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Topic 2: EU Facilities anticipated for DEMO preparation

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Breeding Blanket Project in EUROfusion

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Outline

R&D AND NEXT-STEP DEVICES FOR BREEDING BLANKET DEVELOPMENT TOWARD EU-DEMO

- Introduction to the EU DEMO Programme
- The Breeding Blanket Design
- The R&D Topics towards Breeding Blanket Technology Development
- Facilities necessary to complete the Conceptual Phase.

Introduction: conclusion of the Pre-Conceptual Phase

- The Pre-Conceptual Phase (2014-2020) has been concluded successfully with the Gate#1.
- The large study was based on deep analyses of different plant and system configurations. Comprehensive approach that allowed to detect important interaction among plasma, maintenance, safety, materials and DEMO subsystems (e.g. Breeding Blanket).
- For the Breeding Blanket it was a unique occasion to revise blanket concepts and to prove them in a plant configuration (and variants) able to satisfy a set of key DEMO requirements (e.g. tritium self- sufficiency, electricity production in net, a moderate level of component lifetime).
- FP8 Achievements are well described in:
  - **Special Issue on European Programme towards DEMO: Outcome of the Pre-Conceptual Design Phase,** Edited by Gianfranco Federici, Francesco Maviglia, John Holden, Fusion Engineering and Design, 18 February 2022
  - that includes: L.V. Boccaccini et al., **Status of maturation of critical technologies and systems design: Breeding blanket,** Volume 179, June 2022, 113116

Introduction: the start of the Conceptual Phase (1/2)

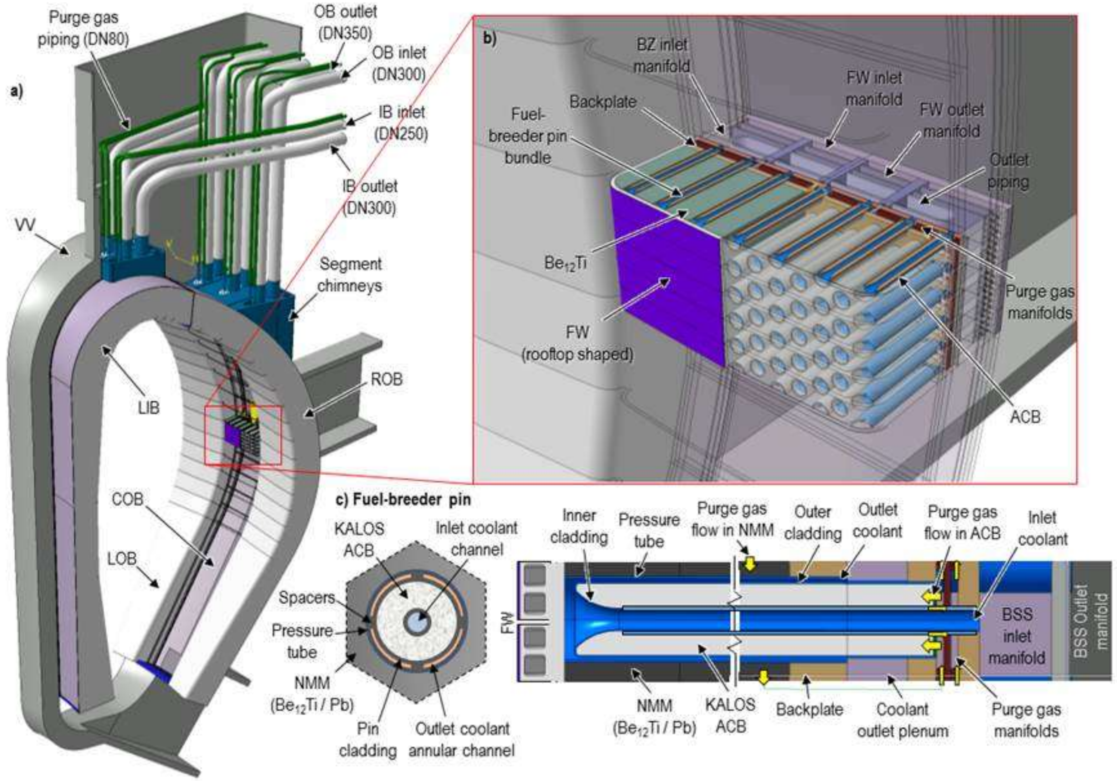
- With the start of FP9 (2021), the EUROfusion programme entered in the Conceptual Phase. This phase is planned into 2 stages:
  - 2021 to 2024: selection of the reference machine (architecture, systems and technologies) to be presented for Gate#2
  - 2025 to 2027: validation of the selected system for the transition to the Engineering phase for Gate#3
- For the Breeding Blanket this means for G2 a selection of a unique blanket concept (that implies the selection and performances of the DEMO coolant systems, the main characteristics and performances of T production, safety features, reactor lifetime).
- For G3 a further deep validation of systems to confirm the selection and complete the data necessary to start an Engineering Phase.
- Details are included in the already cited publication.

