Fusion Engineering and Design, 167, 2021, Article n° 112345; https://doi.org/10.1016/j.fusengdes.2021.112345

Conceptual design of the main Ancillary Systems of the ITER Water Cooled Lithium Lead Test Blanket System

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The Water Cooled Lithium Lead Test Blanket System (WCLL-TBS) is one of the EU Test Blanket Systems candidate for being installed and operated in ITER. In view of its Conceptual Design Review by F4E and ITER Organization (IO), planned for mid-September 2020, several technical activities have been performed in the areas of WCLL-TBS Ancillary Systems design.
In this article the outcomes of the conceptual design phase of the four main Ancillary Systems of WCLL TBS, namely the Water Cooling System (WCS), the Coolant Purification System (CPS), the PbLi loop and the Tritium Extraction System (TES), are reported and critically discussed.
In particular, for each Ancillary System hereafter are reported: i) a short design description, including the conceptual design of their main components together with their operative conditions under the so-called Normal Operational State (NOS), ii) the ESP-ESPN classification for their main components, and iii) their arrangement and integration in the assigned ITER areas (PC#16, Vertical Shaft, TCWS Vault, Galleries and Tritium Process Room).

Keywords: ITER, WCLL-TBS, PbLi loop, WCS, CPS, TES.

1. Introduction

In 2018, a realignment of the European TBM (Test Blanket Module) Programme with the development of the European DEMO Breeding Blanket (BB) took place, in order to take the maximum benefit from the first and unique opportunity to test in ITER the response of representative component mock-ups at relevant operating conditions in an actual fusion environment. This decision was driven by the selection as driver blankets of two BB concepts, namely the Water Cooled Lithium Lead (WCLL) [1] and Helium Cooled Pebble Bed (HCPB) [2]. Consequently, a change of the European TBM options to be tested in ITER has taken place, [3], [4]. In fact, until the 2018, the European TBM Program envisaged the design and testing in ITER of the Helium Cooled Lithium Lead (HCLL) concept together with HCPB.

In such a context, the development of the conceptual design of the WCLL Test Blanket System (TBS) became essential [4], leading the EUROfusion laboratories, in collaboration with Fusion for Energy, to carry-out several technical activities for the finalization of WCLL TBS conceptual design also in view of the ITER Organization (IO) Conceptual Design Review (CDR) planned for mid-September 2020.
This paper is focused on the major outcomes of the conceptual design phase of the four main WCLL TBS Ancillary Systems, namely the Water Cooling System (WCS), the Coolant Purification System (CPS), the PbLi loop and the Tritium Extraction System (TES) [5].
In particular, the first part of the paper briefly describes the systems with their main characteristics, functions as well as currently selected technologies.
Furthermore, the conceptual design has been supported by thermo-mechanical and thermal-hydraulic analyses. Specifically, two different approaches have been

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followed for the investigation of the thermo-mechanical performances of both piping and 3D components under both nominal and design conditions. As to the former, pipe stress analyses have been performed by using the commercial pipe stress code ROHR2 v33.1 [6], while concerning the 3D components, a thermo-mechanical analysis has been carried out for critical components, adopting a theoretical numerical approach based on the Finite Element Method (FEM) and using the commercial code ABAQUS v6.14 [7]. The structural assessment has been therefore carried out by means of a strength-based design approach adopting the design rules reported in the adopted nuclear standard (e.g. RCC-MRx [8], ASME BPVC Sect. III [9]).

For the Water Cooling System and the PbLi loop, thermal hydraulic analyses have been performed with the aim of mapping the thermal-hydraulic profile of the two systems under Normal Operational State (NOS) and Hot Stand-by Operational State (HSOS), in both Beginning Of Life (BOL) and End Of Life (EOL) conditions. The computational activity has been carried out using a modified version of the RELAP5 mod 3.3 system code [10], [11], [12].

On the other hand, for both CPS and TES the pressure profile along the system main flow path has been theoretically computed in BOL and EOL conditions.

