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Advancements in the Helium Cooled Pebble Bed Breeding Blanket for the EU DEMO: Holistic Design Approach and Lessons Learned

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Abstract*—The Helium Cooled Pebble Bed (HCPB) blanket is one of the two concepts proposed as a driver blanket for the EU-DEMO. In contrast to past conceptual design studies, in the frame of the current EUROfusion Power Plant Physics and Technology, the ongoing EU-DEMO pre-Conceptual Design activities have adopted a holistic and integrated (i.e. Systems Engineering) design approach. As a consequence of this new approach, many interfaces and requirements have been identified, some of them driving the design of the blankets. This paper shows the advancements in the HCPB breeding blanket and describes the lessons learned after implementing the new approach. This new set of requirements has led to reconsider fundamental aspects of the HCPB blanket design, especially in the way how the heat is extracted from the blanket. Among others, the requirement to achieve a mature Balance of Plant (BoP) system plays a central role as a key design driver and has forced us to reduce pressure drops in the breeding blanket. In this regard, the blanket has been redesigned, leading to an enhanced concept based on single module segments with a hexagonal matrix of fuel-breeder pins. Both the fuel-breeder pins and the First Wall (FW) are equipped with turbulence promoters (augmented wall roughness in the fuel-breeder pins and V-ribs in the FW), following a similar idea as in the past MAGNOX, Advanced Gas Reactor (AGR) and Gas Cooled Reactor (GCR) programs in fission. This has led us to minimize the pressure drops while maximizing the heat transfer. Also, the blanket outlet temperature has been extended to 520 °C, following the same principle as in Gen IV's GCRs of maximizing the temperature difference across the core to minimize the reactor mass flow rate and thus the circulating power. All these features have led to a remarkably low plant circulating power (80-90 MW) and the required power per helium blower (5-6 MW), which potentially solves the long, key standing problem of the BoP technology readiness level for a ≈2.4 GW$_{th}$ helium-cooled DEMO reactor.

***Index Terms*—HCPB, fuel-breeder pin, tritium breeding, TBR**

I. Introduction: Holistic Design Approach

CONTRARILY to former fusion power plant studies, the current EU DEMO pre-Conceptual Design Phase is strongly focused on a Systems Engineering approach [1][2]. Following this new approach, the different systems in DEMO, and in particular one of the candidates as breeding blanket for DEMO, the Helium Cooled Pebble Bed (HCPB) breeding blanket, are developed in a holistic and integrated way.

After the application of this approach, more than 40 systems have been identified at a level 1 of the Plant Breakdown Structure (PBS), which has also revealed a large amount of systems interfaces [3]. For the case of the breeding blanket (Fig. 1), more than 10 interfacing systems can be identified.

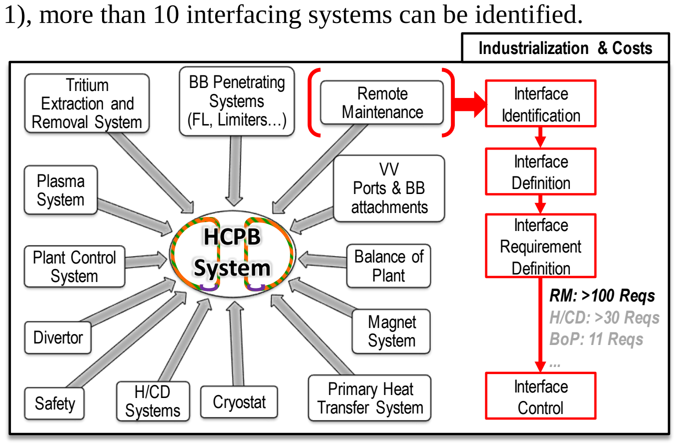

Fig. 1 Block diagram of the HCPB breeding blanket, interfacing systems and interface management.

For each pair of interfacing systems interfaces are identified, the associated requirements are defined and the interfaces are at that point controlled through a rigorous interface management process. As examples, more than 100 requirements have been identified with the Remote Maintenance (RM) system, more than 30 for the Heating and Current Drive (H/CD) system, 11 for the Balance of Plant (BoP), etc. where some of them have sufficient importance for the plant to even drive the design of the breeding blanket.

On top of this, work and interactions conducted by the Power Plant Physics and Technology (PPPT) Department of the EUROfusion Consortium with industry and with Gen IV

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projects have prompted us to start prioritizing solutions that are able to demonstrate their industrialization and cost-effectiveness [1]. As a consequence of this new holistic and integral approach to the design of DEMO, several key lessons learned can be derived for the design of the breeding blanket.

II. Lessons Learned

Many important lessons have been learned after the application of the Systems Engineering design approach to the breeding blanket. These have been grouped in four categories and are described in the following.

A. On plant integration

Currently, the EU DEMO studies aim at designing a “low extrapolation” system [1], meaning that DEMO should be based on mature technologies, whenever that is possible. The BoP system is of course directly affected and it has turned out to be a major (if not the main) design driver for any gas-cooled blanket for DEMO. This originates mainly from the fact that the state-of-the-art on gas cooled circulator technology (He or CO_2) is currently proven up to ~6 MW/unit [4]. This leaves a narrow margin for the total plant (electric) circulating power and therefore to the maximum plant pressure drop (Δp) without incurring a large number of circulators, which would penalize the plant reliability, footprint, coolant inventory and costs or which would assume additional R&D for the He circulator technology in order to develop larger units. Therefore, a blanket design which minimizes pressure drops is of paramount importance.

