Helium refrigeration system for wendelstein 7-X

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The Greifswald Branch of the Max-Planck-Institute for Plasma Physics (IPP) is currently constructing WENDELSTEIN 7-X, a new fusion experiment of the stellarator type. This paper gives an overview on the cooling requirements as well as on the refrigeration system chosen for the superconducting magnet system and cryo vacuum pumps of the experiment.

A flexible refrigerator was developed which is able to run in quite different working conditions. Special features are single phase forced flow cooling with adjustable supply temperatures down to 3.4 K using cold circulators and cold compressors. The various operating modes, combined with the requirement to limit the power input, day-night load leveling, and the spatial boundary conditions for the system layout were a challenge for process and construction designers.

INTRODUCTION:

With a complex arrangement of 70 superconducting coils the Wendelstein 7-X (W7-X) stellarator type fusion experiment will achieve a confinement field up to 3 T on the plasma axis. The cooling requirements for this magnet system, and principal refrigeration solutions were described earlier [1-3]. This paper presents an overview of the finally chosen refrigeration system and coolant distribution.

The total refrigeration capacity exergetic equivalent to 4.5 K will be about 7 kW without LHe support. This is a modest value as compared to the LHC refrigerators at CERN which perform a 4.5 K equivalent capacity of 18 kW. Nevertheless, the W7-X refrigerator will hold another record: It will be equipped in the final stage with thirteen turbo-machines, namely seven turbo-expanders, two cold compressors and four supercritical helium pumps. In the first stage all turbines but only one cold compressor and two pumps will be installed which allow W7-X operation up to the standard field of 2.5 T without cryo-vacuum pumps (CVPs). Suitable interfaces will be provided for the remaining equipment.

REFRIGERATION REQUIREMENTS

Six different consumers will be supplied with cryogenic refrigeration. These are the coils, the coil housings and coil support structures, the cryo-vacuum pumps, the current leads, the W7-X cryostat heat radiation shield, and the shield of the CVPs. For the CVP-shield, a two phase forced flow of liquid nitrogen is foreseen as refrigerant; for all the other consumers forced flow of single phase helium is used.

A particularity in the technical specification of this refrigerator is the considerable load variation between standby operation and the operation during experiments. During experiments not only the heat load is increased, the refrigerator has to provide more supercritical flow to the different consumers and this flow is required at a lower temperature. More flow increases the pressure drop in the coils which in return results in a disproportionately increased heat load from the circulators.

The refrigeration requirements are mainly characterized by a long time base load at standby conditions, and short-lived peaks during the W7-X experiments (s. Table 1). A cold buffer in form of a 10000 l helium dewar is used to cover refrigeration peaks during limited periods.

Table 1 Specified refrigeration capacities and operation times.
(Exergetic powers represent reversible values.)

Peak Power Mode (3.0 T – operation) 50 hours per year		Coils	Housings Structure	CVP	Current Leads	Radiation Shield	CVP-Shield
Fluid		Helium	Helium	He-lium	Helium	Helium	Nitrogen
Heat load	[W]	1100	1800	450	39000	14000	6000
Mass-flow	[g/s]	450	800	250	25	135	300
Supply temperature	[K]	3.4	3.4	3.4	4.5*	≈50	80
Return temperature	[K]	4.4	4.1	4.2	300	≈70	80
Supply pressure	[kPa]	530	340	360	120	<1700	200-800
Pressure drop	[kPa]	230	40	60	15	200	80
Exergetic power input	[kW]	138.3	159.1	44.2	134.7	68.4	16.5

Standard Mode (2.5 T – operation) 700 hours per year		Coils	Housings Structure	CVP	Current Leads	Radiation Shield	CVP-Shield
Fluid		Helium	Helium	He-lium	Helium	Helium	Nitrogen
Heat load	[W]	800	1800	450	23400	14000	6000
Mass-flow	[g/s]	200	300	250	15	135	300
Supply temperature	[K]	3.9	3.9	3.9	4.5*	≈50	80
Return temperature	[K]	4.9	5.1	4.4	300	≈70	80
Supply pressure	[kPa]	370	310	360	120	<1700	200-800
Pressure drop	[kPa]	70	10	60	15	200	80
Exergetic power input	[kW]	60.8	118.1	39.8	82.8	68.4	16.5

Standby 8000 hours per year		Coils	Housings Structure	CVP	Current Leads	Radiation Shield	CVP-Shield
Fluid		Helium	Helium	He-lium	Helium	Helium	Nitrogen
Heat load	[W]	250	1800	450	7800	14000**	6000
Mass-flow	[g/s]	12	86	22	5	135	300
Supply temperature	[K]	7	7	7	4.5*	≈50	80
Return temperature	[K]	10	10	10	300	≈70	80
Exergetic power input	[kW]	8.3	60	15.1	27.6	68.4	16.5

