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Current Status of the European TBM Project and a Possible Use of DONES for Preliminary Testing

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*Former member of TBM Project Team, Broader Approach & Roadmap Projects
**TBM Project Team, Broader Approach & Roadmap Projects

4th DONES Users Workshop | CIEMAT, Madrid, Spain | 15 October 2026

BRINGING THE POWER OF THE SUN TO EARTH

TBM Programme in ITER and European TBM Concepts

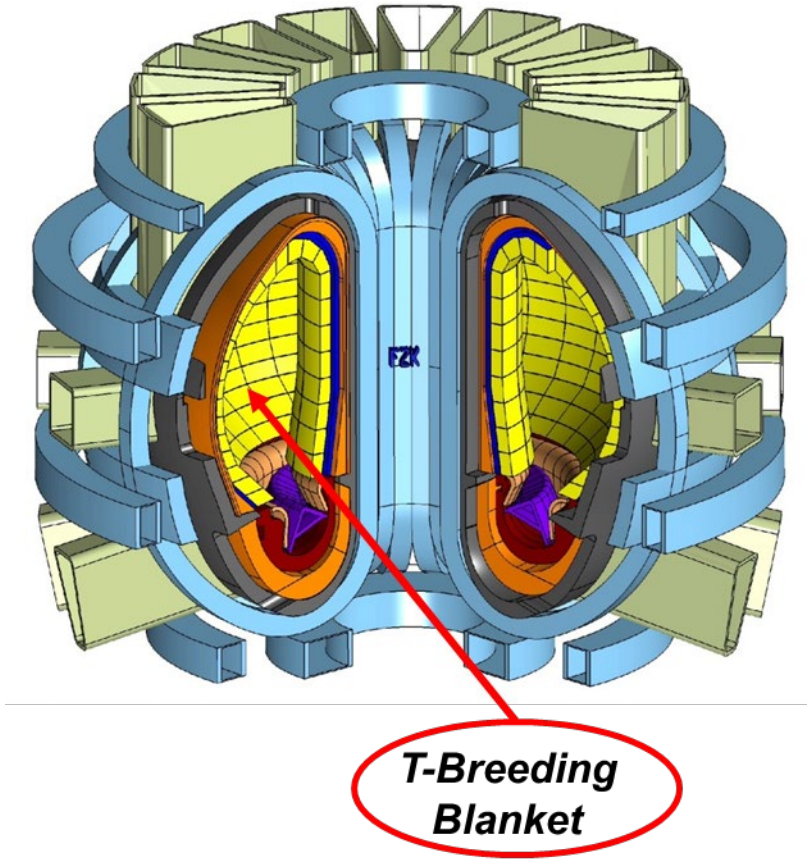
TBM Programme in ITER (1/4)

Definition of the ITER TBM Programme

- 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."

- The **TBM Programme** is therefore a specific research activity run in ITER as **part of the ITER Research Plan**. Two equatorial ports are assigned to the TBM Programme. The plan is to install and operate **4 Test Blanket Systems** *(two in each ports)* that are mock-ups of a complete DEMO Tritium Breeding Blanket.

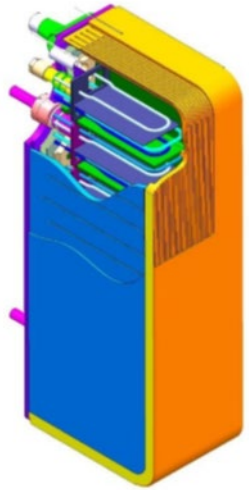


TBM Programme in ITER (2/4)

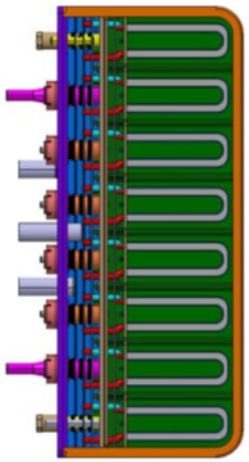
TBM technologies operational during the DT-1 phase

Equatorial Port 16	Equatorial Port 18	Cooling temperature and pressure	Tritium extraction compound	TBM box structural material	Neutron multiplier	Tritium breeder material
WCLL (EU)		295/325 °C 15.5 MPa	in He and 0.1% H_2 at 0.4 MPa	Eurofer97	Pb16Li (90% Li^6)	Pb16Li (90% Li^6)
HCCP (KO&EU)		300/500 °C 8 MPa	in He and 0.1% H_2 at~ 0.3 MPa	Eurofer97	Beryllium pebbles	Li_4SiO_4 or Li_2TiO_3 pebbles (30% to 60% Li^6)
	WCCB (JA)	280/325 °C 15.5 MPa	in He at 0.1 MPa	F82H	Be/beryllide pebbles	Li_2TiO_3 pebbles (30% Li^6)
	HCCB (CN)	300/500 °C 8 MPa	in He at 0.1 to 0.4 MPa	RAFM / CLF-1 or CLAM	Beryllium pebbles	Li_4SiO_4 pebbles (90% Li^6)

