Status of ITER HCLL and HCPB Test Blanket Systems instrumentation development

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Seminario Cientifico-Industrial
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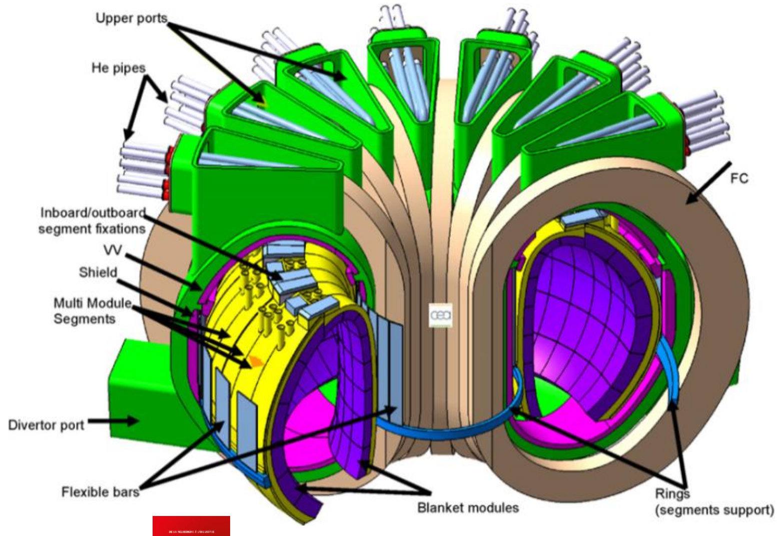
Outline

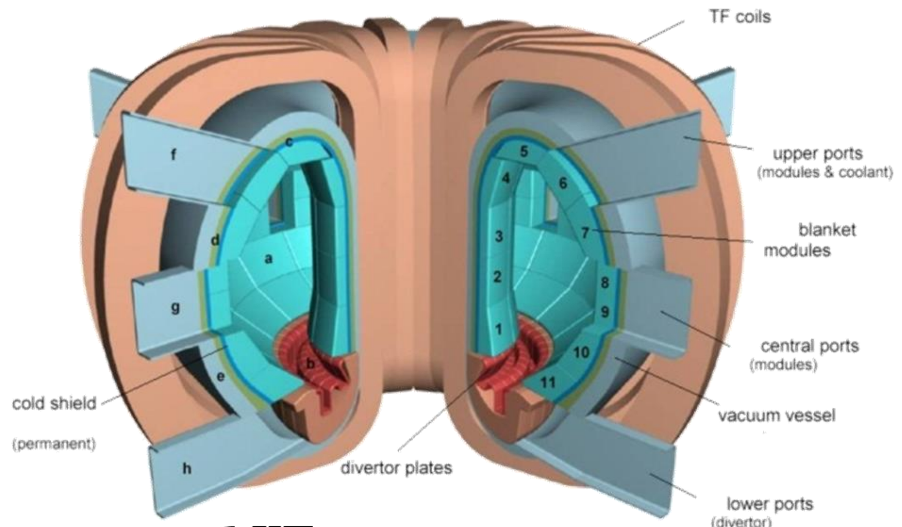
- ITER TBM program: validation of BB concepts
- The HCLL and HCPB Test Blanket Systems
- TBS I&C design overview
- Sensor technology: sub-systems
- Sensor technology: TBM

EU TBM program mission

The mission of the EU TBM program is to test and validate during ITER operation the HCLL and HCPB DEMO tritium breeding blanket concepts



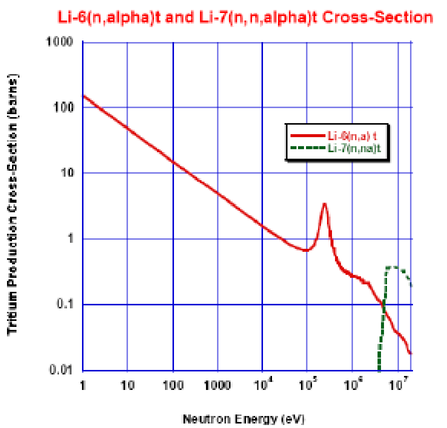
Helium-Cooled Lithium-Lead



Helium-Cooled Pebble-Bed

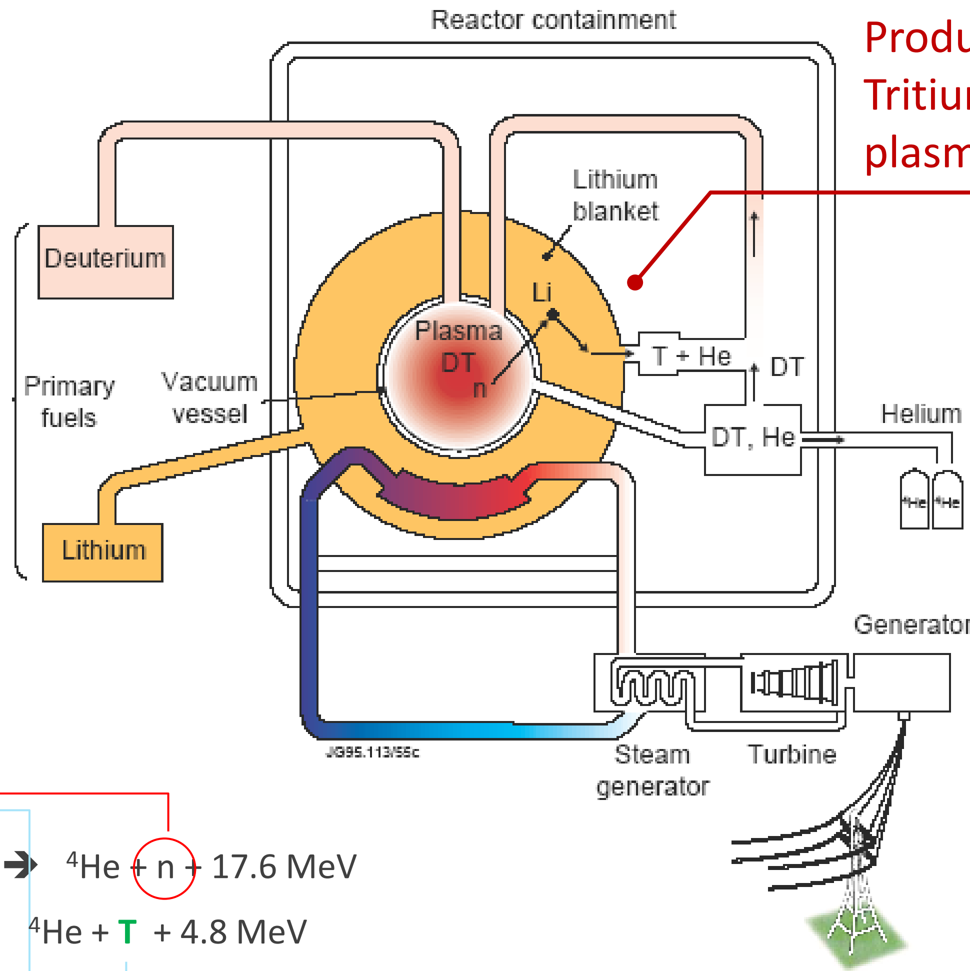
DEMO design is presently being update by EUROFUSION
Reference parameters based on the EFDA Power Plant Conceptual Studies (PPCS)

BB function: tritium self-sufficiency



$^{7}Li + n \rightarrow {}^{3}T + {}^{4}He + n - 2.8\ MeV$

$^{6}Li + n \rightarrow {}^{3}T + {}^{4}He + 4.8\ MeV$



Produce **and recover** Tritium (fuel for DT plasma)

Fusion (plasma): **T** + **D** ➔ ^{4}He + n + 17.6 MeV

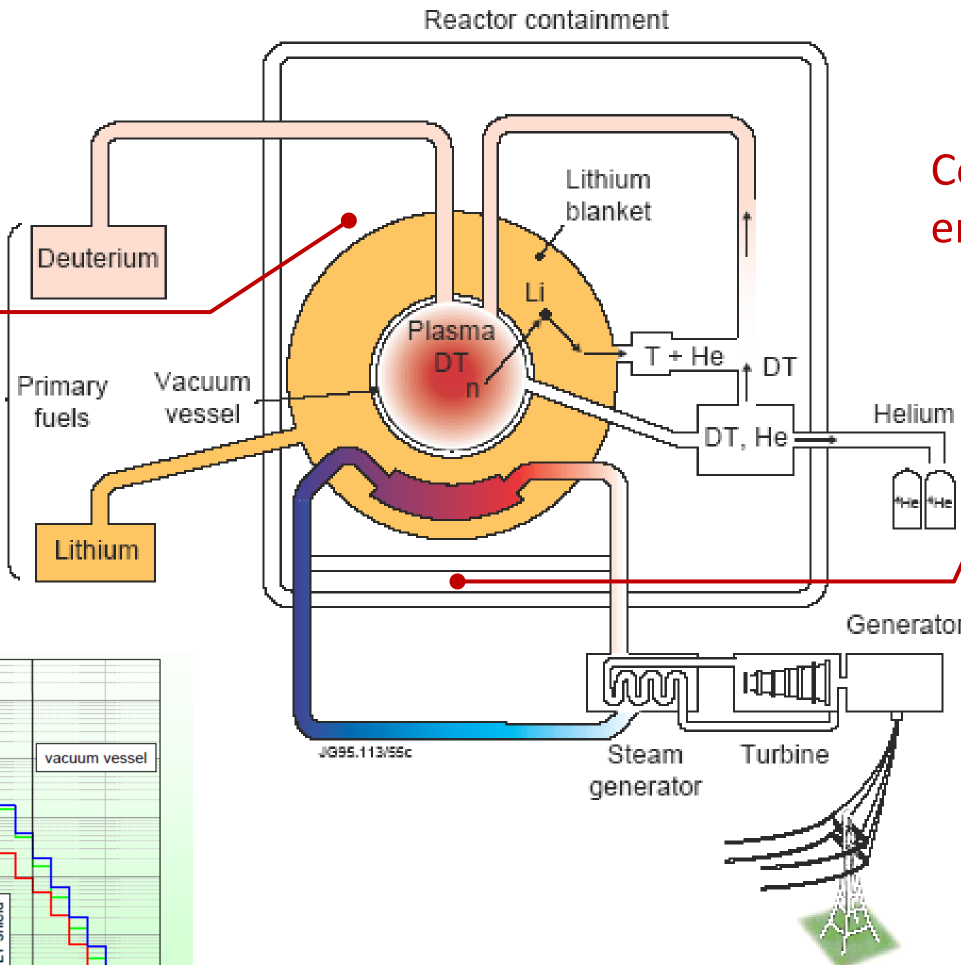
Breeding (blanket): n + **^{6}Li** ➔ ^{4}He + **T** + 4.8 MeV

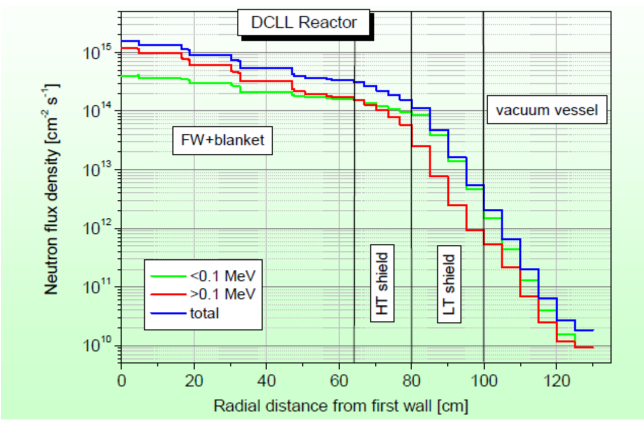
Balance: **D** + **^{6}Li** ➔ 2 ^{4}He + 22.4 MeV

BB function: power extraction

Protect vacuum vessel and coils against radiation damages/heating

Convert neutron energy into heat





Neutron flux radially decreases of around 1 order of magnitude

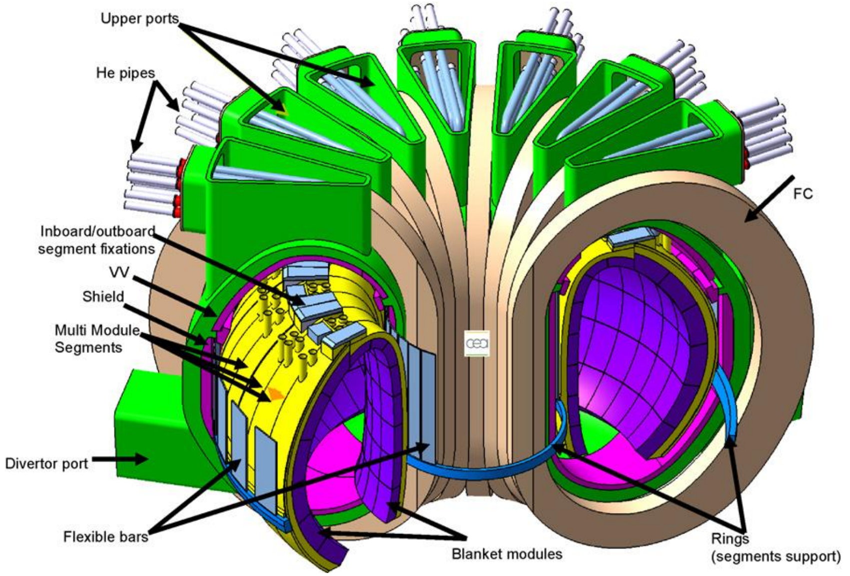
System requirements

Any Breeding Blanket (BB) consists of:

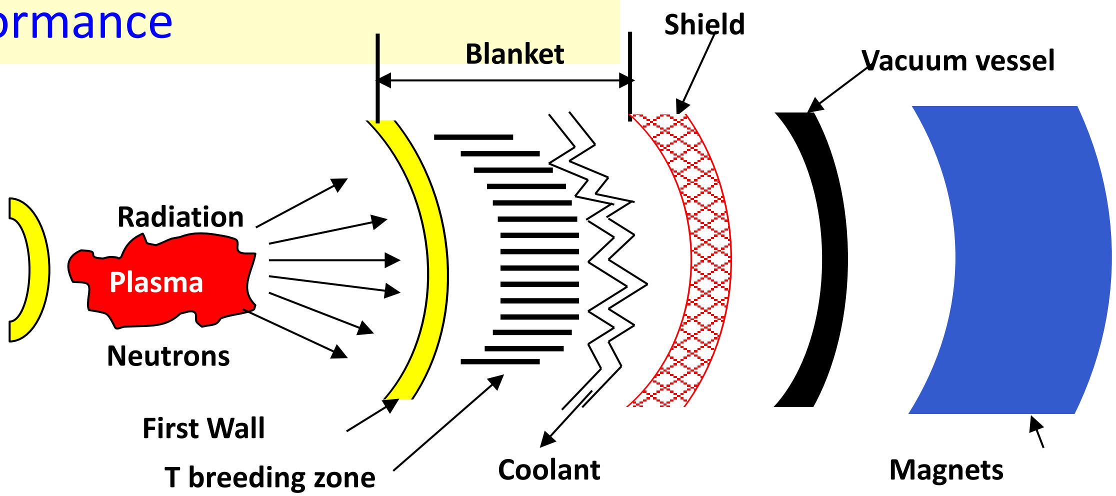
- Li bearing breeding material
- neutron multiplier
- structural material
- coolant

Any acceptable combination has to be satisfactory with respect to:

- safety
- performance



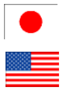
HCLL-DEMO reactor (2007, CEA)