Introduction: the start of the Conceptual Phase (2/2)

- The development strategy of the blanket is based on the following aspects (already fixed in the middle of the Pre-Conceptual Phase):
  - The development of a design that follow strictly a baseline maintained at plant level. This allows a comprehensive evaluation of technologies, design solutions and integration aspects;
  - BB variants are considered for a definitive selection. During FP8 the variants have been restricted to two concepts; the HCPB and the WCLL.
  - In parallel the ITER TBM programme will proceed on the same technological choice, providing data to the DEMO programme to complete the validation with relevant fusion information.
- The work on these two reference designs allows to conduct a large R&D that includes almost all the aspects of interest defined in the last years: the cooling technology (water and helium), the breeder materials (solid and liquid breeders). Manufacturing technologies have been also addressed for the TBM and DEMO.
- The defined R&D programme will be continued also after the selection in G2 to keep alternatives that can be adopted in the continuation of the fusion programme as test in the DEMO itself and in prospective for a first kind of commercial reactor where the focus will be moved to the economical exploitation of the fusion.

The HCPB Design (present baseline variant)

HCPB Reference design (Status 2019)



Helium Cooled Pebble Bed Concept

Structural Material: EUROFER (RAFM steel), ~3000 t

Breeder: KALOS (Li_4SiO_4 + 35 mol% Li_2TiO_3) in form of a pebble bed, ^{6}Li at 60%, ~165 t

Neutron multiplier: Beryllide ($TiBe_{12}$) hexagonal rods, 612 t.

