Helium Loop Karlsruhe (HELOKA) – large experimental facility for the in-vessel ITER and DEMO components

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Abstract. The purpose of this paper is to present the design of Helium Loop Karlsruhe (HELOKA), a new planned FZK experimental facility, dedicated to the testing of various components for nuclear fusion facilities: the Helium-Cooled Pebble Bed blanket (HCPB), the helium-cooled-divertor for the DEMO power reactor, and the High-Flux Test Module (HFTM) for IFMIF. All these components have in common a very complex geometry, with many parallel channels, involving a complex helium flow distribution. Therefore, these components should be tested full-scale before their assembly in ITER and IFMIF. Beside the individual testing of the blanket and divertor modules, the understanding of the behavior of their cooling systems in conditions relevant for ITER operation is mandatory. The main requirements and characteristics of the HELOKA facility and a preliminary conceptual design are described in the paper.

1 Introduction

The conceptual and engineering design of the **H**elium-**C**ooled **P**ebble **B**ed blanket (**HCPB**) and the helium-cooled-divertor for the DEMO power reactor are particularly important long-term activities which are performed at Forschungszentrum Karlsruhe within the framework of the European Nuclear Fusion Program. **T**est **B**lanket **M**odules (**TBM**) of this blanket concept will undergo various tests in ITER. For the qualification of such TBM's, it is indispensable to test mock-ups in a helium loop under realistic pressure- and temperature profiles, in order to validate design codes, especially regarding mass flow and heat transfer processes in narrow cooling channels. For this purpose, a 10 years program has been initiated for designing several test blanket modules, each aimed at specific investigations. Similar testing must be performed for the DEMO blanket, currently under development. Note that the DEMO blanket is approximately one order of magnitude larger than the TBM. It is also envisaged to test divertor modules in ITER, during a later phase of ITER operation. The divertor of a fusion power station must withstand very high peak heat fluxes (up to 15 MW/m^2). The **T**est **D**ivertor **M**odule (**TDM**), currently under development at the Forschungszentrum Karlsruhe, uses helium as cooling agent and it is based on small (in the order of mm) slots made of tungsten and the multi-jet concept. This concept must be validated by experimental investigations. A high power input is required in order to simulate realistically the functioning of the complex cooling system in a fusion reactor. The Forschungszentrum is also responsible for the design, construction, and experimental qualification of the **I**nternational **F**usion **M**aterials **I**rradiation **F**acility (**IFMIF**) test cell for irradiating specimens. This high-flux test module is also planned to be cooled with helium. For experimental qualification of the test cell design, low pressure experiments in a helium loop are required in order to overcome problems such as heat transfer in the narrow gaps, and flow distribution in the complex geometries of the IFMIF test cell.

In general, the design of the above-mentioned helium cooled components is characterized by many parallel channels involving a complex flow distribution in the presence of large temperature gradients. Furthermore, the helium coolant in nuclear fusion facilities is expected to operate at high pressures (up to 100 MPa) and high temperatures (500°C to 800°C). Experimental investigations regarding heat transfer problems and material selection are therefore essential.

The Helium Loop Karlsruhe (HELOKA) facility is envisaged to be build as an experimental facility dedicated to the testing of the above-mentioned components for IFMIF, ITER, and DEMO.

2 HELOKA Requirements

The design of HELOKA has been elaborated in close co-operation with the future potential users, in order to assure that their requirements are fully met. These user requirements defining the nominal operating conditions for each of the fusion components that are planed to be tested in HELOKA are presented in Table 1. In order to cover all the required testing conditions, three distinct sub-loops are planed to be build: **HELOKA**-**L**ow **P**ressure for IFMIF/HFTM (**HELOKA-LP**), **HELOKA**-**H**igh **P**ressure for **TBM** (**HELOKA-HP/TBM**) and **HELOKA**-**H**igh **P**ressure for **TDM** and **DEMO** (**HELOKAHP/TDM+DEMO**) with different pressure- and temperature profiles between 0.3 MPa, 50 °C and 10 MPa, 700 °C. The total power input is planned at about 8 MW.

