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Design Features and Simulation of the New-Build HELOKA-US Facility for the Validation of the DEMO Helium-Cooled Pebble Bed Intermediate Heat Transport and Storage System

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Abstract: For the EU-DEMO Helium-Cooled Pebble Bed (HCPB) concept, an indirect coupled design (ICD) with a molten salt (MS) loop as an intermediate heat transport and storage system (IHTS) is considered for the conceptual design phase. The IHTS with an energy storage decouples the primary heat transport system (PHTS) that undergoes pulse and dwell power cycles from the power conversion system (PCS), and thus can provide stable power to the turbine and grid. However, the maintenance of stable He and MS parameters during transitions from dwell to pulse and vice versa is challenging for the design of the MS loop, and the real performance of the helium–MS heat exchanger (He/MS HX) shall be verified. To investigate such components and conditions, a new R&D infrastructure HELOKA-US (Helium Loop Karlsruhe—Upgrade Storage) is under construction for the validation of prototypical components and the MS loop operation under stationary and transitional conditions. This paper provides the design features of Phase 1a of the project and the simulation results with EBSILON on the power generation phase.

Keywords: HELOKA-US; EU-DEMO; balance of plant; intermediate heat transport and storage system; indirect coupled design; energy storage system; molten salt; EBSILON; EUROfusion



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1. Introduction

One of the main challenges of the European Demonstration Fusion Power Reactor (EU-DEMO) is being able to achieve long plasma operation and demonstrate the net electric output in an industrial scale [1–3]. To achieve this goal, DEMO must be more oriented towards electricity production, hence the Balance of Plant (BoP) must be considered as an essential system, which is a vital extension to ITER since ITER is not designed to generate any electrical power [4]. BoP is envisaged to extract the pulsed thermal power generated by plasma from the PHTS and transport the power to the PCS [5].

The intrinsic challenge of a heat transport chain in a Tokamak-based DEMO plant is the intermittent fusion plasma operation as a primary heat source to the Plant Electrical System, in which pulse operation lasts about 7200 s and the dwell operation period lasts about 600 s, as depicted in Figure 1 [6]. The HCPB-BoP will be capable of providing stable thermal power to the PCS throughout the intermittent plasma operational phases (pulse and dwell) and its realization requires an energy storage system (ESS) integrated into the IHTS.

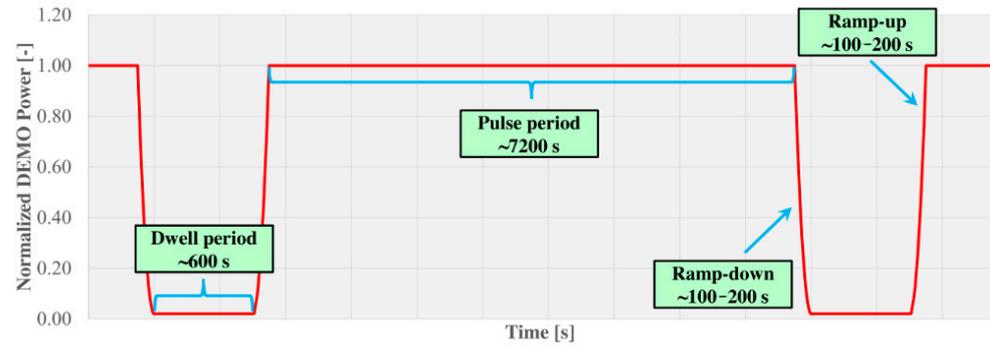


Figure 1. DEMO Primary Heat Transfer System power cycle. Reprinted from [6].

Various variants of the EU-DEMO BoP are under evaluations focusing on the cycling performances of the components, the efficiency, integration possibility, and safety. The variants are classified as either Direct Coupled Design or Indirect Coupled Design (ICD). Among the proposed solutions, the ICD with an large energy storage system (ESS) based on commercial systems already operating in concentrating solar power plants are the most robust [4] (see Figure 2 from [7]). Thus, this HCPB BoP ICD option was selected as the reference variant for the next step of DEMO development, the so-called Conceptual Design Phase. Achievements on the optimization of the BoP system have been reported in [5,7-9] comprising the system conceptual design of the IHTS with the molten salt loop [8,9] and the principal design of the He/MS heat exchanger (He/MS HX) [7]. The critical issue is firstly related to the interface of PHTS and IHTS which are connected with a He/MS HX, and between IHTS and PCS which are connected with a MS Steam Generator [4].