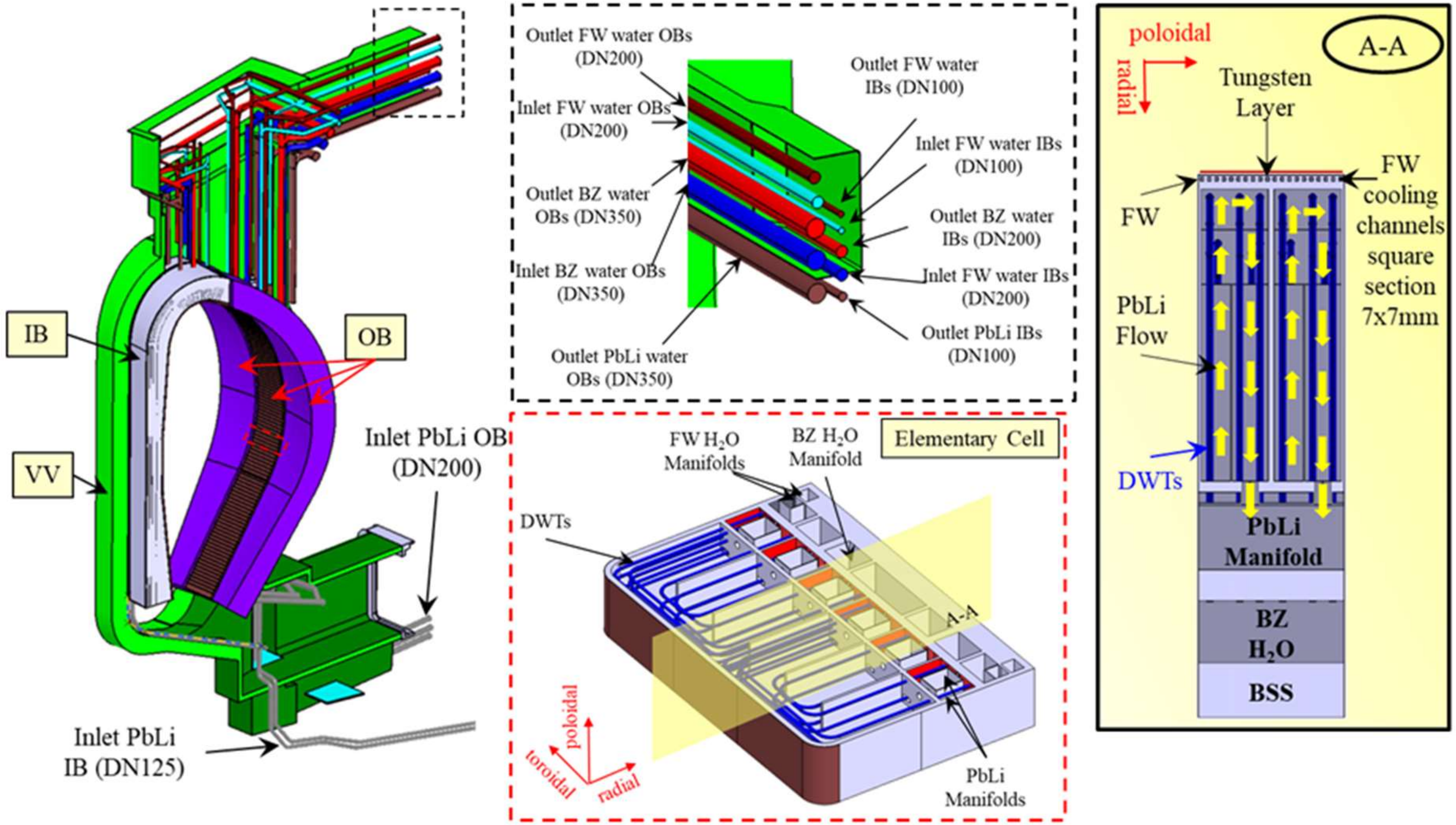
Coolant: helium 300-520°C @ 8 Mpa, 4.2 t

Plasma protection: W layer (2 mm)

T extration with purge Helium: 0.1% H2 @ ~0.2 Mpa: 137 m^3

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.

The WCLL Design (present baseline variant)



Water Cooled Lead Lithium Concept

Structural Material: EUROFER (RAFM steel), ~3500 t

Breeder/neutron multipler: PbLi (^{6}Li at 90%) liquid, ~10,000 t

Coolant: Water (295-338°C @ 15.5 MPa), ~520 t

Plasma protection: W layer (2 mm)

T extraction from recirculating PbLi

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

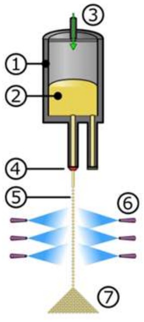
Milestones of the Conceptual Phase for the BB

- **G2: selection of the „driver“ Breeding blanket concept.**
  - Final architecture definition
  - Selection of the T extraction system
  - Selection of T confinement provisions (e.g. coating at the interface PbLi/EUROFER, control of steel oxidation layers in Helium cooled blankets)
  - Selection of T carrier (PbLi or purge helium) purification technologies.
  - Definition of the chemistry control of the coolant
  - Material compatibility demonstration in operation and accidental conditions (e.g. steam-PbLi or steam-Be reactions)
  - Characterisation and definition of production routes for breeder materials (Ceramic, PbLi, Be/Be-alloys)
  - First assessment of breeding blanket manufacturing technologies (pioneer role of TBM).

