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Refrigerator operation during commissioning and first plasma operations of Wendelstein 7-X

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In February 2015 began the cool-down of about 450 tons cold mass of Wendelstein 7-X i.e. 70 superconducting coils, 14 currents leads, massive support structure and the thermal shield, enclosed within a vacuum vessel of about 16 m outer diameter. After a smooth cool-down, the temperatures around 5 K were achieved within about 4 weeks, in the short standby mode with the thermal shield return temperature < 80 K. Later, for more than a year, these components were kept cold at different temperatures within various operating modes of helium refrigerator. The details of the refrigerator operation at different modes, failures, repairs etc. are presented in the paper.

Keywords: Wendelstein 7-X, Cryogenics, Helium refrigerator, Cold machines

1. Introduction

Wendelstein 7-X (W7-X) is a stellarator based fusion experiment designed to operate in steady state condition and sustain the plasma up to 30 min. The defined magnetic flux surfaces with the magnetic field up to 3 T at the plasma centre, are achieved by 50 Non Planar Coils (NPC) and 20 Planar Coils (PC) arranged in a complex 5-fold geometry around the plasma vessel (see Fig. 1). In order to sustain such high magnetic field for longer durations, the coils are made of NbTi superconducting alloy filaments arranged in a cable in conduit conductor and cooled down to 3.4 K to keep the alloy in superconducting state at higher currents up to 18.2 kA. In order to keep the radiating heat loads on the coils low, these are surrounded by a thermal shield kept at temperatures < 80 K. The current is led to the coils via 7 pairs of Current Leads (CL), which are specially designed using high temperature $Bi_2Sr_2Ca_2Cu_3O_{10+\Delta}$ (BSCCO) superconducting tapes and a Cu heat exchanger to minimize the heat input via the leads.

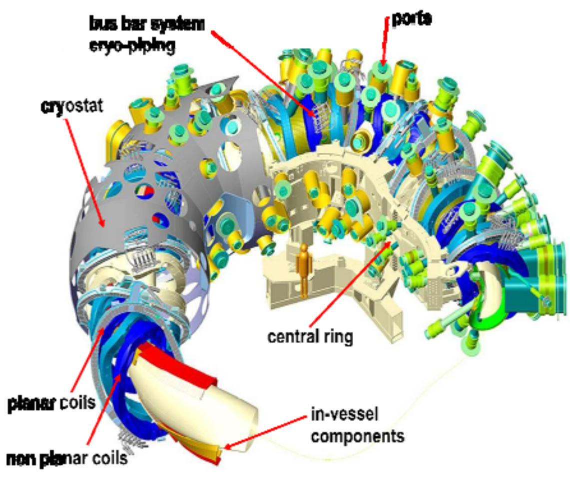

Fig. 1. W7-X stellarator overview

Each of the 70 coils is housed in a casing, the coils and casings are provided with separate cooling paths. The CL are supplied with 50 K helium at Cu heat exchanger, additionally the cold end joint is cooled with the helium returning from casings as well as bus bars.

After the successful commissioning of various W7-X systems [1], within the first Operation Phase (OP1.1) the first helium plasma was produced in December 2015. For OP1.1 the coils were powered with a maximum of 12.8 kA to generate the required 2.5 T magnetic field on the plasma axis.

The cooling of the above components is achieved using a Helium Refrigerator (HR) [2] which is designed to provide an equivalent cooling power of 7 kW at 4.5 K. The main components of HR are shown in Figs. 2 and 4. The needed cooling power is generated with the help of 2 screw compressors consuming 1.6 MW electrical power, 7 turbines and a couple of heat exchangers. The required parameters i.e. temperatures, pressures and mass flows are reached, besides the main Joule-Thomson flow, using 2 cold compressor and 4 cold circulators. The following four operating modes have been defined for HR, to cool the W7-X components at different conditions:

- Short Standby Mode (SSM): with temp. < 10K for weekend and few days break
- Standard Mode (SM): with inlet temp. 3.9 K, 2.5 T plasma operation
- Peak Power Mode (PPM): with inlet temp. 3.4 K, 3 T plasma operation
- Long Standby Mode (LSM): with temp. < 100 K over few weeks break

In the SM, the supply temperatures were reduced to 3.9 K using the first Cold Compressor (CC1) and the mass flows were increased to 200 g/s through the coils and 300 g/s via the coil Casings and Structure (CS) with the help of cold circulators. In the PPM, temperatures are further reduced to 3.4 K using the second Cold

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Compressor (CC2) and increased mass flow of 450 g/s and 800 g/s in the coils and CS circuits respectively. The increased mass flow rate is achieved with additional cold circulator. One additional cold circulator is provided to cool the ten divertor Cryo Vacuum Pumps (CVP) to be installed within the plasma vessel at a later stage [3].

