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Status of EU DEMO Heat Transport and Power Conversion Systems

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DEMO in Europe is considered to be the nearest-term reactor design to follow ITER and capable of demonstrating production of electricity, operating with a closed fuel-cycle and to be a facilitating machine between ITER and a commercial reactor. The aim of this paper is to show the design progress of the complex system's "chain" devoted to the extraction of the plasma generated pulsed thermal power and its conversion into electricity delivered to the grid, including the Primary Heat Transport System (PHTS), the Power Conversion System (PCS) and the Intermediate Heat Transport System (IHTS) -provided by an Energy Storage System (ESS) - in between PHTS and PCS, which is introduced for the scope of smoothing the generated pulsed plasma power removed by PHTS transmitted to PCS for a more continuous conversion/production of electricity and to guaranty plant lifetime. This will be done with reference to two breeding blanket concepts: the Helium Cooled Pebble Bed (HCPB) Breeding Blanket (BB) and the Water Cooled Lithium Lead (WCLL) BB.

The PHTS design criteria and the system design finalization through a descriptive 3D CAD model which shows the system inside the tokamak building is presented. The design and operational challenges as well as the on-going development plans to investigate possible design simplifications and improved technology readiness actions potentially leading to better plant reliability and cost minimisation are briefly described.

Keywords: DEMO, PHTS, Balance of Plant, PCS, ITER

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1. Introduction

The European Union (EU) Roadmap to Fusion Energy aims to produce electricity by nuclear fusion reactors around the middle of this century [1]. In this framework, the EU agency EUROfusion is developing a research project focussed on a DEMOnstration Fusion Reactor Prototype (DEMO) which shall deliver to the electrical grid several hundred MW of electricity at that date. DEMO is to be considered as the nearest-term reactor design following ITER, under construction in France, that will demonstrate its capability of electricity production and sustainability (e.g. of operation with a closed fuel-cycle).

The main objectives of the EU-DEMO project are [3, 4]: i) conversion of heat into electricity for several hundred megawatts, ii) achievement of tritium self-sufficiency (breeding ratio >1), iii) reasonable availability up to several full-power years, iv) minimization of radioactive wastes, with no-long-term storage; v) extrapolation to a commercial fusion power plant.

EUROfusion management team coordinates the design activity of several Fusion Research Units situated in the various EU countries and of their supporting industries, selected mainly among those having experience in fusion plants and Nuclear (fission) Power Plants.

The aim of this paper is to provide an overview of design progresses related to DEMO Balance of Plant (BoP) for two Breeding Blanket (BB) concepts: the Helium Cooled Pebble Bed (HCPB) BB and the Water Cooled Lithium Lead (WCLL) BB.

Differing from NPPs where the main system of the BoP is the Power Conversion System (PCS) that converts in electricity the thermal power extracted from the Primary Heat Transfer System (PHTS), in DEMO, instead, BoP means the complex “chain” of systems devoted to the extraction of the pulsed thermal power generated by the plasma and deposited in BB, Divertor (Div) and Vacuum Vessel (VV) and its conversion into electricity to be delivered to the external grid.

Considering the main goal of the EU-DEMO, it is understandable that the plant design has to be strongly oriented to BoP which must perform its intended function in a safe, reliable and efficient way. This would represent a significant change of the culture in the fusion community that was mainly focused on plasma performances and control and on the design of plasma facing components in order to withstand the plasma instabilities and relevant heat loads.

The paper briefly describes the characteristics of the main systems and components belonging to DEMO BoP, indicating design criteria, systems sizing and preliminary lay-out, transient analysis main outcomes.

The BoP design option described refers to the solution envisaging the use of an Intermediate Heat Transfer System (IHTS) equipped with an Energy Storage System (ESS); it is included in the heat transport scheme between the BB PHTS and the PCS with the aim to buffer energy during the pulse which is returned to the PCS in dwell. This plant solution avoids the transfer of a pulsed load to PCS itself and to the electrical grid; therefore it ensures a more continuous production of electricity guarantying system components lifetime.

PCS in DEMO is a complex system where the secondary circuits of the various PHTS systems of the BB, Div and VV should be integrated into an industrial, reliable and efficient system. Of course, since the BB has to extract about 85% of the power generated by the tokamak, BB PHTS can be considered as the main heat sources of PCS and as such their preliminary conceptual designs (e.g. HCPB BB PHTS and WCLL BB PHTS) were developed with first priority.

Retaining a DEMO overall project strategy to evaluate multiple options for an effective identification of the best solution and in order to minimize technological risks, a parallel work stream dealt to investigate the direct coupling of the BB PHTS to PCS has being initiated and is briefly presented. The aim of this activity is to assess a simpler configuration that, aiming at reducing the complexity of DEMO design and operation is expected to have beneficial impact in term of safety and reliability as well as, ultimately, in costs.

2. HCPB BB BoP

DEMO BoP with ESS for HCPB is represented in Fig.1. In this figure, the systems for the heat transport and power conversion are outlined, namely: the PHTS, the IHTS with the ESS and the PCS which integrates the low temperature sources of Div and VV as feedwater pre-heaters.