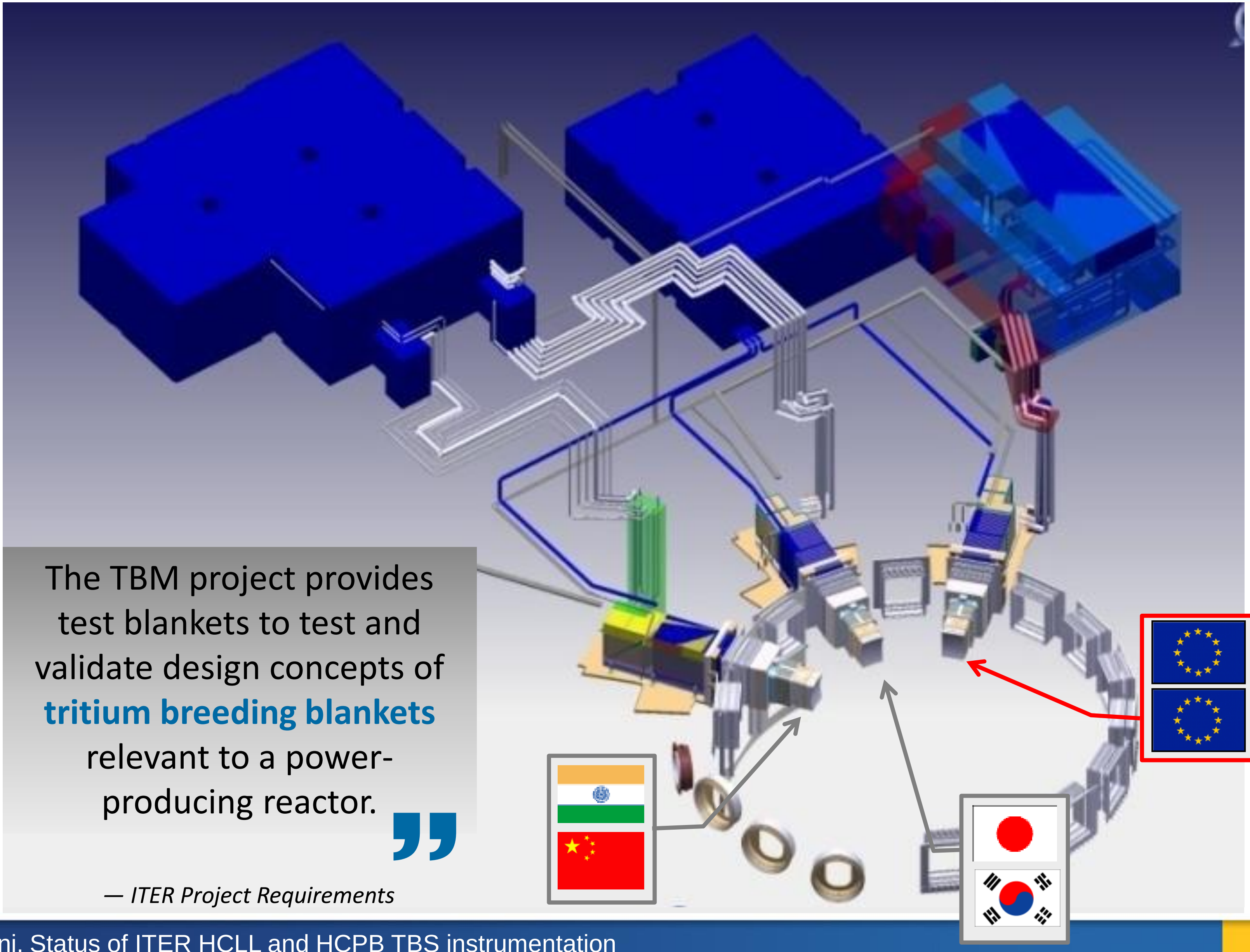
Blanket scheme for TOKAMAK configuration: toroidal-radial view

Concept studies (and associated R&D) on breeding blankets in the world (since the 80's)

FUSION FOR ENERGY

Blanket type	WCLL	HCLL	HCCB	WCCB	LLCB	DCLL	Molten Salt	Li-V	Adv. HCCB	SCLL	Li Evap.
Structural material	RAFM	RAFM	RAFM	RAFM	RAFM	RAFM + ODS	Ferritic Steel	V alloy (+ insulation)	SiCf/SiC	SiCf/SiC	W alloy
Breeder	Pb-16Li (liquid)	Pb-16Li (Liquid)	Li_4SiO_4, Li_2TiO_3 (pebbles)	Li_2TiO_3 (pebbles)	Pb-16Li (liquid) + Li_2TiO_3 (pebbles)	Pb-16Li (liquid)	FLiBe (liquid)	Li (nat.)	Li_2TiO_3, Li_2O (pebbles)	Pb-16Li (liquid)	Li (nat.)
Neutron Multiplier			Be (pebbles)	Be (pebbles)			Be (pebbles)		Be (pebbles)		
Coolant	H_2O (15 MPa)	He (8 MPa)	He (8 MPa)	PWR and Supercritical H_2O (15.5 - 25 MPa)	He (8 MPa)	He (8 MPa) + Pb-16Li	FLiBe (liquid)	Li (nat.)	He (10 MPa)	Pb-16Li	Li (nat.) evap.
T coolant	265 - 325	300 - 500	300 - 500	290 - 520	325 - 500	300 - 480 (He) 460 - 700 (PbLi)	450 - 550	330 - 610	600 - 900	765 - 1100	1100 - 1200
T Structural material	265 - 550	300 - 550	300 - 550	290 - 550	300 - 550	300 - 550	max. 550	330 - 700	700 - 1150	765 - 1000	max. 1300
Reactor concept studies	PPCS-A	PPCS-AB	PPCS-B	SSTR	DEMO-S	ARIES-ST APEX PPCS-C	FFHR-2	ARIES-RS	DREAM A-SSTR2	ARIES-AT TAURO	APEX-EVOLVE
& R&D											

3rd ITER Council (2008) established the TBMs program in ITER

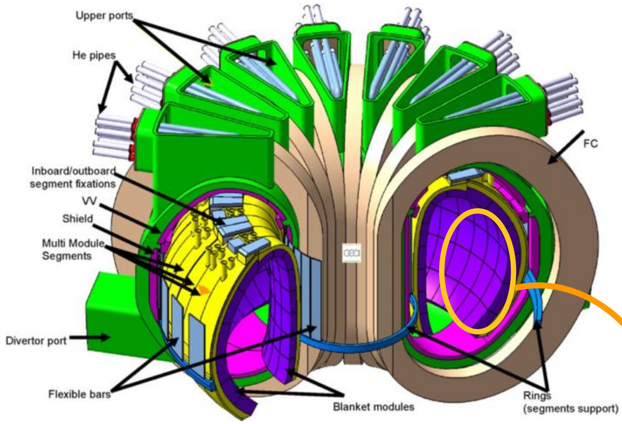


"The TBM project provides test blankets to test and validate design concepts of **tritium breeding blankets** relevant to a power-producing reactor."

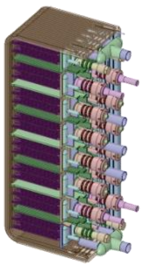
— ITER Project Requirements

TBM Systems will test technological solutions

- DEMO concept studies and basic R&D are not sufficient to decide on selection/ranking of concept(s)
- ⇒ **Need for ROX (Return On eXperience)**
  - Performances under tokamak actual and multi-loadings conditions (B, n, heat flux)
  - Implementation of regulatory obligations (e.g. ESPN, waste disposal, etc.)
  - Methodology for integration of new materials/fabrication in C&S
  - Involvement of Industry, cost
  - Availability (failures database)

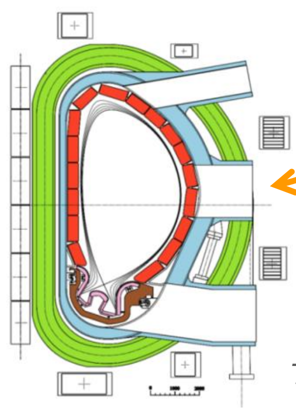


HCLL-DEMO



HCLL-TBM

- The **Test Blanket Module (TBM) Program** in ITER is organizing the implementation & test of blankets **technological solutions**:
  - Test in tokamak (ITER)
  - Regulatory obligations (ITER nuclear plant, ASN)
  - Involvement of Industry; project budgetary constraints; etc.



Test in ITER

Concepts selected for the TBM Program in ITER

FUSION FOR ENERGY

European TBM Program

Blanket type	WCLL	HCLL	HCCB	WCCB	LLCB	DCLL	Molten Salt	Li-V	HCCB	SCLL	Li Evap.
Structural material	RAFM	RAFM	RAFM	RAFM	RAFM	RAFM + ODS	Ferritic Steel	V alloy (+ insulation)	SiCf/SiC	SiCf/SiC	W alloy
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Neutron Multiplier			Be (pebbles)	Be (pebbles)			Be (pebbles)		Be (pebbles)		
Coolant	H_2O (15 MPa)	He (8 MPa)	He (8 MPa)	PWR H_2O (15.5 MPa)	He (8 MPa)	He (8 MPa) + Pb-16Li	FLiBe (liquid)	Li (nat.)	He (10 MPa)	Pb-16Li	Li (nat.) evap.
T coolant	265 - 325	300 - 500	300 - 500	290 - 520	325 - 500	300 - 480 (He) 460 - 700 (PbLi)	450 - 550	330 - 610	600 - 900	765 - 1100	1100 - 1200
T Structural material	265 - 550	300 - 550	300 - 550	290 - 550	300 - 550	300 - 550	max. 550	330 - 700	700 - 1150	765 - 1000	max. 1300
TBM Leaders											

First 10 years of ITER operation

Potentially tested in second phase of ITER op.

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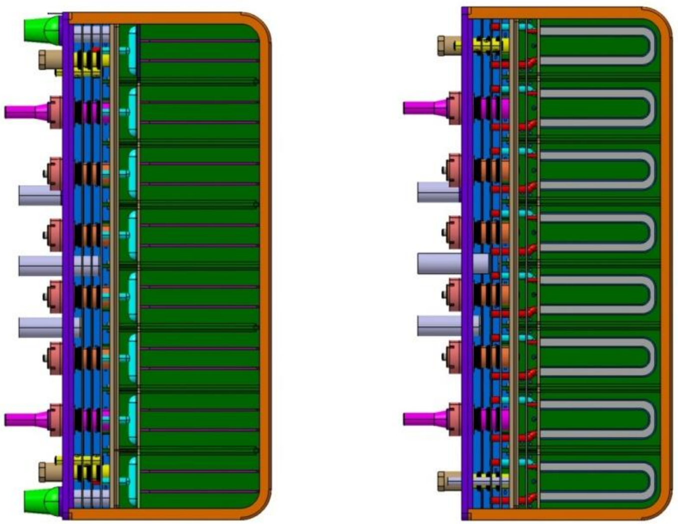
Mission of the EU TBM Program in ITER

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

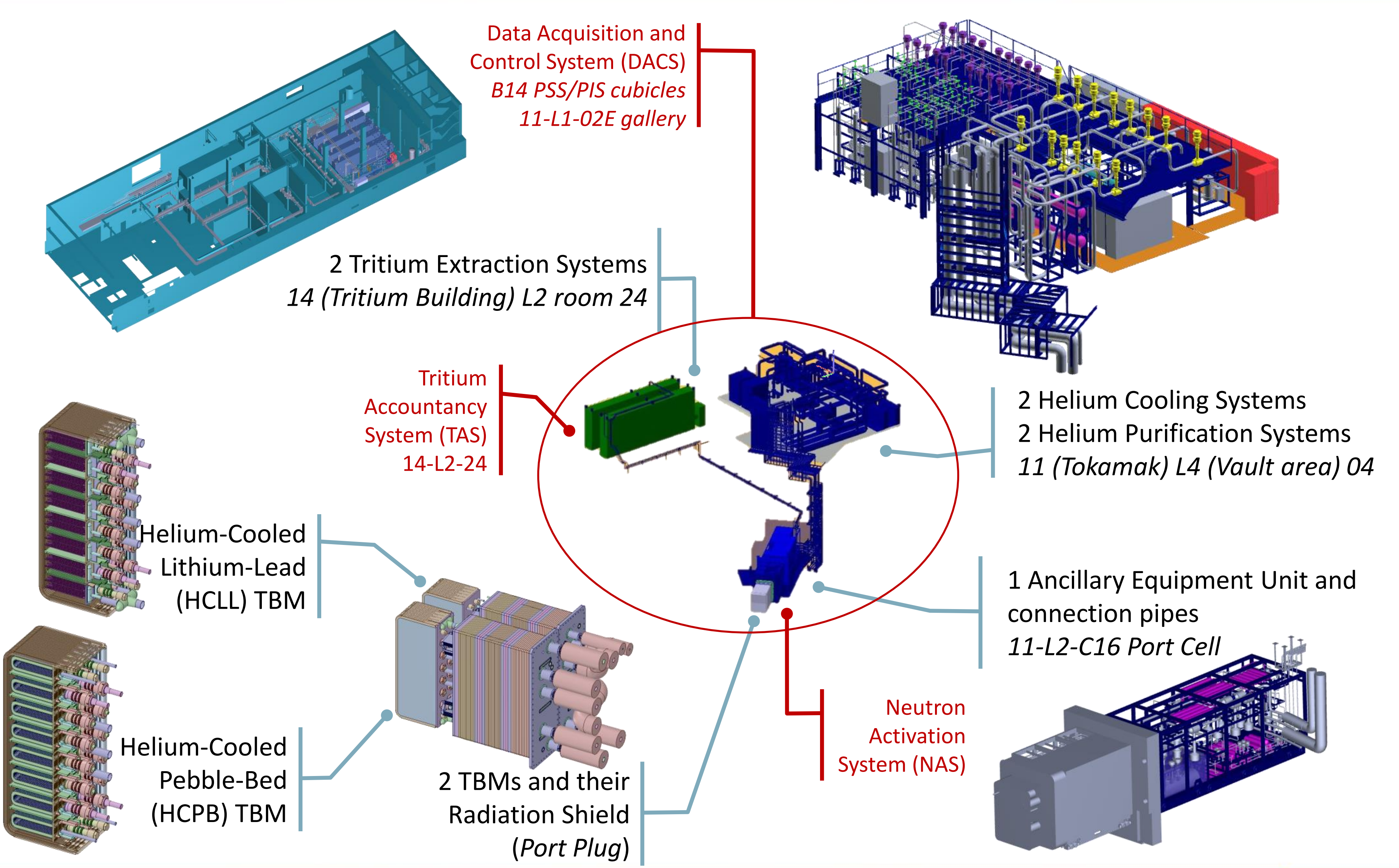
This is achieved by:

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



	HCLL (He-Cooled lithium-Lead)	HCPB (He-Cooled Pebble-Bed)
Structural material	EUROFER97 (RAFM steel)	
Coolant	Helium (8 MPa, 300-500°C)	
Tritium breeder, Neutron multiplier	Liquid: Pb-16Li	Solid pebbles: Li_2TiO_3 / Li_4SiO_4, Be
Sub-systems	HCS, CPS, TES, PbLi loop	HCS, CPS, TES

The HCLL and HCPB TBM Systems (TBS)



4 TBMs in sequence for each BB concept

FUSION FOR ENERGY

In order to perform a comprehensive experimental campaign under the different ITER operating conditions 4 TBMs will be deployed for each DEMO breeding blanket concept:

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

- All TBMs are designed with a common set of instruments participating in **control functions** for pressure, temperature and strain
- Additional sensors are deployed on each TBM to perform specific experiments in **fulfilment of the program scientific mission** (neutronics, thermo-mechanics, MHD, EM response, tritium control and management) tailored to ITER operating conditions
- Sub-system are fully instrumented at the initial installation (not including TAS and NAS)

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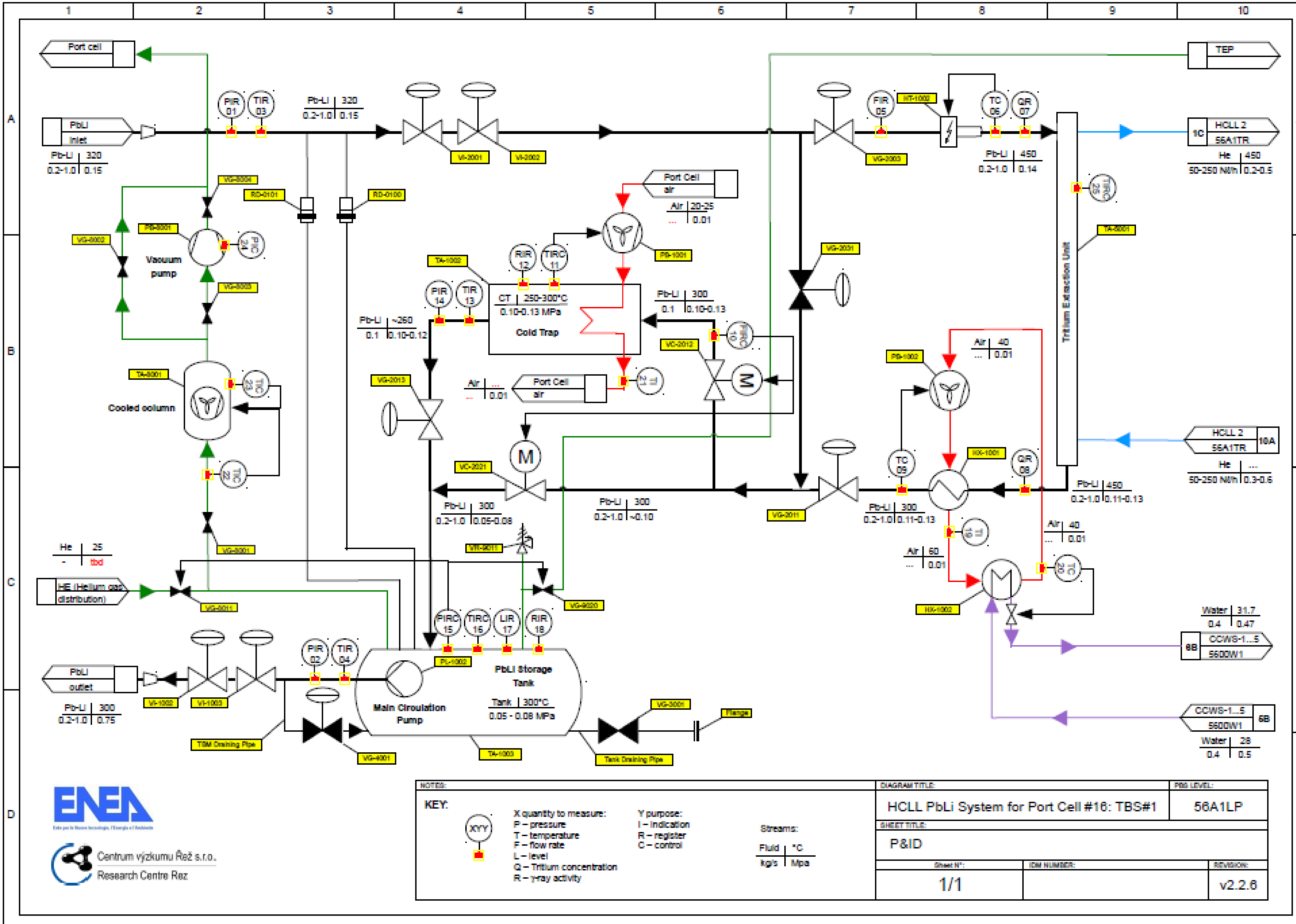