- **G3: validation of the selected „driver“ and „test“ Breeding blanket concepts.**
  - Prototypical testing of blanket and Tritium extraction systems
  - Availability of modelling tools for PbLi, helium, water and ceramic pebble beds.
  - Pre-selection of BB manufacturing technologies to prepare the Engineering Phase

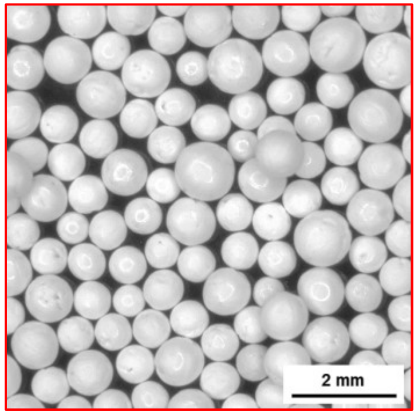
Status of the Present Technologies: solid breeder

(1) Platinum alloy crucible
(2) Melting of pre-reacted synthesis powders at ~1400 °C to form a melt of Li_4SiO_4 and Li_2TiO_3
(3) Application of pressure to the process crucible (~300 mbar)



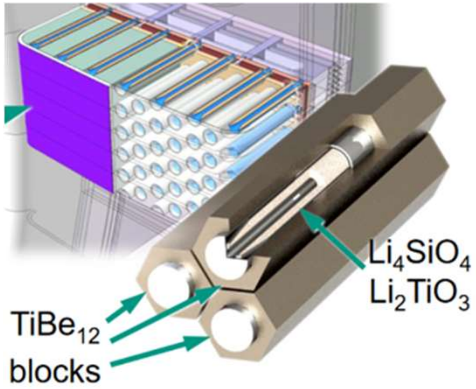
KALOS process schematic

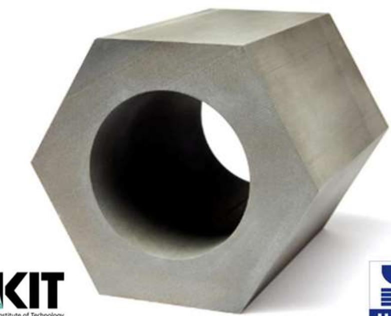
(4) Jet formation through a nozzle (typically Ø = 300 µm)
(5) Break-up of jet into droplets
(6) Solidification with liquid nitrogen spray system
(7) Collection of pebbles



R. Knitter and al, Fabrication of modified lithium orthosilicate pebbles by addition of titania, Journal of Nuclear Materials, 442 (2013), S433–S436

- Solid Breeder: KALOS ceramic pebbles and Beryllide Hexagonal blocks
  - KALOS pebbles well characterised out-of-pile, but necessitates further data confirmation in-pile (T residence time, stability under irradiation, etc.). Production only at laboratory level at a TBM scale (100s kg) to be extended to DEMO (100s t).
  - Beryllide hexagonal blocks are a new technology, but already successfully produced at full scale and preliminary tested in ULBA. Missing irradiation data.