2.1 Ex-Vessel HCPB BB PHTS design

2.1.1 General criteria

The study of Ex-Vessel HCPB BB PHTS has been mainly focused on the preliminary assessment of the main component sizes and performances in order to identify technical feasibility issues, understand commercial availability and R&D needs, establish layout integration and safety requirements. Therefore, the following design strategies and objectives have been pursued:

- Segmentation and separation of the cooling loops to limit the potential consequences of LOCA events and the size of the main components (piping, heat exchangers, compressors)
- Coolant speed between 40 m/s and 50 m/s as a trade-off choice between the need to limit system pressure drop (hence pumping power) and coolant total inventory through suitable pipe size
- Integration of the PHTS outside of the tokamak bio-shield but as close as possible to be compliant with the high DEMO safety requirements limiting the helium coolant inventory and guaranteeing components and instrumentation qualified life

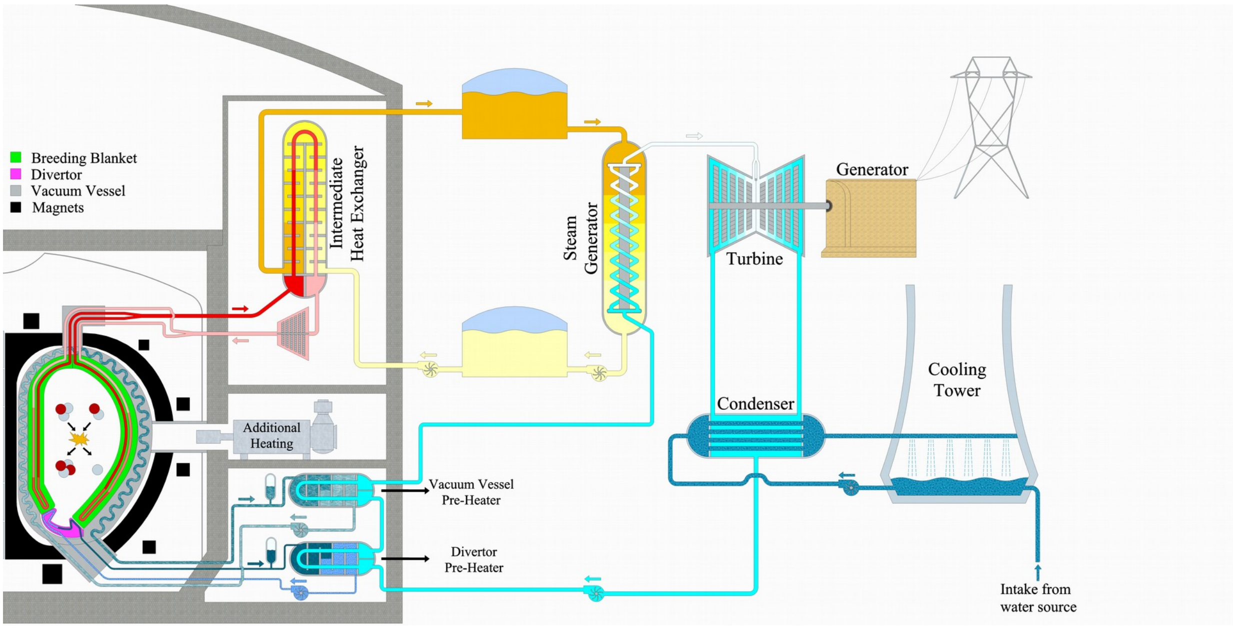

Fig. 1. Conceptual scheme of HCPB BB BoP with ESS.

2.1.2 Thermal-hydraulic interface design parameters

The Ex-Vessel HCPB BB PHTS must provide cooling helium to the In-Vessel HCPB BB cooling system at 8 MPa [7] and 300 °C, and a flowrate of 2303 kg/s must be ensured too in order to comply with the removal of 2389.1 MW BB Power. This means an operating Helium temperature cycle of 300÷500 °C which is consistent with the limitation dictated by the low activation steel EUROFER selected for BB structures to prevent significant embrittlement.

2.1.3 System Layout

According to the abovementioned assumptions a preliminary layout of the HCPB PHTS has been outlined foreseeing a highly degree of segmentation of its cooling loops which are 9. These circuits are completely independent, from mechanical point of view, in order to limit some common mode failures. In particular, there are 3 loops which are designated to cool the IB portion of the tokamak (e.g. IB PHTS) while the other 6 loops are in charge to remove the power from the OB zone (e.g. OB PHTS). Each IB cooling circuit provides helium to 6 blanket sectors and each OB loop cools the segments of 3 blanket sectors.

Each IB/OB loop loop has 3 main parallel hot/cold legs, one Intermediate Heat eXchanger (IHX) and a couple of circulators (2x50%) which allow helium to circulate along the whole circuit.

Fig. 2 shows the 3D-CAD model of HCPB BB PHTS (OB PHTS in green, IB PHTS in blue) and Table 1 summarises the number of main components per loop.

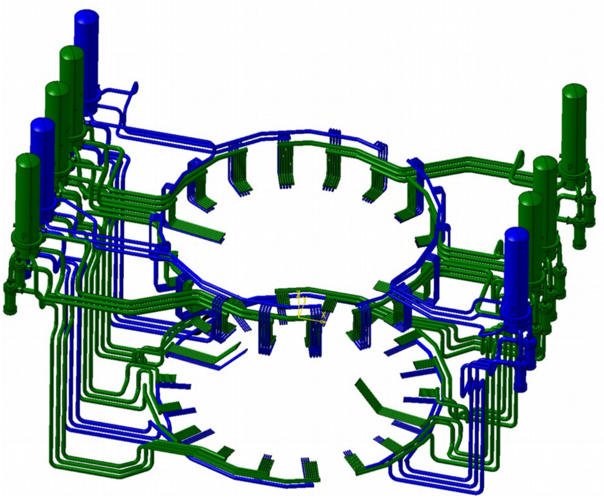

Fig. 2. 3D view of HCPB BB PHTS cooling loops.

Table 1. HCPB PHTS main components per loop**.**

Component	Inboard	Outboard
Hot/Cold manifolds	24/24	18/18
Hot/Cold legs	3/3	3/3
Cold Header	1	1
Compressors	2	2
Heat exchanger	1	1

2.1.4 Piping, IHX and Circulators

Selected Ex-Vessel PHTS piping material is AISI 316L(N); piping maximum size have been limited to DN 800 with the aim to use commercial components.

This design choice, combined with design velocity assumed, caused the need of 3 hot/cold legs per loop which in turn determined the significant overall system piping length (nearly 9 km) and coolant inventory guested (1297 m^3).