Despite its advantage as an investment protection feature, the redundant cooling scheme of past designs (e.g. redundancy with counter-current flowing channels in cooling plates (CPs) [5]) has turned out not to be practical for BoP [6]. Also, the increasing knowledge in the systems integration has revealed that there will probably be a larger number of systems penetrating the blanket, especially due to the need to protect the First Wall (FW) by means of limiters placed at different poloidal positions at the inboard (IB) and outboard (OB) segments of the blanket [7]. This calls for a modularization of the breeder zone (BZ) of the blanket, in order to be able to “remove” parts of the BZ without being forced to completely redesign locally the internals of the affected segments.

B. On efficient thermo-hydraulics

The plant circulating power scales nearly linearly with the plant mass flow rate and the plant Δp. Due to the strict limitation on the plant circulating power as mentioned in II-A, any gas-cooled blanket shall pursue the lowest system pressure drop as reasonably achievable. Equally important, the total plant circulating power shall be kept at a minimum by defining the largest “core” (blanket) temperature difference between the inlet and outlet, as long as this do not result in unacceptable stresses for the structural materials. This calls for a very efficient thermal management of the blanket.

A retrospective to the fission industry reveals that the same issues were present in the Gas Cooled Reactor (GCR) program. An artificial roughening was found to be required to augment the heat transfer coefficient (HTC) and thus to maintain an acceptable temperature of the cladding [8].

In the recent years this past experience has been revisited and applied for the FW [9] with very positive results (i.e. efficient thermal management of the FW for heat fluxes as high as ~1 MW/m² with $\Delta p < 1$ bar). Despite its application in the FW, the Δp in the BZ for former HCPB configurations based on CPs is ~1 bar (e.g. [5]), which is still excessive. As an example, for a reactor thermal power of 2.1 GW_{th}, a blanket $\Delta T = 200$ °C and an inlet pressure of 80 bar, the He mass flow ($\dot{m}$) is 2.3 ton/s. Assuming a typical total Δp in the reactor of $\Delta p_{FW} + \Delta p_{BZ} + \Delta p_{BSS} + \Delta p_{PHTS} = 4$ bar (with Δp in the Primary Heat Transfer System (Δp_{PHTS}) ~1.5 bar and Δp in the Back Supporting Structure manifold (Δp_{BSS}) ~0.5 bar [5]), then the plant circulating power ~140 MW_{el} (considering an electrical efficiency of 90%). Even considering 10 cooling loops with 2 circulators per loop (e.g. one of the largest Advanced Gas Reactors (AGR) is Hartepool (UK) and has 8 loops with 1 circulator per loop), the power per circulator would be still beyond the state-of-the-art for these components. For a reasonable number of 8 loops and 2 circulators per loop, the maximum allowable plant circulating power would be ~100 MW_{el}, which would represent a maximum allowable Δp of ~3 bar for the same reactor configuration of this example.

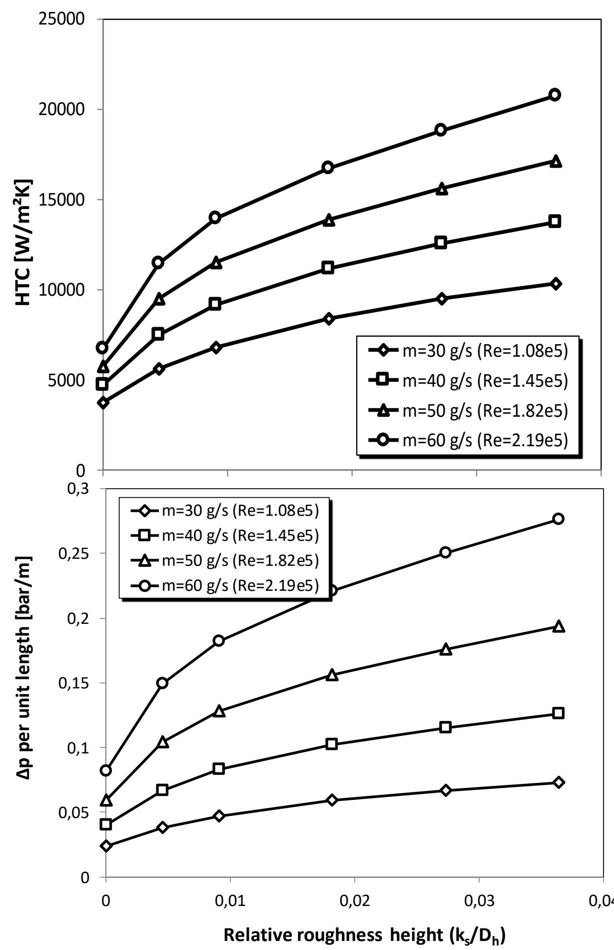

Fig. 2 Thermo-hydraulic characteristics of a generic He-cooled channel with an homogeneous heat flux of 0.5 MW/m². Heat transfer coefficient (top) and

pressure drop per unit length (bottom) as function of the relative roughness of the channel for different mass flows.

Fig. 2 summarizes the strategy followed in the GCR program with the case of a simple pipe uniformly heated with 0.5 MW/m². In the case that smooth channels are used, the HTC augmentation with increasing $\dot{m}$ is modest (Fig. 2 top). Just by increasing the surface roughness of the pipe to a relative roughness height (k_s/D_h, with k_s being the equivalent sand roughness and D_h the hydraulic diameter) of ~0.01, the HTC with $\dot{m}$ = 30 g/s would be the same as with $\dot{m}$ = 60 g/s in a smooth channel. However, while the smooth pipe with $\dot{m}$ = 60 g/s would have a Δp ~0.4 bar/m, the Δp would be about the half for the pipe of k_s/D_h≈0.01 and $\dot{m}$ = 30 g/s (Fig. 2 bottom). On the other side, a pipe with k_s/D_h≈0.036 and $\dot{m}$ = 30 g/s would have the same Δp as a smooth pipe with twice $\dot{m}$ but about twice HTC. The lesson learned here is that where a high HTC is required, the turbulence should be maximized/promoted and the flow speed minimized.