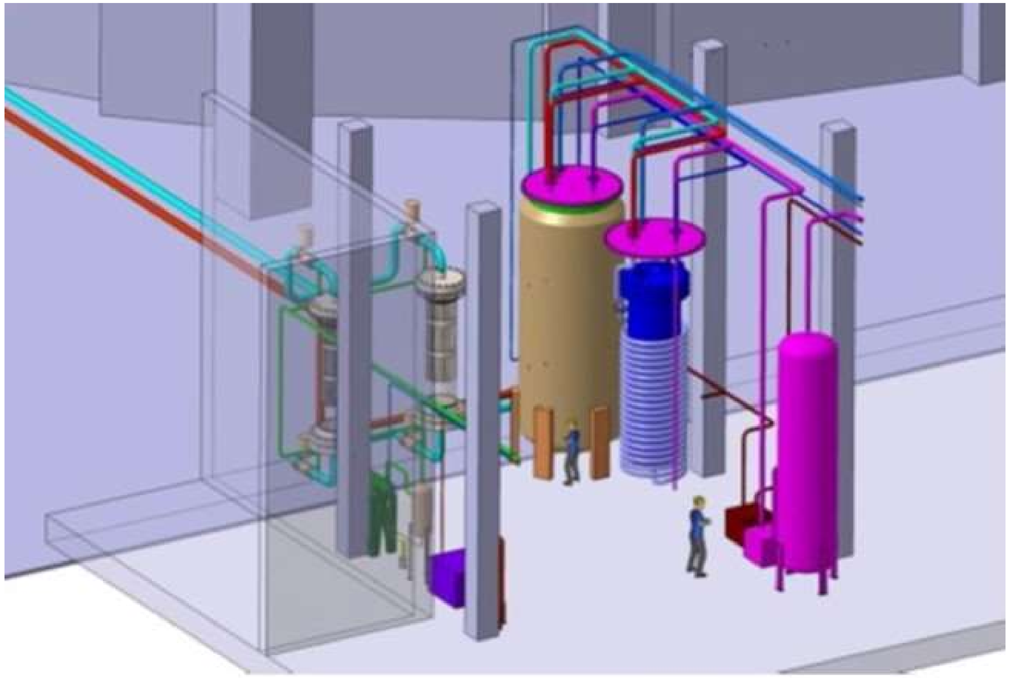


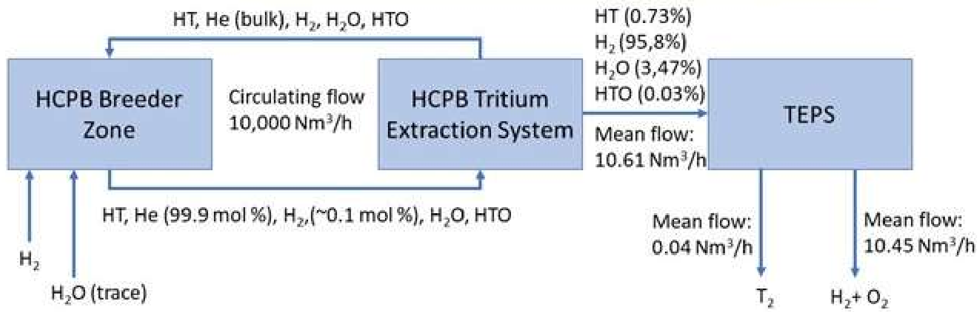
https://www.youtube.com/watch?v=a1pM03VvrOA

P. Vladimirov and al.: Development and characterization of advanced neutron multiplier materials. Journal of Nuclear Materials 543 (2021) 152593. https://doi.org/10.1016/j.jnucmat.2020.152593.

Status of the Present Technologies: T extraction from solid breeder

- Tritium Extraction from Solid Breeder:
  - From Q_2O the reference is Reactive Molecular Sieve Bed (RMSB).
  - From Q_2 the reference is Cryogenic Molecular Sieve Bed (CMSB); alternative: Non-Evaporable Getter (NEG) at room temperature.
- At the present the research is focused on the validation of NEG (instead of the CMSB) to reduce energy consumption and allow high pressure systems.





Status of the Present Technologies: PbLi as breeder

- The PbLi is used at the eutectic composition to minimize the melting point (~235°C); the composition presents scattering data between 15.8 and 17% at Li.
- Uncertainties also in some key properties; e.g. H(T) solubility.
- The scaling-up of the PbLi production is fundamental for the realization of the WCLL BB for DEMO, which should need about 10,400 t of the alloy.