The IHX preliminary conceptual design relies on the well proven "tubes and shell" technology where Helium flows tube side and the Molten Salt (MS) HITEC, with temperature cycle 268°C÷480 °C, crosses the shell side. A two pass shell-side cross-flow TEMA type F configuration has been selected where relevant IHX parameters (tube diameter, pitch, coolant velocities, etc.) have been chosen after a sensitivity aiming at limiting pressure drops and total bundle number of tubes as well as the overall dimensions of the heat exchanger.

Since the power removed by each IB loop is different from that of OB loop (245.2/304.9 MW) two IHX design have being made; they are characterized by 6779 and 8427 tubes respectively of about 17 m length per pass and a volume of 65.3 and 79.2 m^3. Taking into account of IHXs coolant inventory, the overall amount for HCPB BB PHTS raises to 2573.1 m^3 (Table 2).

With the system layout adopted, the total pressure drops in each IB/OB PHTS loops is 4.57 and 4.25 bar respectively causing circulators of 8.9 and 10.3 MW. Loops design velocity and circulators arrangement (two per loop) have been selected also with the aim to limit the size of this components so that to avoid large R&D extrapolation from the existing design (~5 MW) for the development of a specific component for DEMO.

The total pumping power for the HCPB PHTS is very significant, namely of about 177 MW. In any case, further improvements both in In-Vessel and Ex-Vessel PHTS designs are foreseen with the aim of decreasing the total pressure drop of the reactor and overall pumping power with the objective to use proven large compressor design. Table 2 shows the HCPB main design features.

Table 2. HCPB PHTS main data.

Parameter	Inboard	Outboard
Thermal power [MW]	682.8	1706.3
Pumping power [MW]	53.3	123.8
Mass flow rate [kg/s]	658.1	1644.6
Total volume [m^3]	778.7	1794.4
Total piping length [m]	3611	5015
Piping velocity range [m/s]	40÷50	40÷50
Number of loops [-]	3	6

2.2 The design of IHTS with ESS

The pulsed nature of the currently considered DEMO operation imposes unique design problems on the energy conversion system. In DEMO, energy is generated in the reactor for 120 min (burn time) then the reactor is shut down (dwell time) for recharge. 30 min of dwell time has been considered in the present design, but 2017 BoP design update will take into account of the reduction of this parameter to 10 minutes as a result of optimization of central solenoid recharge time and vacuum pump performance.

An IHTS equipped with an ESS using MS (preliminary selected as of Solar type) as heat transfer fluid is being included in the BoP option investigated with the aim to mitigate the impact of plasma pulsing on PCS components, with particular care of steam turbine, and the electrical grid.

The adoption of an ESS, where part of the thermal power removed by MS in the IHXs is accumulated as sensible heat in dedicated tanks, allows to operate the PCS at an almost continuous load equal to about the 80% BB PHTS power with the aim of avoiding undue thermal and mechanical cycling on PCS components. This objective can be reached if enough energy storage is performed in salt tanks to cope not only with the pulsation of the BB power but also with that of other pulsating heat sources integrated in the PCS, namely the Div and VV.

Considering the requirement of a continuous PCS operation at constant load, the MS temperature cycle selected and the characteristic time of the pulsation of DEMO (e.g. pulse and dwell time) it derives the need of about 11300 tons of fluid and then of a tanks volume (hot + cold) of around 12000 m3.

The Thermal-Hydraulic (T/H) design parameters of this system are in the following Table 3.

Table 3. IHTS/ESS design parameters.

Parameter	Value
Thermal power (PHTS side in pulse) [MW]	2566
Thermal power (PCS side) [MW]	1990
Hot tank in. flowrate (pulse) [kg/s]	7871
Hot tank out. flowrate (pulse/dwell) [kg/s]	6209
MS hot tank temperature [°C]	480
MS cold tank temperature [°C]	268
Operating pressure [bar]	1.0

Additional improvement to such system can derive from the replacement of the 2-tanks design to with 1-tank thermocline system as well as from the use of the most performing HITEC salt instead of the Solar Salt.

2.3 The PCS design

The preliminary conceptual design of PCS for DEMO envisages a classical steam Rankine cycle with Steam Generator (SG), Reheater (RH) -in between high and low pressure turbine stages heated by a stream of hot MS-, Deaerator, Condenser and Feedwater pre-heaters, operating at about 58 bar with superheated steam at 445°C [5].

Feedwater pre-heaters are of condensing type or single phase fluid in both tube and shell side. In particular, the latter are represented by the heat exchangers of Div and VV PHTSs which are integrated in PCS as additional (low temperature) heat sources to improve system efficiency .

Table 4 summarises the T/H design conditions of Div and VV PHTSs.

Table 4. Main T/H design data of DIV and VV PHTSs.

Parameter	Div Cass.	Div PFUs	VV
Coolant	water	water	water
Thermal power [MW]	115.2	136	86

Mass flowrate [kg/s]	861.1	3260	19289
Inlet temperature [°C]	180	130	190
Outlet temperature [°C]	210	140	200
Operating pressure [bar]	35	50	31.5

PCS architecture envisaged an additional heat exchanger upstream of the SG supplied by hot MS which works in dwell to compensate the power lost from Div and VV. In fact, in dwell, they reject to PCS only the decay heat (~1% of pulse value). The PCS heat balances both during pulse and dwell times have been obtained through an EBSILON code model of which further details can be find in [5]. From Table 5, where some cycle parameters are reported, it can be observed the reduction of the system efficiency from about 36% (gross) to about 31% (net) evaluated, the latter, taking into account of the electrical power consumpted by PHTS, IHTS and PCS equipment. The reduction of net efficiency is mainly due to the significantly high BB PHTS circulators power.