Fig. 2. View of cold box

2. Operation of refrigerator

2.1 First cool-down

Before beginning the cool-down of W7-X components, all the cooling circuits of W7-X were cleaned thoroughly in three steps. Firstly, by pressurizing the complex circuits with dry nitrogen and expending abruptly to remove the dust particles, secondly, by evacuation and refilling with pure helium, three times and finally by purging the circuits by flowing helium for few days together with the refrigerator.

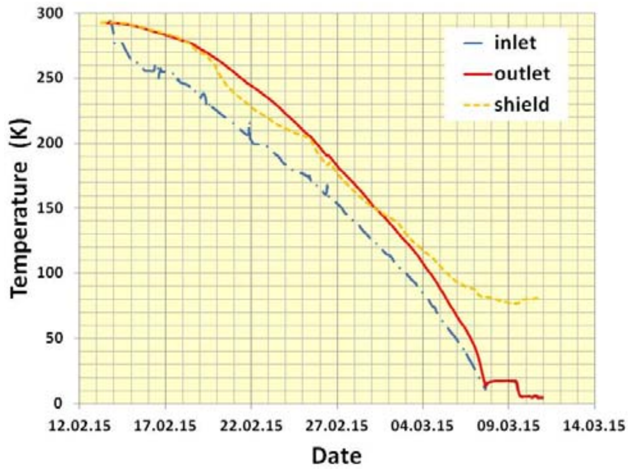

Fig. 3. W7-X cool-down

The cool-down began on 13th of February. The main boundary conditions were, maintaining the cool-down rate of about 1 K/h and limiting the temperature difference across return and supply temperatures of main circuits to 40 K. The main cooling circuits are, coils, CS, thermal shield and CL, each of these having several parallel flow paths. For estimating the 40 K temperature difference, the maximum of temperature within each of these main circuits was taken. Each flow path in casings (70 paths), supports (10 paths) and thermal shield circuits (10 paths) is provided with a manual valve, which was adjusted to equalize the hydraulic flows as well as control the cool-down within each of these main circuits. The cool-down to 5 K in SSM took four weeks as shown in Fig. 3.