HELOKA Test section	He Mass Flow Rate (kg/s)	Pressure (MPa)	Pressure difference at test section (MPa)	He inlet/ outlet temperature (°C)	Heat and power supply (MW)
ITER-TBM	0.88-1.8	8	<0.3	100 / 300 300 / 550	1.5
ITER-TDM	3.0 – 5.5	10	1.0	650 / 700	5
DEMO Blanket	5.0	8-9	<0.4	300 / 550	5
IFMIF-HFTM	0.083 – 1.5	0.3	0.05	50 / 80 - 100	0.12

Table 1. User requirements for HELOKA test sections

The goals of the HELOKA-HP/TBM Experimental Facility are: (a) to validate the design of the TBM, (b) to achieve prototypical operating conditions for the ITER-TBM helium cooling system, (c) to provide measurement values for comparisons with, and improvements in, numerical computations of anticipated pressure and temperature profiles in ITER-TBM. To validate the divertor design the HELOKA-HP/TDM+DEMO loop would need to meet the most demanding testing requirements, namely the highest helium pressure and temperatures at very high mass flow rates, in order to be able to test up to a full-size divertor cassette. The goals of the HELOKA-LP loop are: (a) to achieve and to maintain the pressure and temperature profiles anticipated in IFMIF, (b) to provide measurement values for comparisons with, and improvements in, numerical computations of anticipated pressure and temperature profiles in IFMIF; and (c) to investigate the consequences of accidental loss of pumping power (possible establishment of natural convection cooling of specimens, etc.).

2.1 Time-scale requirements

The time schedules for the HELOKA test sections are imposed by the time schedules of the ITER, IFMIF and DEMO and experimental programs for the respective components. To meet these deadlines, the HELOKA facility will be built in a modular way. The first planned loop is the HELOKA-HP/TBM. This loop should be available at the beginning of 2008. Therefore, the start of construction of this loop is required by the end of 2005.
The construction of the TDM loop is planned to start as soon as the HELOKA-HP/TBM loop will be ready for experiments. The first step will consist in a small upgrade of the loop, in 2009, in order to test small mock-ups of TDM, at the requested pressures and temperatures.

After this step will be completed, the second step could start, namely the construction of the HELOKA-HP/TDM, with the requested mass flow rate and a high heat flux capability. The first experiments with a full divertor target are planned for 2013. It is important to note that the very tight time schedules reflect user-imposed requirements.
Concerning the HELOKA-LP loop, its construction will start once the international agreement regarding the engineering and design activities for IFMIF is obtained and a subsequent agreement on the sharing of the components to be built is achieved. The construction of this sub-loop will take approximately one year.

3 HELOKA Main Characteristics

3.1 Prototypical cooling conditions for ITER

HELOKA-HP will satisfy the same conditions as those required by the TBM to be introduced in ITER. The components and the technologies (procedures) used for the assembly of the loop will ensure a leak rate of maximum 10^{-5} Pa m^3/s for the whole system. Under normal operating conditions, the loop will have a high reliability and will be able to operate during large periods of time with an operating cycle of 2 weeks (24 hours/day) in full power regime, followed by one week in which only the residual heat from the reactor is removed. The loop will also be able to simulate abnormal operating conditions (LOFA, LOCA) in order to define the proper control scenarios for this kind of situations.

3.2 Qualification of H-removal, purification system and coolant quality control systems

HELOKA-HP will offer the opportunity to qualify also the H removal system, the purification system and the coolant quality control system.

3.3 Modular design, which allows the construction in three stages

HELOKA is designed to fulfill testing requirements for TBM's, TDM's and for the IFMIF high flux test module. To ensure that a flexible build-up of the testing modules is possible in accordance with experimental requirements and time schedules, each experiment will be located in a separate room. However, the circulators of the high pressure loop will be used in common by TBM and TDM test sections in order to reduce costs. This modular approach will ensure an efficient operation: during measurements in one test section, another test section can be prepared for experiment.
This approach allows also a stage-by-stage construction of the individual experimental sections and of the loop itself thus offering the possibility to review progress and to react in a flexible way on upcoming experimental requirements, changes of time schedules, and budgets, etc.

