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FUNFI-IT - Italian Meeting on Fusion Neutrons for Fission

Breeding Blanket concepts for the EU-DEMO Fusion Power Plant

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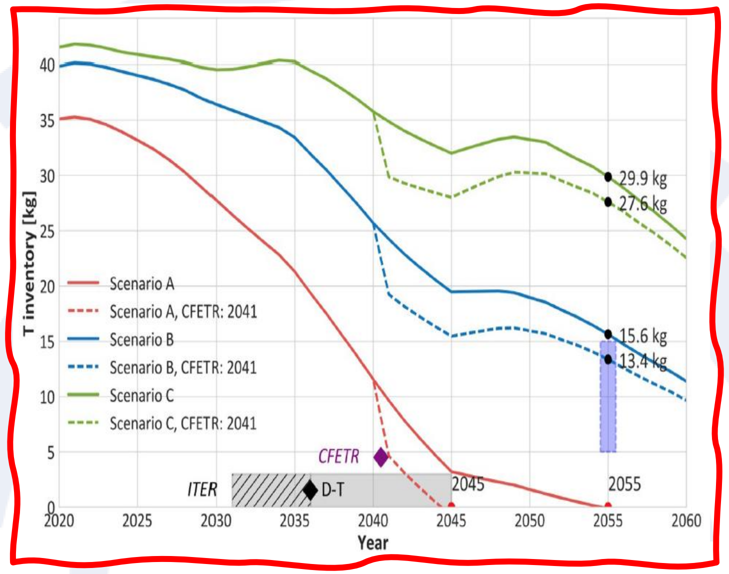
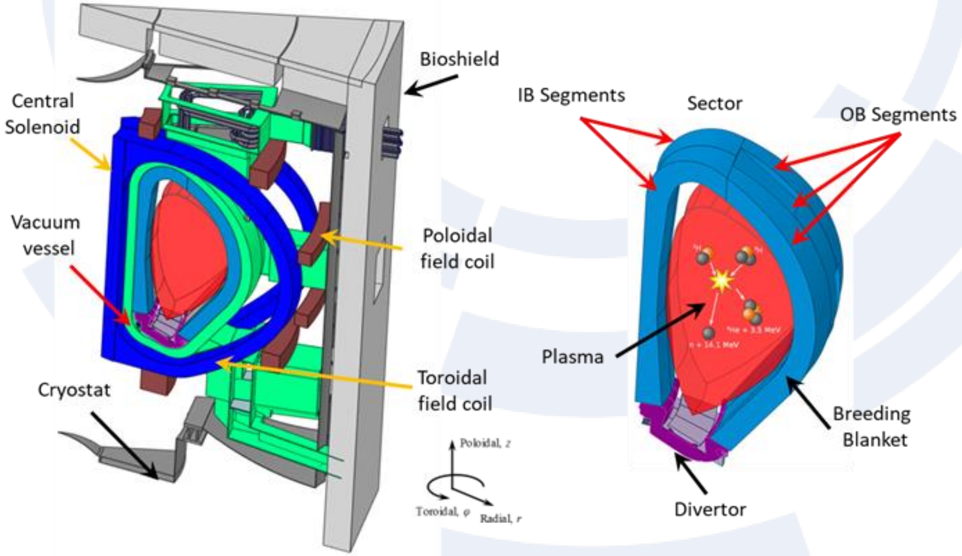
Breeding Blanket R&D Programme: Background

- **Breeding blanket technology is crucial for the development of fusion power, but its maturity is currently very poor.**
  - **Heat removal for electrical production**: (~300-500 MWe) predictably and safely, with minimal environmental impact
    - use Reduced Activation Ferritic-Martensitic 'RAFM' steel → EUROFER
    - minimization of tritium permeation, dust and corrosion products generation
  - **Breed tritium**: *"a 2 GW fusion power DEMO will consume around 111 kg T/FPY, and this clearly underscore the indispensable requirement to achieve T-self-sufficiency"*
  - **Radiation Shielding of the Vacuum Vessel and Coils**
    - Absorb plasma radiation on the first wall
    - Dose in epoxy / 10 fpys - Limit: 50 MGy
    - N-heating - Limit: ~444 W/m³ (TF cond.)
  - **The main BB Loads and boundary conditions are:**
    - **Inertial** (dead weight and earthquake)
    - **Thermal** (nuclear heating and heat fluxes)
    - **Pressure and Electromagnetic loads**
    - **Material damage**



M. Kovari et al, (2018) Tritium resources available for fusion reactors, Nuclear Fusion, 58, 026010, DOI: 10.1088/1741-4326/aa9d25



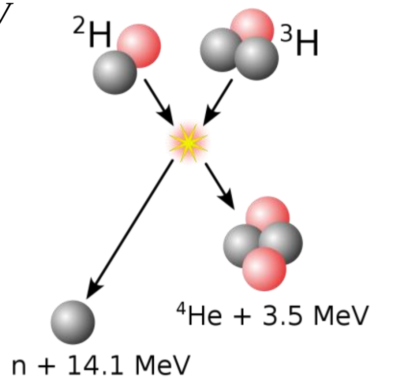
Tritium and Fusion reactions

Why Tritium?

The D-T reaction is the easiest and most promising solution to earth-based fusion

$$^{2}_{1}D + ^{3}_{1}T \rightarrow ^{4}_{2}He + ^{1}_{0}n \quad (Q_{DT} = 17.59 MeV)$$