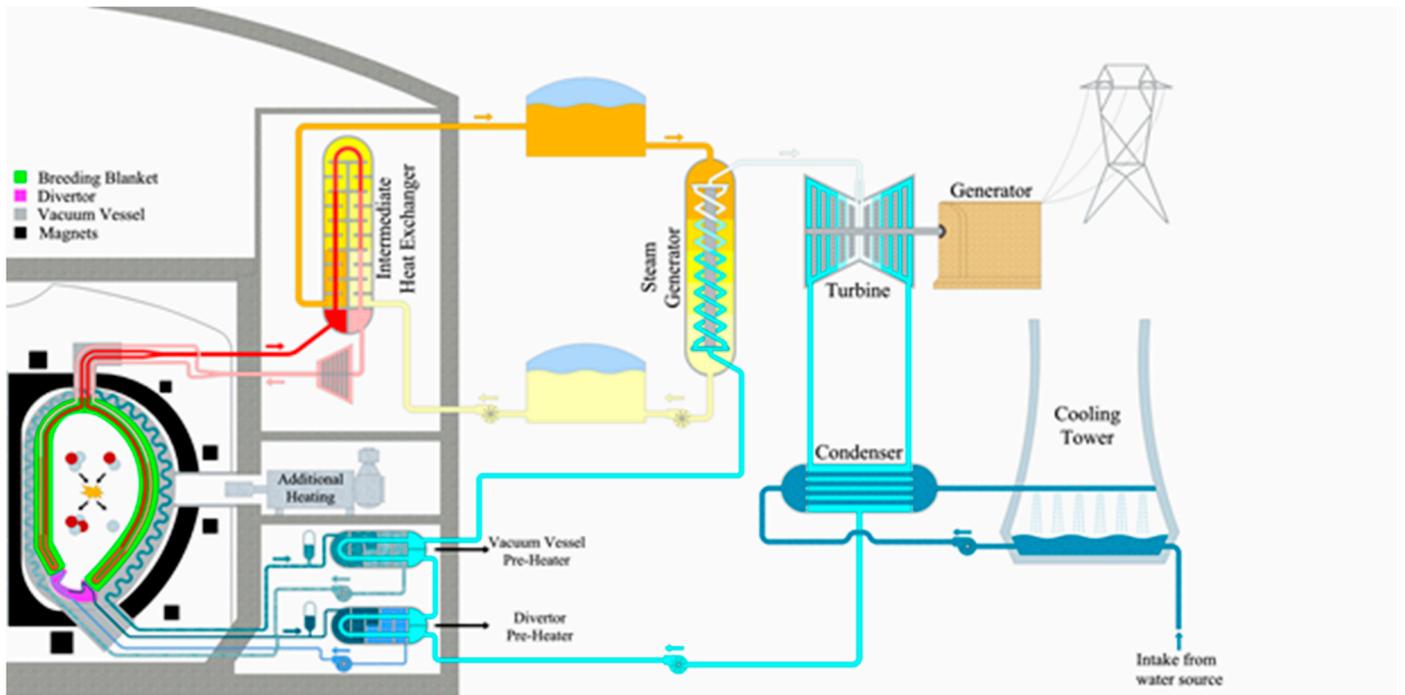


Figure 2. Conceptual scheme of the helium-cooled pebble bed Balance of Plant with an energy storage system. Reprinted with permission from [7]. Copyright 2019 Elsevier.

The main challenges of the thermodynamic and heat transport processes of the IHTS (ESS) system are:

- The helium inlet temperature to the breeding blanket shall be maintained stable during both pulse and dwell operation. Since during dwell time PHTS extracts only 1% of the

full nominal power, the cooling of the PHTS in dwell needs a sensible regulation of the IHTS-ESS;

- The fast transients of pulse-to-dwell ramp-down and dwell-to-pulse ramp-up that take place within 100–200 s requires fast response of the ESS [10];
- Not only the normal power generation modes throughout pulse and dwell phases shall be functional, but also the preparation, standby, and shutdown modes shall be considered;
- The heat transfer characteristics, fabrication, and material fatigue feature of the He/MS HX shall be assessed in industrial and experimental trials.

The interaction of the different systems must be investigated and optimized. Here, the expertise of KIT on helium system operation (HELOKA-HP [11] and KATHELO [12]), as well as the expertise in the high-temperature molten salt field (LIVE [13,14]) are favorably combined within the HELOKA-US project. The conceptual design and technical specification of the Phase 1 components are completed. Engineering layout design and construction will be started very soon.

The construction conception the HELOKA-US facility is presented in Section 2. The design features and operational modes are described in Section 3, including the loop design and components as well as the operation modes considered. Section 4 provides the numerical simulations performed to establish the conceptual design of HELOKA-US as in Phase 1. Finally, the conclusions and coming steps are providing in Section 5.

2. Construction Conception of the Project

The new-build HELOKA-US system bears the aim to investigate the HCPB BoP ICD concept with a molten salt loop as the IHTS with ESS function for the helium-cooled DEMO variant. The power scaling is 1:1000 of one of the eight PHTS circuits, corresponding to 260 kW of nominal power. The total height of the molten salt loop is about 9 m, which is about $\frac{1}{4}$ of the DEMO IHTS vertical dimension. The whole experimental facility will be built in two phases, as depicted in Figure 3.

