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# Refrigeration system for W7-X

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**Abstract**
The refrigeration system for the W7-X superconducting magnet and the divertor cryo-vacuum pumps is presented. In total, five main helium cooling circuits have to be supplied by the refrigerator—four for the magnet including auxiliary equipment like support structure, thermal shield and current leads, and one for the cryo-pumps. For the shields of the latter, an additional $LN_2$—cooling circuit is required. The lowest operating temperature is 3.3 K. It will be provided by evacuating a sub-cooler bath using a cold or warm compressor. Three of the helium cooling circuits use altogether four identical cold circulators. Apart from the current leads which are supplied with the coolant from a LHe storage tank, the peak reserve power required is equal to 7 kW at 4.5 K entropy equivalent. However, this potential maximal demand occurs continuously for periods of only a few hours at most, and altogether for less than 1% of annual time. The refrigerator thus will be designed for 5 kW continuous power at 4.5 $K_{equiv.}$ corresponding to 1.5 MW compressor connected rating. The reserve peak power will be covered, if necessary, by using the latent heat and vapour enthalpy of LHe from a storage tank. This supporting LHe stream is added to the phase separator and fed subsequently to the low pressure return stream at the cold end of the cold box. $LN_2$-pre-cooling equipment of the cold box—which is installed for W7-X cool-down anyway—can also be used to increase refrigeration power. The LHe required for maintaining reserve refrigeration power as well as for running the current leads is generally produced overnight when W7-X is in idle current mode.

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## 1. Introduction

The magnet system of the stellarator WENDELSTEIN 7-X (W7-X) consists of 50 non-planar (npl) and 20 planar (pl) superconducting coils which are arranged in a torus with a mean large diameter of 11 m. All coil windings and the interconnecting bus system are composed of one type of NbTi/Cu cable-in-conduit-conductor (CICC) with Al-alloy jacket. The winding packs are retained by steel casings which in turn are shored up against each other, and which are attached to the ring-shaped coil support structure. The npl and pl coils are of five and two different types, respectively. All ten coils of one type are connected electrically in series. Every one of the seven groups can be supplied independently with currents up to 18.2 kA via a corresponding current lead pair.

This whole assembly has to be cooled down to and operated at ≈4 K. In order to make this possible, the cold components are situated within a cryostat where they are thermally insulated by high vacuum, an actively cooled thermal shield at a temperature between 40 and 70 K, and multi-layer insulation. Shield and insulation layers cover the cryostat walls which are composed of the plasma vessel, the outer vessel, and the port ducts. The latter allow access to the interior of the plasma vessel.

In addition to the cold components associated with the magnet system, also ten divertor cryo-vacuum pumps (in the following 'cryo-pumps' or CP) have to be supplied with helium refrigerant at about the same temperature as that of the coils. The CP panels are situated behind the corresponding divertor units within the plasma vessel. CP shield cooling is provided by sub-cooled liquid nitrogen in a closed circuit driven by a separate $LN_2$—circulator.

First refrigeration concepts were described in earlier papers [1, 2]. Since then much practical R&D work [3, 4] for W7-X was performed, and design as well as component manufacture progressed considerably. Now the system is well known, and the losses can be identified and estimated in detail. This concerns for instance the emissivity of the cold surfaces as well as the quality of thermal insulation which can be achieved within such a complex geometry. By now also the manufacturing tolerances of the CICC are known, whose void fraction spread significantly influences the fluid flow conditions and thus the helium circulation losses. From practical and economical considerations, the refrigerator will be used for cooling the W7-X experiment only, and not for supplying other users of the institute with LHe. By this method only a simple online purifier without impure helium compressor and storage, including logistics, is needed. Further, an open pump circuit was introduced for cooling the coil conductors. This allows us to use the main cold box high pressure stream as a support for the coil circuit circulator in order to reduce its losses.