The second part of the paper is dedicated to an overview of the performed ESP/ESPN classification for the main components of the four ancillary systems.

Finally, the last part of this article briefly describes the final arrangement and the integration of the systems in the three assigned ITER areas, recalling also the design criteria followed.

Figure 1 provides a schematic layout of the WCLL-TBS Ancillary Systems dealt in this article.

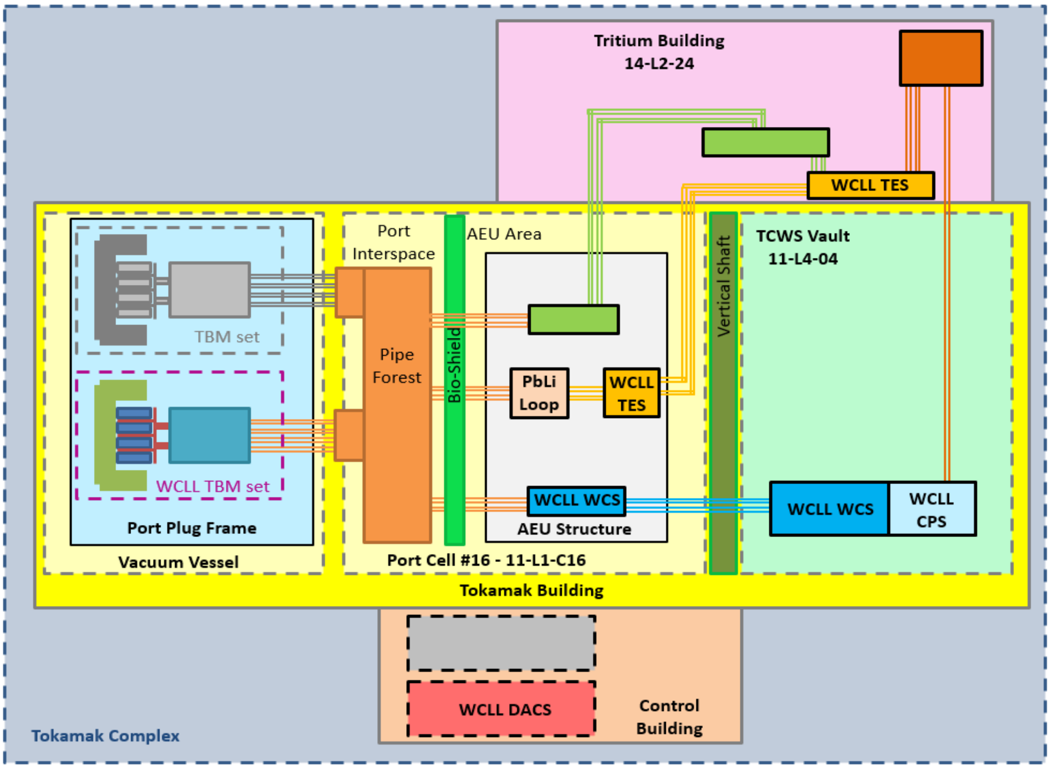

Fig. 1 Schematic layout of the WCLL-TBS Ancillary Systems dealt in this article.

2. WCLL TBS Water Cooling System

The conceptual design of the Water Cooling System of the WCLL-TBM was developed considering the same functions of the EU-DEMO WCLL-BB primary heat transfer system (PHTS), [13], but matching other boundary conditions: a scaled source of power and much lower heat sink temperatures, since the cooling water is provided from the Component Cooling Water System (CCWS) of ITER reactor instead of the DEMO Power Conversion System.

The Water Cooling System is designed to implement the following main functions: i) to provide suitable operating parameters of the water flow for TBM different operational states; ii) to transfer thermal power from WCLL-TBM to CCWS; iii) to provide confinement for water and radioactive products; iv) to ensure the implementation of the WCLL-TBS safety functions.