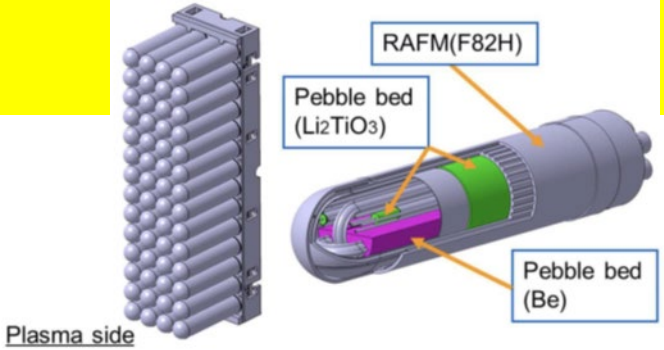
EU-WCLL
Water-cooled
Lithium-Lead



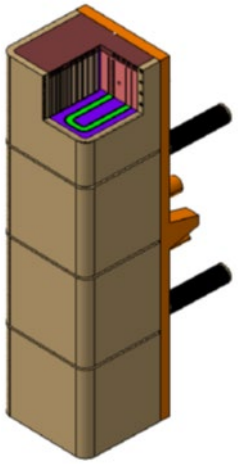
KO/EU-HCCP
Helium-cooled
Ceramic
Pebble



JA-WCCB
Water-cooled
Ceramic
Breeder

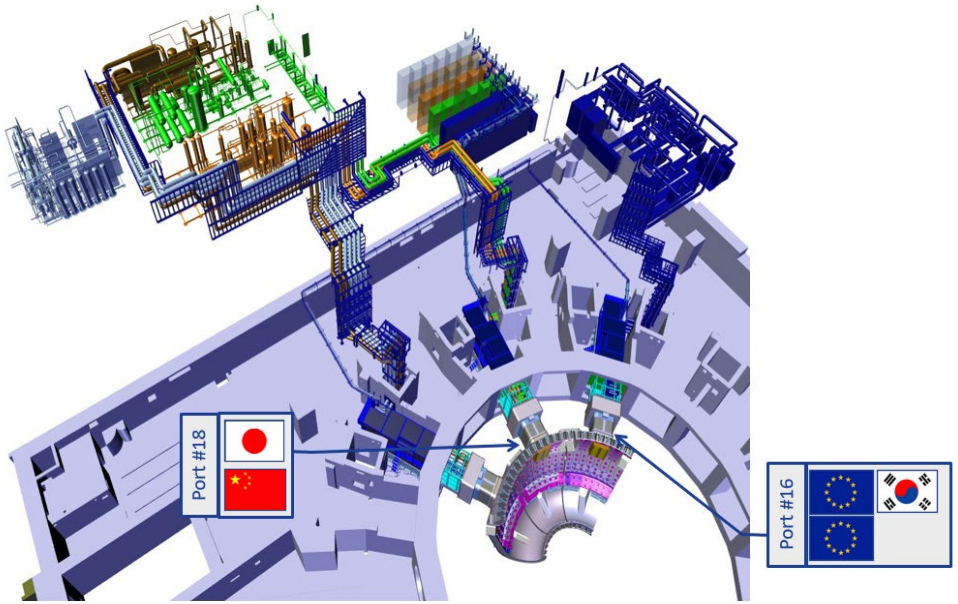


CN-HCCB
Helium-cooled
Ceramic
Breeder

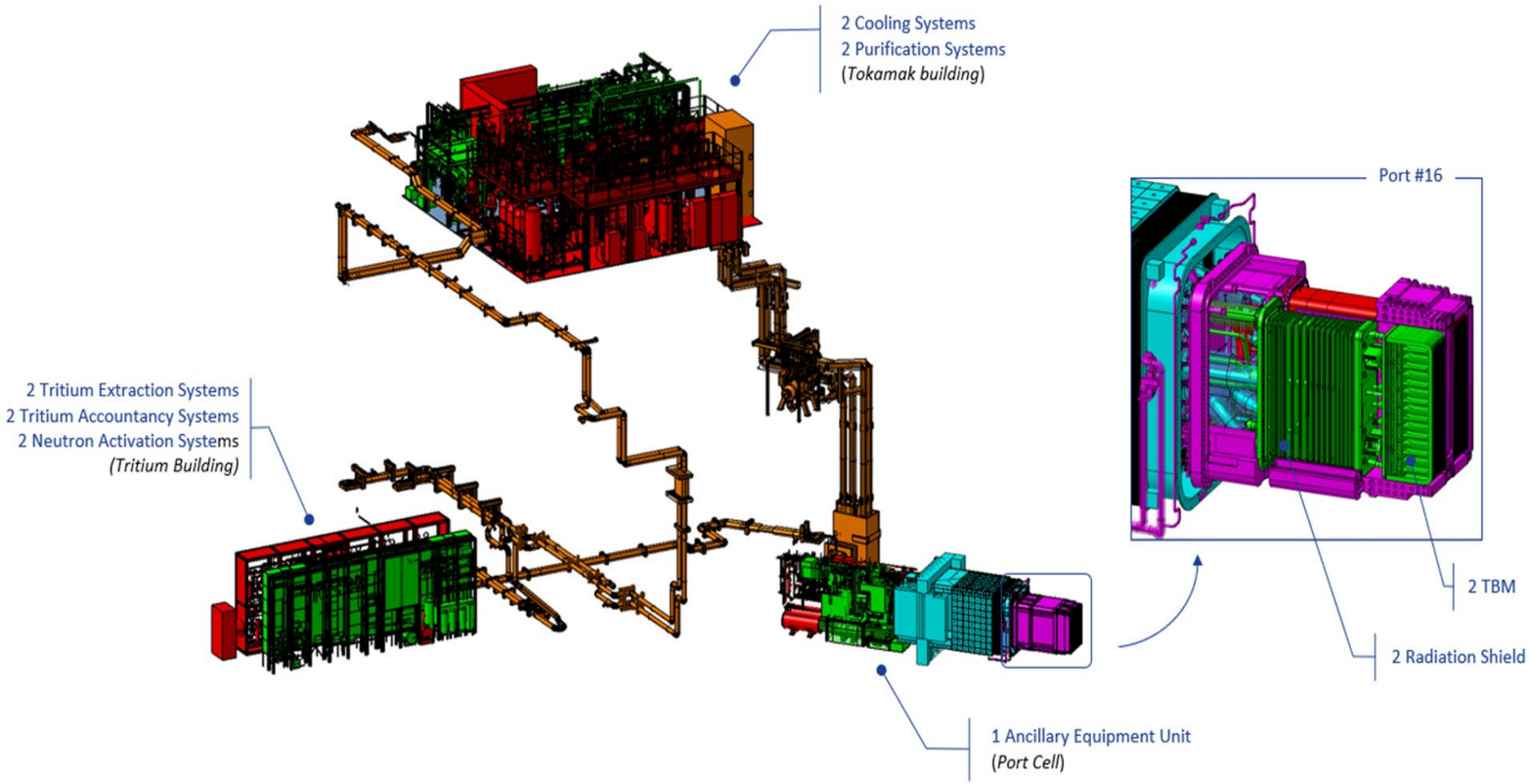


TBM Programme in ITER (3/4)

