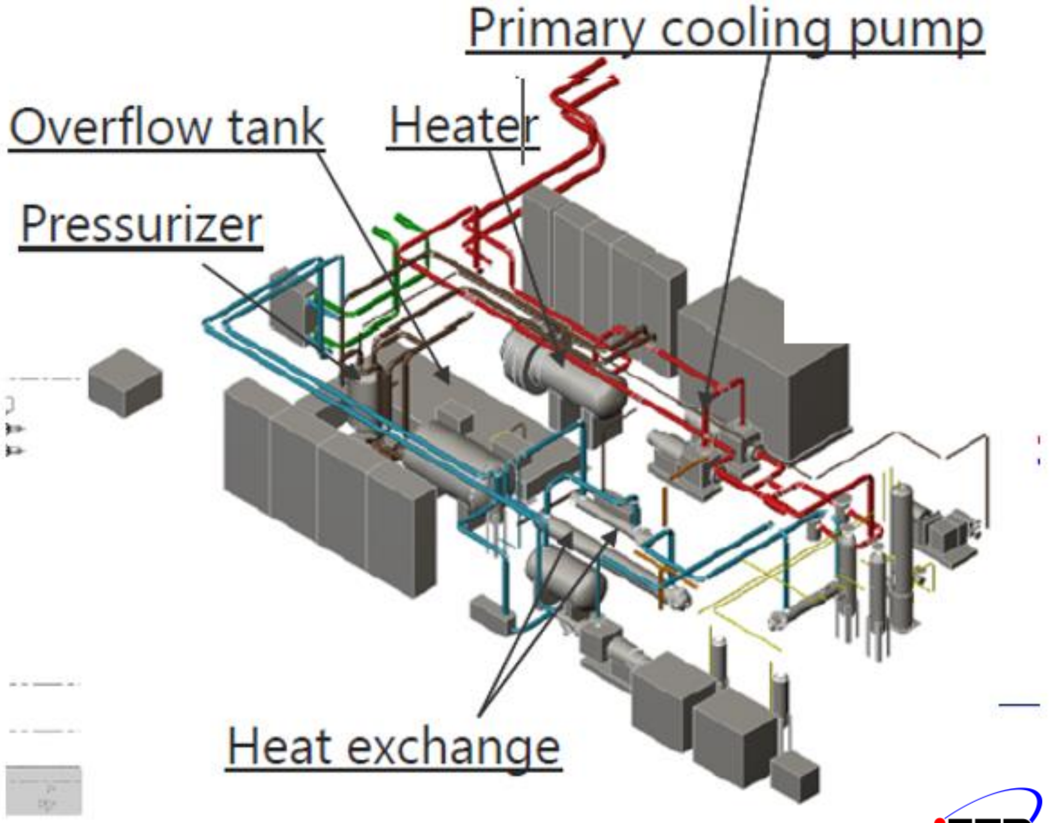
Layout & components of the WCCB WCS



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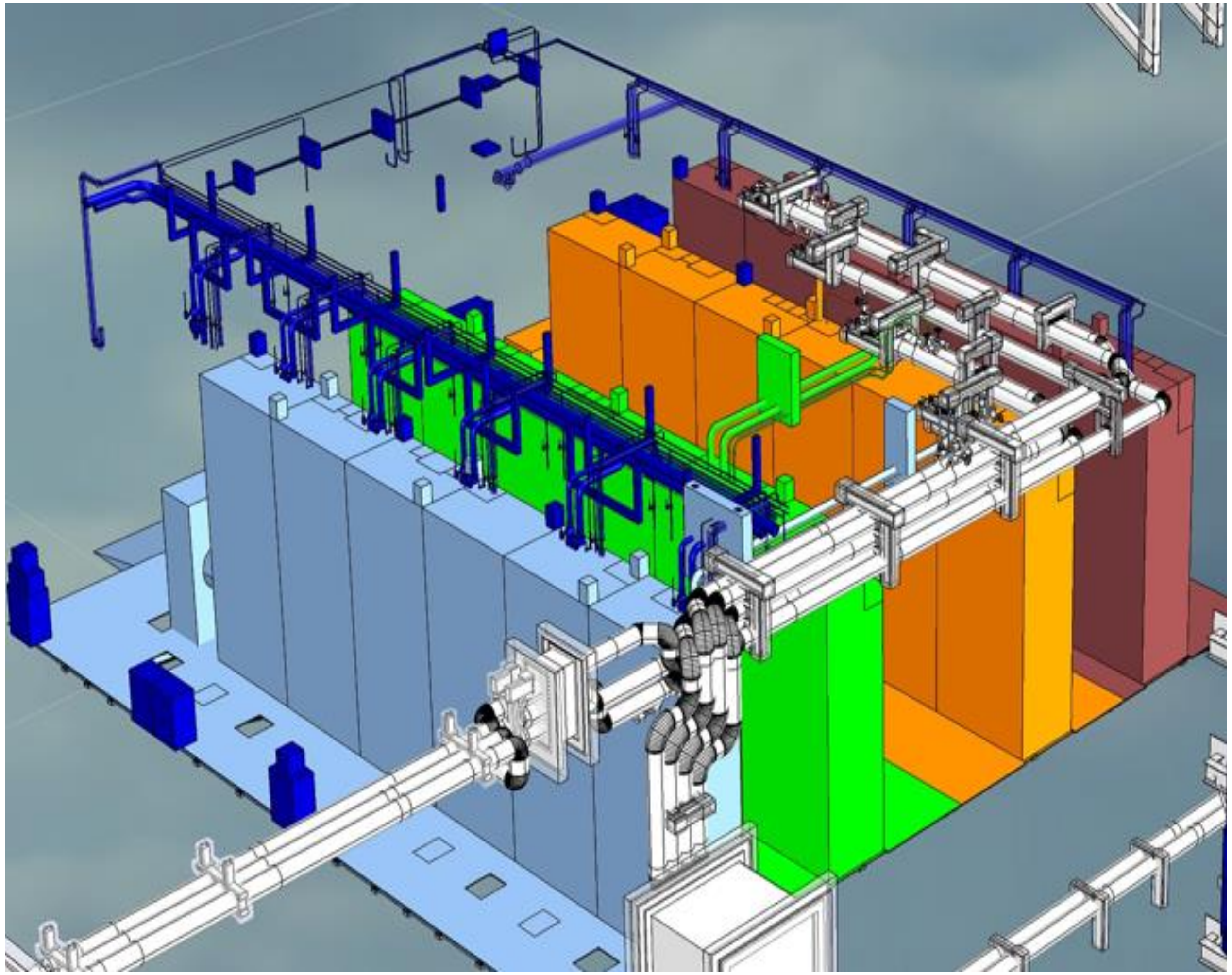
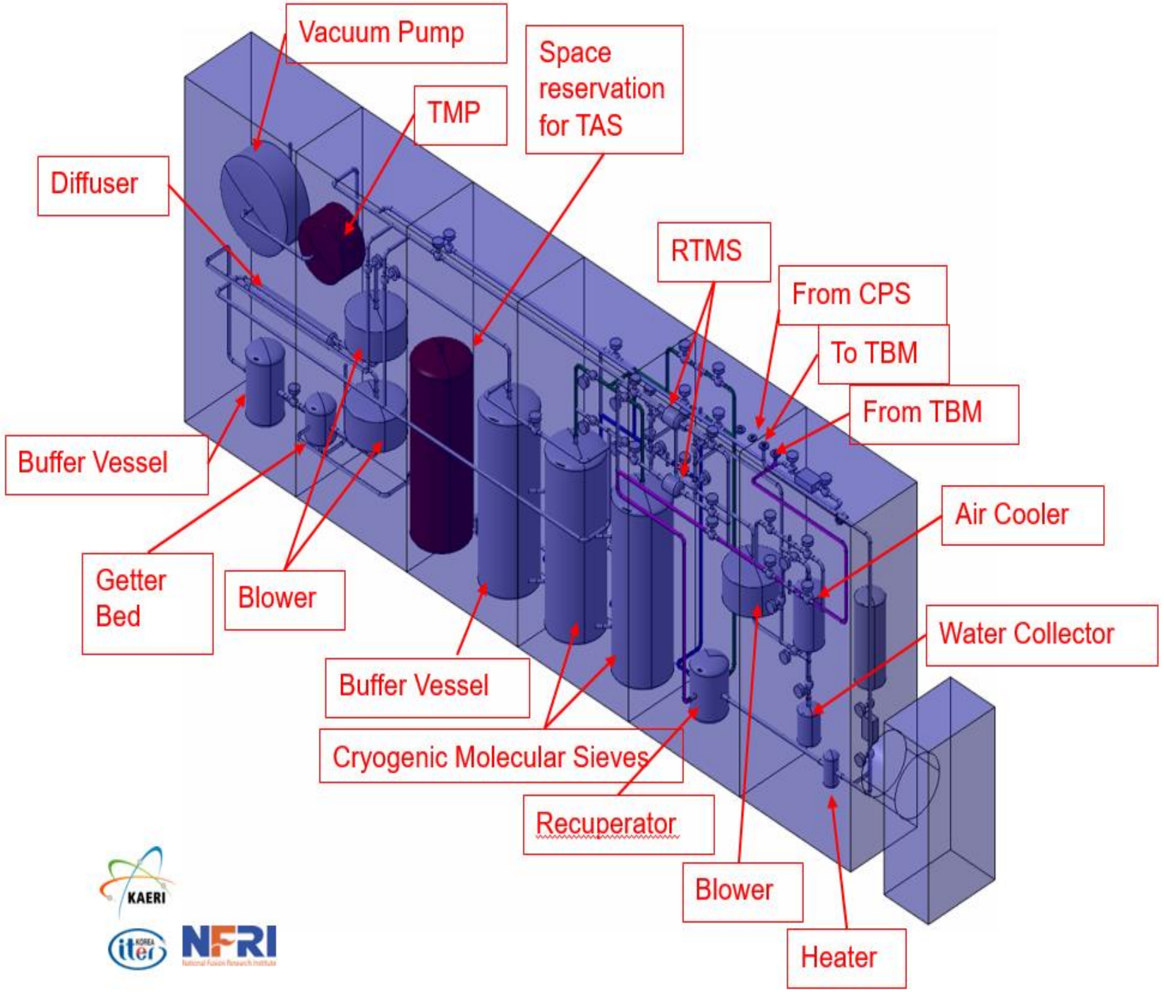
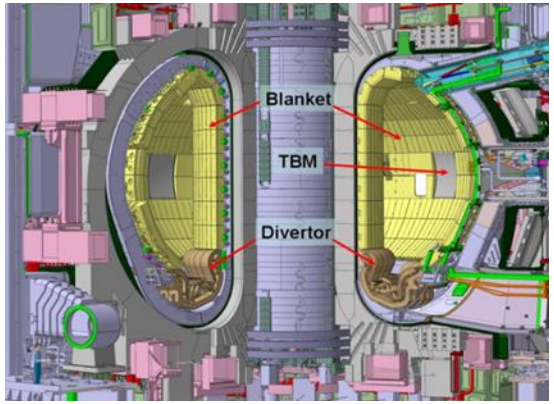
Details of room 14-L2-24: 4 Tritium Extraction Systems + 4 Tritium Accountancy Systems + four Neutron Activation Systems

Volume space reservation for the 4 TBSs (e.g., glove boxes)



Example of components integrated in the space





3 - TBM Program Test Plan and Objectives

Main Objectives of the TBM Program

➔ They will be achieved by using DEMO BB design parameters, DEMO-relevant BB materials and DEMO-relevant sub-systems components.