Table 5. IHTS/ESS Design parameters**.**

Parameter	Value
Gross power (pulse/dwell) [MW]	808/730
Net power (pulse/dwell) [MW]	659/713
Gross efficiency [%]	36.5
Net efficiency [%]	30.7
HP turbine inlet temp. (pulse/dwell) [°C]	445
HP turbine outlet temp. (pulse/dwell) [°C]	177/169
LP turbine inlet temp. (pulse/dwell) [°C]	258/253
LP turbine outlet temp. (pulse/dwell) [°C]	33/30
Feedwater flow rate (pulse/dwell) [kg/s]	791/786
Heat sink temp. [°C]	18

Preliminary transient analyses of the integrated model of HCPB BoP with Apros Code provided an insight of the PCS behaviour especially in the transition from pulse to dwell and then useful elements for the improvement of the preliminary PCS scheme.

In particular they revealed:

- substantial fluctuations in the generated electrical power during the pulse/dwell transition
- the need to pay attention to all the feed-heaters heated by MS since it was the risk of salt freezing (Solar Salt freezing point=220°C) as well as to the consistent temperature cycling in some feed-heaters despite the implementation of the ESS.

As example, Fig. 3 shows the large temperature fluctuations in a pre-heater heated by MS during the pulse/dwell transitions.

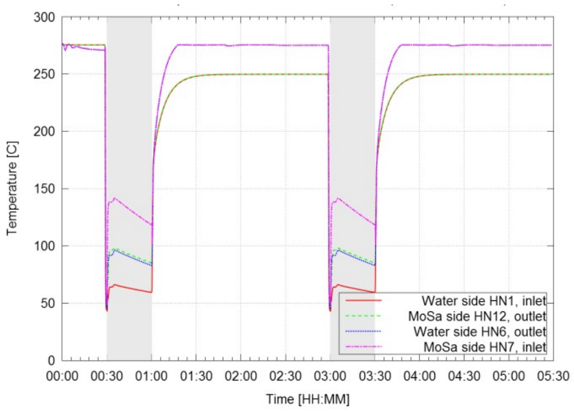

Fig. 3. MS pre-heaters wall temperatures behaviour.

Taking advantage of the analyses results as well as of the experience and suggestion of the involved Industry, on-going activities are developing dealt to improve the PCS parameters fluctuation at the transition between pulse and dwell so that to preserve components.

Then the present focus is mainly on: i) the adoption of HITEC MS instead of solar salt due to its lower freezing point (e.g. ~154 °C) that allows more flexibility to the designers; ii) the implementation of a more detailed steam turbine configuration with the support of industry (number of corps and position of steam extraction points), iii) the attempt to stabilize the feedwater temperature along its path through the introduction of additional feedwater heaters in parallel with Div and VV HXs heating in dwell the feedwater through steam bled from steam line.

3. WCLL BB BoP

DEMO BoP with ESS for WCLL BB is represented in Fig. 4. The main difference between the HCPB and WCLL BoP is that in WCLL the IHTS is not in the middle between the overall BB PHTS and the PCS, instead, it receives and stores a portion of the overall WCLL BB PHTS power, namely that generated in the First Wall (FW) which is released in dwell to the PCS though a suitable SG.

Such architecture allows to limit the size of the IHTS and of ESS too which is penalized in any case by the low temperature cycle of the MS.

Also in this case, the PCS integrates the low temperature sources of Div and VV as feedwater pre-heaters and hence PCS design must cope with the pulsation of their generated thermal power.

3.1 Ex-Vessel WCLL BB PHTS Design [11]

3.1.1 General criteria

Design strategy adopted in the WCLL BB PHTS design is conceptually the same as already mentioned in case of HCPB; therefore also in such case:

- the segmentation and separation of the cooling loops has been pursued to limit the size of the main components (piping, heat exchangers, pumps) as well as for safety reason;
- maximum coolant speed has been limited to 20 m/s as a trade-off choice between the need to limit system pressure drop (hence pumping power) and coolant total inventory (e.g. pipe size);
- integration of the PHTS outside of bio-shield but as close as possible to it in order to limit the size of the system and then the total inventory of water and to guarantee the components and instrumentation qualified life.

WCLL BB PHTS has been designed drawing from the experience gained in fission NPPs.