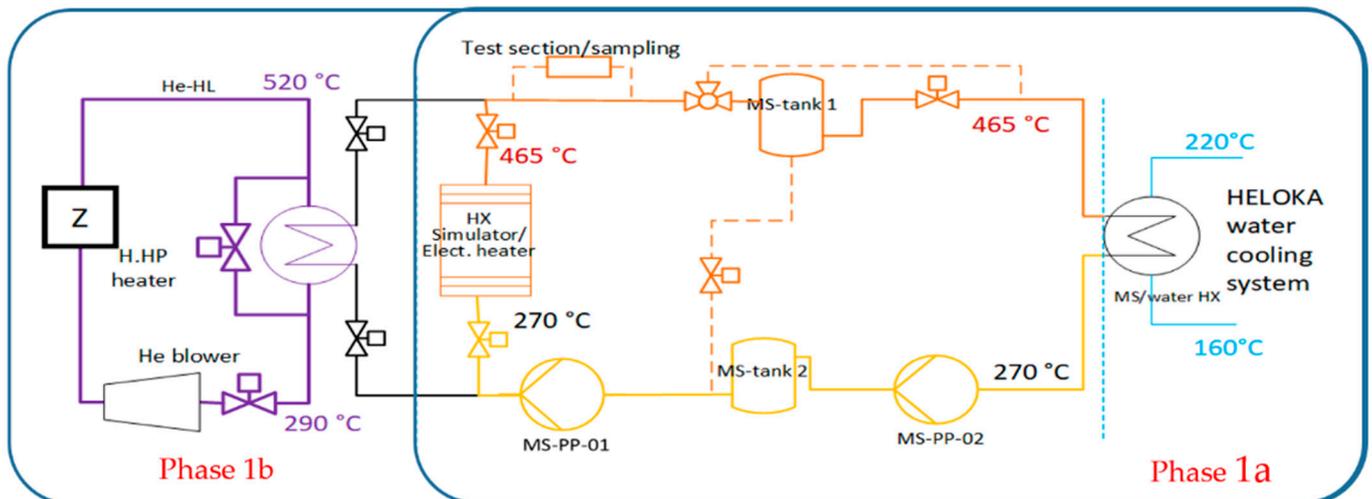


Figure 3. Schematic diagram of HELOKA-US as in Phase 1a and Phase 1b. MS: molten salt; PP: Pump; HX: heat exchanger.

First, the tags of the loops and system and tags of the component in the ES are given in Table 1.

Table 1. Tags of loops/system and tags of component in HELOKA-US.

Tag	Loop/System	Tag	Component
ES	molten salt Energy Storage loop	HE	Electrical heater
NS	Nitrogen cover gas System	HT	Heat tracing
WCS	HELOKA Water Cooling System	HX	Heat exchanger
WHT	High-pressure water loop	LP	Pipeline
HE-HL	HELOKA- High pressure Loop	PP	Pump
		TK	Tank
		VI	Insolation Valve
		VR	Relief valve

Phase 1: The energy storage (ES) loop using HITEC as molten salt coupled with the HELOKA-HP helium loop will be built. This phase is split in two sub-phases: Phase 1a and Phase 1b. The heating source in Phase 1a is an electrical heater supplying 260 kW power, while in Phase 1b, the heated helium from HELOKA-HP will provide the heat source via a He/MS HX, which replaces the electrical heater used in Phase 1a. The heat sink in both Phases 1a and 1b is the HELOKA, an intermediate high-temperature high-pressure water loop (WHT) that is coupled with a water-cooling system (WCS) in normal pressure. A WHT can be operated up to 46 bar, and thus ensures a waterside coolant temperature range of 160–220 °C, which is above the solidification temperature (142 °C) of the HITEC molten salt.

Phase 2: The ES loop will be coupled to a representative DEMO-PHTS helium circuit driven by a scaled-down DEMO prototypical blower.

The coupling of the HELOKA-HP loop, ES loop, WHT system, and WCS at the completion of Phase 1b is depicted in Figure 4. HELOKA-HP, WHT, and WCS are existing infrastructure, as well as the power supply system and the data acquisition and control system, which are the infrastructure of HELOKA-HP. The main focus for Phase 1a is the design and building of the ES and cover gas (N₂) system (NS), the coupling between ES and WHT with a new built MS/water heat exchanger, as well as the coupling WHT-WCS with a water/water heat exchanger. The ES loop and WHT system are connected with NS, which serves as cover gas and pressure regulation for the ES loop and for the pressure control for the WHT system.

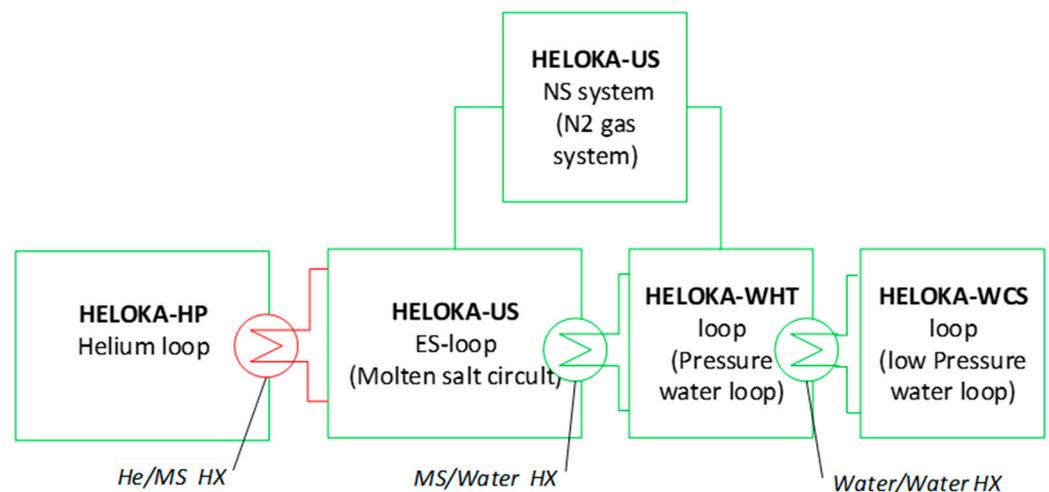


Figure 4. HELOKA-US main systems and their interfaces at the Phase 1b.

