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Thermal-hydraulic analysis of the EU DEMO Helium-Cooled Pebble Bed Breeding Blanket using the GETTHEM code

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A study of the effects of different heat load distributions on the EU DEMO Helium-Cooled Pebble Bed Breeding Blanket First Wall using the GETTHEM code

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***Abstract*—In this paper we present the first application of the HCPB module of the GEneral Tokamak THErmal-hydraulic Model – GETTHEM, which has been updated to the most recent EU DEMO Helium-Cooled Pebble Bed (HCPB) Breeding Blanket (BB) design, to the evaluation of the effects of different plasma scenarios and related heat load on the First Wall of an entire blanket segment. As a first point, the GETTHEM results in a controlled case are benchmarked against the results of 3D CFD computations performed during the design phase, showing an excellent accuracy despite the inherent simplifications in the GETTHEM model, proving how it can be used to perform parametric analyses in a very short time, giving helpful hints to the design teams. It is then shown that the maximum temperature in the EUROFER structure overcomes the design limit of 550 °C in all the considered scenarios, even though in most cases by only few tens of degrees.**

***Index Terms*—nuclear fusion, EU DEMO, HCPB, EUROFER, GETTHEM**

I. Introduction

The EU DEMO will be the first reactor to produce net electrical energy from nuclear fusion in the EU; under pre-conceptual design phase by the EUROfusion Consortium, it should be operating by the 2050s [1]. Within this framework, a system-level code is under development at Politecnico di Torino starting 2015, called the GEneral Tokamak THErmal-hydraulic Model (GETTHEM), with the support of the EUROfusion Programme Management Unit (PMU).

The main aim of the code, developed in a modular fashion using the Modelica object-oriented modeling language, is the fast simulation of thermal-hydraulic transients of the entire Primary Heat Transfer System (PHTS). GETTHEM currently comprises models for the cooling loops of the Helium-Cooled Pebble Bed (HCPB) [2] and Water-Cooled Lithium-Lead (WCLL) [3] Breeding Blanket (BB) concepts and has been already successfully applied to the optimization of the coolant flow in the HCPB BB [4] normal operation, as well as verified/benchmarked against CFD simulations of the WCLL BB [5]. Moreover, GETTHEM is being benchmarked and validated in off-normal operating conditions – it has been applied, for instance, to the safety analysis of an in-vessel Loss-Of-Coolant Accident (LOCA), for both HCPB [6] and WCLL [7].

In the present work, the HCPB module of the code, updated to the most recent HCPB design, is applied to analyze the effect of different plasma scenarios on the performance of the HCPB cooling system, with particular care to the hot-spot temperature in the solid structures of the BB. Fast simulations like those presented here can be considered of utter importance during this phase of the project, as both the plasma parameters and the First Wall (FW) design are constantly evolving, and the temperature in the solid structure is to be kept under control for safety reasons.

The paper is organized as follows: in the first part, the current design of the HCPB BB is briefly introduced, the main features of the GETTHEM code are recalled and the thermal-hydraulic drivers are defined; in the second part, after showing the benchmark of the GETTHEM model against 3D CFD simulations in a controlled case, the main results of the parametric analysis, performed varying the heat load to the FW, are reported.

II. Model and Drivers

A. The 2015 HCPB BB Design

A sketch of the EU DEMO tokamak corresponding to the 2015 baseline design is reported in Fig. 1; the tokamak is subdivided in 18 identical sectors in the toroidal direction, and each sector contains three outboard (OB) and two inboard (IB) BB segments. Four possible BB concepts are being explored: the aforementioned HCPB (object of this study, under

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development at KIT, Germany) and WCLL (responsibility of ENEA, Italy), plus the Helium-Cooled Lithium-Lead (responsibility of CEA, France) [10] and the Dual-Cooled Lithium-Lead (responsibility of CIEMAT, Spain) [11].

Each BB segment contains several Blanket Modules (BMs), in varying number depending on the blanket concept; for the HCPB, 7 BMs are foreseen both for the IB and the OB segments. The BB subdivision is summarized in Fig. 2.

A detailed cross section of a HCPB BM is reported in Fig. 3. The Breeding Zone (BZ) is composed by a tritium-breeding material and a neutron-multiplying material: the tritium breeder is in the form of Li_4SiO_4 pebbles, whereas Be pebbles are used as neutron multiplier; the module is arranged as poloidally-stacked beds of the two materials, separated by metallic plates (called Cooling Plates, CPs), both acting as stiffening structure and providing a pathway for the coolant.

