Fusion Engineering and Design 178 (2022) 113093

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Tokamak cooling systems and power conversion system options

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A R T I C L E I N F O

Keywords:
DEMO
PHTS
Balance of plant
HCPB
WCLL

A B S T R A C T

DEMO will be a fusion power plant demonstrating the integration into the grid architecture of an electric utility grid. The design of the power conversion chain is of particular importance, as it must adequately account for the specifics of nuclear fusion on the generation side and ensure compatibility with the electric utility grid at all times. One of the special challenges the foreseen pulsed operation, which affects the operation of the entire heat transport chain. This requires a time-dependant analysis of different concept design approaches to ensure proof of reliable operation and efficiency to obtain nuclear licensing.

Several architectures of Balance of Plant were conceived and developed during the DEMO Pre-Concept Design Phase in order to suit needs and constraints of the in-vessel systems, with particular regard to the different blanket concepts. At this early design stage, emphasis was given to the achievement of robust solutions for all essential Balance of Plant systems, which have chiefly to ensure feasible and flexible operation modes during the main DEMO operating phases – Pulse, Dwell and ramp-up/down – and to adsorb and compensate for potential fusion power fluctuations during plasma flat-top. Although some criticalities, requiring further design improvements were identified, these preliminary assessments showed that the investigated cooling system architectures have the capability to restore nominal conditions after any of the abovementioned cases and that the overall availability could meet the DEMO top-level requirements. This paper describes the results of the studies on the tokamak coolant and Power Conversion System (PCS) options and critically highlights the aspects that require further work.

1. Introduction

Since the early phases of the DEMO Pre-Concept Design (PCD) studies, emphasis has been given to engineering aspects and design integration challenges that actually affect the architecture of a nuclear power plant, such as technology readiness, power conversion features, safety and related licensing aspects [1,2].

Within the framework of the eight Key Design Integration Issues (KDIIs) identified for analysis during the PCD phase [1], challenges related to the design and operation of the tokamak cooling systems and power conversion systems have been addressed in the KDII 5 [3]. In fact, as DEMO has been conceived to deliver net electric power to the grid [4], proper critical evaluations on the essential features characterizing the Balance of Plant (BoP) systems are needed because they play a pivotal role in the design and licensing of the overall plant [5]. As such, the entire DEMO plant architecture has to focus meeting all BoP challenges in contrast to ITER, in which the heat is dumped to the environment without any energy conversion.

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https://doi.org/10.1016/j.fusengdes.2022.113093
Received 22 August 2021; Received in revised form 12 February 2022; Accepted 7 March 2022
Available online 15 March 2022

In the DEMO PCD phase, alternative architectures of BoP have been developed and analysed coping with the specificities and constraints of the in-vessel clients [6,7], pre-scribed essentially by the two different Breeding Blanket (BB) concepts, namely the Helium-Cooled Pebble Bed (HCPB) BB and the Water-Cooled Lithium Lead (WCLL) BB [8]. At this early design stage, attention was given to identify robust solutions for all essential BoP systems [5], which have chiefly to ensure feasible and flexible operation modes during the main DEMO operating phases – pulse, dwell and ramp-up/down – and to adsorb and compensate for potential fusion power fluctuations during plasma flat-top.

Assessments made on main tokamak cooling systems, the - Primary Heat Transfer Systems (PHTSs) [9,10,11,12], and the relevant Power Conversion System (PCS) options [13-16] have allowed to identify criticalities and issues that must be addressed in the next project phase. This is due to their technical complexity and strong impact on design integration [17], maintenance [18] and safety [19]. On the other hand, preliminary analyses showed very encouraging results that highlight: i) the inherent capability of the designed systems to restore nominal Pulse conditions following any ramp-up after Dwell phase, ii) the possibility to achieve an overall availability of the BoP systems able to meet the DEMO top-level requirements.

1.1. DEMO cooling systems and BoP challenges

DEMO will be a nuclear facility therefore the cooling systems and the entire BoP must meet operating and safety requirements formulated for nuclear power stations [19]. However, with regards to the cooling systems design challenges, an analogy between a fission Nuclear Power Plant (NPP) and the DEMO reactor is not so trivial.

The intrinsic challenge of a heat transport chain in a DEMO reactor is the intermittent fusion plasma operation as a primary heat source to the Plant Electrical System (PES), which places special constraints on all components of the BoP system [20].

The pulsed nature of the fusion power in any Fusion Power Plant (FPP) based on tokamak concept adds a further degree of complexity in the control of normal plant operations, enhancing the dependence of PCS activities on the BB, Divertor and Vacuum Vessel (VV) PHTSs performances. In particular, the DEMO duty cycle involves the alternance of 2 main phases where the reactor power varies from its nominal value, called Pulse time also (also called Burn time, to a minimum, called Dwell time, with the power being around 1÷2% of the nominal due to residual heat stored within the tokamak structures. Pulse and Dwell times are assumed to be 2 h and about 10 min, respectively, and the transition from one phase to the other is made by 2 transitional phases, plasma ramp-up and plasma ramp-down, lasting about 100÷200 s each. An example of DEMO power duty cycle is depicted in Fig. 1

The intermittent DEMO operation posed specific challenges to the BoP, which on the one hand requires to absorb rapidly large fusion output powers and their potential fluctuations and on the other side to smoothen these transients to the interconnected circuits to ensure a reliable power production and suitable components lifetime. It is obvious, indeed, that oscillating loads might challenge the lifetime of the main BoP equipment inducing undue thermal and mechanical cycling. Although it is rather impossible to prevent the occurrence of such cycling in PHTS components, several strategies are being considered to mitigate the potential negative effects of the pulsed operations on PCS main components, such as turbine and steam generators. The study and the development of multiple configurations is being pursued in order to achieve an identification of viable solutions aiming to minimize technological risks [6].

In this direction the leading approach followed is similar to that used in the solar energy industry, attempting to thermally decouple the PCS from the PHTSs thanks to an Intermediate Heat Transfer System (IHTS) equipped with a sensitive heat storage, with is further called Energy Storage System (ESS). The function of the IHTS is to balance the PHTSs and the PCS, by routing a fraction of the thermal power transferred by the PHTSs during the Pulse period to the ESS, which is then available to the PCS during the Dwell period for steam generation. In the ideal case, this will enable power cycles that ensure the use of already qualified components known from NPPs and Concentrating Solar Power (CSP) plants, and thereby reducing specific R&D needs for the DEMO project.

On the other hand, the integration of additional systems (such as the IHTS+ESS) implies an increase of complexity of the whole BoP architecture. Therefore, alternative BoP design options target at a more direct coupling of the PHTSs to the PCS [2,6]. Such a design approach assumes a very low steam flow for operating the turbine and, thus, requires a significantly smaller ESS [5]. These options would “accept” several load changes on a daily basis into PCS equipment, even though they might induce detrimental effects shortening the lifetime of components.

A careful identification of proper PCS architecture, suitable operating procedures and design provisions capable to smooth the transients on components, such as turbine, have been addressed in order to reach safe and reliable operations despite the reactor pulsed operation. Direct-coupling options are clearly more demanding in terms of engineering challenges and R&D programmes [6,7], nevertheless any effort to reduce the complexity of the DEMO BoP, through simplification and a rationalisation of its main systems is expected to be beneficial for the DEMO plant design.

A second aspect that must be considered in developing the tokamak cooling systems and BoP architecture is the presence of multiple thermal power sources, not uniformly distributed, and that operate at different temperature levels Table 1. reports main design conditions for PHTSs.

Contrary to fission NPPs, where a single primary system, namely the Reactor Coolant System (RCS), is designed to extract the thermal power from the core and to deliver it to the PCS through the Steam Generators (SGs), DEMO is equipped with several, separated cooling systems that remove power from the tokamak. Such an architecture is needed because the three main components that extract the thermal power from

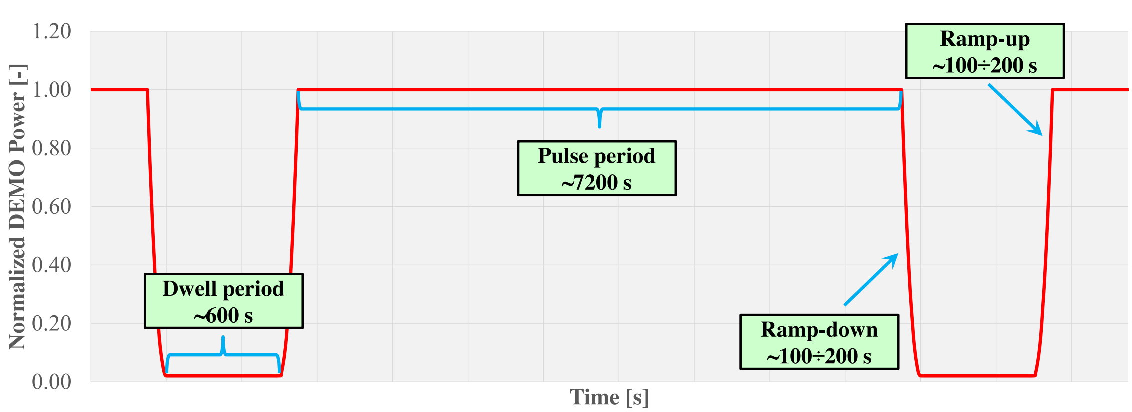

Fig. 1. DEMO power duty cycle.

Table 1
PHTSs main T/H parameters.

Parameter	HCPB BB PHTS	WCLL BB PHTS	Divertor PFC PHTS	Divertor cassette PHTS	VV PHTS
Power [MW]	2029	1923	136	115.2	86
Coolant	Helium	Water	Water	Water	Water
Inlet Temperature [°C]	300	295	130	180	190
Outlet Temperature [°C]	520	328	136	210	200

the machine - BB, Divertor, VV - have different functions and requirements [21].

This operating conditions of the various thermal power sources prevents the adoption of a single cooling circuit, operating with one coolant at the same Thermal-Hydraulic (T/H) conditions. Cooling capabilities are therefore provided with the use of either different coolants (helium/water for the blanket) or water at various temperature and pressure levels according to the specific needs of the in-vessel client.

Although BB collects more than the 80% of the whole tokamak thermal power and its heat is available at the highest temperature level, compatibly with material resistance limits, the recovery of "low- temperature sources" can improve the overall plant yield by a non-negligible amount [22]. Hence, for all BoP concepts investigated, efforts were made to integrate all thermal power sources of the reactor into the PCS with the aim of exploiting the adopted Rankine cycles at their maximum thermodynamic capabilities, thus converting fusion heat into mechanical and then electrical power with higher plant efficiency.