- ✓ **Operation** of a whole Test Blanket System including simultaneously all sub-systems, therefore simulating for the first time the operation a whole DEMO breeding blanket systems under relevant DEMO-conditions
- ✓ **Validation** of the nuclear response predictions with existing modelling codes and nuclear data during TBS operations ➔ Extrapolation to DEMO BB design, including Tritium Breeding Ratio
- ✓ **Experimental verification** of the TBMs thermo-mechanical behaviour at relevant temperature and volume heat sources using the DEMO structural materials (i.e., RAFM steels).
- ✓ **Demonstration** of heat removal with high temperature/high pressure coolant relevant for electricity production in DEMO BBs.
- ✓ **Demonstration** of the tritium management, including validation of Tritium extraction techniques and permeation reduction capability. **Validation** of modelling for extrapolation to DEMO.
- ✓ Tritium Breeding Blanket **performance** for an extended period of time in order to obtain initial reliability data ➔ confirmation of the above performance for a DEMO-relevant period of time
- ✓ Post-Irradiation Examinations (**PIEs**) for TBM material/process data in the IMs premises (after transfer to the IMs premises from the IO Hot Cell)

Comparison ITER/DEMO Operating Conditions

Parameters (TBM relevant)	ITER H phase Design Values	ITER DT phase Design Values	DEMO Typical Values	Comparison ITER versus DEMO
Surface heat flux on First Wall (MW/m^2)	**0.17** (typical 0.08)	**0.30** (typical 0.15)	**0.5**	Lower but relevant for DEMO using engineering scaling
Neutron wall load (MW/m^2)	-	**0.78**	**2.5**	Lower but relevant for DEMO using engineering scaling
Pulse length (sec)	Up to **400**	400 /up to **3000**	quasi-continuous	Relevant even if for some aspects there is the need of significant modeling R&D
Duty cycle	**0.22**	**> 0.22**	-	-
Average neutron fluence on First Wall (MWa/m^2)	-	**0.1** *(first 10 y)* **up to 0.3** *(EOF)*	**7.5**	Much lower, need of tests in other appropriate facilities

➔ Except for the long-term neutron irradiation effects, the Tritium Breeding Blanket performance and behaviour can be validated in ITER by operating the Test Blanket Systems provided the TBMs are made with the same materials and technologies as for the DEMO Breeding Blankets.

➔ In order to approach the DEMO operating conditions, an **"Engineering scaling"** needs to be applied. Therefore, for each TBM design, different TBM versions are tested during the different ITER phases

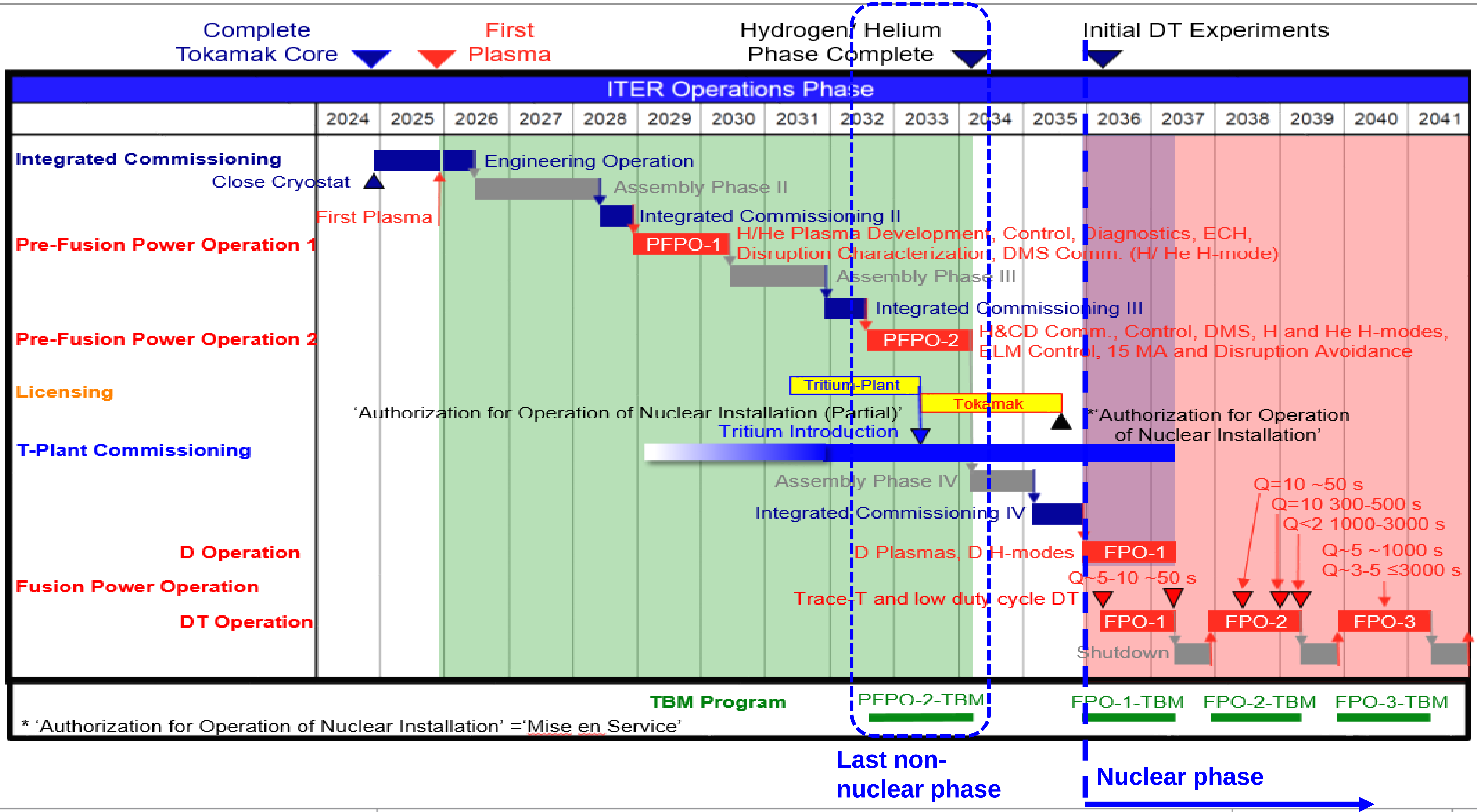
Adopted Strategy for the TBM Program Testing Plan

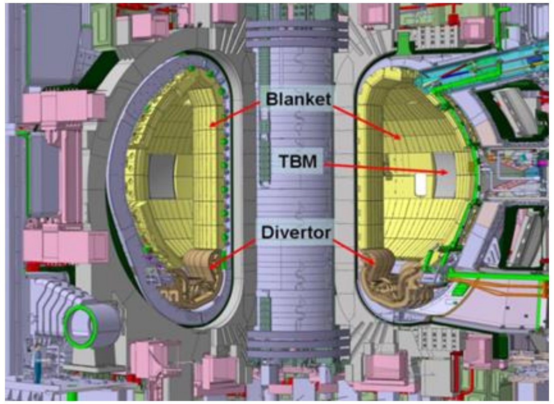
- The TBM testing plan has to be adapted to the ITER operation plan ➔ Need of testing several TBM versions per each TBS in order to account:
  - ✓ of the different ITER operating conditions while simulating the DEMO conditions (i.e., engineering scaling) and,
  - ✓ of the use of different required instrumentation.
- **The TBMs will be replaced at each Long Term Maintenance (LTM) shutdown** *(approximately each 2 years).*
- To replace a TBM implies to replace the whole TBM Port Plug and to transfer all the components of the TBM Port Cells in the Hot Cell using the RH Transfer Cask.

Typical TBS testing sequence:

- TBS learning/validation phase *(also for licensing)*
  - *the PFPO-2 TBM: during PFPO-2 [initial H phase and H-He phase]*
- TBS data acquisition phase
  - *the FPO-1 TBM: during FPO-1 [D-D & initial D-T phase (low duty)]*
  - *the FPO-2 TBM: during FPO-2 [improved D-T phase (higher duty)]*
  - *TBMs for FPO-3 & following FPO-x [long pulses]: possible new TBM/TBS concepts*

ITER Research Plan and associated TBM Program





4 – Activities carried out in IO in support of the Test Blanket Systems

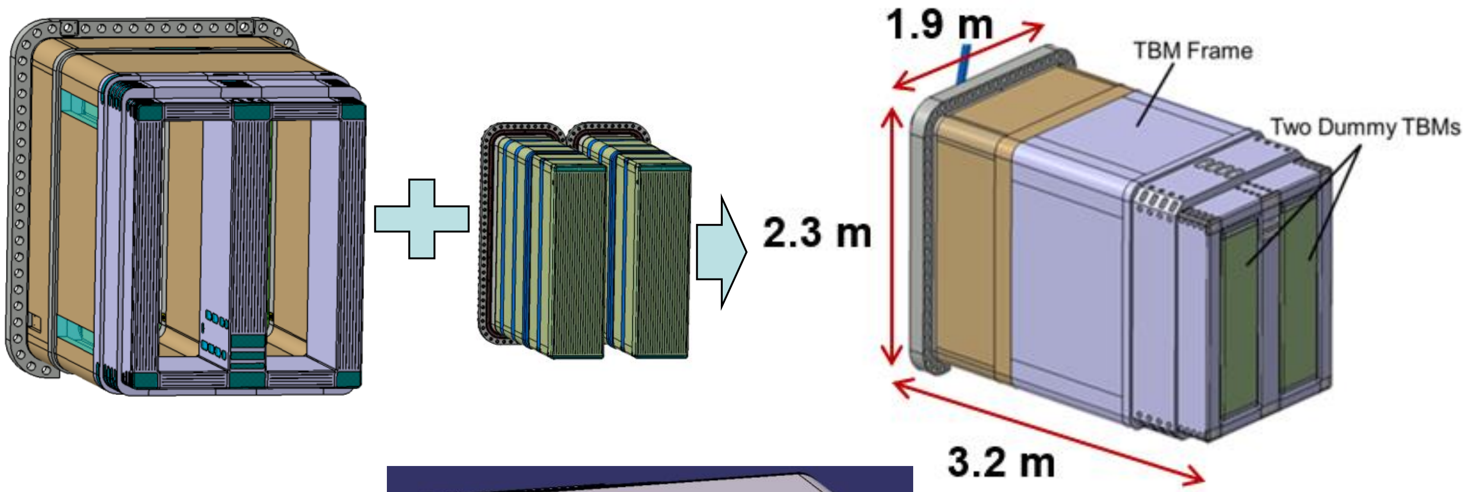
A - Water-cooled Steel Frame and Dummy TBMs