Port cell
TEP
PbLi inlet
Pb-Li | 320
0.2-1.0 | 0.15
FIR 01
TIR 03
VI-2001
VI-2002
VG-2003
FIR 05
HT-1002
TC 06
QR 07
HCLL 2 56A1TR
1C
He | 450
50-250 Nl/h | 0.2-0.5
Pb-Li | 450
0.2-1.0 | 0.14
VG-8004
RD-0101
RD-0100
Port Cell air
Air | 20-25
... | 0.01
VG-8002
PB-8001
PIC 24
Vacuum pump
VG-8003
TA-1002
RIR 12
TIRC 11
PB-1001
FIR 14
TIR 13
CT | 250-300°C
0.10-0.13 MPa
Cold Trap
Pb-Li | ~260
0.1 | 0.10-0.12
Pb-Li | 300
0.1 | 0.10-0.13
VG-2031
VC-2012
TIRC 10
TI 21
Port Cell air
Air | ...
... | 0.01
VG-2013
TA-8001
TIC 23
Cooled column
TIC 22
TA-2001
Tritium Extraction Unit
TIRC 25
PB-1002
Air | 40
... | 0.01
HCLL 2 56A1TR
10A
He | ...
50-250 Nl/h | 0.3-0.6
VC-2021
M
Pb-Li | 300
0.2-1.0 | 0.05-0.08
Pb-Li | 300
0.2-1.0 | ~0.10
VG-2011
TC 09
HX-1001
QR 08
Pb-Li | 300
0.2-1.0 | 0.11-0.13
Pb-Li | 450
0.2-1.0 | 0.11-0.13
TI 19
Air | 40
... | 0.01
Air | 60
... | 0.01
TIC 20
HX-1002
VG-8001
VR-9011
He | 25
- | tbd
HE (Helium gas distribution)
VG-8011
VG-9020
Water | 31.7
0.4 | 0.47
CCWS-1...5 5600W1
6B
FIRC 15
TIRC 16
LIR 17
RIR 18
PL-1002
PbLi Storage Tank
Tank | 300°C
0.05 - 0.08 MPa
PbLi outlet
Pb-Li | 300
0.2-1.0 | 0.75
VI-1002
VI-1003
PIR 02
TIR 04
Main Circulation Pump
TSM Draining Pipe
VG-4001
TA-1003
VG-3001
Flange
Tank Draining Pipe
CCWS-1...5 5600W1
6B
Water | 28
0.4 | 0.5
NOTES:
KEY:
XYY
X quantity to measure:
P – pressure
T – temperature
F – flow rate
L – level
Q – Tritium concentration
R – γ-ray activity
Y purpose:
I – indication
R – register
C – control
Streams:
Fluid | °C
kg/s | Mpa
DIAGRAM TITLE:
HCLL PbLi System for Port Cell #16: TBS#1
PBS LEVEL:
56A1LP
SHEET TITLE:
P&ID
Sheet N°:
1/1
IDM NUMBER:
REVISION:
v2.2.6
Centrum výzkumu Řež s.r.o.
Research Centre Rez

Sub-systems instrumentation

System/ Subsystem	Temperature	Pressure	Flow Rate	Level	Other	Total
HCS *(PC)*	3	3	2	0	0	**8**
HCS *(CVCS)*	4	5	4	0	0	**13**
CPS	19	8	3	0	5	**35**
PbLi Loop	15	6	8	2	7	**38**
TRS *(PC16)*	1	3	2	0	2	**8**
TRS *(B14)*	2	6	2	0	4	**14**
HCLL	***44***	***31***	***21***	***2***	***18***	***116***

Endress-Houser Tc for 8 Mpa helium (HELOKA)

Temperature

K-type thermocouples inserted in thermowells.

For safety (and possibly interlock) sensors digital switches are being integrated in the Preliminary Design.

For conventional sensors head mounted voltage to current converters are considered for higher accuracy, but qualification for Port Cell 16 conditions (radiation, EM noise) is on-going as part of development activities.

Heating elements not yet considered in the analysis.

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Siemens differential pressure sensor for 8 Mpa helium (HELOKA)

Pressure

Diaphragm pressure transmitters on tap lines (capillaries) for temperature control. Comparison of performance of sensors based on ceramic and metallic diaphragm and design and qualification of electronics to environmental conditions are ongoing.

For measurement of the hydraulic pressure of Pb-16Li the pressure taps are filled with an incompressible intermediate liquid - reference from Pb-Bi systems, eutectic sodium-potassium molten salt (Na-22K). Design optimization and experimental validation are ongoing.

Gefran Pb-16Li senosrs tested in IELLLO (ENEA)

Sub-systems instrumentation

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HCS *(PC)*	3	3	2	0	0	**8**
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Flow rate

Reference technology for conventional sensors for helium and Pb-16Li is Coriolis flow meter. Performance validation is ongoing.

Differential Pressure flow meters now considered as safety sensors (simple, reliable).

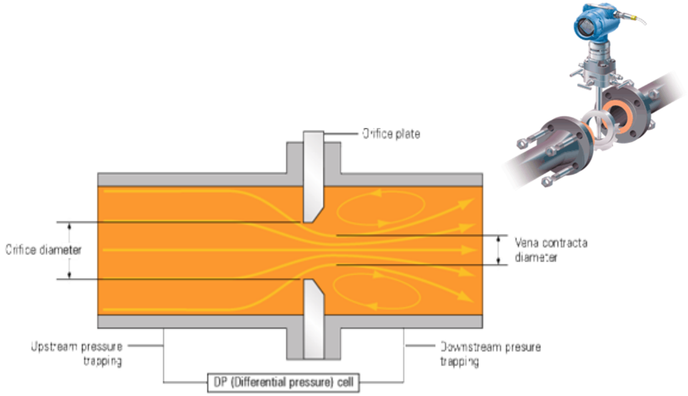
Coriolis mass flow meter operating principle involves **inducing a vibration of the flow tube** through which the fluid passes, which provides the rotating reference frame which gives rise to the Coriolis effect.

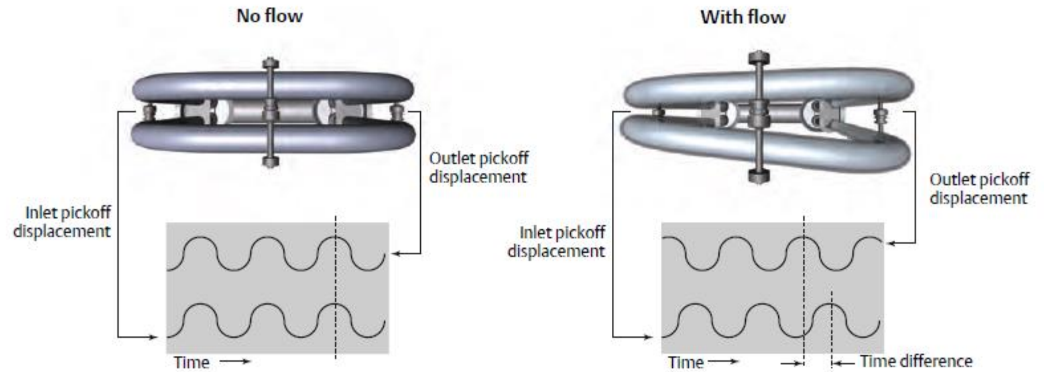
Sensors **monitor changes in frequency, phase shift, and amplitude** of the vibrating flow tubes and relates to mass flow rate and density of the fluid.

Feasibility and optimization for Pb-16Li is part of development activities.

Main advantages:

- **measure mass flow** directly, independent of operating temperature, pressure, or composition
- **not affected by EM noise**.





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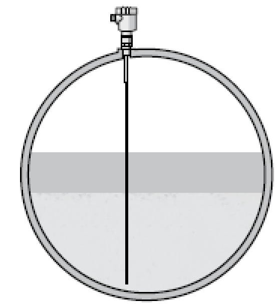
Liquid metal level

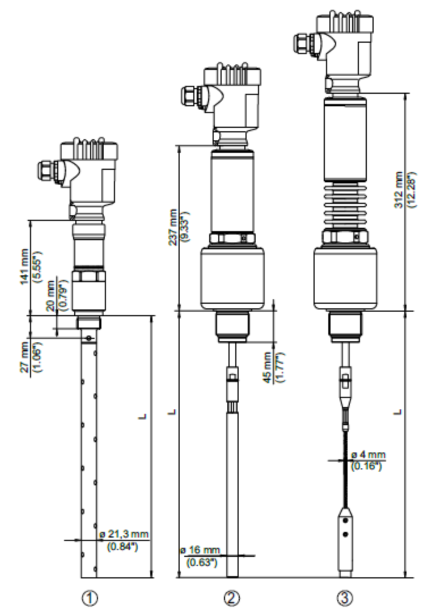
Radar level sensor technology (based on high frequency microwaves) is selected as reference option.

The sensor emits a microwave signal and monitors its reflection from the liquid metal surface. The distance is determined based on the time of flight.

Sensitivity and measurement range depend on the shape of antenna but the sensor response is not affected by dust or condensation.

COTS sensors are available and experimental validation is planned as part of development activities.





Vegaflex 86 probes installed on IELLLO (ENEA)

Sub-systems instrumentation

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Other sensors relate to the measurement and control of the concentration of H isotopes and impurities in fluid streams (in addition to TAS).

- Tritium concentration in Pb-16Li – next slide
- H2 and impurities concentration in CPS: reference design based on mass spectrometer coupled with infrared spectroscopy. An alternative is a system based on a gas chromatography coupled with a humidity sensor. Both options are being tested as part of development activities.
- Control of H2 concentration in helium purge streams (TRS and TES): reference design based on COTS components, flow meters and controllers (for helium and hydrogen) and hydrogen meters based on thermal conductivity detector (TCD) technology.
- Control of cover gas in PbLi loop: reference design based on COTS components, flow meters and controllers.
- Gamma ray detectors embedded in the PbLi loop storage tank and cold trap.
- Additional instrumentation deployed to control and monitor the performance of specific components not identified at this stage of design, for example heating systems and getter bed vessels.
- Chemical analysis of the liquid metal are limited to PIE activities. Feasibility of periodic sampling in the CT by-pass leg coupled with a compact chemical analysis system is under consideration for the next phase of design.

Note:
The monitoring of environmental conditions in PC16 related to radioactive inventories (tritium, including room air and surface concentration monitoring and neutron induced) is outside of the scope of TBS instrumentation because its development and procurement belongs to the operator responsibilities (IO).

Tritium measurement in Pb-16Li

FUSION FOR ENERGY

Permeation capsules is the reference technology tested as part of F4E activities

Electro-chemical sensors based on doped perovskites ceramics are under development

Equilibrium mode

Isolated volume
Wait for $\Delta P/\Delta t = 0$

$C_{L,H} = K_{S,L}\, P_{eq}^{0.5}$

Dynamic mode

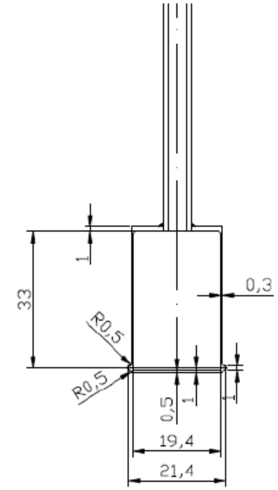
Measured out flow
Wait for $\Delta P/\Delta t = c$

$J_{out,ss} = f(P_{eq}, K_S, D_m, K_{m1}, K_{m2})$

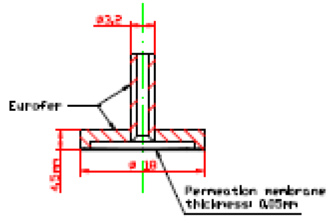
Several design implementations of pure Fe cylindrical capsules tested at ENEA

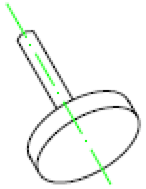
Remaining challenges:

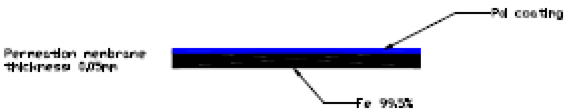
- Response time (eq mode)
- Stability of surface conditions
- Accuracy of isotopic composition measurement (H/T)



Coated membrane capsules (Pd on vacuum side) under development







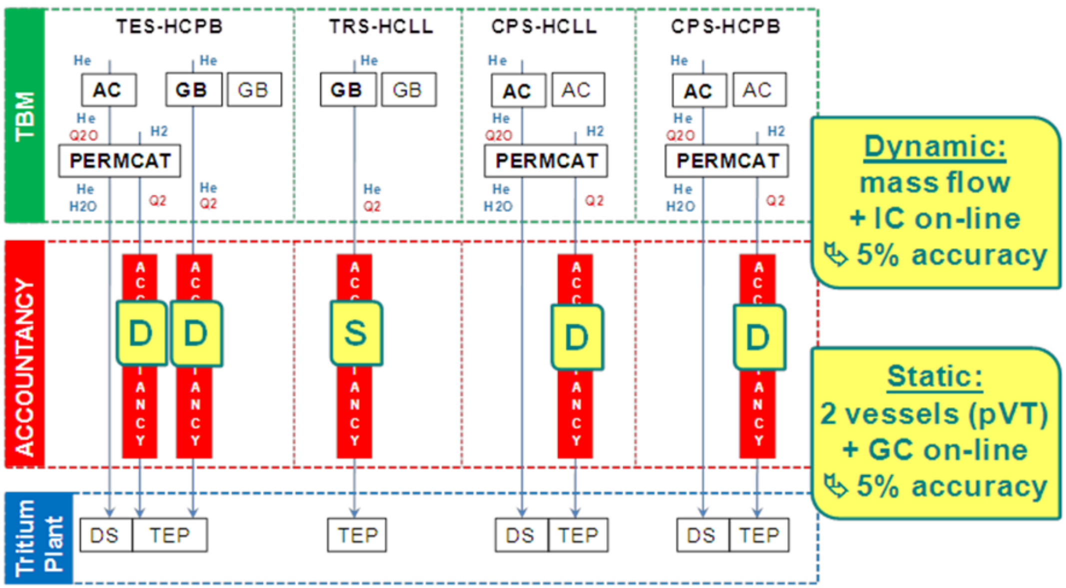
ENEA

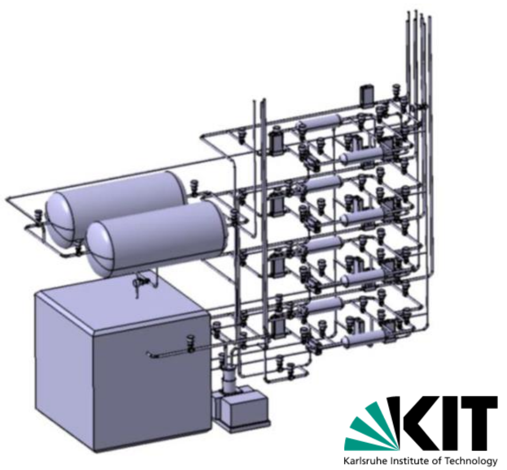
Ente per le Nuove tecnologie, l'Energia e l'Ambiente

Tritium Accountancy Station (TAS)

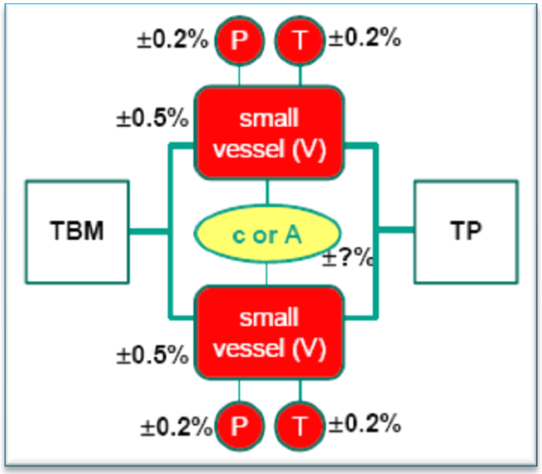
The design of TAS is driven by its two main functions:

- Accountancy, by measuring the amount of tritium that in a given period of time enters the Tritium Plant - an administrative service of basic importance for the nuclear operator.
- Discrimination: through the independent measurement of the tritium amount collected at the end of each TBS sub-system (including isotopic composition when relevant) provides data towards the fulfillment of the TBM project scientific mission. In particular, allows the validation of modeling tools to predict the amount of tritium generated in the TBMs and its transport along the TBS sub-systems.