The HCPB is cooled by helium at 8 MPa, with design inlet and outlet temperatures of 300 °C and 500 °C, respectively, to ensure that the EUROFER Reduced Activation Ferritic Martensitic (RAFM) steel of the solid structures is always working inside the allowed temperature range; in particular, the upper limit is identified as 550 °C. The entire cooling system is divided in two perfectly antisymmetric loops (named “A” and “B” respectively) running in countercurrent. The PHTS layout foresees six separate circuits to cool three OB sectors each, and three circuits to cool six IB sectors each. The cooling loop of each BM, schematized in Fig. 4, is split in two regions, the FW and the BZ, cooled in series.

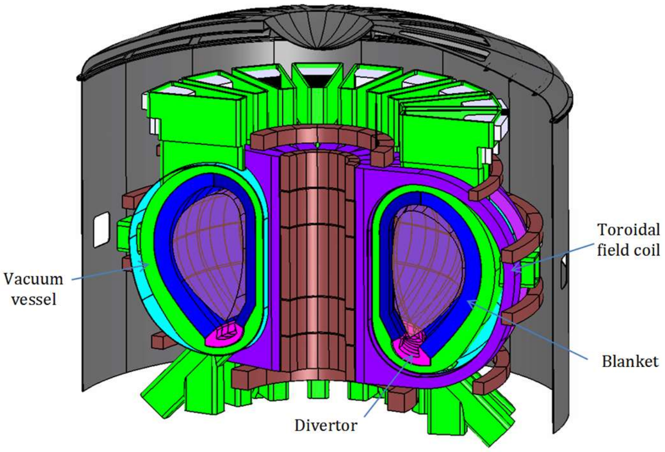


Fig. 1. 2015 baseline design of the EU DEMO1 tokamak [8] [9], showing the main components.

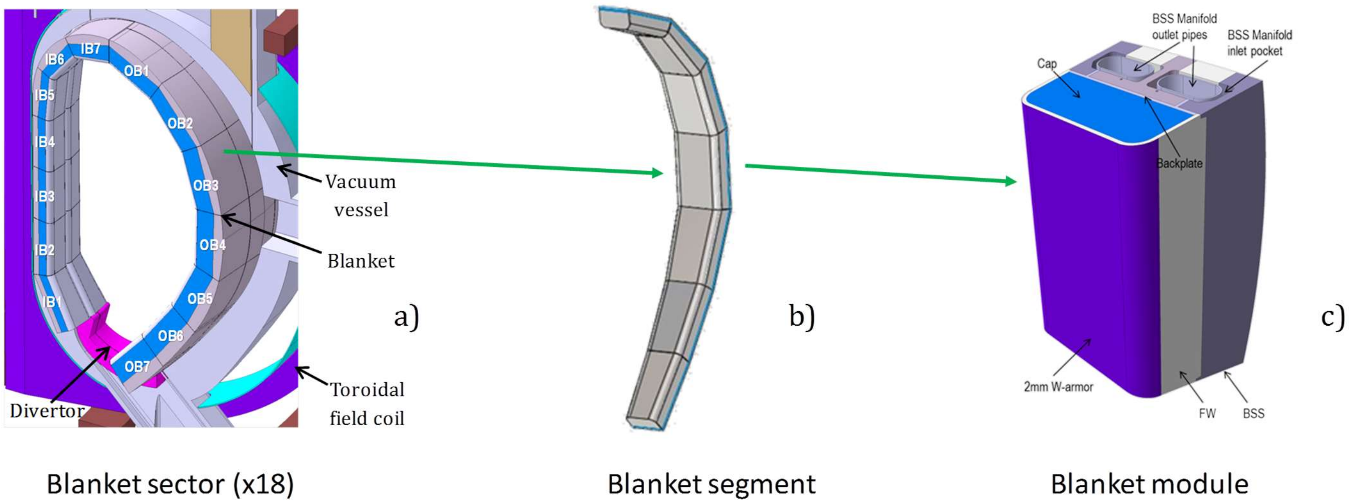
For further information on the 2015 HCPB design, please refer to [2].

B. *The GETTHEM HCPB BB Cooling System Model*

GETTHEM models the thermal-hydraulic transient operation of the HCPB BB cooling system using a 0D/1D approach: for components such as pumps, valves, and manifolds, a 0D transient mass and energy balance is solved, whereas for components such as channels and pipes the 1D mass, momentum and energy balance is solved (see [4] for details on the solved equations); also the energy conservation in the solid structures is solved by means of a simplified 1D model, lumping the EUROFER structure as explained in [4] to obtain an average solid temperature in the lumped volumes. Furthermore, the model has been updated in order to reconstruct also the hot-spot solid temperature, by applying a peaking factor to the average temperature distribution; the value of the peaking factor is determined by looking at the detailed temperature distribution computed through a 3D CFD study on a unit slice of the OB4 BM, which is described in [2] and detailed in [13], [14], [15].

