**Concept for the cryo distribution for the Wendelstein 7-X cryo vacuum pumps**

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**Abstract.** After the completion of the third experimental campaign in 2018, actively cooled high heat flux divertors (10 pcs.) will be implemented within the stellarator fusion experiment Wendelstein 7-X (W7-X). A cryo vacuum pump will be installed in the plasma vessel behind the divertor. These pumps will be cooled with super critical helium at 3.9 K and liquid nitrogen at 80 K. A multichannel transfer line connects the helium refrigerator with a valve box located below the W7-X cryostat. From there, 10 parallel transfer lines run to the cryo pumps inside the plasma vessel. The lay out and the hydraulic design of the distribution system are discussed.

**1. Introduction**

The stellarator fusion experiment Wendelstein 7-X (W7-X) generates its magnetic field with 70 superconducting coils. The cooling of these coils is provided with a helium refrigerator with an equivalent cooling power of 7 kW at 4.5 K. After three experimental campaigns [1] in 2016, 2017 and 2018 W7-X will be further completed with ten actively cooled divertors and ten Cryo Vacuum Pumps (CVP’s). The CVP’s [2] will be installed inside the Plasma Vessel (PV) of W7-X to support the pumping power of the 30 turbo molecular pumps during plasma operation. The thermal shield of the CVP is cooled with Liquid Nitrogen (LN2) at 80 K. The cryo panels of the CVP are cooled with supercritical helium with an inlet temperature of 3.9 K at 360 kPa. The cooling power for the helium circuit is 450 W. The load on the thermal shield is expected to be 6 kW during the initial operation phase 2. Later, when the duration of the plasma shots is increased towards longer pulses (up to 30 minutes) the load on the shields will increase up to 12 kW [3] caused by stray radiation of the microwave plasma heating system. The cold box of the cryo plant already includes the CVP cooling requirement. A dedicated circulator pumps 250 g/s helium through two heat exchangers immersed in two liquid helium baths at different saturation pressures, and the CVP-cooling circuits.

**2. Layout**

As part of a cryo distribution system, a new Common Transfer Line (CTL), a Cryo Valve Box (CVB) and 10 Short Transfer Lines (STL) are required for the CVP (see figure 1). All new Transfer Lines (TL) are multi-channel lines with four internal process pipes, two for helium and two for LN2. The CTL with a length of 55 m, runs from the cryo plant building to the CVB, located below the W7-X cryostat in the torus hall. Inside the box the helium flow is split into 10 parallel loops. Ten STL run from the CVB to the dedicated supply/return ports at the W7-X cryostat. Inside the ports the process pipes run into the plasma vessel up to the individual CVP. Based on the five-fold modular symmetry of the W7-X cryostat...
each module has two such lines. One STL connects the upper port with a length of 16 m and another line to the lower port with a length of 12 m. The scheme is almost the same for the LN2 circuits.

![Figure 1](image)

**Figure 1.** Schematic of the helium supply system for the cryo vacuum pumps. The CTL runs from sub cooler box to the CVB. Ten STL run from the CVB to the ten CVP inside the plasma vessel.

### 2.1. Common transfer line
The CTL has an Outer Diameter (OD) of 323.9 mm and 4 process pipes with an OD of 48 mm each. The process pipes are enclosed by a thermal shield made of copper. Process pipes and thermal shield are fixed with supports made of glass fiber reinforced plastic G10. The thermal shield and the helium process pipes are wrapped with multilayer insulation to minimize thermal radiation from the warm outer shell to the thermal shield and from the thermal shield to the 4 K helium pipes. The nitrogen return line is thermally connected to the thermal shield.

The routing of the CTL is conventional, but the assembly requires a special mounting procedure in the torus hall. The assembly starts in the area of the CVB. A segment of the CTL needs to be lifted up to the ceiling of the floor, is aligned and then partially stringed into the narrow pipe channel (see figure 2). Then the next segment is lifted, aligned and welded to the previous segment. Then the group of segments are stringed further into the narrow pipe channel. This process is repeated seven times. The space restriction limits the maximum length of the segments to 4.6 m.