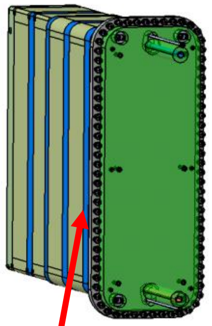
B - PC Common Components: associated Maintenance Strategy and Maintenance Tools/Equipment Development

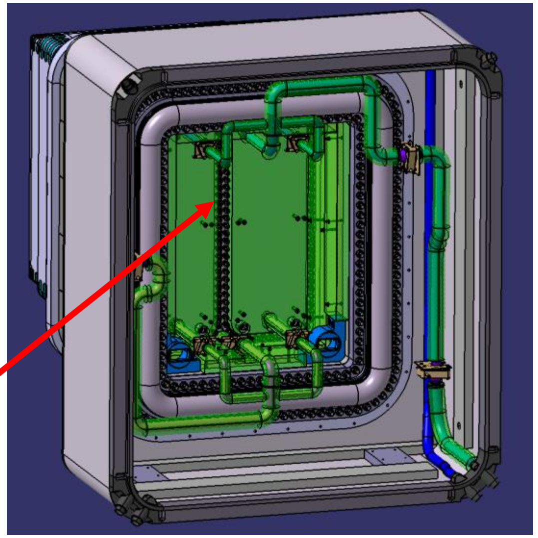
C - Final design and Procurement of the TBS Connection Pipes System

A - Water-cooled Steel Frame and Dummy TBMs

- The Port Plug needs to ensure vacuum tightness
- Dummy TBMs needed if one TBM-Set is not available







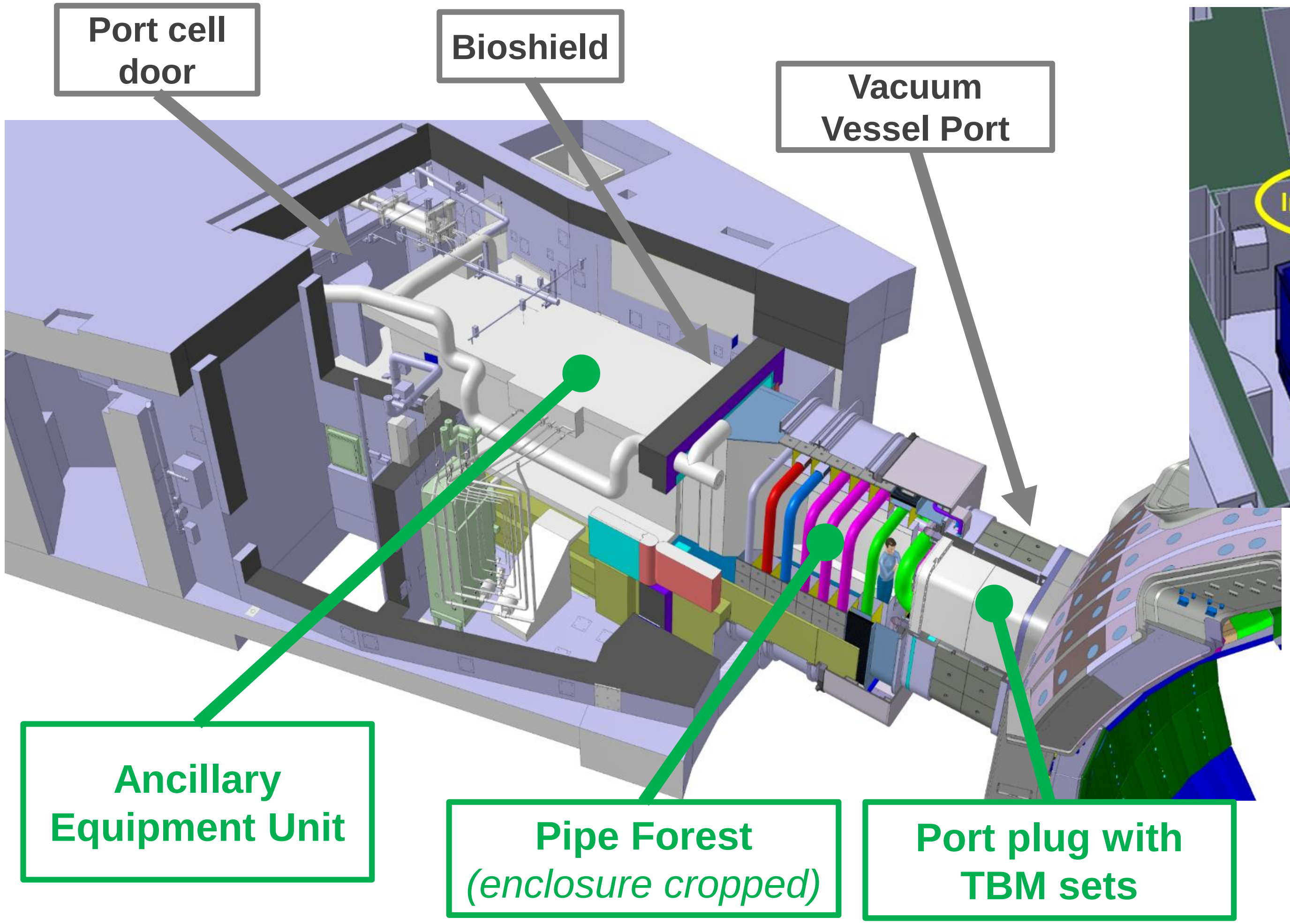
Metal gasket to ensure vacuum

Need to test leakage performance of metal gaskets

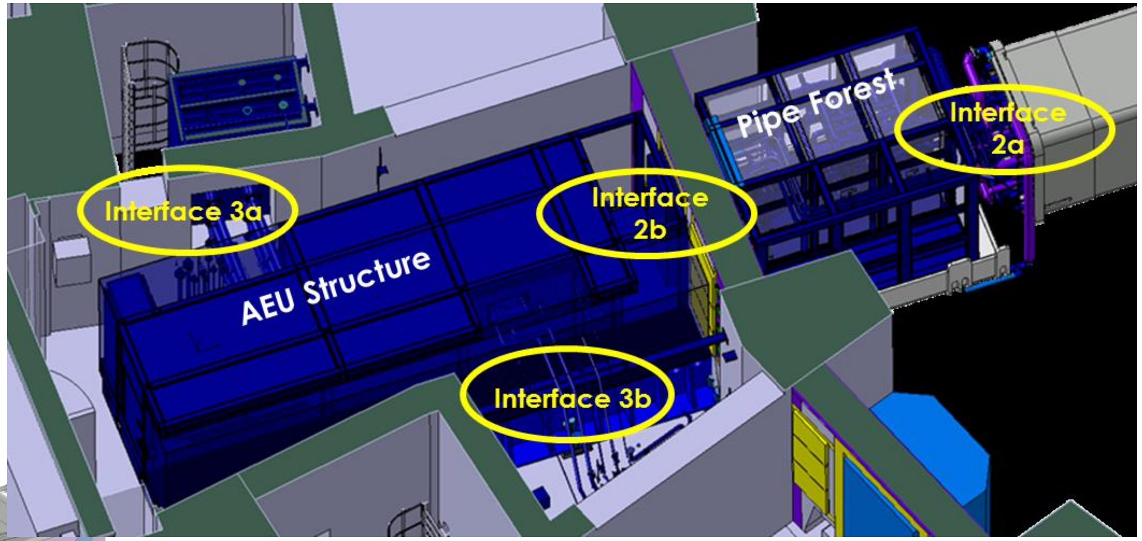
*Testing of metal gaskets for Vacuum sealing & leak test in **scale-1 rig** at IO-site (2019)*

(Technetics Group-France)

B - PC Common Components: Maintenance Strategy & Tools (1/4)



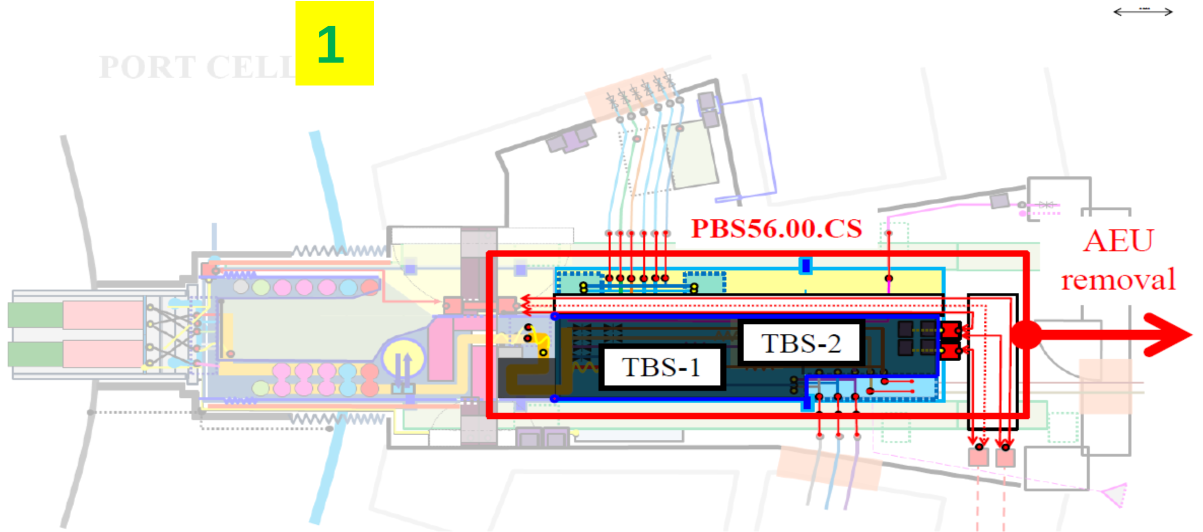
Current design of common TBM Port Cell components, including an enclosures for Tritium containment