The WCS, made in AISI 316L stainless steel, consists of a primary eight shaped loop (nuclear) and a secondary loop (non-nuclear) [14]. In the primary circuit circulates the contaminated water flowing inside the TBM set. In NOS the ranges of primary water temperature and pressure are respectively 328-111 °C and 16.1-15.4 MPaG with a mass flow rate of 3.75 kg/s. The presence of a secondary loop is foreseen to avoid that in any case the contaminated water could enter the CCWS circuit exceeding the allowable radioprotection limits for this system. In NOS the secondary water temperature and pressure ranges are respectively 128-65 °C and 1.97-1.86 MPaG with a water mass flow rate of 4.30 kg/s.

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Since the heat sink temperatures are far lower than those achieved in the TBM (295-328 °C), a single heat exchanger with these thermal boundary conditions is very difficult to design. Hence, the installation of an economizer at the centre of WCS loop is required to divide the overall temperature difference between TBM module and CCWS system in two heat exchangers, the former acting like economizer and the latter as heat sink. The resulting WCS primary loop has an "eight" shape.

The WCS Primary Loop mainly consists of: an economizer (Hairpin heat exchanger technology), which preheats the water headed to the TBM with the hot one out coming from it; a Hairpin heat exchanger located before the pump system and the connections with the Coolant Purification System, that thermally couples the WCS primary and secondary loops; two canned centrifugal water pumps; an electric heater, installed to supply the deficiency of TBM thermal power, a steam bubble pressurizer, two storage tanks to drain the loop, a relief tank and two delay tanks to reduce the radiation field due to ^{16}N-^{17}N generation.

On the other hand, the WCS Secondary Loop mainly consists of: a Hairpin heat exchanger, two canned centrifugal water pumps and a steam bubble pressurizer.

3. WCLL TBS Coolant Purification System

The Coolant Purification System (CPS) is a purification loop entirely located inside room 11-L4-04 (ITER TCWS Vault) and operates continuously, during Plasma Operation and also other ITER Plant Operational States, when Water Cooling System working.

The main functions of the WCLL TBS CPS are: i) WCS coolant purification - to remove activation products in ionic form or as particulates from the WCS to ensure adequate activity levels; ii) WCS coolant chemical control - to maintain the WCS coolant chemistry within the required water chemistry specifications; iii) WCS coolant degassing - to provide the flow path to extract dissolved gases from the WCS coolant and iv) preservation of the WCS pressure boundary - to protect the WCS pressure boundary using redundant, safety-related isolation valves.

The loop, made in AISI 316L stainless steel, starts from WCS, downstream the primary heat exchanger, and returns back to the WCS a little further downstream. Downstream the connection with the WCS the coolant first enters the purification loop through isolation valves, (that isolate the CPS from the WCS in abnormal conditions). Then it passes through the pressure reducer, which brings down the coolant pressure from 15.197 MPaG to CPS working pressure of 0.9 MPaG, while setting, at the same time, the flow rate as required (0.1 kg/s). Water is then cooled by a heat exchanger, from 111°C to 50°C, to be compatible with the resin beds and degasifiers operating conditions.

The purification flow continues through filters, through a mixed bed demineralizer and, optionally, through a cation bed demineralizer. Another set of redundant filters is provided downstream the resin beds to stop any resin fragments inadvertently escaped from the resin bed and to protect the degasifier membrane contactors installed downstream. Two redundant volumetric pumps return the coolant to WCS, after its treatment, if needed, with chemical additives. The addition of liquid chemicals to the coolant is performed through a dedicated chemical injection package while, in case of gaseous chemicals, the addition is carried out inside the CPS tank

4. WCLL TBS PbLi loop

The Pb-Li loop is a closed loop, made in ferritic-martensitic steel, with forced circulation of the Pb-Li liquid eutectic alloy.

The main functions of the WCLL TBS PbLi loop are: i) to provide and maintain Pb-Li eutectic alloy at operating conditions suitable for the WCLL-TBM correct operation; ii) to ensure the circulation of the Pb-Li in the WCLL-TBS; iii) to remove impurities from the Pb-Li alloy; iv) to remove tritium from TBM and to promote external tritium extraction; v) to provide confinement of Pb-Li and radioactive products; vi) to contribute in ensuring safety provisions implementation for WCLL-TBS.