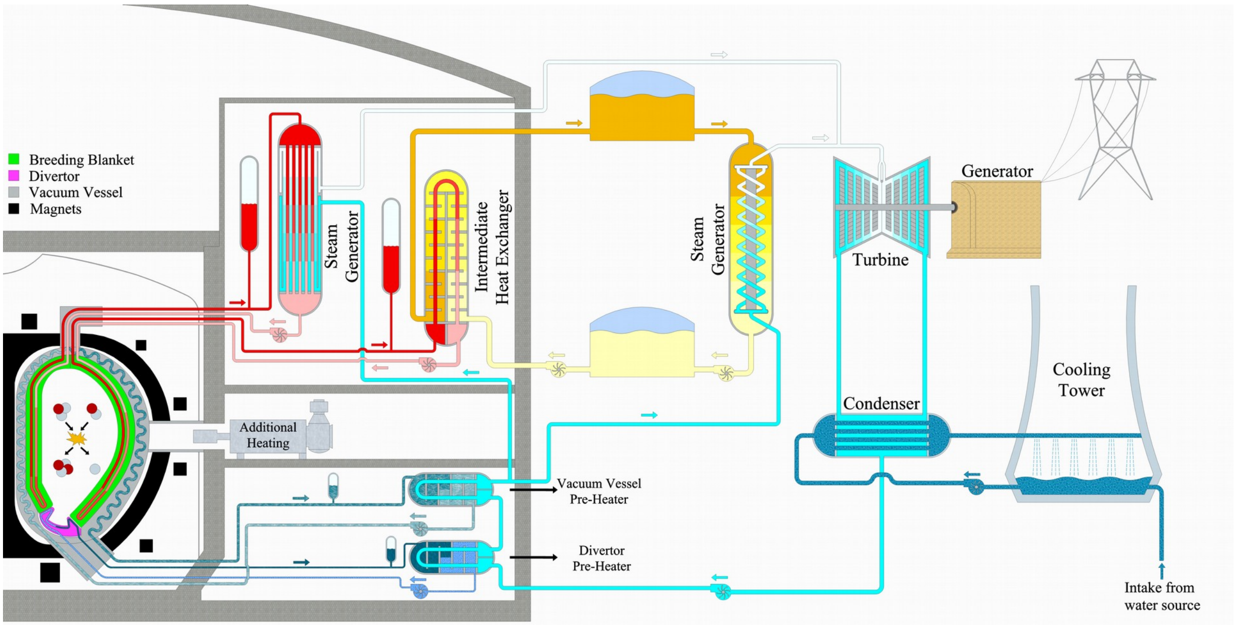

Fig. 4. Conceptual scheme of WCLL BB BoP with the ESS

3.1.2 Thermal Hydraulic interface design parameters

The main function of the Ex-Vessel WCLL BB PHTS is to provide cooling water to the In-Vessel WCLL BB cooling system at the required temperature and pressure. This means that water must be provided to BB at 295 °C and 15.5 MPa, and a flowrate of 10561 kg/s must be ensured to comply with the requirements of the removal of BB power (2045 MW). Water temperature cycle is then 295÷328 °C.

3.1.3 System Layout

The WCLL PHTS is constituted by two independent cooling systems providing cooling water to the Breeding Zone (BZ) and the FW zone of the blanket.

Systems architecture has been developed on the basis of the following additional functional requirement. During the pulse, the BZ PHTS, which is directly connected to PCS, delivers to the steam turbine the BZ generated power by means of four Once Through Steam Generators (OTSG). The FW PHTS, instead, integrally transfers the heat removed from FW to the ESS, belonging to the IHTS, through two IHXs using HITEC MS as fluid. The FW power accumulated to the ESS during the 2 hours of pulsed operation allows to supply the necessary heat to Helical Coils Steam Generators (HCSG) integrated in PCS to ensure the same pulse steam load to the PCS steam turbine during the 30 minutes dwell time.

Both BZ and FW PHTS are constituted by two loops (which are symmetrical with respect the radial-poloidal of the tokamak) in order to limit the size of piping and components. Each BZ PHTS loop includes one OTSGs, 2 pumps, one pressurizer and one hot/cold leg. Each FW PHTS loops includes one IHX, one pump, one pressurizer and one hot/cold leg. Cold/Hot ring headers supply/return water to the BZ/FW loops. Fig. 5 shows the 3D-CAD model of HCPB BB PHTS (BZ PHTS in green, FW PHTS in blue) and Table 6 summarises the number of main components per loop.

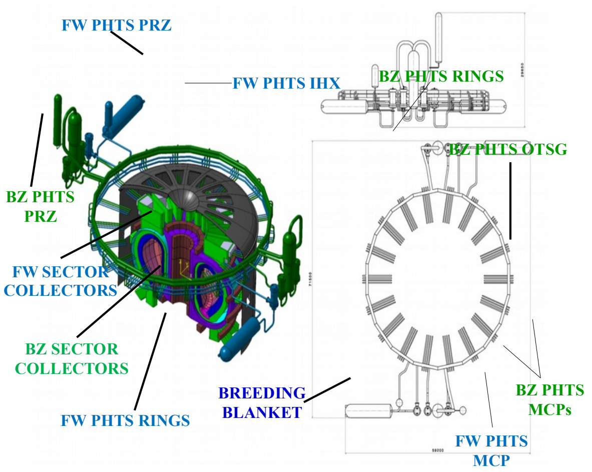

Fig. 5. 3D view of HCPB BB PHTS cooling loops.

Table 6. HCPB PHTS main components per loop.

Component	BZ	FW
Hot/Cold manifolds	9/9	9/9
Hot/Cold legs	1/2	1/1
Hot/Cold header ring	1/1	1/1
Pumps	2	1
Heat exchanger/SG	1	1

3.1.4 Piping, IHX,OTSG, pumps

Selected Ex-Vessel PHTS piping material is AISI 316L(N). The main pipeline diameters outside the vacuum vessel are calculated accounting for coolant velocity of 15 m/s, with a maximum limit of 20 m/s; corresponding commercial piping have being selected on the basis of European standard [12]. Largest pipe size occurs in BZ PHTS where both hot legs and hot ring are DN 750. The overall system piping length is about 1.75 km (whereof ~0.55 in rings) and coolant inventory guested is 218 m^3 (e.g. 169/49 m^3 in BZ/FW PHTS piping respectively) .

Each BZ PHTS OTSG has been designed with reference to the proven technology adopted in fission NPPs. Design data for the thermal sizing have been chosen in agreement with the T/H requirements of BZ PHTS. The OTSG is cooled by PCS feedwater at 6.41 MPa with an inlet temperature is 238 °C. The objective is to produce super-heated steam at 299°C. Therefore, the feedwater flow is of 430.1 kg/s. The sizing results both for BZ OTSG in case of "clean" component are reported in Table 7.

Thermal sizing of the BZ OTSG has been performed through a RELAP5/Mod3.3 calculation after a sensitivity on relevant parameters as lattice type and p/D. It can be observed how the good heat transfer aptitude of both primary and secondary OTSG water allows the component to be smaller than one HCPB OB HX despite an exchanged power higher by a factor ~2.5. Taking into account of OTSG volume, the total water inventory in BZ In+Ex Vessel PHTS is of 303.6 m^3.

As in case of IB/OB HCPB HX also WCLL FW PHTS water/MS IHX is typical single phases tube and shell heat exchanger with two passes and cross flow of the coolant in the shell (e.g. HITEC). Design data for the thermal sizing of each component have been chosen according to the FW PHTS T/H requirements and a secondary coolant thermal cycle of 280-320 °C. The thermal sizing results for a clean component horizontally arranged are reported in Table 7.

Also in this case it can be observed its large dimension compared to the exchanged power. Taking into account of OTSG volume the total water inventory in FW PHTS is of 138 m^3.

Table 7. BZ OTSG and FW IHX preliminary thermal sizing data.