C. On design simplification, industrialization and costs

Due to the large size of DEMO, the volume of the breeding blanket is correspondingly large and therefore the number of subcomponents, channels, welds, etc. quickly escalates if care is not taken in the design. This resulted to be especially true for the former DEMO HCPB design based on the ITER HCPB TBM and which is of especial concern for the reliability and availability (RAMI) of the reactor, which has been already identified as one of the most severe challenges of Fusion Technologies [10]. Also, the resulting masses for breeder ceramics and beryllium multipliers, which are of the order of magnitude of 100 ton call for fabrication strategies that can be scaled-up for the amounts required for DEMO. This results to be especially problematic for the reference fabrication technology of the Be pebbles in the ITER TBM, which are based on Rotating Electrode Method (REM) and which results to be challenging to scale-up for DEMO [13].

D. On safety

The resulting large volume of the breeding blanket in the current DEMO baseline calls for a minimization of the amount of pipes in the PHTS. In former configurations of the HCPB, cooling pipes were foreseen at the upper and lower port in order to optimize the coolant distribution in the modules. This led to an unacceptable long piping [14], which also increases the coolant inventory, negatively affecting the size of the Vacuum Vessel Pressure Suppression System (VVPSS). In order to mitigate this, the piping was afterwards routed through the upper port. Also, the splitting of the segments should be avoided, as this results in a multiplication of the piping.

On the other side, it has been recognized [11] that pure Be retains ~40% of the total tritium produced in that material at ~600 °C, which would result in an inventory of tritium of a few kg after 20 dpa, representing a key safety concern. The use of Be also represents a risk potential in the case of an accidental scenario considering water ingress, e.g. from failed divertors and/or limiters into a failed blanket exposing Be material. These problems are intrinsic of Be and it has been learned that can be only mitigated by switching to beryllides (~0% retention at ~600 °C, much lower reactivity issues) or using a different multiplier like (molten) Pb [12][15].

III. Enhanced Design Solution: HCPB Fuel-Breeder Pin Concept

The lessons learned showed in the last Section II has triggered a research for a design to enhance the HCPB and face the aforementioned challenges.

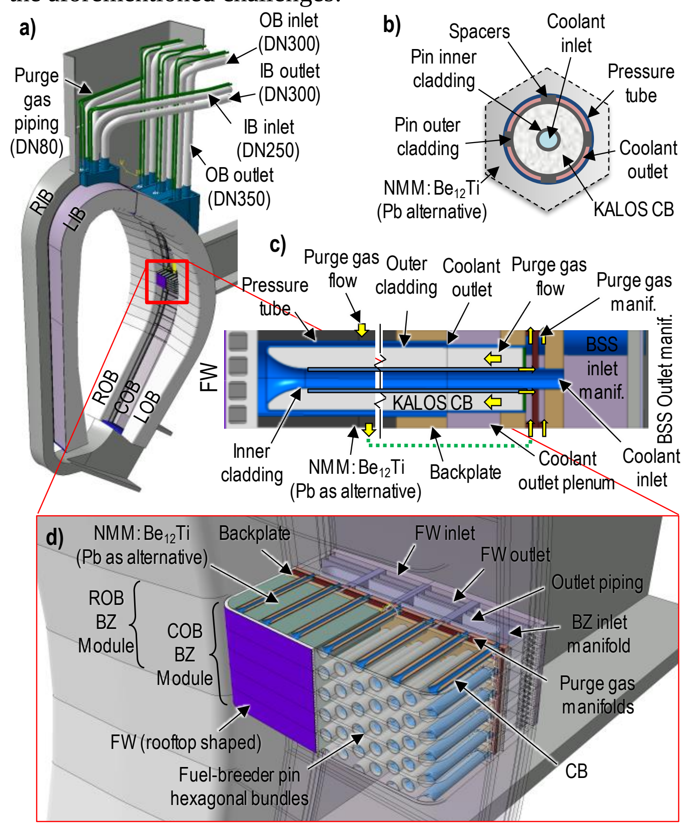

Fig. 3 Enhanced HCPB with fuel-breeder pins: (a) one sector showing the right IB (RIB) and left IB (LIB) segments and the right, center and left OB (ROB, COB and LOB respectively); (b) transversal cross-section view of a fuel-breeder pin; (c) longitudinal cross-section view of a fuel-breeder pin; (d) isometric cut-out view of a COB fuel-breeder pin assembly. CB=Ceramic Breeder, NMM=Neutron Multiplier Material, BSS=Back Supporting Structure.

First, the coolant redundancy has been eliminated due to its unfeasibility in the current DEMO layout and in this way there is no need for counter-current channels in a CP. This opened the path for simpler BZ configurations. Looking for commonalities in fission, the simplest configuration found has been the use of a hexagonal matrix of "fuel-breeder pins" (Fig. 3). Here, the FW and backplate (Fig. 3-c) are connected by a pressure tube of an internal diameter ($Ø_i$) of $Ø_i$75 mm and 4 mm wall thickness. The pressure tubes are key structural elements, as they act as beams against an internal pressurization of the breeding blanket after an in-box Loss of Coolant Accident (LOCA). The fuel-breeder pins consist of an inner and outer cladding formed by 2 concentric tubes of $Ø_i$16 mm and $Ø_i$60 mm with wall thicknesses of 6 mm and 2 mm respectively. The volume created by the cladding is filled by an advanced ceramic breeder (KALOS [13]) pebble bed, which is a mixture of Li_4SiO_4 and Li_2TiO_3. The volume is closed by a filter plate, which allows the purge gas (He+0.1wt.% H_2 as reference) to flow inside the pins. The large thickness of the inner cladding is used to machine longitudinal grooves of 4 mm depth, 5 mm width and closed by a ~1 mm plate (microperforated at the front region of the pin close to the FW). The resulting ducts of 3x5 mm in the inner cladding (Fig. 3-c) are used as return paths of the purge gas towards the purge gas manifolds (Fig. 3-d).