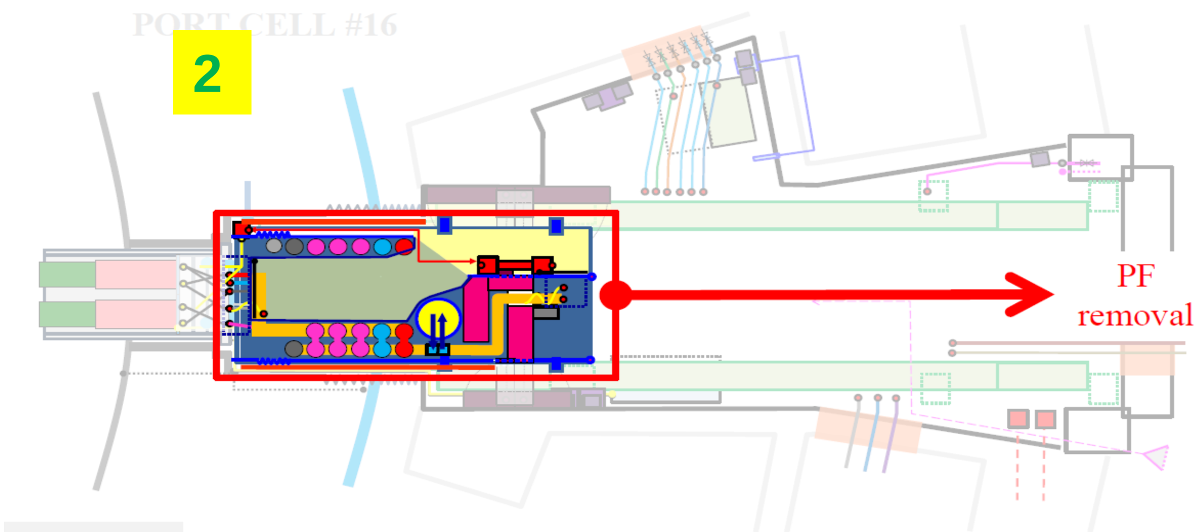


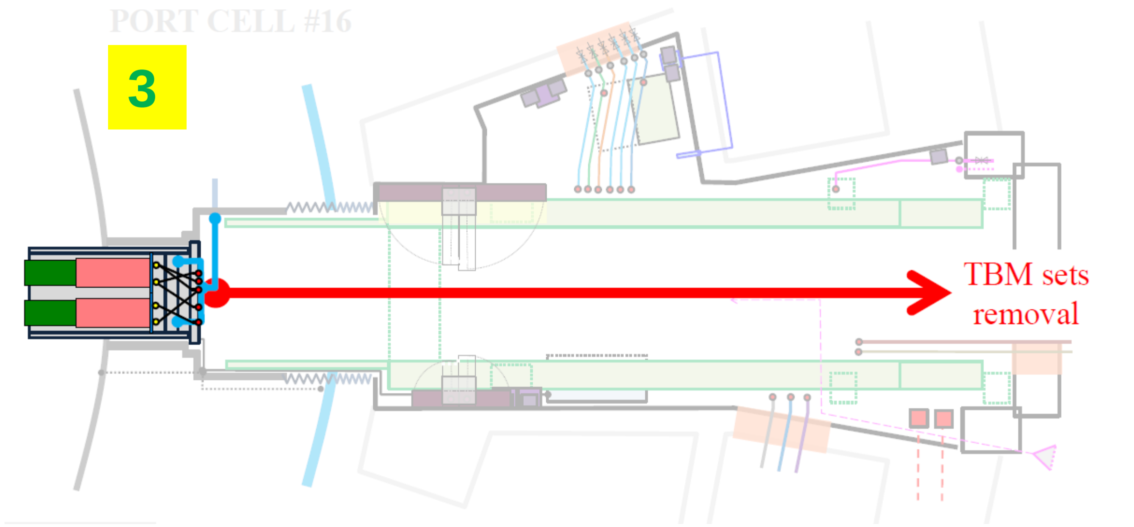
Schematic view of the main common components in TBM Port Cell and location of the main interface points 2a, 2b, 3a, 3b where pipes/cables need to be connected/disconnected *(e.g., cutting/ re-welding)* at each Long Term Maintenance for performing the TBM Port Plug replacement.

B - PC Common Components: Maintenance Strategy & Tools (2/4)

- Maintenance strategy for TBM Port Plug replacement – Needed sequential removal of:
  1. Ancillary Equipment Unit
  2. Pipe Forest
  3. TBM PP (using ITER Transfer Cask)
- Transfer to the Hot Cell
- Reinstallation in the reverse order
- Specific tools and equipment are needed for connection/disconnection (e.g., cut/weld)

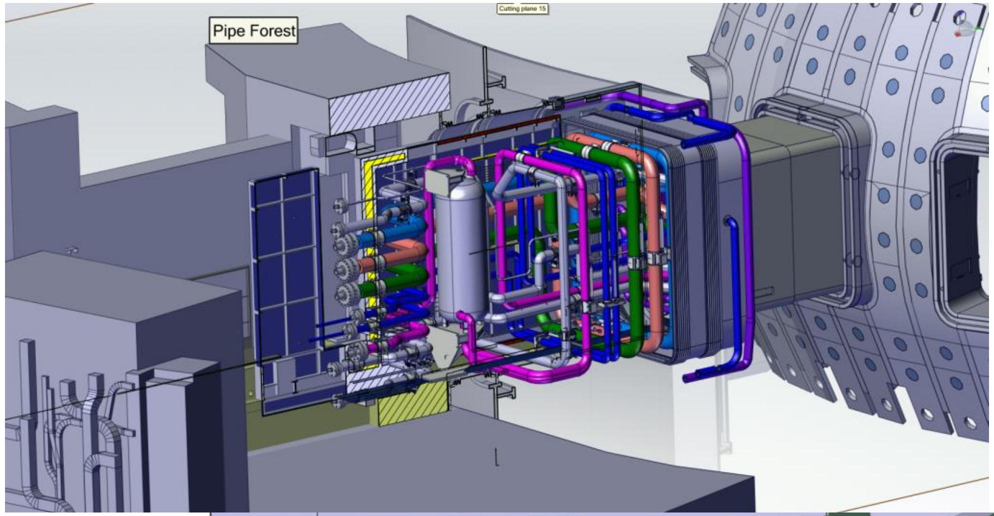


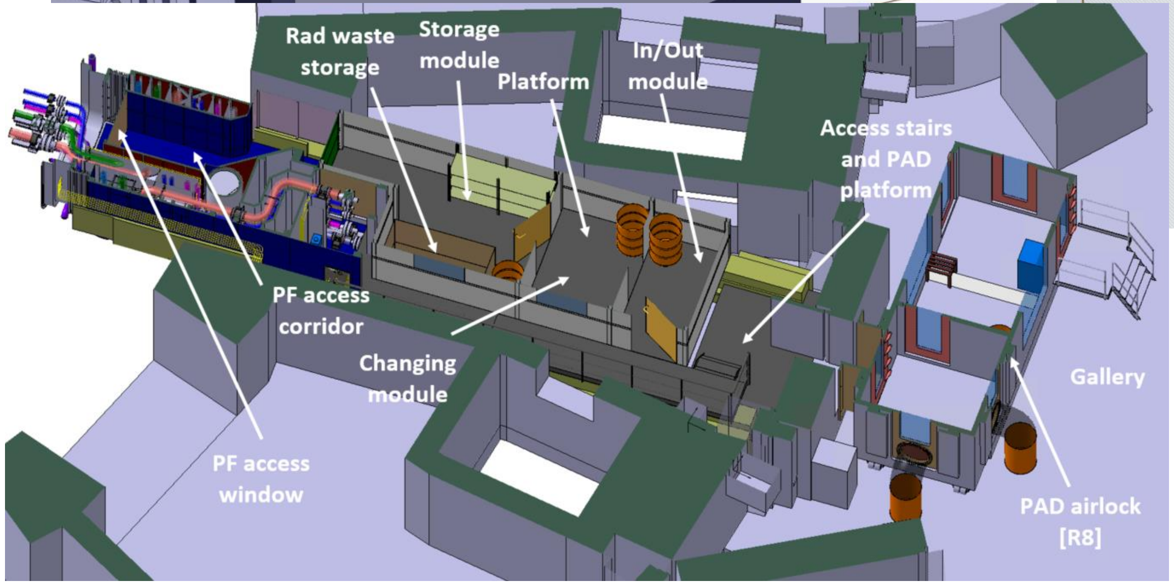


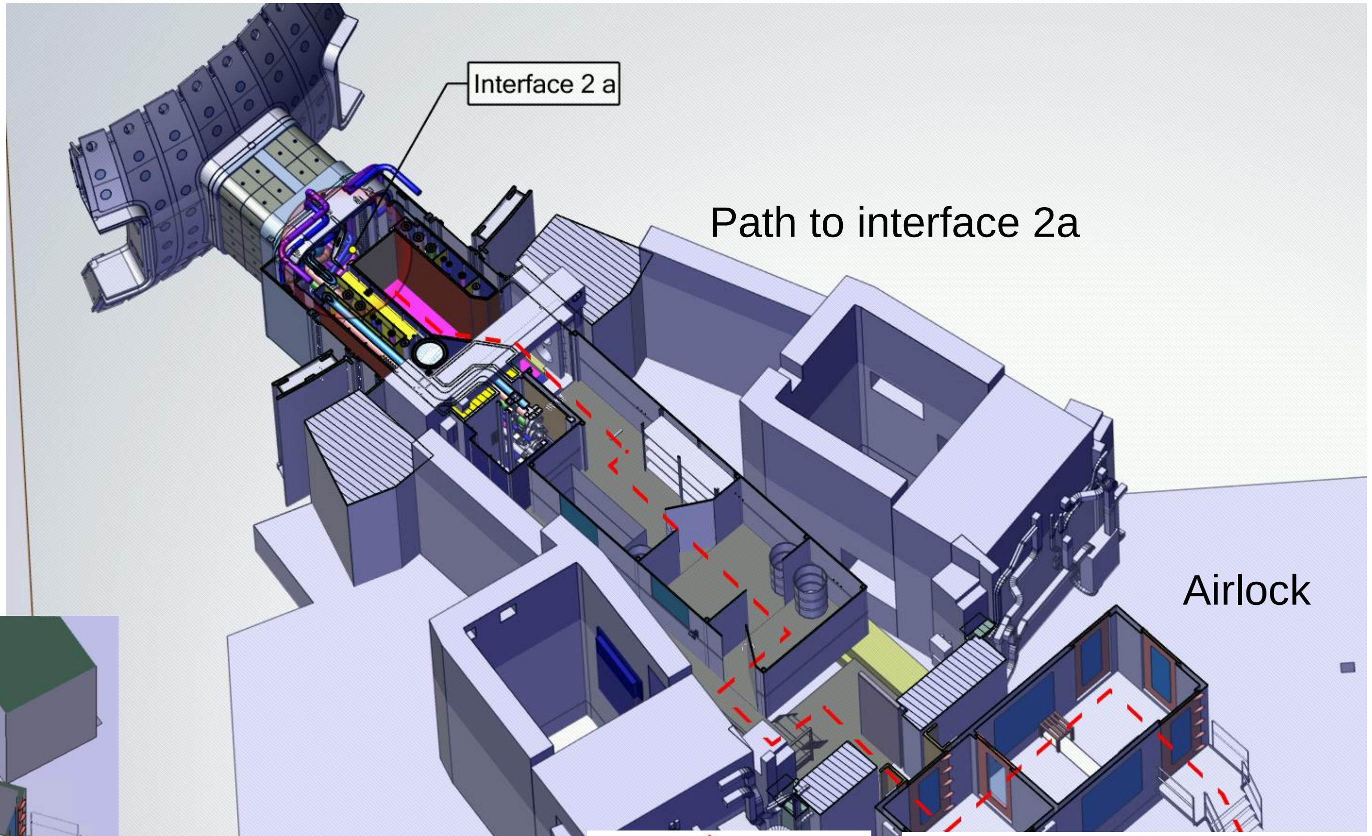


B - PC Common Components: Maintenance Strategy & Tools (3/4)