$$E_n = 14.1\ MeV \qquad E_\alpha = 3.5\ MeV$$

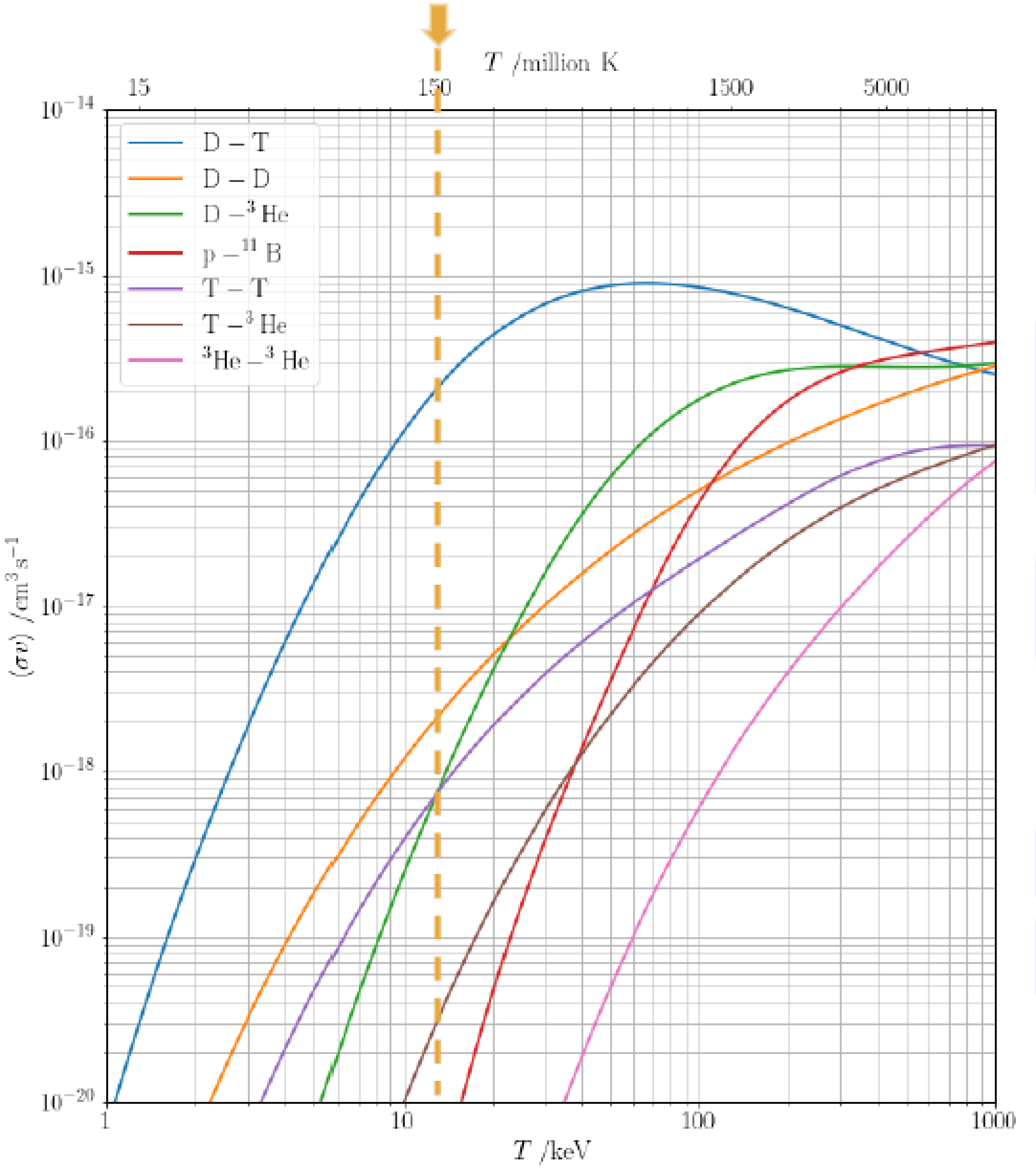


- **Exothermic**
- Good **cross section**
- Good **energy release**
- Deuterium is **largely available**
  - ~154 ppm of D in H
- Tritium can be **bred** from Lithium
- Lithium is **abundant** on the Earth surface and in seawater 230 billion tons 0.1-0.2 ppm

$$^{2}_{1}D + ^{2}_{1}D \rightarrow \begin{cases} ^{3}_{2}He + ^{1}_{0}n & (Q_{DD} = 3.27 MeV) \\ ^{3}_{1}T + ^{1}_{1}p & (Q_{DD} = 4.03 MeV) \end{cases}$$

$$^{1}_{1}p + ^{2}_{1}D \rightarrow ^{3}_{2}He + \gamma \quad (Q_{pT} = 5.59 MeV)$$

$$^{2}_{1}D + ^{3}_{2}He \rightarrow ^{4}_{2}He + ^{1}_{1}p \quad (Q_{DHe} = 18.35 MeV)$$



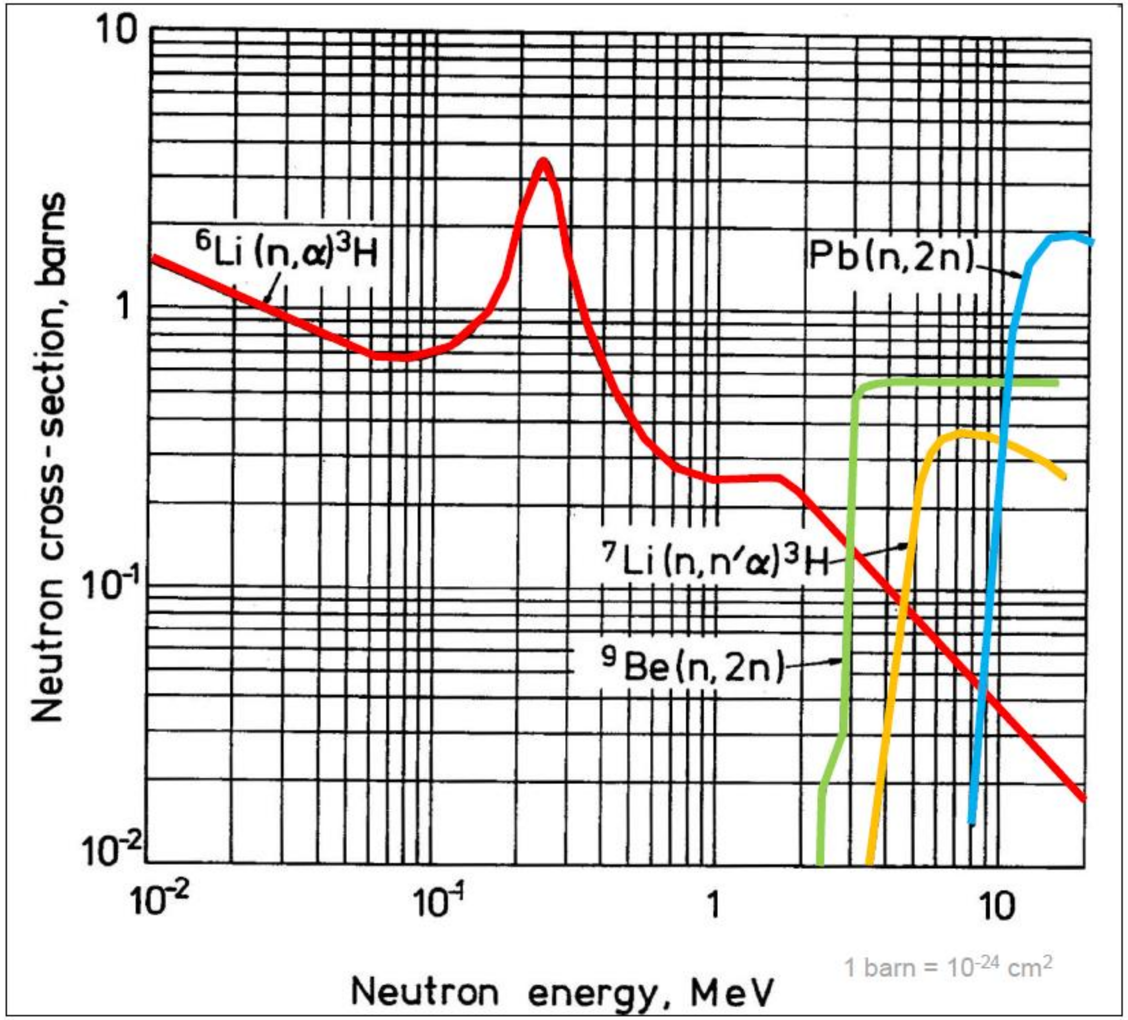
Tritium breeding function

Tritium production in reactor: Li reactions

$$^{6}_{3}Li + n^0 \rightarrow {}^{4}_{2}He + {}^{3}_{1}\boldsymbol{H} + 4.78\ MeV$$

$$^{7}_{3}Li + n^0 \rightarrow {}^{4}_{2}He + {}^{3}_{1}\boldsymbol{H} + n^0\ - 2.47\ MeV$$

- The ^{6}Li reaction has a very high cross section especially in the low-energy region
- The ^{7}Li reaction works with the high energy neutrons. It produce an additional n that is available for a successive reaction
- Natural mixture: ^{7}Li 92.5 % at., only 7.5 % ^{6}Li
    - About 10^{11} kg Lithium in landmass
    - About 10^{14} kg Lithium in oceans



Tritium breeding function

Neutron multiplication

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

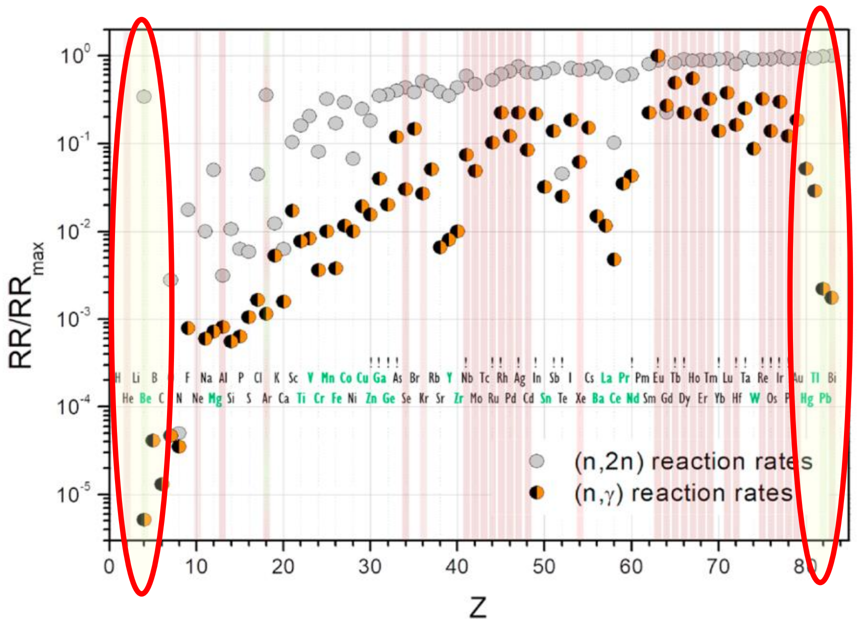
- Li (nat.):
  - sufficient, but only with very low n-absorber materials
  - strong reaction with water and air
  - getter for T (difficult recovery)