### 2.2. Short transfer lines
The ten STL run from the CVB through the center of the torus to the dedicated interface named as AEG-port at the W7-X cryostat (figure 3). The pipe routing in the torus center needs to circumvent support structures and many diagnostics. Routing changes are required in all three directions within a few meters. The OD of the vacuum jacket is limited to 159 mm to avoid collisions with components. At specific locations the diameter is increased to 219.1 mm. That gives space for bellows for the vacuum jacket and space for flexible hoses for the process lines. The OD of the process pipes is 20 mm for helium and 17 mm for N2. The design concept is equivalent to the CTL. An actively cooled thermal shield and multi-layer insulation wrapped around the process pipes and around the shield are required.

The detailed design needs to consider the thermal shrinkage of all process pipes during cool down to the operational temperature. Also the shrinkage of the vacuum jacket caused by a severe leak in the process pipes is to be taken into account in the design. Compensation of the movements of the vacuum
jacket will be done with lateral and axial bellows. Flexible hoses are allowed to compensate the movements of the process pipes.

The impact on the cryo system needs to be minimized in case of loss of vacuum in the transfer lines or in the valve box. So all TL have their own vacuum. Vacuum barriers are needed at each interface to the valve box. Wrapped multilayer insulation around the process pipes reduces the heat load on the pipes when air freezes on the pipe surface.

![Figure 2. Routing of the CTL segments. Narrow spaces allows welding of the segments at the beginning of the channel only. Stringing of segments into the TL channel is indicated with arrows.](image1)

**Figure 2.** Routing of the CTL segments. Narrow spaces allows welding of the segments at the beginning of the channel only. Stringing of segments into the TL channel is indicated with arrows.

![Figure 3. Routing of the 5 lower and 5 upper STL. Valve box and support structures are shown as well.](image2)

**Figure 3.** Routing of the 5 lower and 5 upper STL. Valve box and support structures are shown as well.

### 2.3. Valve box

The valve box is equipped with a feed and return header for the helium flow. The feed flow is distributed to 10 parallel cooling circuits, the return flows are collected in the return header. A control valve and a flow measurement in each feed line allow to adjust the mass flow in each circuit. There are, one temperature sensor in the common inlet line and ten temperature sensors in the parallel return lines. Mass flow and temperature values are key parameters for normal operation as well as for cool down and warm up of the CVP’s during regeneration. Inlet pressure and pressure drop between inlet and outlet are measured as well. A bypass between feed and return header allows to disconnect the W7-X cryostat from the helium flow without stopping the helium flow up to the CVB. An electrical heater inside the box can simulate the head load from the cryostat during tests. The feed and return headers of the helium pipes are equipped with a safety valve each. Non-return flaps in the common feed line and in all safety lines help stabilize the flow and avoid flow oscillations. In case of a very severe heat load on the process pipes there are rupture disks in all short transfer lines. The flow from the safety valves or rupture discs
are connected to an exhaust gas collector feeding the expelled helium to a warm gas storage vessel of large capacity (250 m³) specially kept at 150 kPa absolute. The layout for the nitrogen circuit is a copy of the helium circuit except that the exhaust gas is vented to the atmosphere outside the building.

2.4. Cryo vacuum pumps
Starting from the AEG-port interface the process pipes with a diameter Ø12x1 are routed through the port into the plasma vessel and are finally connected to the ten CVP’s. A CVP consists of six meander stainless steel pipes that are placed inside a stainless steel box with a baffle at the top. Baffle and box are cooled with LN2 at 80 K. On top of the baffle in the pumping path there is a second, water cooled baffle. Pumped gas particles have to pass first the water cooled baffle and then the LN2-cooled baffle before they enter the box with the cooled helium pipes. The overall length of the helium -piping inside the PV together with the ports is 15.8 m.