Special emphasis in the final concept is placed on taking advantage of the special operation conditions of W7-X whose magnet system will be excited during working hours of experimental days only, resulting in long zero field periods up to 90% in the years' average. This fact determined, *inter alia*, the new design of the current leads which will be of conventional, but 'overloaded' type. Another design feature of the refrigeration plant is the possibility of day–night cooling power levelling. Liquid helium, produced by utilizing excess refrigeration capacity during nights, will be used for cooling the current leads, and for potentially supporting the refrigeration capacity in maximal power modes. Another potential reserve power booster will be liquid nitrogen for pre-cooling the refrigerator cold box via heat exchangers. This technique will be used anyway during W7-X cool-down. All these measures allow to limit the refrigerator design capacity to $\approx$5 kW at 4.5 $K_{equiv.}$ which corresponds to a maximal refrigeration plant input power of 1.5 MW.

## 2. Main W7-X cooling circuits

Figure 1 represents a scheme of the cooling circuits within the W7-X cryostat. Shown is one torus module out of five. This module is particular insofar as the refrigerant transfer lines coming from the magnet valve box are connected to it. The main data of the W7-X cooling circuits are given in table 1.

### *2.1. Coils circuit*

The winding pack of the npl coils is subdivided into six double layers wound from the internally cooled CICC. For the pl coils, the winding pack is subdivided into three double layers. This yields a total number of 300 plus 60 parallel cable cooling channels for the npl and pl coils, respectively. Cooling medium is supercritical helium at an inlet temperature of minimally 3.4 K and an outlet pressure of $\geqslant$3 bar. The main cooling streams for both coil types are also in parallel, driven by one common circulator whose flow is split within the magnet valve box into both go-lines, and collected after the coils within one return manifold. The losses of this refrigeration consumer are mainly caused by magnetic field changes at the conductors, by the high number of resistive cable joints, and by heat input into the widespread coil connection and piping system.

A large coolant flow pressure drop is characteristic for this circuit; it results in corresponding high circulation power requirements. The situation is aggravated by the fact that the flow resistance within the CICCs can only be kept within a manufacturing tolerance bandwidth of 40%. Since the required circulator pressure head is given by mass flow through the conductor having the highest resistance, additional circulator losses might be produced by the larger flow through the other conductors without useful effect. In order to improve the