ITER Equatorial Ports allocated to TBM Programme



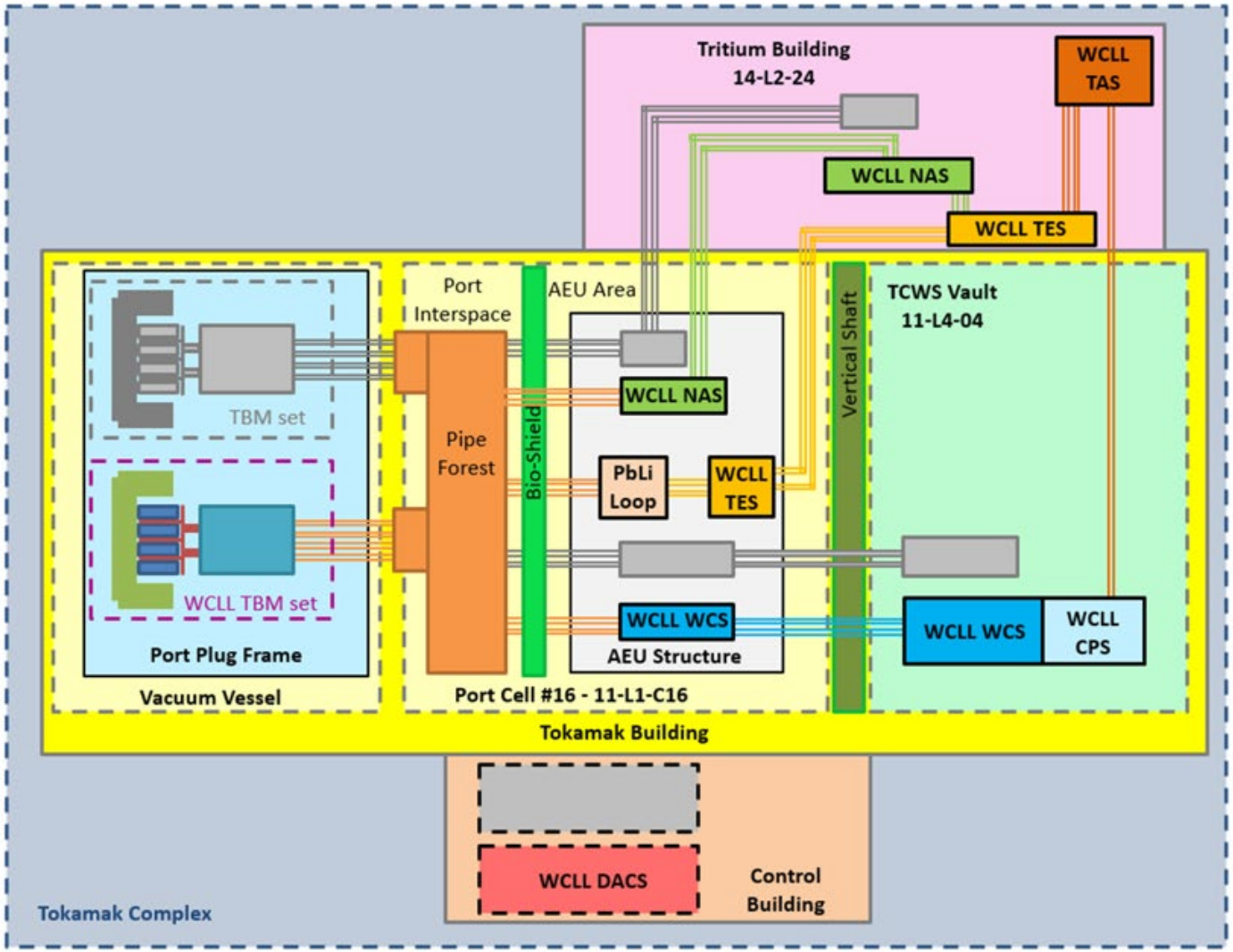
European TBM Systems in ITER



2 European TBM Systems are being prepared for testing in ITER (1 in collaboration with ITER Korea)

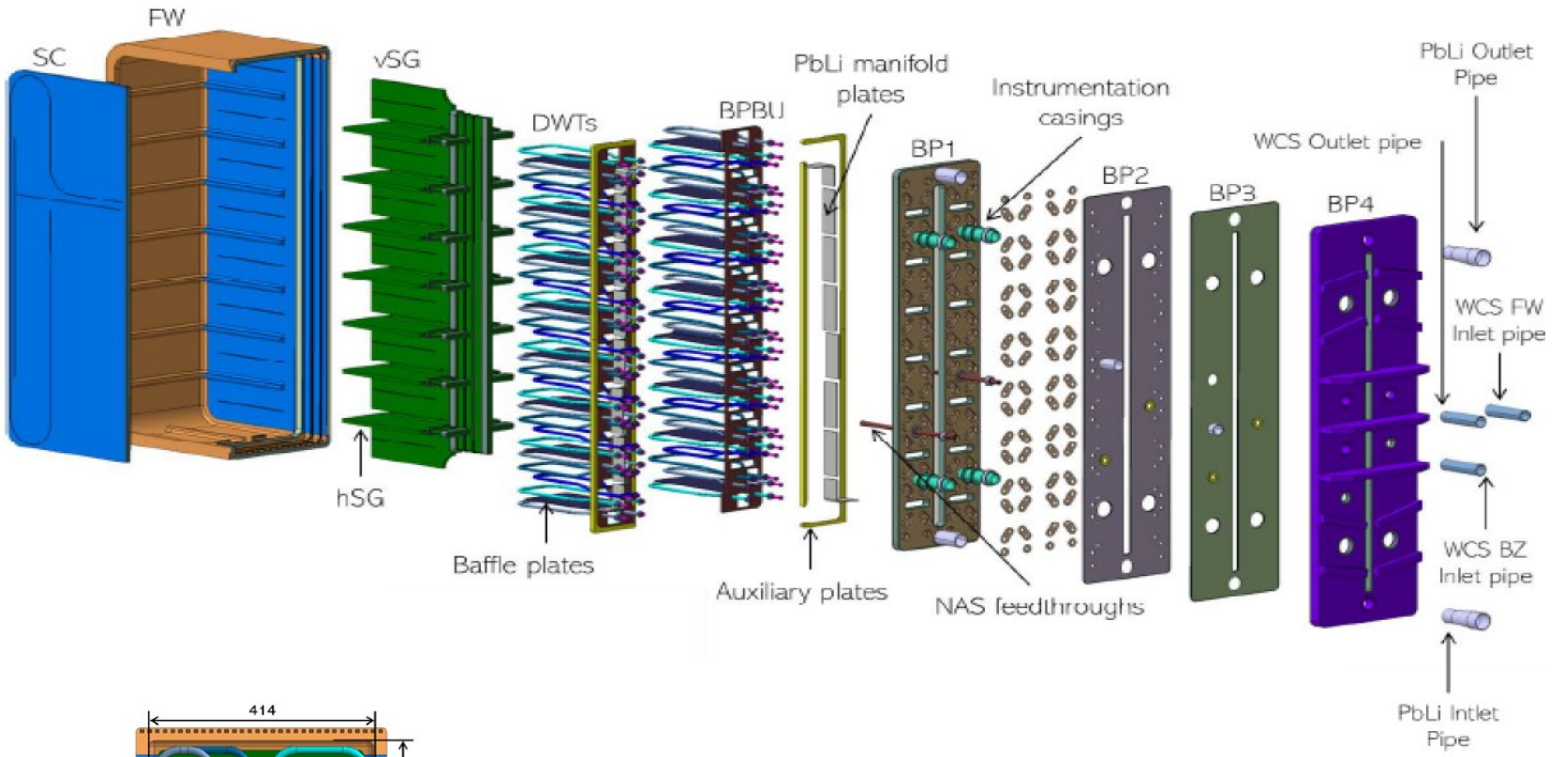
TBM Programme in ITER (4/4)

Test Blanket Systems (TBS) and Their Topology in ITER



Sub-system	
TBM set	(TBM box + shield)
WCS	(Water Cooling System)
CPS	(Coolant Purification System)
PbLi loop	
TES	(Tritium Extraction System)
TAS	(Tritium Accountancy System)
NAS	(Neutron Activation System)

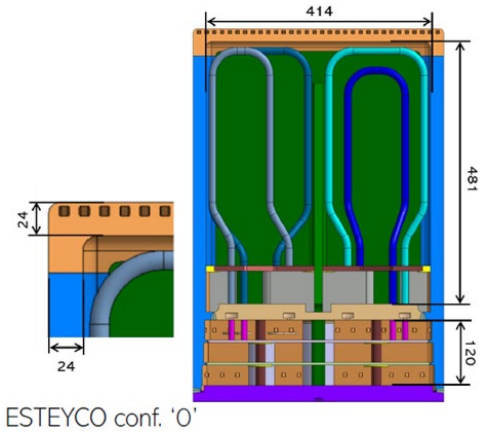
EU WCLL: Water Cooled Lithium-Lead TBM



EUROFER97 (X10CrWVTa9-1) structural material

Pb-16Li alloy – breeder & neutron multiplier (Li enriched at 90% in ^{6}Li for the optimization of the tritium breeding ratio);
Tritium transport for T extraction in a dedicated TES

Pressurized water coolant (15.5 MPa) for heat extraction (295-328 C)



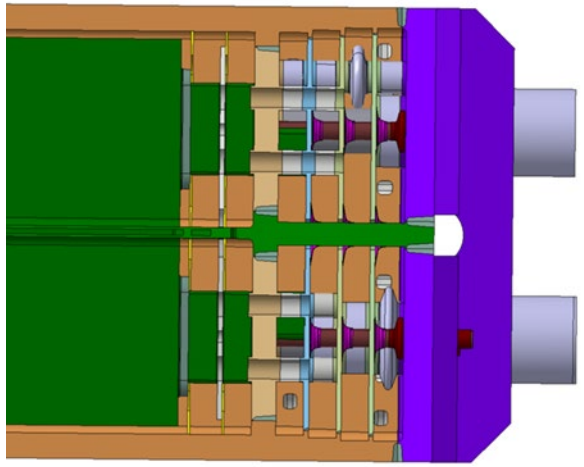
ESTEYCO conf. '0'



WCLL TBM details – Double Wall Tubes (DWT)

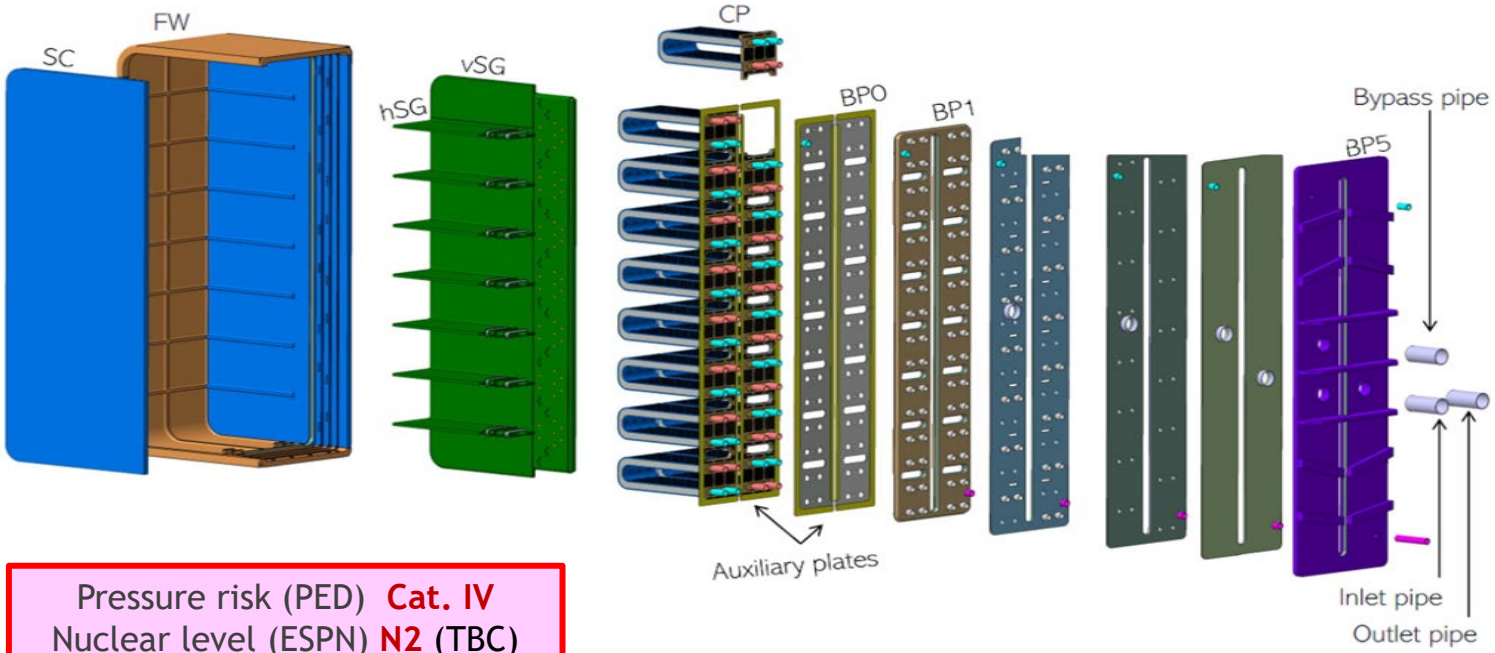
Pressure risk (PED) **Cat. IV**
Nuclear level (ESPN) **N2**

