Symposium “30 years of Tritium Laboratory Karlsruhe”

The Breeding Blanket: The Core of a Thermonuclear Fusion Reactor. Technology, EU Concepts and Perspective

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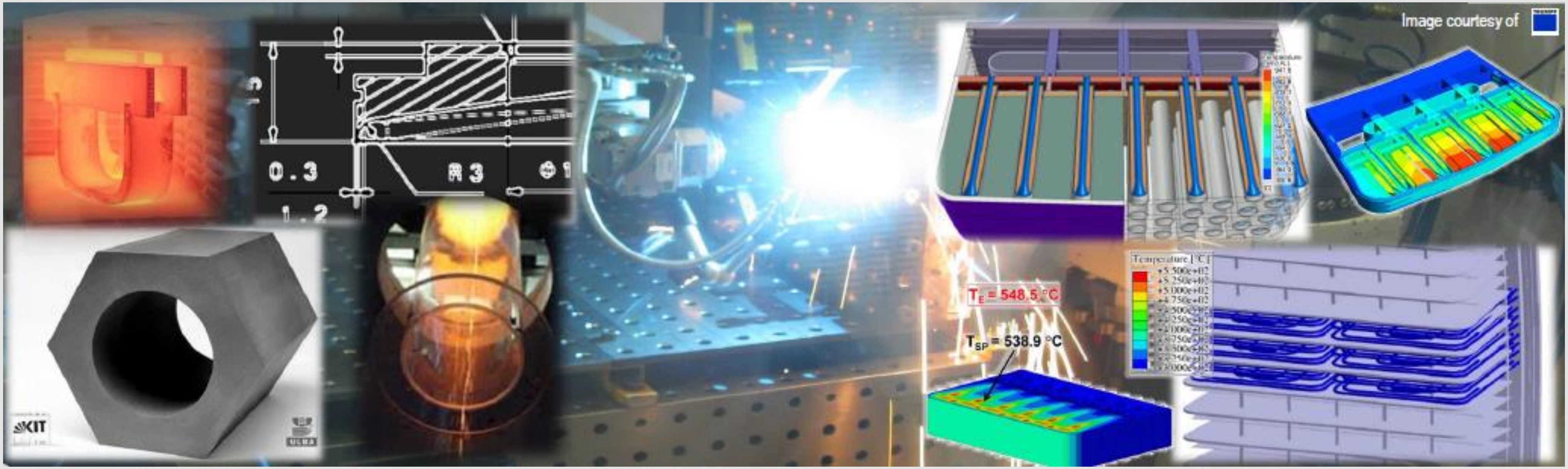
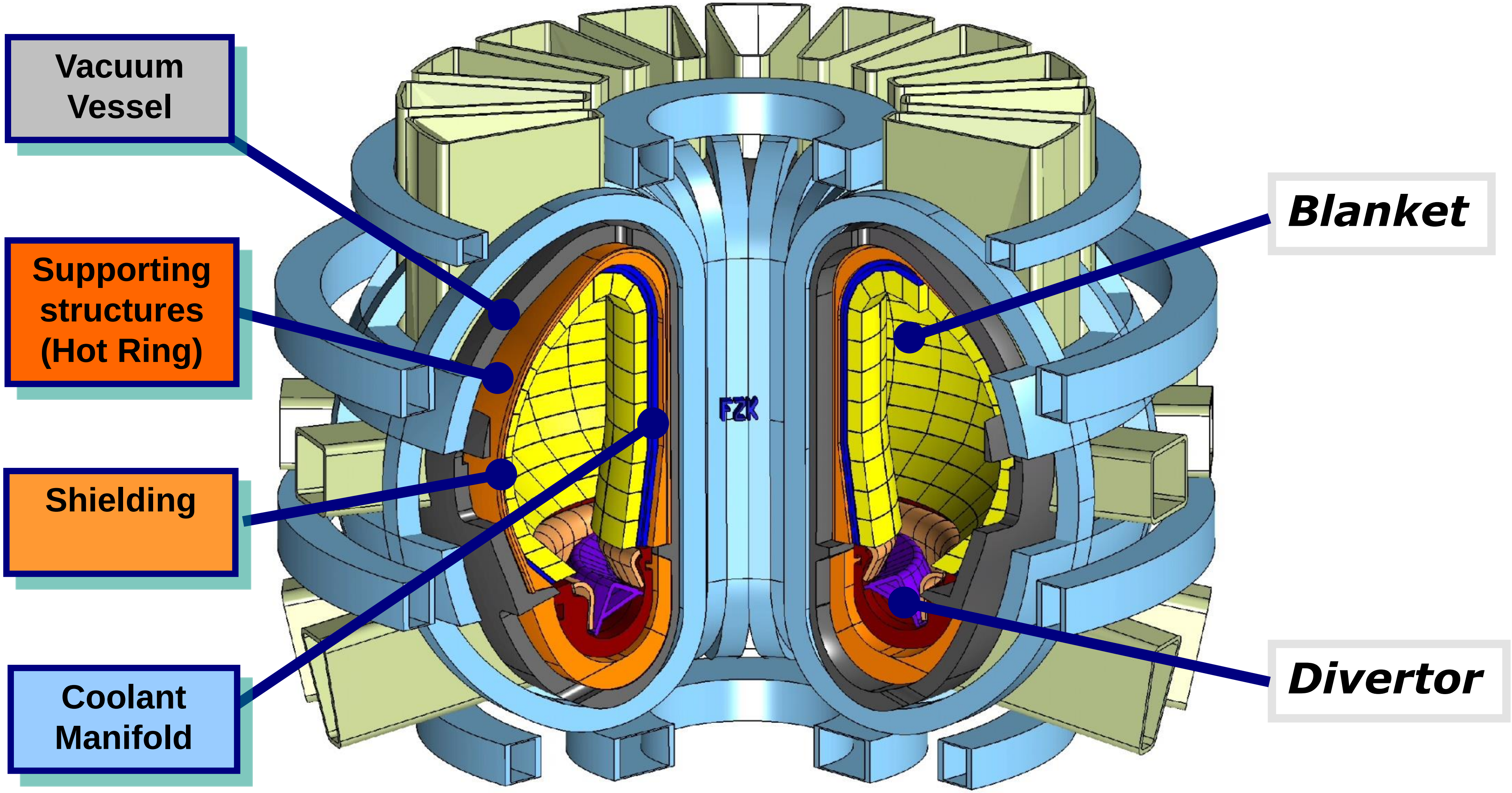


Outline

1. **Breeding Blankets: Introduction**
    - The Tritium Issue
    - Conceptual architecture
2. **Breeding Blankets for the EU DEMO**
    - Concepts
    - Near term architectures
    - The HCPB Blanket
    - The WCLL Blanket
3. **Summary and Outlook**

Fusion Reactor Thermonuclear Core



Vacuum Vessel

Supporting structures (Hot Ring)

Shielding

Coolant Manifold

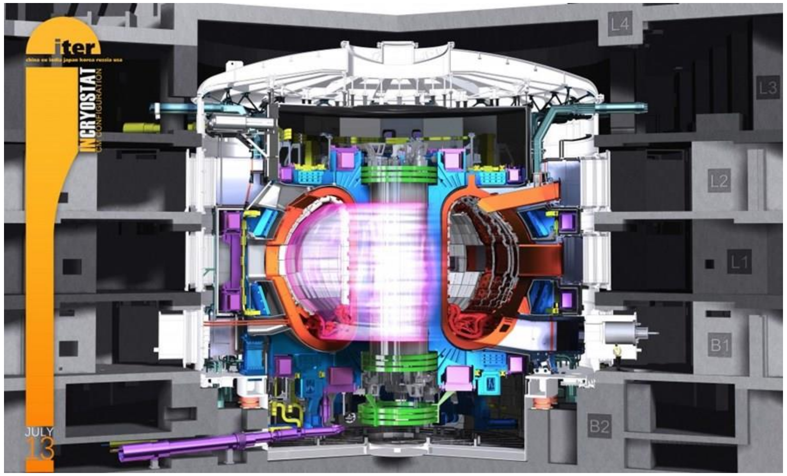
Blanket

Divertor

KIT Design for a DEMO (Demonstration Fusion Reactor Plant)

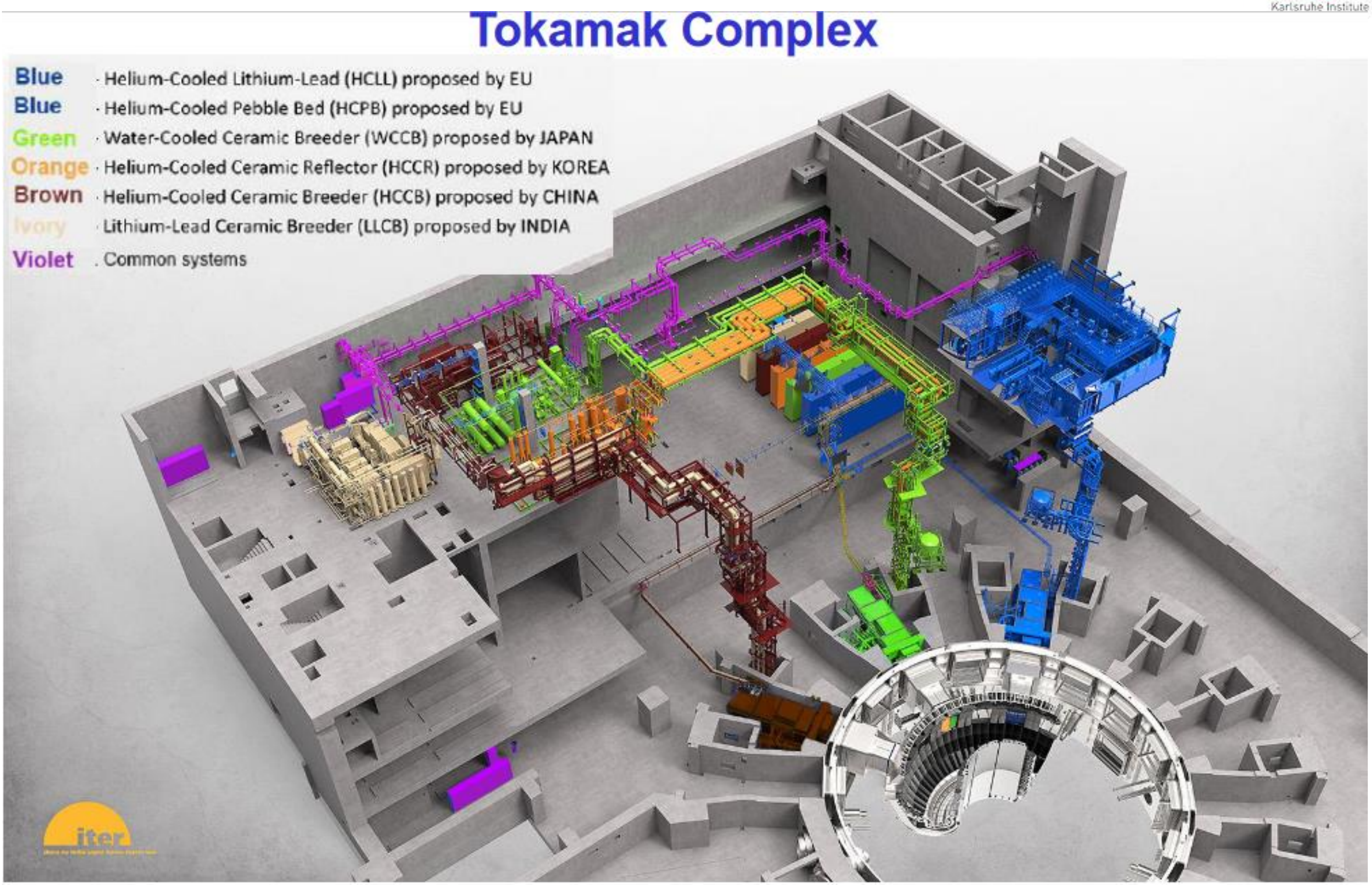
What is the Breeding Blanket?