For the model to be fast to execute, some simplifying assumptions had to be made, in view of the very large number of independent cooling channels to be modelled (~3300 per BM in the current design); so, considering the different scenarios to be analyzed, two separate modules have been developed, with different assumptions, namely one for modeling accidental transients (whose details can be found in [6] for the case of the HCPB and in [7] for the case of the WCLL) and the other for nominal operation.

The nominal operation module, in particular, assumes that the helium coolant can be treated as an ideal gas, which is



Blanket sector (x18) Blanket segment Blanket module

Fig. 2. Blanket segmentation, showing the numbering convention of the HCPB IB1-7 and OB1-7 BMs (adapted from [12] [13]): a) blanket sector; b) blanket segment; c) BM with back supporting structure (BSS).

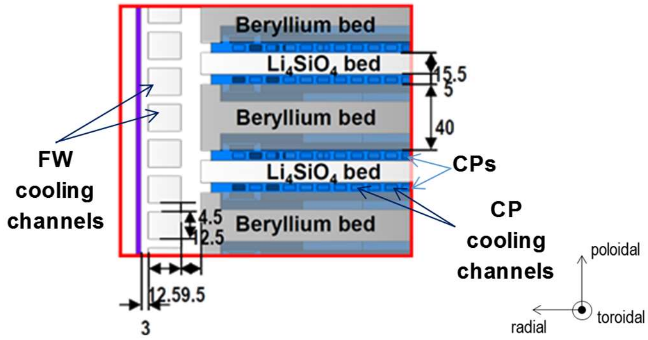


Fig. 3. Radial-poloidal cross section of a HCPB BM, showing the alternate structure of breeder, neutron multiplier and cooling plates (adapted from [2]).

reasonable considering the temperature and pressure of interest. The thermophysical properties of EUROFER are assumed to be independent of temperature, introducing a maximum error below 0.6 %, 18 %, and 5 % on density, specific heat and thermal conductivity, respectively, and an error below 0.3 %, 8 % and 3 % on average; also the heat transfer coefficient between solid and fluid is assumed constant and equal to the values computed in [13] using the Gnielinski correlation [16].

C. Heat Loads

The power generation inside a BM can be split in two components, i.e. the load to the BZ and the load to the FW. The (nuclear) load to the BZ is assumed to be partly conducted to the FW, see [2] and references therein. The distribution of this load, which necessarily differs considering different BB concepts, is computed by neutronic analyses [13], and is reported for the HCPB case in Table I and Fig. 5; in the present work, the BZ load is maintained constant in all the scenarios.

The main loads to the FW are of course those coming from the plasma, in the form of charged particles (ions / electrons) and radiation (photons). These loads depend solely on the plasma equilibrium, and are independent of the BB concept under study, as it is the output of plasma physic calculations. The dependency of the loads on the plasma behavior makes them hard to predict accurately, so that the evaluation of the coolant mass flow to the BMs is done under the assumption of a uniform heat flux distribution. In particular, for the HCPB BB a uniform heat flux of 0.5 MW/m² has been used [13], which leads to the needed mass flow rate distribution as reported in Table I to achieve the target temperature increase. It has to be noted that such steady state heat flux used as reference value for dimensioning the OB4 BM cannot realistically be applied simultaneously on all BMs of a segment by the plasma. The steady state radiative heat flux has been indeed updated and a value of 0.29 MW/m^2 should be considered [17]. The studies performed so far and presented here, even though over-conservative, define the methodology and the performance boundary of the design.

In the present work, several poloidal distributions of heat flux are applied to the FW, to analyze the effect of different plasma scenarios on the peak EUROFER temperature, starting from plasma equilibrium calculations performed in [17], and considering as reference case the aforementioned uniform distribution of 0.5 MW/m²:

- As "extreme" condition, the worst-case scenario A, where all the modules face the highest possible heat flux, is considered; even though it may look unlikely, in view of the large uncertainties in plasma physics this extremely conservative assumption is nevertheless useful for the present kind of analyses, allowing to identify an upper bound for the EU DEMO technological challenges, as stated in [17].
- As two additional scenarios, B and C, the heat loads computed for the start-of-flattop (SOF) and end-of-flattop (EOF) plasma phases are considered.
- Finally, two loads corresponding to off-normal situations, such as "mini-disruptions" and Edge Localized Modes (ELMs), are applied (scenarios D and E, respectively).

The FW heat flux distributions for the five abovementioned scenarios are reported in Table II[1] and Fig. 6. In all of these scenarios, the heat flux is assumed to distribute uniformly on the front part of the FW of each BM; moreover, in all the simulations, the mass flow rate distribution among the BMs is maintained as in Table I, as the aim is to highlight the effects of a different power distribution, compared to that considered during the design. Therefore, the possibility to react to a change of heat loads form the plasma and adjust the mass flow rate in the different BMs is not considered here.