Parameter	BZ OTSG	FW IHX
Thermal power [MW]	788.6	233.8
No. of tubes [-]	7569	5211
Tube D_{ext} [mm]	15.88	15.88
Thickness [mm]	0.864	0.864
Length of tubes [m]	12.987	28.9
Lattice [-]	Square	Square
p/D [-]	1.28	1.28
Heat transfer area [m^2]	4369	6701
Water volume [m^3]	20	23.7
D_{ext} vessel [m]	2.9	3.5

Considering both the BZ and FW PHTS, six Main Coolant Pumps (MCPs) are foreseen in the current preliminary PHTS design of DEMO: four MCPs, two per loop, in the cold legs of the BZ PHTS, two MCPs in the FW PHTS.

WCLL PHTS main coolant pump comes from NPPs experience. According with the BZ and FW PHTS calculated pressure drops, 0.88 MPa and 0.84 MPa respectively, requested total pumping power for WCLL BB PHTS is about 15.8 MW in the hypothesis an efficiency of 78%. It is very smaller than that required to circulators of HCPB BB PHTS. Table 8 shows the WCLL PHTS main design features.

Table 8. WCLL PHTS main data.

Parameter	BZ	FW
Thermal power [MW]	1577	467.6
Pumping power [MW]	12.3	3.5
Mass flow rate [kg/s]	8146	2415
Total volume [m^3]	303.6	138
Total piping length [m]	850	850
Piping velocity range [m/s]	7÷20	7÷20
Number of loops [-]	2	2

3.2 The design of IHTS with ESS

Also in case of the WCLL BB the heat removal chain of systems includes an IHTS equipped with an ESS to decouple the intermittent generated power from that, continuous, transmitted to PCS. The latter is kept about constant between pulse and dwell thanks to the energy stored in a suitable ESS in pulse that is used as heat source for steam production in PCS in dwell.

As stated, during the pulse, the FW PHTS power is rejected to the MS IHTS and totally stored in the MS tanks as sensible heat of the fluid (3.37×106 MJ). It acts as heat source during the 30 minutes dwell allowing a continuous operation of PCS at the about the same load (~1600 MW). In this option, therefore, the transition from pulse to dwell is characterized by the switch of the main heat source of PCS from BZ PHTS to IHTS.

The WCLL IHTS concept is totally analogous to that envisaged for the HCPB BB plant. It includes pipelines connecting the IHX/Steam Generator to the hot and cold MS tanks (e.g. the ESS), the tanks themselves, the steam generator and the MS pumps.

Considering that the MS temperature cycle is 280÷320 °C and the power transferred by FW PHTS of 467 MW, it derives the need of a pulse charging flowrate of 6000 kg/s; moreover considering the 2 hours of operation, an amount of MS equal to 43200 tons is stored in the hot tank (~23500 m^3). This means that the total volume required for hot+cold MS tanks of ESS are of about 47000 m^3. It can be observed from Table 9 as the low operating temperature cycle of the MS causes the very large request of fluid inventory and tanks volume. In any case, it is envisaged a consistent reduction - almost linear - of the present large size of MS tank due to the reduction of the dwell time to 10 minutes according to DEMO recent development [2].

Table 9. IHTS/ESS design parameters**.**

Parameter	Value
Thermal power (PHTS side in pulse) [MW]	470
Thermal power (PCS side in dwell) [MW]	1870
Hot tank in. flowrate (pulse) [kg/s]	6000
Hot tank out. flowrate (dwell) [kg/s]	24000
MS hot tank temperature [°C]	320
MS cold tank temperature [°C]	280
Operating pressure [bar]	1.0

During the 30 minutes dwell time, a MS flowrate of 24000 kg/s is discharged from hot tank to IHTS Steam Generator and then to cold tanks. It transfers a thermal power of 1870 MW_{th} to PCS water which allows to compensate (through an additional generation of steam flow) the power loss of Div and VV heat sources (e.g. ~ 300 MW). This ensures to the steam turbine practically to work at constant steam load.

IHTS steam generator are four Helical Steam Generators (HCSGs also called MS-SG)). The feedwater enters in the HCSG with an inlet temperature of 238 °C and exits with an outlet temperature of 299 °C at 6.41 MPa. The HITEC mass flow rate per HCSG is 7757.1 kg/s, and the feedwater mass flow rate, calculated with the enthalpy balance, is 255 kg/s.

The thermal sizing of the MS-SG has been performed with in-house algorithm and validated with RELAP5/Mod3.3 suitably modified to include HITEC and relevant heat transfer correlations. Main design geometry data are reported in the following Table 10. It can be observed that it has the same heat transfer area of BZ PHTS SG despite the smaller design power.

Table 10. Main MS-SG thermal sizing data**.**

Parameter	Value
Thermal Power [MW]	467.5
Number of Tubes [-]	1446
Tube D_{ext} [mm]	16.0
Thickness [mm]	0.8
Length of tubes [m]	68.0
Heat transfer area [m^2]	4448
Water volume [m^3]	16.0
HITEC volume [m^3]	37.18
D_{ext} vessel [m]	3.0

3.3 The PCS design

PCS is classical steam Rankine cycle operating at about 64 bar and providing slightly superheated steam at 299°C to the steam turbine. Relevant components are the two steam generators OTSG and MS-SG that, alternatively, provides the main steam load for pulse and dwell operation. Other relevant equipment are: RH -in between high and low pressure turbine stages heated by a steam bled from steam line-, Deaerator, Condenser and Feedwater pre-heaters. Also in case of WCLL PCS Div and VV heat sources are integrate din PCS as feedwater pre-heater.

A Gatecycle™ analysis [13] of PCS has been performed in order to evaluate the heat balance in pulse and dwell. The PCS for the WCLL concept has already introduced two feedwater pre-heaters in parallel to Div Cass and Div PFCs and VV HXs to face the dwell period avoiding large fluctuation of operating parameters.