- **„The blanket is one of the key components of a future fusion reactor“**
- **Functions**
  1. Transforming fusion power into high grade heat and collection of the heat for electricity production
  2. Tritium production (breeding) and extraction
  3. Contribute to neutron shielding of sensitive elements behind it (VV, TFC).
- **This component will be present for the first time in a DEMO reactor.**
- **ITER has no Breeding blanket only a Shielding Blanket. The breeding function is tested in small scale with Test Blanket Modules (TBM).**



ITER	**vs.**	**DEMO**
No electricity generation	vs.	few 100s MW_{net}
No tritium production	vs.	tritium self-sufficiency
Low lifetime (~3 dpa)	vs.	20+50 dpa

The TBM programme



Tokamak Complex

Blue	· Helium-Cooled Lithium-Lead (HCLL) proposed by EU
Blue	· Helium-Cooled Pebble Bed (HCPB) proposed by EU
Green	· Water-Cooled Ceramic Breeder (WCCB) proposed by JAPAN
Orange	· Helium-Cooled Ceramic Reflector (HCCR) proposed by KOREA
Brown	· Helium-Cooled Ceramic Breeder (HCCB) proposed by CHINA
Ivory	· Lithium-Lead Ceramic Breeder (LLCB) proposed by INDIA
Violet	. Common systems

Deuterium-Tritium Fusion

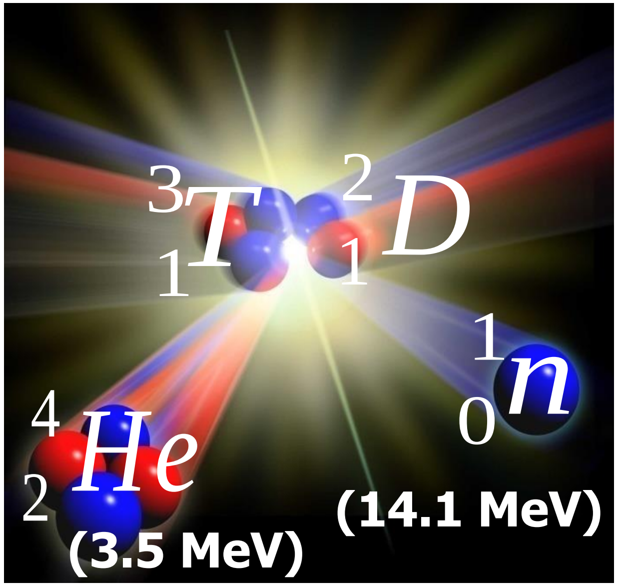
$$^{2}D + ^{3}T \rightarrow ^{4}He + n + 17.6\ \text{MeV}$$

⊕ ⊕ ⊕⊕

○ ○○ ○○ ○

⊕ Proton

○ Neutron



- Kinetic energy (½ m v²) of α-particles (^{4}He) and neutrons = **17.6 MeV**
- α-particles and neutrons shall have the **same impulse** **(**$m \times v$) → neutron 4x faster than Helium

➡ kinetic energy distributed by inv. mass ratio $\frac{m_\alpha}{m_n} = \frac{4}{1} = \frac{14.1}{3.5}$

➡ **80% of energy in kinetic neutron energy**

Fuel Consumption

For a prototypical 2700 MW_{fusion} (i.e. ~1000 MW_e) reactor:

Note: 1eV = 1.602 10^{-19} As*V = 1.602 10^{-19} Joule

1. **Energy per fused tritium** atom (17.6 MeV fusion energy in Joule):

$$17.6 \cdot 10^{6} * 1.602 \cdot 10^{-19} = 2.82 \cdot 10^{-12}\ \text{J};$$

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2. **Fusion frequency** = P/E = $2700 \cdot 10^{6}$ J/s / $2.82 \cdot 10^{-12}$ J = $9.57\ 10^{20}$ 1/s;

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3. **Tritium mass flow** = 3 * mass of proton (neutron) * frequency =

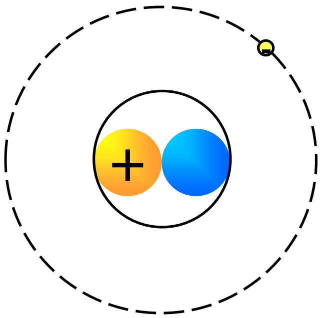
$$3 * 1.67 \cdot 10^{-27}\ \text{kg} * 9.57 \cdot 10^{20} * 24 * 60 * 60 * 1/\text{day} = \underline{0.41\ \text{kg/day}}$$

Tritium T (^3H):	**~ 0.41 kg/day**	**~ 150 kg/fpy**
Deuterium D (^2H) :	**~ 0.27 kg/day**	**~ 100 kg/fpy**

***fpy* = full power year**

To compare:1000MW coal plant @ η=40% requires 2.16Mt coal and produce 5Mt CO_2

D: Deuterium



$$^{2}_{1}H$$

Property	D_2O (Heavy water)	H_2O (Light water)
Freezing point (°C)	3.82	0.0
Boiling point (°C)	101.4	100.0
Density at STP(g/mL)	1.1056	0.9982
Temp. of max. density (°C)	11.6	4.0
Viscosity (at 20°C, mPa·s)	1.25	1.005
Surface tension (at 25°C, µJ)	7.193	7.197
Heat of fusion (cal/mol)	1515	1436
Heat of vaporisation (cal/mol)	10864	10515

Can be found: in ocean water
at a H/D ratio of ~6500 (~150 ppm)

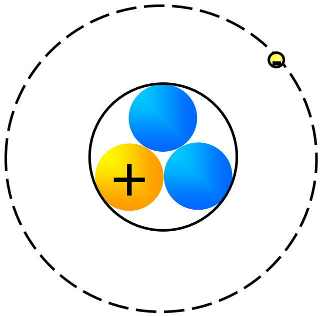
Used: in nuclear energy (e.g. D_2O in CANDU reactors)

Production methods (D_2O):
e.g. Girdler-Sulfid-Proces (isotopical exchange) + vacuum distillation

Extimated earth availability:
$5*10^{16}$ kg (in oceans)

Sufficient for several billion years !!

T: Tritium



$$^{3}_{1}H$$

Radioctive with a half life of 12.33y

$T \rightarrow {}^{3}He + e^{-} + 18.6\ keV$

Can be found in nature:

in neglegible amount as product of cosmical rays

$${}^{14}N + n \rightarrow {}^{12}C + {}^{3}T$$

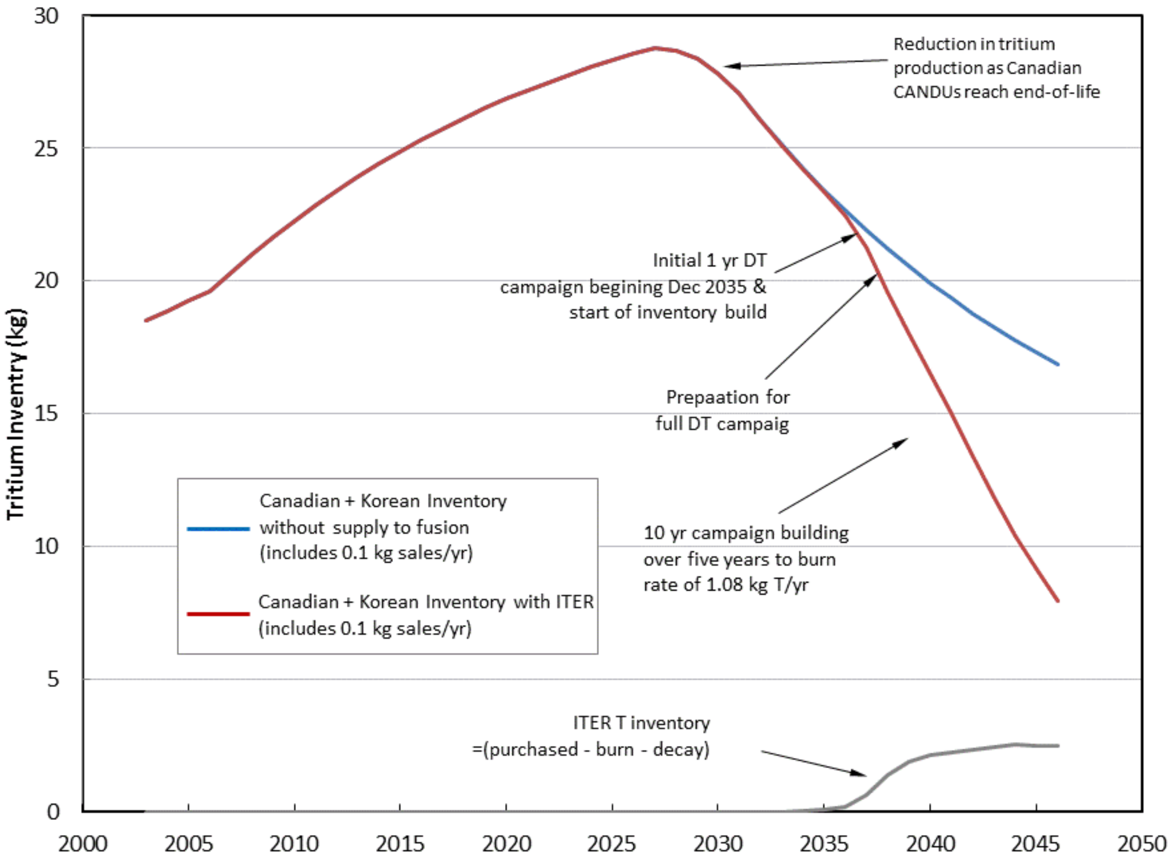
Production as waste of nuclear D_2O reactors (e.g. CANDU):

$D + n \rightarrow T$ ~2 kg/year

No available production to support fusion reactors as external sources.

ITER will consume less than 20 kg in its whole life.

Tritium availability



Tritium availability remains a very critical issues for each reactor or test machine that esploits the D-T reaction:

- For a T self-sufficient machine (like DEMO and a FPP) for the necessity of few kgs of T for the start-up
- For a test reactor (like ITER or Fusion Test Devices) that doesn’t produce T or only a fraction of the need to fuel the operations

Scenario developed in ITER (S. Willms)

Tritium Production in a reactor: Li reactions

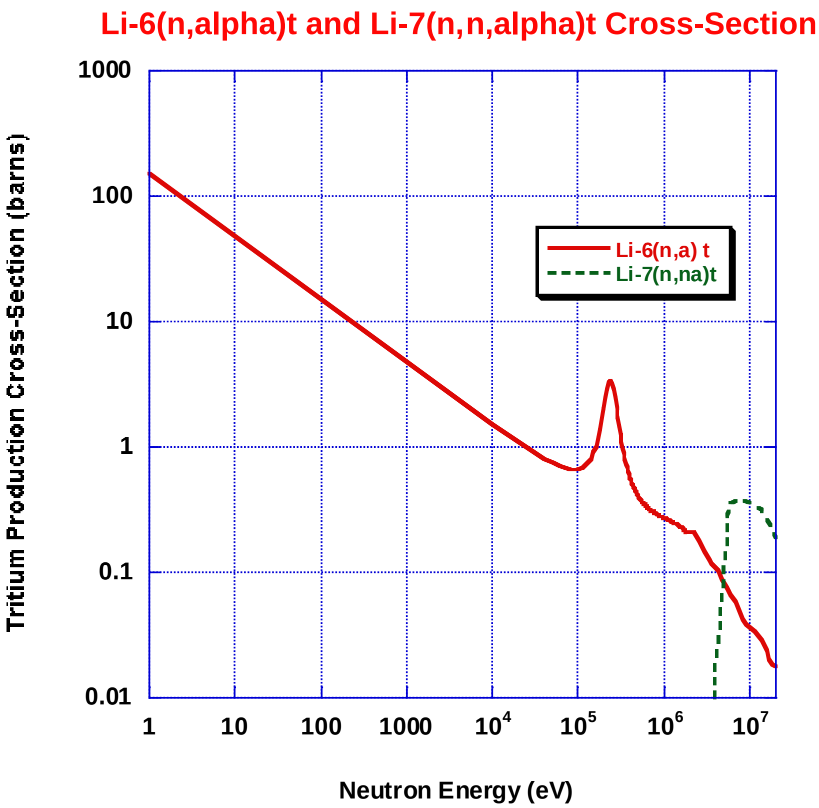
Li together with D are the ultimate *fuels* of the D-T fusion reactor:

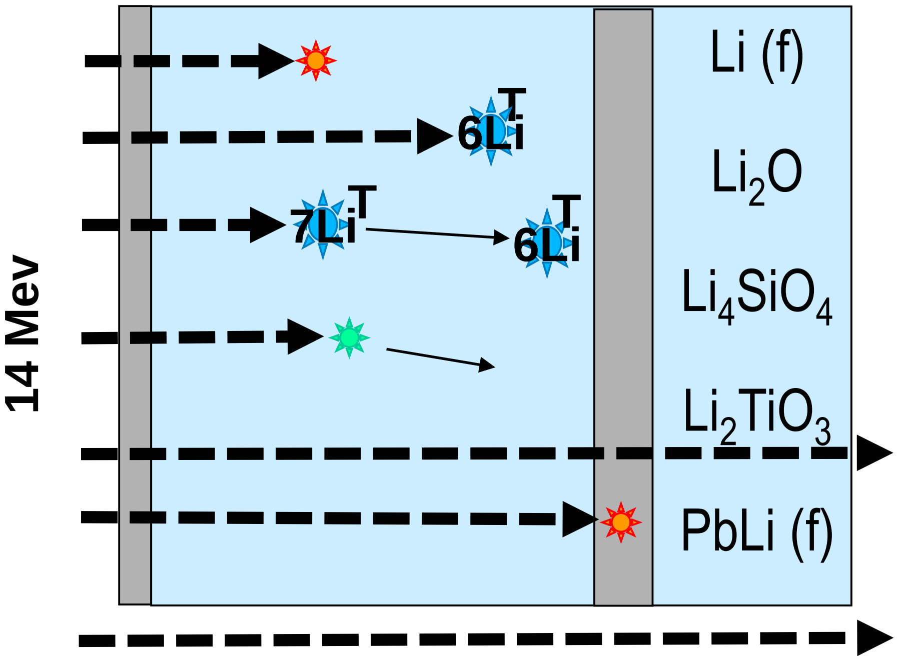
$^{6}Li + n = T + {}^{4}He + 4.8$ MeV.

$^{7}Li + n = T + {}^{4}He + n - 2.466$ MeV

Natural Li: 92.5 at.% ^{7}Li, 7.5 at.% ^{6}Li

- ≈10^{11} kg Li in landmass: ok for $3 \cdot 10^{4}$ y
- ≈10^{14} kg Li in oceans: ok for $30 \cdot 10^{6}$ y

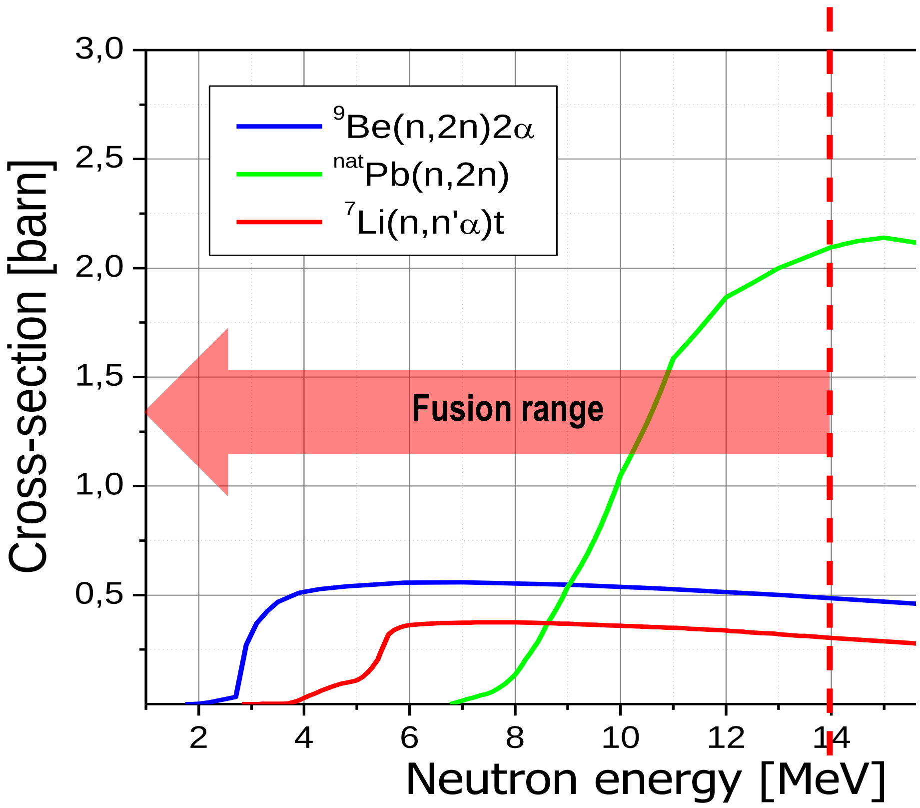




$n_T = n_f * X_b * X_T * m$, **shall be $n_T / n_f > 1$**

Neutron Multiplication

Required (n,2n) reactions with high σ in Energy range up to 14MeV



Li(nat):

- Sufficient only with very low n-abs materials
- Strong reaction with water and air
- Getter for T (difficult recovery)

Beryllium (Be):

- low *E* threshold for (*n*,2*n*)
- good moderator (shielding)
- exothermal reaction with H2O beyond 600°C
- Be dust toxic + small resources: high costs

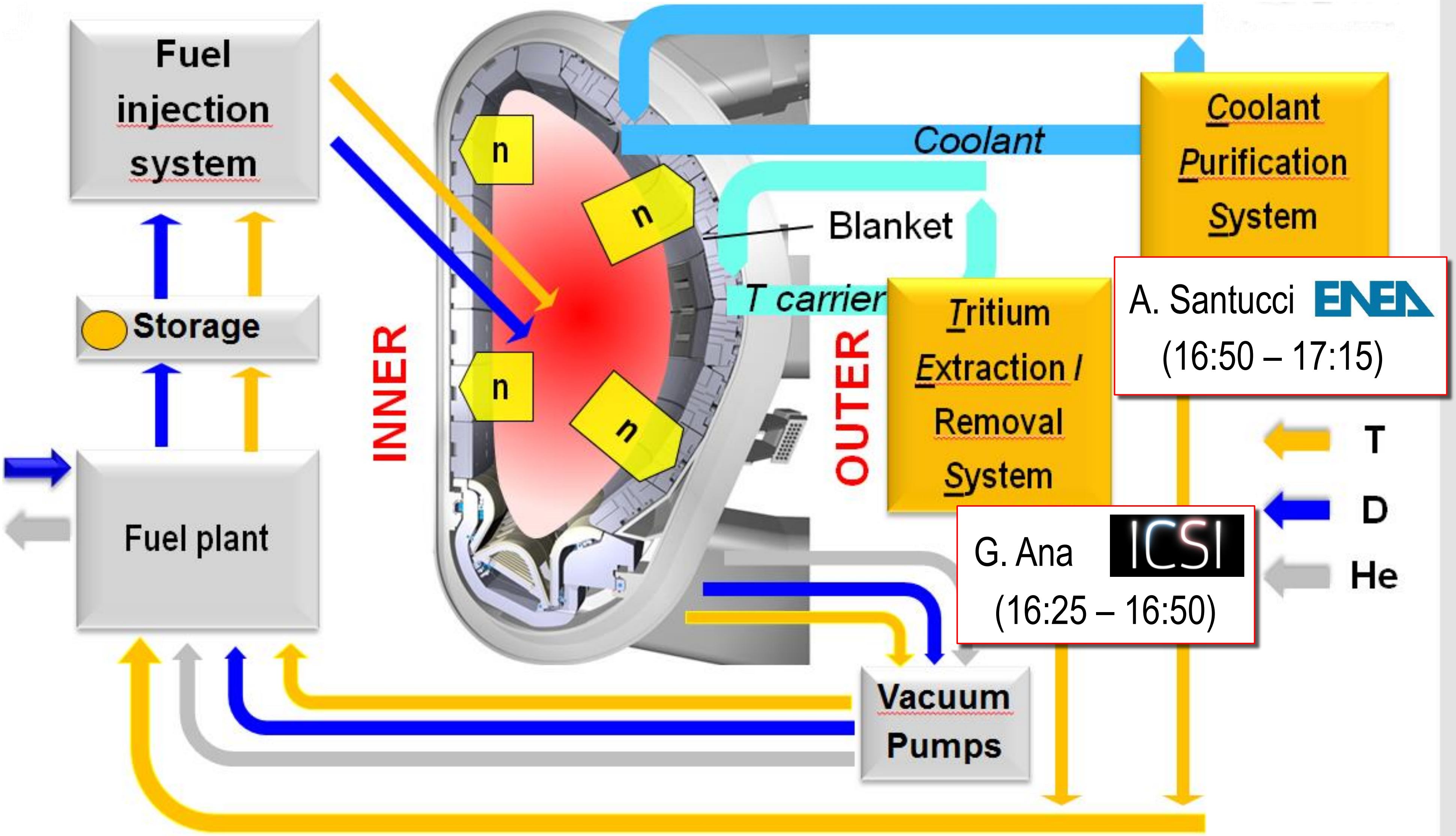
Lead (Pb):

- high availability, low cost
- can be used as coolant
- corrosion with material (e.g. steels)
- weight
- activation through Po formation
- Melting point ~235°C
- (moderate) reaction with water

Possible strategies:

- Li(nat) with V as structural material.
- **Better** => Adding a more effective multiplier (Be or Pb) and increasing the ^{6}Li enrichment (40%-90%) to use efficiently low energy *n*

Fuel Cycle: Inner and outer cycle



A. Santucci ENEA
(16:50 – 17:15)

G. Ana ICSI
(16:25 – 16:50)

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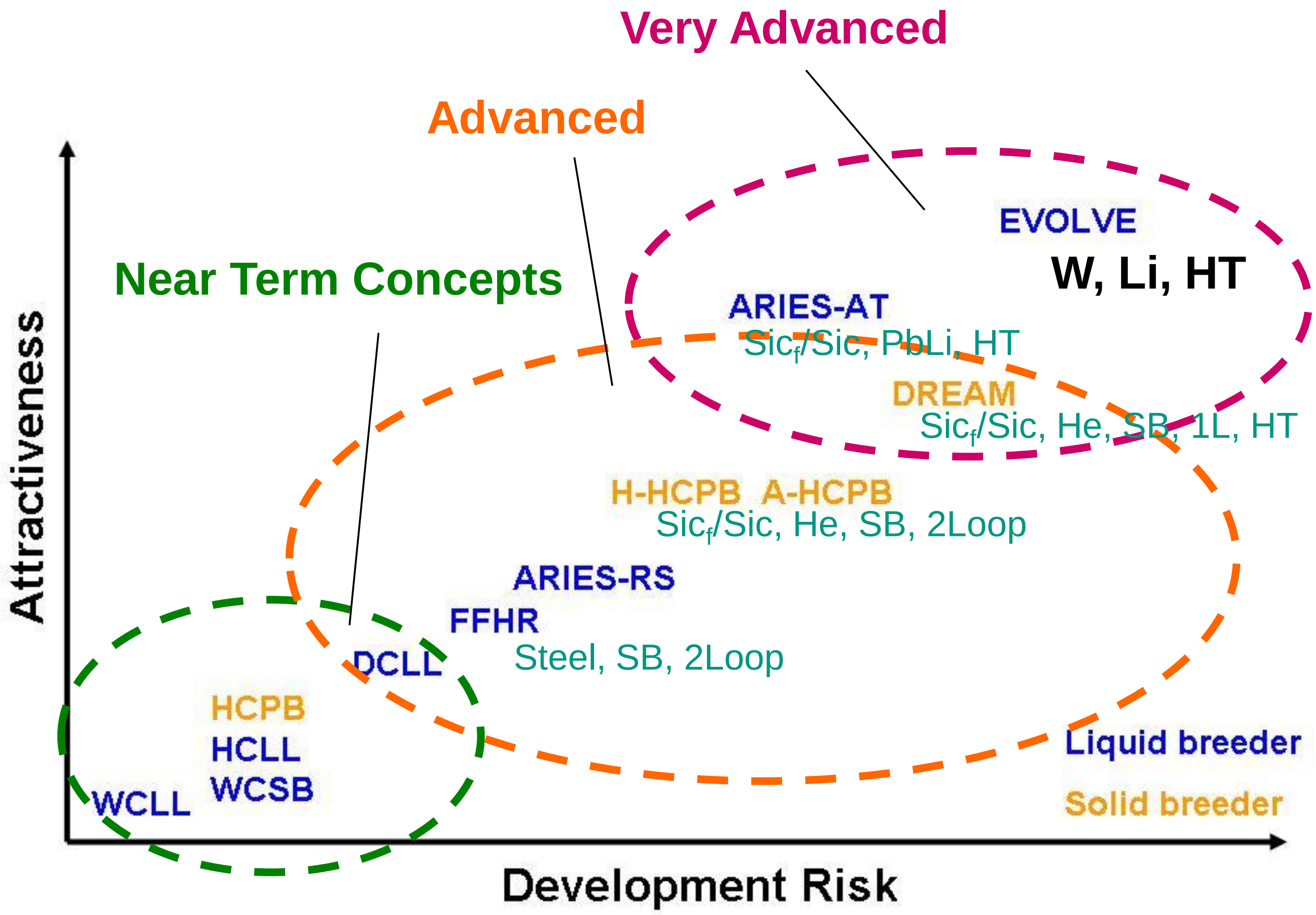
Possible Blanket Concepts