2. Procedure to address high level requirements

Compared to ITER, the two major differences in DEMO are the self-sustaining tritium production and the electrical power production. Especially for BoP the latter implies severe requirements to all systems of the heat transfer chain due to the pulsed characteristics of the tokamak principle, since DEMO alternator has to remain synchronized with the grid. It is already known from grid simulations that future energy and electricity market will change for the time when DEMO or a subsequent Fusion Power Plant (FPP) will become operational. In fact, it is expected a variation of the topology of the European grid and its infrastructures to cope with requirements coming from: i) the increased share of Variable Renewable Energy Sources (VRES) and electro-mobility, ii) the substitution of fossil heat by electricity and iii) the reduction of the inertia ensured by large power plants. As regard to the latter, the continuous decrease of inertia that large generation points are currently supplying to the grid might jeopardize the stability of the grid itself. Therefore, the large turbo-generators of DEMO and FPP bring inherent stability to the grid.

This high-level requirement affects all heat transferring and converting systems, so proper measures have to be included to prevent the turbo-generator from being affected by the pulses in a reliable, safe and effective manner. Suitable BOP operation is required to prevent any loss of synchronism with the grid.

Aside from the energy transfer task, the PHTS shall provide the primary confinement for Activated Corrosion Products (ACP) and tritium and maintain operational leak tight integrity during operation and maintenance [23]. This implies that all PHTS components must ensure the most appropriate nuclear quality to minimise as much as possible the coolant leakages from weld seams, equipment with moving and rotating parts (e.g. valves stem packing, pumps seals), flange gaskets, etc. Moreover, the selected materials or structures shall minimize tritium uptake, ease the decontamination, simplify maintenance (avoiding remote maintenance when possible) and minimize the radioactive waste production.

The BoP-PHTSs Structures, Systems and Components (SSC) that are important to safety must be clearly identified and then classified on the basis of their function and significance with regard to safety. A preliminary attempt to identify these systems and provide an early safety classification was made in [24]. Nevertheless, further assessments are on-going to consider the recent design evolutions and the new results of deterministic analyses on postulated accidental sequences.

3. Primary heat transfer systems

DEMO presents four independent PHTSs. The largest PHTS is devoted to remove the thermal power from the BB, two PHTSs are necessary to extract heat from the DIV while the last one is intended to cool the VV. HCPB and WCLL rely on different BB PHTS layouts while divertor and VV PHTSs adopt basically the same arrangement for both concepts. However, it is worth to underline that small changes in the design of main heat exchangers coupling the PHTSs to the secondary circuit might occur according to the different BoP variants under investigation.

An overview of the main PHTSs characteristics is provided in order to facilitate the understanding of the DEMO BoP options discussed later.

3.1. Helium-cooled pebble bed breeding blanket PHTS

In the present design (that may evolve in the future), the HCPB BB PHTS is segmented in 8 separate cooling loops, equally distributed over two sides of the Tokamak building, see also [25]. Each cooling loop provides pressurized helium in forced convection to the blanket segments of 2 Tokamak sectors.

The main function of the HCPB BB PHTS is to extract thermal power from the BB components and transfer it to the IHTS through the Intermediate Heat eXchangers (IHXs). The HCPB BB PHTS concept is based on the use of forced convection pressurized helium as coolant medium at about 8 MPa and inlet/outlet temperatures of 300/520 °C. Each of the 8 cooling loops feeds 2 BB sectors made of 10 blanket segments, 4 inboard Blankets (IBs) and 6 Outboard Blankets (OBs), respectively. Each cooling loop consist of: In-VV BB cooling circuits belonging to two VV sectors, an IHX, two circulators, and the connecting piping between these components. An overview of the system is shown in Fig. 2.

The eight IHXs are located on two opposite sides in the tokamak cooling rooms on the upper level of the Tokamak Building (see Fig. 3). On one location all IHXs are located in a row and equally distributed.

The helium circulators are located nearby the bottom head of the IHXs; two short pipes, upstream and downstream each circulator, connect the component to the IHX and the cold leg, respectively. Further information can be found in [26-29].

Table 2 and Table 3 report the main parameters of the system/loops and the relevant number of components, respectively.

3.2. Water-cooled lithium-lead breeding blanket PHTS

The main function of the WCLL BB PHTS is to remove thermal power from the BB components and to deliver the power to the PCS. In the present design that may still evolve in the future, the WCLL BB PHTS is composed of two separated cooling circuits: the Breeding Zone (BZ) PHTS and the First Wall (FW) PHTS. Each cooling circuit delivers power to the PCS by means of two Once Through Steam Generators (OTSGs). The thermodynamic cycle of both PHTSs is based on pressurized water at 15.5 MPa and inlet/outlet temperatures of 295 °C and 328 °C, respectively [30] Fig. 4. depicts the main equipment of the system.

Each primary circuit has two cooling loops, each feeding eight tokamak sectors. The coolant pumps are located nearby the OTSG exit. A short pipe connects the pumps to the OTSG; downstream, the pumps are connected to the cold legs [30].

The main figure of merits of the WCLL PHTS are summarized in

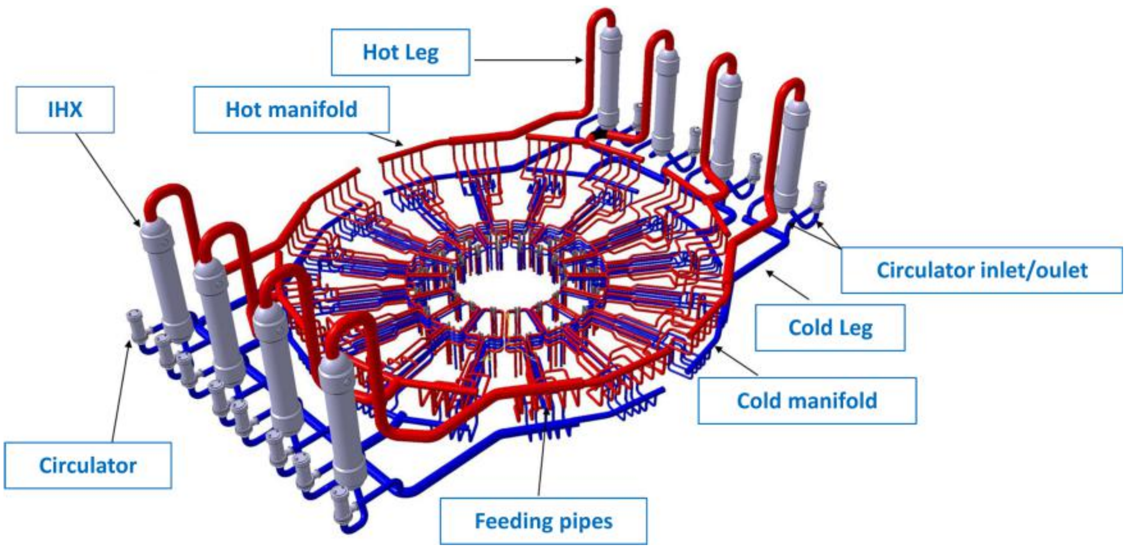

Fig. 2. Overview of the HCPB BB.

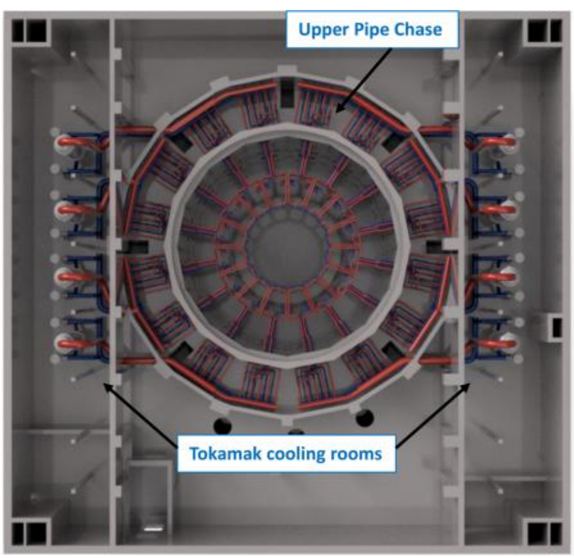

Fig. 3. Integration of the HCPB BB PHTS into the Tokamak building.

Table 2
Main parameters of the 8 HCPB PHTSs.

Parameter	Unit	Value
Total BB Thermal Power	MW	2029
Total circulator power to coolant	MW	83
Total circulator electrical power	MW	92
Total helium volume	m^3	1735
Total pipework length	m	6300

Table 3
Number of components per HCPB BB PHTS circuit.

Component	Value
Intermediate heat exchanger	1
Circulator	2
Feeding pipes (hot/cold)	10/10
Manifolds (cold/hot)	1/1
Main legs (cold/hot)	1/1

Table 4 and Table 5.

Main system components are located on two opposite sides of the Tokamak building, as shown in Fig. 5.

3.3. Divertor plasma facing components and cassette body PHTSs

The divertor is currently divided in 48 cassettes, three for each VV sector of the reactor, to enable their remote replacement. Each cassette is composed of a Cassette Body (CB), equipped with a Shielding Liner and two Reflector Plates (RPs), and two Plasma Facing Components (PFCs), namely an Inner Vertical Target (IVT) and an Outer Vertical Target (OVT). The CB and the PFCs are cooled by two separate PHTSs, fed by water coolant at different T/H conditions.

Both, the divertor PFCs PHTS and the divertor Cassette PHTS are segmented into 2 separate cooling circuits, equally distributed over two sides of the Tokamak building. Each cooling loop provides pressurized water in forced convection to the divertor PFCs and the Divertor cassette bodies, respectively, of 8 Tokamak sectors. Heat removed from the PFCs and CBs is transferred to the Power Conversion System via one HX per circuit [12].

The main function of the divertor PHTSs is to extract thermal power from the divertor PFCs components and the cassette bodies and transfer it to the PCS through the HXs. The ex-vessel parts of the divertor PHTSs have the function of providing primary confinement to the coolant that contains tritium and activated particles (e.g. activated corrosion products).

Each loop consists of: In-VV cooling circuits belonging to eight VV sectors, a HX, a pressurizer, a main coolant pump, and connecting pipes between these components. The piping (per cooling loop) foresees hot leg, cold leg, collector, distributor and six feeding pipes per each sector (3 pipes to retrieve hot water from each sector and 3 to feed them with cold water), see Fig. 6.

The main PHTS components are located on the lower level of the Tokamak Building on two opposite sides in the Tokamak cooling rooms. The HXs are integrated in the BoP Rankine cycle as pre-heaters of the feed water (which flows on the secondary side).

Table 6 and Table 7 summarize the main features of the two PHTSs Fig. 7. gives an overview of the divertor PFCs PHTS integration into the Tokamak building. Primary cooling system for the divertor cassette body is arranged in a similar fashion [12].