Issue still in related technologies (large R&D ongoing):

- T extraction from PbLi
- PbLi/steam reaction
- Corrosion (necessity of protection coating at the interface PbLi-Steel)
- PbLi purification (from He, Po, solid activation and corrosion products)
- MHD issues (e.g. pressure drops)

Concurrent systems under selection for the T extraction

PAV (permeation against vacuum): Necessitate large permeation surface, high T diffusivity in membrane materials (e.g. V, Nb)

GLC (Gas Liquid Contactor) helium bubble flow in counter-current respect to the PbLi flow. T concentrates in the gas bubbles.

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..

Status of the Present Technologies: Coolant

WATER In other WPs of PPPT Department (see Topic 1): **HELIUM**

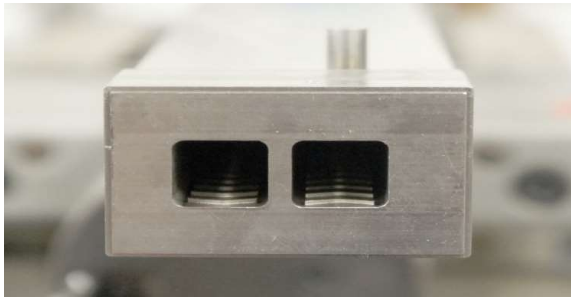
Water:
- Plan Design and components
- T purification

Helium:
- Plan Design and components
- T purification

Specific in the WPBB Programme:

- **Water chemistry:** this topic is intensively studied to understand the major differences from standard fission (e.g. EUROFER in Blanket together with SS steel in the PHTS, 14-MeV-neutronic spectrum, higher radiolysis level, strong magnetic fields, and T presence in the cooling water).

- **High Heat Flux Systems:** under development a helium cooled first wall up to 1 MW/m^2 using turbulence enhancement technology.



Present pool of facilities available in WPBB

- MHD validation: MEKKA and **MAPLE** in KIT.
- T extraction from PbLi: TRIEX-II in ENEA, CLIPPER in CIEMAT
- PbLi Purification: MELILOO and COSA (IPP.CR)
- Water Heat Transport Coefficients: HADES (CEA)
- Safety experiments in PbLi (e.g. steam-PbLi reaction): **LIFUS5/Mod4** (ENEA)
- Ceramic production: KALOS facility (KIT)
- T transport coefficient measurements: Hyperquark (ENEA), COOPER, Absorption-Desorption facility, Thermoperm and PermRIG (CIEMAT)
- **TLK** in KIT as infrastructure for T experiments.
- Several PbLi loops for corrosion testing: CiCLO (CIEMAT), IELLO (ENEA), PICOLO (KIT).
- Facilities for component testing: DIADEMO (CEA), HEFUS-3 (ENEA), **HELOKA-HP** (KIT)

MAPLE: large magnet with hydraulic mechanism.

New Facilities to be built or updated in FP9

The common feature of these facilities is to start the exploration of integral effects and complex systems behaviour.

