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Final acceptance tests of helium refrigerator for Wendelstein 7-X

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Abstract

Following successful installation and commissioning, final acceptance tests were carried out on the helium refrigerator for Wendelstein 7-X. The tests were carried out for the normal operating modes i.e. peak power mode (3.4 K), standard mode (3.9 K), short standby mode (< 10 K) and long standby mode (< 100 K). Besides the normal modes, the transient modes including, cool-down and warm-up, auto interchanging between various modes and the purging modes were tested. In addition, the handling of quench, emergency signals such as cryostat vacuum break, utility failure, alarm and trip signals were checked.

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1. Introduction

Wendelstein 7-X (W7-X) is an advanced stellarator based fusion experiment, which is, after completion of assembly, presently under commissioning at Greifswald branch of Max-Planck-Institute for Plasma Physics. The main components which require cooling at low temperatures are namely: 70 complex superconducting coils and their casings, support structures, thermal shields, current leads and diverter Cryo Vacuum Pumps (CVP). The CVP will be installed within the plasma vessel (PV) at a later Operating Phase (OP 2). The coils, casings and supports together with CVP are cooled down to 3.4 K for 3 tesla magnetic field operations. The corresponding refrigerator operating mode is named as Peak Power Mode (PPM). The refrigerator cools down the cold mass to 3.9 K in the so called

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Standard Mode (SM) of the refrigerator for the 2.5 tesla operation [1]. The thermal shield is supplied with helium between 50 and 70 K. A dedicated helium refrigerator has been envisaged to cater the cooling requirements for all the cryogenic applications mentioned above. The refrigerator is supplied by Linde Kryotechnik AG and has an equivalent cooling capacity of 7 kW at 4.5 K [1-2]. The variations in cooling capacity during various modes are managed by making use of additional Liquid Helium (LHe) which is produced during Short Standby Mode (SSM) / Long Standby Mode (LSM) and used during PPM/SM. In addition, the use of Liquid Nitrogen (LN2) is also planned to limit the use of LHe to enable longer PPM/SM operations. The main components of the refrigerator are compressor system, cooling water system, oil removal system, dryer, cold box, subcooler box and valve box. After successful installation and commissioning of all the systems, the final acceptance tests on the complete refrigerator were carried. The results are presented in the following sections.

2. Guarantee values

The specified guarantee values which have to be demonstrated by the final acceptance tests on the whole system are listed in tables 1 & 2. However for the acceptance criteria the derived values were used taking into account the accuracy of measuring instruments. During the course of manufacturing, several tests were carried out on individual components, nevertheless after the commissioning of individual systems, the compressor system as well as the cold adsorber beds were tested for their full performance. Since the actual cooling applications at W7-X were not ready, the respective cooling capacities were simulated by installing test heaters in two vacuum insulated test boxes, one installed close to the Magnet Valve Box (MVB) simulating the coils, casings, thermal shield, and the other close to the subcooler box simulating the CVP and its shield loads. The current lead loads were simulated using an external heating block and band heaters. The hydraulic resistance in each circuit was simulated by the control valves in respective circuits.

3. Acceptance tests and results

Before beginning the acceptance tests, checks of all the documentation i.e. meeting protocols, drawings, process diagrams etc. were done. Following the documentations, the checks of the mechanical integrity, electrical components and the cabinets, instrumentation performance, control program and the safety systems were finished. For the acceptance tests, a detailed test procedure was worked out mentioning the complete description of each test and subtests. A running list of open points was made to mention all the points found not in accordance with the specification. If any of the point had implication on the test then it needed to be corrected immediately, in case of no implications, the open points needed to be settled before the end of the contract with final acceptance. The details of the tests carried out are the following:

3.1. Initial preparations

Following initial checks were done successfully in order to start the actual tests:

- Functional test: Involving opening and closing of the valves, checking the valves end switches, functional tests of instrumentations, pumps, heaters and the gas analyzer;
- Alarm and trip limits: by checking the alarm and trip limits for all the components as provided by the respective manufacturers and Linde Kryotechnik AG;
- Simulation of utility failure: fail safe state of the refrigerator in the case of loss of electrical power, instrument air and cooling water;
- Check of control software for current leads: by checking the operation of fourteen valves for the current leads, controlled by the temperature and mass flow signals.

3.2. Long Standby Mode (LSM)

LSM is foreseen during longer breaks for the plasma operations. In this case the W7-X cold components are planned to be cooled at the temperatures ≤ 100 K while simultaneously LHe has to be produced to fill the Dewar. The tests needed to be carried out without and with LN2 precooling.

The tests were completed satisfactorily, with the duration of about 9 ½ and 6 ½ hrs for the tests without and with LN2 precooling respectively. The applications were cooled to the temperatures of about 73 K in steady state with the production of about 27 g/s LHe in parallel, meeting the guarantee value of 20 g/s (see tables 1 & 2). The liquefaction rates were calculated by the amount of gas withdrawn from the gas buffer tanks.