- Example of Connection/disconnection operations at interface 2a and associated tooling

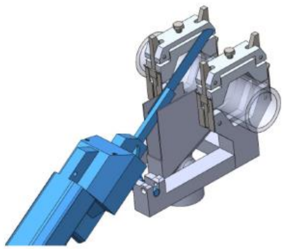






Pipes Align tool

Welding tool

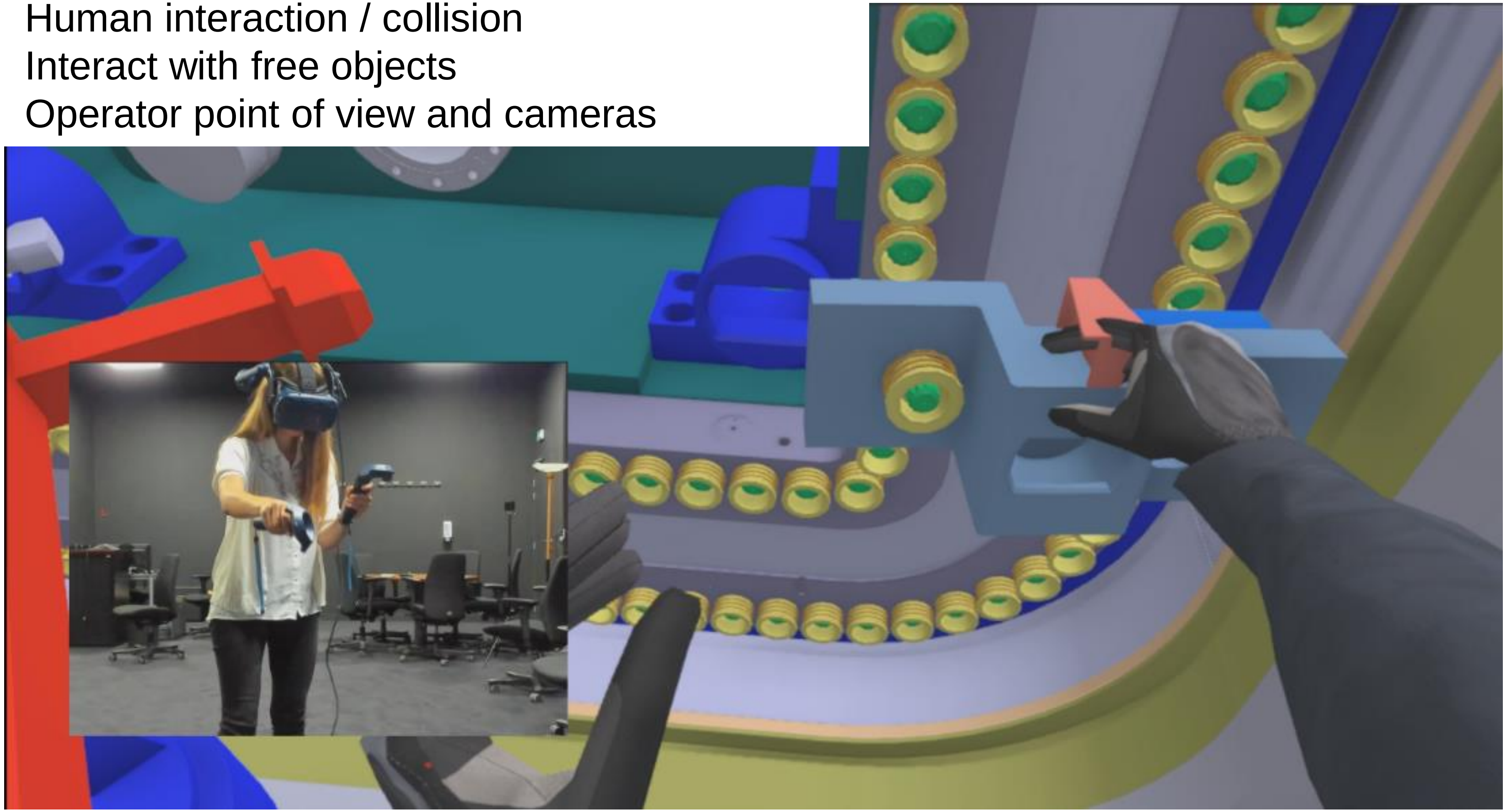


Cutting tool

B - PC Common Components: Maintenance Strategy & Tools (4/4)

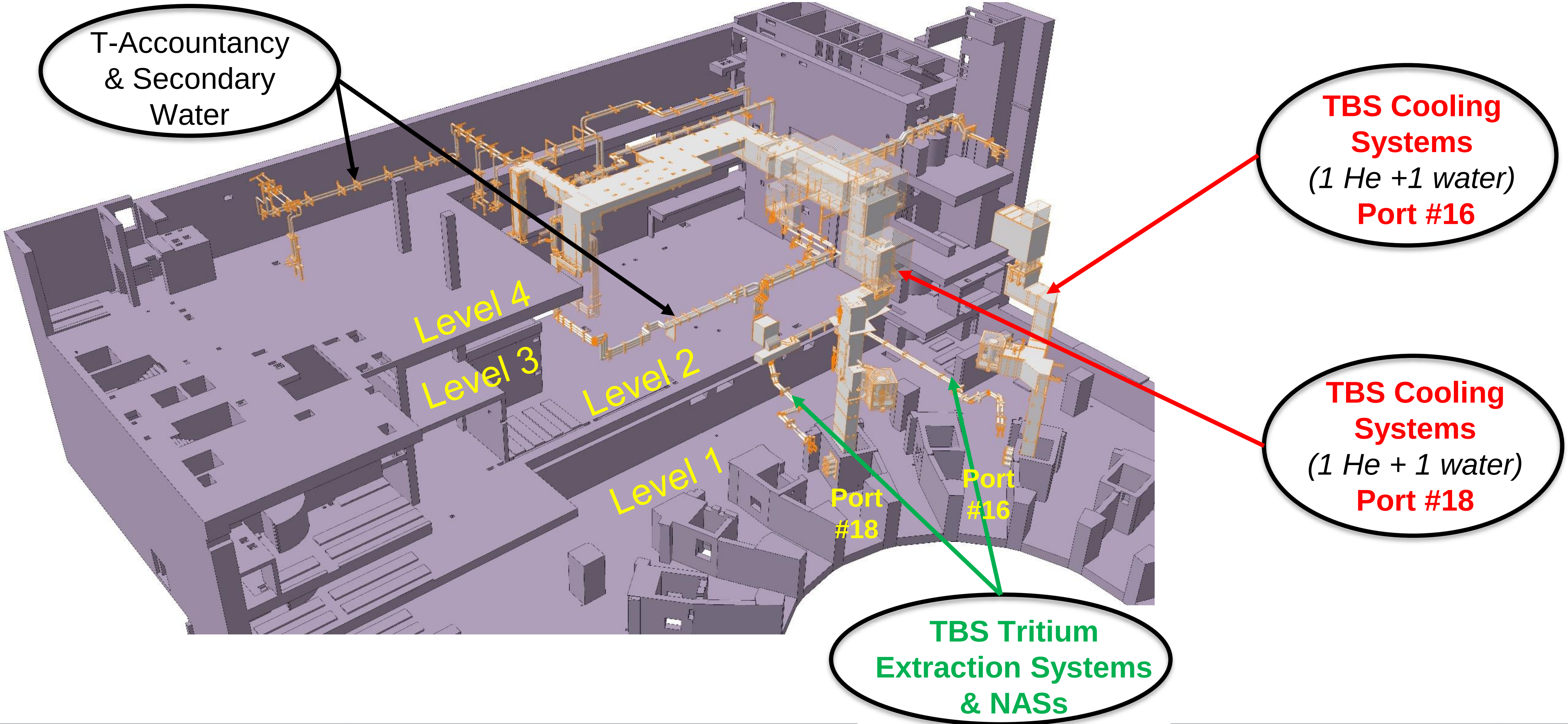
Virtual and Augmented Reality simulations for TBM Port Cells reconfiguration operations/PP replacement - Human Factor Real Time simulation (relevant also for DEMO)

- Full human manikin in the scene
- Human interaction / collision
- Interact with free objects
- Operator point of view and cameras



C - Final design and Procurement of the TBS Connection Pipes System (1/2)

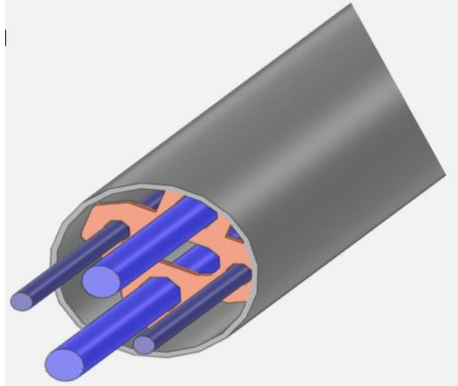
- **TBS Connection Pipes** are captive components and, therefore, need to be installed in the initial assembly phase. They involve: (i) TBS Cooling Systems, (ii) TBS Tritium Extraction Systems, (iii) Neutron Activation Systems, (iv) Tritium Accountancy Systems, (ii) Distribution of the Secondary Water System CCWS-1



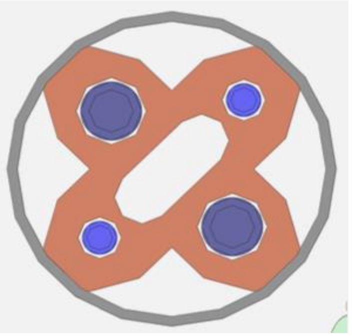
C - Final design and Procurement of the TBS Connection Pipes System (2/2)

TBS Connection Pipes are captive and, therefore, need to be assembled and installed before the First Plasma. Some parts have already been manufactured and will be installed soon.