3.4 Multipurpose loop

In the HELOKA design, a variety of conditions have been considered, making the facility quite general. For example, the low-pressure loop considered initially for testing the IFMIF high-flux test module, is under consideration to be also used for testing the purge gas for ITER-TBM.
In the current status of the ITER design, each TBM is cooled by a separate helium cooling system. Space restrictions and economics may require that several TBM have to be cooled using one helium loop with a flow rate higher than 1.8 kg/s which is required for cooling a single TBM. The high-pressure, high mass flow rate part of HELOKA-HP (with a mass flow rate up to 5.5 kg/s) could eventually be used to demonstrate the reliable operation of a system with flow rate high enough to service two TBM modules in ITER.

3.5 *Tests with 1:1 mock-ups of the Test Blanket Module*

The experimental programs for the design, testing and commissioning of the respective TBM contain: (i) the full qualification of the TBM design by doing tests with various mock-ups sizes from very small to 1:1; (ii) integral tests of the TBM and of its cooling system, and (iii) commissioning tests in order to understand the critical issues during commissioning in ITER.

4 HELOKA Conceptual Design

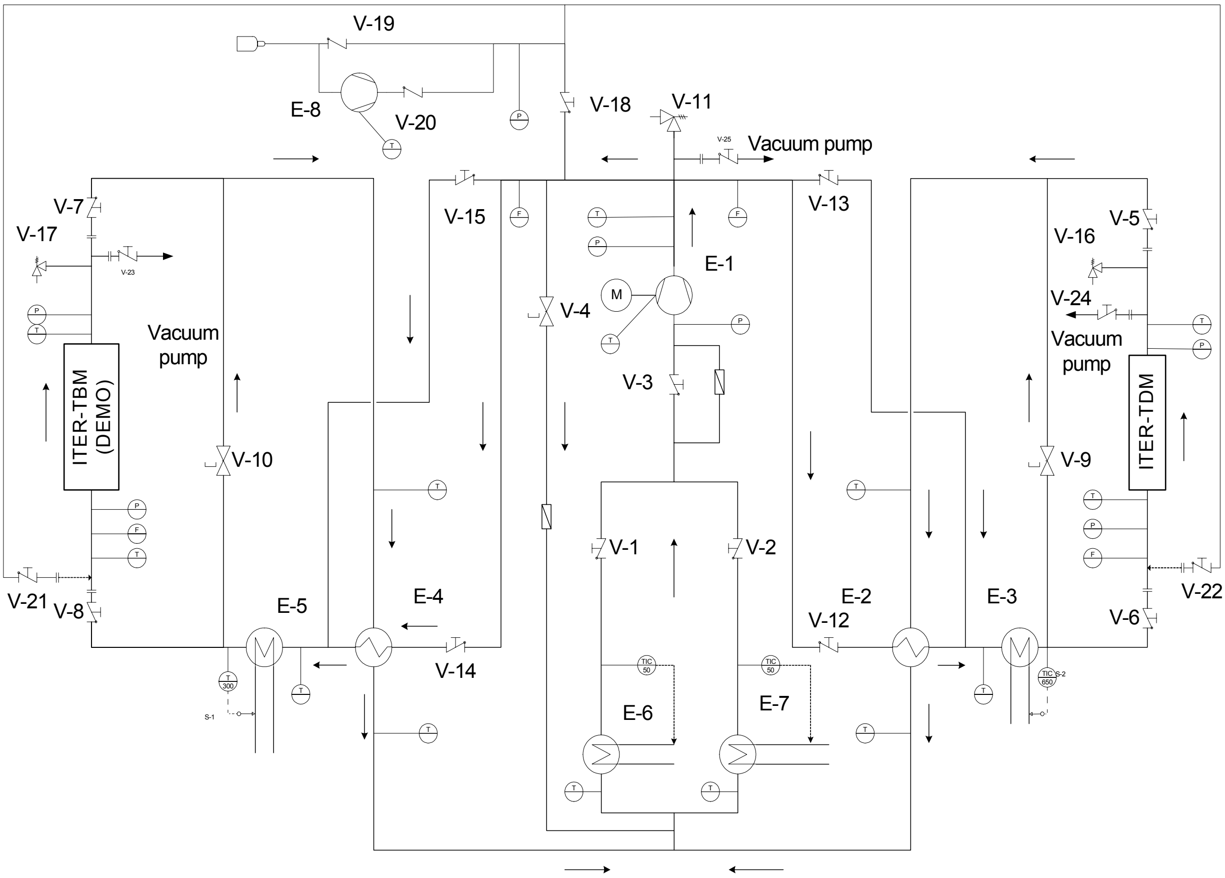

Figure 1. HELOKA-HP/TBM + TDM Piping and Instrumentation Diagram

The current status of the piping and instrumentation diagram for the complete HELOKA-HP is presented in Figure 1. The loop is designed as two "8"-shape loops, one for TBM and the other for TDM, sharing the circulator and the Helium supply system. To achieve the maximum required flow rate (5.5 kg/s for TDM) a group of three blowers in