3. Functional requirements

3.1. Helium system
The allowed numbers for heat loads on the piping and the pressure drop are listed in table 1. In addition the values for the CVP are given for comparison. The different heat loads on the helium distribution system for all lines sum up to 164 W compared to 450 W design value for the circuit with 10 CVP. The maximum allowed pressure drop for the full circuit is limited to 60 kPa that is the design value for the helium circulator. Assuming an equal distribution of the flow for all 10 circuits the pressure drop of the circuit is calculated and plotted in figure 4. Plotted are the inlet/outlet pressure values in the direction of flow for the CTL, the CVB, the STL, the CVP and the way back. The steady state compressible flow calculation considers pressure drop caused by pipe friction, pipe bows, valves, and density change due to pressure drop and heat loads [4]. The temperature rise is also plotted in figure 4. The overall pressure drop is 42 kPa. 68% of the pressure loss is generated by the CVP. The helium temperature rises from 3.9 K to 4.55 K.

| Table 1. Functional requirements for the transfer lines and CVB. |
|---------------------------------------------------------------|
| Heat load on helium line on nitrogen line                     |
| CTL W/m                                                      |
| ST L W/m                                                     |
| CVB W (total)                                                |
| CVP W (design)                                               |
| Pressure drop                                                |
| - He 250 g/s                                                 |
| ≤ 3.2 kPa                                                    |
| - Two phase LN2, 68 g/s                                      |
| ≤ 1.0 kPa                                                    |
| ≤ 2.2 kPa                                                    |
| ≤ 5.0 kPa                                                    |
| ≤ 2.5 kPa                                                    |
| ≤ 5.5 kPa                                                    |
| ≤ 40 kPa                                                     |
| ≤ 100 kPa                                                    |

3.2. LN2 system
The nitrogen circuit is cooled with LN2. The mass flow of the individual circuits will be controlled, so that return flow has a mass vapor fraction of about 90% (no overheating of the gas phase). A load of 1200 W per CVP requires a flow rate of 6.8 g/s. The feed flow is calculated as liquid nitrogen and the return flow as gaseous nitrogen (conservative approach). The actual pressure drop for the two phase flow will be smaller. The calculated total pressure drop is 54 kPa, the CVP causes 66% of that drop. The pressure along the flow path is plotted in figure 5 (dashed line).

As an alternative way of cooling it is planned that sub cooled nitrogen can be circulated with a cold circulator. An allowed temperature rise of 10 K results in a mass flow rate of 600 g/s. The resulting pressure drop is 50 kPa for the full circuit. Pressure and temperature are plotted along the flow path in figure 5. The return pressure should be above 400 kPa to avoid evaporation of nitrogen in the circuit.
3.3. Load variation

Detailed analysis of the loads on the CVP [3] indicates that the effect of the microwave stray radiation on a CVP depends on the module where the CVP is mounted. The heat loads on the helium flow in Module 1 (M1) and M5 might increase up to 62 W, loads in the other modules are lower. This implies that for M1 and M5 the flow rates requirements are increased. With the available pressure drop of 60 kPa the mass flow rate could only be increased to 30 g/s for M1 and M5. The outlet temperature increases then by 0.08 K. The same logic is true for the LN2 circuit. The loads in M1 and M5 might increase to 1800 W per CVP. A mass flow of 102 g/s is then required resulting in a pressure drop of 105 kPa for the 2–phase flow condition.

4. Conclusion

After the 3rd experimental campaign that will end October 2018, the Wendelstein 7-X experiment will be equipped with an actively cooled divertor plus 10 CVP. The pumps are cooled with supercritical helium at 3.9 K and LN2. The supply is realized with a four channel transfer line from the subcooler box of the cryo plant to the valve box located below the W7-X cryostat. Inside the box, the flow is distributed to 10 parallel cooling circuits. Each circuit is connected with a four channel TL with the cryostat interface and from there with the 10 CVP inside the PV. The circuits are equipped with safety valves and rupture discs. Pressure drop and the heat loads of the distribution system are defined and fit to the basic design data of the cryo plant and the cryo vacuum pumps.

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