WCLL TBM details – Manifold area



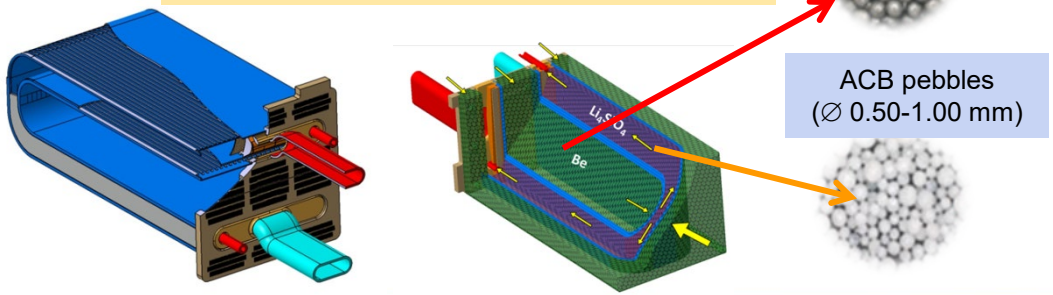
EU-KO HCCP: Helium-Cooled Ceramic Pebble TBM

(within the EU-KO partnership agreement)



Pressure risk (PED) **Cat. IV**
Nuclear level (ESPN) **N2** (TBC)

Breeder Unit with 2 U-shape Cooling Plates & detail of Li-breeder and Be multiplier



Be pebbles (∅ 1 mm)



ACB pebbles (∅ 0.50-1.00 mm)

EUROFER97 structural material (RAFM steel)

Li-ceramic breeder in the form of **pebble beds** (Li enriched at 90% in ^{6}Li)

Reference CB material: **Advanced CB = mixture of Li_4SiO_4** (LOS) with **Li_2TiO_3** (LMT) (~25-35 mol%) as a secondary phase (improved mechanical properties); produced by melt-spraying process; total weight of **~80 kg**

Beryllium neutron multiplier in the form of **pebble beds;** total weight **~190 kg**
Reference NMM: **1mm Be pebbles** produced by REP (NGK, JA)
Alternative NMM: Be chips (UMP, KZ)
DEMO/Future TBM: Advanced Be material: **beryllium alloys/beryllides** (e.g. $Be_{12}Ti$) → lower swelling, better T release, better oxidation resistance, smaller reactivity with structural material

Pressurized Helium coolant (8 MPa) for heat extraction (300-500°C)

Low-pressure (0.4 MPa) **Helium purge gas** He+0.1vol%H_2 for tritium extraction

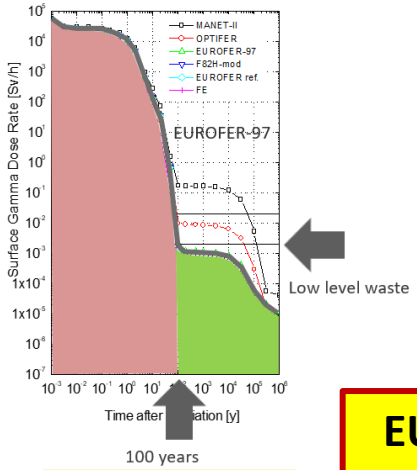
EUROFER97 structural material

- **EUROFER97** (from family of **ferritic-martensitic steels - X10CrWVTa9-1**) has been developed on the basis of conventional 9Cr-1Mo steels used in fission
- But, highly activating alloying elements (Mo, Nb) are replaced by (W, Ta) offering lower activation
- Highly activating impurity elements (Nb, Mo, Ni, Cu, Al, Si, Co,..) are reduced to the "lowest" content, that is technically achievable at reasonable cost

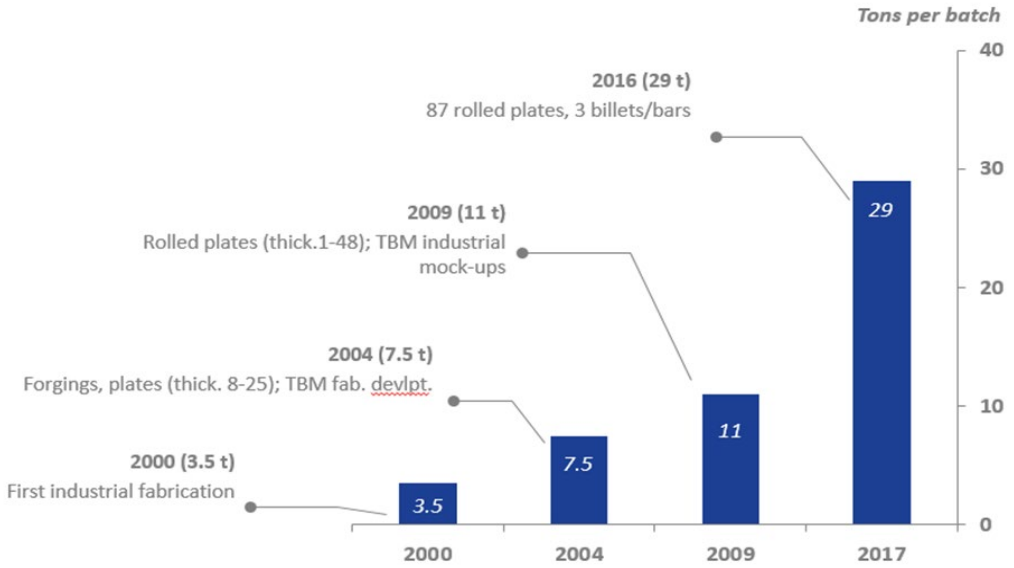


Recently **EUROFER section in the RCC-MRx Ed.2012 & subsequent** *(under "**Probationary Phase Rules RPP4-2012-EUROFER**")*





Hands-on operations **after ~100 yrs**



2024-25: EUROFER97-5 procurement (~40 t) => TBM qualification, EUROFER97 codification; plates th. 7-55mm, bars

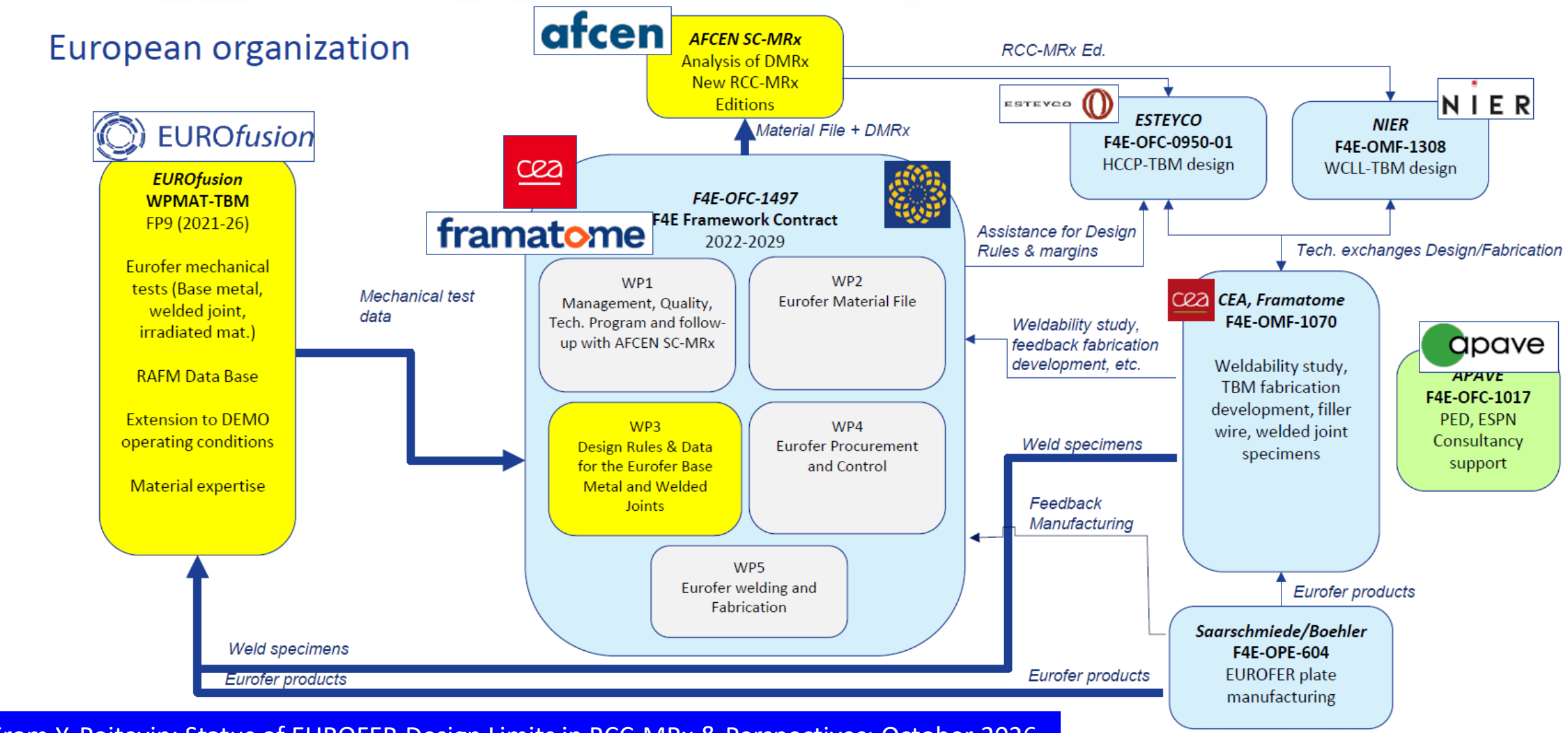
Procurement according to RCC-MRx; **Manufacturing route qualification & demonstration following RM 014-0**