parallel are considered. Because of the significant difference between the inlet/outlet temperature conditions, each test section has its own cooler, recuperator and heater. This solution is preferred to a cheaper solution where all the components are shared by the test sections, because it allows us to have dedicated components for each application. This will increase the reliability of the loop while keeping the extra costs to a minimum since the blowers (which are the most expensive parts) will be common to both loops.

For the ***first stage of HELOKA construction,*** the left side of the diagram will be built. The loop is an "8"-shape loop which uses an economizer/recuperator (E-4) to transfer a part of the heat from the hot leg of the loop into the cold leg. Thus, the amount of heat removed by the cooler (E-6) is reduced as well as heat that has to be introduced in the loop by the heater (E-5). The circulator(s) (E-1) is a low temperature blower with an inlet temperature of 50°C. However, the loop could be converted into a simpler to control "O"-shape loop (similar with the preliminary design for the Helium Coolant system performed in 2001), using the bypass to the recuperator and, thus, isolating the cold and the hot leg of the loop one from another. At this stage of construction, only one blower is required to achieve the mass flow rate that is necessary to cool the TBM (1.8 kg/s). Even though the required Helium pressure for the TBM cooling system is only 8MPa the loop will be designed to withstand the 10MPa required for the TDM to avoid unnecessary certification when the second part of the loop (HELOKA-HP/TDM) will be constructed. Figure 2 shows the current layout for the HELOKA-HP/TBM loop.