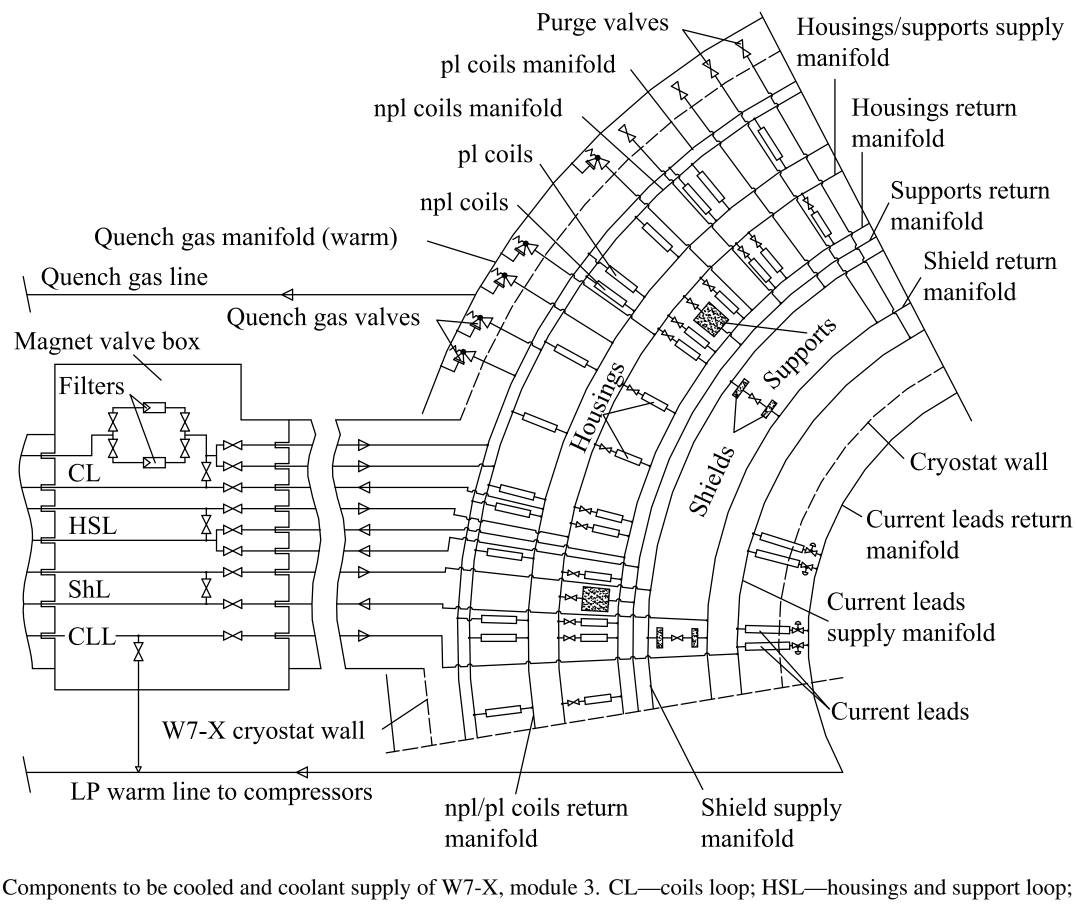


**Figure 1.** Components to be cooled and coolant supply of W7-X, module 3. CL—coils loop; HSL—housings and support loop; ShL—shield loop; CLL—current leads loop.

**Table 1.** Losses of the W7-X cooling circuits.

| | Peak power mode<br>18 kA coil current<br>(losses; mass flow; pressure drop) | Standard Mode<br>14 kA coil current<br>(losses; mass flow; pressure drop) |
|---|---|---|
| Coils circuit[a] | 1.1 kW at 3.3 K; 500 $g\,s^{-1}$; 2.3 bar | 0.8 kW at 3.8 K; 200 $g\,s^{-1}$; 0.7 bar |
| Hous./supp.[b] | 1.9 kW at 3.3 K; 800 $g\,s^{-1}$; 0.4 bar | 1.9 kW at 3.8 K; 300 $g\,s^{-1}$; 0.1 bar |
| Shield[c] | 14 kW at 40–70 K; 90 $g\,s^{-1}$; 0.2 bar | 14 kW at 40–70 K; 90 $g\,s^{-1}$; 0.2 bar |
| Current leads | 25 $g\,s^{-1}$ LHe | 14 $g\,s^{-1}$ LHe |
| Cryo-pumps | 0.4 kW at 3.3 K; 200 $g\,s^{-1}$; 0.8 bar | 0.4 kW at 3.8 K; 200 $g\,s^{-1}$; 0.8 bar |
| CP shield | 4.7 kW at 80 K; 250 $g\,s^{-1}$; 0.6 bar; $LN_2$ | 4.7 kW at 80 K; 250 $g\,s^{-1}$; 0.6 bar; $LN_2$ |
| Compr. loss | 1 kW at 3.3 K | 0.4 kW at 3.8 K |
| Total losses[d] | 7 kW | 5.1 kW |

[a] The circulator of this circuit is supported by the refrigerator JT stream.
[b] $\lesssim$100 W additional eddy current losses occur during normal magnet field changes.
[c] Plasma vessel and ports at 60°C.
[d] Total losses at 4.5 $K_{equiv.}$; not included are CP shield losses, current leads losses, and the additional compression losses for storing the current lead return gas as well as the refrigeration power boosting He-vapour to the GHe tanks.

situation, it was chosen to support this loop circulator with the main cold box Joule Thomson (JT) stream.

### *2.2. Housings and support circuit*

For speeding up cool-down and warm up the coils, and for interception of heat input from outside, the coil housings are cooled separately via copper shields covering the housing surfaces. Cooling pipes are thermally contacted to the copper shields, thus yielding a total number of 70 cooling channels. Supercritical helium at $\geqslant$3 bar is again the cooling medium having an inlet temperature identical to that of the coils.

The coil support structure, carrying all 70 coils, rests on 15 fibre glass—epoxy feet. It is cooled by a supercritical helium stream parallel to that of the housing loop, driven by the same circulator. In maximal power mode, two circulators are running in parallel for sufficient mass flow corresponding to the required outlet temperature. The inlet coolant temperature is again the same. The number of cooling channels is ten.