Very Advanced

Advanced

Near Term Concepts

Attractiveness

EVOLVE

W, Li, HT

ARIES-AT

Sic$_f$/Sic, PbLi, HT

DREAM

Sic$_f$/Sic, He, SB, 1L, HT

H-HCPB A-HCPB

Sic$_f$/Sic, He, SB, 2Loop

ARIES-RS

FFHR

Steel, SB, 2Loop

DCLL

HCPB

HCLL

WCSB

WCLL

Liquid breeder

Solid breeder

Development Risk

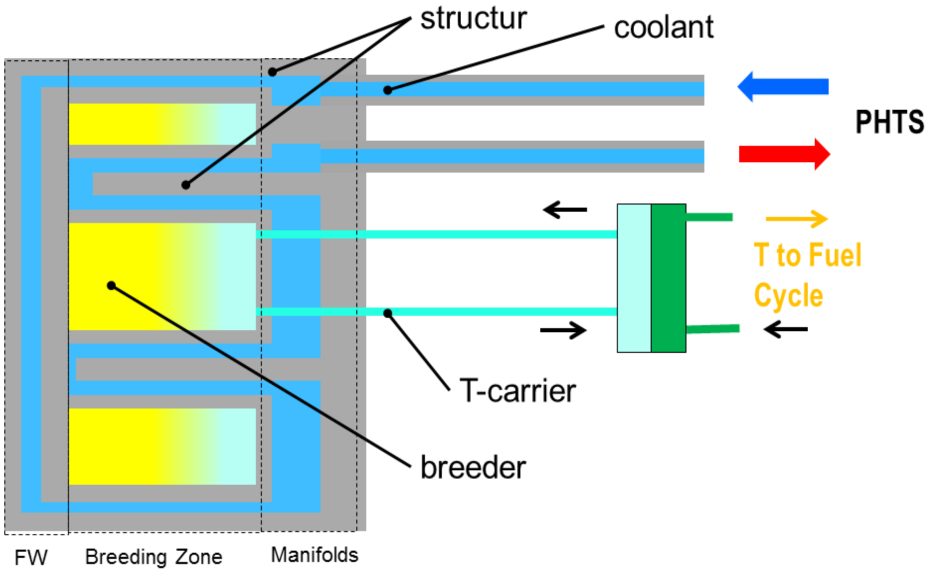
Not exhaustive

Classification according to:

- Maturity level (near term->Very Advanced)
- Structural material (e,g. steel, SiC$_f$/SiC or V-alloy)
- Breeder / multiplier (solid and liquid breeder)
- Coolant (water, gas, liquid metal, molten salt)
- Heat and T extraction (e.g. Self Cooled, Dual Coolant)

Architecture of the near term blankets

- “Near term”: breeder and coolant contained in 2 separate circuits, separate functions.
- **Coolant loop function:** remove heat, to be transported to PCS through PHTS for electricity production. Coolants: high pressure helium or water (8-15.5 MPa, @ T>300°C).
- **Breeder loop function:** has to produce T and allow its transport outside the vessel. To be pre-treated in the TER and delivered to the Fuel Cycle. Negligible heat extraction.



Advantages:

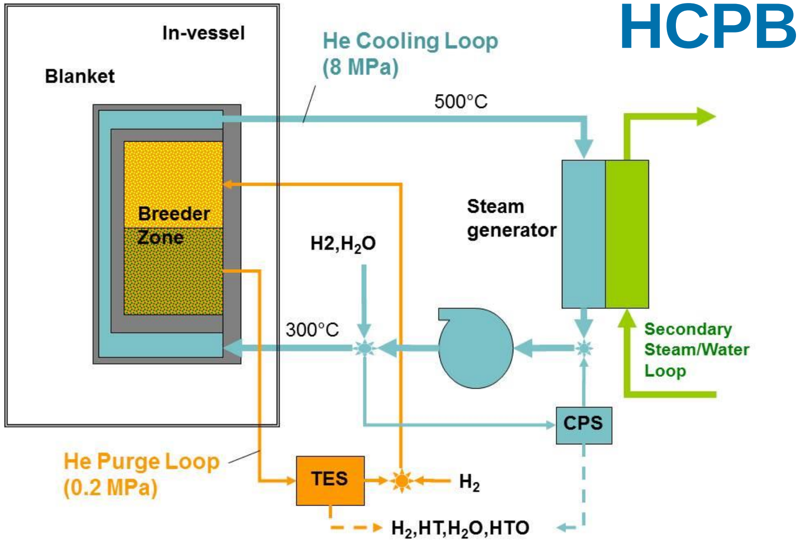
- T can be concentrated in the T carrier (easier extracted/removed).
- Coolant is less contaminated by T: T extraction from coolant is not economic and the safety case better (less probable that large T inventory reaches the environment after leak into the secondary circuit through a SG.

Drawbacks:

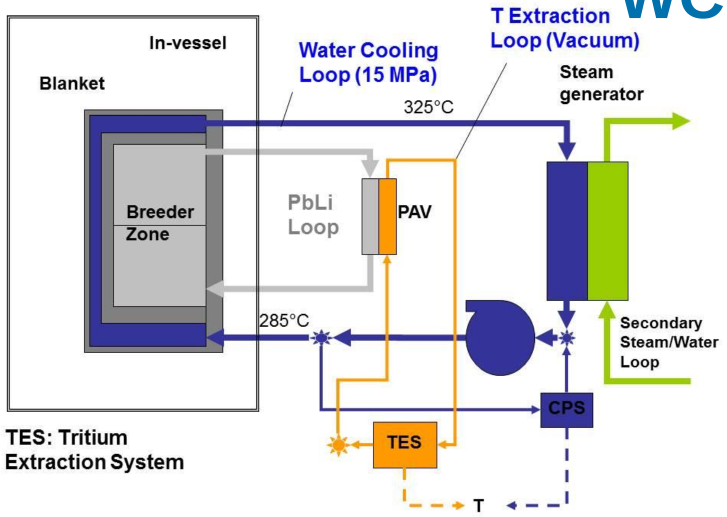
- Complex design of the breeding zone (~13,000 m^2 interface)
- Large quantity of steel (e.g. => TBR & mechanical design issues)
- Issues of T permeation from the breeder to the coolant loop.

Blanket architecture: conclusive remarks

HCPB



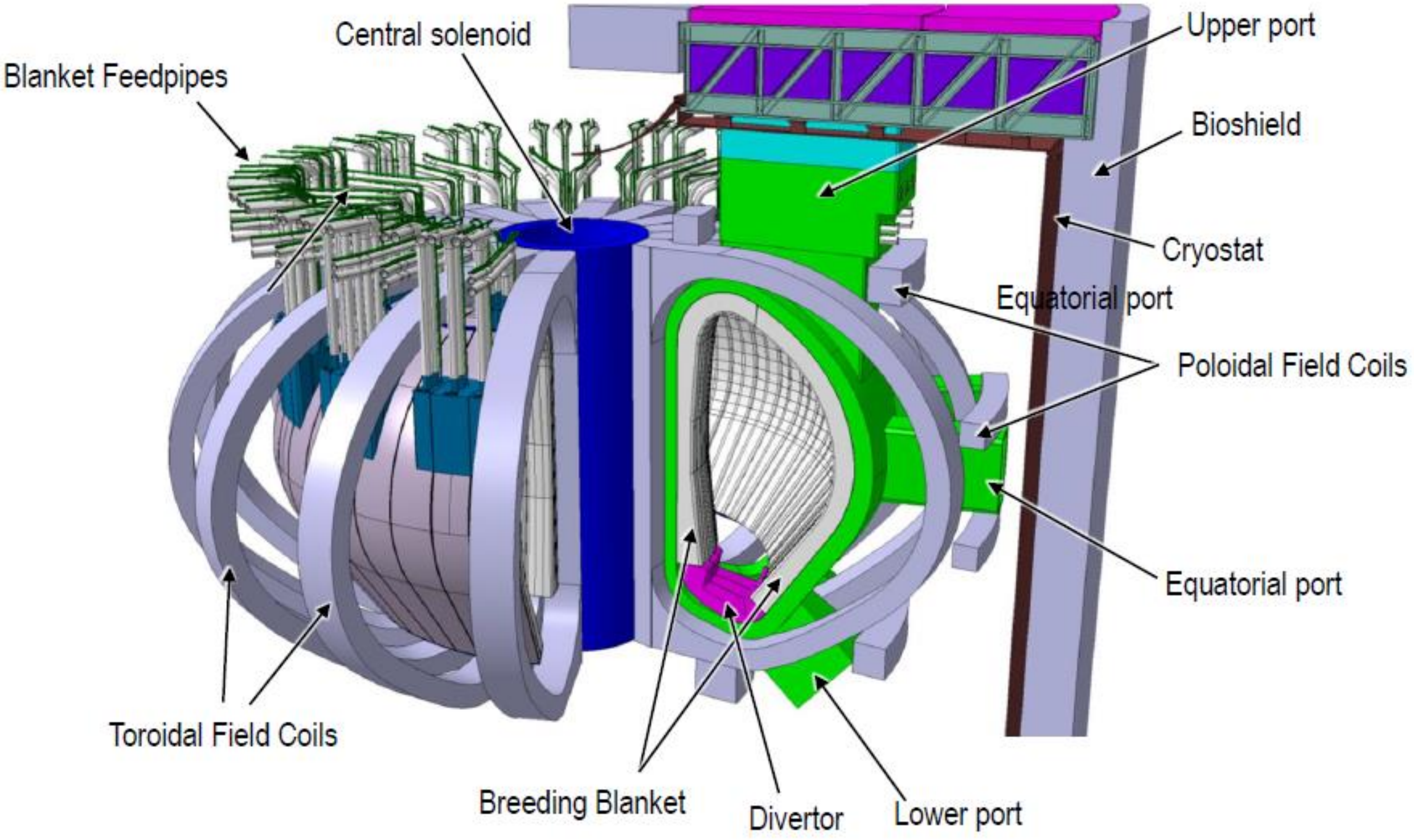
WCLL



TES: Tritium Extraction System

- Despite of the differences (material combinations), these blankets share a very similar architecture.
- The main architecture of three of these systems (HCPB, WCCB, HCLL and WCLL) foresees a strict division among coolant and T breeder zone
- The coolant at high pressure (water or He) cools directly the steel structure flowing mainly in small channels
- A T carrier (a purge gas for the solid or the breeder PbLi itself in liquid breeder concepts) fills the breeder zone and flows in independent loops at low pressure transporting T outside the reactor.
- Also if PbLi is used as carrier, its recirculation rate (10-20 inventories pro day in WCLL and HCLL, respectively) is so slow that no significant heat is removed in these loops; the same is for the He purge in the HCPB.