2015-17: EUROFER97-4 (~29 t), plates th. 1-45 mm , bars => TBM mock-ups fabrication and WPS qualification; **procurement following RCC-MRx code RQs**

EUROFER → structural material for TBM & DEMO

European supply chain established, but manufacturing route qualification pending

Organization of EUROFER97 Codification in RCC-MRx



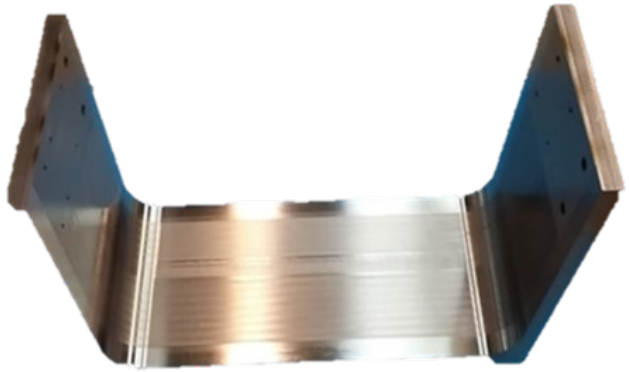
From Y. Poitevin: Status of EUROFER Design Limits in RCC-MRx & Perspectives; October 2026

An Example - TBM Manufacturing Feasibility Studies

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TBM subcomponents fabrication

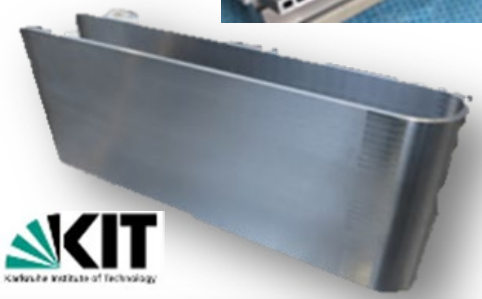
First Wall with embedded Cooling Channels

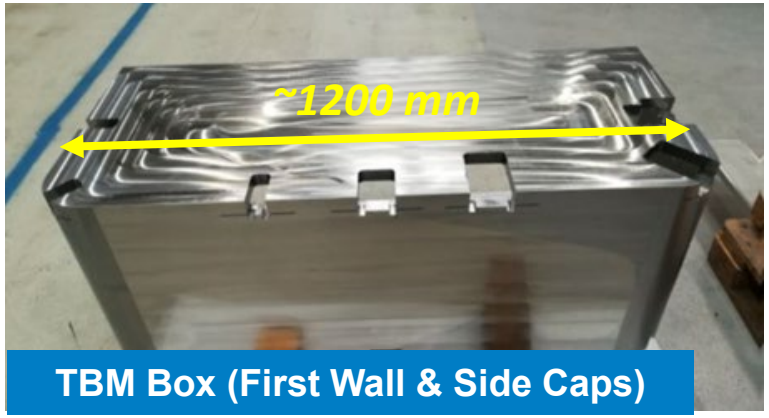




HCCP Cooling Plate

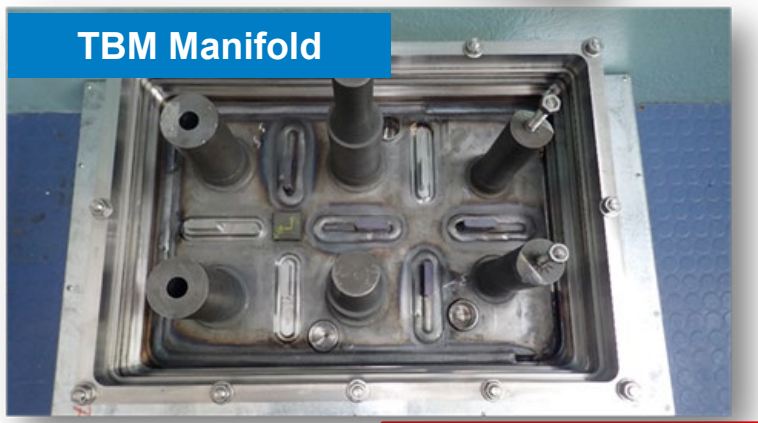






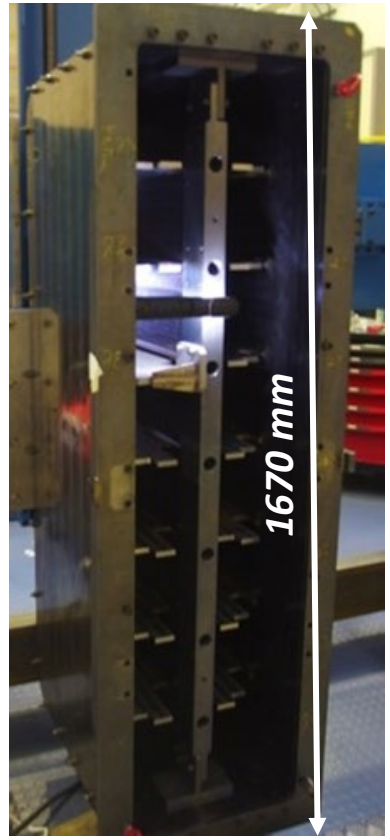
TBM Box (First Wall & Side Caps)

TBM Manifold



TBM Box Structure Assembly (TBM Box & Stiffening Plates)