Since the Pb-Li loop is directly connected to both the Water Cooling System (WCS) by the WCLL-TBM and the Tritium Extraction System (TES) by the Tritium Extraction Unit (TEU), several design requirements are foreseen for this ancillary system, ensuring the correct operation of the whole WCLL-TBS and its safety systems during both nominal and accidental scenarios. In particular, the WCS/Pb-Li loop interface plays a pivotal role in the design due to the likelihood of an in-TBM LOCA, followed by the interaction between Pb-Li and water leading to an exergonic chemical reaction [15].

Moreover, due to the considerable production of activated elements (both Pb-Li impurities and corrosion products) and tritium inside the Pb-Li alloy during its flow through the WCLL-TBM and the rest of the loop, all the main components of the circuit have to be classified as nuclear pressurized equipment.

During the Plasma/Normal Operational State (POS/NOS), the Pb-Li alloy returns from the TBM to the loop at a temperature in the range of 300-322 °C, with a nominal mass flow rate of 0.65 kg/s, even though it can range from 0.2 to 1.20 kg/s, depending on the working scenario.

The Pb-Li flow is then heated up to 450 °C and enters the TEU, whose function is to extract tritium from its solubilized state in the liquid metal into a suitable gas phase. The Gas Liquid Contactor (GLC) technology based on packed columns in counter-current flow has been evaluated as the main suitable process for the adoption to the WCLL TBS. The packed columns are vertical columns filled with packing device providing a large interfacial surface between liquid and gas phase.

After having passed the TEU, the Pb-Li stream is cooled down to 300 °C by a cooler.

Once cooled, the Pb-Li mass flow is divided into two branches. A first portion of the Pb-Li flow enters in a cold trap for alloy purification, while the remaining part of the flow is directly sent to the Storage/Recirculation Tank. From such tank, it is pumped by means of an immersed circulation pump and sent again to the WCLL-TBM.

5. WCLL TBS Tritium Extraction System

The Tritium Extraction System (TES) plays the key role of removing the tritium coming from the stripping gas of TEU of the Pb-Li loop, concentrate it, and send it to the Tritium Plant through the Tritium Accountancy System.
Consequently, the main functions of WCLL TBS TES are: i) to extract tritium from the stripping gas coming from TEU; ii) to route the extracted tritium to the tritium processing system in the Tritium Plant in a form suitable for an accurate tritium accountancy; iii) to control the chemical composition and physical properties of the stripping gas; iv) to remove solid particles from the stripping gas.
The temperature of the purge gas coming from the TEU is approximately 450 °C and, since the process of tritium extraction/concentration requires that the purge gas is at nearly room temperature, it is necessary to cool it. Because of the very small amount of power to be exchanged, this temperature lowering is simply implemented by means of heat exchange between the room atmosphere and the external surface of the not insulated pipes connecting TEU to the process room.
The purge gas contains tritiated hydrogen in molecular form (Q_2). All these species are removed by means of the Q_2 getter beds. The proposed purifier system consists of two beds, one working in adsorption phase and one in regeneration phase.
The purge gas from the Q_2 getter bed can eventually detach and drive solid particles that have to be removed. For this reason, a filter is placed downstream of the Q_2 getter bed. After the filter the purge gas is routed back to TEU by means of a He-compressor.
When a Q_2 getter bed is saturated, the purge gas is deviated on the other one. The saturated Q_2 getter bed is regenerated using a flow of He driven by means of a compressor and heated up to approximately 300 °C by means of heaters integrated inside the getter beds.