- Beryllium (Be)
  - (n,2n) threshold energy ≈2 MeV
  - good moderator (shielding)
  - exothermal reaction with water > 600°C
  - Be dust is toxic

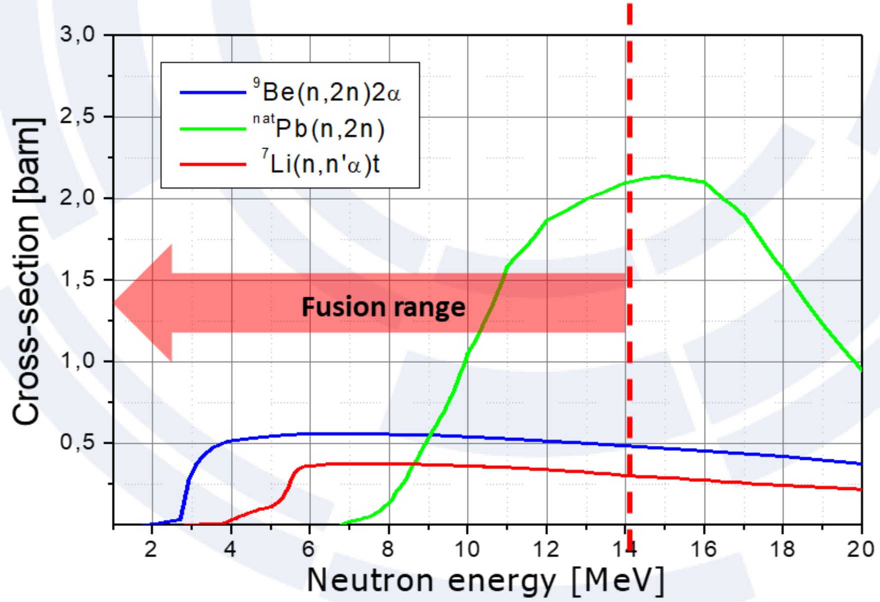
- Beryllides ($TiBe_{12}$, $CrBe_{12}$, etc.)
  - Tritium breeding ratio 1.20
  - Well developed industrial technology
  - Excellent combination of properties
  - Annual production of Be 300 t/ yr
  - Cost of Be 650 $/kg

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

- Plumbides ($LaPb_3$, YPb_2, Zr_5Pb_3)
  - (n,2n) threshold energy ≈7.5 MeV
  - No industrial technology
  - Properties are not well studied
  - Annual production of Pb 11 mln t/ yr
  - Cost of Pb 6 8 $/kg



(n, 2n) and (n, γ) relative reaction rates for the elements up to Bi (Z=83)



Tritium breeding function

Tritium Breeding Ratio (TBR)

TBR = 1 is achieved when every fusion neutron produces a triton from lithium

$$TBR = \frac{\text{Tritium Bred}}{\text{Tritium Burnt}} > 1$$

- It has to be **> 1** for reactor **auto sufficiency**;
- Depends on the choice of **materials** and **geometry**
- Relies in neutron multiplication and reflection
- Can be calculated using Montecarlo codes (MCNP)
- Can be validated by experiments
- Typical design targets of the global TBR are in the range of **1.05 – 1.15**

❖ Whether achievable in a fusion reactor is a question of design integration…

❖ Multipliers need to offset absorption in all other components and materials, e.g. FW, divertor, pellet injectors, heat & current drive components, diagnostics, etc.

U. Fisher et al, (2015) Neutronics requirements for a DEMO fusion power plant, FED 98–99, 2134–2137

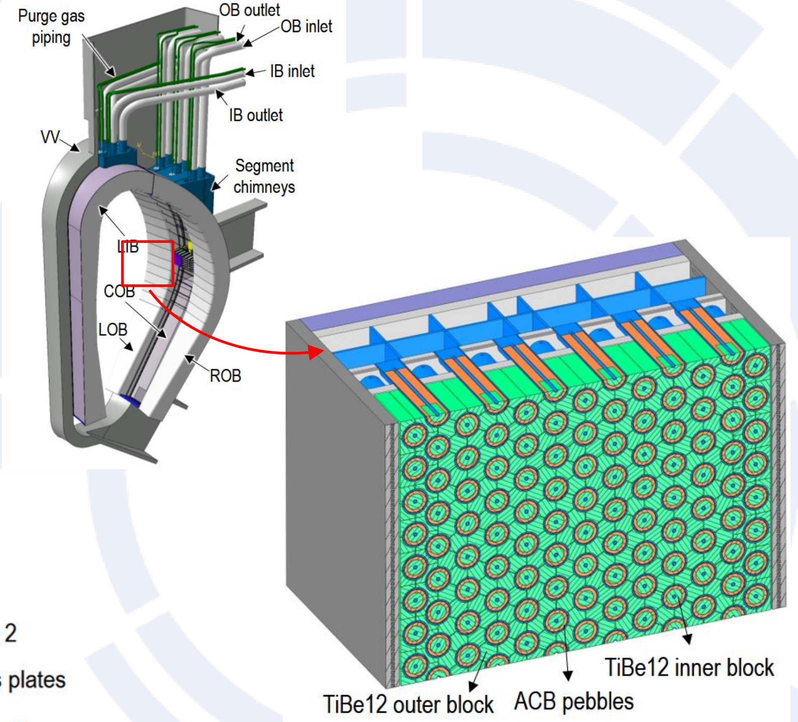
- How large the TBR should actually be during the lifetime of the FPP is depending on the **dynamics** of the entire fuel cycle for the D-T plant. It accounts for:
  - **possible losses of tritium** in the different parts of the process and tritium trapping in the materials
  - **reduction of breeding** in the time with the Li burn-up
  - **duplication time** (time necessary to produce the tritium amount necessary to start a new FPP)
  - **storage capabilities**
  - **natural decay** of tritium (half-life of 12.3 y)
  - **safety** inventory **limits**

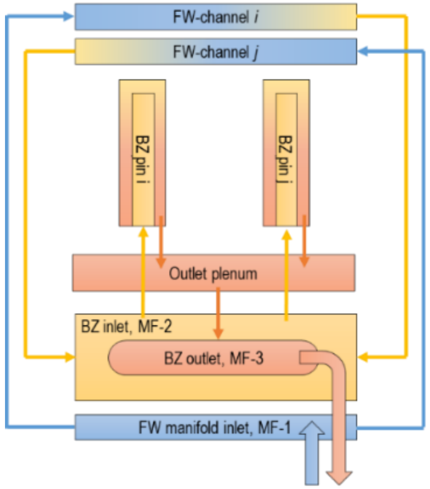
Current BB design variants: the HCPB concept

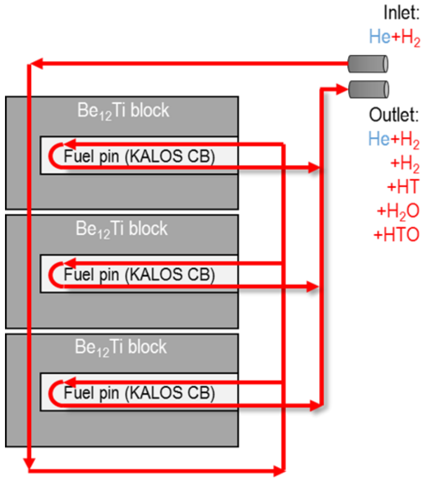
Helium Cooled Pebble Bed Concept (HCPB)