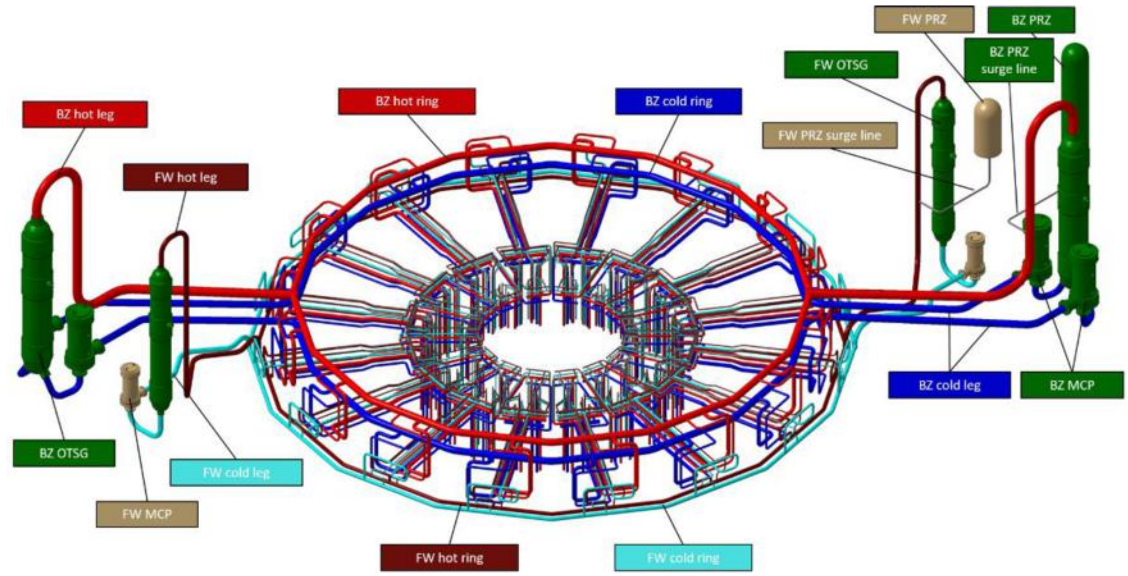

Fig. 4. Overview of the DEMO WCLL BB PHTS.

Table 4
Main WCLL BB PHTS design parameters.

PHTS type	Unit	BZ	FW
Thermal Power [MW]	MW	1483	440
Total pumps power to coolant	MW	12	4
Total water volume	m^3	563	159
Total pipework length [m]	m	3200	3700

Table 5
Number of main components per circuit.

PHTS type	BZ	FW
Steam generators	2	2
Pump	4	2
Pressurizer	1	1
Feeding pipes (hot/cold)	32/32	32/32
Header rings (cold/hot)	1/1	1/1
Main legs (cold/hot)	2/1	1/1

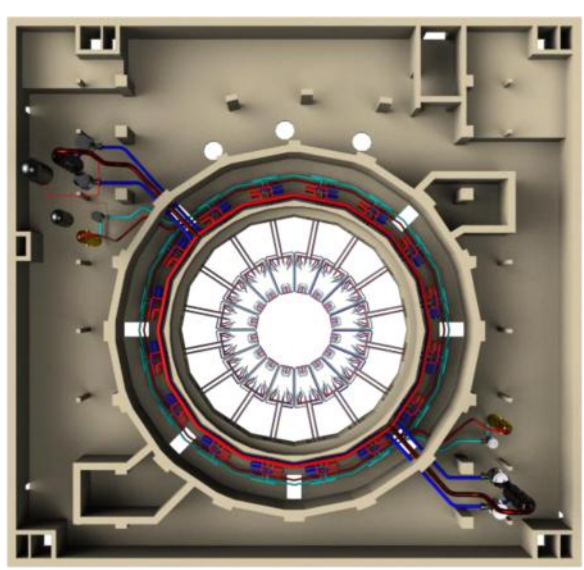

Fig. 5. Integration of the WCLL BB PHTS into the Tokamak building.

3.4. Vacuum vessel PHTS and decay heat removal system

The VV PHTS is segmented into 2 separate cooling circuits, one serves the even sectors of the Tokamak, the other feeds the odd ones. Heat removed from the VV is transferred to the PCS via 2 HXs (one per circuit) [31].

A Decay Heat Removal System (DHRS), powered by a small safety-classified pump, is annexed to the VV PHTS to cope with emergency cooling scenarios. Relying on natural flow is an alternative option that might be considered in the future.

Fig. 8 shows the main PHTS and DHRS components

The main function of the VV PHTS is to extract thermal power from the VV structures and transfer it to the PCS through the HXs. The VV PHTS provides the primary confinement to the VV coolant that carries tritium and activated particles. Currently, the VV PHTS concept is based on the use of forced convection pressurized water as coolant medium at about 3.1 MPa and inlet/outlet temperatures is 190 °C and 200 °C, respectively [31].

The main parameters of the VV PHTS are shown in Table 8 Table 9. shows the number of components per VV PHTS circuit.

The DHRS is designed to provide the safety function of emergency decay heat removal when the other PHTSs are unavailable. In line with the ITER approach, it was decided to use the Chilled Water System (CHWS) as main heat sink for the DHRS, which has to remove the decay heat from all in-VV components during emergency conditions. The assumption of using the CHWS is preliminary and will be further discussed during the next DEMO Concept Phase. The DHRS is present in each VV cooling loop, so that, in case of loss of one of the two independent VV PHTS circuits, it is possible to rely on the DHRS equipment annexed to the available VV PHTS loop (full redundancy criterion). DHRS HX and DHRS pump are placed in a cooling line that bypasses the main HX and MCP. Further DHRS improvement is envisaged that will arrange the two systems in different area of the PHTS area so that to implement the criterion of physical separation of safety redundant systems.

A VV PHTS loop consists of: In-VV cooling circuits belonging to eight VV sectors, a main HX, a pressurizer, a main coolant pump, and connecting pipes between these components. The annexed DHRS is made of a HX, a pump and connecting pipes. The piping (per each cooling loop) foresees hot leg, cold leg, crossover pipe, hot ring, cold ring, sixteen feeding pipes, DHRS hot leg, DHRS cold leg, and DHRS crossover pipe.

All main equipment is located in the Tokamak cooling room on the

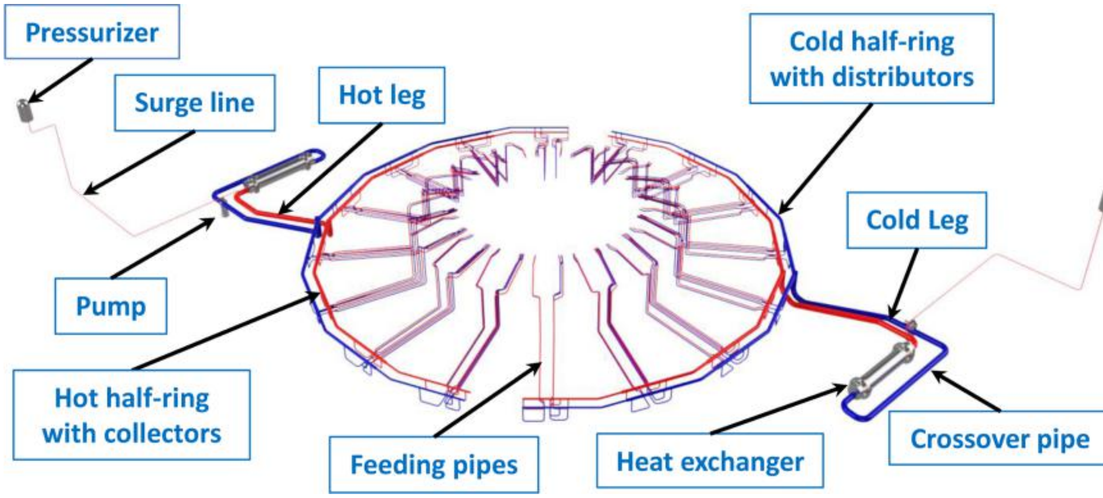

Fig. 6. General arrangement of the two circuits of divertor PFCs PHTS.

Table 6
Main divertor PHTSs design parameters.

PHTS type	Unit	PFCs	Cassette
Thermal Power	MW	136	115
Pumps power to coolant	MW	14	2
Total water volume	m^3	114	130
Total pipework length	m	1550	2790

Table 7
Number of components per divertor PHTSs loop.

PHTS type	PFCs	Cassette
Heat exchanger	1	1
Pump	1	1
Pressurizer	1	1
Feeding pipes (hot/cold)	24/24	24/24
Header rings (cold/hot)	1/1	1/1
Main legs (cold/hot)	1/1	1/1

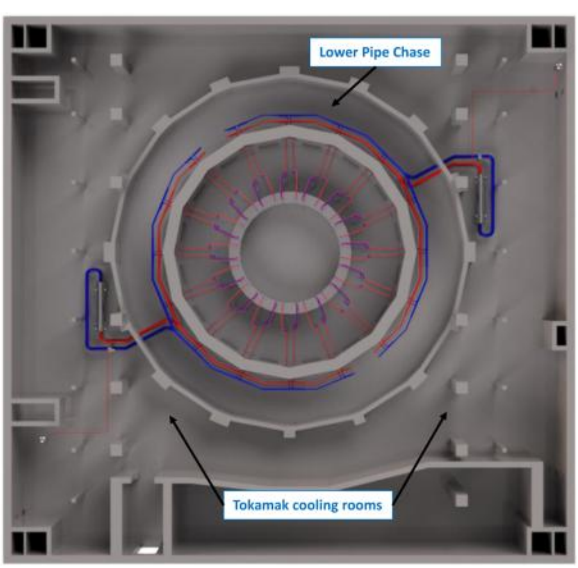

Fig. 7. Integration of the divertor PFCs PHTS into the Tokamak building.

upper level of the Tokamak Building (see also [25]) Fig. 9. shows the preliminary integration of the system into the Tokamak Cooling Rooms. The pumps are located near the exit of the main HXs; a crossover pipe connects the HX to the pump, which, downstream, is connected to the cold leg.

4. HCPB BoP

Transfer of fusion power to the electrical grid can be performed using either direct or indirect variants. During the PCD Phase, several variants were investigated to assess advantages, drawbacks and potential showstoppers. For HCPB four variants were investigated [6]: three direct coupled, one with a gas fired auxiliary large boiler (HCPB DCD BoP-AUXB) [32] and two with a small ESS (HCPB DCD BoP [33] and HCPB DCD BoP-Solid storage system [34]) and the reference HCPB-DEMO design, the Indirect Coupled Design HCPB ICD BoP [35].

4.1. Investigated variants

As previously mentioned, the two main requirements considered in the assessment of the variants are:

- to avoid disconnection from the grid at each pulse/dwell phase;
- to reduce the impact of frequent temperature transients to structures and components.