6. Ancillary systems ESP/ESPN Classification

A preliminary ESP/ESPN classification of the WCLL TBS Ancillary Systems, with respect to the European 'Pressure Equipment Directive' (PED) [16] and the French Order 'Equipments Sous Pression Nucléaires' (ESPN) [17], has been defined in [5]. The approach and the work have been subject of discussion with F4E, thus a common understanding of the ASN guidelines and IO implementation of the regulations has been reached.
The PED is the European directive adopted to classify components, mainly on the basis of the nature of fluids contained and their maximum allowable pressure, in four categories, from I (lower) to IV (highest level of risk). Thus, depending on the category, a component has to be designed and fabricated according to a specific set of rules (increasing with the category). Components not included in the PED have to be designed according to the Sound Engineering Practice (SEP).
Concerning the nuclear classification (ESPN), the relevant French regulation foresees the classification of components on the basis of the magnitude of the radioactive emissions that could result from failure of the equipment. Three categories are foreseen, from N1 to N3. Due to their characteristics, WCLL TBS components may fall under N2 or N3 categories (radioactivity release higher than 370 GBq or 370 MBq, respectively). Also in this case, on the basis of the nuclear classification, a specific set of rules is foreseen by the law and has to be followed for the design and fabrication of the component. Components whose failure leads to a radioactivity emission lower than 370 MBq does not fall under this regulation (Non-ESPN).
The summarized results below are taken from the WCLL TBS Ancillary Systems ESP/ESPN Classification reported in detail in [5] and in [18].
1. Water Cooling System: concerning the PED classification, equipment falls under categories II, III and IV, while all the piping is under category I. As far as the nuclear classification is concerned, with the exception of the delay tanks, placed in Port Interspace and at level 3 that are classified N2, all other components are classified N3 or Non-ESPN. The same classification (N2, N3 and Non-ESPN) applies also for piping.
2. Coolant Purification Systems: main components and piping fall under PED category SEP. The only devices in category IV are the safety pressure devices, mainly safety isolation valves. Concerning nuclear classification, both equipment and pipes are under categories N3 and Non-ESPN;
3. PbLi Loop: components are classified mainly as pressure categories II or IV, while piping is SEP. From the nuclear point of view, the level N2 is predicted for all items, with the exception of the portion of the CCWS circuit falling under the responsibility of the PbLi loop;
4. Tritium Extraction System: with respect to the PED, all main components and pipes have been designed adopting the SEP category. The only devices in category IV are the safety pressure devices, mainly safety isolation valves. From the nuclear point of view, Non-ESPN and N3 classified components and piping are foreseen.

7. Ancillary Systems integration

As mentioned, the main ancillary systems are installed in three different locations in the ITER Tokamak Complex: i) the TCWS Vault area – Room 11-L4-04; ii) The Port Cell (PC) #16 Ancillary Equipment Unit (AEU) - Room 11-L1-C16 and the Tritium Building - Room 14-L2-24.
The layouts of the systems [19] have been chiefly based on the following design criteria: 1. Feasibility of installation of equipment and pipes; 2. Accessibility of all components for maintenance; and 3. Proper clearances between components for supporting structures.
Moreover, pipes and valves have been arranged according to the following additional criteria: 1. Sufficient straight pipe sections are provided for instrumentation (not implemented); 2. Distances between pipes and pipes to walls is consistent with ITER assembly/cad rules present in the ITER CAD manual;

and 3. Additional space for insulation is considered (although not implemented).

TCWS Vault Area – Room 11-L4-04

Most of the equipment of the WCS and the whole CPS will be hosted in TCWS Vault area (room 11-L4-04). The separation in two different volumes dedicated to WCLL-TBS and HCPB TBS has been foreseen avoiding the intricate integration foreseen in the past for HCLL and HCPB TBSs.

The part of WCS hosted in that TCWS Vault area is connected to the water pipes in AEU areas through two connection pipes hosted in the Vertical Shaft. The interfaces between the connection pipes in the Vertical Shaft and WCS components in TCWS Vault area are well identified.

The CPS components (orange colored) are arranged at the middle of the WCLL-TBS volume. All the other available space is used for WCS (pink colored) primary loop (upper part) and secondary loop (lower part). CPS components have been placed at height in order to guarantee the proper drainage to a common storage tank. The related supporting structure has been provided as a space reservation and should be discussed in future design activities. Figure 2 shows the Arrangement of WCS (pink) and CPS (orange) in TCWS Vault area – L4.