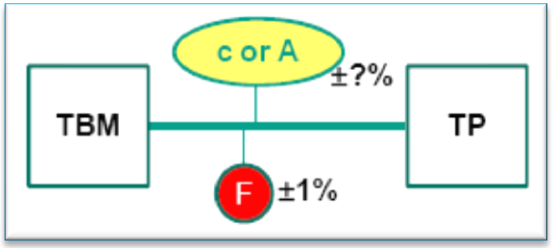




Components of the secondary barrier (in particular, the Glove Box hosting the system in the Tritium Process Room) are common between HCLL and HCPB TBS. TAS is considered an independent sub-system of the I&C.



Static vs dynamic approach



Conceptual design of TAS

Priority on reliability, simplicity and validated performance

	Approach	Total amount	Tritium concentration	Accuracy
HCPB-TES-AC	No accountancy	Coriolis	In-line ionisation chamber	n.a.
HCPB-TES-PC	Dynamic	Thermal mass flow meter	On-line ionisation chamber	4%
HCPB-TES-GB	Dynamic	Coriolis mass flow meter	On-line ionisation chamber	4%
HCLL-TRS-GB	Static	pVT	Gas chromatography	5%
HCPB-CPS-AC	No accountancy	Coriolis	In-line ionisation chamber	n.a.
HCPB-CPS-PC	Dynamic	Thermal mass flow meter	On-line ionisation chamber	4%
HCLL-CPS-AC	No accountancy	Coriolis	In-line ionisation chamber	n.a.
HCLL-CPS-PC	Dynamic	Thermal mass flow meter	On-line ionisation chamber	4%

Outline

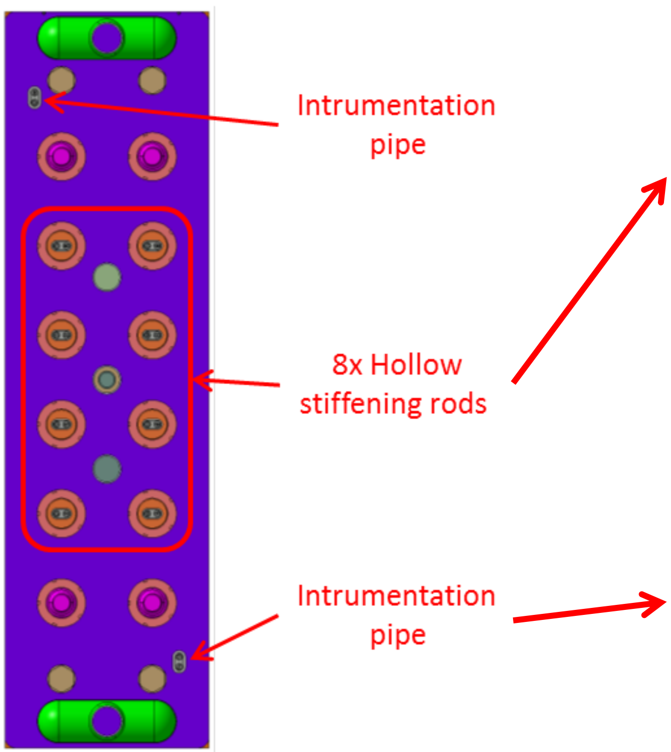
FUSION FOR ENERGY

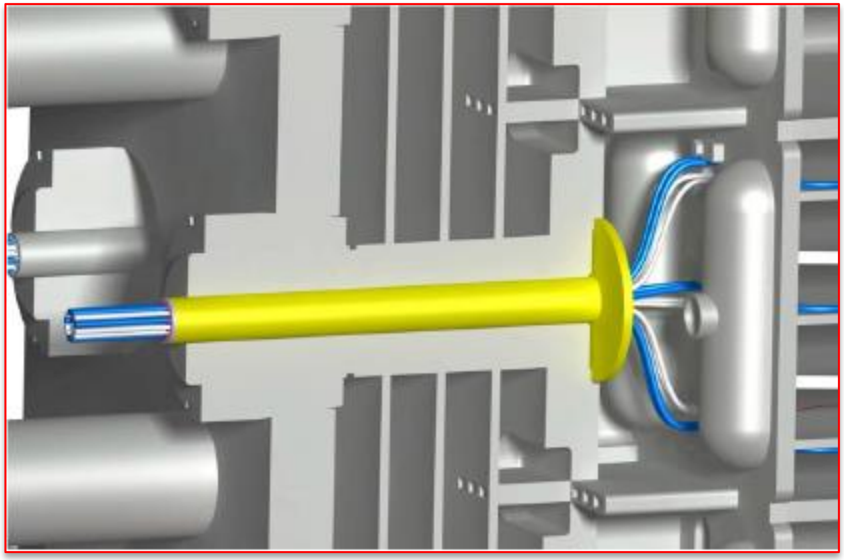
- ITER TBM program: validation of BB concepts
- The HCLL and HCPB Test Blanket Systems
- TBS I&C design overview
- Sensor technology: sub-systems
- Sensor technology: TBM

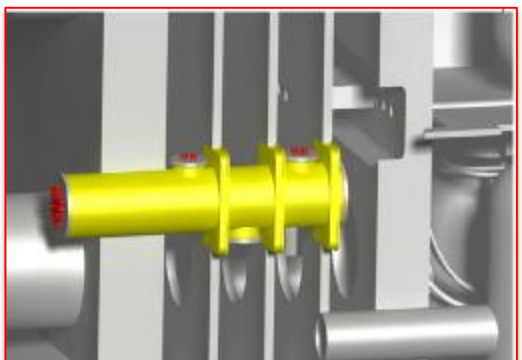
Sensors integration in TBMs (1)

3 types of mounting:

- **External**
- **Hollow stiffening rods (BU)**
- **Manifold pipes**





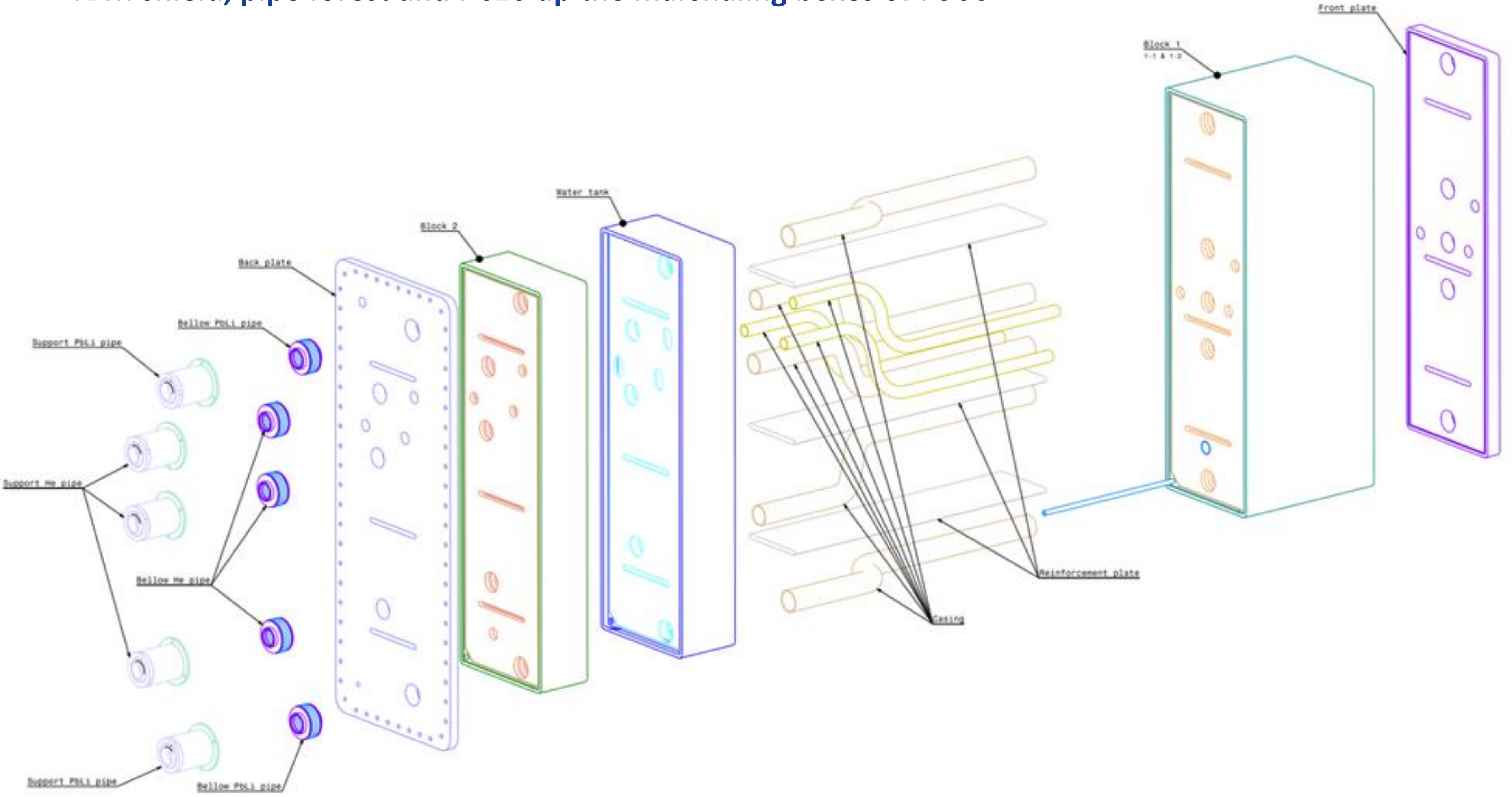


Note:

Proposed solutions are preliminary. Integration aspects related to assembly and fabrication procedures (ie, weld heat treatment) will be considered for further development.

Sensors integration in TBMs (2)

All sensor cables are routed thru 3 instrumentation sleeves in the TBM shield, pipe forest and PC16 up the marshaling boxes of PSCC



Synergies with other ITER systems

Integrate development activities (design + qualification) with blanket (PBS-16) / divertor (PBS-17):

- **sensors installed outside of the TBM box to measure structure temperature and mechanical response (strain), conventional and optical fiber based;**
- **main aspect specific to TBM would be the different substrate material (EUROFER97) for the development and qualification of braising or other bonding procedures.**

With diagnostics (PBS-55):

Area	*ITER diagnostic*	*PBS #*	*Action type*
Temperature measurement	Vis/IR EP	55.G1	Operational requirements
	Thermocouples	55.G2	Design synergies
EM measurements	Rogowksi coils	55.A	Design synergies
	General issues		Design synergies
Neutronics	In-situ calibration	55	Operational requirements
	Micro-FC	55.B3	Design synergies
	NAS	55.B8	Design synergies
	RNC detectors	55.B1/2	Design synergies
Tritium	No reference	55.GC	No reference
Pressure gauges	Capacitance manometers	55.G3	Design synergies
F4E neutron irradiation tests		55	Operational requirements; design synergies

Temperature measurement

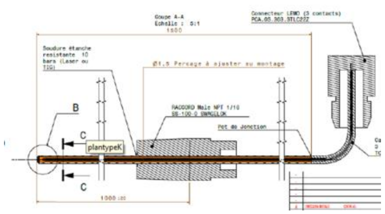
Reference thermocouples:

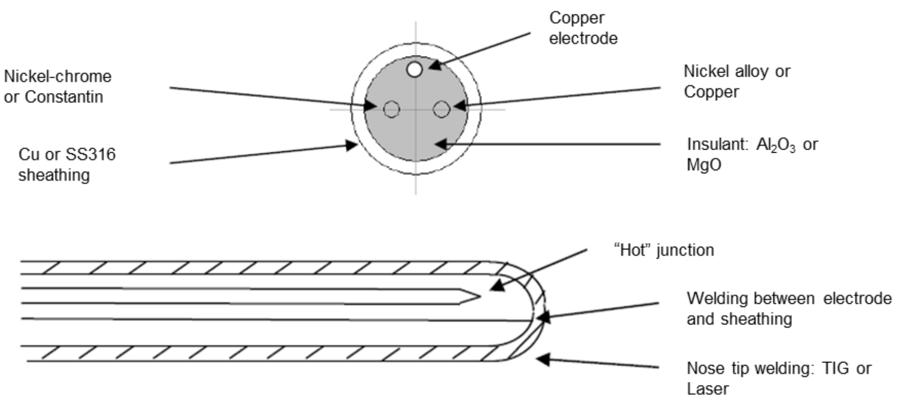
- Type N (Nicrosil/Nisil) for ITER in-vessel components (SCK EFDA report 2003)
- Type K (Chromel/Alumel) for TBM (operate > 150 C)

Based on effects of irradiation (de-calibration from transmutation and RIEMF) and DC magnetic field (Ettingshausen-Nernst effect).
Experimental validation of material properties database for TBM temperature range of operation (300 – 550 C) is ongoing (in particular, Nernst and Righi-Leduc coefficients).

TEMperature and POtential (TemPo) probes for Pb-16Li:

- based on modified ungrounded TCs to which a third wire is added and welded internally to the external jacket
- measure temperature and electrical potential at specified positions to map liquid metal flow distribution and directly compare with numerical simulations.