- Connection Pipes for TBS Tritium Extraction Systems, Neutron Activation Systems, and Tritium Accountancy Systems : use of guard pipes for improving confinement.



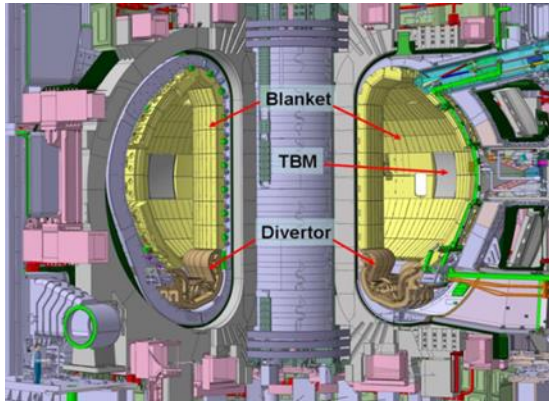
View of a TES guard pipe with two TES process pipes and two NAS process pipes inside



Front view of the guiding spacer that supports the process pipes inside the guard pipe

View of the mock-up of the guard pipe + process pipes manufactured in 2021

- Connection Pipes for TBS Cooling Systems: final design completed by mid 2023. *Need to implement Tritium Permeation Barriers (with PRF>10) inside the He-coolant pipes (Packed-cementation Alumina coating).*



5 – Examples (not exhaustive) of on-going R&D on Test Blanket Systems carried out by the ITER Members

5a – TBM structural materials

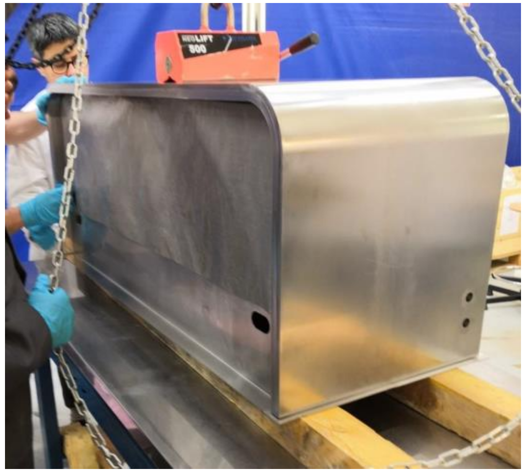
5b – Experimental loops

5c – Dedicated facilities

5a - R&D on Reduced Activation Ferritic/Martensitic Steel *(carried out by EU)*

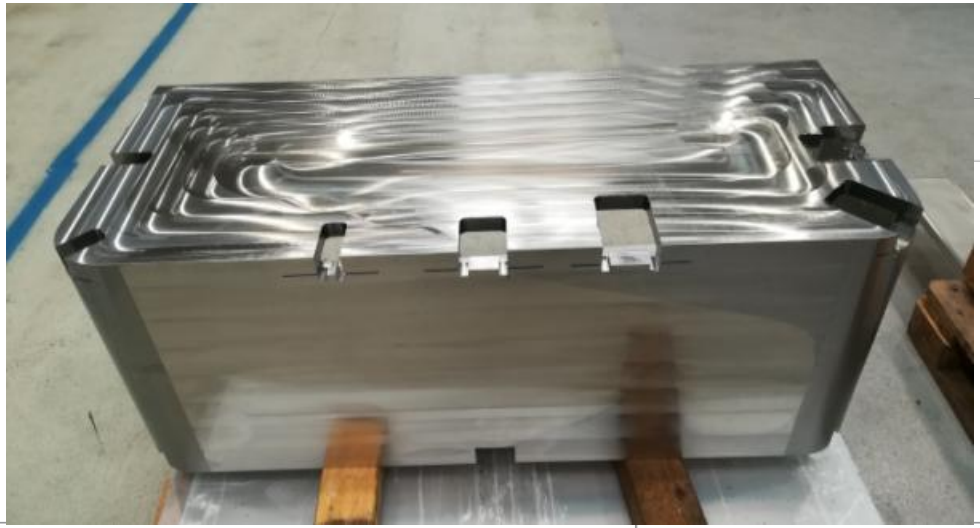
Manufacturing technologies using EUROFR-97

Welding external walls by HIPing



pWPS for the TBM box assembly

- 2-step HIP process
- EUROFER97 steel
- NDT and DT completed

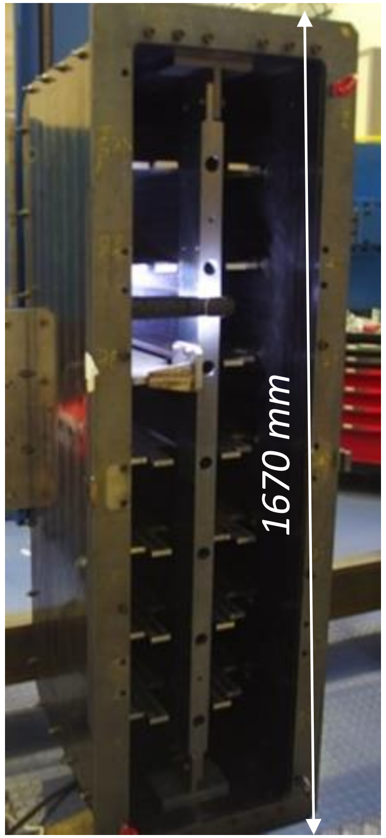


ATMOSTAT ALCEN

COMMERCY ROBOTIQUE

cea

Welding internals by robot

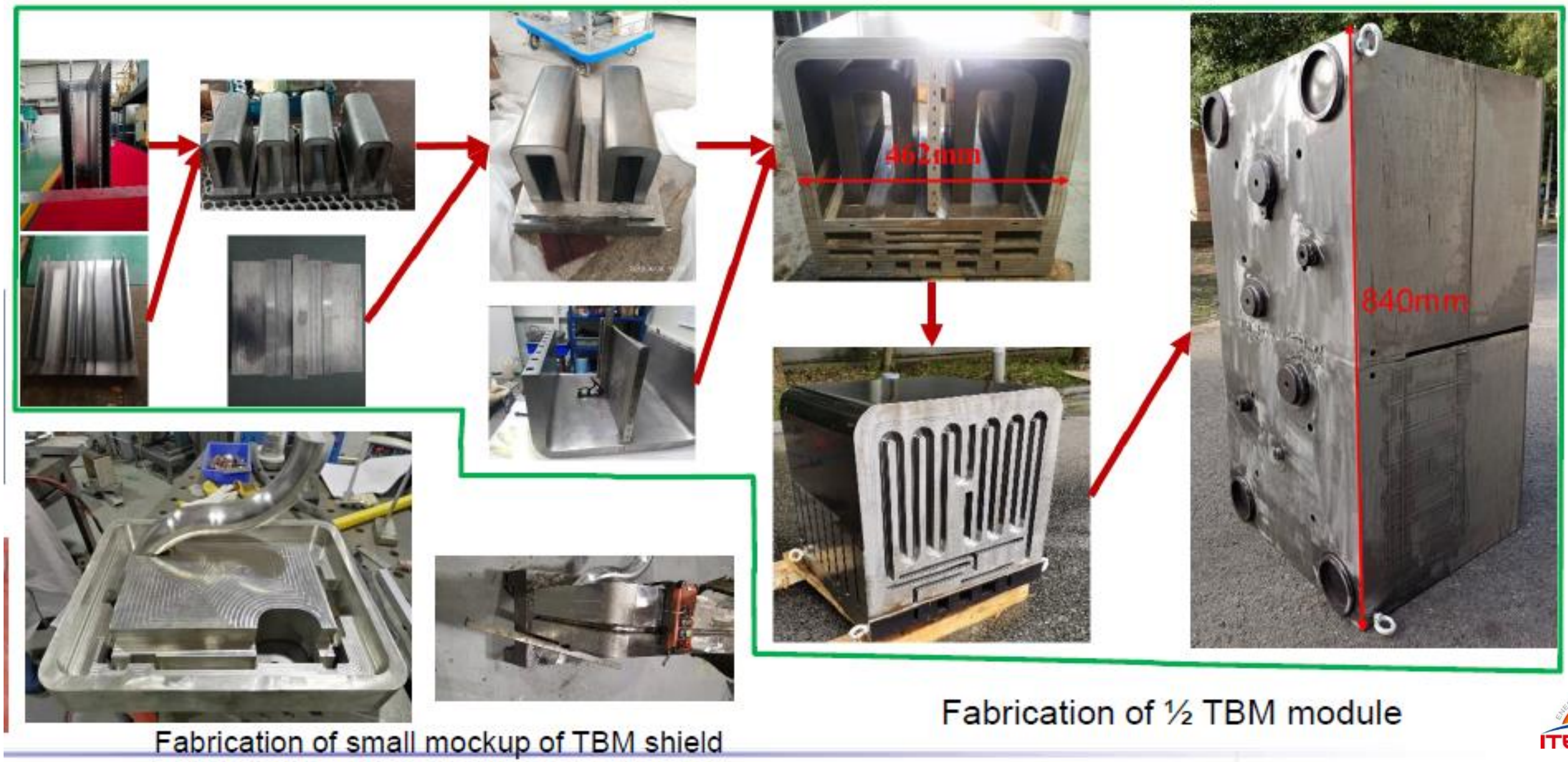


TIG welding robot assembling TBM mock-ups with narrow space accessibility

Multi-pass GTAW (Gas Tungsten Arc Welding) process

5a - R&D on Reduced Activation Ferritic/Martensitic Steel *(carried out by CN)*

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).



ITER CHINA

5b - R&D for Helium-Cooled Ceramic Breeder TBS *(carried out by CN)*

- A new He-coolant experimental loop (HeCEL-3) with electromagnetic bearing circulator and Printed-Circuit Heat Exchanger (PCHE) has been constructed. The overall operation parameters of HeCEL-3 achieve 2.5 kg/s @ 8-12MPa, operation temperature at the testing section can achieve 550°C. The performance of key components are under testing.

HeCEL-3 (2.5kg/s@8-12MPa&550°C)

ITER CHINA

5b - R&D for Helium-Cooled Solid Breeder TBS *(carried out by KO)*

- A prototype He-circulator has been developed to provide up to 1.5 kg/s of helium flow during nominal operation of the HCS and is tested using a performance test facility, HESS, to verify design parameters and performance of the He-circulator.