The volume surrounding the pressure tubes is filled with the neutron multiplier (Fig. 3-b), which is $Be_{12}Ti$ as reference and molten Pb as back-up solution. As the content of Be per unit volume is lower in beryllides with respect to pure Be, it is expected that the Tritium Breeding Ratio (TBR) is lower for $Be_{12}Ti$ than for pure Be when the same thickness of multiplier is considered. Fig. 4 shows a plot of a normalized Tritium Breeding Ratio (TBR/TBR_0) vs. the maximum $Be/Be_{12}Ti$ thickness between fuel-breeder pins, defining TBR_0 as the TBR of Be with a thickness of 50 mm. This thickness has been chosen as reference for the normalization, as it is the maximum achievable for Be before reaching the design temperature limit of this material (~650 °C [16]) at the equatorial OB region, which is mainly driven by the excessive swelling in Be at higher temperatures. For the same thickness, the TBR with $Be_{12}Ti$ drops about 7% with respect Be. However, the TBR with beryllides can be compensated by increasing the multiplier thickness as shown in Fig. 4, as $Be_{12}Ti$ experiences much lower swelling than Be and therefore does not show a temperature limitation like Be [17]. As a matter of fact, the operation of beryllides could be extended to ~1000 °C and virtually beyond, being the main limitation probably the oxidation rate at such temperatures.

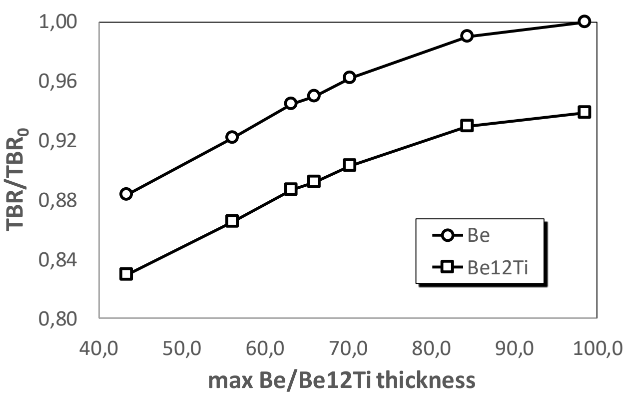

Fig. 4 Parametric analysis of TBR vs pin pitch for a HCPB based on a fuel-breeder pin with Be and $Be_{12}Ti$ as neutron multiplier.

Having Be in form of a pebble bed as the breeder ceramics was long recognized to be a possible solution for the acute problem of swelling in Be when used in form of blocks, especially if they are to be brazed to the surrounding cooling structures [18]. However, the very low swelling of beryllides means that a pebble bed may not be required. Also, the greatly enhanced tritium release in beryllides supports the idea of using beryllides in a slab or block form. Moreover, the large amount of multiplier needed for breeding blanket (~400 tons) requires production technologies for the neutron multiplier that can be easily and cost-effectively scaled-up to such amounts required for DEMO. This has been proven to be very challenging when the multiplier is in form of a pebble bed [13]. By using the multiplier in form of blocks, the last production step of producing pebble material would be removed, resulting in a significant advantage in production costs and scalability.

The use of Be or Be compounds in form of prismatic blocks is similar to the fission industry, as such configuration can be found in different test reactors around the world (Fig. 5). In particular, the MIR reactor (Russian Federation) use hexagonal Be prismatic blocks as moderators (Fig. 5-bottom left) in which the fuel elements are inserted, which is a similar configuration as the one that can be proposed for the HCPB fuel-breeder pin design. Although there has been no fission reactor using $Be_{12}Ti$ as moderator, some industries have experience producing such material. In particular, Ulba Metalurgical Plant (UMP, Kazakhstan) has produced $Be_{12}Ti$ ingots (Fig. 5-bottom right) under a project with JAEA, Mitsubishi Heavy Ind. and NGK as a previous step for pebbles production using REM. There is therefore an opportunity to set an industrial production in the near term.

Fig. 5 Examples of industrial production of prismatic blocks of Be/Be compound. Top, left to right: BeO blocks in the Aircraft Reactor Experiment (ARE) in US, Be reflector block for the Advanced Test Reactor (ATR) in US and Be moderator block matrix of the Belgian Reactor 2 (BR2) in Belgium. Bottom: Be moderator block of the Multi-loop Reactor (MIR) in Russia (left) and $Be_{12}Ti$ ingots (right) produced by UMP.

In fission reactors with prismatic blocks and fuel elements inserted in them, the coolant usually flows between the fuel elements and the blocks. At the neutron energies and fluencies of DEMO, the amount of tritium produced in the Be/Be compound multiplier is not negligible (<1% of total tritium production). Therefore, a fission-like configuration where the He would be in contact with the beryllide is not desirable, in order to avoid releasing the tritium produced in the beryllide directly to the coolant. Therefore, if a configuration with prismatic blocks is pursued for the multiplier, the heat transfer between the beryllide and the closest pressure tube will mainly happen through conduction through a medium. Three options for the interface between the pressure tube and the beryllide blocks can be envisaged: (1) brazed connection, (2) interfacial pebble bed and (3) gas gap. Although option (1) offers the best heat transfer, the possible differential thermal expansion and swelling rates between beryllide and pressure tube pose serious questions about its feasibility. Option (2) would require a pebble bed from a material which has a low neutron capture (graphite, SiC) or directly a ceramic breeder. This option raises questions about material compatibility and/or temperature control of the blocks during the lifetime of the blanket and assembly complexity. Option (3) would rely on the purge gas (mainly He) as heat transfer medium. This option is similar to the fuel elements in fission reactors, as there is a gas gap of <1 mm between the cladding and the ceramic fuel pellets. Due to the poor thermal conductivity of the gas, the gas gap will increase the temperature of the beryllide beyond that of the pressure tube. This is also desirable feature, as this interfacial temperature jump will raise the temperature of the beryllide to a level where the tritium is easily released, provided that an adequate gap range is kept during the lifetime of the blanket. The gas gap can also accommodate differences in the thermal expansion and swelling. Due to these advantageous features and the assembly simplicity, option (3) is the one chosen for a prismatic block configuration for the HCPB.