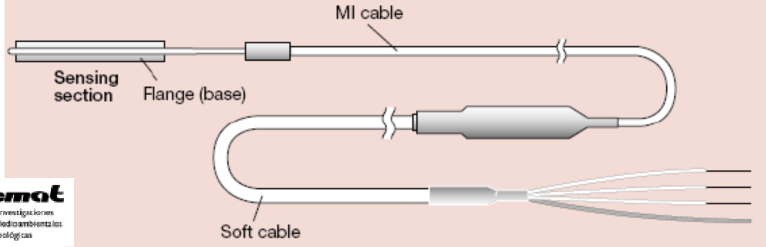




Strain measurement

- Resistance-based strain gauges designed to operate in TBM relevant conditions are available commercially and have been partially validated in operation (in particular, test of Kyowa sensors in JMTR)
- Uniaxial gauges with nickel-chromium wires to minimize magnetic field effects
- Uniaxial, encapsulated design for compatibility with breeder materials

Experimental validation of performance of Kyowa sensors mounted on Eurofer plates at TBM temperature ongoing



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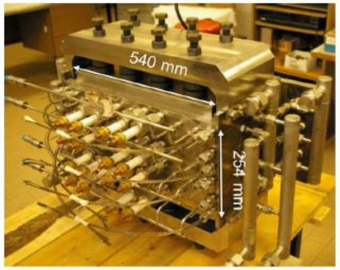
Laboratorio Nacional Fusión



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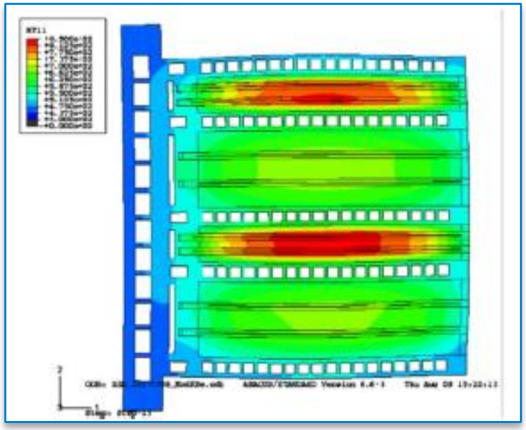


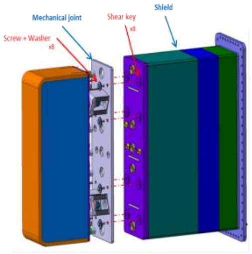
Sensors for HCPB pebble beds

For validation of PBTM numerical models direct contact sensors would be desirable (piezo-electric based) but not commercially available for integration – development not foreseen

Force reconstruction method

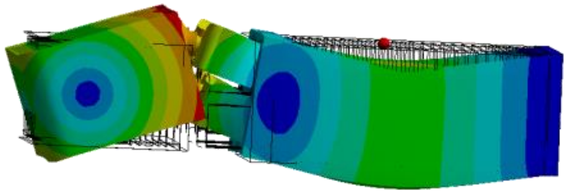
By measuring strain on the TBM to shield attachment and the use of a force reconstruction algorithm it is possible to:

- Validate electro-magnetic models and codes predictions
- Reconstruct forces during operation as input for structural analyses as long as time scale of other loads (pressure/temperature) is decoupled

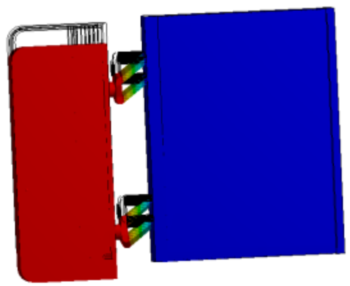


EM simulation → Force distribution → Modal matrix from experimental modal analysis → Comparison of **modal forces** to validate EM models and codes ← Force Reconstruction algorithm

Comparison of **modal forces** to validate EM models and codes ↓ Force distribution ↓ Input forces for structural analysis



Mode 9 (247 Hz)

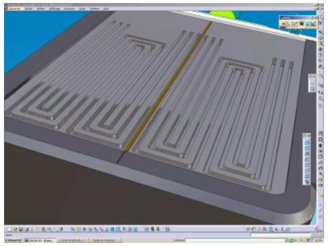


Mode 1 (19 Hz)

Mode No	Frequency in Hz			
	HCLL	HCLL + shield	HCPB	HCPB+ shield
1	25	19	38	29
2	39	27	64	42
3	116	76	177	104
4	138	97	201	107
5	139	116	220	154
6	296	117	322	176
7		161		180
8		218		235
9		247		257

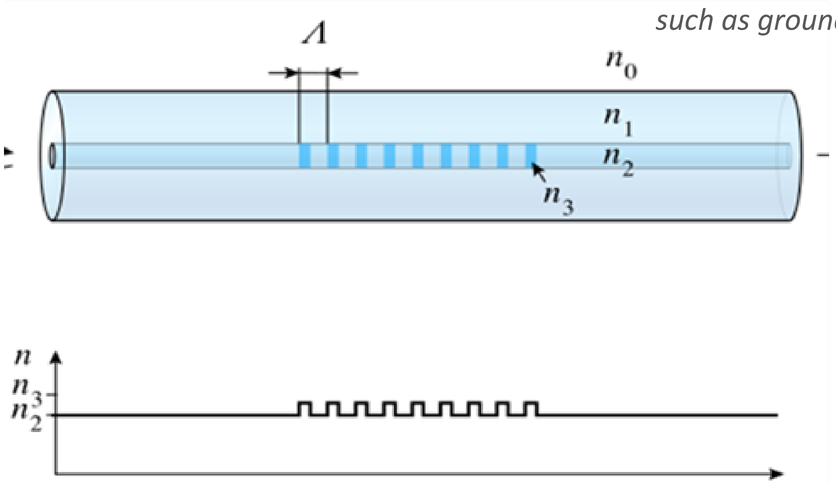
Distributed OF measurements

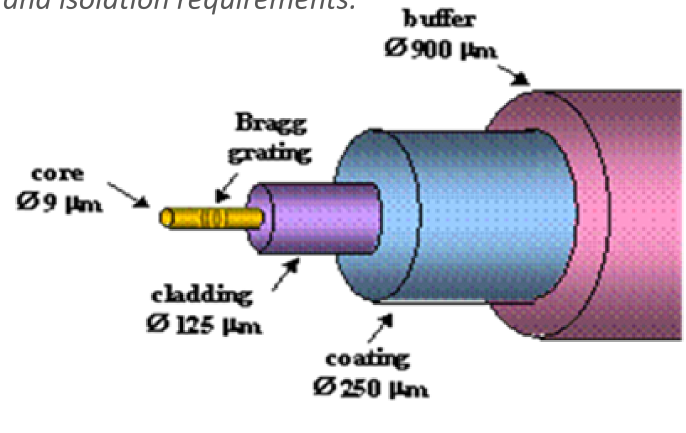
Issue: K-type Tc installed in grooves and COTS encapsulated resistive strain gauges are deployed for control and calibration, but the number proposed in design analysis for temperature and strain mapping (ie, 112 Tcs for HCLL TBM) is not compatible with integration of sensors and cables.



⇒ **Solution**: Combine limited number of Tc with distributed Optical Fiber Sensors (OFS) to measure temperature at multiple locations of a single fiber.

OFS are immune from EM noise and other electrical issues, such as grounding and isolation requirements.





- Distributed measurement by Fiber Bragg Grating (FBG): patterns inscribed in small sections of the fiber core with varying refractive index
- For TBM application (< 600 C) reference core material is silica fiber with laser inscribed grating

FBGs for high temperature (1/5)

Sensing temperature with FBG

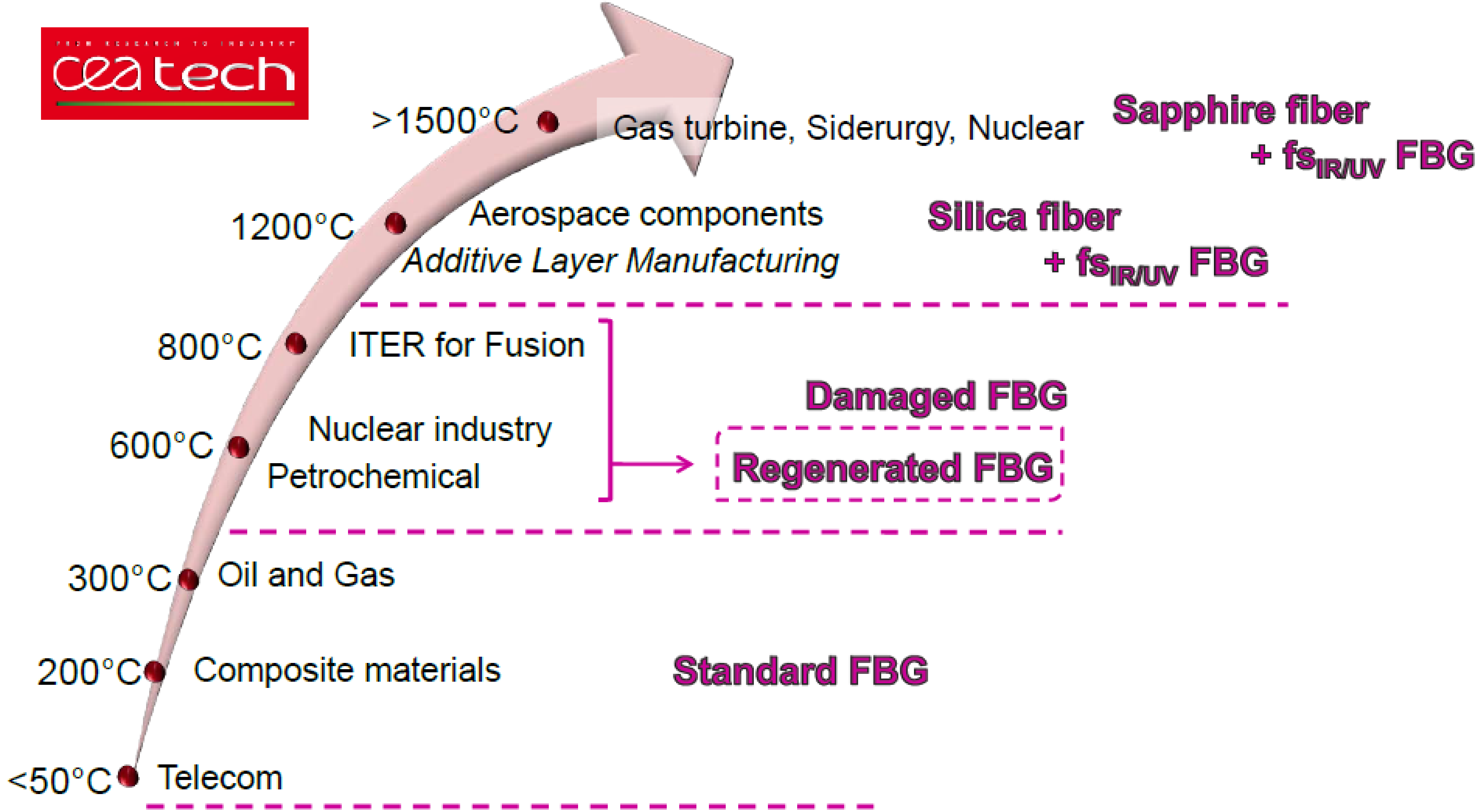
- **Bragg peak shifts with T°→ sensing application ~10 pm/°C**
- Non-linear sensitivity over wide temperature range
- **Calibration is mandatory,** S_T=f[substrate, dopants, wavelength]
- Response time mainly dependent on the packaging

T° is not only a measurement parameter

- **Cross-sensitivity [Strain/T°]:** need for compensation techniques
- **Ageing factor: decrease in reflectivity leading to grating's erasure**
  Bragg wavelength drift, coating degradation, fiber's fragility
- **Accelerated erasure at high T° → typ. ΔR=70% [7 days @ 600°C]**

⇨ **Several ways to stabilize FBG at high T°…**

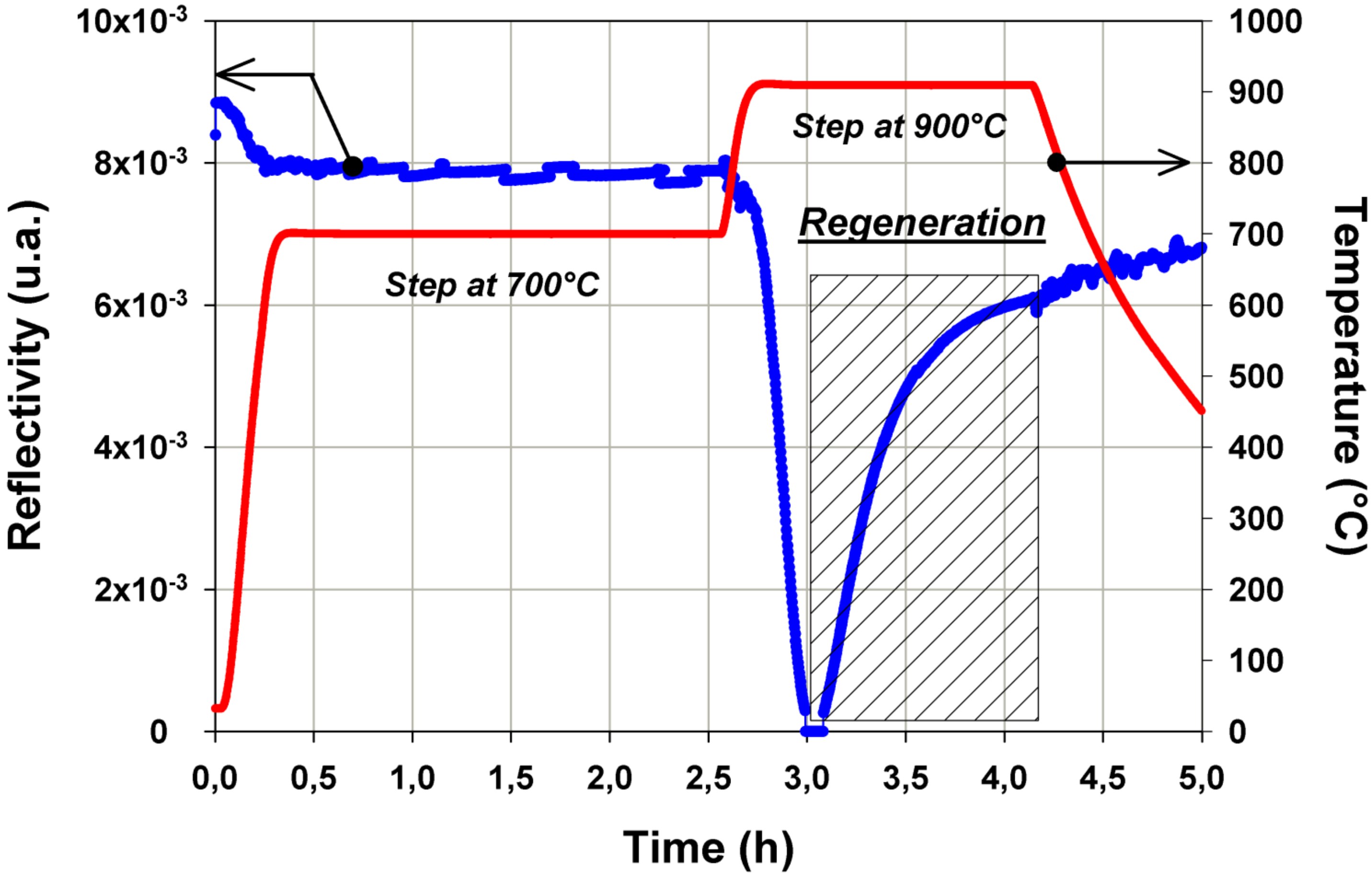
FBGs for high temperature (2/5)



Select the right grating…

FBGs for high temperature (3/5)

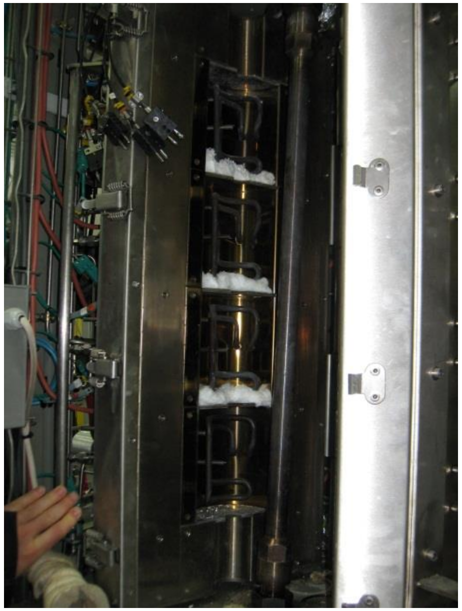
To regenerate Fiber Bragg Gratings:



FBGs for high temperature (4/5)

Three applications in which regenerated FBGs have a role to play

- Oil and Gas: study of catalytic agents
- Nuclear: 4th Generation of Nuclear Reactor
- ITER diagnostics and TBM project



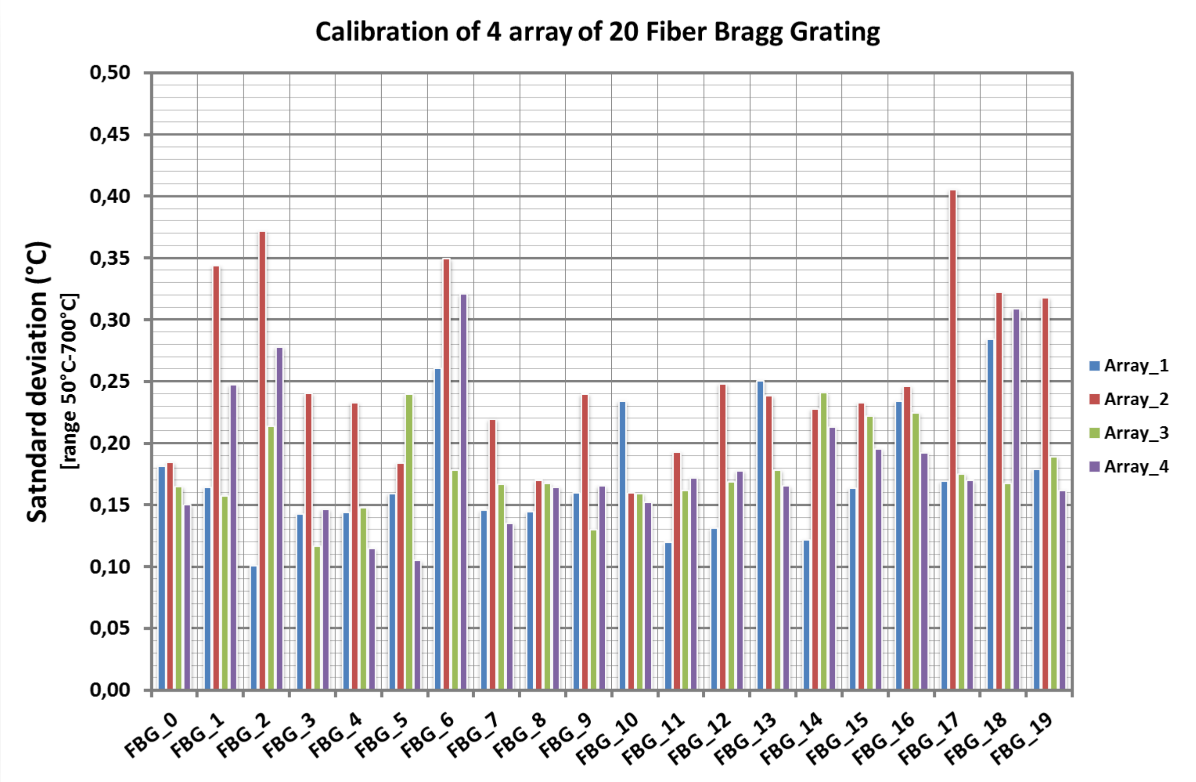
Petrochemical process monitoring

New catalytic agents

- ✓ Accurate T° profile up to 600°C
- ✓ 1 mm channel for sensor insertion
- ✓ No moving sensors
- ✓ « Real time » profile monitoring
- ✓ Metrology: Regenerated FBGs *vs* Calibrated TC