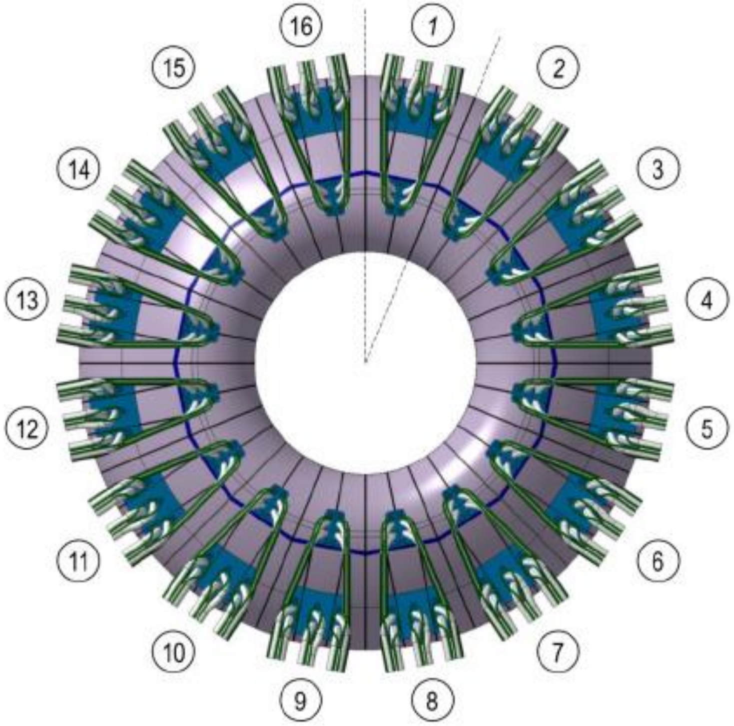
The EU DEMO: plant configuration

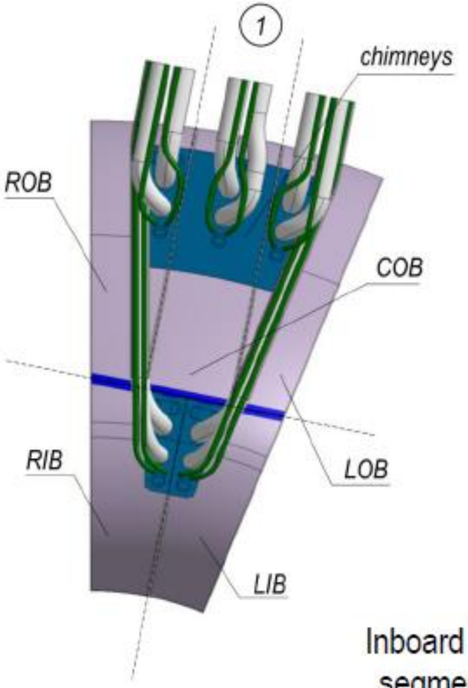


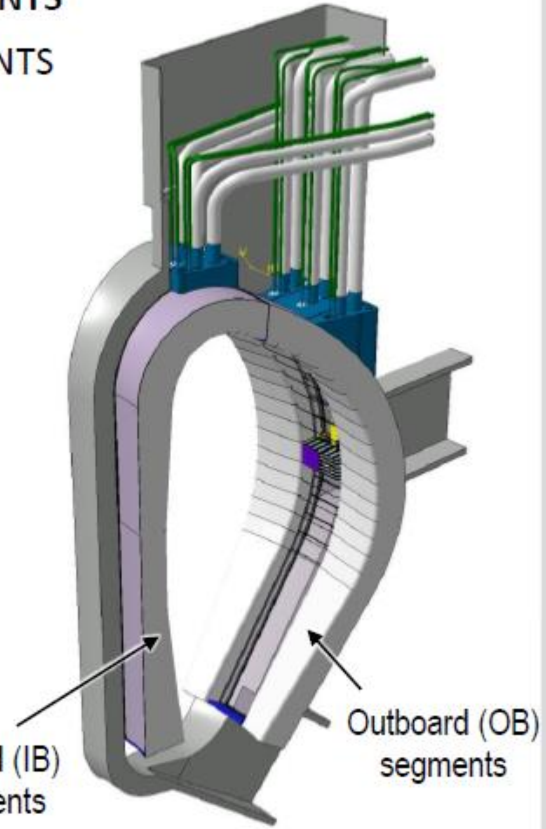
- EU DEMO BL2017: R_0=9m, A=3.1, P_{fus} 2GW
- Pulsed machine: flat top ~2 h, dwell time ~10 m
- Electricity production: few 100s MW_{net}
- Reactor availability: >30%
- Lifetime: ~70 dpa (i.e. ~7 fpy @NWL~1MW/m^2)
- To facilitate the transition between ITER and FPP

The EU DEMO: segmentation

- EU DEMO Tokamak Baseline 2017 (latest reference, R_0=9m, A=3.1, P_{fus}≈2GW)
  - Tokamak divided in **SECTORS** (16 sectors as of 2017)
  - Breeding Blanket SECTORS divided in Blanket **SEGMENTS**
  - Blanket SEGMENTS divided in **INBOARD** and **OUTBOARD SEGMENTS**
  - Per SECTOR: 2x INBOARD SEGMENTS and 3x OUTBOARD SEGMENTS

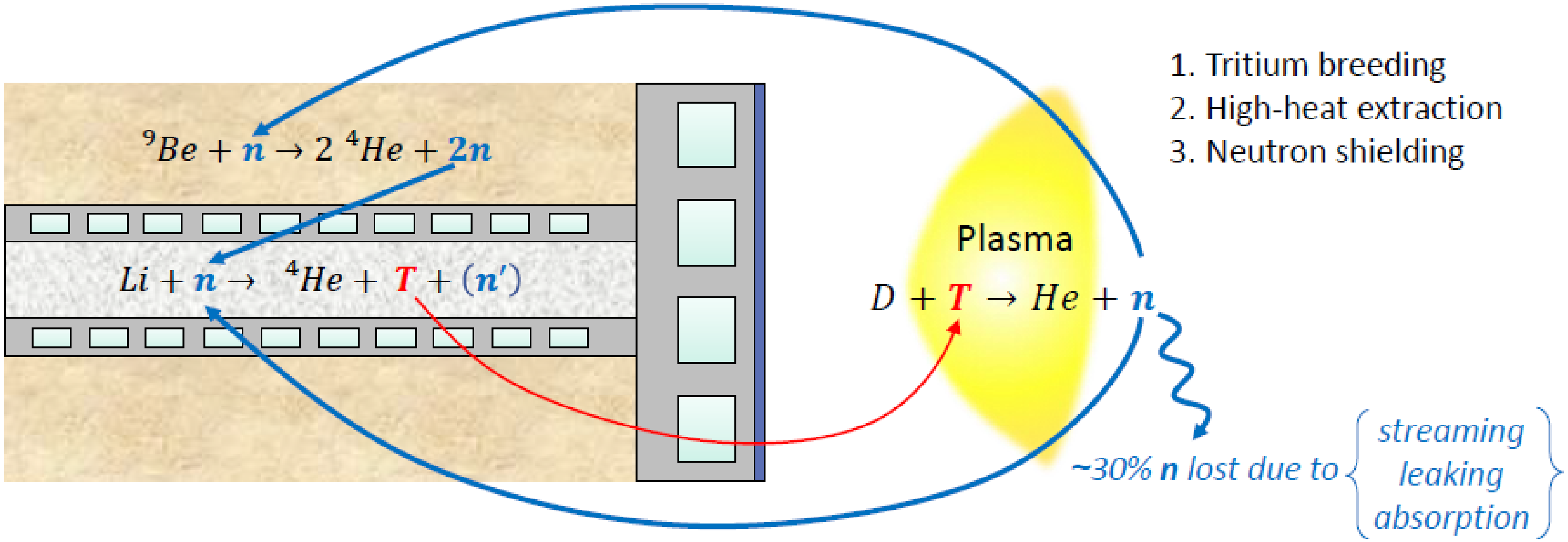






What is a HCPB Blanket?

- ***Helium Cooled Pebble Bed Breeding Blanket*** (HCPB BB)



1. Tritium breeding
2. High-heat extraction
3. Neutron shielding

- Tritium Breeding Function

  $Li + n \rightarrow \;^4He + T + (n')$

  ↳ *Li compound (Li ceramics) as* ***T*** *breeder*

- Neutron multiplier (NM) function:

  $^9Be + n \rightarrow 2\,^4He + 2n$

  ↳ *Be/Beryllides as* ***n*** *multiplier*

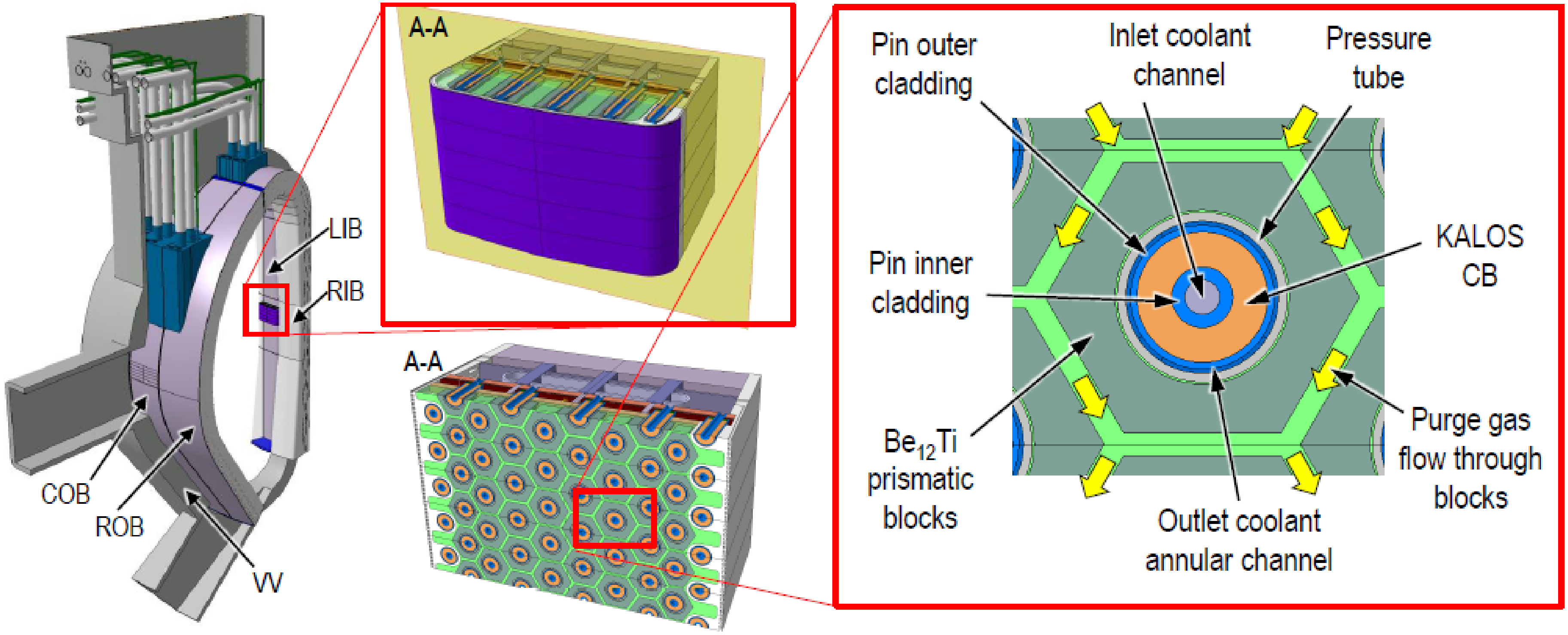
- Structural material: Reduced Activation Ferritic Martensitic (RAFM) steel, EUROFER97

- Heat extraction: Helium (HTR-like)

The HCPB Blanket

F. Hernández, et al., Advancements in the Helium-Cooled Pebble Bed Breeding Blanket for the EU DEMO: Holistic Design Approach and Lessons Learned, Fusion Science and Technology, 75:5 (2018) 352-364.