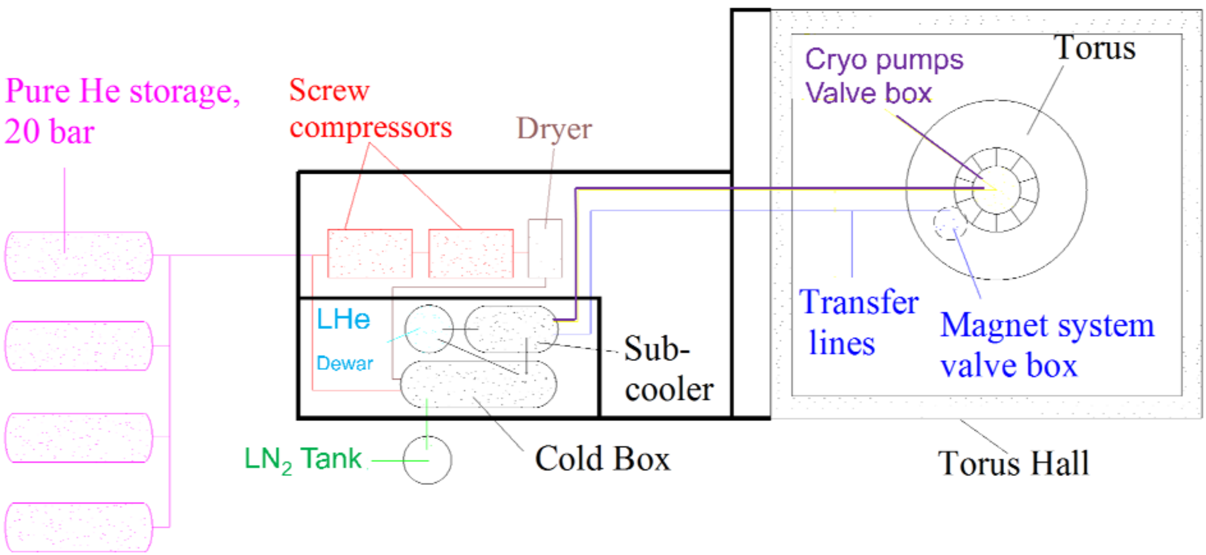

Fig. 4. Schematic layout of Refrigerator systems.

2.2 Coil tests and plasma operation

After cooling down to SSM, the check of designed flow conditions and the heat loads was made. The designed flow conditions were achieved and the estimated loads (see table 1) were found to be well within the limits.

Table 1. Performance during SSM and SM modes.

Mode	SM	(3.9K)		SSM
	CS	Coils	Shield	(<10K)
T_{in} (K)	3.9	3.9	50	5.2
Flow (g/s)	300	200	110	160
ΔP (mbar)	140	360	1180	140-290
Load (W)	426	256	5600	566
Design load (W)	1800	800	9000	1800

After all the tests in SSM, the mode is changed to SM by starting the two cold circulators for the coils and CS circuits each and the CC1. CC1 creates subcooled conditions within a phase separator which is then used to reduce the supply temperatures to coils and CS down to 3.9 K. The Joule-Thomson stream is then used for the CVP cooling circuit, due to the unavailability of this component in W7-X, this flow path is short circuited with the HR subcooler box. After reaching the SM, the designed flow parameters and the loads are confirmed. The measured loads are found to be less than the designed values. Based on this fact as well as the missing CVP loads, the available extra cooling power is used for the liquefaction of helium, once the Dewar is filled than the high pressure is reduced to about 13 bar to equilibrate the cooling power with the available loads.

After stabilizing the SM, the coils and CL tests were started. The inlet and outlet temperature profiles during the coil tests with NPC and PC fed with 12.8 kA and 5 kA respectively are shown in Fig. 5.

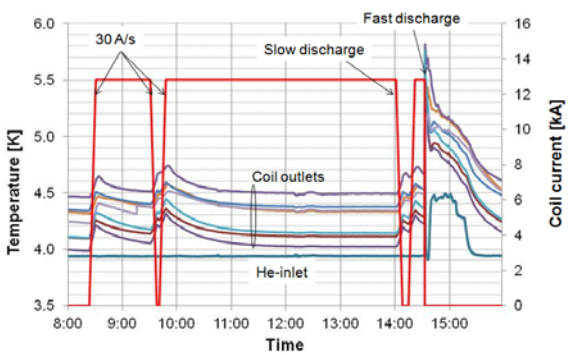

Fig. 5. Helium temperatures during coils test

During the tests of coils the helium mass flow of 50 K helium supplied to each of the 14 CL is optimized by limiting the warm end of the BSCCO superconductors to 60 K. This is done for the zero current as well as the operating current values for the NPC (arranged in 5 groups i.e. 1-5) and PC (arranged in 2 groups, i.e. A & B) and shown in table 2. The respective CL numbers are marked with ABF**.

Table 2. Optimized mass flow rates (g/s) for CL.

Circuit	CL Nr.	SM 0kA	SM 5kA	SM 12.8kA
NPC-1	ABF70	0.43		0.95
	ABF69	0.43		0.95
NPC-2	ABF71	0.45		0.95
	ABF72	0.43		0.95
NPC-3	ABF62	0.44		0.95
	ABF64	0.40		0.91
NPC-4	ABF67	0.43		0.93
	ABF68	0.35		0.93
NPC-5	ABF65	0.43		0.95
	ABF66	0.43		0.95
PC-A	ABF63	0.42	0.50	
	ABF61	0.43	0.54	
PC-B	ABF74	0.45	0.56	
	ABF73	0.35	0.51	

Since the cooling power from HR was sufficient enough to meeting the SM loads and no support of liquid helium from the Dewar was required, it was possible to operate the SM during full week and change the mode to SSM during the weekends. After successful tests of coils, CL [4, 5] and other W7-X systems, the helium plasma operation was started on 10th December 2015. Later, as a routine several plasma shots were taken over the day, however as expected, HR did not see any affect due to these operations. Before the plasma operations started, the LSM and PPM modes were tested. For LSM the temperatures of all the cooling circuits were raised to 100 K and for PPM it was reduced to 3.4 K using CC2.