Thermal regulation along the catalytic agent

Results for the calibration

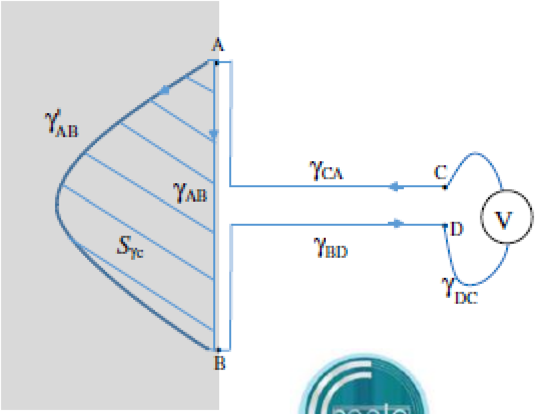


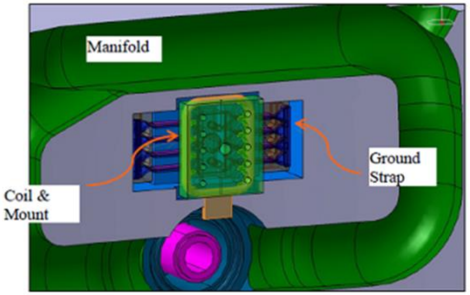
Development of regenerated FBGs for distributed measurement of T and σ is ongoing. The FBG pairs will be inserted in metallic capillaries and mounted on the Eurofer plates. Assessment of irradiation effects is considered as part of F4E irradiation activities.

B field measurement

The TBM structure (ferritic steel) creates a local disturbance of the magnetic field that affects its performance but is not measured by ITER diagnostics. Direct and indirect measurement of the magnetic field is necessary to validate codes prediction and EM loads

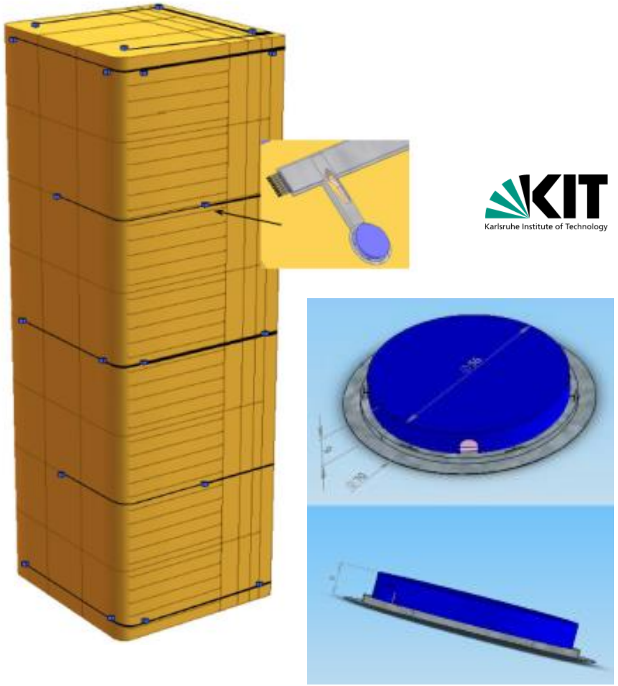
Development of potential probes for the measurement of induced eddy current on the TBM external surfaces





ITER blanket modules design of Rogowski coils at grounding straps (pending TBM design integration)

Magnetic field measurements at TBM box surfaces with Hall sensors



Neutron field measurement

FUSION FOR ENERGY

Why do we need to measure the neutron field inside TBMs?

Along with heat flux, is the source term of test conditions in the TBM, from thermo-mechanical loads to tritium generation

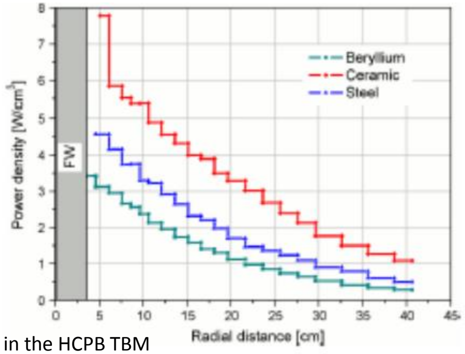
Neutron wall load (source term) not uniform

Effect of surrounding components enhanced by 120 mm recess

Neutron flux (and power density) strongly attenuated radially

Effect of breeder and multiplier materials

Up to 80% attenuation

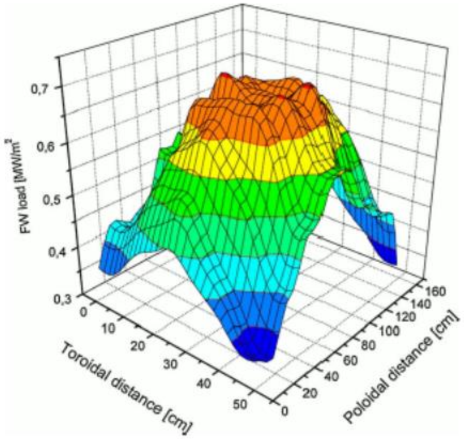


Radial power density distribution in the HCPB TBM

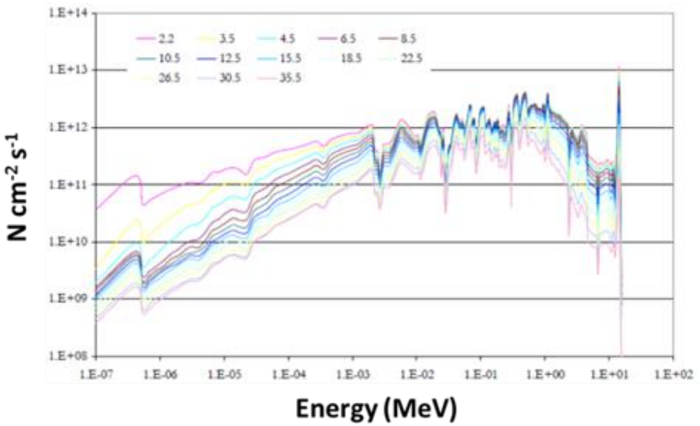
Energy distribution strongly modified in the TBM volume

The contribution of high neutron energy component (E>1MeV) decreases from 37% in the front to about 13% in the rear zone

Toroidal-poloidal distribution of n wall loading for the HCPB TBM
U. Fischer, et al., Fusion Engineering and Design 86 (2011) 2176



Neutron flux spectra at different radial positions of the HCLL TBM, expressed in distance (cm) from the FW



Neutronic sensors

Sensors/instrumentation under development:

Passive sensors (activation foils)

Priority for D plasma op:

- Can discriminate neutron energy (spectra)
- Can be optimized to measure low flux/fluence

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

Karlsruhe Institute of Technology

- **The TBM NAS measures the absolute neutron fluence and the absolute neutron flux with information on the neutron spectrum in selected positions of the TBM**

All sensors under development are considered for testing in JET-DT campaign

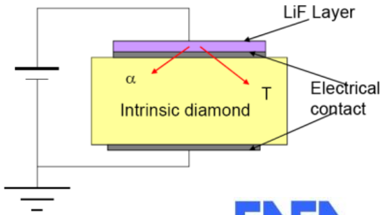
Active sensors

Validate in pulse DT plasma op:

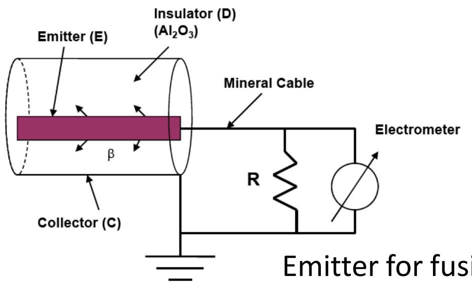
- Low technological maturity
- potential for high sensitivity

^{6}LiF-diamond (SiC) detectors

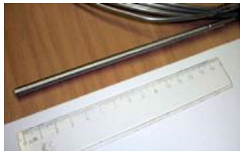
Under development:
Modified SCD and other Li-based sensor technology for TPR; main challenge is high temperature operation (validated to 250 C)



Self-powered neutron detectors

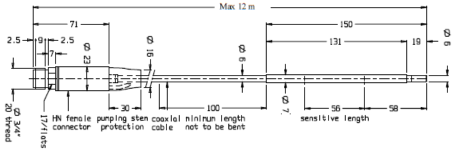


Emitter for fusion spectra: Cr, Be



Miniaturized SPND tested in ENEA

Miniaturized fission chambers

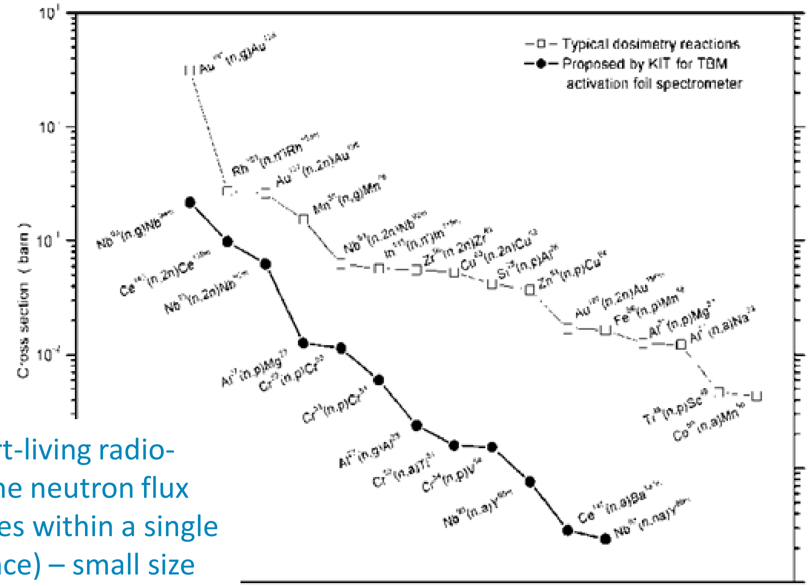


NAS feasibility analysis

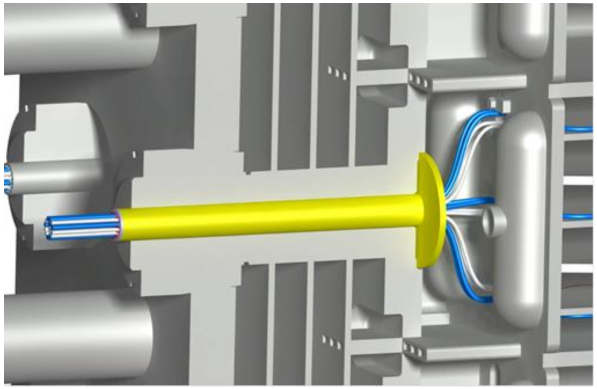
TBM NAS design based on the one operating in JET, applying the same design modification proposed for ITER NAS (part of diagnostics)

Coaxial, self-cooled irradiation end based on ITER NAS.
Y. Lee, et al., Fusion Engineering and Design 89 (2014) 1894.

Comparison of effective cross sections of dosimetry reactions often used in neutronics experiments and the proposed dosimetry reactions leading to SLI for HCPB. The dots are connected for visual guidance only.
A. Klix, et al., Fusion Engineering and Design 87 (2012) 1301.



Probe design including short-living radio-isotopes (SLI) to measure the neutron flux parameters at different times within a single plasma pulse (400 s reference) – small size (8 mm OD) and inventory < 100 µCi possible



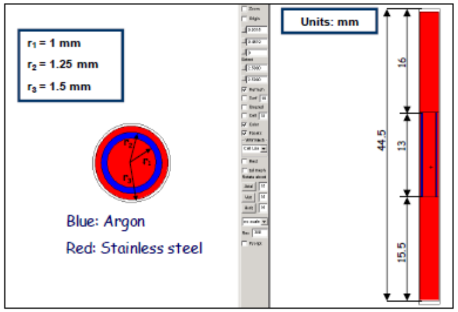
TBM design integration.
The use of hollow stiffening rods, common to all internal instrumentation, allow penetration of the module box and rear manifolds containing high-pressure coolant.

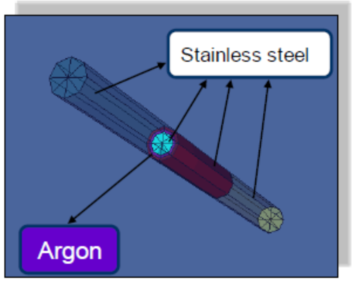
The counting station consists of several spectrometers that measure gamma-rays from the activated samples. Design based on TUD facility used for testing SLI probes and JET.

Fission chambers

The assessment of a commercial fission chamber (Photonis model CFUR43/C5B-U8, 3 mm diameter) has been performed as part of F4E activities for deployment in the IFMIF High Flux Test Module (HFTM) test cell (max op T < 250 C).

It included the assessment of the sensor response by neutronic calculations with MCNP models with integrated sensor …





… and experimental validation by test in the material testing reactor BR2 (SCK·CEN, Belgium)

A similar assessment of the integration of 3 to 6 similar sensors in the HCLL and HCPB TBM with max op T < 600 C (Photonis model CFUE32, 7 mm diam) is ongoing.

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FUSION FOR ENERGY

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- TBS I&C design overview
- Sensor technology: sub-systems
- Sensor technology: TBM