Moreover, integration, performance, safety and cost aspects are taken into account in the integral analysis performed for each variant. The latter are not reported here.

A list of the main HCPB BoP variants investigated is reported in Table 10. It summarizes and compares the most relevant features of each variant, highlighting high-level design choices and the identified critical issues together with the points to be further investigated during the DEMO CD Phase.

4.1.1. Indirect coupling design with intermediate storage loop (ICD)

The first variant was the HCPB ICD BoP, which uses an Intermediate Heat Transfer System operating with molten salt (HITEC) to decouple regular plasma strokes from the PCS. The IHTS design uses qualified technology coming from CSP plants (150 MW_e and energy storage up to 1 GWh_{th}).

The analysis performed including design improvements by industry focused on different PHTS and the PCS (i.e. feedwater train optimization for pulse and dwell conditions) have allowed the BoP team to find reasonable answers for all challenges investigated so far. The HCPB ICD

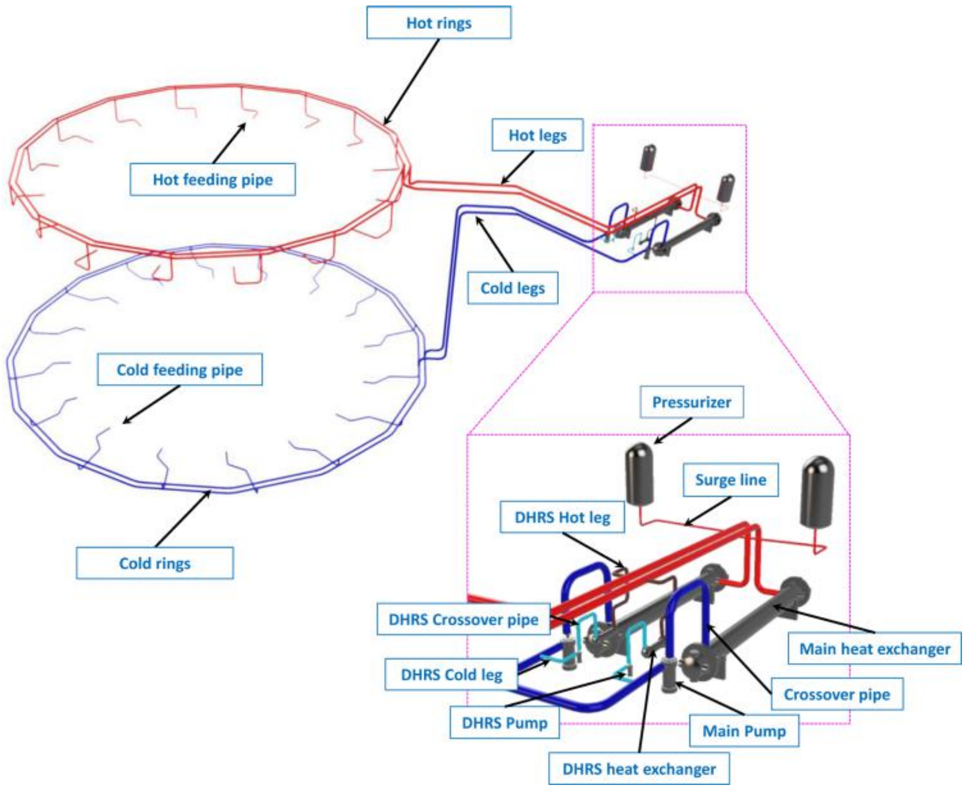

Fig. 8. Overview of the VV PHTS and DHRS.

Table 8
VV PHTS design parameters.

Parameter	Unit	Value
Thermal Power	MW	86
Pumps power to coolant	MW	2
Total water volume	m^3	300
Total pipework length	m	2480

Table 9
Number of components per VV PHTS circuit.

Component	Value
Heat exchanger	1
Pump	1
Pressurizer	1
Feeding pipes (hot/cold)	8/8
Header rings (cold/hot)	1/1
Main legs (cold/hot)	1/1

BoP is therefore considered as the reference variant for the next step of DEMO development and will be explained in more detail in Sect. 5.2.

4.1.2. Direct coupling design with large auxiliary boiler (DCD-l)

In order to avoid the loss of synchronization during dwell time, a gas-fired boiler was considered to provide steam flow to keep the power train in operation. The size of the boiler is directly connected to the minimum steam mass flow rate through the turbine. Different turbine concepts allow different levels of lowest operation power keeping the frequency constant. The main challenge is however to cope with the fast power transients, while keeping the turbine in a safe operational state.

A second challenge is to keep the required power of the auxiliary boiler in the range of several hundreds of MW during dwell time. This requires an additional infrastructure, which consists of an Auxiliary Heater Section (AHS), comparable to a small gas fired power station (around 200 MW_{th} if turbine would be driven at about 10% of its nominal power), requiring a sufficiently large gas pipeline. Main drawback is that during pulsed operation the boiler experiences temperature and pressure transients that are difficult to manage. The assessment of costs, requested size and heat transfer constraints lead to the decision to keep this option as potential back-up solution. Nevertheless, it should be remarked that the adoption of a relevant heating source from fossil fuel in support of a fusion plant makes this solution unattractive with respect to other proposals.

4.1.3. Direct coupling design with small boiler plus solid state ESS (DCD-s1)

The second DCD variant collects fusion energy during pulse and stores it in a solid-state ESS for dwell time purpose. This reduces boiler size and DEMO power output so that this variant becomes more reasonable. A significant drawback here was the energy storage system, realized adopting concrete-like storage material (HEATCRETE®) [36], which cannot release the thermal energy within the relatively short dwell time.

Furthermore, piping and control systems become very complicated and, most important, the solid-state ESS works also as a HX: during pulse the PHTS supplies heat to the concrete-like storage material that contextually stores energy and transfers power to the PCS, which then removes the stored heat into the concrete during dwell. This would imply that the whole ESS should be placed within the tokamak building to ensure that an adequate number of confinement barriers between PHTS and the environment would be kept against radioactivity releases. For these reasons, further investigations were postponed to the CD Phase as a remote back-up solution.

4.1.4. Direct coupling design with small ESS plus electrical boiler (DCD-s2)

A third variant developed by industry uses HITEC molten salt (400 m^3) and a 41 MW_e electrical heater [37,38]. This is done to maximize electrical power production of the PCS during the pulse and to maintain synchronized the electrical generator to the grid during the dwell period, when the steam turbine is being operated at a minimum

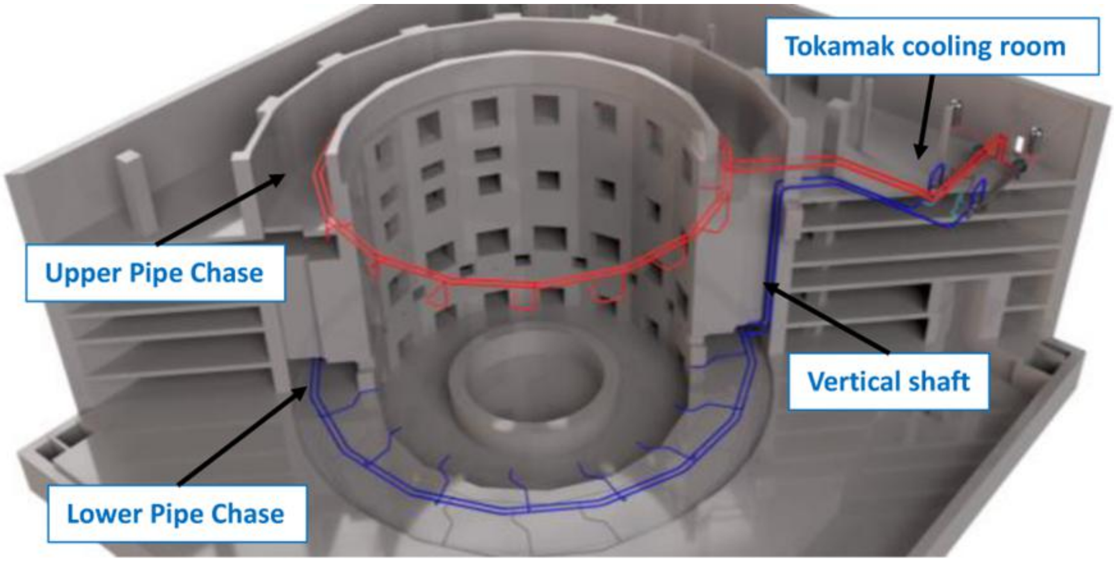

Fig. 9. Preliminary integration of the VV PHTS and DHRS into the Tokamak building.

operational load of 10%. All auxiliary components belonging to PCS are concentrated in the AHS section.

The preliminary architecture and transient analyses have been done and have shown that, amongst the three direct-coupling options investigated, this is the most suitable for accomplishing DEMO needs. Further studies, focussed on creep assessment and start-up evaluation are needed to confirm this solution, which, in such case, would be considered as first back-up choice if the ICD option would present some design integration challenges; the latter in fact might be optimized through the adoption of this more compact solution.

4.2. Reference variant: HCPB ICD BoP

The HCPB ICD BoP variant comprises the three different loops. A simplified scheme of the HCPB ICD BoP variant is reported in Fig. 10 while its 3D CAD layout is shown in Fig. 11.

The designs of the IHTS and PCS benefitted from industrial CSP experience. The base design was supported by industry so that for the next step a scaled system becomes necessary to investigate all dynamic capabilities. To provide that step, dynamic models and coupled simulations have been prepared. Preliminary studies on the Cost of Energy (CoE) have already been performed. During pulse, 90% of the power is delivered to supply the grid while 10% is stored in the ESS. During dwell time, the ESS releases energy to the PCS supplying 104% of the pulse electrical output (882 MW_e) to facility and grid.

4.2.1. IHTS

The IHTS collects energy from the BB PHTS in the ESS during pulse, controls BB inlet temperature via HX secondary side inlet temperature and then transfers thermal energy to the steam generator/superheater as requested by the PCS.

During dwell, the HITEC mass flow rate is adjusted to the need of the BB decay heat removal on the left side of Fig. 10 using a dedicated small pump. On the right side of Fig. 10, like in the pulse time, it follows the requests of the PCS. To achieve such a decoupling function, 2–3 HITEC pumps are foreseen, both operating independently from each other. For operation and safety reasons, twin pumps are required to guarantee redundancy. For simplification, the ESS is realized as a classical two-tank solution. On-going research (in CSP domain) focusses on the more compact single tank solution, which has the advantage to avoid the costly high temperature HITEC pump and to reduce space for the IHTS. For the molten salt steam generator, a technical offer and price indication from Company Siemens AG is available. The Company Siemens AG supplies both the design for the turbogenerator and the steam generator, as the interaction of these two large components have a high impact on system performance and space and cost optimization.