IV. HCPB Performances

A first comprehensive set of neutronics, thermo-hydraulics and thermo-mechanics has been performed and are described in the following.

A. Neutronics

A full heterogeneous half sector of a DEMO baseline 2017 (BL2017) has been modeled in MCNP-1.60 [19]. Two main features of the most recent EU DEMO BL2017 are: (1) the reduction of the OB blanket thickness from 1.3 m to 1.0 m [20] and (2) a rooftop shape FW requirement, which is considered to be essential for ITER [21] and therefore also for DEMO, in order to shadow any leading edge, as it cannot be ensured that the discrete limiters will completely protect the FW from charged particles. A TBR = 1.16 has been reached for a HCPB model using $Be_{12}Ti$ in form of a pebble bed with a packing factor of 63%. An updated analysis using $Be_{12}Ti$ in form of prismatic blocks results in a TBR = 1.20. Both multiplier configurations leave an important margin to accommodate large penetrations for systems integration and/or to allow self-sufficiency in more compact fusion reactors [22].

Regarding the shielding performance of the blanket, the resulting power density in the toroidal field coils fulfills the requirements, though with low margin. Future research will be conducted to improve the blanket shielding keeping the compactness of the blanket, whenever this is possible.

B. FW thermo-hydraulics

The heat flux loading knowledge on the FW has been largely improved during the recent years [23]. The total heat flux (HF_{tot}) on the FW is the sum of incident radiation (HF_{rad}) and charged particle (HF_{part}) heat fluxes.

Fig. 6-top shows a typical steady state heat flux distribution on the FW (left) and a distribution of the HF_{part} on the FW region where the highest peak HF occurs. On top of the HF_{part}, a nearly constant HF_{rad} of ~0.2 MW/m² adds to the HF_{tot} in this region. As stated in Section II, a very efficient power dissipation based on turbulent promoters is envisaged here, in order to keep the structural material temperature under reasonable levels (<550 °C) as well as to minimize the Δp_{FW}. One of the best solutions found for the heat transfer augmentation for a He-cooled FW is the use of V-ribs [9][24].

For the numerical assessment of the thermal management of the FW with V-ribs, complex CFD procedures based on the use of Large Eddy Simulation (LES) and/or Scale Adaptive Simulation (SAS) are needed to correctly capture the flow physics in the rib-roughened FW [25]. Unfortunately, these CFD models are still today computationally costly with respect to standard RANS models and currently cannot be used on a full scale FW model [26].

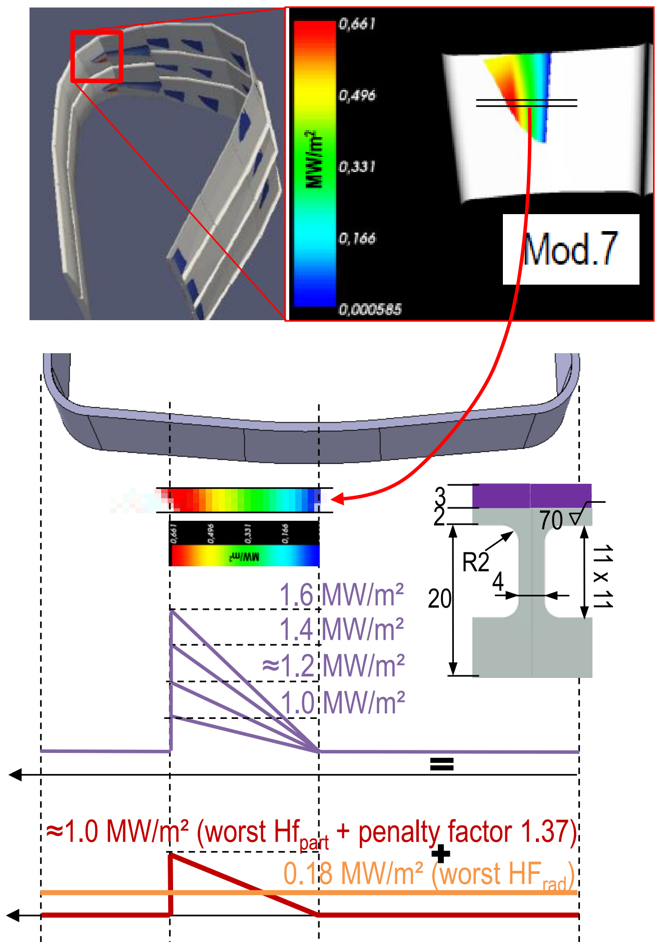

Fig. 6 FW heat flux scoping analyses. Top: detail of the most loaded region of the FW [23]. Bottom: detail of the heat flux boundary conditions for the scoping analyses on a region of the IB FW at the most loaded region.