After completion of plasma operations, on 17th March 2016, the warm-up was started with the similar criteria for rate of warm-up and the temperature difference, as defined for the cool-down, and took five weeks. The return gas was purified through the cold adsorbers, as long as it was possible to keep them in cold condition.

3. Problems and further improvements

3.1 Operational

During the coils operation, it is observed that the CC1 operated close to the edge of its operating range and is seen to be sensitive to the small load variations. Few times with the fast ramp-up of current in all the coils, the generated losses due to eddy currents, ac losses etc. the CC1 had a trip. The optimization of its operating range is presently being evaluated.

The spindle bearing of two cold circulators showed problems and needed to be sent for repairs. It was possible to remove the cold circulators with HR being operated in SSM. The auto switchover of the cooling water pumps with the redundant ones failed some times.

3.2 Failures

There occurred a number of failures within HR subsystems and external supplies such as water, electricity, leading to trips of either individual components or few times the whole HR. As summarized in Fig. 6, the highest of 12 such failures appeared in valves which were due to either malfunctioning of valves or the end switches.

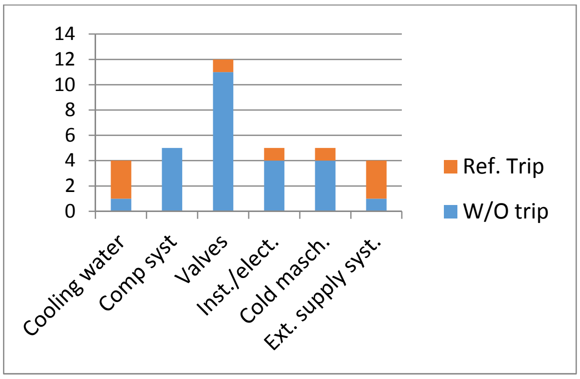

Fig. 6. Failures occurred on HR systems during OP1.1.

Since the HR operation continued for more than a year, it was necessary to correct the problems on a running system or short stop of HR during the days without plasma operation i.e. Monday and Fridays or on weekends. It is very much useful to store enough spare parts to carry out quick repairs.

3.3 Helium gas loss

Helium gas is stored in 4 tanks each having a volume of 250 m^3 and maximum operating pressure of 19 barg. During the coils operation, one of these tanks needed to be defined as quench tank to accommodate the helium return from the coils in case of a quench of superconductors.

With the helium inventory over the whole operation OP1.1 as shown in table 3, the estimated loss of helium is about 20%. The main account of loss is due to the initial purging and cleaning of whole W7-X as well as the HR circuits. Additional losses occurred during the regeneration of adsorber /dryer beds and during a trip in SM with opening of safety valves.

Table 3. Helium gas loss during OP1.1.

Helium gas status	Volume (Nm^3)
Before start of operation	13600
Purchase during operation	6500
At the end of operation	16000
Loss during operation	4100

3.4 Further improvements

On the control systems improvements are being made on the hardware as well on the program. On the hardware side, the old operating stations as well as servers are being replaced with the new ones and the number of operating stations is being increased with the virtual stations. The operating system is also being upgraded. The control program is being updated by sorting out the problems encountered during the OP1.1.

The cooling water system is modified by installing the rubber isolations across the pumps to reduce the vibrations into the pipings and instrumentations. In order to have the sufficient helium storage, the capacity is planned to be upgraded. In order to minimize the component failure during the continuous operation, the preventive maintenance of each component is being carried out as specified by the respective manufacturer.

4. Summary

For the commission of HR together with W7-X components, tests of coils and the operation of W7-X, the HR was in continuous operation for about 14 months performing satisfactorily. In case of few trips, it was restarted as soon as possible and in most cases brought back into operation in a couple of hours. The problems encountered are being solved and the maintenance is being carried out. Improvements on the controls, cooling water system, and helium storage are being made and preparing the HR for the next W7-X campaign starting by mid 2017.

Acknowledgments

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