The housings and support circuits have a common supply manifold, and two separate return manifolds which merge within the magnet valve box. The main loss source of this circuit is heat flow onto the extended surfaces having high emissivities. The surfaces will partly be covered by multi-layer insulation. Heat conduction losses from support feet, from instrumentation wires, valve stems, and tubes to ambient temperature level etc. are relatively small. Eddy current losses of a few percent occur during normal magnet field changes.

### *2.3. Current leads circuit*

The largest single loss contribution comes from the 14 current leads connected to the seven coil groups. The leads are cooled by helium from the 10 000 litres LHe storage tank at a temperature of ~4.5 K. Within the current leads, the helium is warmed up to ambient temperature and then collected within a warm manifold. This cooling system allows to shift the corresponding cooling power demands on the refrigerator into night hours when the magnet system is in idle current mode.

For the time being it is planned to supply LHe in parallel loops to the current leads. Experience will show whether flow control problems arise from two-phase He conditions. In that case vapour only—produced by a heater within the tank—will be supplied to the leads. This means that only the vapour enthalpy of He will be utilized and the small percentage of evaporation enthalpy (latent heat) will be lost.

### *2.4. Shield circuit*

The cryostat shield will be cooled by helium of the high pressure cold box stream at an inlet temperature of about 40 K. The number of cooling channels for the shield is ten. During normal operation the plasma vessel and ports are kept at a temperature of 60°C in the average. For ultra high vacuum purposes, the plasma vessel and ports will be occasionally baked at 150°C with correspondingly higher heat input to the shield. This circuit also supplies all shields of the transfer lines, valve boxes, and of the sub-cooler and phase separator.

The shield losses are determined mainly by radiation losses from ambient temperature which are significantly influenced by the assembly quality of the multi-layer insulation between shield and cryostat wall. Conduction losses mainly from heat flow intercepts of tubes, valve stems, instrumentation wires, support feet etc are relatively small as compared to the radiation losses.

### *2.5. Cryo-pumps circuit*

The ten cryo-pumps will be supplied from a separate CP valve box (not shown in figure 1) via ten separate transfer lines led through corresponding ports into the plasma vessel. The pump panels shall be cooled by forced flow supercritical helium with an inlet temperature identical to that of the coils, and an outlet pressure $\geqslant$3 bar. The flow is driven by a separate cold circulator. The losses are not continuous and occur according to the plasma conditions during W7-X operation. Additionally, transient refrigeration power is needed for regeneration of the CPs. It is planned to perform regeneration during night hours only.

Each cryo-pump panel will be surrounded by a shield which will be cooled by a circulator-driven forced flow of sub-cooled nitrogen at an input temperature of about 80 K. $LN_2$-supply is provided from the 30 000 litres storage tank.

## 3. Operational modes

W7-X and, consequently, the cryo-plant will not be operated continuously, but in the following modes.

### *3.1. Peak power mode*

In this mode the coils are run with a current of 18.2 kA to excite the maximal magnetic field. This will be the case for approximately 50 h per year, and maximally 8 h per day only. However, in the first years of W7-X-operation the per day maximal mode time will be even shorter. The installed 10 000 litres LHe tank for providing current lead cooling and reserve refrigeration peak power will be sufficient for many years of operation. At a later stage the LHe storage capacity can be increased if necessary.

### *3.2. Standard mode*

The operation time at these conditions will be approximately 700 h per year. The coils are supplied with a current of ∼14 kA. For this, the nominal refrigeration power, including reserves, is sufficient. No $LN_2$-pre-cooling is planned for routine operation in the standard mode.

### *3.3. Short stand-by mode*

The idle current mode will last for about 5000 h per year. Its duration is made up of relatively short periods of time as nights, week-ends, etc, up to about one week. The whole W7-X cold mass shall be kept near LHe-temperature, with the actual temperature level depending on the stand-by duration. This mode will also comprise the occasional baking out of the plasma vessel and the ports at 150˚C lasting about one week, the regeneration of the adsorbers in the cold box, regeneration of the divertor cryo-pumps, etc.