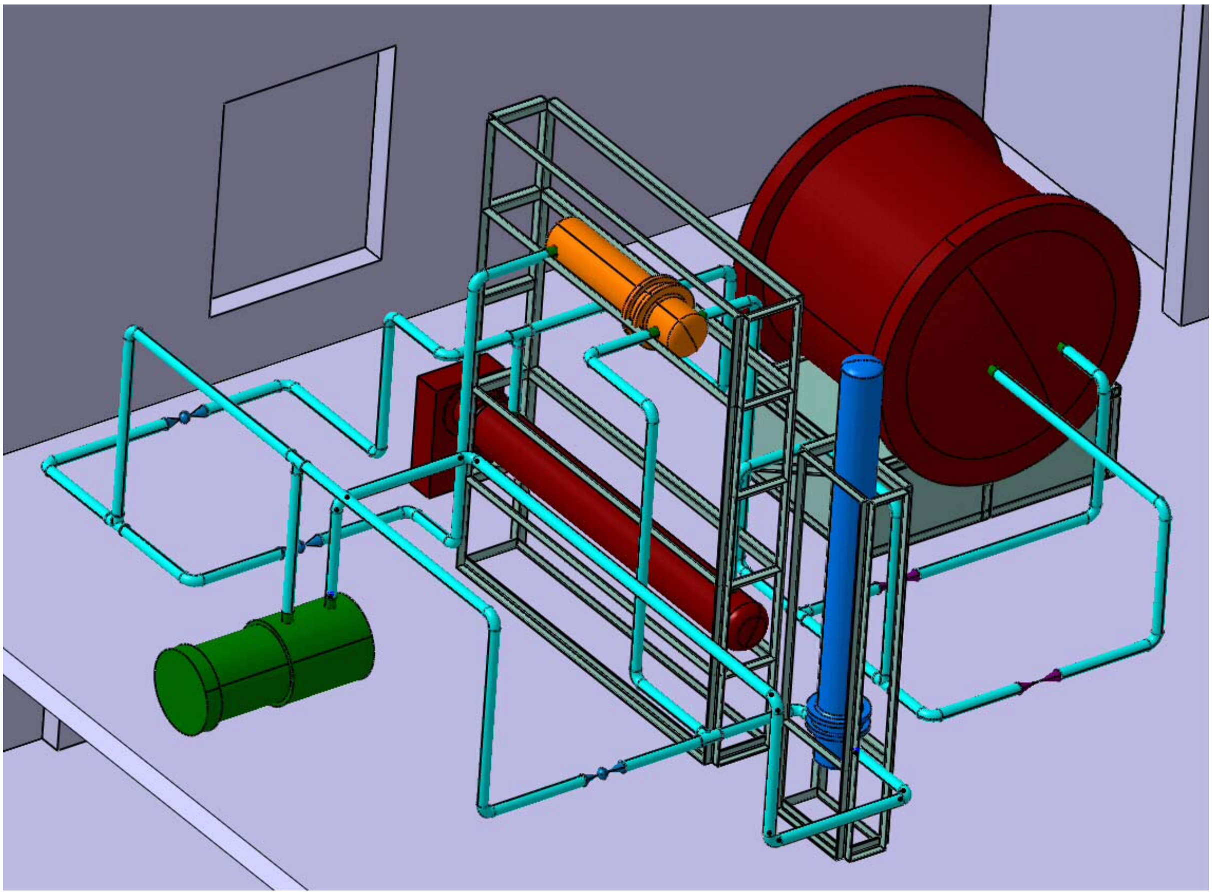

Figure 2. HELOKA-HP/TBM Diagram

As already mentioned, the construction of HELOKA-LP loop will start once the international agreement regarding the engineering and design activities for IFMIF is obtained and a subsequent agreement on the sharing of the components to be built is achieved. Nevertheless, we assume that this will consist on ***the second stage of the HELOKA construction.***

The proposed HELOKA-LP loop is shown in Figure 3. It will include the following major components: circulators, coolers, control valves and pipe work. In order to fill up the loop with helium at 3 bar, a helium bottle will be used after the air has been removed from the loop using a vacuum pump. In order to ensure the requested Helium flow rate at the inlet of the test section, 4 compressors in parallel will be used. The control of the flow rate is done using a bypass to the circulators. In the test section the Helium is used as a coolant agent therefore its temperature increases up to 80°C (max. 100°C). For removal of the excess heat due to the compression of the Helium and the heating in the test section three kinds of coolers are used.

The current design has been discussed with different companies and changes have been done according to the availability of the components on the market. The solution considered now is based on the offer of the Swiss company, HAUG Kompressoren. The assembly of the loop is also divided in two steps:

(i) the initial step, with 3 circulators in parallel, will allow the performance of experiments in the ranges showed in the Table 1, above;

(ii) the upgraded step, with an additional circulator in parallel will allow the performance of experiments with increased mass flow rates, for studying the behavior of the test module above the nominal values.