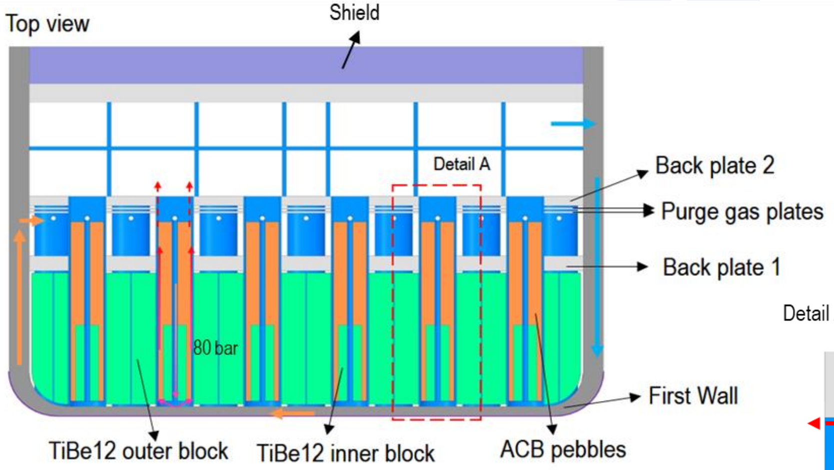
- **Structural Material**: EUROFER (RAFM steel), ~3000 t
- **Breeder**: KALOS (Li_4SiO_4 + 35 mol% Li_2TiO_3) in form of a pebble bed, ^6Li at 60%, ~165 t
- **Neutron multiplier**: Beryllide ($TiBe_{12}$) hexagonal rods, 612 t
- **Coolant**: helium 300-520°C @ 8 MPa, ~ 4.2 t
- **Plasma protection**: 2 mm W layer (wo Limiters)
- **T extraction with purge Helium**: 0.1% H_2 (%H_2O) @ ~8 MPa, ~ 137 m³

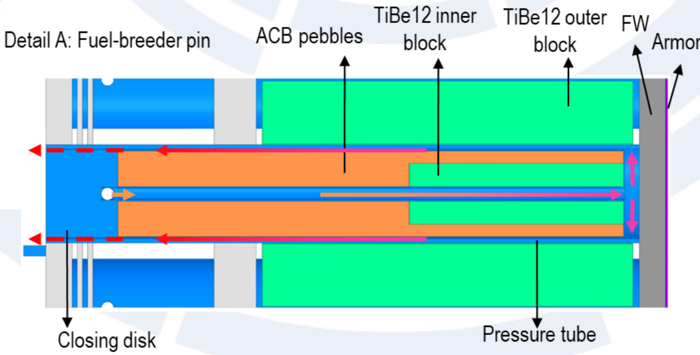
G. Zhou et al, (2023) The European DEMO Helium Cooled Pebble Bed Breeding Blanket: Design Status at the Conclusion of the Pre-Concept Design Phase, Energies, 16, 5377 , DOI: 10.3390/en16145377







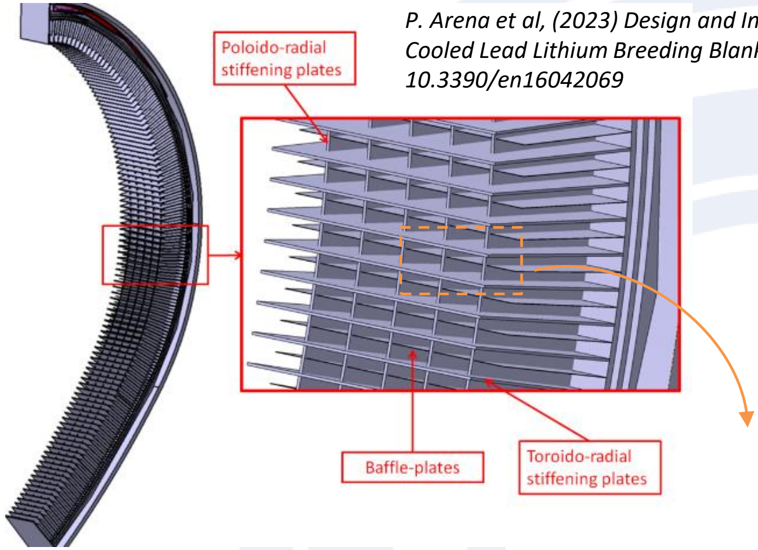




Current BB design variants: the WCLL concept

Water Cooled Lead Lithium Concept (WCLL)

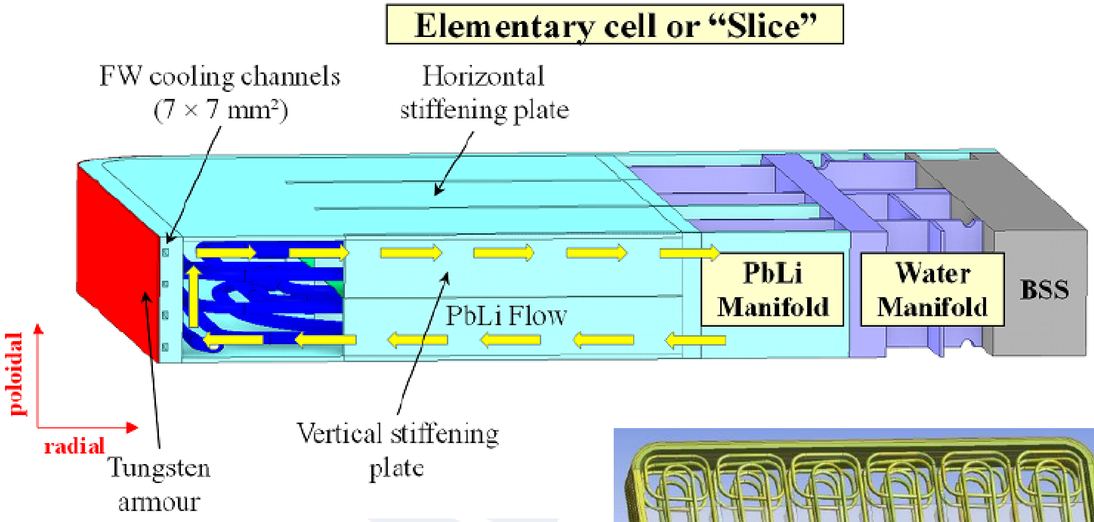
- **Structural Material:** EUROFER (RAFM steel), ~3500 t
- **Breeder/neutron multiplier:** PbLi (^{6}Li at 90%) liquid (~330 °C @ 0.25-1.55 MPa), ~10,000 t,
- **Coolant**: Water (295-328°C @ 15.5 MPa), ~520 t
- **Plasma protection:** 2 mm W layer (wo Limiters)
- **T extraction from recirculating PbLi**

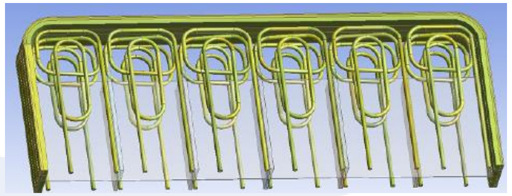


P. Arena et al, (2023) Design and Integration of the EU-DEMO Water-Cooled Lead Lithium Breeding Blanket, Energies, 16, 2069 , DOI: 10.3390/en16042069

- Identified risks as of end pre-CD phase:

	Risk ID	Risk
WCLL	.001	Low reliability of BB system
	.002	Low efficiency of PbLi draining
	.003	FW based on thin EUROFER + W-armor
	.005	Low tritium breeding performance
	.006	Large amount of transmutation helium in PbLi
	.010	Large T permeation to coolant
	.012	WCLL operating with EUROFER temp. irradiated <400 °C (DBTT shift)
	.013	Pressure transient uncertainties due to PbLi-water interaction
	.022	Diffusion of Li into anti-permeation barriers and production of T + He there





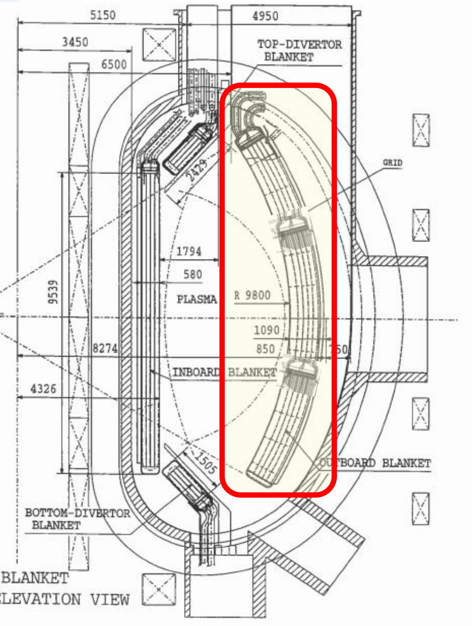
Motivation for water-cooled BB Alternative variants