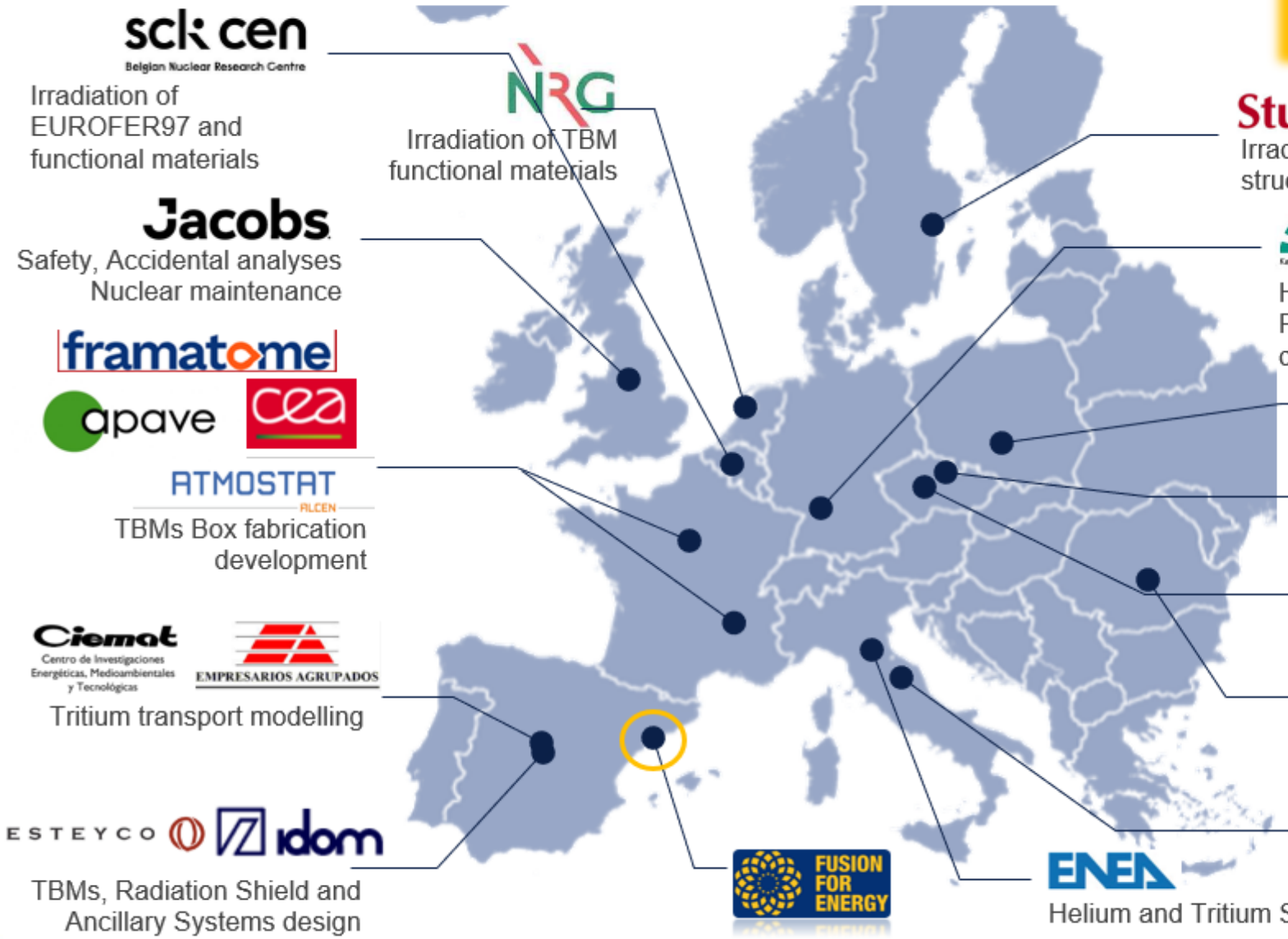




Manufacturing feasibility demonstrated, but scale-up, mock-up fabrication & qualification remain

ATMOSTAT ALCEN cea COMMERCY ROBOTIQUE

European Contributions to TBM Programme



+ many other European Labs and SMEs

SCK CEN (Belgian Nuclear Research Centre)
Irradiation of EUROFER97 and functional materials

NRG
Irradiation of TBM functional materials

Studsvik
Irradiation/PIE of TBM structural materials

Jacobs
Safety, Accidental analyses
Nuclear maintenance

KIT (Karlsruhe Institute of Technology)
Helium and Tritium Systems, Functional Materials, TBM Box fab. develop., modeling, KBHF

framatome

apave

cea

FIRMUS
Material storage

ATMOSTAT ALCEN
TBMs Box fabrication development

ATEKO
Helium turbo-circulators

CVŘ
Pb-Li technology, maintenance

Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

EMPRESARIOS AGRUPADOS
Tritium transport modelling

RATEN ICN PITEȘTI (Institutul de Cercetări Nucleare)
Irradiation of structural materials

NIER
TBM-set design

ESTEYCO **idom**
TBMs, Radiation Shield and Ancillary Systems design

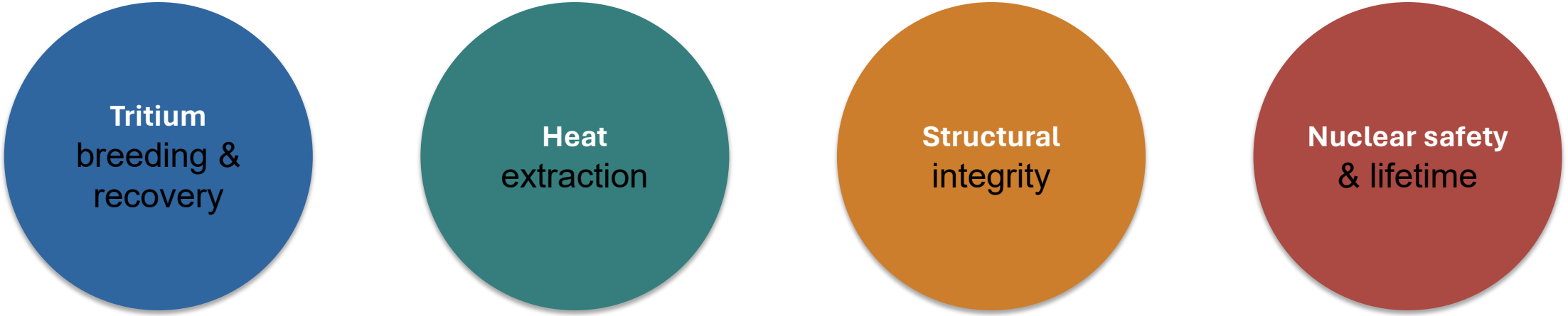
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ENEA
Helium and Tritium Systems, Experimental tests

Possible Experimental Programme in DONES for TBM & DEMO BB Qualification

Why breeding blanket qualification is a critical issue

Breeding Blanket must perform several safety-critical and plant-critical functions simultaneously



Strongly coupled physics + materials + manufacturing + tritium technology

No single facility can reproduce all DEMO blanket conditions

ITER TBM: unique contribution — and limitation

ITER is indispensable for integrated system evidence; BUT it is not a high-dose materials-qualification facility

ITER / TBM uniquely provides

- Integrated blanket system
- Fusion neutron spectrum
- Strong magnetic field + EM loads
- Plasma-facing / transient conditions
- Tritium production & recovery
- Coupled multi-physics behaviour

But for materials qualification…

- Limited accumulated damage
- Limited specimen statistics
- Difficult systematic parameter variation
- Low-dose / beginning-of-life evidence
- Not optimized for high-fluence property databases

ITER question: “Does the integrated blanket system work in a tokamak?”

Where can DONES add unique value?

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The following materials and related topics are considered to be addressed in DONES:

- **Structural materials** (EUROFER97 and possibly other candidate RAFM steels), representative welds (TIG, EBW, LBW), HIP joints and selected dissimilar-material interfaces
- **Functional materials**: ceramic breeders, neutron multipliers (Be/beryllides), corrosion & tritium permeation barriers/coatings and PbLi/Pb materials
- Selected simplified HCPB and/or WCLL **Breeder Unit (BU) mock-ups** with representative thermal, breeder, coolant and purge functions
- **Instrumentation qualification** for survivability, drift, calibration and transient response
- **PbLi interaction** → compatibility, corrosion, helium bubbles and liquid-metal embrittlement
- **WCLL water chemistry technology**, under fusion-relevant irradiation → water chemistry control, pH optimization, radiolysis, ECP, corrosion and ACP (Activated Corrosion Products) transport - subject to facility feasibility

DONES question: How does irradiation drive degradation?

Irradiation conditions and qualification outputs

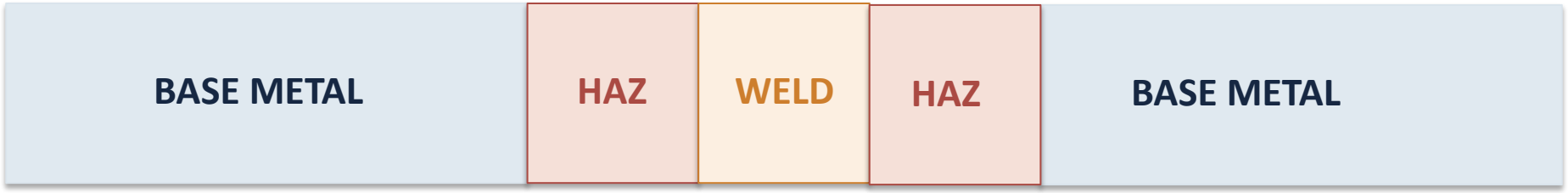
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An Overview of R&D / Qualification Issue and their Outputs from DONES Tests

R&D problem	DONES exposure	Key measurements	Qualification output
EUROFER97 / RAFM	Fusion-spectrum neutrons; controlled temperature and dose	Tensile, toughness, fatigue, creep, microscopy	Irradiated property database/design limits
Welds / HIP / dissimilar joints	Same; joint-representative specimens	Hardness, tensile, fracture, fatigue, NDE, microscopy	Joint-specific degradation factors
Breeder / multiplier	Controlled neutron fluence and temperature	Tritium release, retention, thermal/mechanical properties	Functional-material qualification
Tritium/corrosion coatings	Neutron exposure ± representative environment	Permeation, adhesion, phase/surface stability	Barrier/coating qualification basis
PbLi interaction	Neutron exposure with representative structural materials	Corrosion, dissolution, deposition, coating damage	Irradiation-assisted compatibility data
Functional HCPB/WCLL BU	Coupled irradiation + controlled thermal/flow/breeder/coolant conditions	Thermal-hydraulic performance, tritium release, pressure drop, sensor response	Functional degradation data and model validation
WCLL water chemistry	Neutron field + controlled water chemistry	H2/O2/H2O2, pH, ECP, corrosion, ACPs	Fusion-specific chemistry/corrosion database

EUROFER97 and manufactured joints

Joints are at least as important as the base material for TBM qualification



representative irradiation scenario → fusion-relevant neutron exposure

250-550°C, ~50 dpa DONES HFTM targets

Yield / tensile	Ductility	Impact / fracture toughness
Fatigue / crack growth	Creep / dimensional stability	Microstructure + He/H effects

Key question: Does irradiation preferentially degrade the joint / interface?