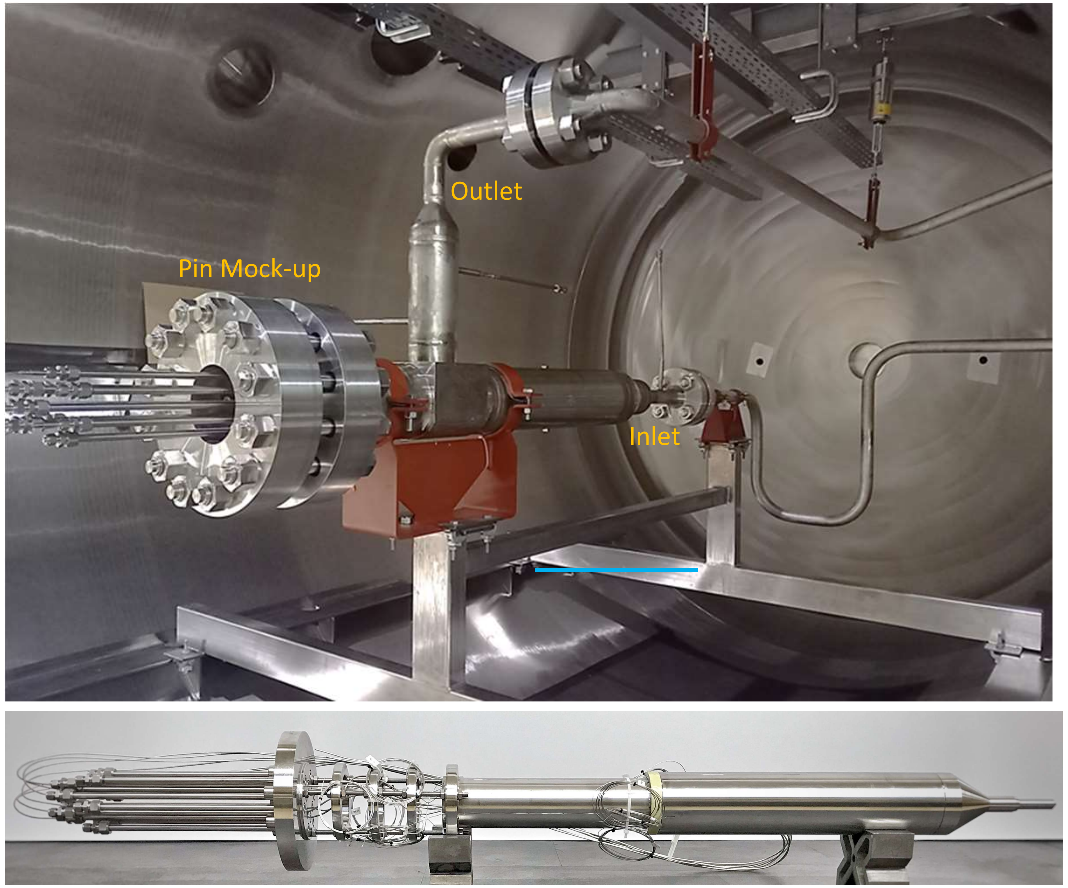
- **HELOKA HUB** (in operation since 2016): 3 different helium loops at high (5-9 MPa) and low (0.1-0.6 MPa) pressure and temperature range (20-650°C).
- **Water Loop in ENEA** (under design): analogous facility as HELOKA but with water. Testing of component at TBM full scale, water loop relevant for the TBM Cooling System, electron beam for surface heating.
- **PbLi TER facility** (only from 2025): DEMO scaled loop able to qualify all the component necessary for the DEMO TER Loop (T extraction from PbLi, purification systems, tanks, pumps, valves, etc.).
- **He Purge TER facility** (only from 2025): DEMO scaled loop able to qualify all the component necessary for the DEMO TER Loop (RMSBT, CMSB/NEG, circulators, valves, filters, etc.).
- **KALOS upgraded** (in construction): implementing a continuous production process for ceramic pebbles and increasing the production to cover TBM needs.
- UKAEA Contribution (in construction): **CHIMERA** (water/PbLi loop with electromagnetic fields and laser heating) and **H3AT** (offering capacity for T experimental campaigns).