- Motivation:

	ID	Risk	Addressed in
WCLL	**.001**	**Low reliability of BB system**	**(1)**
	.002	Low efficiency of PbLi draining	(4)
	.003	FW based on thin EUROFER + W-armor	
	.005	Low tritium breeding performance	(3)
	.006	Large amount of transmutation He in PbLi	
	.010	**Large T permeation to coolant**	(2)(6)
	.012	WCLL operating with EUROFER temp. irradiated <400 °C (DBTT shift)	
	.013	**Pressure transient uncertainties due to PbLi-water interaction:**	(5)
	.022	Diffusion of Li into anti-permeation barriers and production of He there	(2)(6) may avoid barriers

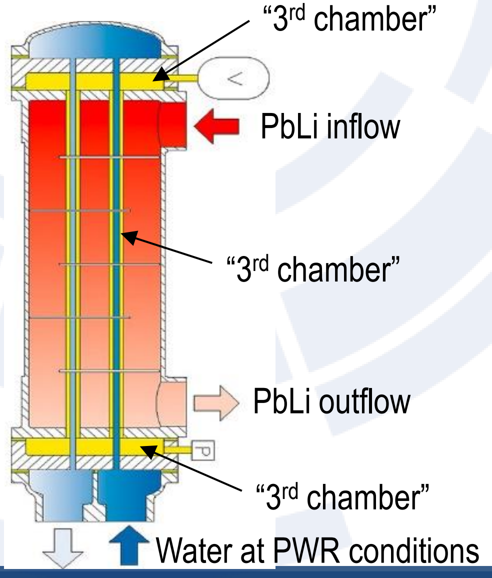
F. A. Hernandez et al, (2023) Alternative water-cooled BB concepts for the EU DEMO: Overview on studies and perspectives, Presentation @ISFNT-15, Las Palmas

- Poloidal water tube distribution:
  - Poloidal tubes:
    - (1) Less tubes, less welds, ↑ **reliability**
    - (2) Less tubes, less surface, ↓ **T-permeation**
    - (3) Less tubes, less water, more PbLi, ↑ **TBR**
    - (4) Easier draining
  - BB similar to HX/SG => ↑ **TRL/RoX**
  - Segments split in several poloidal regions
    - Limit heat flux per tube
    - Allows systems integration (H/CD, limiters…) w/o splitting segments

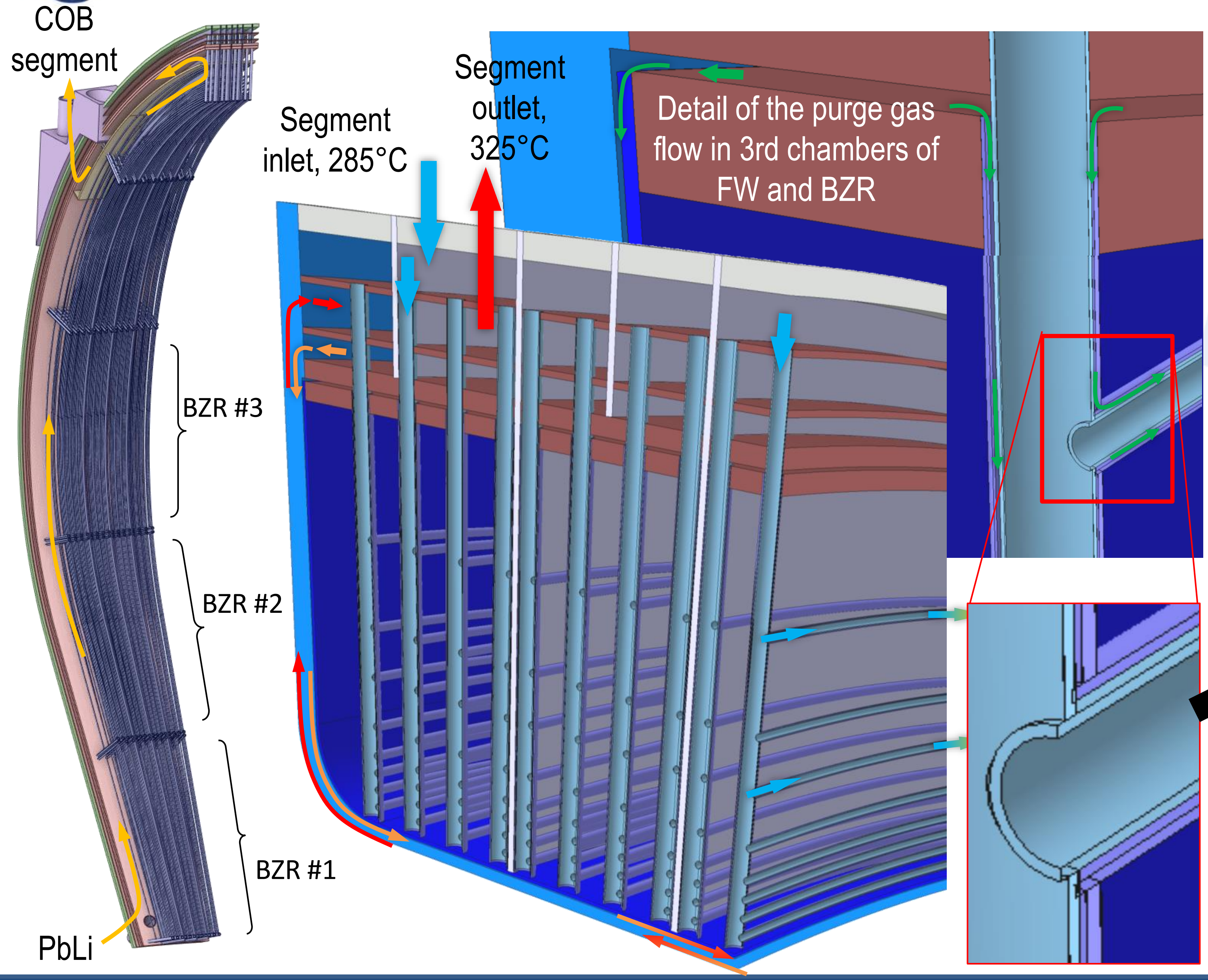


Giancarli et al. (1995)

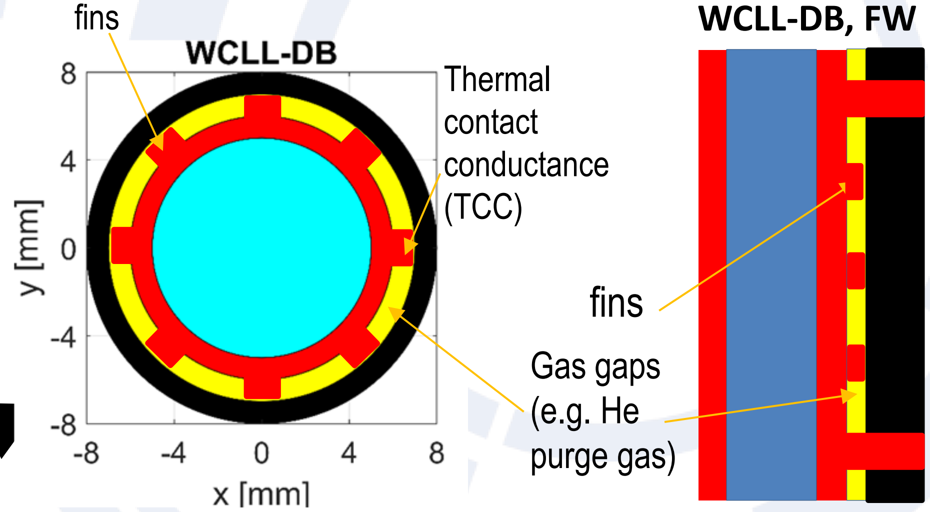
- „Double bundle“ of simple tubes
  - 3-chamber idea of S&T HX (K.-H. Funke)
    - (5) Intermediate chamber between PbLi and water to avoid contact in case of internal LOCA
    - (6) 3rd chamber filled with He gas: used to remove permeated T before it reaches water