### *3.4. Long stand-by mode*

This mode lasts for the remaining almost 3000 h per year, given mainly by shut-down and maintenance periods longer than a week or so. The whole W7-X cold mass is allowed to warm up to around $LN_2$ temperature, depending on the stand-by time. Refrigeration during this time is provided by the high pressure cold box stream only without circulators. The refrigeration might be produced by $LN_2$-pre-cooling of the cold box only.

## 4. Components of the W7-X cryo-plant

The W7-X cryo-plant consists of the following main components (figure 2); some characteristic data are given in table 2.

- Four 20 bar pressure vessels with a capacity of 250 $m^3$ each for pure helium.
- One 10 000 litres liquid helium tank.
- One 30 000 litres liquid nitrogen tank.
- Two stages of screw compressors from atmospheric pressure to nominal 20 bar helium compression, including oil removal system, full flow dryer, and cold adsorber.
- Cold box comprising heat exchangers, turbines, adsorbers, etc.
- Phase separator containing LHe at ≈4.4 K, integrated either within the cold box or the sub-cooler.
- Sub-cooler comprising a liquid helium bath kept at sub-atmospheric pressure for a bath temperature ⩾3.3 K, heat exchangers, and cold circulators.

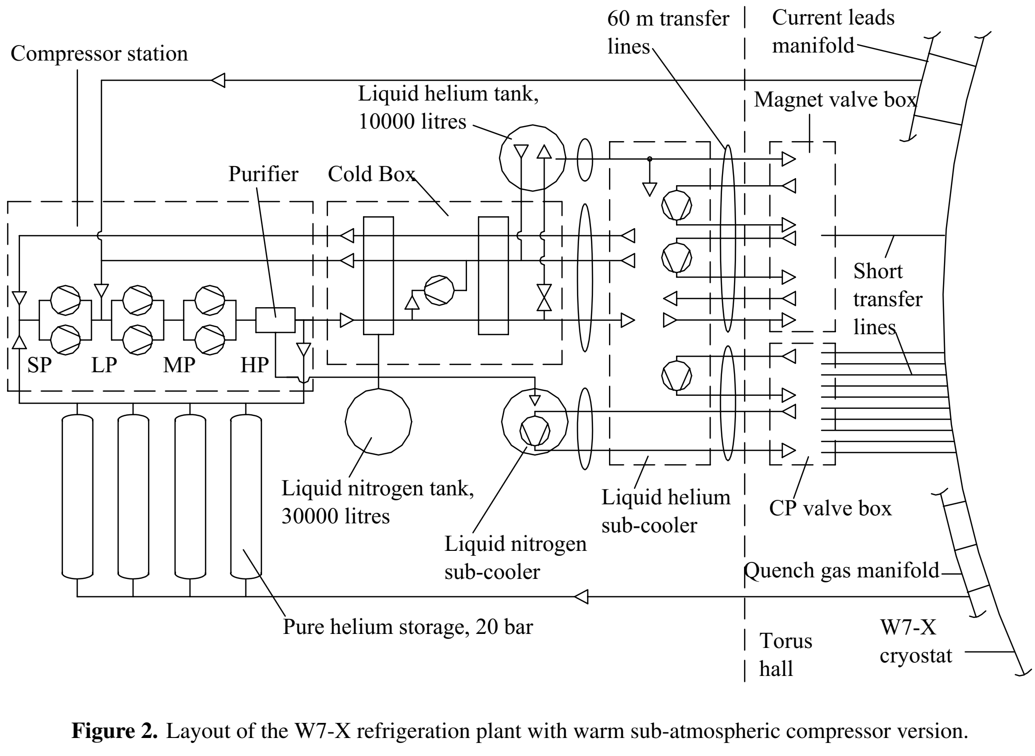


**Figure 2.** Layout of the W7-X refrigeration plant with warm sub-atmospheric compressor version.

**Table 2.** Main refrigeration plant data.

| | |
|---|---|
| Mains connection power | 1.5 MW |
| Refrigeration power at 4.5 $K_{equiv.}$ | 5.1 kW |
| Refrigeration power at 4.5 $K_{equiv.}$ with LHe support | 7 kW |
| LHe for peak reserve power support (at 22% efficiency) | $<50$ g s$^{-1}$ ($\approx$1500 litres h$^{-1}$) |
| Maximal JT stream with He vapour support at LP side | 300 g s$^{-1}$ |
| Maximal JT stream without He vapour support | 255 g s$^{-1}$ |
| HP He stream at $\approx$40 K outlet, $\approx$70 K inlet | 90 g s$^{-1}$ |
| Max. HP He stream at $\approx$40 K outlet, $\approx$80 K inlet (plasma vessel baking during short stand-by mode) | 140 g s$^{-1}$ |
| 1st compression stage: LP–MP (LP $\approx$ 1 bar) | Screw compressor ($\geqslant$2 in parallel) |
| 2nd compression stage: MP–HP (HP $\leqslant$ 20 bar) | Screw compressor ($\geqslant$2 in parallel) |
| Sub-atmospheric compressor (SP $\approx$ 0.36 bar) (for 3.3 K sub-cooler bath temperature) | Cold compressor (2 in series or parallel) or warm compressor ($\geqslant$2 in parallel) |
| Cold circulators | $4 \times 400$ g s$^{-1}$; $\Delta p \leqslant 2.5$ bar; $\eta \geqslant 55\%$ |
| Online dryer: 2-bed, 12 h alternate operation | Inlet water: 50 ppm; outlet $<$1 ppm |
| Online cold adsorber: 2-bed, 12 h alternate operation | Inlet air: 100 ppm; outlet $<$1 ppm |
| LHe storage tank | 10 000 litres |
| Pure He gas storage tank | $4 \times 250$ m$^3$ at 20 bar: 20 000 Nm$^3$ |
| $LN_2$ storage tank | 30 000 litres |