PbLi / EUROFER97 interaction under irradiation

fusion-spectrum irradiation
→ dpa + He/H production

EUROFER97 / welds / HIP joint

coating / permeation barrier

flowing PbLi

Coupled degradation mechanisms

Corrosion / dissolution	mass transfer • deposition
Irradiation-assisted corrosion	oxide / barrier stability
Gas-bubble effects	He/H nucleation & growth
Cracking / LME	stress + surface + microstructure

High-value experiment = irradiation + PbLi exposure + selected mechanical loading

Simplified functional Breeder Unit mock-ups

- **Functional mock-up is the possibility to investigate coupled phenomena that cannot be reproduced by isolated material specimens**
- **The mock-up dimensions, operating conditions and instrumentation must be compatible with the available irradiation volume, neutron field and facility interfaces**

HCPB / HCCP BU Mock-up

- EUROFER97 structural section
- Ceramic breeder + multiplier
- Controlled purge-gas flow
- Temperature / pressure / neutron field
- Tritium-release / transient measurements

Outputs

thermal response • breeder stability • purge effectiveness • T-release • sensor drift

WCLL BU Mock-up

- EUROFER97 structural section
- PbLi volume / flow path
- Simplified water-cooling path
- Coatings / joints / interfaces
- Temperature / pressure / flow sensors

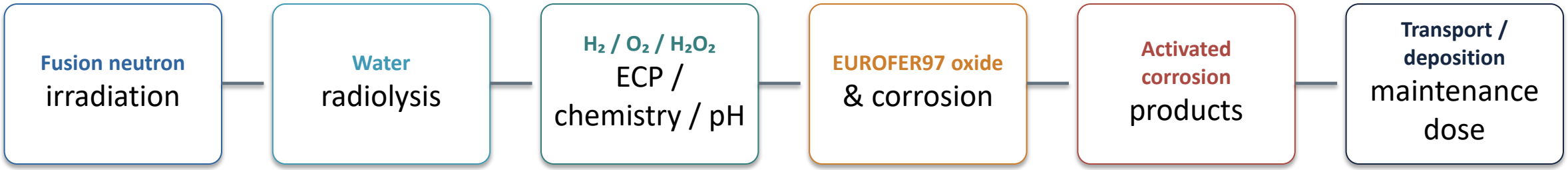
Outputs

heat transfer • PbLi behaviour • interface degradation • containment • sensor response

The **BU mock-ups** designed for functional characterization ***before*** irradiation, ***during*** irradiation and ***after*** irradiation → **to quantify degradation of functional performance**
Focus on dominant phenomena — not full TBM geometry

A possible new DONES topic — WCLL water chemistry

An advanced capability to assess, not an assumed present DONES capability



Core question

Does an optimized WCLL chemistry window remain effective under fusion-relevant irradiation?

Requires a dedicated high-pressure loop + chemistry control + safety envelope

Impact on DONES infrastructure and possibly for the license for operation and handling

Priorities proposed for TBM/BB qualification perspective

Preliminary proposal for discussion, subject to DONES experimental capabilities, technical feasibility and programme priorities

Priority	Test area	DONES contribution	Main output
P1	**EUROFER97 + weld/HIP joints**	High-fluence irradiation + PIE	Design limits / joint qualification
P1	**PbLi / EUROFER97 interaction**	Irradiation + PbLi + loading	Degradation & interaction models
P1	**Functional HCPB/WCLL BU**	Coupled irradiation + thermal/flow	Functional / model validation
P2	**Breeder / multiplier / barriers**	Irradiation + transients + PIE	Functional-material qualification
P2	**Instrumentation / diagnostics**	Drift / survivability / transients	Qualified performance / uncertainty
P2*	**WCLL water chemistry**	High-pressure irradiation loop	Chemistry / corrosion / ACP evidence

*** subject to DONES technical and safety feasibility**

Summary

Summary

1. TBM testing in ITER remains essential for integrated blanket testing, technology demonstration and RoX
2. Some qualification gaps remain, particularly for EUROFER97 and manufactured joints, functional materials, tritium technologies and irradiation-assisted degradation
3. DONES offers a complementary qualification pathway towards DEMO, provided the proposed experiments are translated into realistic requirements and test-module concepts → possible impact on DONES infrastructure, interfaces, license/regulation aspects to be considered → ITER/TBM programme experience exist

👉 **Key message:**

ITER TBM is an indispensable element of BB qualification, but it must be complemented by dedicated irradiation and validation facilities (e.g. IFMIF-DONES) within an integrated European fusion roadmap





Thank You For Your Attention



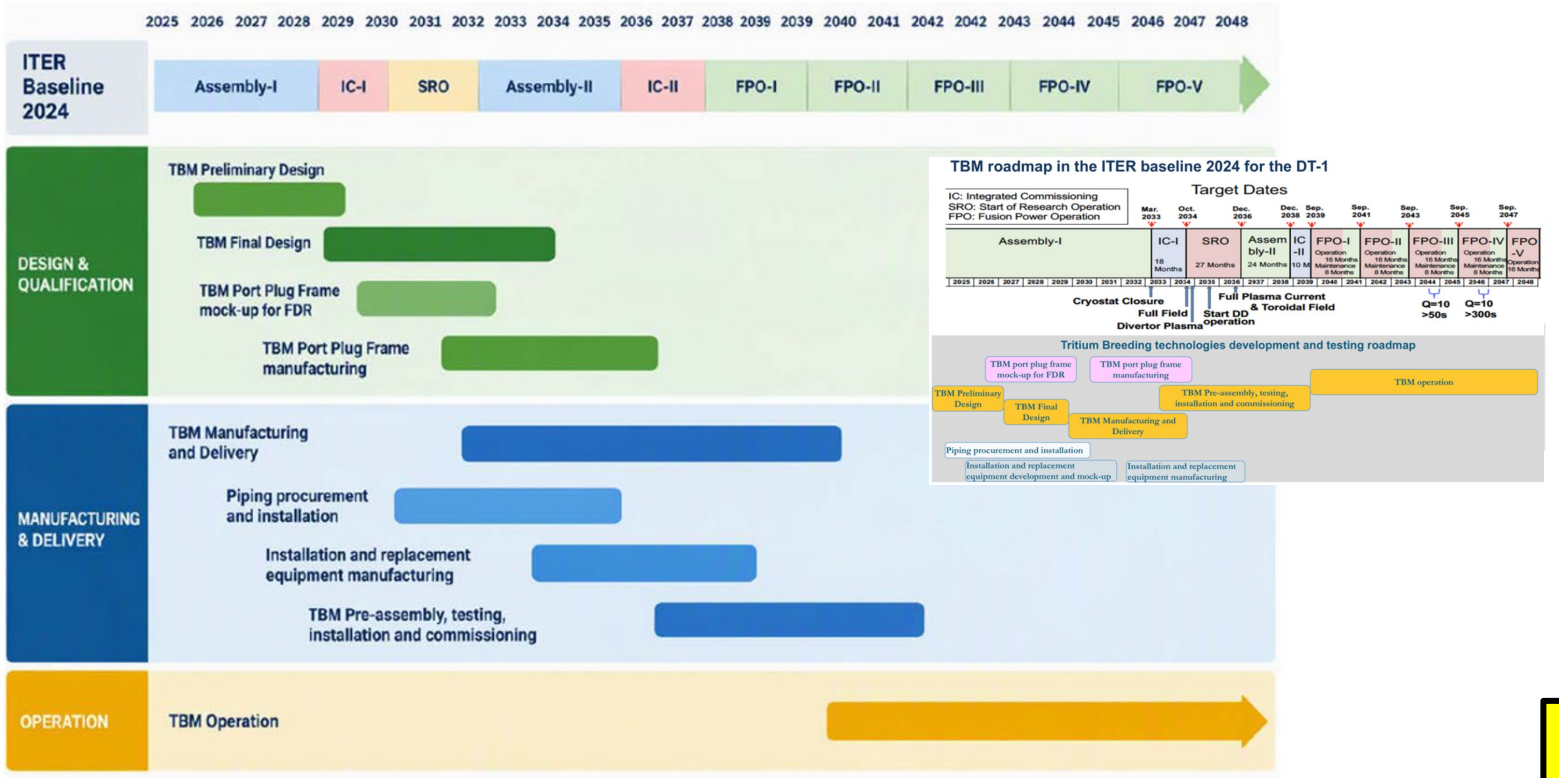
Any Questions?