3. Design Features and Operational Modes of HELOKA-US

3.1. Molten Salt Properties

The HITEC salt with molar ratio of $\text{KNO}_3:\text{NaNO}_3:\text{NaNO}_2$ in 44:7:49 is selected as the heat transfer fluid for the ES loop following the DEMO HCPB BoP ICD specifications. Its chemical and physical behavior is well-studied in the field of concentrated solar power plants [15–17]. The strongest argument for the HITEC is its low solidification temperature of 142 °C, which enables it to be used as a heating source of low coolant temperature, e.g., in the steam generator. The HITEC is chemically stable under N_2 gas at least up to 465 °C and can even be applied briefly at higher temperatures up to 538 °C.

3.2. Loop Design and Components

ES loop: The Pipe and Instrumentation Diagram of the HELOKA-US is depicted in Figure 5. A two-tank system in direct connection with the main loop is applied. A list of the main components in the ES loop is given as follows:

- Two tanks (TK): ES-TK-01 and ES-TK-02 (DN450, each tank, $\sim 0.8 \text{ m}^3$);
- Two pumps (PP): ES-PP-01 and ES-PP-02 ($2.5 \text{ m}^3/\text{h}$, total developed head: 15–20 m);
- One external electrical heater (HE): ES-HE-01 ($\sim 260 \text{ kW}$);
- One internal electrical heater in ES-TK-01: ES-HE-02 ($\sim 30 \text{ kW}$);
- Six control valves (VC): ES-VC-01 to ES-VC-06 (DN25, DN33, DN40);
- Eight isolation valves (VI): ES-VI-01 to ES-VI-08;
- Two MS separators (SE) above the tanks: ES-SE-01 and ES-SE-02;
- Pipelines (LP): ES-LP-01 to ES-LP-14 (total $\sim 40 \text{ m}$, DN32 in main loop, DN25 in side piping, material stainless steel 1.4571);