HELOKA (Helium Loop Karlsruhe) Technology Hub

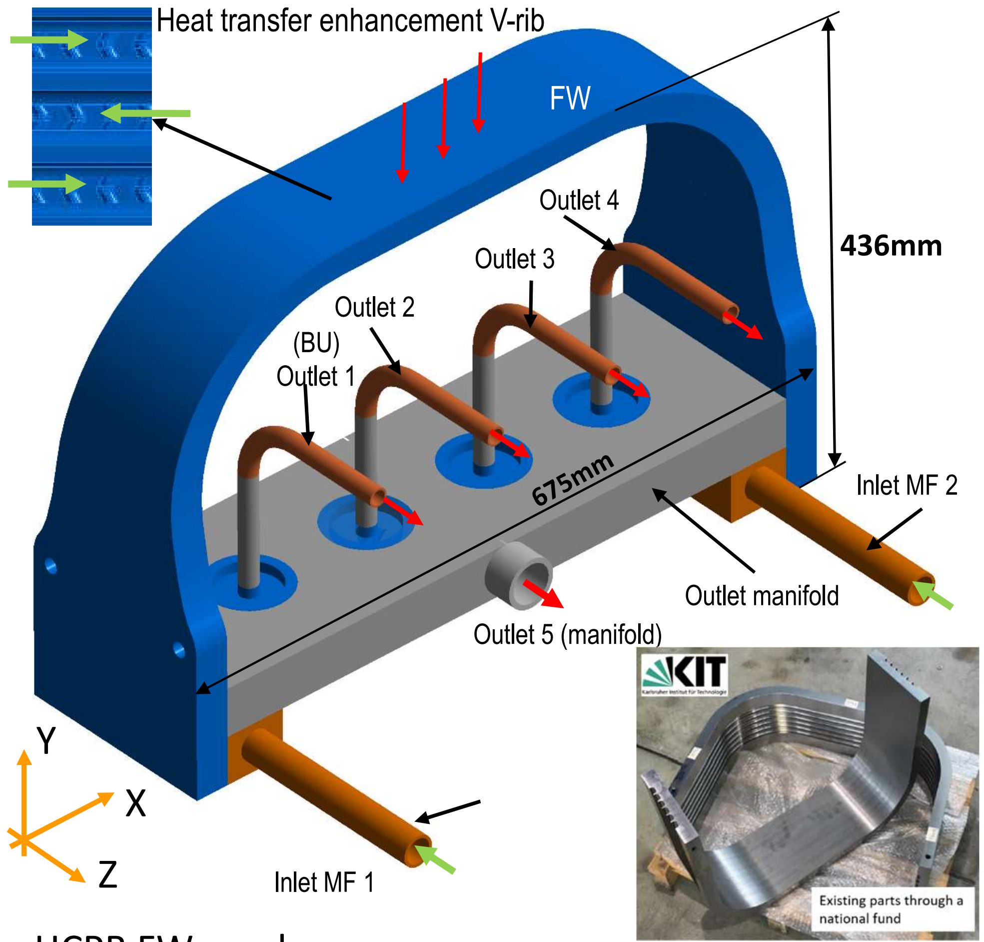
- Three helium-cooled loops:
  - **HELOKA-HP**: 4-9.2MPa, 70-550°C, 1.3kg/s (HCPB-TBM)
  - **KATHELO**: 4-10MPa, 70-650°C, 250g/s
  - **HEMAT**: 0.1-0.6MPa, 20-650°C, 5-20 g/s
- High-heat flux testing rig: **HELOKA-HHF**
  - EB-gun 800kW
  - 24.4m³ vacuum chamber (3m diameter)
  - Capable of testing mock-ups connected to either HELOKA-HP or KATHELO
  - Low pressure, low temperature water cooling capabilities also available

B-U. Ghidersa et al., Thermal-hydraulic experiments in support of the Helium Cooled Pebble Bed Blanket design within the EU-DEMO project, oral planned for the SOFT 31 (Dubrovnik, 21st September, 2022)

HELOKA: next experiments



HCPB Breeder Zone (pin) mock-up



HCPB FW mock-up

Conclusions

- The EU DEMO Programme concluded its Pre-Conceptual Phase in 2020 (in FP8) with the Gate#1.
- The Conceptual Phase started in 2021 with the goal to define a DEMO architecture and to select technologies to realise it. For the WPBB the milestones are the selection of a suitable breeding blanket system (G2-2024) and validate its conceptual design to start the Engineering Phase (G3-2027).
- A complex R&D programme has been defined to reach these milestones. This involves (among others) the final selection of the BB architecture, Tritium extraction technologies, PbLi and purge gas purification systems, water chemistry, T confinement provisions, etc.
- A new generation of facilities for integral tests has been defined to support the TBM and DEMO programme.