III. RESULTS

A. Reference Scenario

In the reference scenario, the overall load to each BM is the same that was used to determine the flow distribution; so, the reference scenario is also used as a benchmark case against a CFD study of the GETTHEM capabilities to compute the hot-spot temperatures in the two regions.

First of all, as the mentioned CFD study [13] has been carried out on a periodic slice with symmetry conditions on top and bottom surfaces, it cannot consider boundary effects, i.e., it is a representation of a BM with infinite length in the poloidal direction; moreover, it has been applied on the OB4 BM, which is the only one for which a detailed design is available. For this reason, the CFD results are compared with the GETTHEM results in a channel at the midplane, in order to reduce as much as possible the boundary effects.

As a final remark, please note that the Be and Li_4SiO_4 layers are not modelled in GETTHEM, as well as the purge gas; in particular, this last term is shown in [14] to affect the helium outlet temperature $T_{\mathrm{He,out}}$ by less than 0.3 %, the maximum BZ temperature $T_{\mathrm{max,EUROFER,BZ}}$ by ~2 % and the maximum FW temperature $T_{\mathrm{max,EUROFER,FW}}$ by ~0.1 %.

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[1] The lowermost outboard module OB7 is by far the most singularly exposed to the heat flux coming from the plasma. As the need for an update of the design of the FW shape of OB7 was already highlighted in previous work by other authors [17], we will not consider OB7 in scenarios A to E.