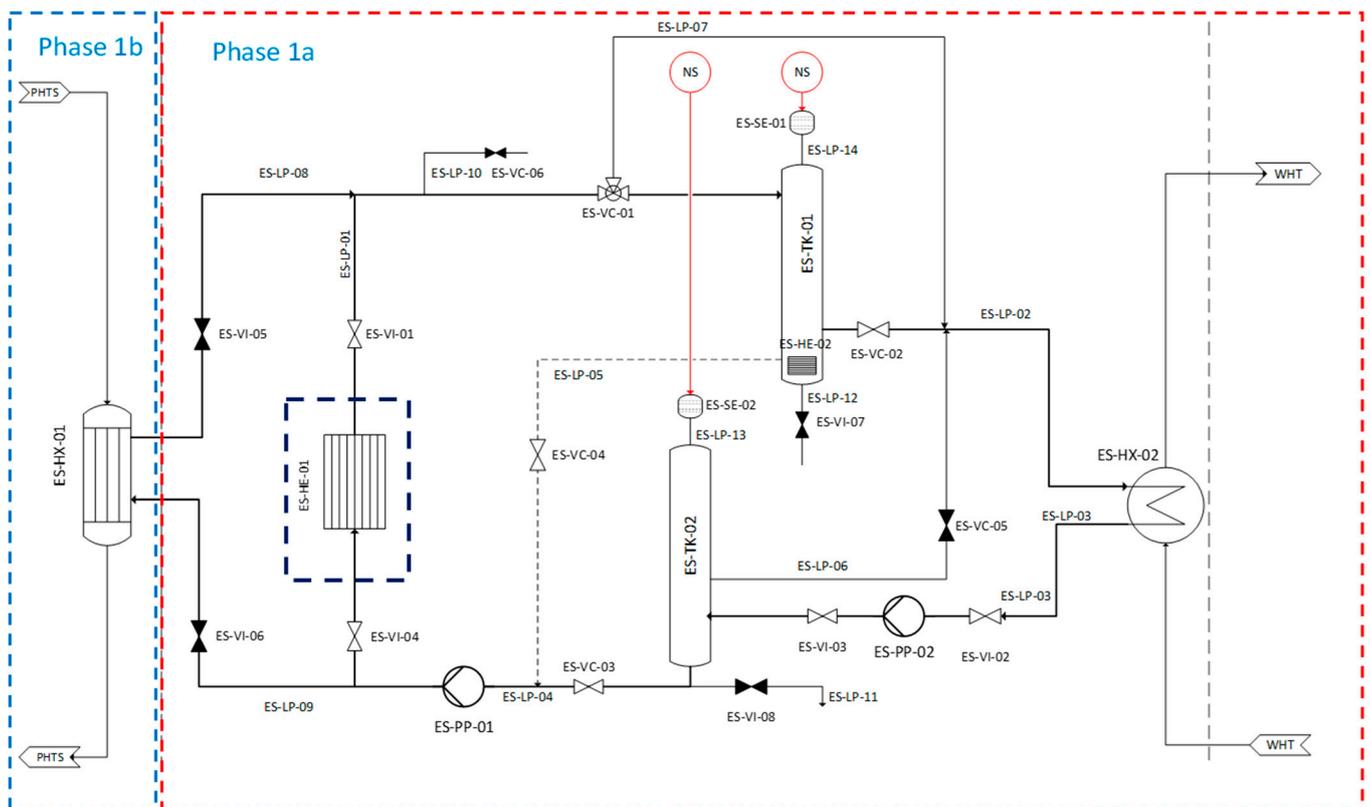


Figure 5. Pipe and Instrumentation Diagram of Phase 1 of the HELOKA-US system. Phase 1a energy storage system (ES) and nitrogen gas covering system (NS) components are enclosed in the red frame, and Phase 1b components are in the blue frame.

Besides the visible components in Figure 5, the ES loop is equipped with the following periphery installations:

- Instrumentation on temperature, pressure, flowrate, and level sensors in the tanks;
- Trace heaters on all ES equipment and piping (max. temperature 300 °C);
- High-temperature thermal insulation;
- Data acquisition and control system in hardware and software of the ES and NS systems.

The external electrical heater, ES-HE-01, enclosed in a dashed frame in Figure 5, will be replaced by the optimized He/MS HX (ES-HX-01) in Phase 1b. The general design temperature and design pressure of the ES loop are 550 °C and 0.6 MPa, respectively. An internal electrical heater in the tank ES-TK-01 is foreseen for the initial heat-up phase to melt the HITEC salt up to operational temperature. For maintenance operations, drainage piping connecting tanks, pumps, and valves are included but not shown in the Figure 5 for simplicity. A port for melt sampling and a material test section are also foreseen downstream of the He/MS HX (ES-LP-10).

The ES loop comprises three bypasses (ES-LP-05, ES-LP-06 and ES-LP-07) for experimental purposes, ramp-up/down, and maintenance. The functions of the bypasses are described in detail:

- Fine-tuning of MS flow in order to maintain stable MS and He temperatures during steady states of pulse and dwell, as well as during the ramp-up and ramp-down transients. The bypass ES-PP-05 from the tank ES-TK-01 to the pump ES-PP-01 is especially effective to regulate a small MS flow through ES-LP-04 to the He/MS HX in the dwell phases, when only 1% of the nominal power will be extracted;
- Enabling different flow paths during startup, shutdown, and standby phases.

WHT: The design temperature and pressure of the high-temperature high-pressure water system, whose interface to the ES loop is shown at the right side in Figure 5, are 220 °C and 4.6 MPa, respectively.

Dimension and Location

The HELOKA-US platform is built at 4 m level to provide space and adequate height for HELOKA-US components. The platform aligns to the existing HELOKA-HP platform to allow connections to He and cooling water sources. The arrangement of the new components is depicted in Figure 6. For the latter Phase 1b, the He-MS HX will be located at 8.5 m on the existing HELOKA-HP platform. The allocation of the components considers the connection to the water and helium sources, the KIT operational safety requirements, and maintenance space. The two tanks are in a slim geometry with a height of about 5 m to approach the tank height in DEMO HCPB ESS as closely as possible. The two tanks include additional volume to allow margins of experimental operation and to simulate the heat transfer inertia in the whole DEMO HCPB IHTS piping system.