The main design and operating parameters of the HCPB ICD BoP IHTS are summarized in Table 11.

4.2.2. PCS

During the PCD Phase, the PCS (Fig. 10, right side) has been optimized based on the different variants and the available energy sources. The detailed design proposed by industry gave a breakthrough properly tuning the turbine-feedwater train.

In particular, the steam turbine configuration consists of a steam turbine with two steam re-heaters that use steam from steam extractions of the high/intermediate pressure steam turbine. The main idea is that all hot molten salt should be used for steam generation, all the steam should go through the steam turbine before being used anywhere else for steam re-heating or feedwater pre-heating. In the DEMO PCS, there are also two low pressure feedwater preheaters and two high pressure feedwater preheaters that use steam from different steam extractions of the steam turbine. A special steam extraction of the steam turbine is also connected to the deaerator.

The steam generator of the proposed DEMO BoP configuration is a two-stage Steam Generator (SG). During pulse, first stage SG generates steam at ~291 °C and ~59 bar while the second stage SG generates steam at ~446 °C and ~121 bar. During dwell time steam parameters are slightly different. First stage SG generates steam at ~293 °C and ~60 bar while the second stage SG generates steam at ~442 °C and ~134 bar. Steam parameters leaving the first stage of SG are nearly constant during the whole DEMO operation so to keep the temperature of the cold molten salt returning to the cold tank at ~270 °C.

Table 12 reports the main parameters of the HCPB ICD BoP PCS. In this respect, it may be underlined that the cycle and the overall efficiencies have been calculated according to the procedure described in [6].

The flexibility of the reference HCPB BoP variant allows adapting DEMO to the needs when design requirements are finalised.

4.2.3. Architecture and feasibility

The reference solution was mainly conceptualized by the research units involved in the HCPB development. Then several equipment as well as the PCS thermal cycle were checked by industry (Siemens and Kraftanlagen Heidelberg) and no critical issues on IHTS and PCS components were identified. Nevertheless, some areas of further

Table 10
Ranking map of the HCPB BoP variants.

System	System/component main characteristics & market readiness	DCD-l	DCD-s1	DCD-s2	ICD
PHTS	BB PHTS SG/HX	He-Water SG	He-Water SG	He-Water SG	He-MS HX
		He circulator[1]	He circulator	He circulator	He circulator
	BB PHTS SG/HX	Gas Nuclear Reactor	Gas Nuclear Reactor	Gas Nuclear Reactor	Gas Nuclear Reactor and CSP
	PHTS Technological Derivation	Medium-High	Medium-High	Medium-High	High-~Atmospheric
AHX/IHTS	IHTS/ESS Fluid	-	-	HITEC	HITEC
	IHTS/ESS Storage Capacity	-	-	2x400m^3	2x3000m^3
	Other Thermal Storage	-	Concrete	-	-
	Auxiliary Heating System	Gas (220 MW_{th})	Gas (93 MW_{th})	Electric (41.2 MWe)	-
	Gas Fired Boiler Supply	Large	Medium	-	-
	Space for Aux. Heating Syst./IHTS (+Storage)	Large (Aux.)	Large (Aux+ Conc.)	Very Small (Electr.+ very small ESS)	Large (IHTS+ Large ESS)
PCS	Turbine readiness for operation at dwell load	TBI	TBI	TBI	Yes
	Tolerant to frequent pulse-dwell transients	TBI	No	TBI	Yes
Variant	Power output/Supplementary power needed	Yes, small in dwell + Gas	Yes, small in dwell + Gas	Yes, small in dwell + Electr. Power	almost constant -
Safety	Inherent Safety Barriers to PCS (T, ACP)	1	1	1	2
Summary	**Variant critical components**	Ext. Gas Boiler; He-Water HXs; ST; He circulator.	Concrete ESS; He-Water HXs; He circulator.	He SG: MS SG, Reheater: ST; He circulator.	He-MS HX; He circulator; MS SG.
	Preliminary Variant Feasibility Assessment Status	TBI	TBI	TBI	TBI

Legend

- (pink) Critical issue regarding component size and integration or functional feasibility or market readiness or strategic aspects).
- (light blue) Market readiness: producible but not in shelf.
- (yellow) Market readiness: near or at present feasible and producible.
- (green) Market readiness: component from shelf/ technology available.
- TBI TBI TBI (grey shades) To Be Investigated further; since no full confirmation of the variant feasibility has been achieved in Pre-CDP. Grey intensity proportional to the extent of investigation performed on the variant.
- \- No/Not Applicable.

[1]No relevant market available for such large compressors which results in a lowered interest for currently producing such kind of He-compressors. Positive outlook is expected in case of a future fusion market scenario.

improvements were identified to be investigated in detail in the Concept Design Phase, especially with respect to the effect of operational transients previously mentioned.

The HCPB ICD architecture allows to operate the PCS under conditions very similar to conventional power plants, thus state-of–art technology can be easily employed.

Similarly, the IHTS and the ESS are designed adopting components and coolant conditions that are in-line with latest solutions developed

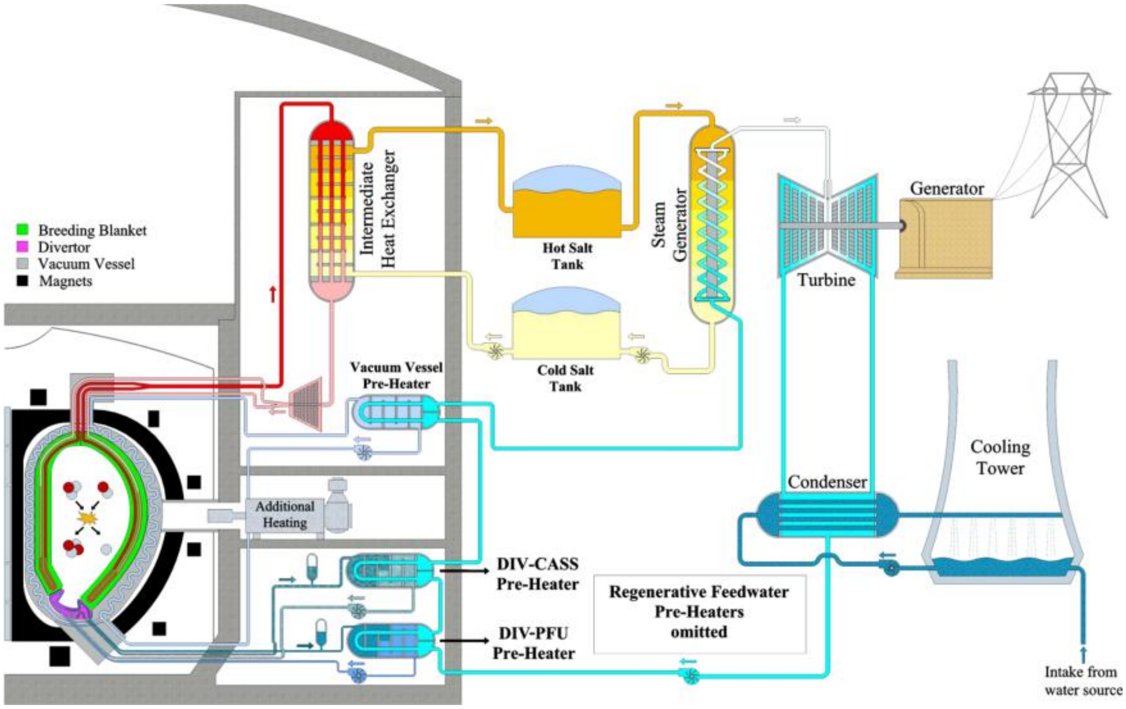

Fig. 10. HCPB ICD BoP simplified scheme [6].

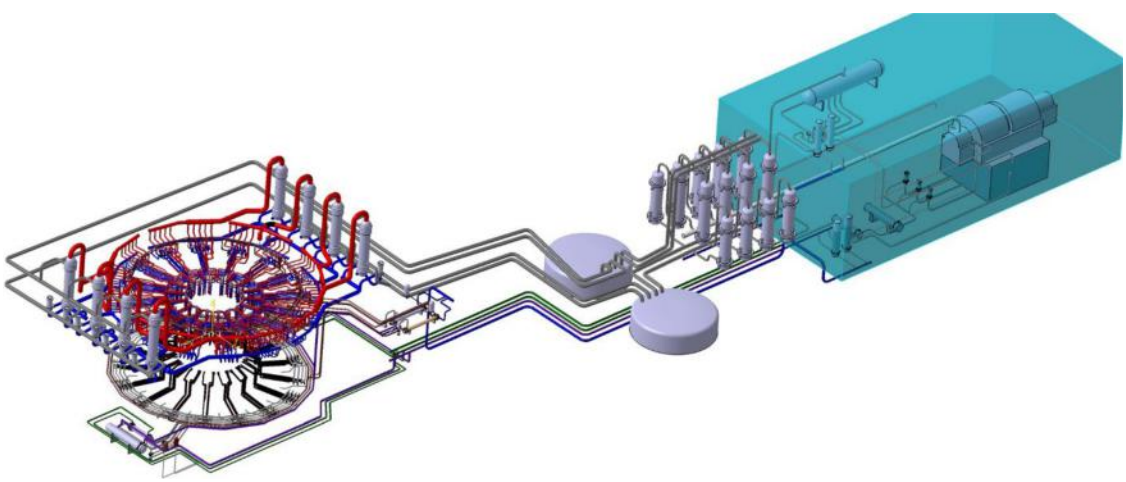

Fig. 11. HCPB ICD BoP layout.

Table 11
HCPB ICD BoP IHTS Main Parameters.

Parameter	Value
ESS capacity [MWh]	426
ESS hot/cold tank number	1/1
ESS tank molten salt volume [m^3]	2600

Table 12
HCPB ICD BoP PCS Main Parameters.

Parameter	Value
Gross Output (pulse/dwell) [MW]	882/930
Cycle efficiency (pulse/dwell)	37.6%/43.8%
Overall efficiency	34.1%
Steam turbine type	SST5–6000

for the solar power plants in commercial operation.

The system that still needs particular attention is the BB PHTS. The main equipment of this system has been designed considering the maximum heavy manufacturing capabilities demonstrated over the past decades by the nuclear industry [39]. Feasibility of pipework, heat exchangers and circulators seems to be achievable [40,41]: from preliminary discussions with relevant nuclear industries, PHTS components fall in a range of sizes/characteristics that can be manufactured with processes suitable to meet design and operational requirements foreseen for DEMO.

However, the helium technology may suffer from the lack of vendors that can supply nuclear equipment that must be qualified and quality controlled. The presence of few industries that keep know-how and expertise to develop helium components subjected to nuclear licensing might result in a poor market availability of the main PHTS elements. The risk is therefore to develop components that are hardly attractive for the market, thus preventing investments of resources from the suppliers.