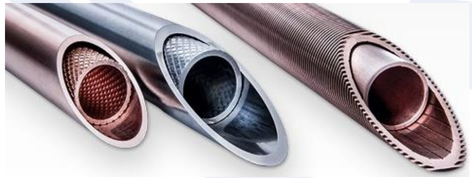


Exploring variants: WCLL Double bundle



- Design description:
  - PWR cooling (285-325°C, @15.5 MPa)
  - BZ and FW in series ($T_{in,FW}$≈315 °C)
  - 5 BZRs, poloidal PbLi flow
  - „3rd chamber“ between the double bundle, filled *with a He purge gas*





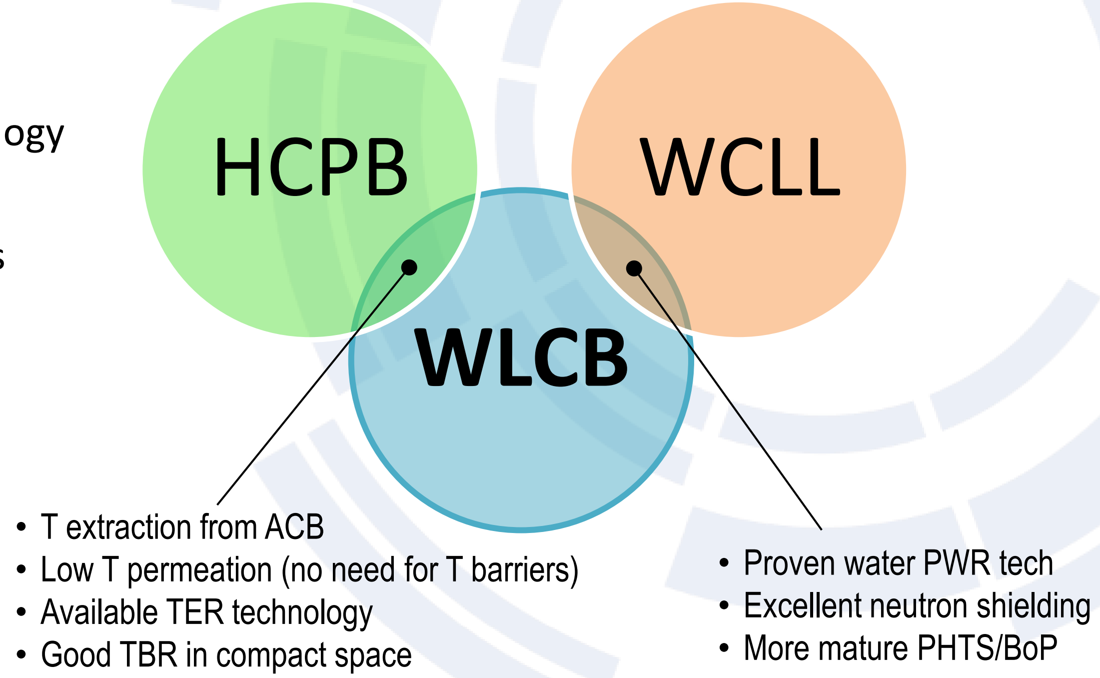
E.g. Wieland Safety Tubes:
https://www.wieland-thermalsolutions.com

F. A. Hernandez et al, (2023) Alternative water-cooled BB concepts for the EU DEMO: Overview on studies and perspectives, Presentation @ISFNT-15, Las Palmas

Exploring variants: Water-cooled Lead Ceramic-Breeder (WLCB)

- Background: a short story…
  - Idea started in **FP8**: HCPB issue with beryllium -> deep exploration of alternative n-multipliers -> Pb/Pb-alloy
  - **He-cooled molten Pb and ceramic breeder blanket**: oral presentation at SOFT 2018 (FED-2019, FED-2019)
  - Curiosity for a water-cooled version -> WLCB, as radial CB pins (FED-2021, FED-2021)

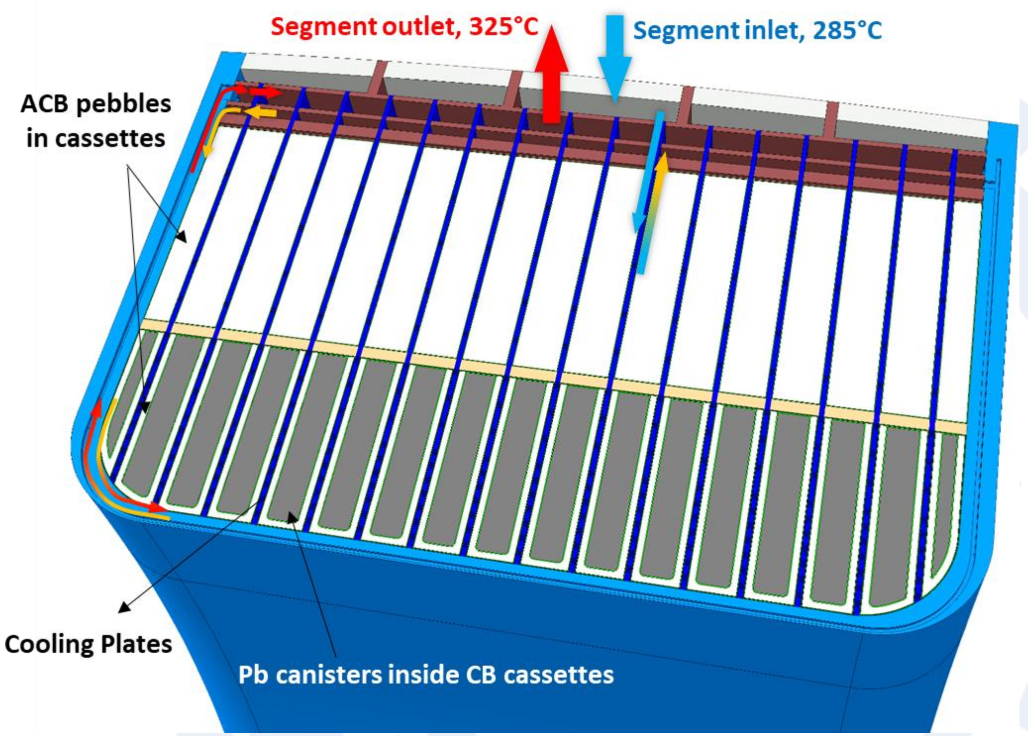
- FP9: further work on a WLCB with poloidal configuration of advanced ceramic breeder (ACB) tubes and simpler cooling structures
- Seen as a best trade-off between HCPB and WCLL:
  - To avoid current issues in HCPB with shielding, multiplier technology and costs
  - To mitigate issues with T-permeation and avoid T-extraction risks from PbLi in WCLL variants
  - To avoid use of anti-permeation barriers in BB (**TBC**)
  - To use proven water PWR tech

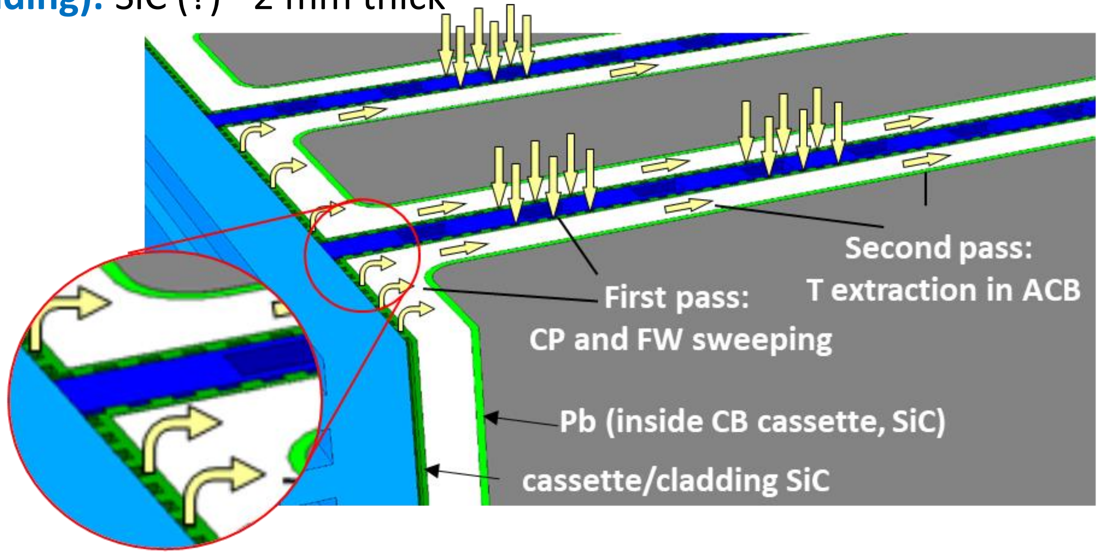


F. A. Hernandez et al, (2023) Alternative water-cooled BB concepts for the EU DEMO: Overview on studies and perspectives, Presentation @ISFNT-15, Las Palmas