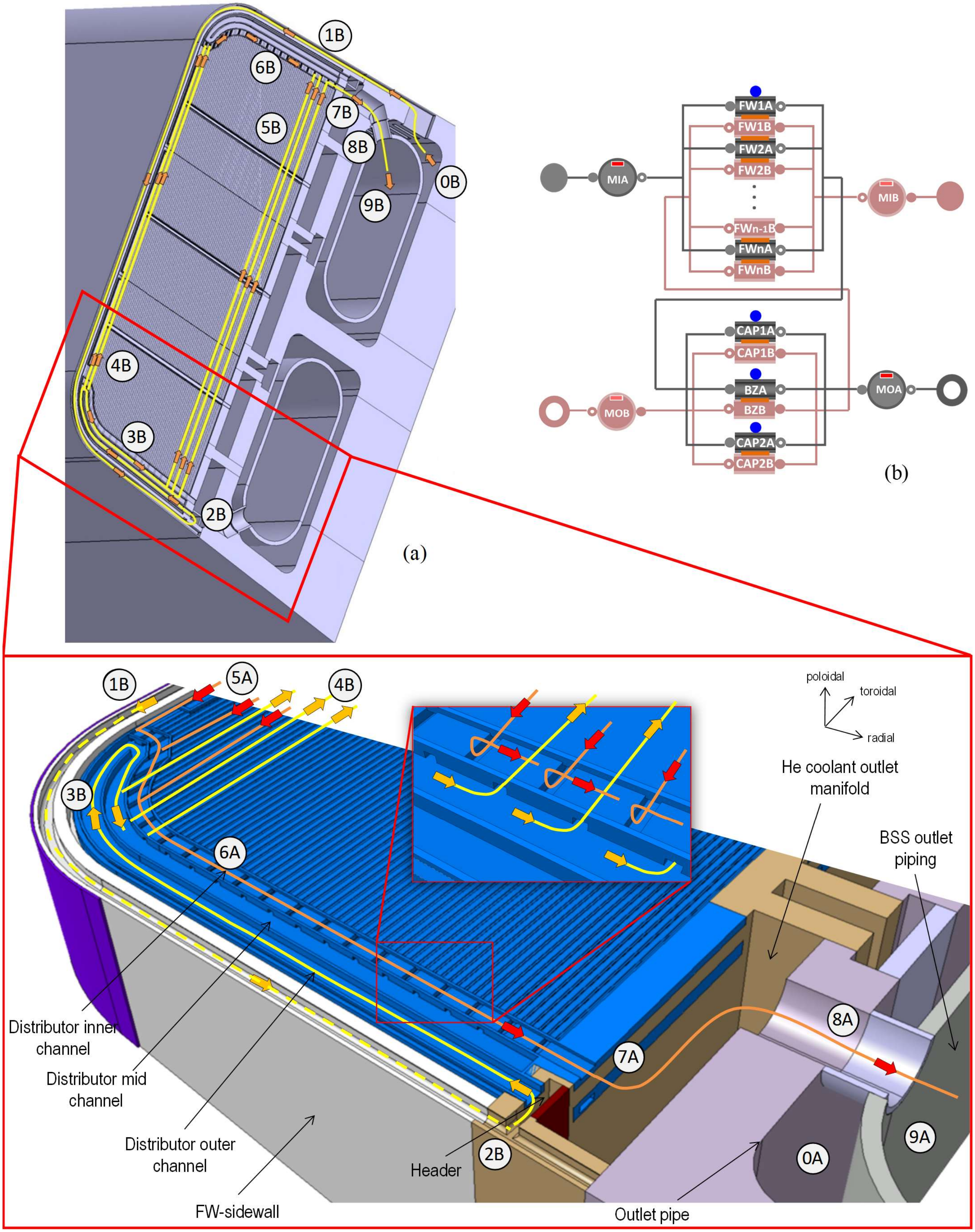


Fig. 4. Scheme (a) and block diagram (b) of the coolant flow path inside a HCPB BM (adapted from [2], [4], [13]). The coolant is distributed initially from the manifold in the BSS (bullet 0) to the FW square cooling channels (bullet 1), and it is successively collected and redistributed (bullets 2 and 3, respectively) to the CP rectangular cooling channels (bullets 4 and 5) by a rather complex system of internal manifolds, before being collected again in a manifold inside the CP at first (bullet 6) and in a BM-wide manifold (bullet 7), which finally delivers the hot coolant to the outlet manifold inside the BSS (bullets 8 and 9).

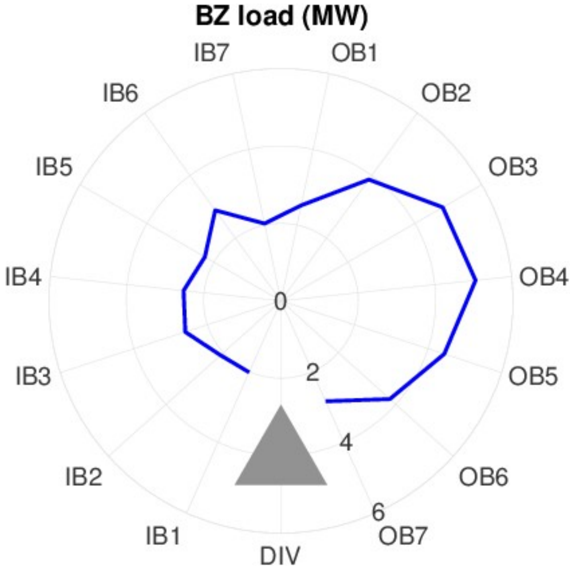


Fig. 5. Poloidal distribution of the power generation in the BZ (DIV = divertor).

TABLE I
POLOIDAL DISTRIBUTION OF BREEDING ZONE LOAD AND COOLANT MASS FLOW [13]

Module	Load (MW)	Mass flow rate (kg/s)
OB1	2.52	3.4
OB2	3.87	5.0
OB3	4.83	6.0
OB4	5.06	6.3
OB5	4.44	5.7
OB6	3.79	4.9
OB7	2.84	3.8
IB1	2.02	2.9
IB2	2.10	2.9
IB3	2.60	3.4
IB4	2.53	3.4
IB5	2.27	3.0
IB6	2.89	3.6
IB7	2.04	2.9

TABLE II
POLOIDAL DISTRIBUTIONS OF THE FIRST WALL LOAD (kW/m²) [17]

Module	Heat flux scenario					
	Ref.	A	B	C	D	E
OB1	500	440	394	405	340	440
OB2	500	460	384	408	360	460
OB3	500	410	383	383	370	410
OB4	500	390	376	376	370	390
OB5	500	400	382	417	370	400
OB6	500	390	380	380	390	380
OB7	500	2090	1571	2020	950	1770
IB1	500	560	335	335	525	335
IB2	500	420	295	295	420	295
IB3	500	340	260	260	340	260
IB4	500	305	260	260	305	260
IB5	500	650	285	600	315	650
IB6	500	1020	643	845	340	1020
IB7	500	840	840	630	345	830