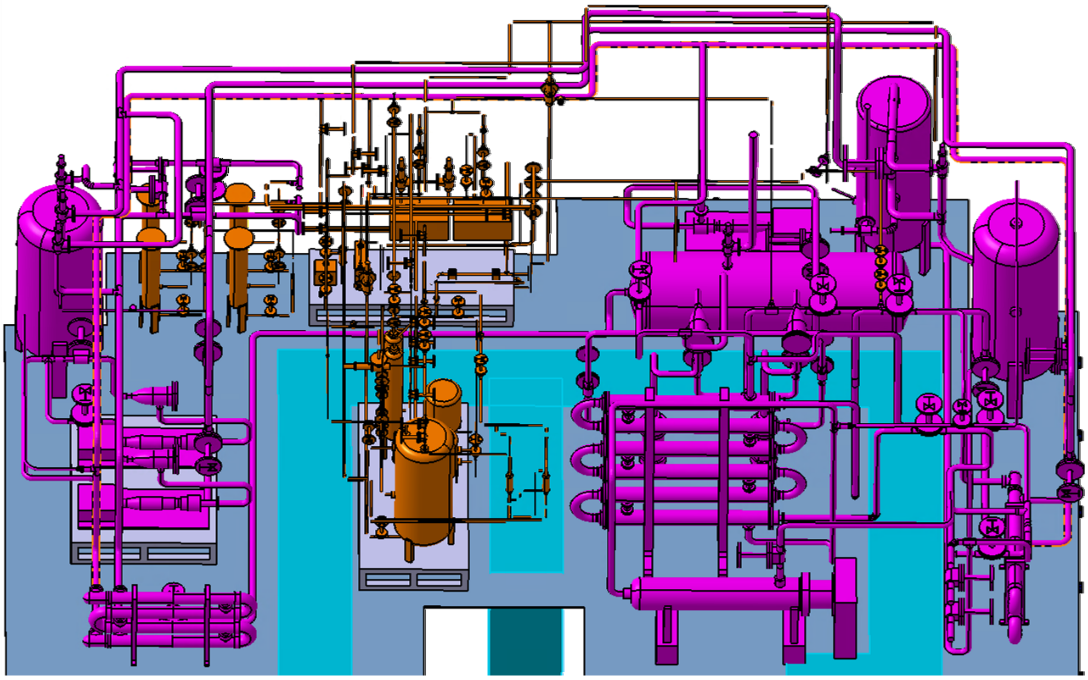

Fig. 2 Arrangement of WCS (pink) and CPS (orange) in TCWS vault area – L4.

Port Cell #16 (room 11-L1-C16)

Integration of the WCLL-TBS ancillary systems (together with HCPB-TBS ancillary systems) inside the PC#16 has been a complex task, mainly because of the strong space constrains. This task has been carried out taking into account the further following requirements and design assumptions: 1. All components foreseen in PC#16 will have to be placed inside the AEU; 2. Pb-Li loop will be located in the part of the AEU closer to the bio-shield in order to limit the AEU region receiving the highest gamma dose; 3. Pipes crossing the galleries have to be at room temperature; 4. The Pb-Li loop storage/recirculation tank and the cold trap are shielded to limit the gamma emission; 5. Human accessibility must be assured for maintenance task to be implemented during both short and long term maintenance.

The layout of PbLi loop inside the PC#16 AEU - Room 11-L1-C16 is mostly based on the space available with the new space allocation (design completely independent from HCPB). In spite of the limited space available, all the components whose maintenance is foreseen (e.g. TEU, vacuum pumps, cold Trap, etc.) were arranged in view of the human access.

Given the limited space available, WCS piping inside the PC#16 AEU - Room 11-L1-C16 has been routed based on the available space. In particular, the WCS pipework in PC#16 consists of: two DN-40 pipes for WCS outlet; one DN-80 pipe for WCS inlet; four safety isolation valves; two control valves; and a temporary water storage tank.

Also, some components of TES will be located in the PC#16 Room 11-L1-C16.