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Back-up Slides

New ITER Baseline and TBM Programme



An impact of new ITER baseline

- ↓ **Neutron fluence** (~×100) → limited validation:
  - tritium breeding & extraction
  - materials behaviour under relevant conditions
- Short pulses → **no steady-state thermal conditions**
- Long DD plasma phase → **reduced relevance for blanket physics**

👉 **Mitigation measures ongoing:**

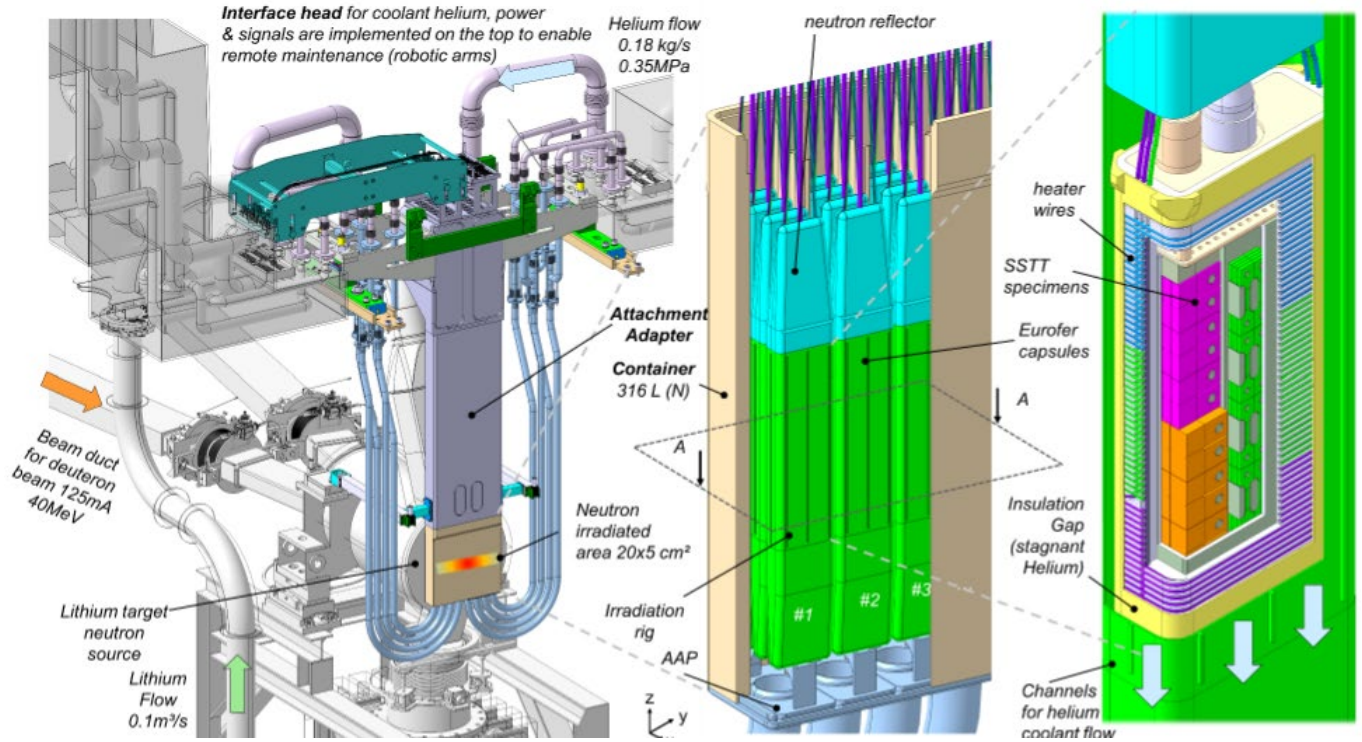
- **longer DT pulse** sequences
- **design modifications** (electrical heating in TBM, enhanced instrumentation,…)

- ❑ **3 TBM-Sets in DT-1 phase** → (TBM-1, TBM-2 and TBM-3), covering **FPO-1/2 (TBM-1)**, **FPO-3 (TBM-2)** and **FPO-4/5 (TBM-3)**
- ❑ Direct **impact on the instrumentation** to be integrated in each TBM-Set

Despite ITER constraints, the TBM Programme remains the only integrated experimental programme capable of generating breeding blanket data and relevant RoX in a fusion nuclear environment

Envisaged IFMIF-DONES Testing Possibilities

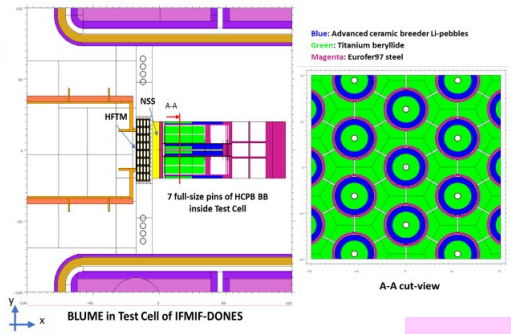
IFMIF-DONES Testing Possibilities in relation to the Breeding Blanket Concepts



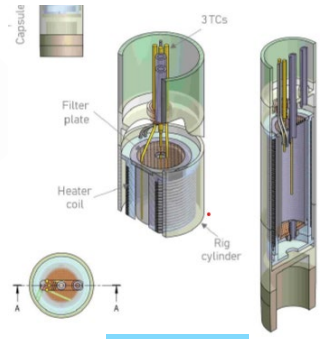
- **IFMIF-DONES Blanket Function Material Module**, **BLUME**, for testing BB functional materials of the Helium Cooled Pebble Bed breeding blanket, HCPB BB
- **IFMIF-DONES Liquid Breeder Validation Module**, **LBVM**, to address several R&D issues associated to the Liquid BBs, e.g. performance of functional materials such PbLi under intensive neutron irradiation and in relation to the Water-Cooled Lithium-Lead breeding blanket, WCLL BB
- **IFMIF-DONES Tritium Release Test Module**, **TRTM**, for checking performance of functional materials acting as tritium breeder (Lithium ceramics) and neutron multipliers (Beryllides)

IFMIF-DONES and TBM are complementary. IFMIF-DONES provides accelerated materials and functional-material testing, while TBM provides integrated blanket-system validation in a fusion reactor environment

From paper: F. Arbeiter et al., The IFMIF-DONES Irradiation Modules (2025)



BLUME



TRTM

Breeding Blanket Qualification Possibilities

FUSION FOR ENERGY

Contribution of the different facilities in achieving Technology Readiness Level (TRL) goals

Irradiation Facilities: timeline estimates and prospects for TRL advancement

Timeline	Available now	in ~5 years	in ~10 years	in ~15 years	in ~20 years
TRL	TRL 2, 3	TRL 3, 4	TRL 4, 5	TRL 5, 6+ (DT2)	TRL 7, 8

heavy ion irradiation:



- superficial penetration
- fundamental material development

protons from cyclotrons:

- small samples
- displacement transmutation
- activation



Material Test Reactors:

- thermal neutron spectra
- Limited bulk heating
- Currently low dose rate
- Small samples / capsules



BR2 Core at Mol-Belgium

D-T neutron sources (FLARE-like @SHINE):

- 14-MeV neutrons
- Limited but relevant bulk heating
- Low but relevant dose rate
- Small samples / capsules



@SHINE

DONES:

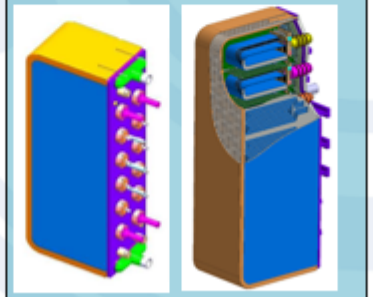
- High-energy (<50 MeV) neutrons
- High dose rates (up to 20 dpa/FPY)
- HTFM conceived for material tests
- Ongoing studies for feasibility of Tritium Breeding Unit testing



DONES Testing Zone

ITER EU-TBMs:

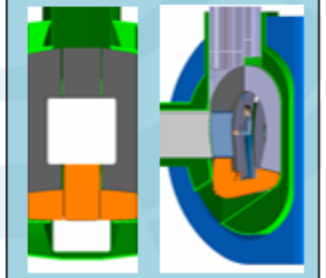
- Relevant testing platform
- love dose rates
- Integral tests with ancillary systems in operational conditions



WCLL and HCCP TBMs

VNS:

- Relevant testing platform suitable for breeding module, segment and sector
- Relevant dose rate (4-6 dpa/FPY)



VNS

From presentation: F. Hernandez, DDEMO qualification (2026)