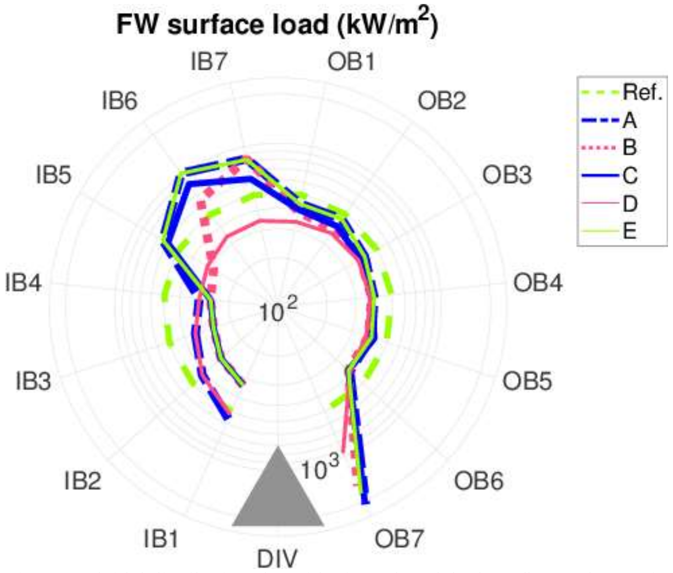


Fig. 6. Poloidal distribution (logarithmic scale) of the heat flux to the FW in the different scenarios considered in the paper.

A helium outlet temperature of 471.2 °C in the unit slice was obtained in the reference CFD study, while GETTHEM calculations in the midplane reported an outlet temperature of 466.0 °C, with a relative error on the temperature increase of ~3 %, highlighting the good performances of GETTHEM on the thermal-hydraulics of the cooling channels, despite the simplifications.

By looking only at the results reported in [2], [13] and [14], a peaking factor, defined as ($T_{\text{max,EUROFER}} - T_{\text{He,in}}$) / ($T_{\text{ave,EUROFER}} - T_{\text{He,in}}$), where $T_{\text{He,in}}$ is the helium inlet temperature of 300 °C, is extracted and applied to the GETTHEM calculation of the average EUROFER temperature. This peaking factor, computed on the unit slice of the OB4, is applied with no modifications to the entire blanket segment, both on IB and OB, whereas the actual peaking factor may differ from module to module in view of the different dimensions of the structures; however, as no detailed dimensioning of the other BMs was ever been performed, no additional information could be exploited. Moreover, as all the BMs will share the same design approach, this difference is expected not to influence the results dramatically.

Also considering the solid temperatures computed using this peaking factor, an excellent agreement between the two models has been found, with an error below 1% on the two solid temperatures. The comparison between the GETTHEM results and the 3D CFD results is summarized in Table III.

The GETTEHM results for the other modules, in term of poloidal hot-spot temperature distribution, are reported in Fig. 7, where the temperature limit of 550 °C is also shown. As a first point it is worth noticing that the peak temperature is higher than the limit, not only in the OB4 BZ where it was expected from the CFD analyses, but in all the modules, with the most critical point being the IB1, where the FW temperature overcomes 653 °C. The only other modules to reach temperatures above 600 °C are IB2 and OB1, pointing out how, also in case of a uniform FW load, the peripheral modules are somehow disadvantaged with respect to the equatorial ones (even though they face the lowest BZ load). Hence, particular attention shall be posed when designing more in detail these BMs. In all the other BMs, the situation is less critical, with the hot-spot temperature overcoming the limit by few degrees in the OB and by few tens of degrees in the IB; on average (including all the BMs), the limit is overcome by 50 °C in the IB and by 23 °C in the OB.

TABLE III
BENCHMARK OF GETTHEM CALCULATIONS AGAINST 3D CFD

Variable	GETTHEM result	CFD result [13], [14]	Error
$T_{\mathrm{He,out}}$	466.0 °C	471.2 °C	3 %
$T_{\mathrm{max,EUROFER,FW}}$	514.5 °C	514.4 °C	0.05 %
$T_{\mathrm{max,EUROFER,BZ}}$	556.9 °C	556.6 °C	1 %

The error is computed as relative to the temperature increase

B. Other Scenarios

The results for all the scenarios, in terms of overall and local (BZ or FW) hot-spot EUROFER temperatures, are reported in Fig. 8 and 9, respectively.

None of the scenarios A to E completely fulfils the requirement on the maximum EUROFER temperature, with the scenario D being the most favorable one, overcoming the limit only in IB1 and IB2, by 120 °C and 29 °C, respectively. Apart from that, all the other scenarios foresee a temperature significantly above the limit in IB1, IB5, IB6 and IB7. This is