In fact, in pulse, the PCS operating steam is produced in OTSGs which remove the BZ power, whilst the heat extracted from the BB FW is accumulated in the MS tank. Feedwater pre-heating is ensured also by virtue of Div and VV heat sources (~330 MW) integrated in PCS layout. During the dwell, when the thermal power of all the reactor heat sources is reduced down to their decay heat level (assumed to be 1% of their nominal value), steam is produced in MS-SG and feeds the HP turbine (ST1), the RH, and two additional (condensing) heat exchangers used to complement HXs of Div PFCs, Div Cassettes and VV. They use steam bled from stem line with the aim to pre-heat the feedwater as in pulse.

Thanks to this scheme the steam turbine works in a continuous mode with a limited variation of the steam load during the pulse and dwell, being the system able to cope non only with BB pulsating power but also with the generated pulsed power of Div and VV. Consequently no significant impact on turbine lifetime consumption is expected as well as on other PCS equipment due to the anticipated limited fluctuation of pressure and temperature overall the cycle.

The Gatecycle™ analysis of the PCS predicts that the system is able to operate at an almost constant gross electrical power of about 700 MW and gross average efficiency of ~ 37% (considering both pulse and dwell phases). The average electrical efficiency of the cycle reduces to about 34%, with the consideration of the electrical load of PHTSs, ESS and BoP components.

Further details of the Gatecycle™ analysis can be find in [13]. Moreover, improvement of PCS envisages a refinement of some feedwater pre-heaters arrangement in order to limit the still high temperature oscillation, as in case of Div-Cass HX. In addition all the cycle will be submitted to a revision due to the impact of the new (smaller) dwell time. In fact, the reduction of the heat to be stored in MS tanks will drive a PCS operation at higher power with MS-SG working (at reduced power) also during the pulse.

4. Main issues identified and further assessment

The HCPB and WCLL BoP designs are considered to be feasible and no major showstoppers have been identified, however some aspects have to be further investigated before drawing any firm conclusions. In particular, further assessments will be addressed to the main identified issues discussed in the following..

The overall dimensions of both PHTSs may cause integration, inspection and test difficulties as well as increment of cost. Analyses are on-going to reduce the total length of pipes, in particular for HCPB concept.

The adoption of equipment design solutions which are available on the market would be desirable. Both concepts match such objective for HXs and SGs while from the turbomachinery point of view only the water concept has already achieved this goal instead of the HCPB concept which, due to its actual PHTS pressure drop, might need a R&D campaign to design its compressors. Different technical solutions are under investigation to reduce the pressure drop of the primary circuits, therefore to keep the pumping power in a window that is compliant with the state-of-art for such components.

The presence of N16 and N17 into the WCLL PHTS might be significant during the plasma operation increasing the radiation doses to some sensible equipment (i.e. I&C) near the area which surrounds the primary circuits. Analyses are on-going to improve the layout and shielding of the system.

In case of In-Vessel LOCA scenario an expansion volume is necessary to keep the VV over-pressurization below the design limit. The HCPB concept needs a very huge volume to accommodate the helium expansion while for the WCLL, the possibility to use a steam suppression pool makes the required volume reasonable. Improvements in the HCPB design are expected through: i) a reduction of the helium inventory by means of optimization of PHTS design; ii) less severe LOCA reference scenario and iii) the use of some areas of the tokamak building as expansion volume.

In case of Ex-Vessel LOCA, the WCLL concept shows more critical aspects than the HCPB because the former would cause a bigger overpressure into the tokamak building respect to the latter during the reference accident. Integration and safety studies are under discussion to see the adequacy of the few volumes available in the tokamak building. Moreover, is also under investigation the use of isolation valves to limit the amount of coolant released outside the PHTS circuits.

The ESS makes simpler the PCS operations but, on the other hand, increases the complexity of the plant. In particular, for the WCLL concept, the volume required to store the energy is very huge (~47000 m3). The reduction of the dwell time from 30 to 10 minutes would decrease almost linearly the quantity of MS to be stored. Moreover, the option that conceives the elimination of the intermediate loop is also under development for both concepts

The presence of Activate Corrosion Products (ACPs) and Tritium inside the PHTSs requires the employing of auxiliary systems which manage to maintain their concentration below the safety limits. The HCPB concept, oppositely to the water option, should not show any issue caused by ACPs since the inert nature of the helium, however it might exhibit more problems to handle the Tritium due to its aptitude to leak from the circuits. Assessments are scheduled for both concepts, in particular, for the water-cooled DEMO, they will take into account the solutions adopted by ITER to be licensed.

For licensing process, the operating experience on systems and components is very important. In case of the WCLL concept such feature is significant thanks to the large diffusion of water-cooled NPPs. The Helium-cooled DEMO can rely on limited experience since few helium NPPs have been built hence some R&D might be necessary for this option.

For both PHTS cooled by He and water, an assessment of the cost will start as soon as the preliminary design is finalized, later this year.

5. Further development: the direct coupling of PHTS and PCS

DEMO design approach to address multiple options for system and/or technologies with high technical risk or novelty has been applied also to BoP.

In fact, stating the complexity and the issues related to the BoP above described (with IHTS+ESS using MS as heat transfer fluid), work is on-going with the support of the industry to investigate a simpler option that envisages the direct coupling of the BB PHTS to PCS. This simplification will positively impact on costs as well as in Rankine cycle efficiency due to the higher thermal power transmitted to PCS.

In case of direct coupling, one of the main design issues to solve is the identification of a PCS architecture, related system components operational procedure and/or design provisions that will allow a safe and reliable operation despite the pulsating nature of the transmitted power by PHTS and that, in addition, will prevent from undesired components lifetime reduction due to the potential mechanical/thermal transients loads experienced.