In order to circumvent this, the thermo-hydraulic performance of a V-rib has been compared with a simpler surface roughened FW. It has been found that a surface roughness of average roughness R_a≈70µm has a similar Nu and friction factor evolution with increasing Reynolds number as a reference V-rib. With this result, a full-scale portion of the IB FW at the region of the maximum peak HF has been modeled (Fig. 6-bottom) and scoping analyses varying the HF_{part} from 0.8 MW/m² to 1.4 MW/m² with a profile as shown in Fig. 6-bottom has been performed, assuming in all cases a constant HF_{rad}=0.18 MW/m². This analysis has revealed, that for the required HF_{tot}=1.0 MW/m² for the OB and HF_{tot}=1.2 MW/m² for the IB (taking into account in both cases a penalty factor of 1.37 for the HF_{part}) can be handled with a channel mass flow of about 30 g/s and 40 g/s respectively, keeping the structural material temperature around the design limit of 550 °C and resulting in $\Delta p_{FW,OB}$≈0.37 bar and $\Delta p_{FW,IB}$≈0.64 bar, respectively. A peak heat flux up to 1.4 MW/m² could be handled with a channel mass flow of about 50 g/s, resulting in a still reasonable Δp_{FW}≈1 bar.

C. *BZ and manifold thermo-hydraulics*

Following the discussion in Section II, rough surfaces are envisaged also in the fuel-breeder pins so as to enhance the heat transfer by keeping a low flow speed. This is especially needed at the annular channel of the pins, as the flow speed drops here considerably (<10 m/s, Re~5000, Fig. 7) and a reasonable HTC can only be achieved by increasing k_s/D_h to ~0.05, as the $\dot{m}$ per pin is fixed due to the fixed (required) coolant temperature window.

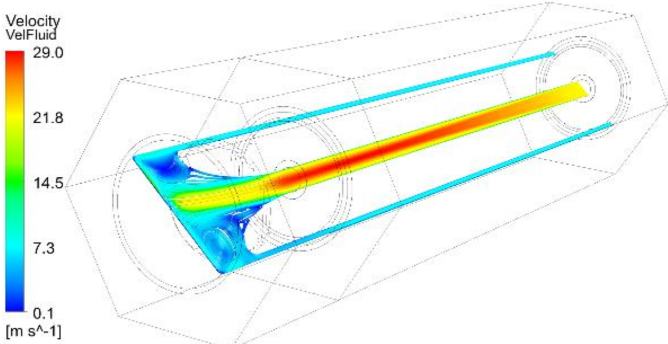

Fig. 7 Cross section velocity magnitude plot of a single fuel-breeder pin.

A detailed CFD steady state analysis of a unit slice considering $Be_{12}Ti$ in pebble bed form has been performed (Fig. 8) and benchmarked with a simplified thermal model using 1D fluid elements [12]. Both results are in good agreement, despite of the use of empirical correlations in order to describe the heat transfer in fully rough regime (Bhatti and Shah correlation [27]) in the fluid lines. The main discrepancy between both models is in the hot spot of the structural steel of the pins close to the FW.

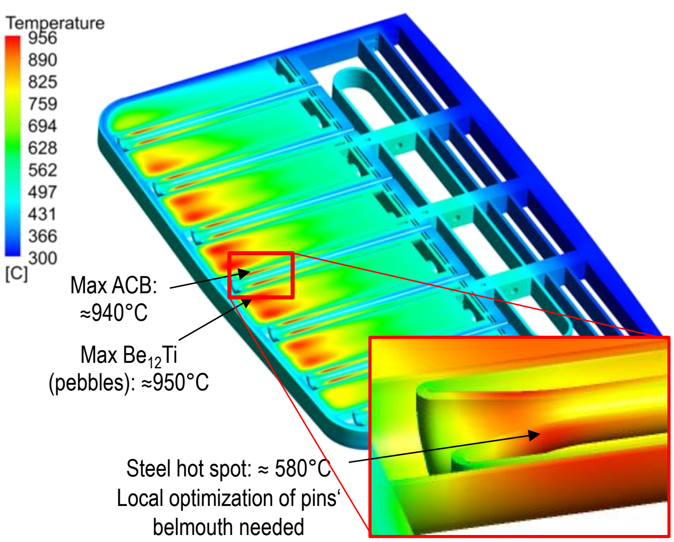

Fig. 8 Detailed CFD conjugate heat transfer thermos-hydraulic analyses of a unit slice of the BZ of the HCPB with fuel-breeder pins at the equatorial OB.

Due to the sudden expansion of the helium in a region where the power density is still high, local hot spots are present in the structural material. This effect has not been taken into account in the simplified thermal model. The design of this region of the pins will be a matter of future optimization. On the other side, the KALOS breeder ceramic has as well a peak temperature about 2% higher than the recommended design limit, nevertheless, in a very localized region which does not jeopardize its operation.

Due to the better thermal dissipation of the pins, the outlet temperature of the blanket could be increased from 500 °C to 520 °C. These additional 20 °C are a key enabler to reduce Δp_{PHTS}, as well as to slightly increase the thermal efficiency.

In the CFD steady state model of the unit slice it has been observed an asymmetry in the flow distribution in some pins, which may produce hot spots in the materials. Fig. 9 shows a cross section plotted by velocity magnitude at an instant and two magnified views. As a matter of fact, the pins which inner cladding is further from the FW (Fig. 9-a) show an unsteady jet pattern, while the others closer to the FW become steady.