Helium Circulator

Helium Supply System (HeSS) for HCCR TBS HCS performance test

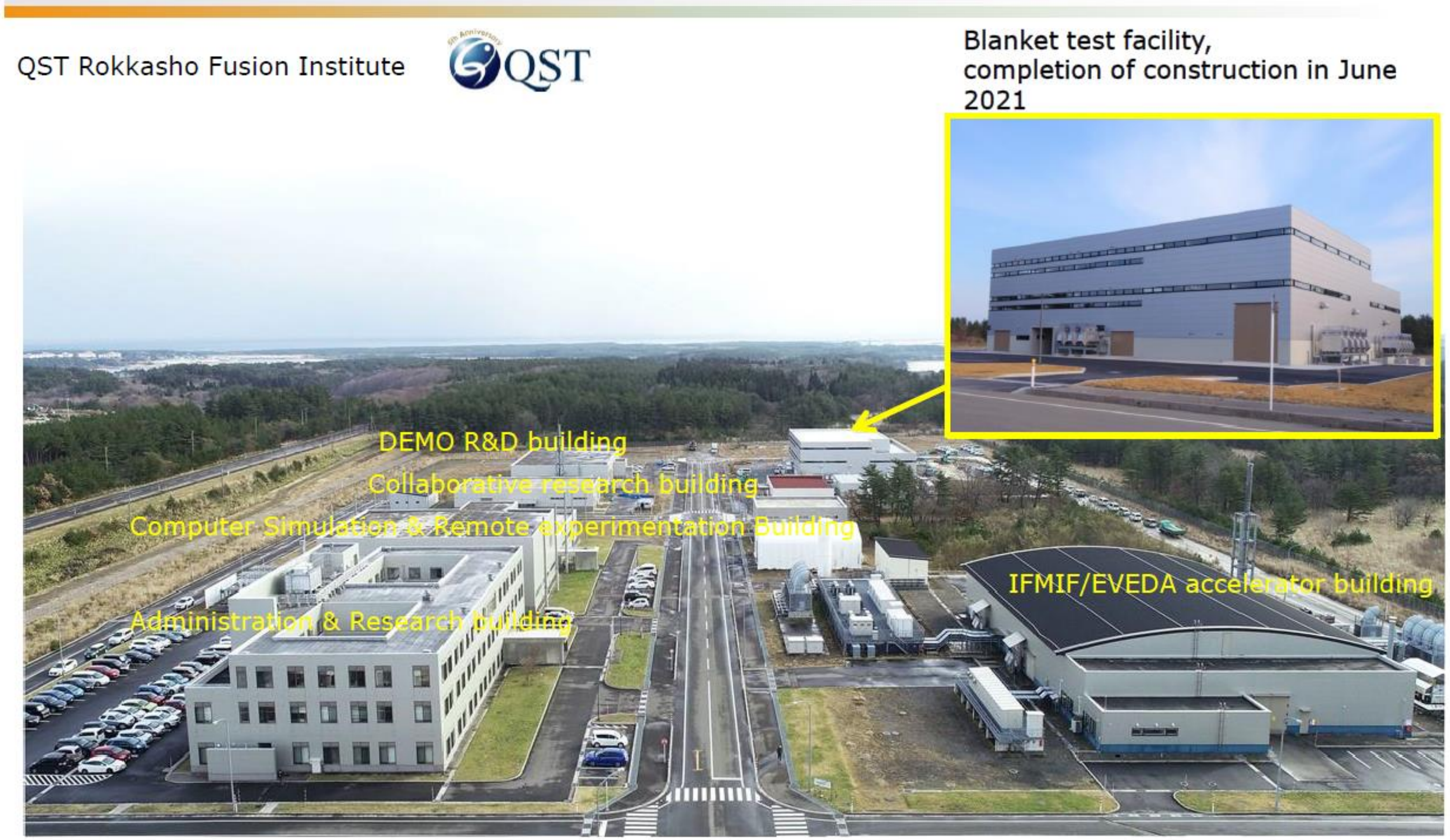
5b - R&D for Water-Cooled Lithium-Lead TBS *(carried out by EU)*

- TRIEX-II experimental facility at ENEA-Brasimone.
- Operated to determine the extraction efficiency of a gas liquid contactor for WCLL-TBS.
- The experimental campaign has been carried out using D_2 as dissolved gas in Pb-16Li stripped by He+H_2 (0.1%vol.).

FUSION FOR ENERGY

5c - R&D for Water-Cooled Ceramic Breeder TBS *(carried out by JA)*

View of the Blanket Test Facility completed in Rokkasho site in July 2021
(first of the kind in the world)

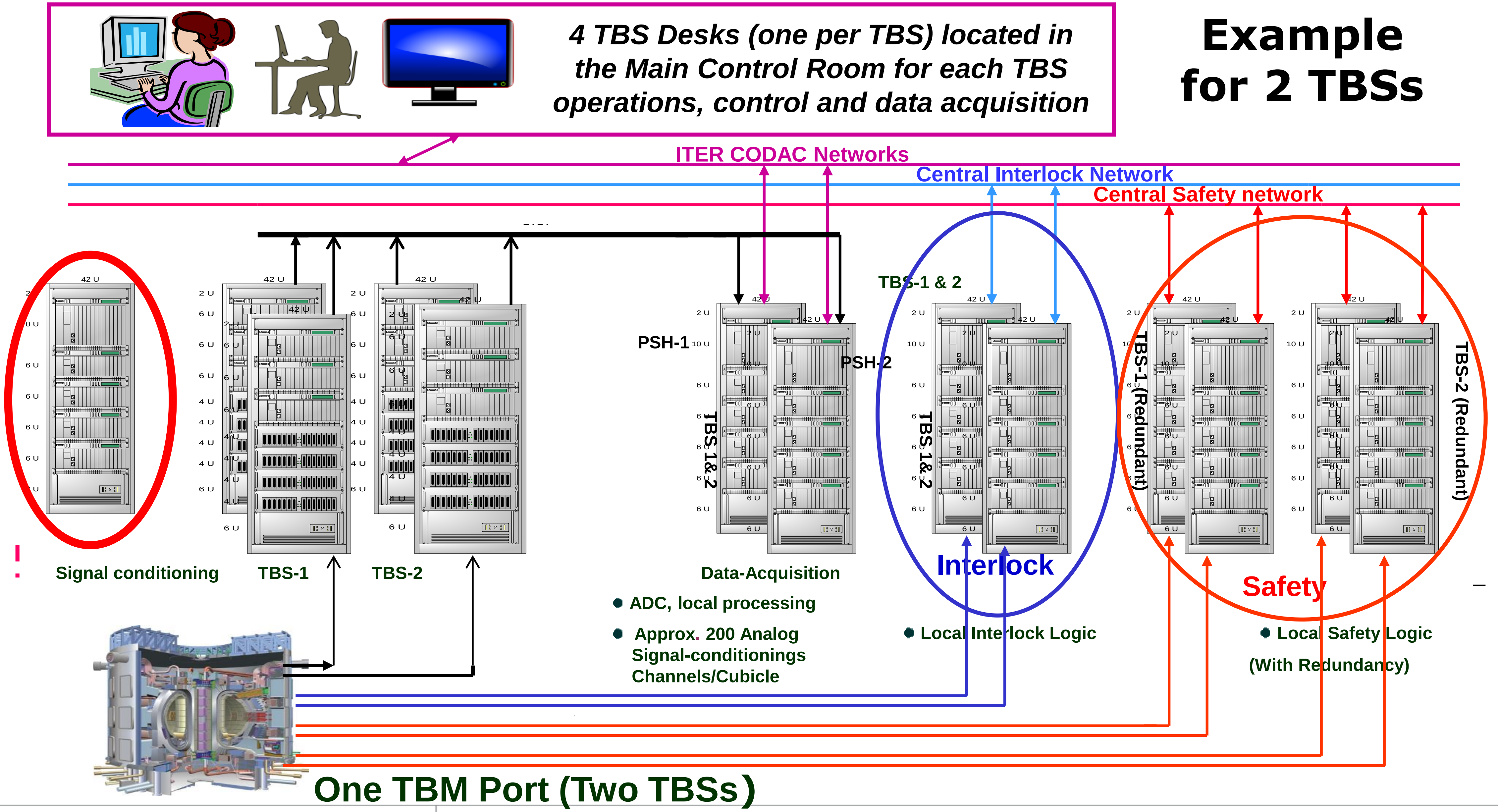


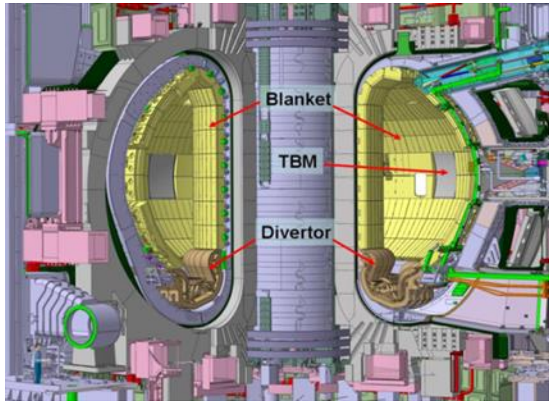
Fully dedicated to WCCB-TBS R&D

Planned/on-going tests are for instance:

- Heat load test on TBM FW
- In-Box LOCA test
- Reaction between water and Beryllium pebbles
- Cooling-water flow accelerated corrosion test.

Scheme of Instrumentation & Control Network for Test Blanket Systems





6 – Further Considerations on the Achievements of the TBM Program in support the DEMO TBBs development

Expected achievements of the TBM Program

- The **general objectives** of the TBM Program were addressed in previous slides. Basically, they consist in learning, from the design and operations of the TBSs, how a DEMO TBB have to be designed and operated.
- These objectives **can be fulfilled if and only if** the *ITER Test Blanket Systems use DEMO BB design parameters, DEMO-relevant BB materials and DEMO-relevant sub-systems components*. The examples of TBS designs, of manufacturing aspects and of TBS sub-systems components operated in experimental loops have been given to show the status of the TBSs development that are expected to be delivered in ~2030 after **complete validation/qualification processes**.
- In fact, **these TBS validation/qualification processes** (to be achieved before the TBS installation in ITER) give already large contributions and recommendations for the design of future DEMO TBBs. I would like to stress the "effective" contributions to the following five relevant aspects:

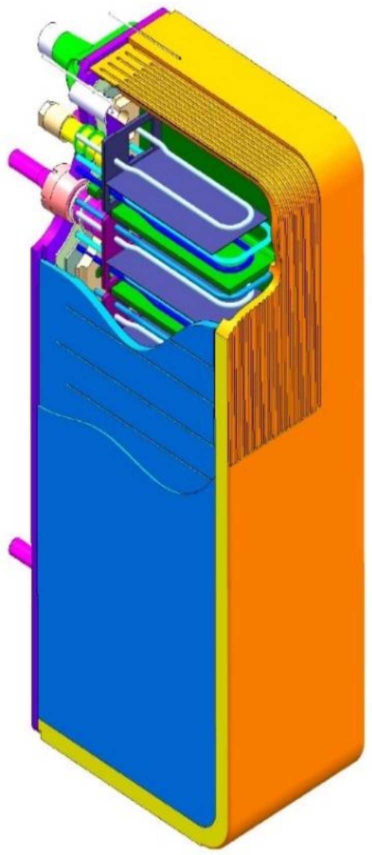
1. *TBM structural materials*
2. *Tritium management and Tritium permeation barriers*
3. *TBS Safety aspects*
4. *Measurements and control systems*
5. *TBS components reliability/availability*

Some considerations on these five aspects are given in the following slides, limited to what the TBM Program can offer in terms of understanding and progress. It is out of the scope of this talk to address a complete assessment of these aspects in the framework of DEMO (including cost implications).