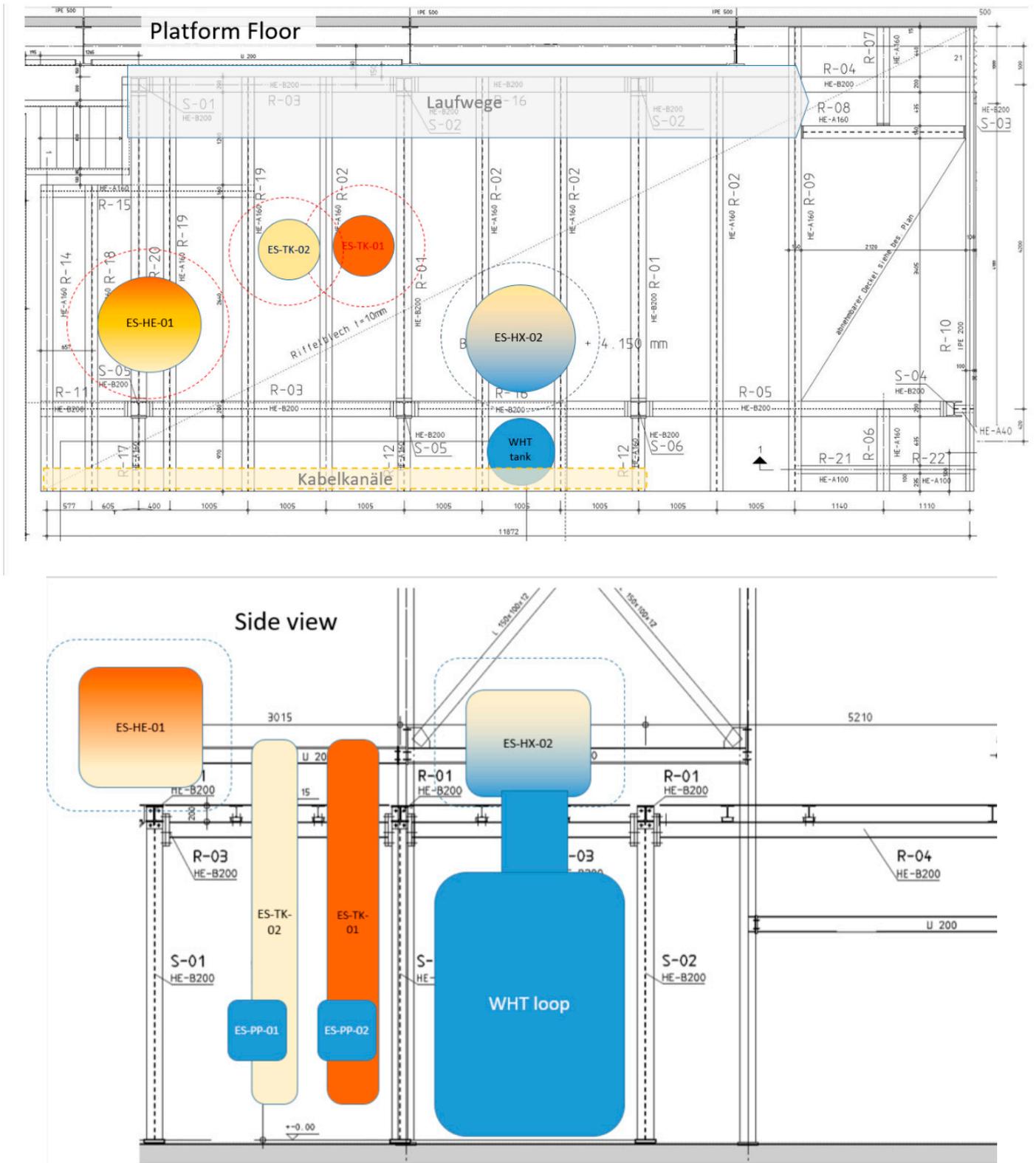


Figure 6. Location of ES components. Top: top view at the 4 m-platform. Bottom: side view.

3.3. Operation Modes

With the loop configuration in HELOKA-US is able to simulate and investigate both conditioning modes and power generation modes conceptualized in DEMO as shown in Figure 7. Figure 8 interprets the HELOKA-US preparation/maintenance modes and normal

power general modes with the transient routes. The operation modes inside the red frame indicate frequent and fast transitions among the modes. The temperature levels of cold standby and hot standby I are about 200 °C and 270 °C, respectively. In the hot standby II mode, addressing the preparation for the first pulse operation, the MS in tank ES-TK-01 is heated up to 465 °C and the hot leg is heated up to 290 °C.

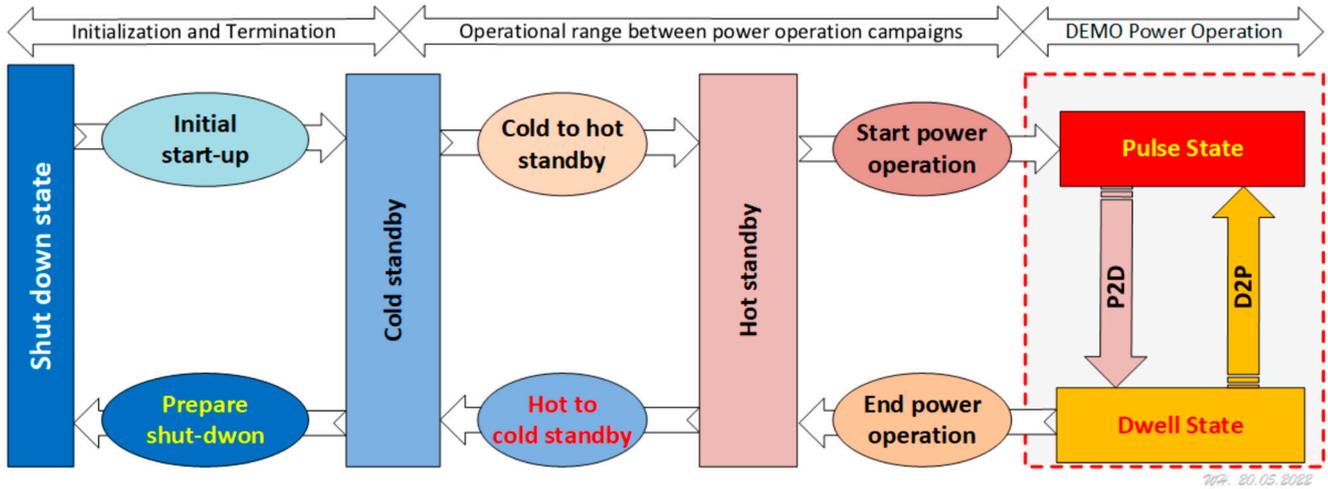


Figure 7. DEMO operational modes including all states and transitions. P2D: pulse-to-dwell transition, D2P: dwell-to-pulse transition.