- A sub-atmospheric compressor, either warm as a pre-stage to the screw compressor station, or as a cold version installed into the sub-cooler or the cold box.
- Two cryogenic transfer lines from the refrigerator hall to the W7-X torus hall.
- Magnet system and CP valve boxes.
- Piping and armatures.
- Control system.

### *4.1. Compressor station*

Arrangement of the compressor station follows logically from the existing four pressure levels of the W7-X cryo-plant:

- Sub-atmospheric pressure (SP) above the LHe surface in the sub-cooler.
- Low pressure (LP) at a value slightly higher than the atmospheric pressure. Phase separator, LHe tank, current lead exhaust, and possibly turbine exhaust essentially correspond to that pressure level.
- Medium pressure (MP) is an intermediate pressure for avoiding high compression ratios. It might also be used as exhaust pressure level for the expansion turbines.
- High pressure (HP) as inlet pressure for the cold box expansion turbines and the main Joule Thomson (JT) helium stream.

Compression is hence performed in three sequential stages, SP–LP–MP–HP. Whether the SP–LP-stage will be warm or cold will be finally decided together with the manufacturer. Every warm stage consists of at least two parallel and identical compressors. Their capacities are chosen such that the cooling requirements of the standard mode, without considering reserve power, are fulfilled by one compressor less per stage than available. By that means redundancy is provided for the standard, however, not for the maximal operating mode. In case cold compressors are used, there will be two pieces only; it will be decided during the detail design phase whether it is more advantageous to operate them in parallel or in series.

Every warm compression stage is followed by a bulk oil separator, common for all compressors within the same stage. A fine oil separation system, including coalescing filters and oil adsorber, follow the oil separator only in the HP stage. A dryer operating at ambient temperature for removal of moisture is installed within the main helium stream, after the oil adsorber. An adsorber at $LN_2$-temperature is arranged consecutively for removing residual air. Both the dryer and cold adsorber consist of two identical and alternating stages each. The cold online adsorber is used only before first cool-down of W7-X, after opening of any cooling circuit, or after delivery of new helium. It will be by-passed during normal operation.

### *4.2. Cold box*

The cold box will be designed for optional pre-cooling with liquid nitrogen. This option will mainly be exercised during cool-down and warm-up of the whole W7-X cold mass, during periods of baking the plasma vessel and diagnostic ports at 150˚C, and for improving liquefaction power during the short stand-by mode. The cold box shall be able to handle properly also the steady-state maximal operational mode supported by $LN_2$ pre-cooling in case such reserve power is needed.