TBM Program aspects implemented before TBS delivery relevant for DEMO /1

➊ TBMs structural materials

- The TBMs are mock-ups of the corresponding TBBs (=same designs).
- Since they use the same Reduced Activation Ferritic/Martensitic (RAFM) steels planned for DEMO, the manufacturing technologies developed for TBMs have direct consequences on the choices to be made for DEMO.
- The TBMs are classified as (Nuclear) Pressure Equipment and Quality Class-1. Therefore, their manufacturing needs to be compliant with the associated requirements on control and inspections, on qualification, on material certificates.
- As a consequence, a large number of experimental data on mechanical properties for base and irradiated materials (up to 3 dpa) and for the used welding technologies are being produced and the corresponding data base have to be completed before installation.
- Each ITER Member develops specific RAFM steel, namely EUROFER-97 in EU, CLF-1 and CLAM in CN, F82H in JA and ARAA in KO. For all these materials, the data base and associated qualification will directly profit to the corresponding DEMO TBBs design.



TBM Program aspects implemented before TBS delivery relevant for DEMO /2

❷ Tritium management and Tritium permeation barriers (TPB)

- Tritium managament has been indentified as one of the major issues for D-T fusion reactors since a long time. Besides the TBR aspects mentioned above as a main TBM Program objective, the demonstration that Tritium can be sufficiently **“confined and recovered“** is also a very essential aspect.
- Based on present modeling capability, it appears that the TBSs He-coolant system (because of the high outlet temperature of 500°C) might have a too high Tritium permeation in the Tokamak Complex and might require a **Permeation Reduction Factor (PRF) of 10** (or above).
- Since no Tritium Permeation Barrier (TPB) are present in the TBMs, it has been decided **to implement TPB in the internal surface of He-pipes** (planned to be manufactured in 2025/26) by using an industrial manufacturing process. This implementation will allow to assess the compliance of the TPB with the Pressure Equipement requirements. It could be needed also for He-cooled DEMO TBBs.
- Concerning the water-coolant system it has been found that the T-concentration in the water become too large after a couple years of D-T operation in ITER. The water detritiation appears not feasible because the associated system would require a too large space. Therefore, **the water has to be drained and refilled each two years**. For DEMO, in case of water-coolant, it is recommended to design an appropriate water detritiation system (improving the present detritiation technology).
- Of course, the ideal solution would be to reduce the T-permeation at the source by implementing TPBs **in the TBMs**. However, because of the effect of irradiation on the TPBs, this approach is not available in medium term.

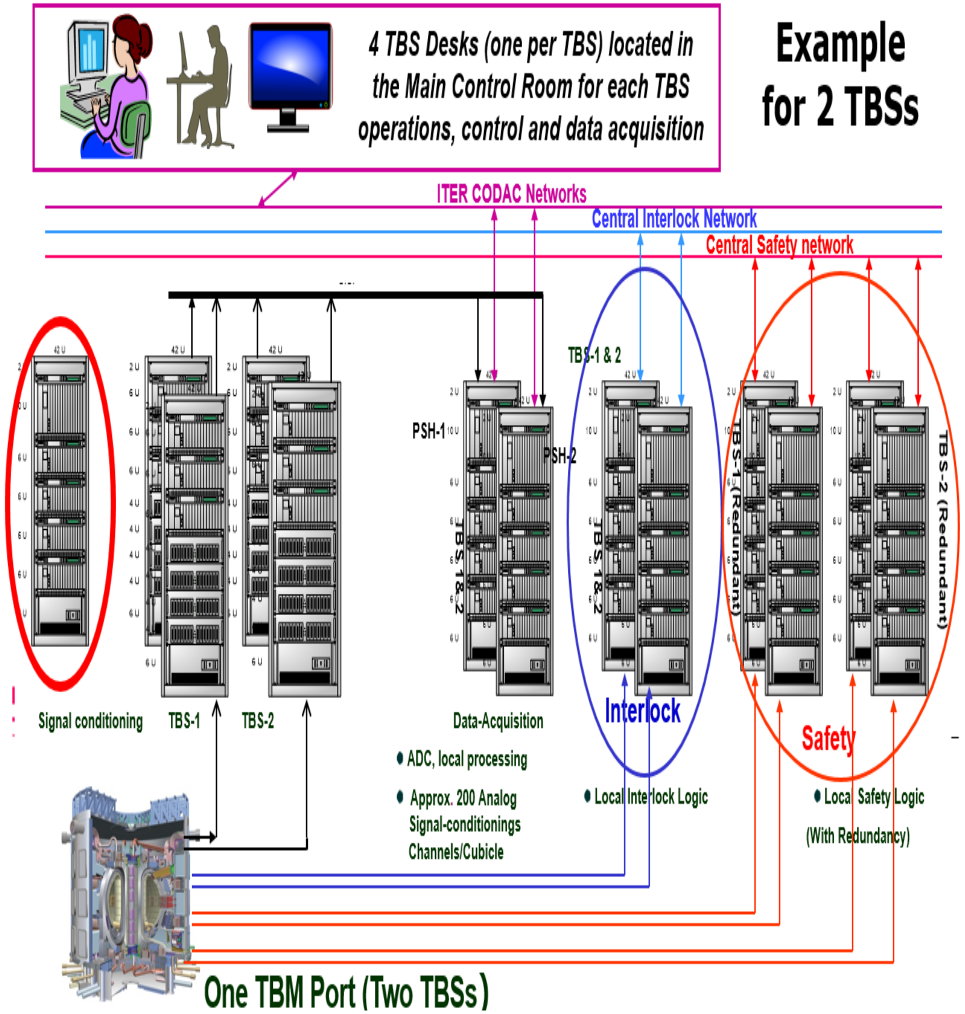
TBM Program aspects implemented before TBS delivery relevant for DEMO /3

❸ Test Blanket Systems – Safety aspects

- A large amount of Safety analyses are on-going for each TBS and will have to be completed for achieving the approval of the TBS Final Designs.
- The list of possible accidents/incidents has to be exhaustive and the categorisation of the various accidents has to be agreed by the IO as Nuclear Operator.
- The whole TBSs Safety Demostration has to be included within the ITER “Rapport Preliminaire de Sureté“ and endorsed by the ASN (French Safety Authority) before the installation of the TBSs within ITER.
- All the Safety Functions have to be properly defined and the associated safety-related instrumentation (e.g., detectors) and components (e.g., safety valves) need to be well defined and qualified in the appropriate environmental conditions (such as radiation field, seismic loads, electromagnetics field).
- The TBSs are mock-ups of the corresponding DEMO TBB sytems and, therefore, most of the above safety-related activities could be directly applied to the DEMO TBBs alloying to have a consolidated Safety Dossier associated with the DEMO TBB designs.

④ 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, the Interlock (Investement Protection) Systems (Central+Plant) and the regular CODAC system. 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.



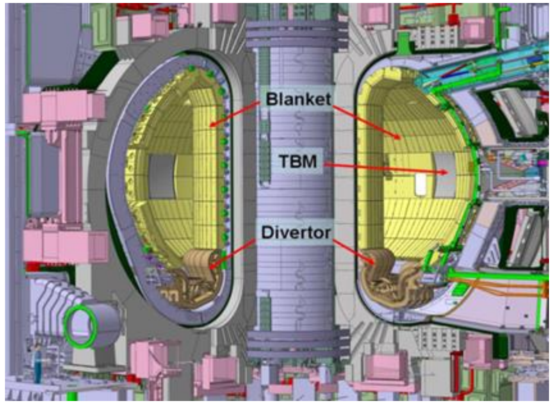
❺ TBS components reliability/availability

- A significant anayses work is on-going to address the TBS components RAMI (Reliability/ Availability/ Maintainability/ Inspectability). Only a limited number of relevant input data are available (i.e., failure rates), therefore large unceratinties are present.
- It is known that for the DEMO TBB system components, RAMI is a critical issue. It is also a critical issue for the TBS components.

$$\text{Availability} = \frac{\text{MTBF}}{\text{MTBF} + \text{MTTR}}$$

MTBF – Mean time between failures
MTTR – Mean time to repair

- TBSs components failures could need machine shutdown. Depending on the locations, the replacement of the failed components could need long time. It is the case for the components within the Vacuum Vessel but also in other areas with high radiation fields and high contamination, such as in the TBM Port Cells.
- Therefore, already for the TBSs it is necessary to improve the MTBF of several components since for the OFF-THE-SHELF versions it could be too low. The on-going RAMI analyses will indicate the type and number of components for which a significant R&D have to be launched for achieving reasonnable values.
- Since many TBS components/technologies are expected to be used also for the DEMO TBB, the TBS development can directly profit to DEMO.



7 – Conclusions

Conclusions

- The TBM Program has the objective to install and simultaneously operate four Test Blanket Systems, starting from the last ITER non-nuclear phase (PFPO-2). The TBS operating parameters and the used materials are derived from the corresponding DEMO Tritium Breeding Blankets.
- All the Test Blanket Systems have passed the Conceptual Design Phase. 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. Several testing loops (e.g. water-coolant, He-coolant, Pb16Li loops, Tritium Extraction) simulating the TBSs sub-systems characteristics are operating or under construction.
- Basically, the TBM Program objectives consist in learning, from the design and operations of the TBSs, how a DEMO TBB have to be designed and operated and in demonstrating the Tritium breeding capabilities of a given design. The successful outcome of the TBM Program is therefore essential for designing, manufacturing and operating a DEMO TBB.
- It has been shown that the contribution of the TBM Program to the DEMO design activities is very important already during the TBS design and manufacturing phases. Few examples of direct significant contribution have been given, namely TBM structural materials R&D, Tritium management and Tritium permeation barriers, TBS Safety aspects, measurements and control systems R&D and TBS components reliability/availability assessment.

To be continued towards DEMO…

Thank you for your attention