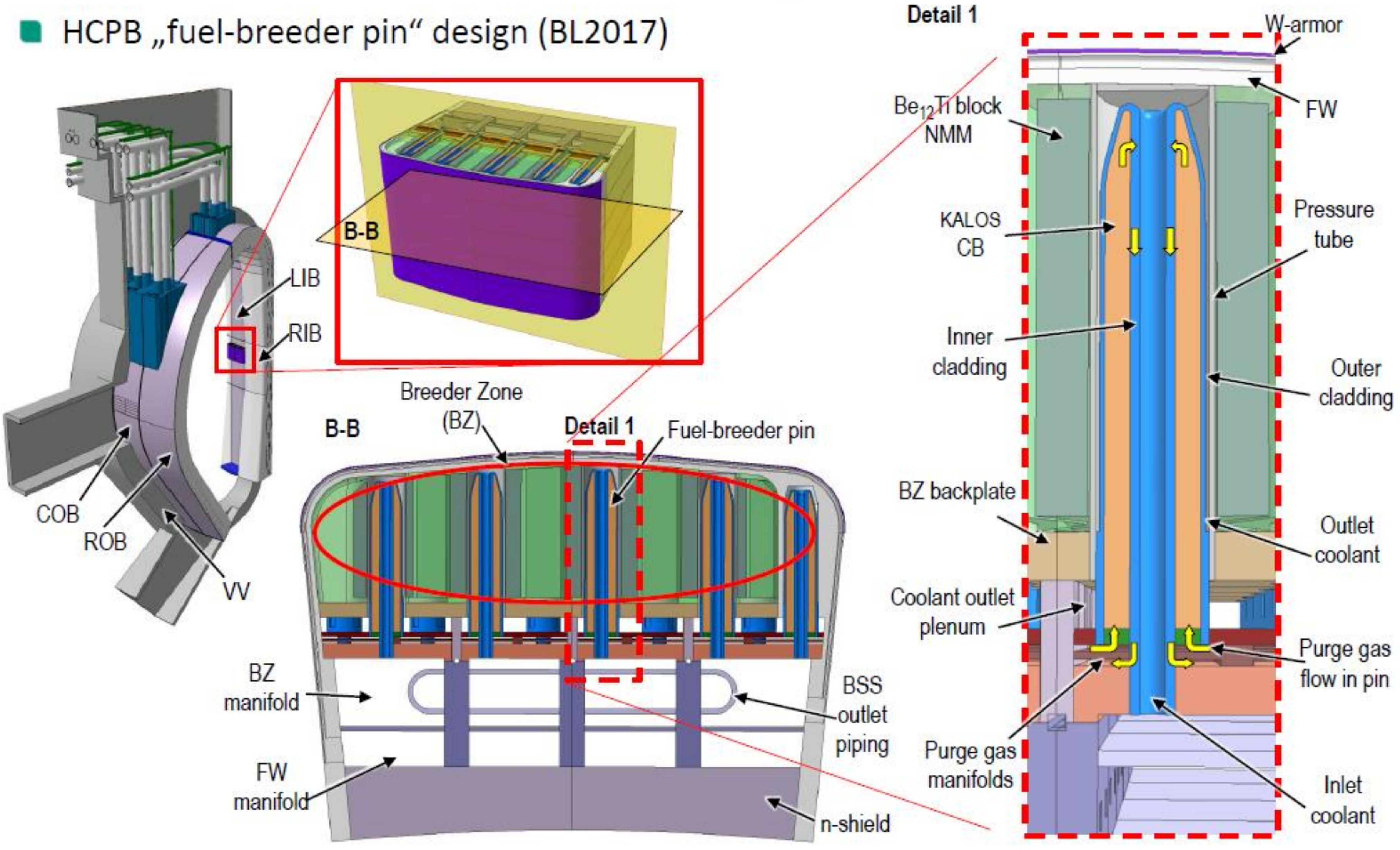
- HCPB „fuel-breeder pin“ design (BL2017)



- Arrangement of fuel-breeder pins containing ***T*** breeder material
- Pins inserted into hexagonal prismatic blocks of neutron multiplier
- Structural steel: EUROFER97

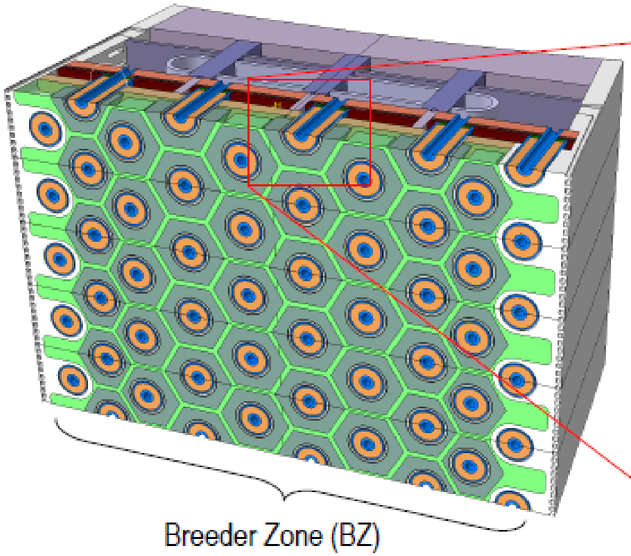
The HCPB Blanket: Breeder Zone

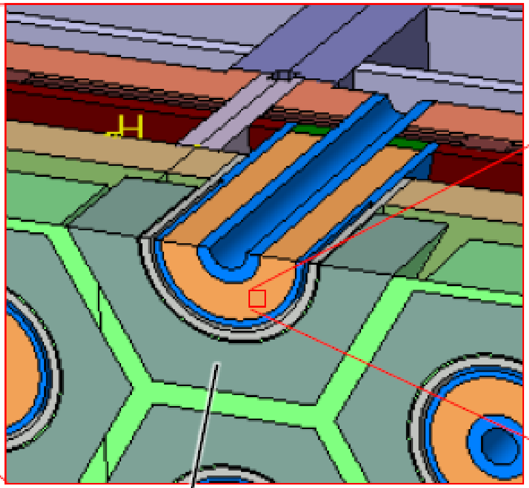
- HCPB „fuel-breeder pin“ design (BL2017)



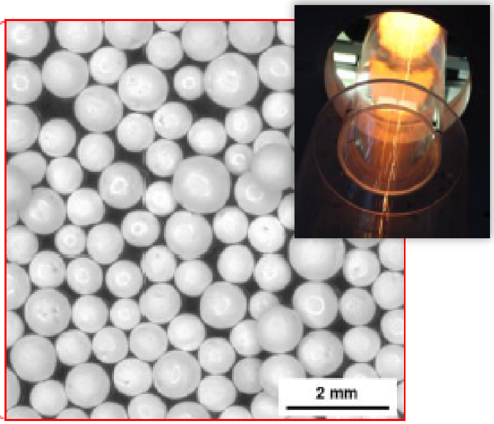
The HCPB Blanket: Functional materials

- Functional materials

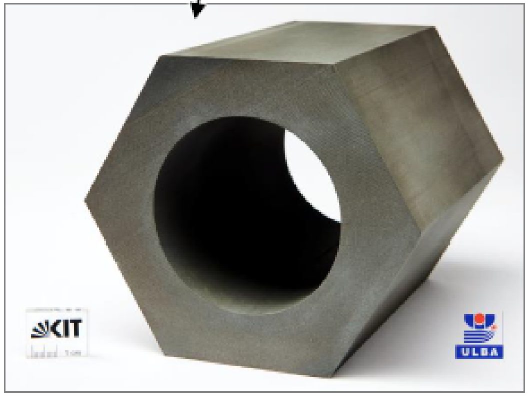


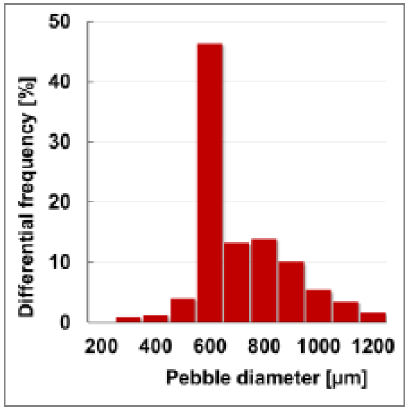


- *T* breeder: Li ceramics (Li_4SiO_4 + 35%mol Li_2TiO_3), ^6Li 60% enriched, in form of pebbles



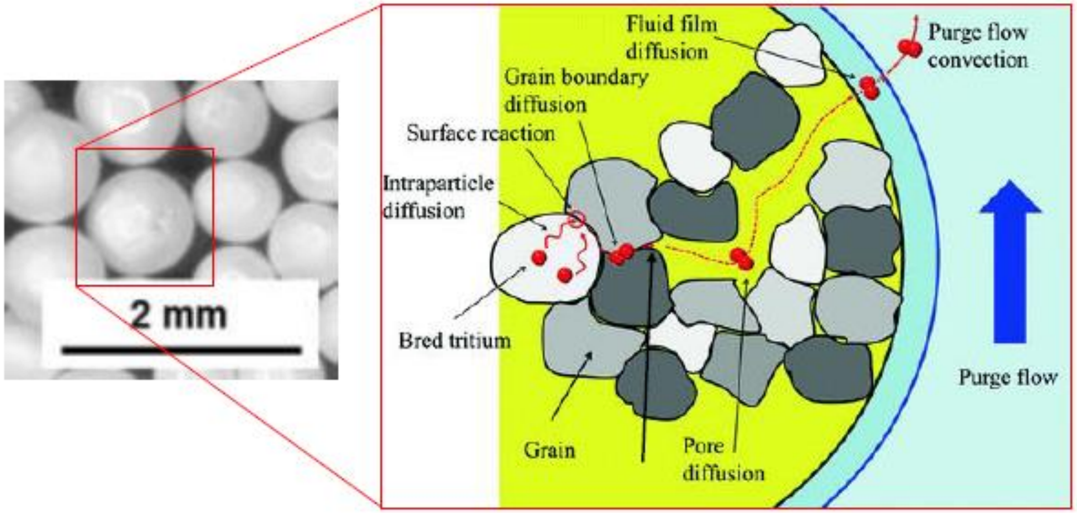
- Neutron multiplier: Be intermetallics ($Be_{12}Ti$) in form of hexagonal prismatic blocks



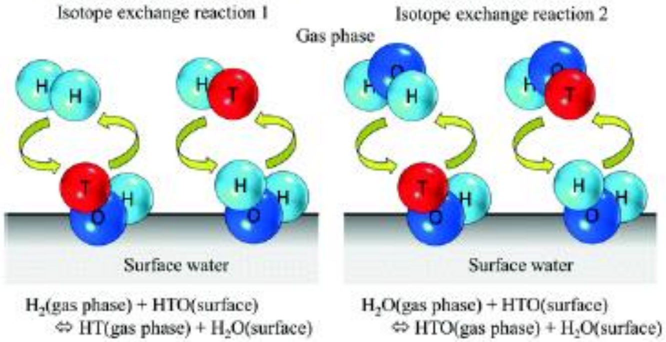


The HCPB Blanket: Tritium extraction

- *T* breeding and extraction: Purge gas function
  - *T* is formed in the Li ceramics (pebbles) and it is already extracted at the BB in form of H*T*O, H*T*
  - A purge gas flow through the pebble beds collects H*T*O, H*T* and transports it out of the BB
  - Purge gas chemistry: carrier (He) + doping agent (H_2/H_2O) to favour isotopic exchange reactions
  - *T* transport mechanisms at pebble bed level:



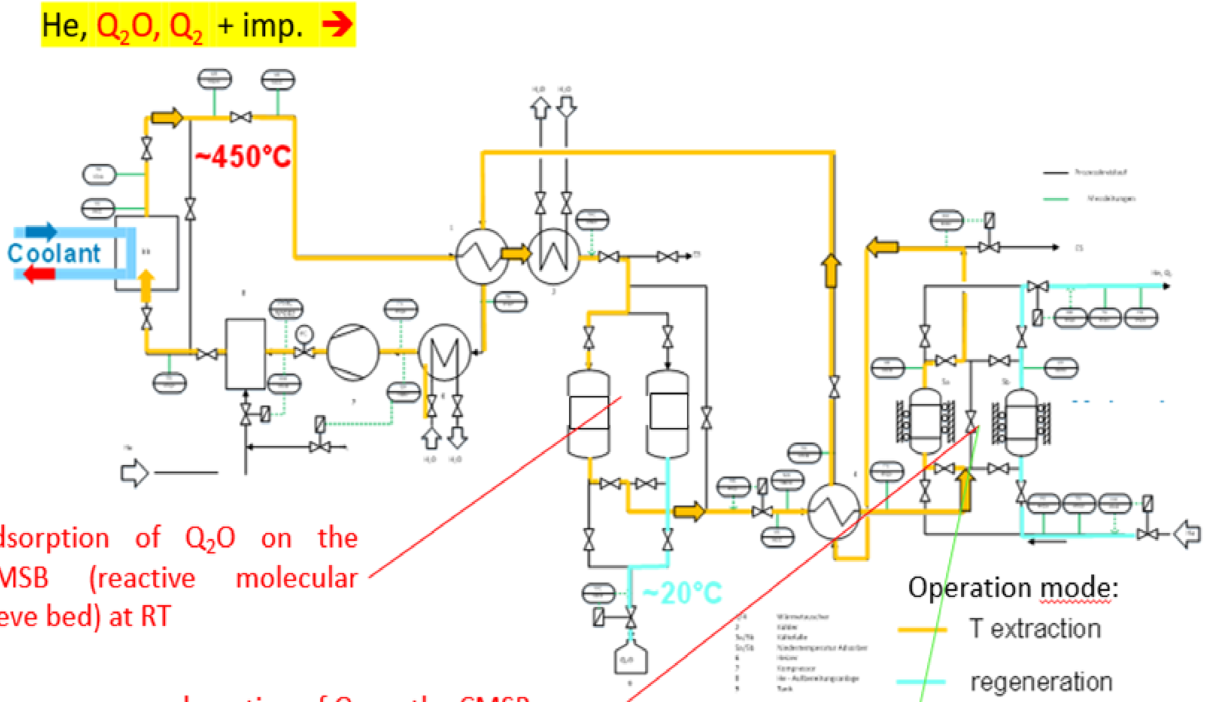
1. Intergranular diffusion through grain bulk
2. Surface reactions (isotopic exchange)



3. Grain-boundary diffusion to a pore
4. Surface adsorption / desorption into the pore
5. Pore diffusion to pebble boundaries
6. Release to purge gas flow and convection

  - Use of Li ceramic pebbles: Minimize temperature gradients in ceramics and the *T* residence time

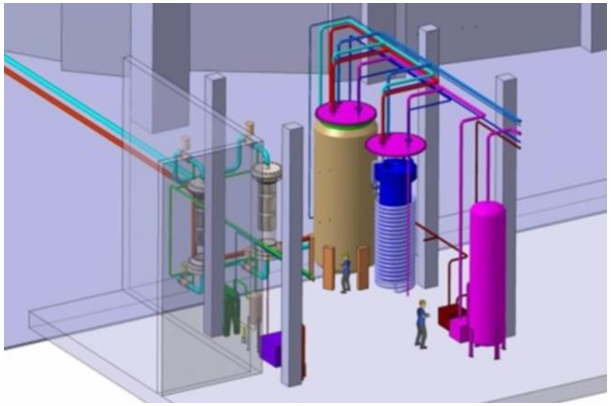
The HCPB Blanket: T-Extraction and Removal



adsorption of Q_2O on the RMSB (reactive molecular sieve bed) at RT

adsorption of Q_2 on the CMSB (cryogenic molecular sieve bed) at 77K.

alternative: Non-Evaporable Getter (NEG) at room temperature.

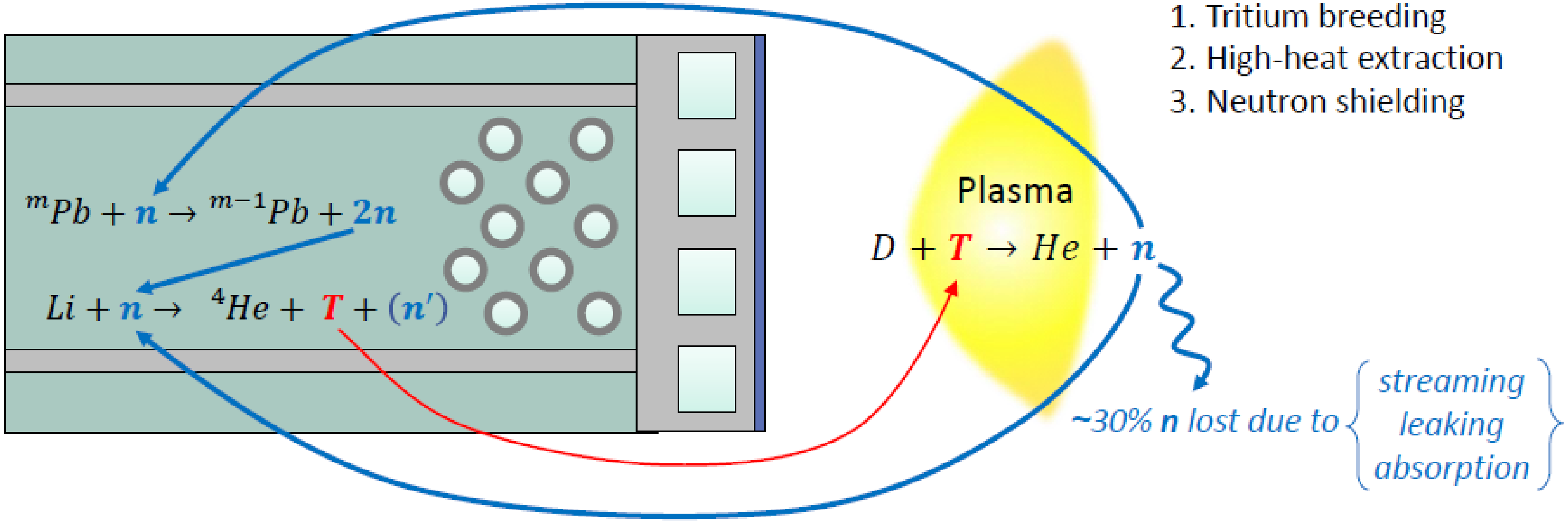


- Reference: T removal based on trapping/adsorption processes.
- Developed in the 90-ties based on a well established cryogenic industrial process.
- FP8: studies to substitute the cryogenic process with Getter Beds at RT. If successful it opens a way to reduce the energy consumption and 8 Mpa operation
- Issue of T permeation: study to increase the steam content in the purge gas to minimize the T permeation from purge gas into the coolant.

What is a WCLL Blanket?

- ***Water Cooled Lead Lithium Breeding Blanket*** (WCLL BB)

1. Tritium breeding
2. High-heat extraction
3. Neutron shielding



- Tritium Breeding Function

$$Li + \mathbf{n} \rightarrow {}^{4}He + \mathbf{T} + (\mathbf{n'})$$

- Neutron multiplier (NM) function:

$$^{m}Pb + \mathbf{n} \rightarrow {}^{m-1}Pb + \mathbf{2n}$$

Li – Pb alloy (17%Li-83%Pb eutectic)

as $\mathbf{T}$ *and* $\mathbf{n}$ *multiplier*

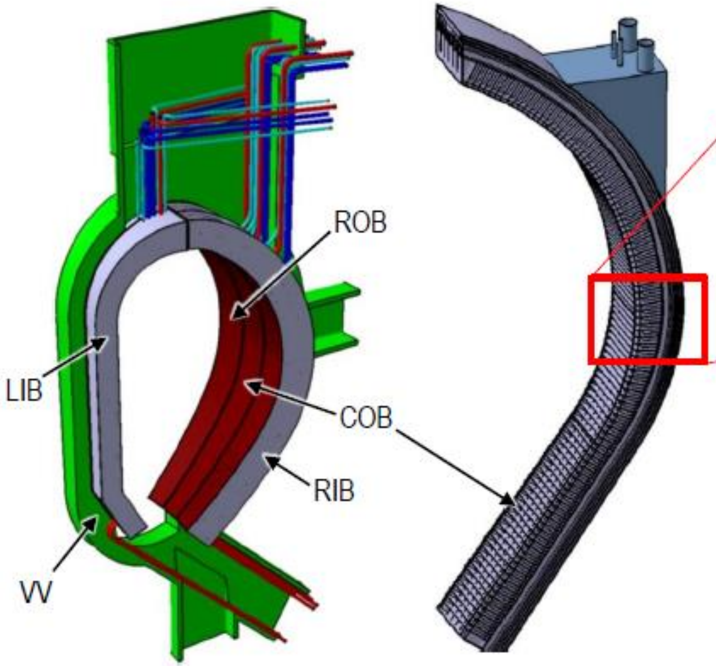
- Structural material: Reduced Activation Ferritic Martensitic (RAFM) steel, EUROFER97

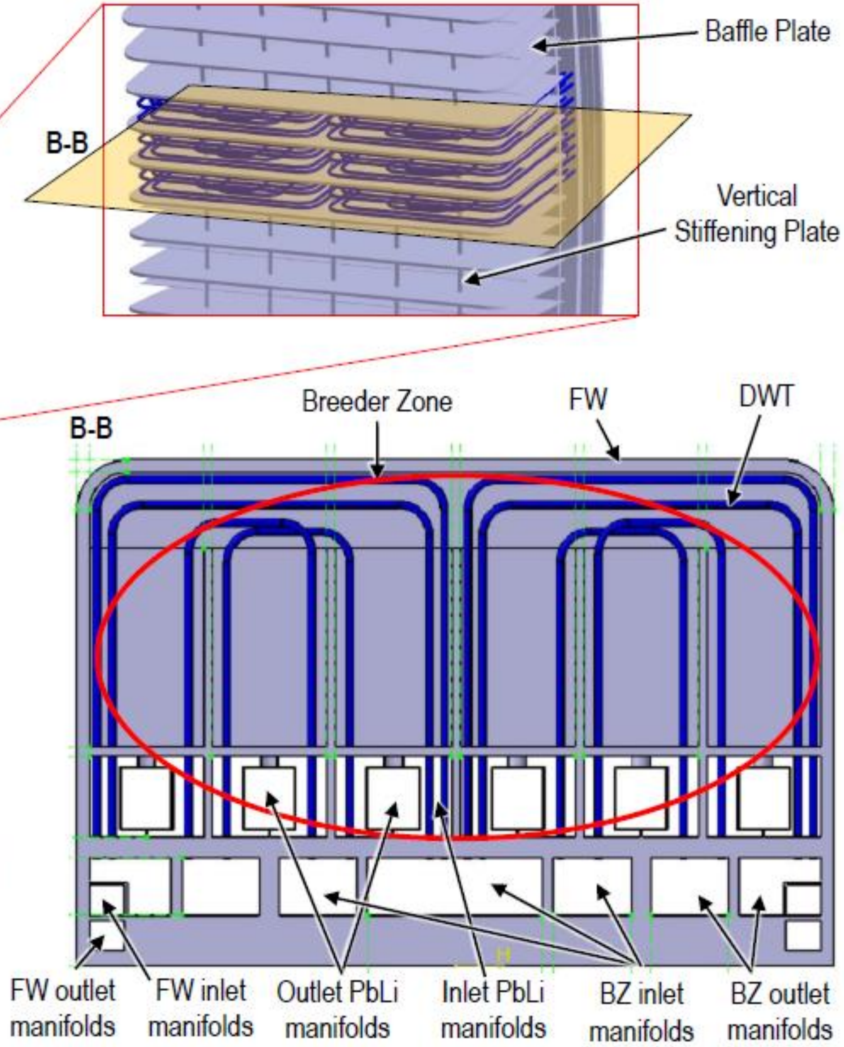
- Heat extraction: Water (PWR-like)