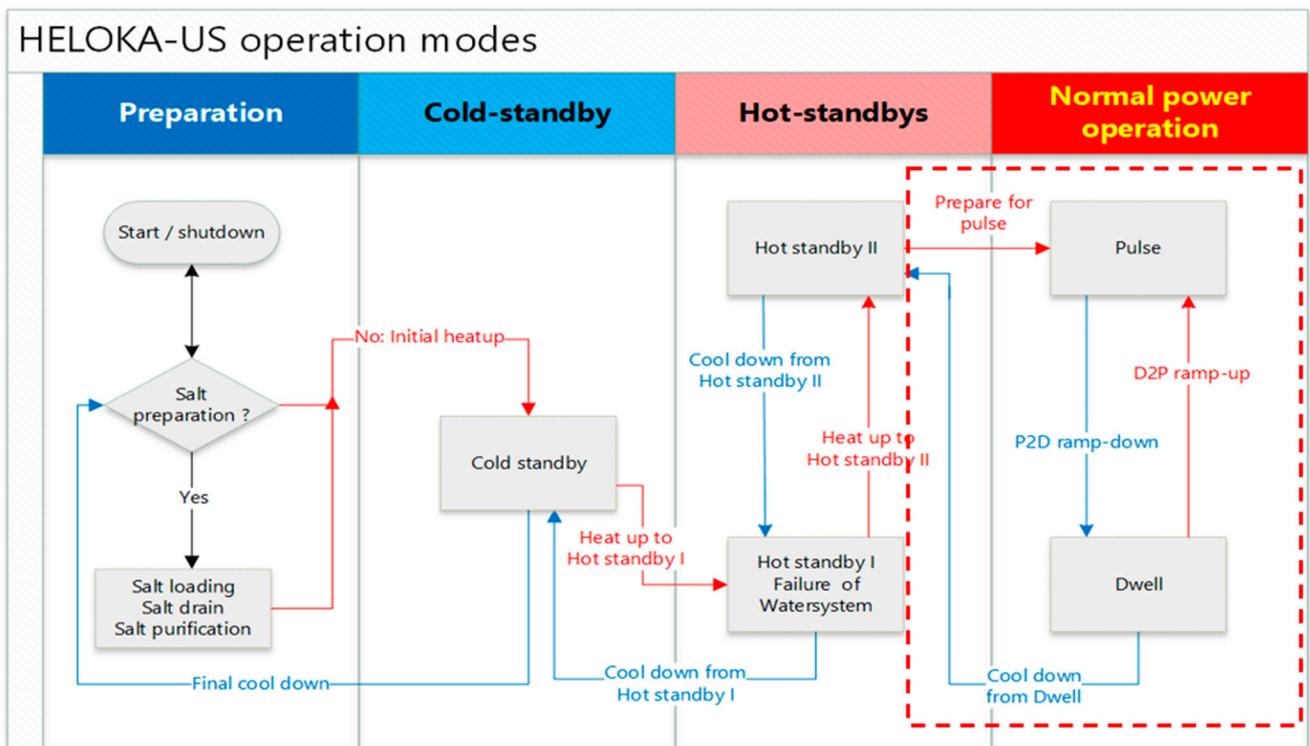


Figure 8. Operation modes in HELOKA-US. P2D: pulse-to-dwell transition, D2P: dwell-to-pulse transition.

In Figures 9 and 10, the temperature and mass flow of MS in pulse and dwell modes are depicted, respectively. The functions of pulse and dwell modes are briefly described as follows:

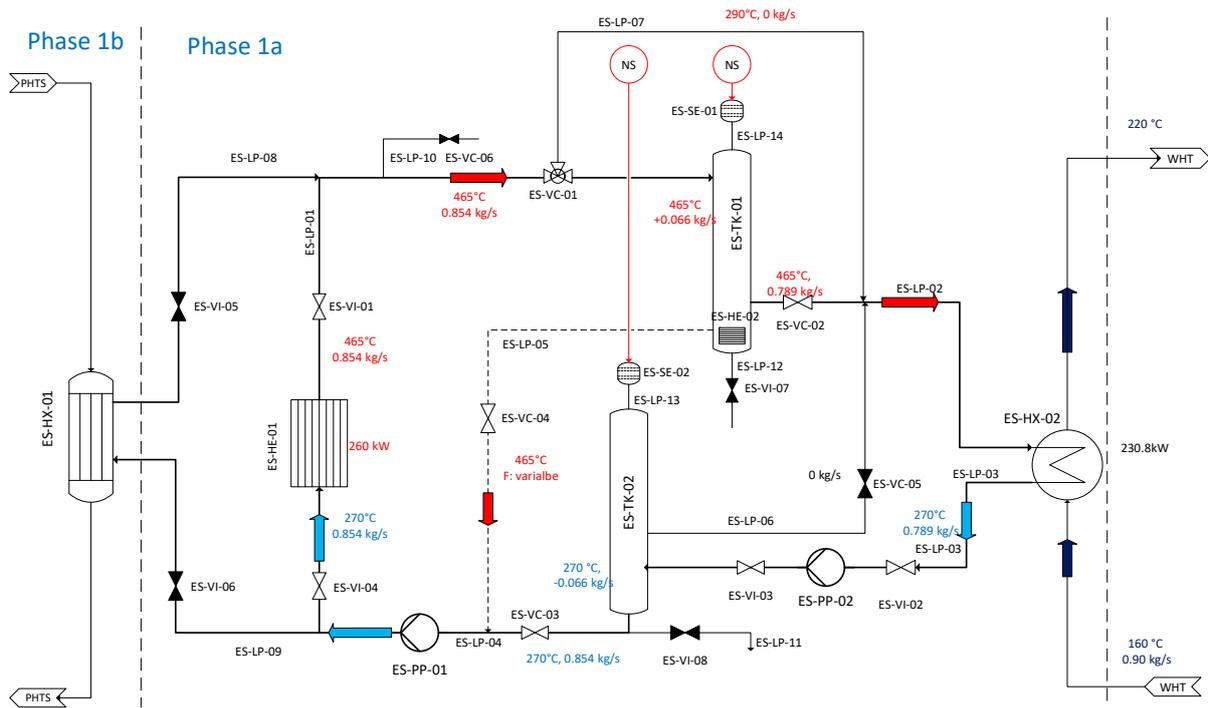


Figure 9. Pulse flat top mode in ES loop.

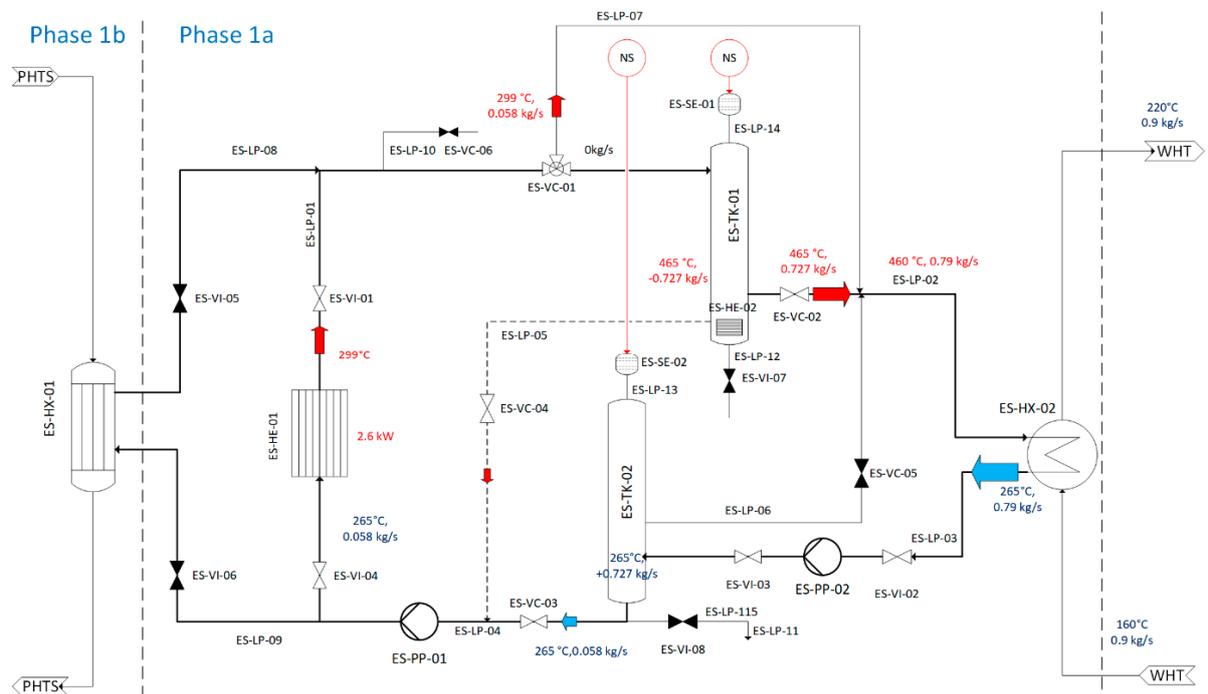


Figure 10. Dwell flat bottom mode in ES loop.

Pulse flat top: ES-HE-01 simulates the heat source of the helium with 260 kW. The bypass ES-LP-05 with the valve ES-VC-04 regulates the precise demand on the MS inlet and outlet temperatures in ES-HE-01. Duration: about 7200 s.

Dwell flat bottom: The ES-HE-01 power level is 2.6 kW and it is cooled by a small stream of MS from ES-TK-02. The bypass ES-LP-05 regulates the inlet and outlet MS temperatures through ES-HE-01. MS from the ES-HE-01 is directed to bypass ES-LP-07 and

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

BoP	Balance of Plant	IHTS	Intermediate Heat Transfer System.
DEMO	DEMOstration power plant	KIT	Karlsruhe Institute of Technology
D2P	Dwell-to-Pulse transient	MS	Molten Salt, HITEC™ in HELOKA-US
ESS	Energy Storage System	P2D	Pulse-to-Dwell transient
HCPB	Helium-Cooled Pebble Bed (Blanket)	PCS	Power Conversion System
HCPB BOP ICD	HCPB Indirect Coupling Design variant of Balance of Plant	PHTS	Primary Heat Transfer System
HE	Helium		
HELOKA	Helium Loop Karlsruhe		
HELOKA-US	HELOKA—Upgrade Storage system		
HELOKA-HP	HELOKA High temperature high pressure Helium Loop		
HITEC	Commercial mark of a nitrite/nitrate molten salt		
HX	Heat Exchanger		
ICD	Indirect Coupling Design		

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