The cold box will house heat exchangers, turbines and other standard equipment as required. It will be designed for at least four temperature stages. However, the final decision about the cold box layout and detail design will be made together with the manufacturer.

The following cooling streams are delivered from the cold box:

- The main JT stream for filling the sub-cooler, the phase separator, and the LHe tank, and for directly cooling the coil conductors. The splitting of the JT-stream depends on the operation mode.
- A mass flow for cooling the shields is branched off the cold box high pressure stream at a temperature of $\sim$40 K, and is returned at $\sim$70 K.

### *4.3. Sub-cooler*

The sub-cooler (s. principle in figure 3) is necessary to cool supercritical helium to temperatures between 3.4 and $\approx$4.3 K. It will house a LHe-bath at 3.3 K, four cold circulators, heat

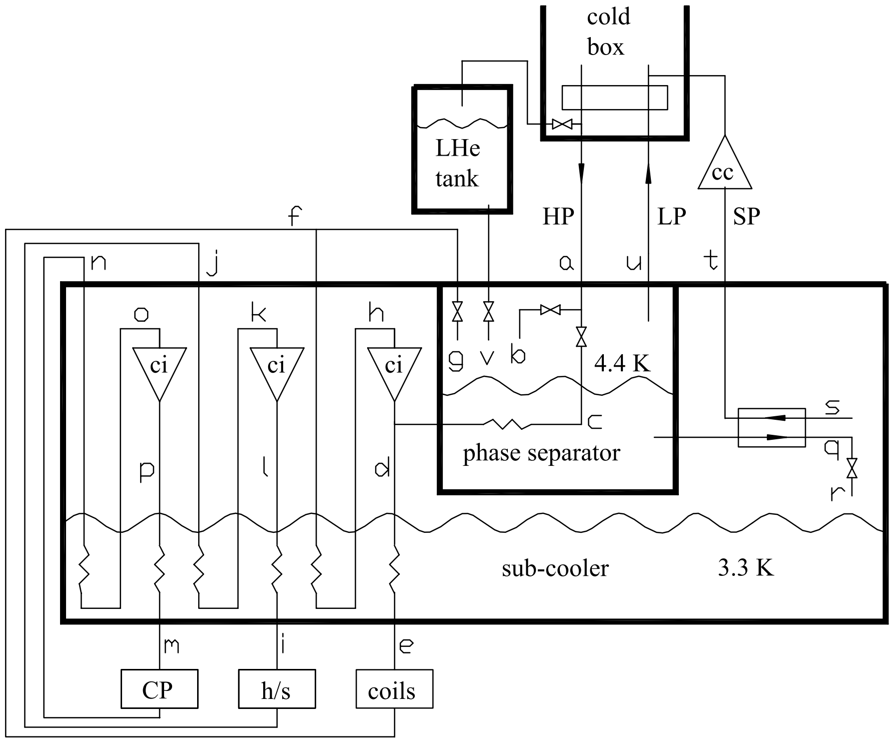


**Figure 3.** Basic sub-cooler and phase separator arrangement with cold SP compressor version. HP—high pressure stream; LP—low pressure stream; SP—sub-atmospheric pressure stream; cc—cold compressor; ci—cold circulator; CP—divertor cryo-pumps; h/s—housing and support circuit; coils—coils circuit.

exchangers, and the appropriate valves and piping. Options are the installation of the phase separator, i.e. a LHe-bath at ≈4.4 K, and of the cold compressors into the sub-cooler. The sub-cooler, or parts of it, might also be integrated into the cold box. The heat exchanger upstream of the cold compressor, for pre-cooling the LHe coming from the phase separator, reduces the mass flow. However, without detail design, it is at this stage not clear whether it is advantageous with respect to the overall optimum. Again, the decision on all these variants will be made together with the manufacturer.

Two cooling circuits of the magnet system will be supplied from the sub-cooler, and the helium circuit for the divertor CPs. For these three circuits, in total four identical circulators will be installed. In the peak power mode, two circulators in parallel are needed to drive the housings and support circuit, in the standard mode there is one circulator in stand-by as redundancy for any of the three circuits.