Exploring variants: Water-cooled Lead Ceramic-Breeder (WLCB)

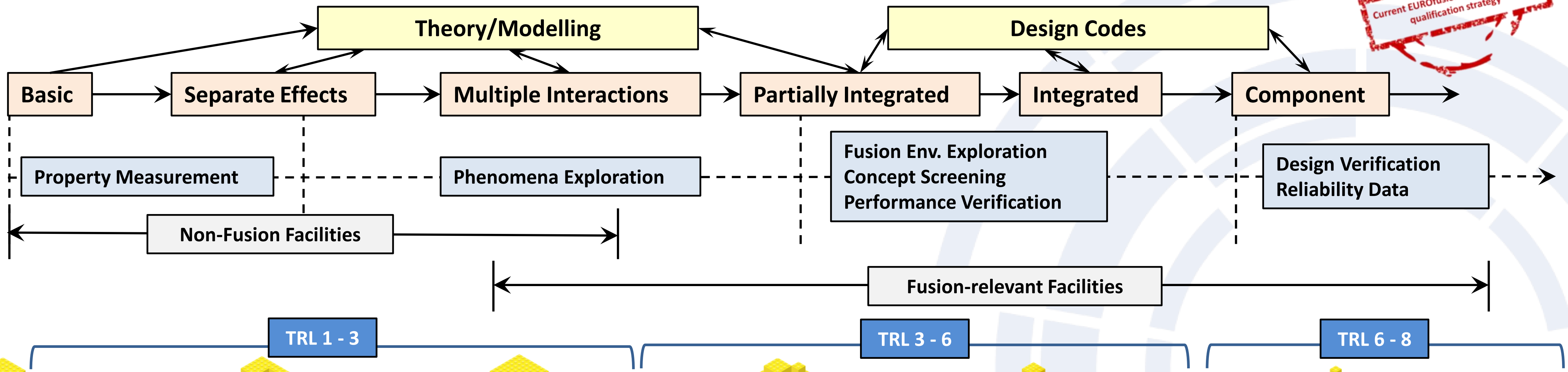
- **Structural Material**: EUROFER (RAFM steel)
- **Coolant:** Water at PWR conditions (285-325 °C @155 bar)
  - **cooling scheme:** BZ and FW in series
  - **radial cooling plates** (acting as stiffeners)
- **Breeder**: ACB (Li_4SiO_4 + 35 mol% Li_2TiO_3) in form of a pebble bed, ^6Li at 60% and Li_8XO_6, X=Pb, Zr…) in cassettes
- **Purge gas:** He + %H2 @2bar
- **Neutron multiplier:** molten Pb in cassettes
- **Neutron spectra shifter:** metal hydride such as ZrH_x (?) or YH_x (?) in cassettes
- **Cassettes (cladding):** SiC (?) ~2 mm thick





Breeding Blanket Qualification Strategy: the general approach

Current EUROfusion BB and F4E TBM qualification strategy



Basic experiments

- Basic or intrinsic property data
- Single material specimen

Single-effect experiments

- Explore a single effect, phenomenon, or interaction of a limited number of phenomena to develop understanding and models
- a single environmental condition and a clean geometry

Multiple-effect/multiple-interaction experiments

- Explores multiple environmental conditions and multiple interactions to develop understanding and prediction capabilities
- Includes identifying unknown interactions and directly measuring specific parameters

Partially integrated experiments

- Partial integration test but without some important environmental conditions for large cost savings
- All key physical elements of the component and not necessarily full scale

Integrated experiments

- Concept verification and identification of unknowns
- All key environmental conditions and physical elements, although often not full scale

Component test

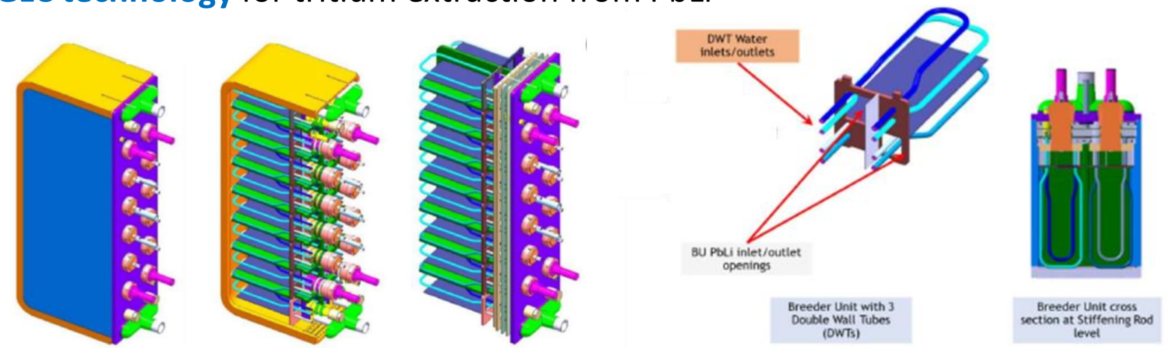
- Design verification and reliability data
- Full-size component under prototypical operating conditions

M.A. Abdou et al. (2015) Blanket/first wall challenges and required R&D on the pathway to DEMO, FED 100, 2-43, DOI: 10.1016/j.fusengdes.2015.07.021

Current EU-TBM Programme

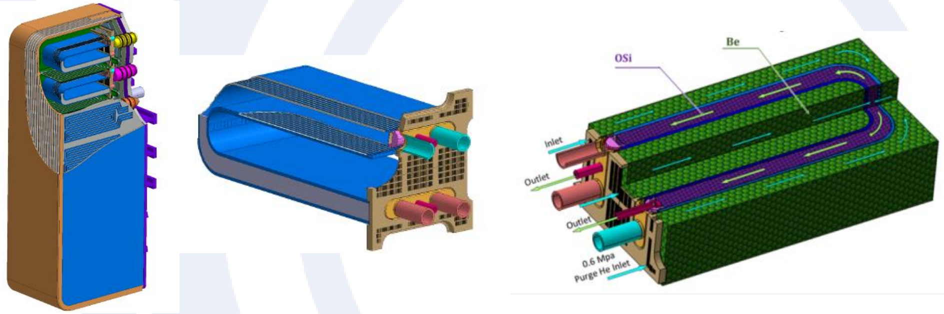
Water Cooled Lead Lithium Concept (WCLL) - TBM

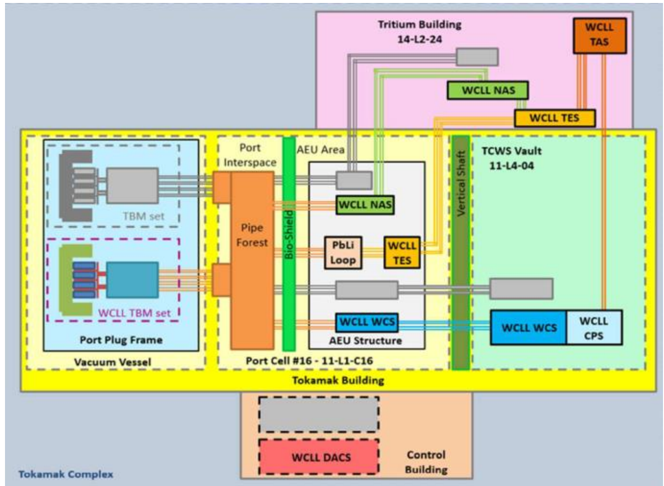
- The **FW** actively cooled with 7 x 7 mm² square channels
- **Double Wall Tubes (DWT)** with Øi 8 mm kept for DEMO relevancy
- **Coolant** water at @15.5 MPa, 295-328 °C
- **Recirculating PbLi** @0.2-1 kg/s
- **GLC technology** for tritium extraction from PbLi