Moreover, as with other generation technologies, supply constraints plus escalating steel and energy prices flow on to plant costs). Therefore, it is strongly recommended for the next CD phase that different manufacturers with well-established experience in the design of nuclear power plant components would be invited to contribute and optimize the design and development of the HCPB BB PHTS equipment; in particular, first priority should be given to helium circulators, which appears to be the most critical components to be developed and qualified to fulfil the strict PHTS requirements (high efficiency, excellent reliability, maximum leak tightness, large mass flow rate regulation, etc.).

6. WCLL BoP

Three main variants have been considered in the analysis [6]:

- one Indirect Coupling Design (ICD), consisting in an indirect configuration with an Intermediate Heat Transfer System and Energy Storage System (IHTS+ESS);
- two Direct Coupling Designs (DCD), consisting in a direct configuration with a small ESS and a direct configuration with an AUXiliary Boiler (AUXB).

6.1. Investigated variants

Each of the variants introduced presents advantages and drawbacks that must be taken into account in the analysis for the definition of the reference configuration for the DEMO plant.

The main requirements for the design of each variant are to avoid the disconnection from the grid for each pulse/dwell phase and to limit the impact of frequent temperature transients to structures, considering at the same time the feasibility of the solutions proposed, as well as performance, safety and cost aspects.

The design activity will continue to attain as a comprehensive as possible design development to allow the selection of a single WCLL variant, minimizing the risks of the still pending uncertainties.

The main WCLL BoP variants investigated are reported in Table 13. It summarizes and compares the most relevant features of each variant highlighting high-level design choices and the identified critical issues together with the points to be further investigated during the DEMO CD Phase.

6.1.1. Indirect coupling design (ICD)

The BoP DEMO plant configuration with Indirect Coupling Design (WCLL ICD BoP) foresees the use of an IHTS+ESS operated with molten salt (HITEC) to decouple the regular operational transients of the Tokamak from the PCS operation [42,43]. The energy recovered from the Breeding Zone (BZ) is delivered to the PCS, while the First Wall (FW) power is delivered to the IHTS, then to the PCS. The power from BZ and FW is used to produce the main steam at condition suitable to feed steam turbine. The energy recovered from the cold source, i.e. divertor and VV, is used instead of feedwater heaters, in order to improve the thermodynamic efficiency. The ESS of IHTS is designed to deliver 100% of the nominal power during the dwell time, assuring continuously the nominal power to the turbines for steam generation.

The main advantage of this configuration is the design requirement of continuous and nearly constant electrical power delivered to the grid in both pulse and dwell. The primary to intermediate system heat exchanger (Water/HITEC) is simple and it can be operated in conditions involving low thermal and mechanical stresses. Furthermore, the IHTS design can use qualified technology coming from the experience on solar power plants applications.

A disadvantage might be given by the large dimensions of the energy storage tanks. In fact, as consequence of the requirement of constant electrical power supply during dwell (i.e. ~100%), the amount of molten salt stored, and thus the dimensions of the storage tanks, are designed considering such power scenario. It should be also considered that large molten salt ESS tanks (around 11,000 m^3) might pose challenges not only in term of plant integration but also from a safety point of view because the storage systems may become a sink for the tritium migrating from primary system through the IHXs [44].

6.1.2. Direct coupling design with small ESS (DCD)

The DEMO plant configuration with Direct Coupling Design (WCLL DCD BoP) is based on the direct cycle [43,45], in which the BZ and FW Once through Steam Generators (OTSGs) are directly connected with the steam turbine of the PCS. The heat from the divertor PHTSs and VV PHTS are used as preheater for the PCS feedwater to increase the thermodynamic efficiency. The system foresees the adoption of a small ESS (with two tanks of 1500 m^3 each) operated with molten salt (HITEC), capable of feeding the steam turbine during dwell with a steam flow rate of about 10% of the nominal steam flow rate, maintaining the connection with the electrical grid with a minimum production of the electricity (enough for the PHTSs and BoP auxiliaries).

The BoP architecture has been studied with a detailed transient analysis and stress assessment [46] highlighting the effectiveness of the solution. The adoption of the small ESS simplifies the control of the system and, in particular, of the turbine.

The WCLL DCD BoP is considered as the reference variant for the next step of DEMO development and it is explained in more detail in Sect. 6.2.

6.1.3. Direct coupling design with auxiliary boiler (DCD AUXB)

A second solution has been conceived for the BoP DEMO plant configuration with Direct Coupling, with the adoption of an Auxiliary Boiler (WCLL DCD AUXB BoP) [47]. In this configuration of direct cycle, the BZ and FW PHTSs are directly coupled with the PCS through two OTSGs. The energy recovered from the divertor and VV is used to heat the PCS feedwater. The steam flow rate during dwell is assured by the auxiliary boiler, which consists of gas-fired boiler, designed to be directly connected to the turbine and sized to provide the minimum steam flow rate of 10% of the nominal value. The component works during both pulse and dwell time, providing 250 MW of power, thus the turbine works during dwell time at 10% of nominal power.

The main design features of components are comparable with existing ones from nuclear and conventional industry. This implies no challenge for the design, the manufacturing, the operation and the inspection. Nevertheless, the main drawback of this solution is the large power of the auxiliary boiler required to have an external source for operating the BoP at minimum load in dwell [48], envisaging a very large boiler, which makes this solution non-convenient with respect to other proposals.

6.1.4. Preliminary work on additional variant and suggestion from design review

A very preliminary study, useful to both confirm the feasibility and provide an optimization of DCD has been started and discussed at DR; it adopts basically the same architecture of DCD, but minimizing the energy storage to ensure a safe operation of the steam turbine in dwell; for the latter an innovative connection of the High Pressure section to the LP one is also postulated (HP ST connected to the LP stage through a clutch). This configuration, called "WCLL DCD NO STORAGE", will be further explored in the CD phase as part of the validation program of the DCD; it could represents an interesting optimization of the DCD itself after demonstration of the availability of the adopted technologies (i.e. high power clutches) and the feasibility of the concept (ST operation at very low steam load).

One suggestion from the panel of experts, who reviewed the WPBoP work in 2020, has been to take into account a BoP ICD option with an (Small) Energy Storage sized to the scope of operating at low load the steam turbine in dwell.

This architecture has been proposed considering the challenges of

Table 13
Ranking map of the WCLL BoP variants.

System	System/component main characteristics & market readiness	DCD	DCD-AUXB	ICD	DCD No Storage	ICD low load
PHTS	PHTS Technological Derivation	LWR NPP	LWR NPP	LWR NPP and CSP	LWR NPP	LWR NPP and CSP
	BB PHTS SG/HX	Water-Water SG	Water-Water SG	Water-Water SG; Water-HITEC HX	Water-Water SG	Water-HITEC HX
	BB PHTS HX/SG Pressures	High-Medium	High-Medium	High-Medium; High-Low	High-Medium	High-Low
AHX/IHTS	IHTS/ESS Fluid	HITEC	-	HITEC	HITEC/Water	HITEC
	IHTS/ESS Storage Capacity	2x1500m^2	-	2x11000m^2	~120/~300[1]	2x1500m^2
	Other Thermal Storage	-	-	-	-	-
	Auxiliary Heating System	Electric (41.2 MWe)	Gas (250 MW_{th})	Trace heating	Electric[2]	Trace heating
	Gas Fired Boiler Supply	-	Large	-	-	-
	Space for Aux. Heating Syst./IHTS (+ Storage)	Small (Elec.+ Small ESS)	Large (Aux)	Very Large (IHTS+ Large ESS)	Very Small (very small electr. and ESS)	Medium (IHTS+ Small ESS)
PCS	Turbine readiness for operation at dwell load	TBI	TBI	Yes	TBI	TBI
	Tolerant to frequent pulse-dwell transients	Yes	Yes	Yes	TBI[3]	TBI[4]
Variant	Power output/Supplementary power needed	Yes, small in dwell / + Electr. Power	Yes, small in dwell / + Gas	Almost const.. / -	Yes, very small in dwell- / + Electr. Power	Yes, small in dwell / -
Safety	Inherent Safety Barriers to PCS (T, ACP)	1	1	2	1	2
Summary	**Variant critical components**	SGs; ST	Ext. Gas. Boiler; SGs; ST	ESS tanks; SGs; Water-HITEC HX	SGs; ST; ?	H_2O-HITEC IHX; ST; ?
	Preliminary Variant Feasibility Assessment Status	TBI	TBI	TBI	TBI	TBI

Legend

Pink	Critical issue regarding component size and integration or functional feasibility or market readiness or strategic aspects).
Yellow	Market readiness: near or at present feasible and producible.
Light blue	Market readiness: producible but not in shelf.
Green	Market readiness: component from shelf/ technology available.
TBI TBI TBI	To Be Investigated further; since no full confirmation of the variant feasibility has been achieved in Pre-CDP. Grey intensity proportional to the extent of investigation performed on the variant.
-	No/Not Applicable.

[1]Preliminary upper estimates.
[2]An aux. heating system option postulates the use of a very small Electric Heater to heats up the coolant of the storage system.
[3]No assessment of thermomechanical stress available.
[4]Expected outcomes as in case of WCLL DCD with Small ESS; reported "TBI" light grey since the variant has not yet specifically addressed at all.

the WCLL DCD with small ESS, and it is judged to be possibly an interesting back-up solution for the WCLL BoP. This configuration would allow to minimize the uncertainties related to the regulation of the BoP systems during DEMO operation phases (e.g. simpler control of the primary circuit by means of single-phase to single-phase heat exchangers and avoidance of any stability issues related to the operation at decay heat power of the large steam generators).

6.2. Reference variant: WCLL DCD BoP

The current reference variant of the DEMO WCLL is the Direct Coupling Design (WCLL DCD BoP) with small ESS. In this configuration, energy transferred from the BB PHTS (BZ and FW) to the PCS through steam generators is used to produce the main steam in conditions suitable to feed the turbine. The energy from the divertor and VV PHTSs is used to preheat the PCS feedwater. The integration of divertor and VV heat exchangers in the feedwater heat-up chain allows improving the overall plant efficiency. The WCLL DCD BoP results to be the most promising variant, since it is designed to maximize electrical power production during pulse and to maintain synchronized the generator to the grid during dwell period. This is obtained implementing a small molten salt ESS (about 200 GJ of thermal energy stored in a hot tank of about 1500 m^3 with molten salt inventory of about 2700 tons) that is necessary to produce sufficient steam flow to drive the steam turbine and to keep main PCS components hot. The power compensation during dwell occurs downstream the SG. This configuration has been selected in order to limit complexity (and hence safety and integration challenges) of BB PHTS.