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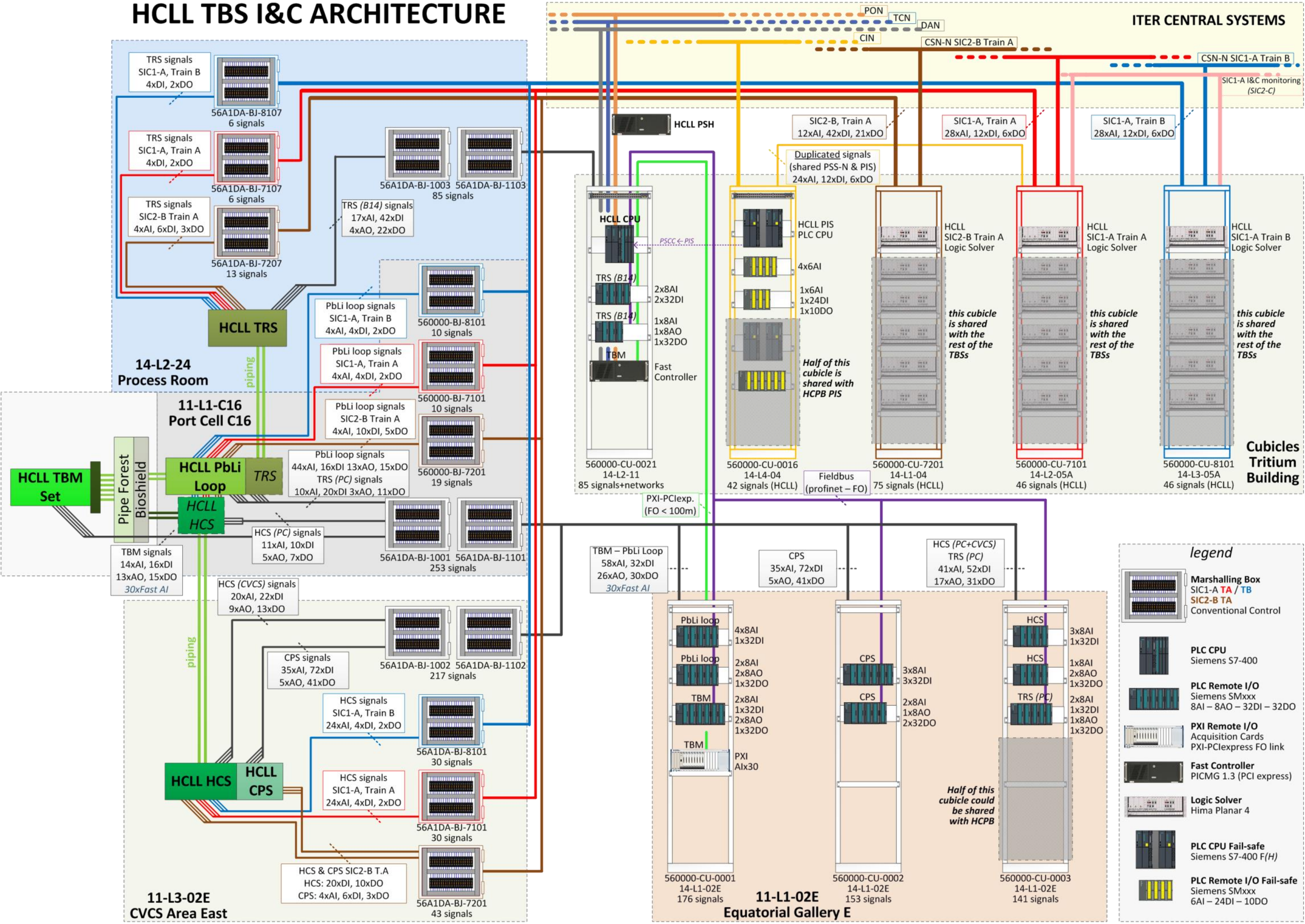
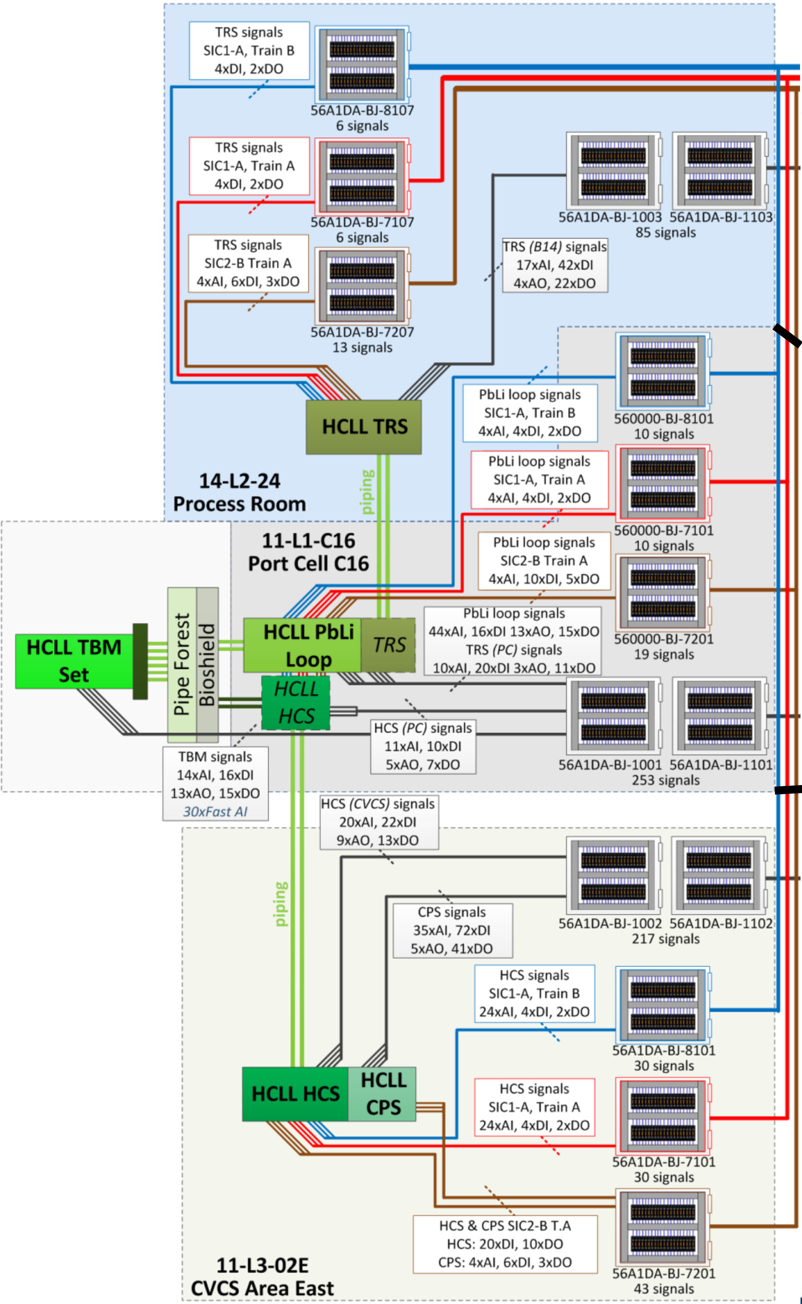
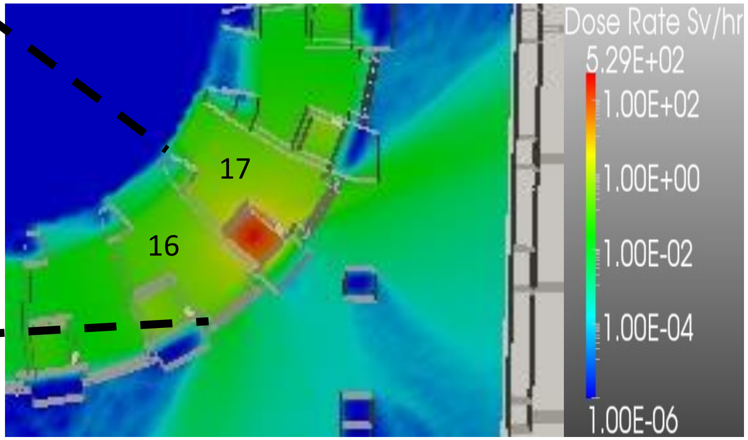
HCLL TBS I&C ARCHITECTURE



HCLL TBS I&C ARCHITECTURE



- Environmental conditions and related requirements are design drivers for sensors and electronics of the I&C sys: **temperature, pressure, radiation and B field** (RF, …).
- Radiation Hardness Assurance (RHA) is a key requirement for safety and interlock components and all system electronics and is taken in consideration from this early design phase (IO RHA Working Group observer). Main criteria is to **avoid active electronics in RHA areas**.



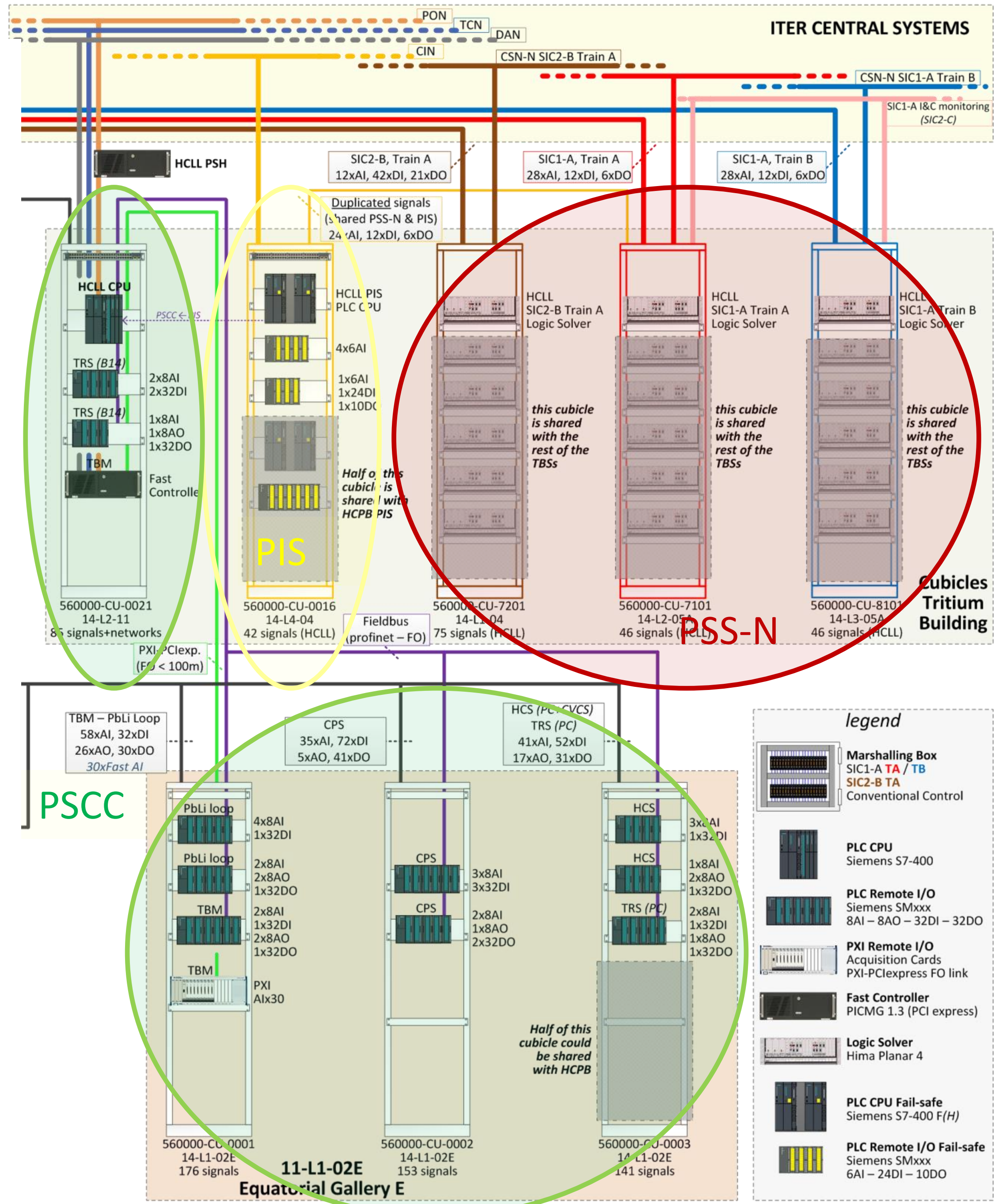
- Radiation maps developed following RHA WG guidelines show a very inhomogeneous field during plasma operation (from PC17 cooling water shaft), with 1-2 Sv/h (equivalent dose in silicon) considered as average reference for systems in PC16.
- Qualification of electronic equipment to a reference value of 100mT in the Port Cell, or to 15mT in the Tokamak corners is planned according to guidelines contained in the ITER 'Electrical Design Handbook (Part 4)'.

HCLL TBS I&C ARCHITECTURE

Plant Systems located in DACS cubicles in Tritium Building

Static magnetic field qualification not required in room 14-L2-21

Field remote I/O modules for SS are located in DACS cubicles in the Equatorial Gallery E of the Tokamak Building



Safety (and interlock) sensors

FUSION FOR ENERGY

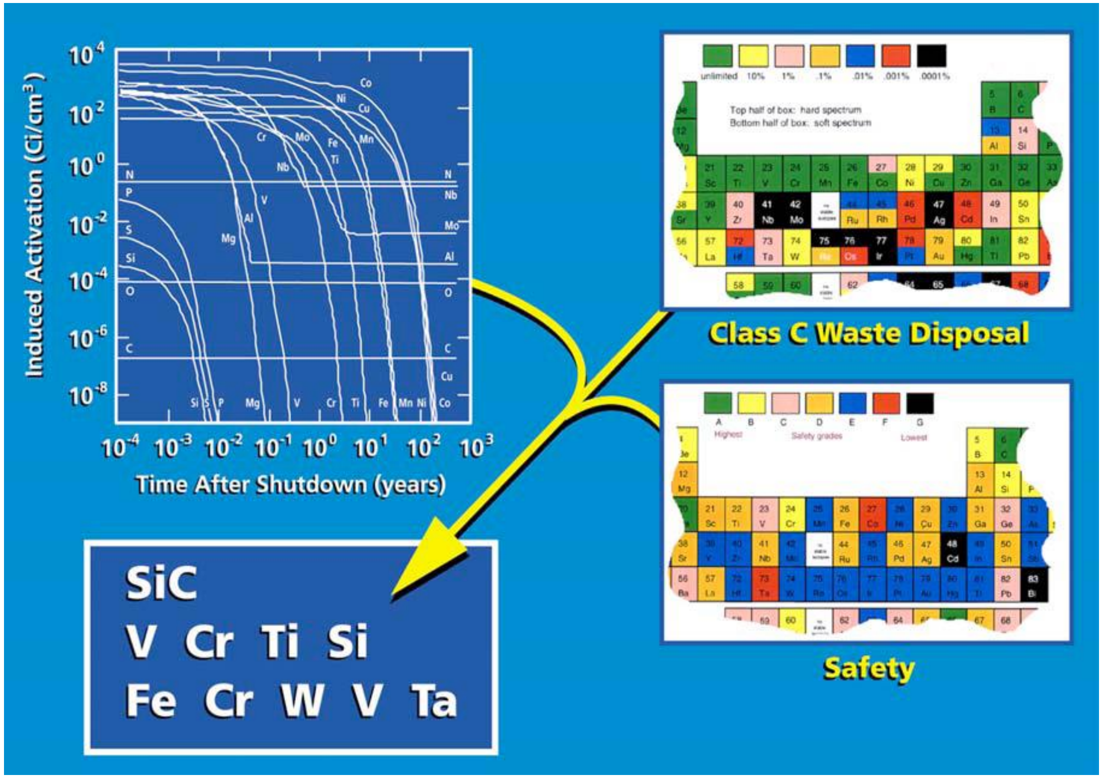
I&C needs (sensors and actuators) required for the implementation of 6 safety functions identified in the 9 accident scenarios (HCLL TBS)

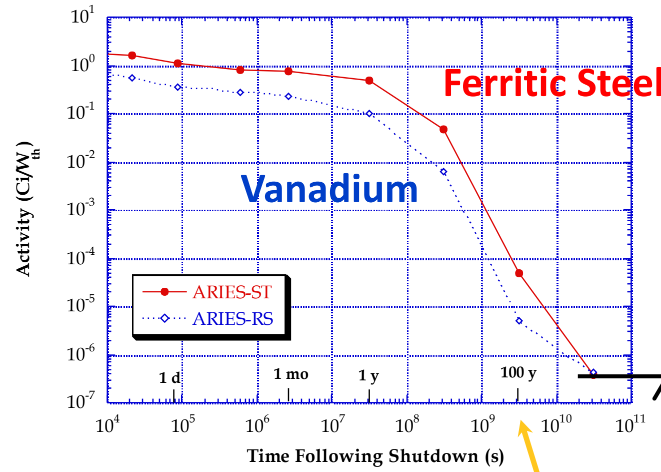
		AI								DI		DO	
HCLL	SIC1 cat. A SCENARIO	Equip. Type	Locations	sensor per location	Train A/B	TOTAL	Equip. Type	Locations	Train A/B	sensor per location	TOTAL	actuator per location	TOTAL
HCS	Ex-vessel LOCA	Pressure	4	1	2	8	Valve	2	2	2	8	1	4
	LOHS	Temperature	4	1	2	8							
	LOFA	Mass flow	4	1	2	8							
		He circulator current	4	1	2	8							
	In-vessel LOCA	Pressure	4	1	2	8							
		Flow rate	4	1	2	8							
Pbi Loop	In-TBM LOCA	Pressure	4	1	2	8	Valve	2	2	2	8	1	4
TRS	-	-	-	-	-	-	Valve	2	2	2	8	1	4
					TOTAL AI	***56***				***TOTAL DI***	***24***	***TOTAL DO***	***12***

		AI								DI		DO	
HCLL	SIC2 cat.B SCENARIO	Type	Locations	sensor per location	Train A/B	TOTAL	Type	Locations	Train A/B	sensor per location	TOTAL	actuator per location	TOTAL
HCS	-	-	-	-	-	-	Valve	10	1	2	20	1	10
CPS	CPS pipe break	Pressure	4	1	1	4	Valve	3	1	2	6	1	3
PbLi Loop	PbLi pipe break	Pressure	4	1	1	4	Valve	5	1	2	10	1	5
TRS	TRS pipe break	Pressure	4	1	1	4	Valve	3	1	2	6	1	3
					TOTAL AI	***12***				***TOTAL DI***	***42***	***TOTAL DO***	***21***

Note:
HCS-PCS failure was not considered at the time of the analysis

Rad-waste disposal: development of low activation structural material





After 100 years, only 10,000 Ci remain in the 585 tonne ARIES-RS fusion core.