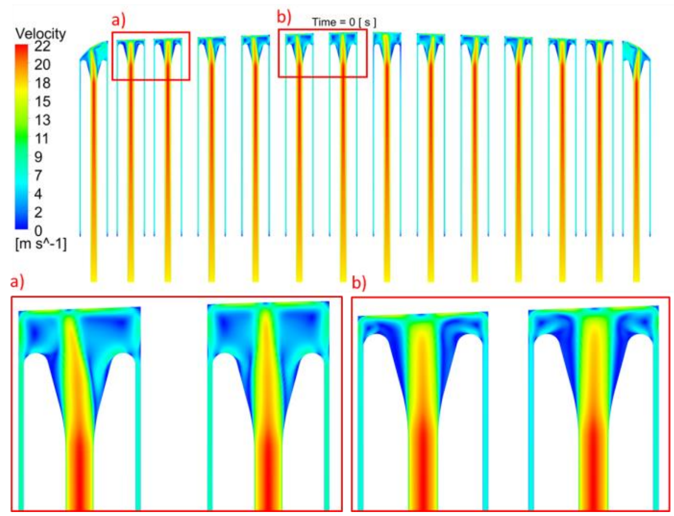

Fig. 9 Snapshot of a CFD transient analysis of a unit slice of the equatorial OB

Future research will be conducted to design two experimental campaigns during the next two years [28]. One experiment will be oriented to validate these CFD results and to better understand the design space where the jet unsteadiness can be reduced or even avoided. A second experiment has as goal to validate the Bhatti and Shah correlations used to describe the heat transfer in the roughened fuel-pins.

Preliminary scoping thermal analyses have been conducted as well for the prismatic $Be_{12}Ti$ blocks. Clearly, the fact of having a block instead of a pebble bed raises a question about the temperature control of such elements inside the BZ during the lifetime of the block, as it accumulates irradiation damage.

Fig. 10 shows a 2D cross section of a fuel-breeder pin and its associated prismatic $Be_{12}Ti$ block. The cross section is at 50 mm behind the FW, which approximately coincides with the temperature maxima of the different materials. The power densities at this location are: KALOS bed ~14 MW/m³, EUROFER97 ~7 MW/m³, $Be_{12}Ti$ block ~6.3 MW/m³. The HTC in the inner and annular channel are ~2000 W/m²K and ~1600 W/m²K respectively, with bulk temperatures ~390 °C and ~400 °C respectively. Between the pressure tube and the $Be_{12}Ti$ block there is a proposed He gas gap of 1 mm at the assembly, which allows the heat transfer from the block to the pin. The gap is ensured either with additional spacers or with protrusions at the pressure tube or the block sides.

Fig. 10-a shows the temperature profiles considering a thermal conductivity of an irradiated block as after the HIDOBE-02 campaign (650 °C@37.1 dpa of the Be7%Ti pellets). Fig. 10-b shows the hypothetical temperature profiles using the conductivity of a pebble bed for the $Be_{12}Ti$ block, as an extreme case of thermal conductivity deterioration. Despite this extreme condition, the block does not reach the melting point of $Be_{12}Ti$ (1570 °C). Fig. 10-c shows the temperature profile considering a thermal conductivity of $Be_{12}Ti$ at the beginning of life. The thermal field does not significantly change for both unirradiated and irradiated conditions. Fig. 10-d shows an example of tolerance error, in this case adding a concentricity error of 0.5 mm, as sensitivity analysis. It can be observed that such errors in the gap can be accommodated thanks to the relatively good thermal conductivity of $Be_{12}Ti$.

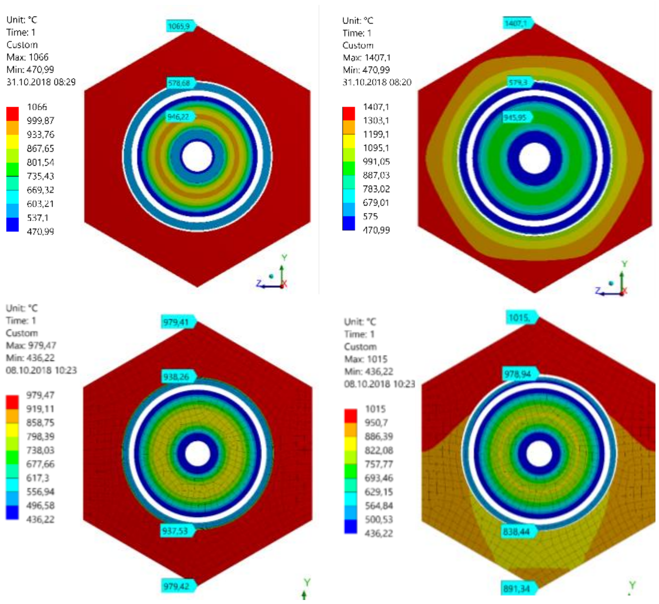

Fig. 10 Scoping analyses of a 2D cross section of a single fuel-breeder pin at the equatorial OB with $Be_{12}Ti$ prismatic blocks. The spacers between the prismatic blocks and the pressure tube, as well as between the pressure tube and the outer pin cladding are not represented here.

V. Primary Heat Transfer System Integration

The integration of the HCPB (and any) breeding blanket in its corresponding PHTS keeping a high Technology Readiness Level (TRL) for the whole system plays a central role, as discussed in Section II. Currently, the HCPB DEMO BoP is formed by the PHTS loop (He-cooled), an Intermediate Heat Transfer System (IHTS) and a Power Conversion System (PCS) formed by a classic Rankine cycle. The IHTS is a molten salt (HITEC® salt, 7% $NaNO_3$ + 53% KNO_3 + 40% $NaNO_2$ [30]) which acts as an energy storage system in order to supply power during the dwell time of the pulse [31][32].