A sketch of the WCLL DCD BoP layout is reported in Fig. 12 3.D CAD model of the whole BoP variant is provided in Fig. 13.

6.2.1. PCS and ESS

The WCLL PCS is composed of one loop fed by the steam coming from the BB PHTS SG and it is connected with the VV, the divertor-PFC and the divertor-cassette PHTSs using their main HXs as preheaters. The PCS is integrated mainly into the turbine building, with few piping connections from the tokamak building (for divertor-PFU, divertor-cassette and VV HXs). The reference thermodynamic cycle of the PCS is based on superheated steam at 6.41 MPa and 299 °C, preheating the feedwater at 238 °C.

The PCS Rankine cycle is composed of: steam turbine with condenser, low pressure and high pressure feedwater heaters, deaerator, condensate extraction pump, feedwater pump, low pressure forwarding pump, condensing cooling water pump and the connecting piping between these components.

The PCS Small ESS loop is composed of: molten salt pumps and tanks, electrical heaters, steam generator and the connecting piping between these components. The tanks have a volume of 1500m^3, containing an inventory of about 2700 tons of molten salt. The total thermal energy stored is about 200 GJ.

The small ESS loop feeds the steam turbine during the dwell at about 10% of the nominal steam flow rate, maintaining the connection with the electrical grid with a residual production of the electricity (enough for the PHTSs and PCS auxiliaries). The thermal power needed to heat the HITEC comes from an electrical heater operated during pulse.

The PCS include also the electrical generator which, in any case, is not part of the WPBoP design activity.

Concerning the ESS, a comprehensive analysis was performed in the past [49] where flywheel both at high (20,000 rpm) and low speed (1500–3600 rpm) were considered. Nevertheless, due the maximum stored energy, they were found inadequate to handle the DEMO dwell phase. It should also be noted that in the mentioned study, molten salt storage were considered reliable as ESS, since it has been demonstrated in solar plants. A recent industry study on WCLL DCD option with small ESS confirmed molten salt as the optimal choice in term of maturity and suitability of the solution for DEMO application.

6.2.2. Architecture and feasibility

It has to be noted that an important study has been committed to a lead Industry operating in the field of the power plant (ANSALDO ENERGIA-AEN) to identify a suitable PCS architecture. The study included the evaluation of the heat balances during pulse and dwell, preliminary components size, plant control loops design and transient analysis with the main aim to evaluate thermal and mechanical loads in

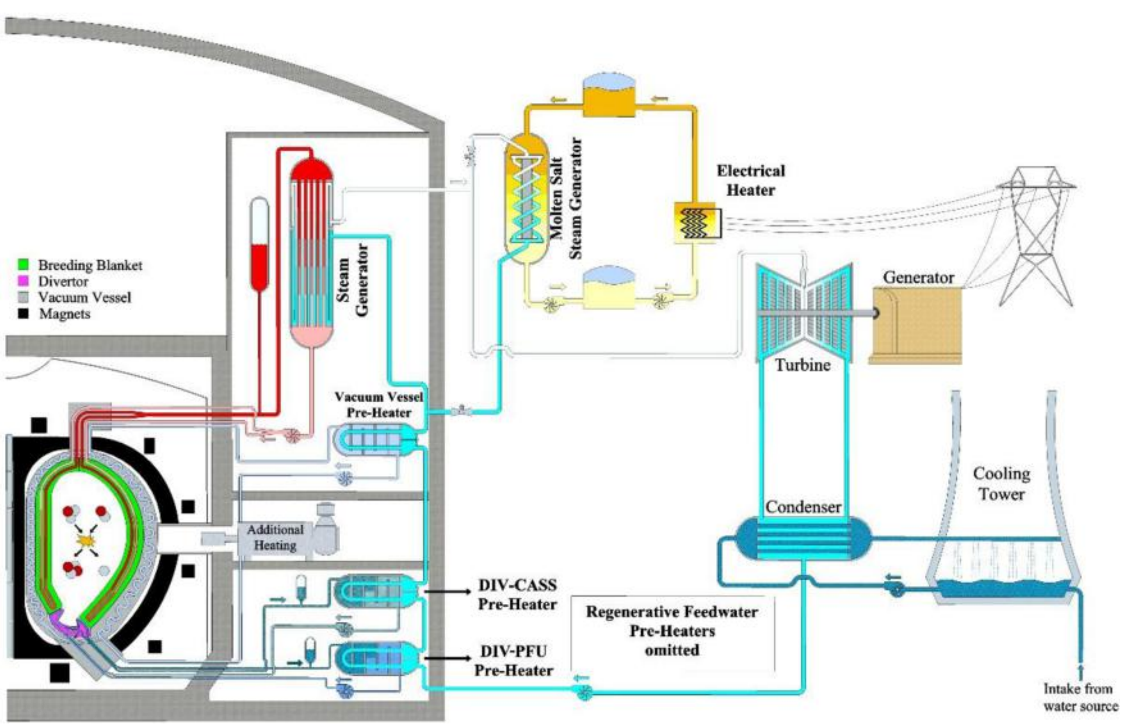

Fig. 12. WCLL DCD BoP simplified scheme.

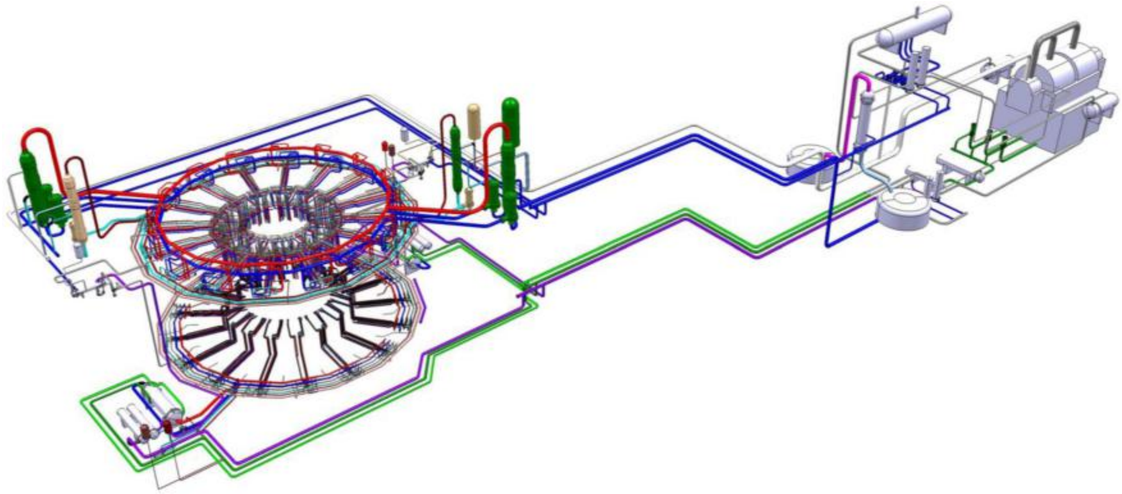

Fig. 13. WCLL DCD BoP layout [6].

PCS components including the steam turbine (see [46,50]).

The PCS is optimized in order to limit thermal stresses and maintain the generator synchronization with the grid during dwell, thanks to the actuation of an auxiliary circuit to produce a low steam load (around 10% of nominal) ensuring continuous operation also in dwell. Concerning the operation of the PCS, the regulation strategy proved to be effective in sustaining the whole transition pulse-dwell-pulse and in bringing each operative parameter back to its original value after the transient. The thermal and mechanical stress levels are very low in each PCS components (and hence also in the divertor and VV integrated HXs and BZ/FW PHTS OTSGs) including steam turbine, for which a dedicated transient FEM analysis was carried out. Thus, it can be stated that for this plant option, the PCS feasibility is not challenged by stress concerns.

The direct control of the primary temperature represented a significant challenge due to the small operational saturation margin at the OTSG outlet and the very fast plasma dynamics requiring a fast response incompatible with the secondary side thermal inertia of the heat exchangers. In addition, the requirement of the constant nominal primary coolants mass flowrate (of the order of thousand kg/s) in pulse and dwell to be controlled by a small feedwater flow in dwell (of the order of a ten of kg/s). This means that it has not been possible to achieve a direct fine control of the primary coolant temperature to the required setpoint (e.g. the coolant average temperature in dwell). Nevertheless, further improvements could be obtained through a more refined model considering of BB/divertor/VV thermal inertia, of a detailed knowledge of the plasma and heat exchanger dynamic behaviour and its modelization (to compensate with ad-hoc anticipated ramps and a dedicated model predictive control) or, better, enhancing the saturation margin (which instead has the potential drawback of changing the PCS operational point).

In any case, it is worth to say that an alternative indirect regulation based on the control of the DEMO heat sources rejected power to PCS provided good results. Namely, the average primary coolant temperatures are kept very close to the setpoint without harming ST with water and limiting, as stated above, the thermal stress everywhere in PCS. It seems then necessary to evaluate the impact on BB/divertor/VV PHTS design in order to verify the possibility to relax the requirement and accept this regulation strategy.

A comprehensive assessment (including a suitable R&D included as part of WPBoP [7]) aims at verifying the safe and reliable operation of the steam turbine at low load (presently @ 10%), will address the possibility to: i) operate the turbomachinery without adverse LP blade ventilation or vibration issues; ii) make design modifications to turbine if needed. These actions will be carried out in the frame of a broader plan focusing on the investigation of the minimum flowrate to operate safely the steam turbine in dwell so that to minimize the required storage for dwell operation (the NO storage configuration introduced above).

Considering the challenges of the WCLL DCD with small ESS, an interesting back-up solution for the WCLL BoP might be an ICD option with a small ESS to operate at suitable low load the steam turbine in dwell. This configuration would allow minimizing the uncertainties related to the regulation of the BoP systems during DEMO operation phases (e.g. simpler control of the primary circuit by means of single-phase to single-phase heat exchangers and avoidance of unconventional operation of the PCS equipment). In addition, such a variant would keep the size of the energy storage as close as possible to that of the WCLL DCD Small ESS concept.

7. Safety considerations

The DEMO safety investigations were conducted in the Work Package Safety and Environment (WPSAE) [51]. The focus here is on scenarios affecting BoP systems.

Presently, the Work Package Safety (WPSAE) is working on the definition of a Room Book definition [52], providing preliminary information about the environmental conditions at which various SSC (including SIC) will operate during the DEMO life, both during normal and accidental scenarios, for the rooms of the DEMO Tokamak building.

The Room Book will be useful to verify the suitability of the present design (e.g. feasible qualification of SSC, particularly those SIC classified) or instead the need to optimise it.

. Interaction with WPSAE is underway to evaluate the completeness of a Design Basis Accident (DBA) as well as to decide to retain or not in DEMO the Leak Before Break (LBB) design approach for high energy lines. WPSAE is also performing analysis of major accident as In-VV BB/divertor LOCA, Ex-Vessel BB/divertor LOCA, LOFA.