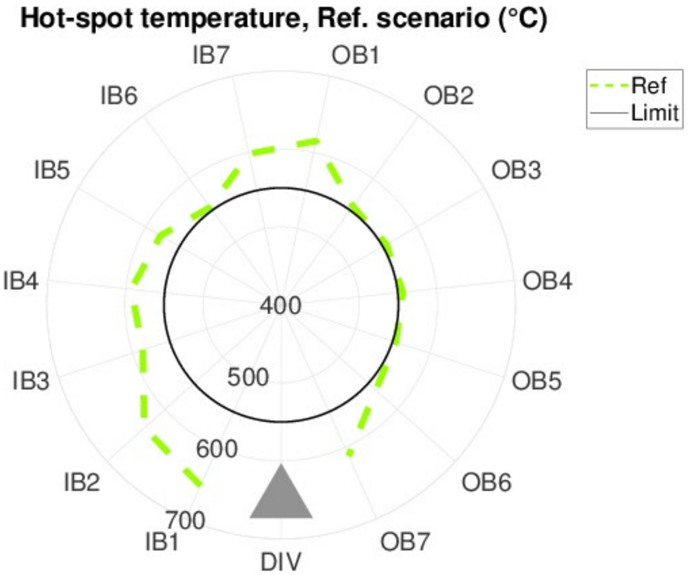


Fig. 7. Overall peak EUROFER temperature in a HCPB segment for the reference scenario. The thin, solid, black line represents the operational upper limit of 550 °C

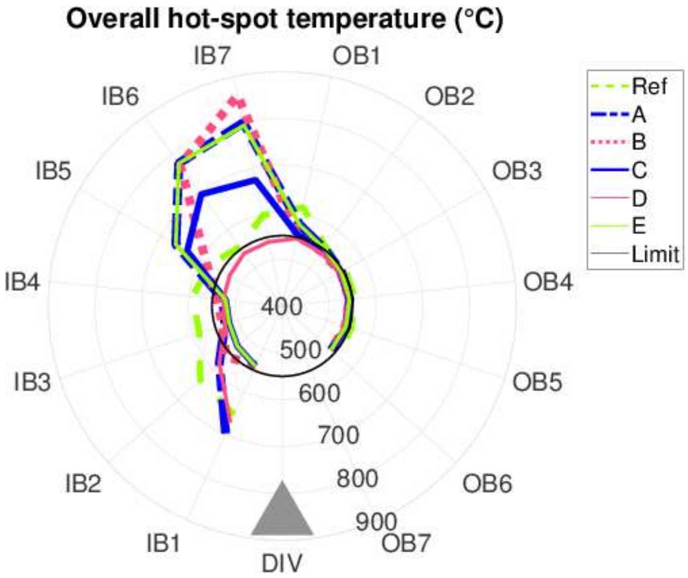
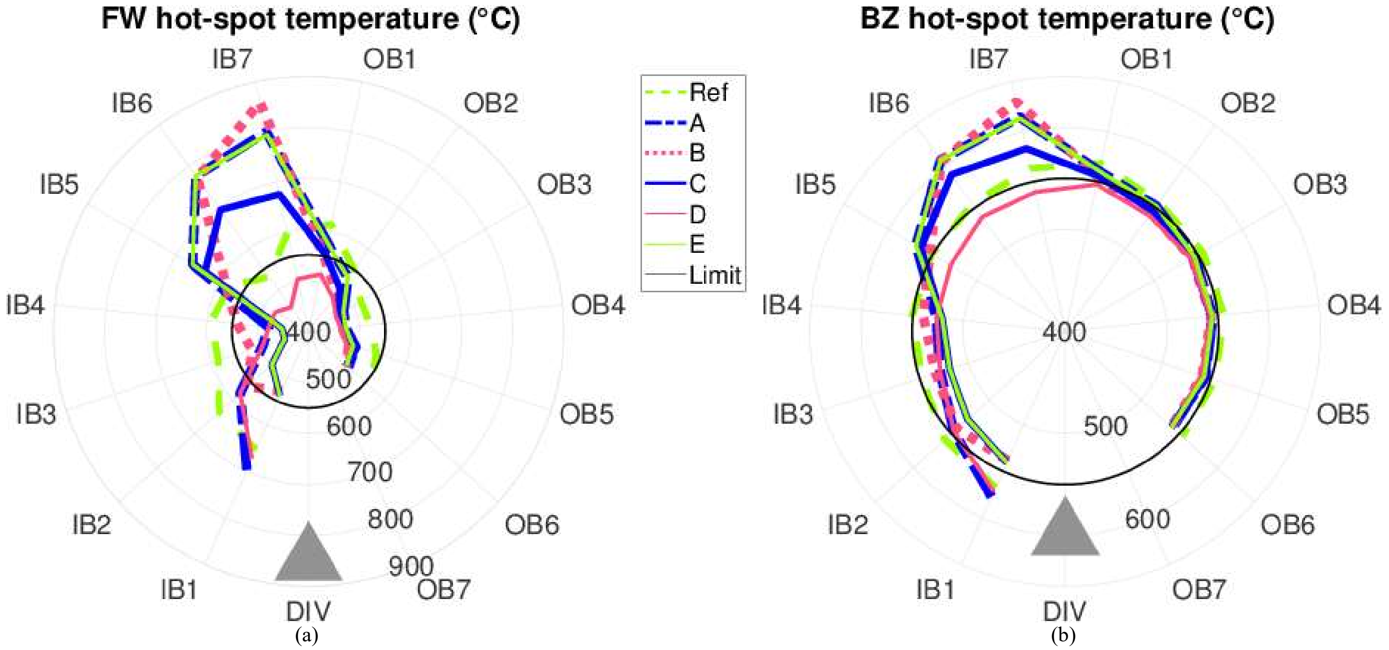


Fig. 8. Overall peak EUROFER temperature in a HCPB segment for the different scenarios. The thin, solid, black line represents the operational upper limit of 550 °C.