Figure 3 reports the arrangement of WCS (pink), PbLi loop (grey) and TES (green) in PC#16.

Tritium Building – Room 14-L2-24

Most pieces of equipment of WCLL TES will be hosted in the Tritium Building - Room 14-L2-24. The 3D model of this ancillary system has been designed based on the PFDs and the conceptual design. At the current design stage, pumping units have not been selected and are represented as boxes for space allocation purposes.

In the TES (green) glove box have been placed also other two Ancillary Systems, the Tritium Accountancy System and part of the Neutron Activation System.

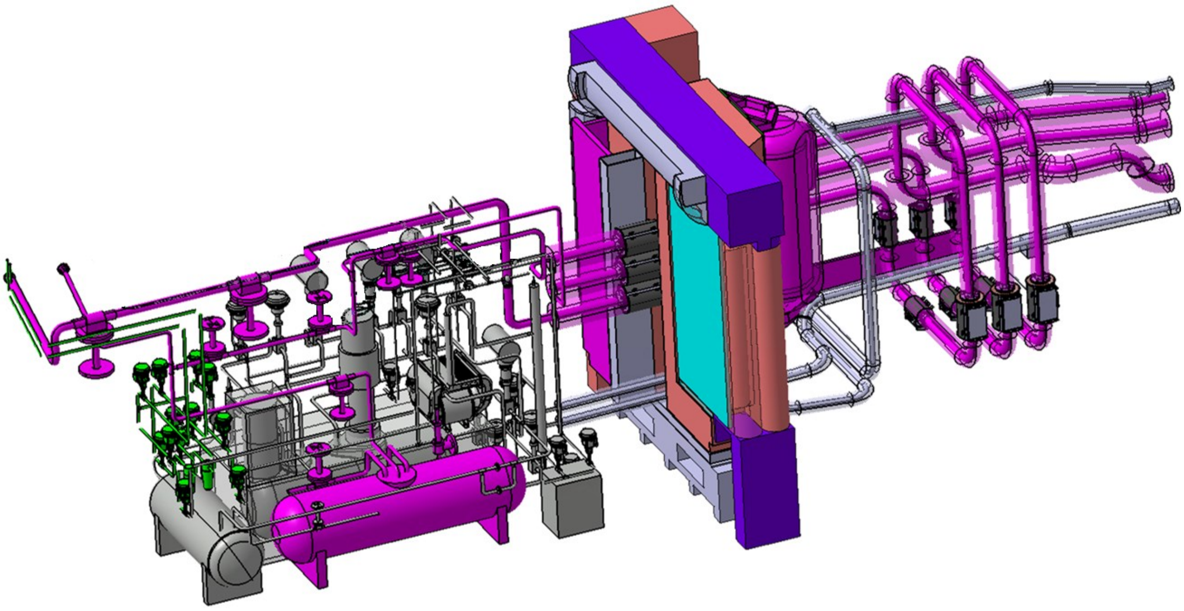

Fig. 3 Arrangement of the four main ancillary systems: WCS (pink), PbLi loop (grey) and TES (green) in PC#16.

8. Conclusion

In the framework of the WCLL-TBS Conceptual Design areas of Ancillary Systems Design, Modelling, Instrumentation Development PHASE I and PHASE II EUROfusion contracts, several technical activities have been performed for the completion of the WCLL-TBS conceptual design.

Among these activities, in particular have been successfully completed: i) the conceptual design of the WCS, CPS, PbLi loop and TES, including their ESP/ESPN Classification; ii) the preparation of their CAD models, as well as their integration in the ITER rooms; iii) the thermal-hydraulic and thermo-mechanical analyses; iv) the I&C design and v) the preparation of elements of system engineering (although points iv and v are not described in this paper).

A complete and comprehensive set of design and engineering reports have been produced by EUROfusion Laboratories in close cooperation with F4E and at mid-September 2020, the outcome of Reviewers Panel has been that the level of the WCLL TBS design is mature enough to pass the ITER Organization Conceptual Design Review.

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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