Fig. 11-top shows the PHTS of the previous version of the HCPB (HCPB BL2015 V3, [5][13]). Here, 9 cooling loops were defined (6 OB and 3 IB), with 2 circulators per loop [29]. The IB and OB in-vessel Δp is 2.14 bar and 1.74 bar respectively and 0.88 bar and 0.85 bar for the IB and OB piping (ex-vessel), respectively. The respective IB and OB Δp for the Intermediate Heat Exchanger (IHX) is 0.88 bar and 0.85 bar. The selected IHX is here a two-pass shell & tube (S&T) heat exchanger. The logarithmic temperature difference across these IHX is ΔT_{log} = 28 °C, which is modest and imposes relatively large flow speeds to reach a large enough heat transfer between the molten salt of the IHTS and the He of the PHTS. This temperature is limited by the operational temperature windows defined by the PHTS and the IHTS and clearly, increasing ΔT_{log} reduces the Δp in these components. The resulting circulating power for this PHTS is about 130 MW, which is a significant improvement from former figures of more primitive designs (~200 MW, [14]), but which still results in a large power per circulator (>6 MW).

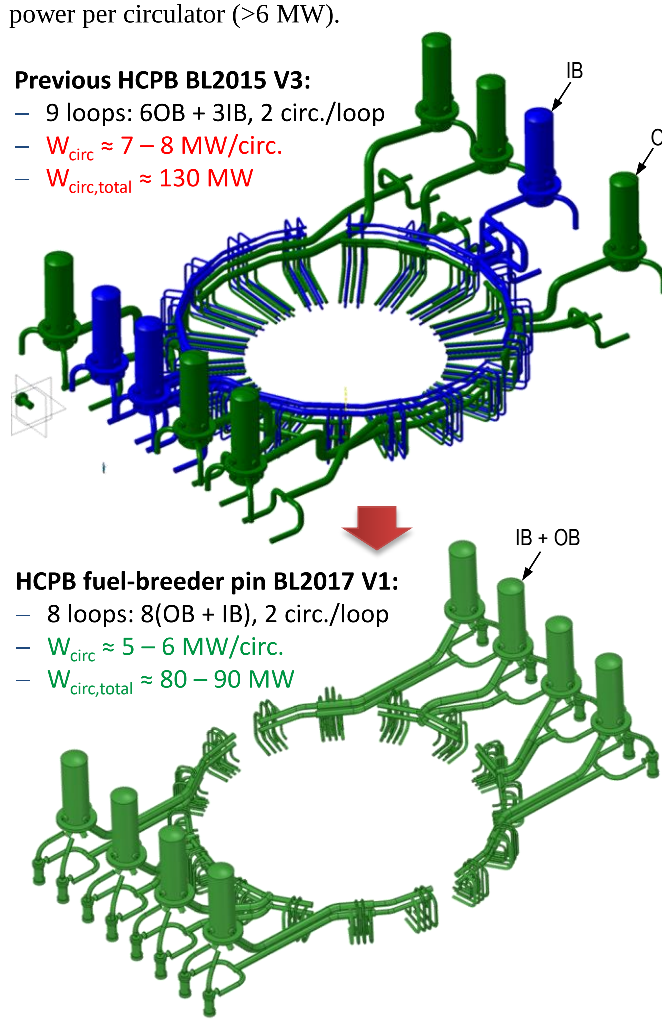

Fig. 11 PHTS comparison between previous and current HCPB design.

Fig. 11-bottom shows the proposed PHTS [29] for the enhanced HCPB design with fuel-breeder pins (HCPB BL2017 V1, [12]). Due to the fuel-breeder pins in the BZ the IB and OB in-vessel Δp has been further reduced to 2.14 bar and 1.74 bar

respectively. Due to this reduction, it is possible now to propose merging OB and IB loops in order to have equal components, despite the slight increase of Δp that this represents. Here, 8 cooling loops are defined (OB + IB), with 2 circulators per loop. The Δp for (ex-vessel) IB and OB piping is 0.45 bar and 0.94 bar respectively. As both IB and OB loops are connected but have different in-vessel Δp, the OB ex-vessel piping is used to compensate for this Δp difference, therefore the large Δp here. The blanket helium outlet temperature of 520 °C plays a key role for this PHTS. The ΔT_{log} can been increased to 36 °C, which significantly increases the HTC with lower flow speeds. Even proposing a one-pass S&T heat exchanger as IHX, the resulting Δp is 0.63 bar. An advanced configuration using a Coiled Wound Heat Exchanger (CWHE) as IHX can further reduce the Δp in these components to 0.34 bar [29]. The circulating power for the case of one-pass S&T IHX is 94 MW and 84 MW for the case of CWHE IHX, both resulting in circulator units <6 MW, within the state-of-the-art for these components and setting a remarkably low figure for a He-cooled class DEMO.

VI. Summary and Outlook

The new Systems Engineering approach for the design of EU DEMO has identified many interfacing systems with requirements that have resulted to be design drivers for the breeding blanket. Some of them, namely safety, system cost-effectivity and the goal to reach a mature BoP system have resulted to be design drivers for the blanket. After a review of the lessons learned, the HCPB has been redesigned in order to minimize the plant circulating power to a level where the state-of-the-art He turbomachinery can be used and the resulting BoP system can be regarded as mature. Also, the use of beryllides have been found to be essential to mitigate key safety issues present with the use of pure Be. The better tritium release in beryllides motivates also to propose their use in form of prismatic blocks instead of pebble beds, mitigating issues associated with the industrial production and costs of this material in this form.

The resulting enhanced HCPB blanket with a fuel-breeder pin configuration potentially meets the present very challenging interface and functional requirements in a cost-effective manner. The TBR is further enhanced with the use of prismatic beryllide blocks (TBR=1.20) and the fuel-breeder pins improve the thermal management of the BZ allowing a blanket outlet temperature of 520 °C. The resulting plant circulating power is currently 80-90 MW, a remarkably low figure paving the way for a mature DEMO-HCPB BoP, as well as for an improved plant efficiency.

Future work for the coming years will be aimed at reaching the design maturity of this enhanced concept, which includes first experimental campaigns in HELOKA [33] with fuel-breeder pin mock-ups, as single-effects proof-of-concept and validation test rigs.

VII. Acknowledgment

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