(a) (b)

Fig. 9. Peak EUROFER temperature in a HCPB segment for the different scenarios, in the two regions: (a) FW; (b) BZ. The thin, solid, black line represents the operational upper limit of 550 °C.

maybe due to a suboptimal heat transfer in the IB modules, which may derive from the fact that the only BM that has been designed in detail so far is OB4. In addition to that, it must be noted that, while in the FW the distribution varies dramatically, mainly reflecting the power distribution, in the BZ the situation is more uniform, which was expected as the power distribution in that region is the same that was used to determine the mass flow rate, as mentioned earlier. Being the BZ cooled in series after the FW, however, the effect of the FW power distribution is somehow propagated also to this region, as it is especially clear for the most loaded modules (IB5, IB6 and IB7).

In all the other modules, the temperature may be above or below the limit, but always close to 550 °C; in these cases, as exemplified by Fig. 10 (referring to OB1 in the scenario C), the temperature is above the limit only in some portions of the FW, which are typically located downstream the boundary channels (i.e., the uppermost and lowermost in the poloidal direction), and, by conduction, also in the neighboring ones: in fact, in these two channels the beneficial effect of the alternating countercurrent channel structure is half of that of the "bulk" channels, as the heat transfer happens between two channels instead of three. This boundary effect is also causing the "band" structure of the 2D temperature map on the FW, clearly visible in Fig. 10: in fact, the channels in the "bulk" have a perfect symmetry in the toroidal direction, whereas the channels close to the boundaries in poloidal direction do not feel the "averaging" effect of the countercurrent structure, reaching a higher temperature downstream and a lower temperature upstream. Since the first and last channels run in opposite directions, by conduction this "diagonal" band is formed in the temperature distribution.

We finally note, as a side remark, that the GETTHEM simulations above are very light in term of computational cost: for instance, the simulation of a ~150 s transient of an entire segment runs in only ~20 min on a single Intel® Core™ i7-4810 CPU (2.8 GHz).

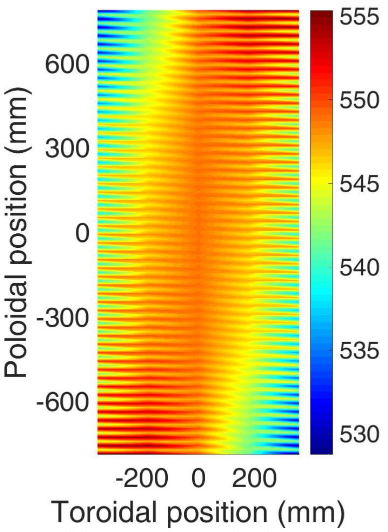


Fig. 10. Map of the solid temperature in the front part of the OB1 BM for scenario C.

IV. CONCLUSIONS AND PERSPECTIVE

The GETTHEM system-level code, under development at Politecnico di Torino with the support of the EUROfusion PMU, offers as a possible solution to the need for fast tools able to rapidly analyze several different scenarios; this should help the designers by quickly identifying in a very short time the critical points, as well as the areas where efficiency improvements are possible. GETTHEM has been applied here for a first parametric analysis of the effect of different FW loads, corresponding to different plasma conditions, to the HCPB hot-spot temperature. The code, which correctly reproduces the results of detailed 3D CFD analyses in a controlled case, highlighted how the peripheral modules are always in worse conditions with respect to the equatorial ones, also in the case of uniform load, deserving thus some special attention in the detailed design phase. Even though in this study an over-conservative value of steady state radiative heat flux has been applied on the FW, and the mass flow rate has been fixed once for all as defined by the steady state analyses, the flexibility and light computational cost of GETTHEM clearly point to its potentiality to support the designers in exploring a variety of possible combinations (different set of heat loads, possibility to individually adjust the mass flow in the BMs etc.). This capability becomes crucial when GETTHEM will include the modelling of the PHTS.

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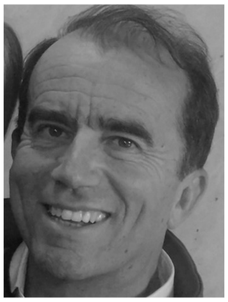

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