*) saturated vapor of 4.5K **) 28000 W during plasma vessel baking

THE COLD BUFFER

During 90% of the scheduled operating time the refrigerator will be in standby mode. Only 10% of the time is planned for W7-X experiments, and the refrigeration for most of these experiments is performed in the standard (2.5 T) mode. Only for a few tests, which currently are scheduled for less than 1% of total operating time, the peak power mode will be required. Thus, it was decided to design a refrigerator, which performs the specified capacities in the stan-

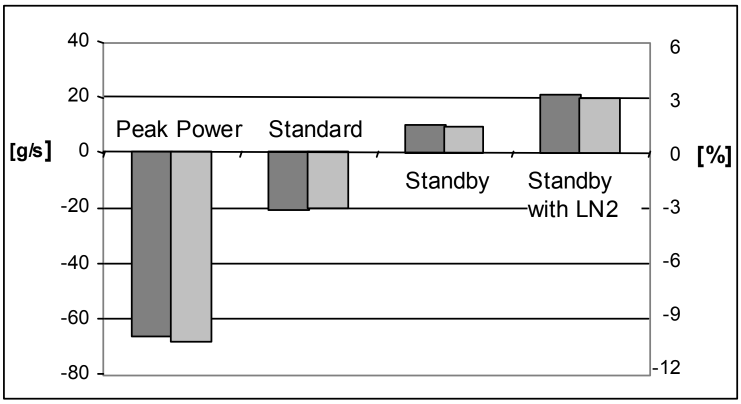

Figure 1 Liquefaction (+) and evaporation of liquid (-) in different modes in g/s and as percentage of the high pressure flow.

dard mode and in the peak power mode only with the support of liquid helium from a dewar. A single test at peak power conditions will take not longer than four hours according to the LHe tank which is available. During the standby periods the refrigerator shall re-liquefy the helium. In the warm state the helium inventory is stored in a 1000 m^3 tank battery, in the cold state in a dewar of 10 m^3. Figure 1 shows the quantities of helium which swaps between the two buffers. The refrigerator is tuned to get the best rate of yield from the stored coldness. It maintains the dewar permanently at 120 kPa and redraws the liquid helium into one of the sub-atmospheric sub-coolers. There, by the heat of evaporation, this helium contributes to the refrigeration. The vapor enthalpy compensates for the refrigeration of the current leads; it perfectly covers the exergetic losses of the heat exchangers, and it contributes to the shield cooling. The turbines provide the refrigeration for the Joule Thompson stage, for the cold compressors, and for most of the radiation shield cooling. During the peak power mode, the turbines T1 and T2 (Fig.2) are not operated.

During standby the circulators for supercritical liquid helium are switched off, and the temperatures of all the turbines are slightly increased. The high pressure level is reduced, the medium pressure level increased, and all the turbines keep running, by this way providing a high liquefaction rate (Fig. 2).