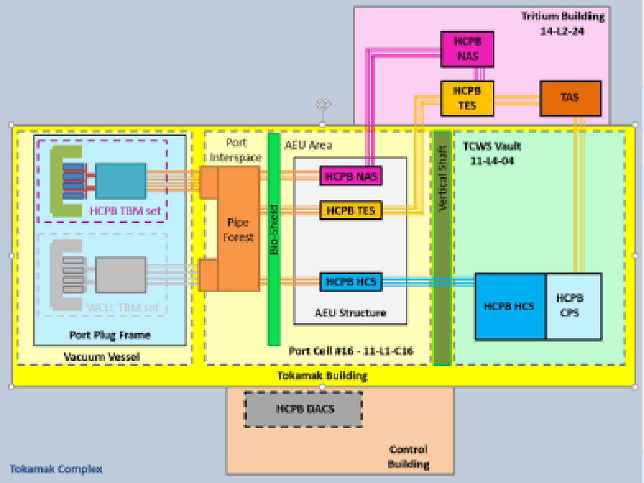
Helium Cooled Ceramic Pebble (HCCP) - TBM

- The **FW** actively cooled with 15x15 mm² square channels.
- Breeder: **Li_4SiO_4** in pebbles beds
- Neutron multiplier: **Be in pebble beds**
- **Coolant**: He at 8 MPa, 300-500 °C inlet/outlet temperature
- Power extraction through **curved cooling plates**
- **Purge gas for T extraction**: He + H_2 @0.2-0.4 MPa





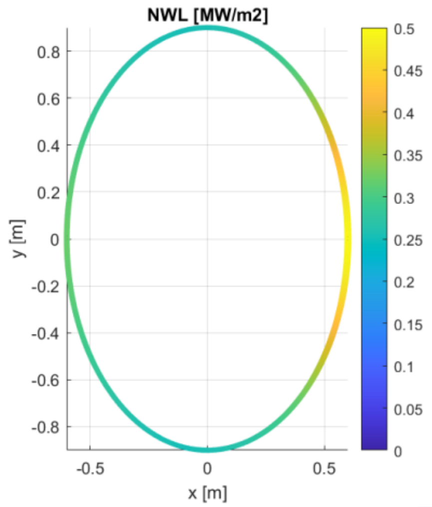
WCLL TBM Parameters	
$P_{TBMtherm}$ = 718 kW	Norm. to P_{fus} ~500 MW
HF_{min} = 0.3 MW/m² HF_{max} = 0.41 MW/m²	
G_t = ~18.6 mg/d	
< 2 dpa	
NWL_{max} = 0.63 MW/m²	

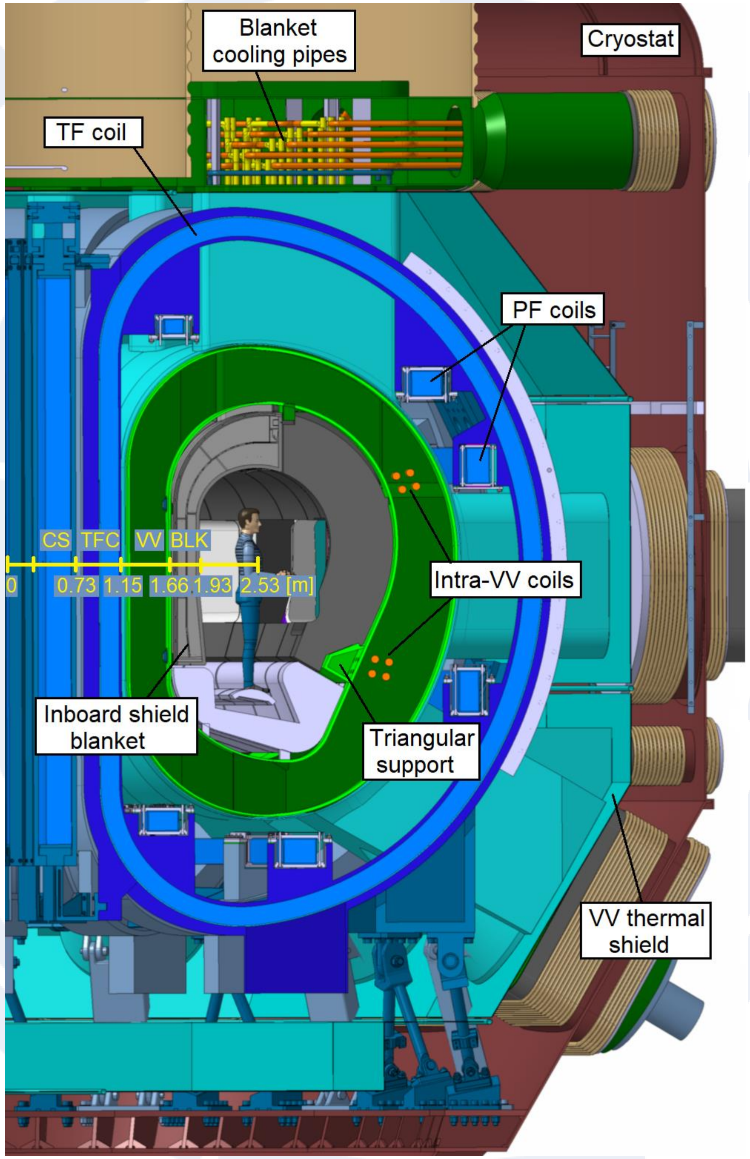


HCCP TBM Parameters	
$P_{TBMtherm}$ = 839 kW	Norm. to P_{fus} ~500 MW
HF_{min} = 0.3 MW/m² HF_{max} = 0.41 MW/m²	
G_t = ~23.6 mg/d	
< 2 dpa	
NWL = 0.79 MW/m²	

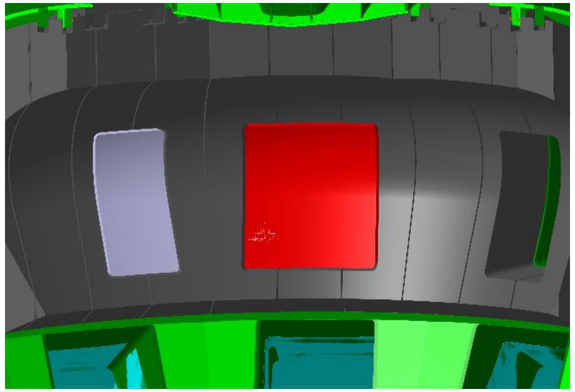
A VNS for the nuclear qualification of Breeding Blanket concepts

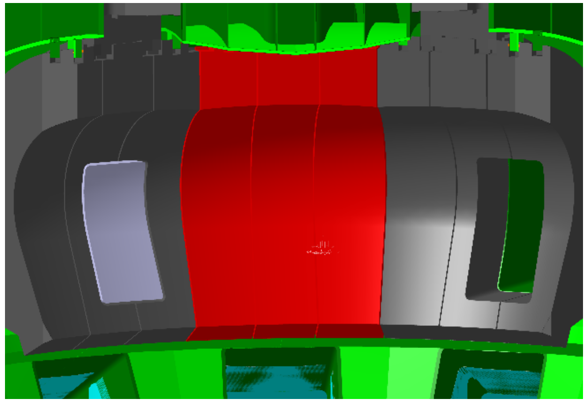
R = 2.53m, B_0 = 5.4 T	
A=4.6	High aspect ratio to create space on the inboard side while minimising the surface
CS	Nb_3Sn, sized to ramp up the plasma, I_p = 1.76 MA
TF coil	Nb_3Sn or HTS, B_{max} =12.8 T – trading-off B with TFC size
P_{fus} / P_{aux}	29 MW / 42 + 10 MA





Testing options and testing approach in the VNS





… for your kind attention!