Arrangement of piping and armatures inside the sub-cooler is realized so as to ensure operation of all helium circuits with the main HP flow from the cold box during W7-X cool-down or warm-up periods. By this way supply of helium at variable temperature and high pressure is guaranteed. Two additional lines—go and return—are foreseen within the sub-cooler and cold box for regeneration of the cryo-pumps during short stand-by modes.

### *4.4. LHe-tank*

The 10 000 litres LHe tank is integrated into the refrigeration system for day–night load levelling by supplying the 14 current leads with helium, and for providing reserve peak power above 5 kW at 4.5 $K_{equiv.}$ by potentially adding LHe to the phase separator. In both cases, the excess helium coming from the LHe tank will be compressed by the screw compressors from LP to HP, and delivered into the pure helium gas storage tanks.

The LHe tank pressure is kept slightly above LP in order to drive the current lead coolant flow. An alternative would be to install a commercially available submerged LHe pump.

### *4.5. $LN_2$-sub-cooler*

From this $LN_2$-bath the CP shields will be supplied with sub-cooled nitrogen by a circulator. The $LN_2$—sub-cooler is independent of the He refrigeration system, and is situated separately within the cold box hall.

### *4.6. Transfer lines*

The sub-cooler is connected to W7-X by means of two ≈60 m long transfer lines. The first one serves for cooling the magnet system whereas the second one is intended for cooling the divertor cryo-pumps. The magnet system line contains seven cryogenic pipes belonging to four circuits. These are the coils circuit, and the housings and support circuit with one go and one return line each. The shield circuit (go and return pipe) is coming from the cold box and led via the sub-cooler into the transfer line. Similarly, the only pipe of the current leads circuit is also led through the sub-cooler into this transfer line.

The transfer line for the divertor-CP contains one go and one return pipe each for the helium and $LN_2$ circuits.

### *4.7. Magnet system and CP valve boxes*

The transfer lines lead into valve boxes near the W7-X cryostat. Within the magnet system valve box (figure 1), the coils supply loop is split up into the feed lines for the npl and pl coils, and the housings and coil support return manifolds are joined. A set of 10 $\mu$m mechanical filters is installed within the coils circuit to prevent the CICCs from being blocked by solid particles. An own valve box insulation vacuum space avoids impairment of the vacua of the transfer line or the W7-X cryostat in case of a fault. The short transfer line connecting the valve box to the torus is part of the W7-X cryostat with a common insulation vacuum.

The CP valve box serves for cryogen distribution to the cryo-pumps. Each of the ten cryo-pump panels is connected to the valve box by its own transfer line. Every line carries four pipes, two for the helium and two for the nitrogen circuit, and has two barriers separating the line vacua from those in the plasma vessel and the CP valve box.

Within both valve boxes, by-pass valves allow separate cool-down of the respective transfer lines—possibly together with the sub-coolers—after interruption of the cryo-supply. This is especially important for the magnet system transfer line if its temperature reaches high or even ambient values when the W7-X cold mass temperature is still low.

Another purpose of the valve boxes is to allow acceptance tests of the cryo-plant without W7-X being connected.

## 5. Summary and outlook

After finishing the W7-X prototype phase and start of component production there is sufficient knowledge available about achievable quality and tolerances influencing the cooling conditions. It is now possible to finally specify the refrigeration plant. The continuous refrigeration capacity is 5 kW at 4.5 K entropy equivalent which is in accordance with an 1.5 MW mains connection. The particular operation scenario of W7-X allows day–night load levelling by cooling the current leads with LHe from the storage tank, and to provide the estimated reserve refrigeration capacity up to 7 kW at 4.5 $K_{equiv.}$ for the short peak power periods by stored cold power in form of latent heat and vapour enthalpy of LHe and $LN_2$.

The detail design of the refrigeration system will be performed by the manufacturer in agreement with IPP. In the course of that work it is expected that the layout of the system can be further optimized. Special attention will be paid to achieve smooth and stable transitions between different operation modes which should be performed automatically as far as reasonably possible. It is expected that due to the use of the circulators—which effectively de-couple the refrigerator from the load—these transitions can be achieved fast enough without affecting the routine operation of W7-X.

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