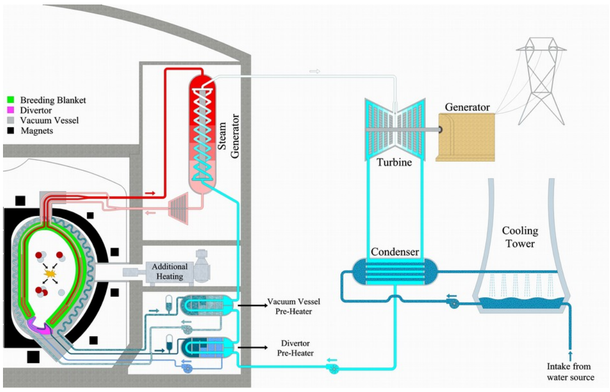

Fig. 13. Direct coupling of PHTS to PCS (scheme for HCPB).

Three mode of operation have been investigated in order to evaluate the impact on PCS components starting from steam turbine: i) steam turbine start and stop with the same periodicity of DEMO plasma power profile, ii) steam turbine un-loaded and maintained spinning by electrical motor, iii) steam turbine operated at a minimum steam load in dwell using a small auxiliary boiler.

From the preliminary studies performed, the operating mode i) is discouraged; in fact, the manoeuvre of unloading/uploading of the steam turbine (ST, Figure 14) and its stop/start at each pulse/dwell transition (10 cycles/day, in case of 2h pulse, 30 minutes dwell) will cause cyclic mechanical loads due to continuous acceleration and deceleration (Low Cycle Fatigue phenomenon) that will determine quick turbine wear and consequent structural failure in few years of operation. If fast ramp up/down rate are used to upload and unload the steam turbine thermal stresses could not be adversely impacting, in any case dangerous LCF occurrence will increase the need of revision cycle and related cost of operation.

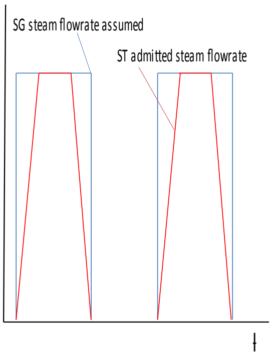

Fig. 14. SG steam production and ST steam admitted profiles.

Similar concern applies also to the electric generator where a sudden load decrease (trip) during turbine operation can lead to mechanical damage. In addition, there is the need of continuous electrical generator synchronization to the grid with impact on the reliability and efficiency of the plant.

Other issues reducing the lifetime/functionality of PCS components are: load and stresses on boiler feed pumps due to the transient flow condition in Rankine cycle and the thermal cycling of the feedwater preheaters caused by not constant feedwater pre-heating over all DEMO period (pulse + dwell).

Stating the problems above listed, the others operating mode (ii) and iii)) considered share the requirement to keep spinning the steam turbine because of the important drawbacks related to the start and stop of the machine.

Operating mode ii) consists in the alternator motorization, that means dragging the unloaded steam turbine (admission valves closed) at nominal speed in dwell thanks to the electric generator used as syncronous motor. This procedure has no significant drawback for what the electric generator is concerned since this machine is a “reversible” equipment, then it cannot be expected neither electromechanical nor electro-dynamic relevant stresses; nevertheless the alternator motorization can adversely impact the ST because of the potential of high frequency vibration of the ST blades (High Cycle Fatigue (HCF)), ventilation effects and erosion by water droplet injected by attemperator.

Operating mode iii) envisages the ST ramped-down as the dwell approaches maintaining the control valves a little open in order to admit a minimum quantity of steam to generate power and delivery it to the grid. This way of operation allows to manage the turbine in a similar way to conventional application. It is worth of taking into consideration this scenario in particular if it will be assessed that, thanks to inertia effects, the generated steam in SG will have a smoother profile than a square wave -as practically it is for what plasma generated power is concerned-, so that to be able to provide the minimum steam flowrate required to ST in dwell. In the hypothesis shown in Figure 14 instead, an auxiliary boiler will be needed to supply steam to ST in dwell at the same temperature condition as in pulse to avoid cooling of the machine. Preliminary evaluation suggests a boiler size of about 8% of nominal load. However a verification of the behaviour of the turbine in this “OFF design “ mode of operation is necessary to assess the possibility of undesired occurrences (HCF, overheating, erosion, etc.). In addition the impact of such operation mode on turbine control, plant reliability and on the remaining Balance of Plant components have to be carefully assessed too.

6. Conclusion

The demonstration of the feasibility of electricity production before 2050 in an EU-DEMO that produces its own fuel represents the primary objective of the fusion development program in Europe. As such DEMO shall be strongly Balance of Plant oriented. This would represent a novelty in the fusion community that up to now has been mainly focused on plasma performances and control.

Two options are presently under investigation for both WCLL BB and HCPB BB BoP with the aim to develop multiple configurations for an effective identification of the best solution and in order to minimize technological risks: i) the use of an Intermediate Heat Transfer System equipped with the Energy Storage System to prevent the plasma generated pulsed power to be transmitted to Power Conversion System and ii) the direct coupling of the BB Primary Heat Transport System to the Power Conversion System where instead the pulse load is rejected to the PCS.

Option i) is more consolidated and a preliminary sizing of the BB PHTS, IHTS,ESS and PCS has been performed having as master design guideline the use at the maximum extent of the experience gain in fission NPPs design and then the adoption of proven technology so that to limit DEMO specific R&D needs.

Preliminary systems design have been performed paying attention to the identification of potential technical feasibility issues; to the verification of the TRL of the required components and to the establishment of layout requirements for evaluation of the integration implications with other systems.

BB PHTS, IHTS,ESS and PCS are considered to be feasible and no major showstoppers have been identified. However, some aspects have to be further investigated in the prosecution of the activity before drawing any firm conclusions.

Option ii) represents an attempt to simplify the BoP stating the huge impact of ESS at least from what design integration implications and costs are concerned.

It is under analysis with support of Industry with the aim to identify PCS architecture, suitable operating procedure and design provisions capable to soften the transients on the turbine and on other components of the PCS and to allow a safe and reliable operation despite the pulsation of the steam load.

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