The WCLL Blanket

A. Del Nevo et al., Recent progress in developing a feasible and integrated conceptual design of the WCLL BB in EUROfusion project, Fusion Engineering and Design, 146 (2019) **1805-1809, DOI:10.1016/j.fusengdes.2019.03.040**

- WCLL design (BL2017)





- Arrangement of horizontal and vertical stiffening plates, baffle plates and DWT which cool structures and functional material
- Functional material: liquid metal Pb-Li eutectic alloy, ^{6}Li 90% enriched
- Structural steel: EUROFER97

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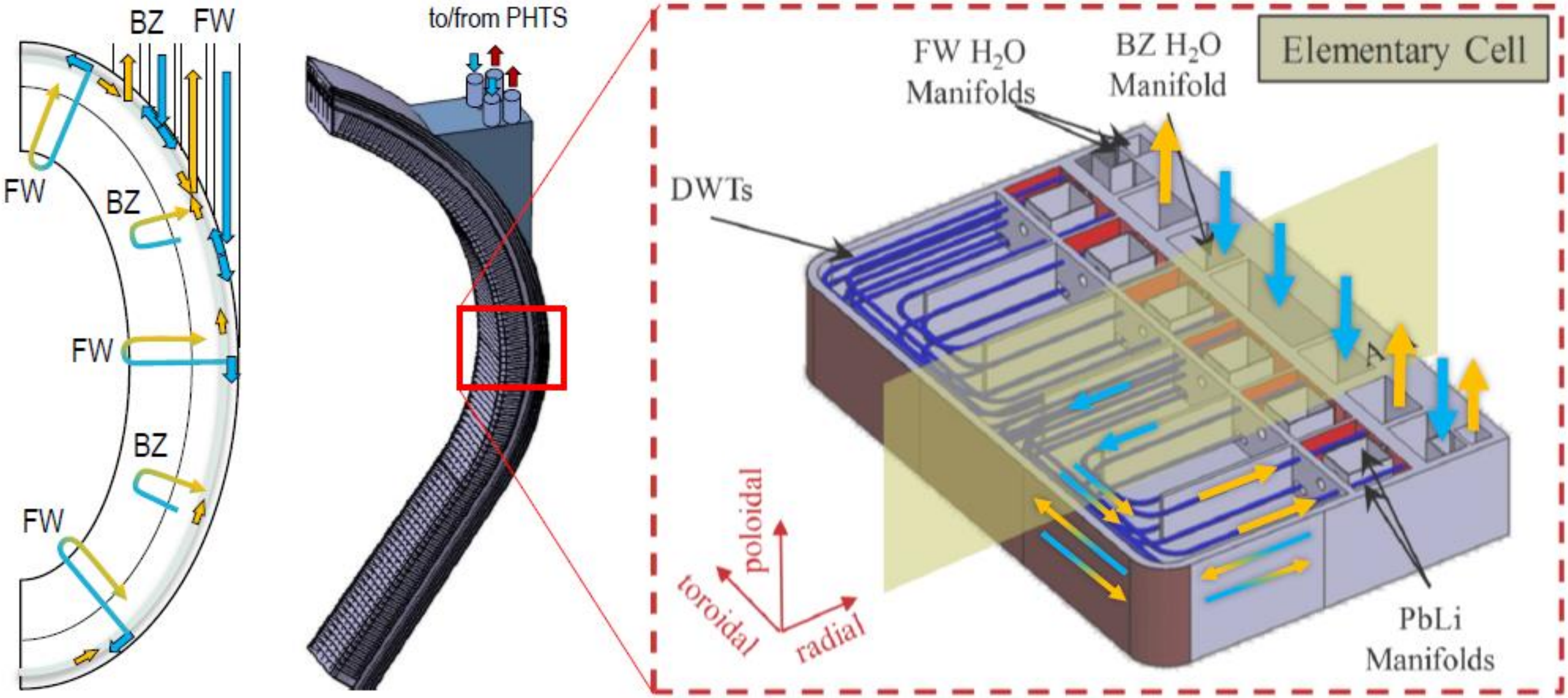
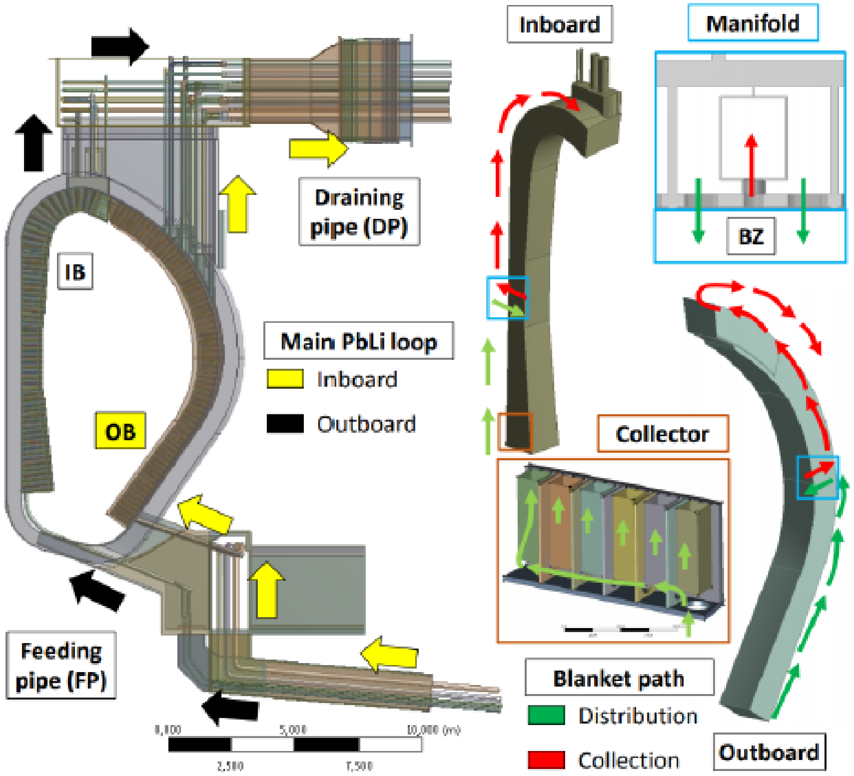
The WCLL Blanket: Cooling system.

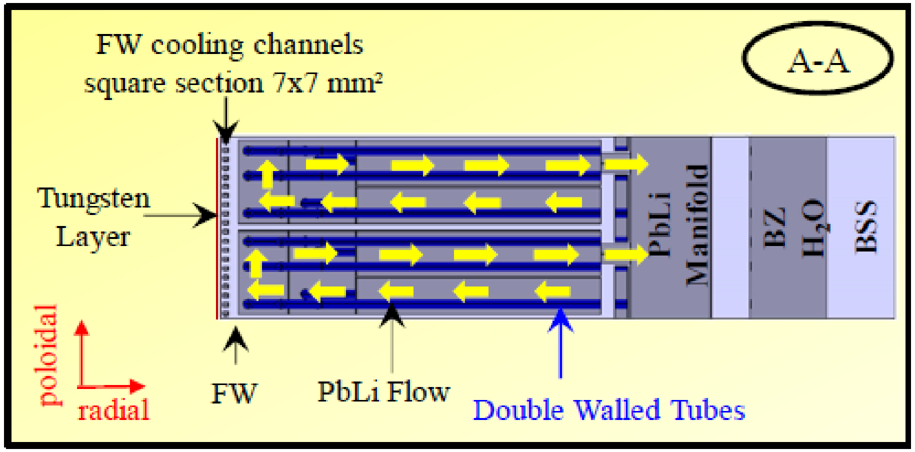
- Coolant thermo-hydraulic parameters:
    - Water 155 bar, T_{in} = 295°C, T_{out} = 328°C, PWR-like conditions
    - FW and BZ cooling loops in parallel, separated (design choice, impact in PHTS architecture)



The WCLL Blanket: PbLi circulation

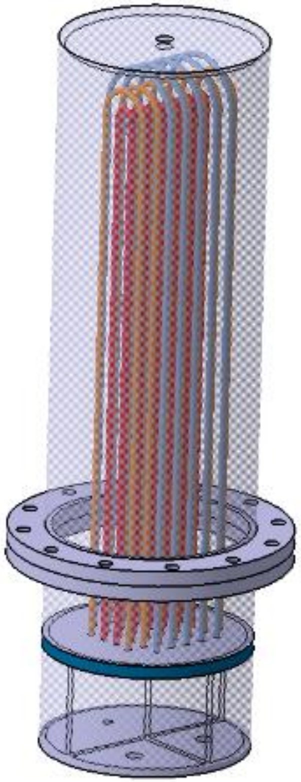
- Functional material parameters:
  - Material: PbLi, liquid metal eutectic alloy, 90% ^{6}Li, T_{in}= 330°C, T_{out}= 500°C
  - *T* is bred in PbLi, PbLi transports the molecular *T* bred in the BZ, however in order to avoid large pressure drops due to MHD, PbLi flows very slowly (mm/s) => *T* permeation issue
  - *T* is therefore extracted from the functional material (PbLi) outside the BB, in the TER



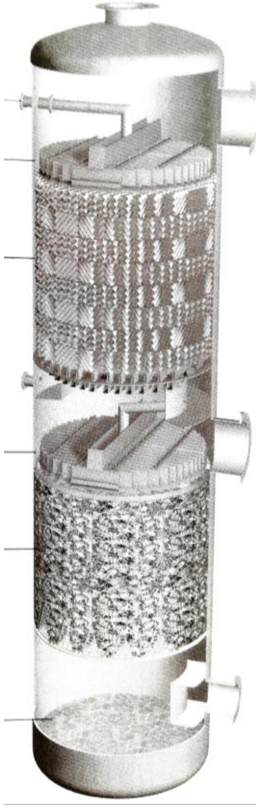


The WCLL Blanket: T-Extraction and Removal

- Selection of a reference technology not yet possible:
  - Uncertainties are still present on the scaling of these technology to DEMO.
- Concurrent systems under selection for the T extraction
  - PAV (Permeator Against Vacuum):
    - Large permeation surface, high T diffusivity in membrane materials (e.g. V, Nb).
    - Present R&D: a) membrane performances (critical is the surface condition); b) vacuum technology; c) manufacturing; d) process efficiency in view of DEMO-scale
  - GLC (Gas Liquid Contactor)
    - He bubble flow in counter-current respect to the PbLi flow. T concentrates in the gas bubbles.
    - Present R&D: a) materials of the packed bed at PbLi exposition; b) purging technolgy of tritium extraction; d) extraction efficiency in view to design DEMO-scale systems
  - LVC (Liquid Vacuum Contactor)
    - PbLi is exposed to vacuum without membranes. E.g. Vacuum Sieves: droplets fall in a vacuum chamber and T is extracted.
    - Less mature technology: a) vacuum technology; c) manufacturing; d) process efficiency in view to design DEMO scale systems



PAV



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Outline

1. **Breeding Blankets: Introduction**
    - The Tritium Issue
    - Conceptual architecture
2. **Breeding Blankets for the EU DEMO**
    - Concepts
    - Near term architectures
    - The HCPB Blanket
    - The WCLL Blanket
3. **Summary and Outlook**

Summary and Outlook

- The Breeding Blanket is **a key component** for DEMO and the first generation of fusion power plant: energy production, T-self-sufficiency and lifetime.
- BB requires new technologies that are never been demonstrated before.
- Several concepts of blankets with different combinations of materials (structural, breeder, coolant, etc.) have been proposed in the past.
- At the present some near term technologies have been selected and further developed for DEMO-reactors.
- In EU, two BB concepts have been extensively investigated: the HCPB and the WCLL, each with their own TER system.