Level in Coal Ash

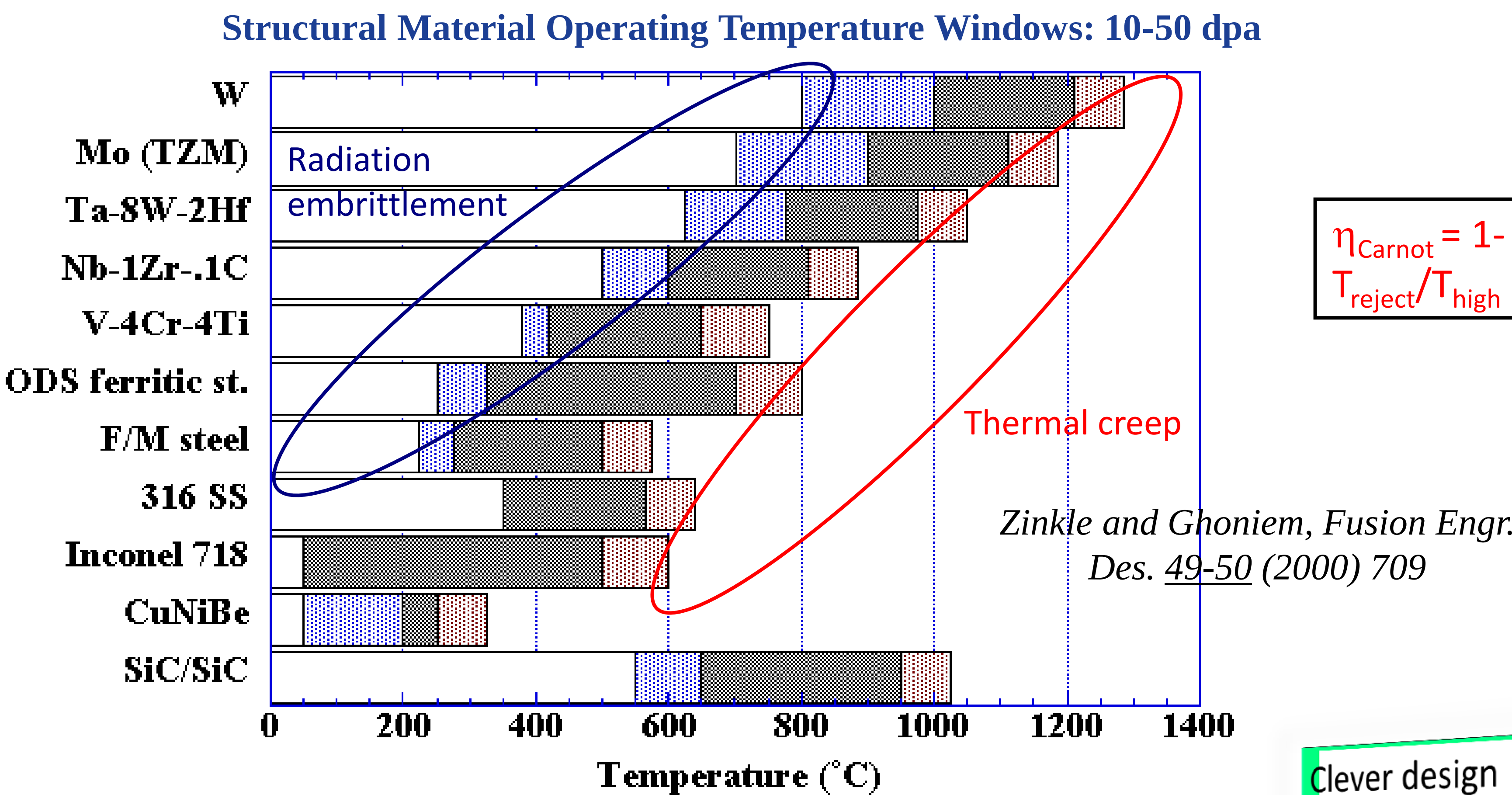
Fe-9Cr steels: builds upon 9Cr-1Mo industrial experience and materials database

- 9-12 Cr ODS steel is a higher-temperature option

SiC/SiC: High risk, high performance option (early development)

W alloys: High performance option for PFCs (early development)

High thermodynamics efficiency of power cycle



$\eta_{Carnot} = 1 - T_{reject}/T_{high}$

Additional considerations such as He embrittlement and chemical compatibility may impose further restrictions on operating window

Clever design can compensate for material limitations

Tritium self-sufficiency condition

Achievable TBR $\Lambda a \geq \Lambda r$ Required TBR

Λr is 1 + G, where G is the margin required to account for:

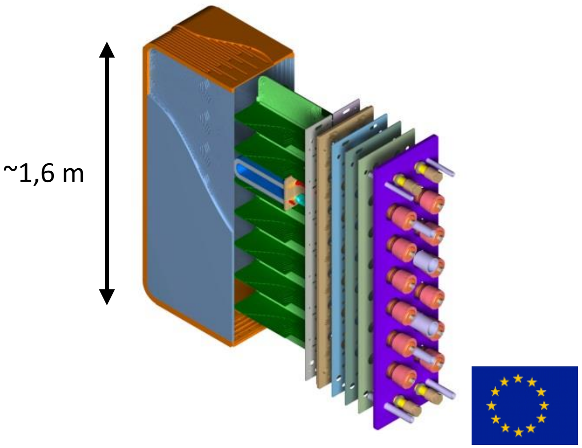
- Losses via radioactive decay (5.5%/year)
- Next power plant: start-up inventory and doubling time
- Tritium factional burn-up
- Reserve time
- Fuel cycle required processing time and efficiency
- Trapped Tritium inventories

Λa is a function of the Tritium Production Rate (TPR) but also of other technological, material and physics phenomena:

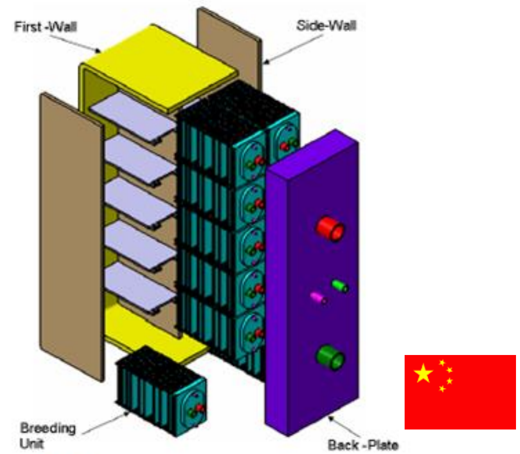
- Blanket design solutions
  - Breeder materials (Li^6 enrichment, …)
  - FW thickness
  - amount of structure
- In-vessel components (additional coils, plasma heating/fueling/exhaust,…)
- Plasma heating/fueling/exhaust, PFC coating/materials/geometry.
- Plasma configuration

Conceptual designs do not include rigorous structural mechanics analysis to determine structural requirements.

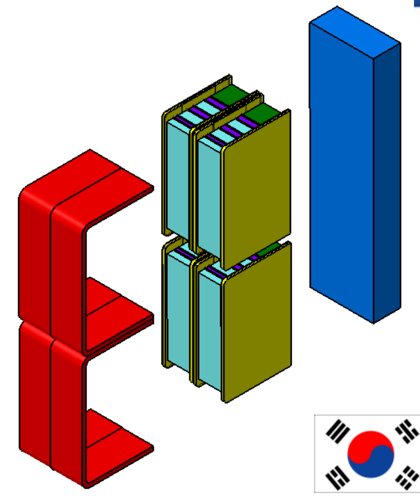
Test Blanket Modules (TBM) for testing in ITER



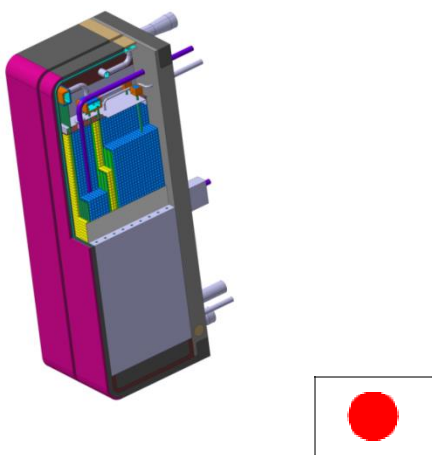
Helium-Cooled Pebble-Bed



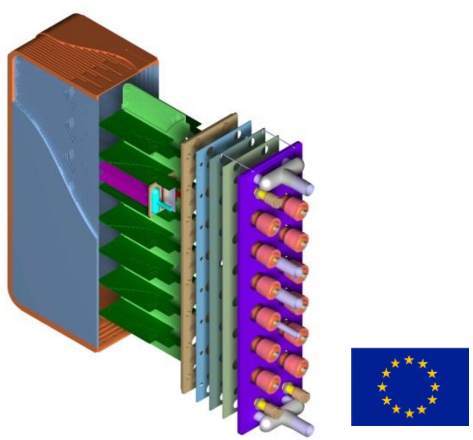
Helium-Cooled Ceramic Breeder



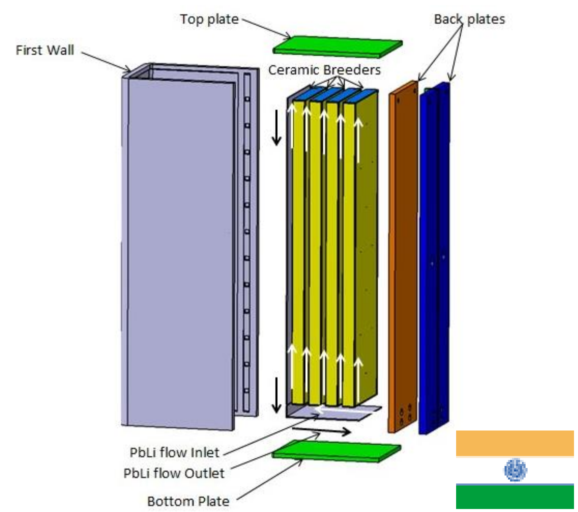
Helium-Cooled Ceramic Reflector



Water-Cooled Ceramic Breeder

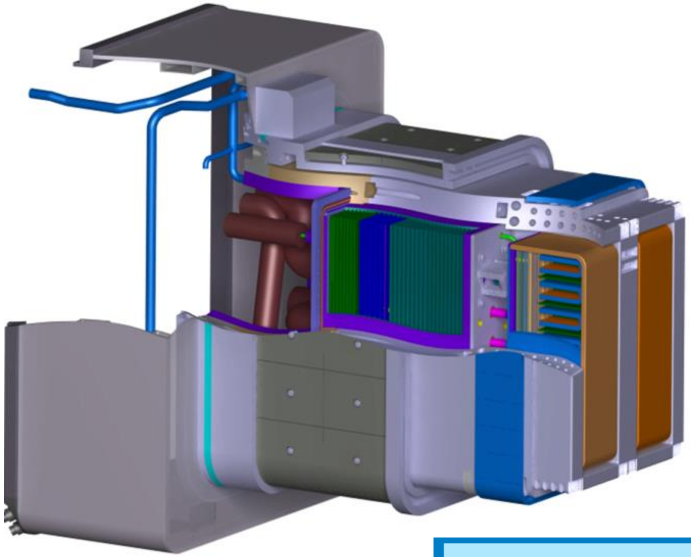


Helium-Cooled Lead-Lithium

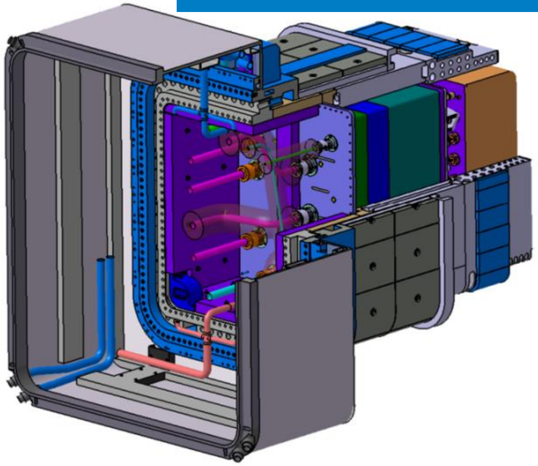


Lead-Lithium Ceramic-Breeder

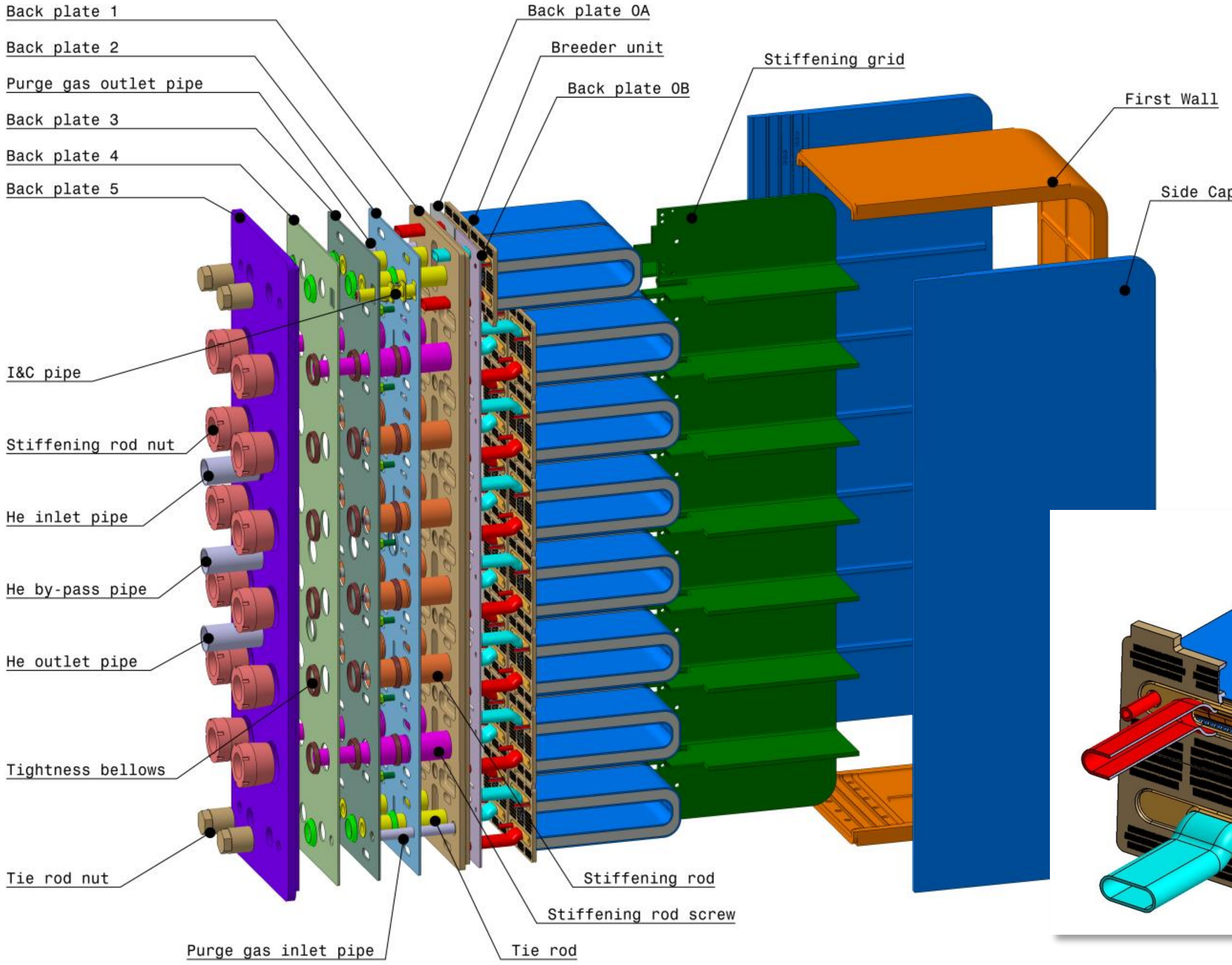
Contents

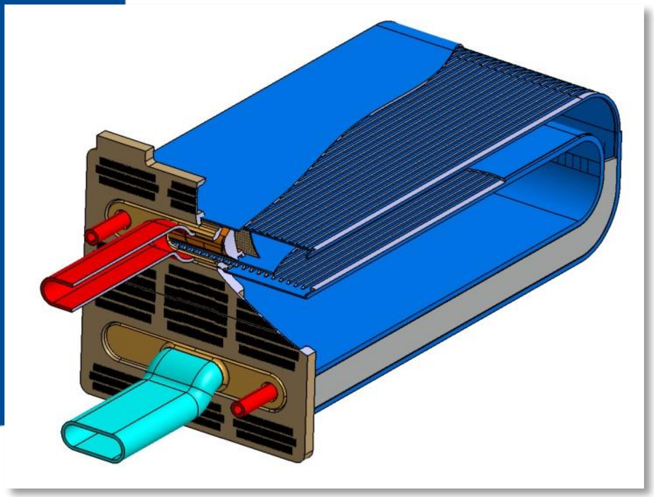


TBM-sets integration in the Equatorial Port Plug #16



Helium Cooled Pebble Bed TBM





Helium Cooled Lead Lithium TBM