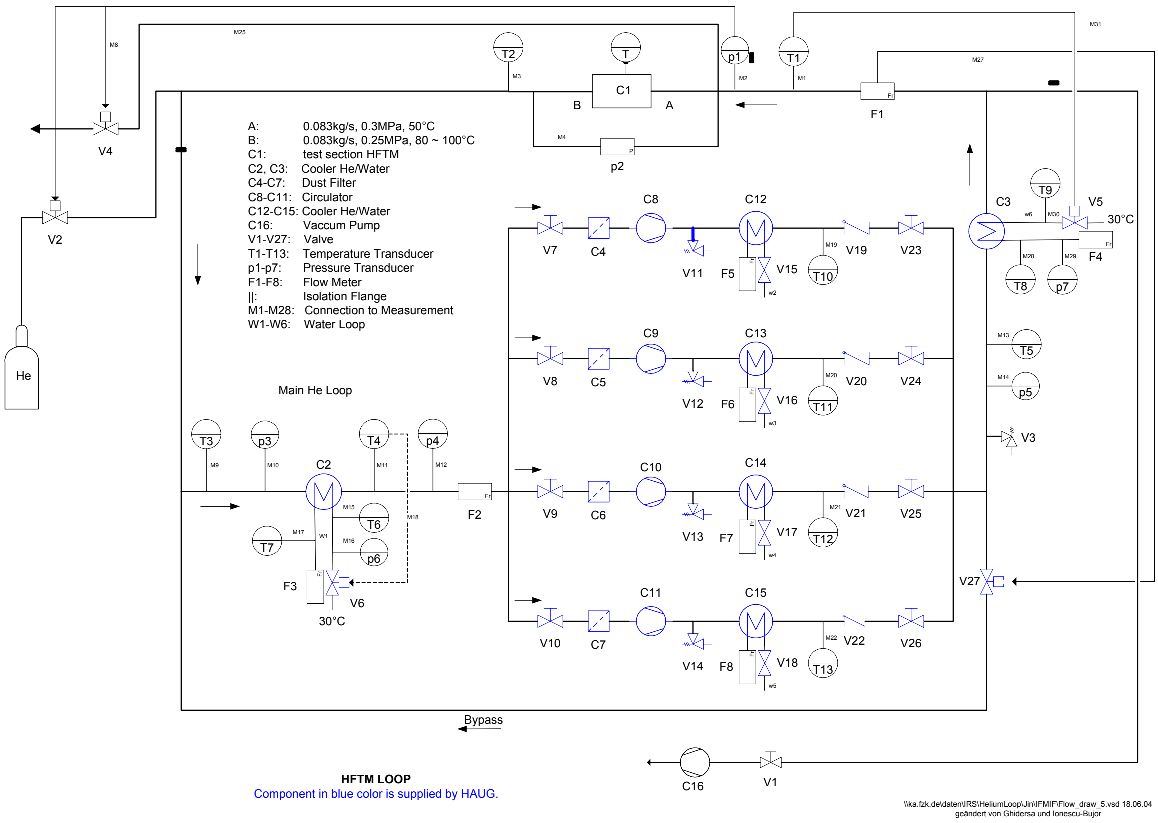

Figure 3. HELOKA-LP Piping and Instrumentation Diagram

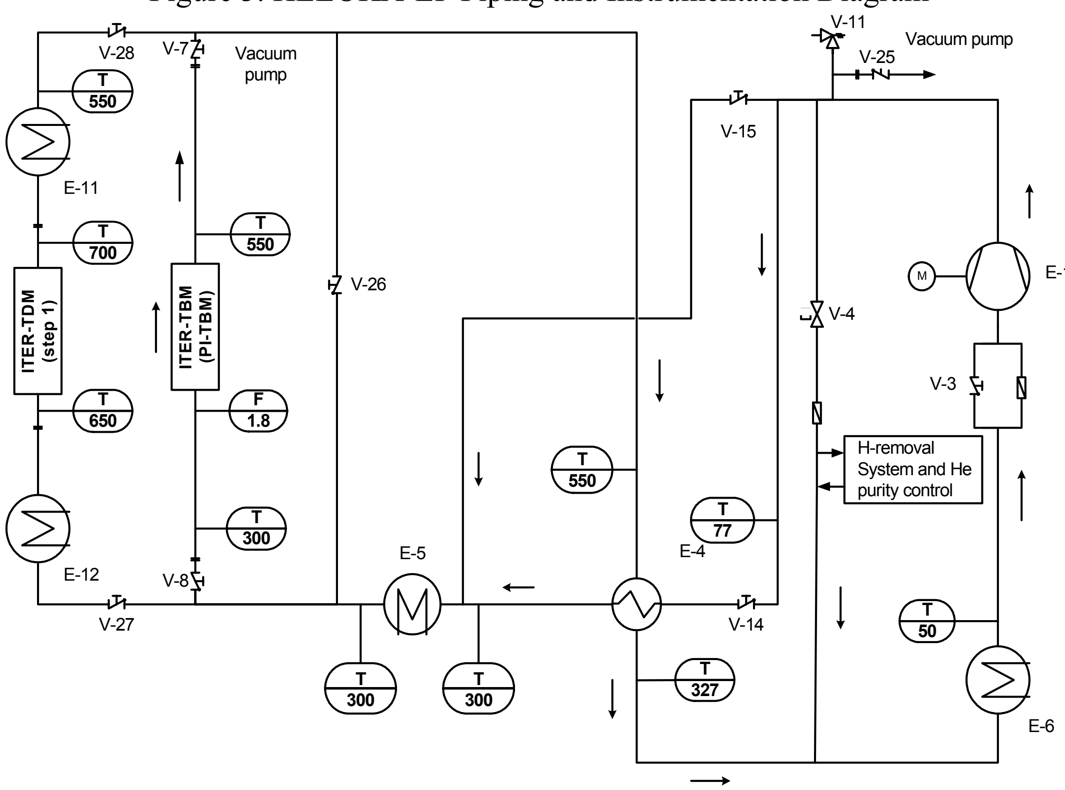

Figure 4. HELOKA-HP/TBM and TDM Step1

The third stage of HELOKA construction will consist in building the loop for TDM (right side of the diagram in Figure1). However, since the development of the helium cooled divertor is only in its early stages, at this moment it is possible to define only a general strategy for the test program of TDM. Therefore, it is foreseen to subdivide this program, and consequently the development of the HELOKA-HP/TDM, into individual consecutive steps, whereby, after each step, a review will take place that will determine the experimental content of the next step as well as the required investments. Based on today's knowledge these steps may look as follows:

(i) the first step consists in upgrading the HELOKA-HP/TBM loop in order to test small mock-ups using only the existing circulator (see Figure 4) for which the flow rate of 1.8 kg/s will be sufficient. The intention is to operate the TDM test section with parallel connections to the TBM section by simple addition of two further components: (a) a 1 MW heater in front of the TDM test section to heat the He gas from 300°C to 650°C and (b) a 1.5 MW cooler at the exit of the TDM section to cool the He gas from 700°C to 540°C. This allows the supply of 1.8 kg/s of helium at a temperature of 650°C and a pressure of 10 MPa to the TDM module.

(ii) for the second step an upgrade of the circulator group to three blowers to achieve a mass flow rate of 5.5 kg/s at an operating pressure of 10MPa and the construction of the "8-shape" loop corresponding to the right hand side of the HELOKA-HP diagram (Figure 1).

5 Conclusions

The proposed Helium Loop HELOKA fulfils the requirement of being prototypical for the cooling- and extraction loops to be installed in ITER and thus the successful execution of the suggested long term experimental programme will give assurance of a reliable operation of the blanket and divertor systems in ITER over extended periods of time. In particular, HELOKA-HP is able (i) to perform full-scale tests of TBM and TDM under realistic conditions; (ii) to test other components (pump, HX) of the He-cooling systems in ITER; (iii) to qualify the purification system and the coolant quality control system; (iv) to assess reliability and availability of He-cooling system in ITER; and (v) to obtain information for the design of the ITER cooling system.

Therefore HELOKA is not only a tool to develop the blanket and divertor modules for ITER and DEMO in vessel components but also a tool to develop and qualify their helium cooling system for the above described very demanding parameters.