With regard to the reference HCPB BoP, the PHTS segmentation (8 loops BB PHTS) reduces the potential release rate in the worst case of an in-vessel LOCA to two BB PHTS loops, so that pressure build-up in the VV, including all connected cavities, can be accommodated by an optimized VVPSS/EV system [53,54]. Solutions used in process and chemical engineering are investigated and their application to the VVPSS/EV assessed. To solve the challenge to cool-down and clean the helium before releasing it into the huge vaults of the Tokamak cooling rooms detailed dynamic analyses are foreseen in the CD Phase. Backup solutions are under investigation to reduce contamination.

On the other hand, concerning the reference WCLL BoP, the WPBoP has started an internal study to evaluate the: i) activity along BB PHTS due to the decay of isotopes ^{16}N and ^{17}N [55] and ii) the spatial distribution of Photonic and neutronic dose [56,57]. The study was aimed at evaluating the absorbed dose at the PHTS location where a hypothetical isolation valve could be placed and method of mitigation. Results of these assessments are also summarized in [58,44].

Some studies of In-VV LOCA are described in [44]. Moreover, additional considerations on the Ex-Vessel LOCA scenarios and the implication on the integration of the PHTSs within the tokamak building are reported in [25].

With specific regard to a LOCA for the HCPB concept, the event of (very) fast discharge of helium coolant from a highly pressurized system might challenge the area in proximity of the break location (jet impingement, pipe whip, sub-compartment pressurization, and fluid system decompression). Although these phenomena are present and must be investigated even in case of a rupture in a water-cooled system, the time scales characterizing these transients in a helium circuit are usually much shorter, therefore the consequences on the structures can be more severe. It is hence recommended to make, during the CD Phase, detailed assessments of the effects that are localized to the area of the break and are a result of the dynamic effects of a pipe rupture.

For the main safety objective to keep Tritium and Activated Corrosion Products (ACP) inside the nuclear island, the main heat exchangers of the PHTSs act as interfaces which should minimize (ideally avoid) any contamination of the IHTS/PCS. The variant HCPB ICD BoP with the IHTS might offer some advantages, being present an additional barrier system between the BB PHTS and the water/steam in the PCS. However, the potential contamination of huge inventory of molten salt due to tritium migration through the IHXs is cause of concerns if a non-nuclear classification of the IHTS equipment wants to be pursued. The permeation of Tritium to the HITEC system is presently under investigation [59] to control T level in the molten salt. Preliminary analyses and considerations on this topic have been addressed within the KDII2 activities [44,60].

8. Conclusions and lesson learned

The study presented in this paper aimed at assessing and comparing direct and indirect coupling BoP variants for DEMO, in order to find out the most promising option for both HCPB and WCLL BB concepts. This study was motivated by the need to highlight pros and cons for the different BoP variants conceived for both blanket concepts to ensure:

- acceptable operation conditions of the main PCS components;
- stable working conditions in all BoP systems, PHTS, PCS and IHTS (if any);
- good RAMI predictions.

With the caveats described in the text, this study has led to the identification of a clear reference solution for each BB option.

Concerning the HCPB BoP, the ICD variant appears the most promising concept amongst the BoP variants investigated. The adoption of the IHTS equipped with an ESS allows the connection of the PCS to the grid and enable DEMO to work as baseload power plant. Helium thermal cycle allows keeping the ESS size within reasonable values. The two storage tanks would be around 3000 m^3 each, which is well below the current dimension employed in Concentrating Solar Plant (more than 10,000 m^3 each).

On the other hand, the DEMO WCLL DCD with small ESS configuration appears the most promising concept amongst the WCLL BoP options investigated and it has been taken as reference variant to be further investigated in the future for design and technology choices verification and validation. It allows to supply the turbine with a modest amount of steam (around 10% of nominal) necessary to avoid high thermal transients in the main equipment and keep the stresses below the acceptable limits with reasonable safety margins. Furthermore, this option manages to maintain the turbo-generator at the nominal speed (and then synchronized with the grid) because a reasonable amount of steam is continuously provided to the turbine during all DEMO operational phases.

This configuration has been selected to limit complexity and hence safety and integration challenges of the whole BoP architecture. On the other hand, a pure direct cycle (without any kind of storage system and postulating a steam turbine “ON/OFF” operation in pulse/dwell or dragged by the electric generator) seems not viable at the current status of the studies due to the adverse impact on qualified life of some equipment, especially the steam turbine.

Considering the challenges of the WCLL DCD with small ESS, an interesting back-up solution for the WCLL BoP might be an ICD option with a small ESS. This configuration would allow to minimize the uncertainties related to the regulation and stability of the BoP systems during DEMO operation phases (e.g. simpler control of the primary circuit by means of single-phase to single-phase heat exchangers and avoidance of large steam generation operation at decay heat power).

Regarding the design and integration issues, it was confirmed that use of helium as blanket coolant facilitates the adoption of an ESS as the larger temperature window allows the BoP to be equipped with storage systems whose size, with the same amount of stored energy, is quite smaller than in case of water-cooled blanket. However, it was interesting to notice that also in case of WCLL ICD BoP option, the overall tanks capacity that should be installed (less than 25,000 m^3) is well below the state-of-art of current CSP technology ($\approx$130,000 m^3) [61,62].

Preliminary RAMI analyses of both the reference options have been performed through Failure Mode, Effect Analysis (FMEA) and the Reliability Block Diagram (RBD) methodologies [63]. A complete list of potential failures that could occur inside the plant has been outlined and the estimation of the time for the unavailable system/reactor has been predicted for two cases, with and without intervention of system protections. These assessments have also showed that appropriate actions (e.g. design and maintenance improvements) can enhance the overall availability of cooling and balance of plant systems.

However, it is worth to notice that preliminary RAMI assessments were based on very preliminary design information. Therefore, although systematic and rigorous analyses were carried out, the results highlight what could have been anticipated by intuition: at this stage of the project the parameter that mostly affected outcomes was the number of system components. As a matter of fact, the larger number of critical components in the HCPB BoP configurations with respect to the WCLL configurations produces lower availability values for this concept. Similarly, the inherent simplicity of PHTSs respect to ESS and PCS (presence of a few of active components vs huge number of valves, pumps etc.) indicates that, in general, tokamak cooling circuits seem the less critical systems from the reliability point of view as regard to the heat transport chain.

9. Outlook and challenges to be faced in DEMO concept design phase

One of the main objectives is the improvement of the overall reliability of the systems to ensure the best availability of the plant. To this end, the use of proven processes with commercial components will be a relevant strategy together with the reduction of the complexity of the plant.

The feasibility of HCPB BoP configuration is judged mature and the manufacturing of main equipment seems possible with limited extrapolation for some components (e.g. circulators) respect to state-of-art technologies. However, it must be emphasized that helium technology may suffer of the lack of vendors that can supply the plant with nuclear qualified and quality controlled components. The risk is therefore to develop a design of cooling system options that are hardly attractive for the market, thus requiring additional costs to be manufactured. It is strongly recommended for the next CD phase that different manufacturers, with well-established experience in the design of nuclear power plant components, would be invited to contribute and optimize the design and development of the HCPB BoP equipment. In particular, first priority should be given to helium circulators, which appear to be the most critical components to be developed and qualified to fulfil the strict PHTS requirements (high efficiency, excellent reliability, maximum leak tightness etc.).

The feasibility of WCLL BoP with DCD option can also take advantage from the use of available commercial components (PWR experience), even though some of them might operate under unconventional working conditions. Despite the encouraging outcomes obtained during the PCD phase, it must be remarked that further effort, both in terms of numerical analyses and R&D tests, are necessary to validate this promising option and address the remaining technical uncertainties. Currently, there is very little experience of NPP PCS cyclic operations in such a wide range of power, but it is well-known that under certain conditions and features of the circuits, two-phase flow instabilities may occur in components such as the steam generators, when they are operated at low load. Similarly, low load operations might undermine the blade performances of last stages of steam turbines causing local problems of various nature into the component (ventilation, vibrations, overheating, etc.). Future activities will be therefore devoted to analyse in detail operations of steam generators and turbine in the large off design conditions they experience in dwell,ranging from around 1% (very low load) to around 10% (low load). Specific test, supported by numerical assessments with dedicated tools are hence foreseen during the development of DEMO CD phase to verify the appropriateness of the design solutions and performances of the relevant equipment when operating outside of the usual working ranges.

It should be noted that if a DCD solution is chosen as preferred BoP architecture, the gross electrical output of the plant will experience variations of about one order of magnitude between Pulse and Dwell periods, therefore studies on the response of the grid and the Plant Electrica System [20,64] are needed to support the BoP design choices.

As regard to the approach for the management of technical risks, it is mandatory that RAMI activities on critical systems are carried out, as they are an essential driver in the decision and selection amongst different concepts. In addition, future studies will need to be accompanied by some experimental tests on the use of turbines and other PCS components with cyclic feeds. Due to lack of reliable data for systems operating in cyclic mode, preliminary RAMI evaluations for all BoP variants, adopted failure models available in literature, which usually refer to continuous and stable operating cycles. However, ICD and DCD options have different time loads on main PCS components therefore the assumptions made must be hereafter validated or modified when there will be more reference feedback to be taken. In addition the (poor) database for Helium and molten salt components needs to be extended in the CD-phase.

As a final remark, it should be emphasised that the remaining integration challenges, not addressed within the study presented here, will be faced in the DEMO Concept Design phase. In fact, these preliminary study started in PCD phase, did not have the ambition to cover all possible engineering and integration challenges that might impact the design of cooling systems and the whole DEMO BoP. It was decided to follow an approach aimed at a deep understanding of some key points concerning thermal-hydraulics and reliability/availability issues peculiar of the cooling systems of the DEMO plant. This was judged as the most effective way to down-select the most promising solutions amongst the various BoP architectures proposed.

A further insight on issues and perspectives strictly related to the technology maturation of the BoP systems and components will be presented in another chapter of this issue [7].

Other important aspects related to cooling systems design and development are discussed elsewhere in this special issue (see for example [44,58]).

For instance, safety challenges such as incidents and accidents management or characterizations of radioactive source terms are addressed in [65,51]. Problems and solutions related to the control and mitigation of tritium migration through cooling circuits and the tokamak building, therefore concerning the development of permeation barriers, tritium recovery processes maintaining a very low tritium activity in the coolant, and control of the coolant chemistry can be found in [44,58]. Additional activities addressing solutions and future actions to fulfil the need of segregating and minimizing radioactive inventories carried by coolants and peculiar of FPPs are still traceable in [44,58] (e.g. issues related to ^{16}N and ^{17}N isotopes due to water activated under high energy neutron fluence).

CRediT authorship contribution statement

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014–2018 and 2019–2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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