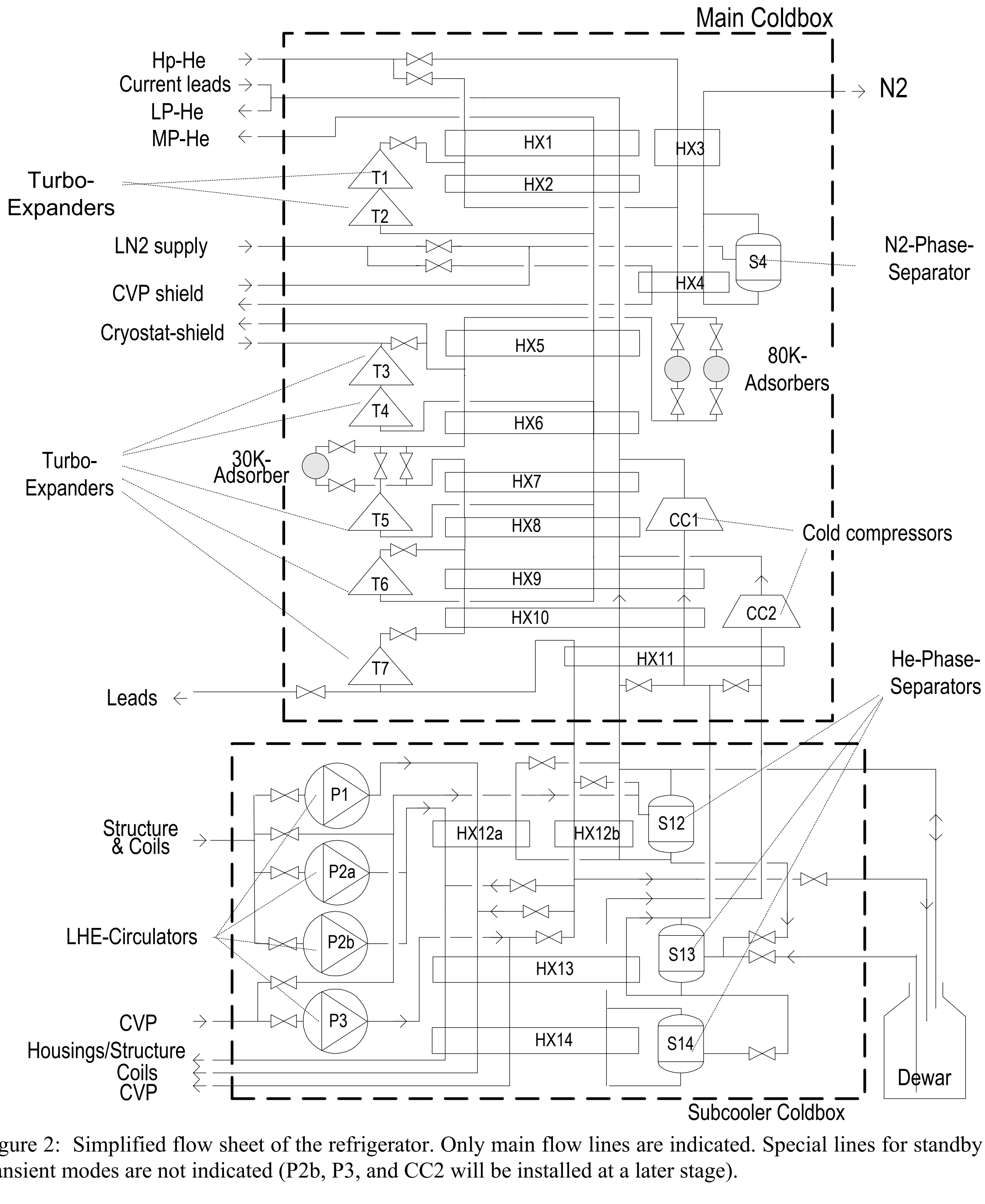

Figure 2: Simplified flow sheet of the refrigerator. Only main flow lines are indicated. Special lines for standby and transient modes are not indicated (P2b, P3, and CC2 will be installed at a later stage).

If necessary, the liquefaction rate of helium may be increased with liquid nitrogen pre-cooling. A two phase nitrogen flow is also used to provide 6 kW of refrigeration to the shields of the cryo-vacuum pumps. This nitrogen flow returns to the refrigerator mainly as vapor which is further used to support the helium cooling in the heat-exchangers HX1 and HX2. An interface is provided to boost this nitrogen flow at a later stage with an additional pump, if necessary.

THE SUB-COOLING - AND DISTRIBUTION SYSTEM

Special attention is paid to the sub-cooling and distribution system (Fig.2). Each of the supercritical streams to the refrigeration consumers can be circulated either by a liquid helium pump, or for the purpose of redundancy, by the redirected Joule Thompson stream of the refrigerator.

Three helium evaporation stages at three different temperature levels provide conditioning of these streams. The vapor phase of the first stage is connected to the refrigerators low pressure line at 120 kPa and holds the saturation temperature of 4.4 K. The two other stages are operating at sub-atmospheric pressures. The vapor returning from them is recompressed to low pressure level in the two cold turb compressors CC1 and CC2. Their suction pressures are adjustable by varying the rotation speed. The provided pressures are 66 kPa (3.8 K) for CC1 and 37 kPa (3.3 K) for CC2. Supply temperatures to the refrigeration consumers of more than 3.8 K are provided with only CC1 in operation. This arrangement provides the following advantages:

- The three evaporators do not only save energy, they save investment costs too. Applying a system with only two evaporators, the total power input into the system during the peak power mode would be 20% more. Only a small part of these 20% could be compensated by drawing more liquid helium from the dewar. Inescapably a bigger compressor size and more turbine capacity would be required.
- At the specified heat loads, in the peak power mode as well as in the standard mode, the cold compressor CC1 is running at optimal conditions. The cold compressor CC2 is running at design conditions in the peak power mode and in the standard mode it is simply turned off.
- Due to the different pressure ratios the two cold compressors can be placed at different temperature levels in the process. This is helpful for the layout of turbines and heat exchangers.
- By using cold turbo compressors instead of a warm process vacuum system, none of the heat exchangers above 15 K requires more than three streams, and the used streams flow in all the operating modes. This enables a heat exchanger design with a comparably small cross section and with a good heat transfer rate.

CONCLUSIONS

With the W7-X refrigerator, Linde Kryotechnik AG and the Max Planck Institute for Plasma Physics broke new grounds. Thanks to the well directed use of the cold buffer as well as the extremely optimized sub-cooling system the refrigerator will save costs and energy. Due to the application of cold compressors and time distributed loads the warm compressor system will be comparably small. Apart from saving costs, space within the buildings is saved as well.

The W7-X refrigerator was ordered a few months ago, and currently we are in the phase of basic engineering. Commissioning is planned for 2008 and experiments will be started in 2010. The Linde Kryotechnik AG and the Max-Planck-Institute for Plasma Physics will use the opportunities of future conferences to give more information concerning progress and experiences.

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