3.3. Short Standby Mode (SSM)

After achieving the cool-down as well as during shorter breaks of the plasma operations e.g. weekends, the W7-X components are needed to be kept in SSM (at ≤ 10 K) and simultaneously replenish the Dewar with the LHe. The test was required to be carried out three times without and with LN2 precooling and additionally with the thermal shield test loads increased from 14.1 kW to 28.1 kW to simulate the PV baking at 150^{o} C. Additional tests were performed with CVP cooling mode with regeneration up to 80 K and 300 K. Also regeneration cycles of 80 K and 20 K adsorber beds were tested. The tests without and with LN2 and PV baking (with LN2) continued for about 16, 7 ½ and 12 hrs with the LHe production of about 18.7 g/s, 31.8 g/s and 20.4 g/s respectively meeting the guarantee values (see tables 1 & 2). The adsorbed bed regeneration as well as CVP regeneration were completed as planned. The LN2 consumption of 115.2 g/s (see table 2) included also the contribution from CVP shield which was not directly measured (estimated to be about 15 g/s), therefore the actual LN2 consumption for the precooling of helium alone could be within the specified values.

3.4. Standard Mode (SM)

In this mode the W7-X applications were required to be cooled down to 3.9 K with the help of the cold compressor pumping down a dedicated subcooler vessel to about 640 mbar, only Joule-Thomson (JT) stream to be used for the coils (200 g/s) and the flow in the casings (300 g/s) and CVP (250 g/s) to be provided by the cold circulators in each circuit. The Supercritical Helium (SHe) was required to be supplied at different pressures, however the return pressure to be kept above 3 bara in order to keep the SHe in the stable condition. Two independent tests were foreseen, i.e. without and with use of LN2 precooling. The performance of this mode required larger cooling capacity to be provided by the refrigerator for which besides the 7 kW cooling capacity provided by the refrigerator, additional capacity was needed by using a maximum of 22.5 g/s (without LN2) and 15 g/s (with LN2) LHe from the 10000 liter Dewar. The LHe withdrawal from the Dewar was to be calculated by amount of gas helium discharged to the gas buffer tanks.

All the above operations were demonstrated successfully during the test which continued for about fourteen hours for the test without LN2 precooling and about nineteen hours with LN2 precooling, until the LHe level in the Dewar dropped below 2000 l. The start of the two cold circulators and the cold compressor and reaching of their nominal operating conditions were without any troubles. The measured average values for various parameters in comparison with the guarantee values are shown in Tables 1 & 2. The measured temperatures of 3.84, 3.87 and 3.86 K in the coils, casings and CVP circuits respectively are smaller than the guarantee value of 3.9 K (see table 1), which in fact gives a slightly more temperature margin for the superconducting coils, therefore these are acceptable. For the CVP the measured pressure values of 3.02 bara at the inlet and 2.49 bara at the outlet are smaller than the guarantee values, this was due to a different operating condition chosen to test CVP due to unavailability of a control valve downstream of the cold circulator to generate the pressure drop simulating the actual CVP, this was in fact done by another control valve at the suction side of the cold circulator leading to different pressure values. This test procedure was agreed well in advance with the contractor. For the CVP shield, the measured inlet LN2 supply pressure as 1.35 bara is smaller than 2 bara (see Table 2) since it was reduced to limit the two phase return flow to a small phase separator which was getting overflow, therefore it was acceptable.

3.5. Peak Power Mode (PPM)

The performance of this mode required maximum cooling capacity to be provided by the refrigerator for which additional capacity was supported by ≤ 69 g/s LHe from the Dewar. The test was required to be performed without using LN2 precooling. The LHe level in all the three phase separators / subcoolers i.e. at 4.5, 3.8 and 3.3 K was to remain stable. In addition to the JT flow in the coil circuit, a cold circulator needed to be used with the total flow of 450 g/s. The second cold circulator was required to be started in the casing circuit with the total flow of 800 g/s. By starting the second cold compressor the temperature in the third subcooler vessel was to be reduced to 3.3 K such that the SHe could be supplied to the applications at 3.4 K. The inlet pressure needed to be varied for different applications with a maximum of 5.4 bara to coils circuit, by raising the discharge pressure of the last turbine. All the above operations were demonstrated successfully during the test which continued for about four hours until the LHe level in the Dewar dropped below 2000 l. The start of additional cold circulators and the cold compressor while the others were still in operation and achieving to the new operating conditions for all the cold machines was quite smooth. The measured average values for various parameters in comparison with the guarantee values are shown in tables 1 & 2. The explanation of the measured values of temperatures for coils, casings and CVP as well as the pressure for CVP being outside the guarantee values are same as described for SM.

Table 1. Guarantee values (as specified) and measured average values of various parameters during PPM, SM (with and without LN2 precooling), SSM (with and without LN2 precooling and with PV baking) and LSM (with and without LN2 precooling) [3].

Parameter (Units)	Peak power mode (PPM)		Standard mode (SM)		Short standby mode (SSM)		Long standby mode (LSM)	
	Guarantee value	Measured average value	Guarantee value	Measured average value	Guarantee value	Measured average value	Guarantee value	Measured average value
Coils:								
Inlet temp. (K)	3.4≤T≤3.9	3.35	3.9≤T≤4.5	3.84				
Outlet temp. (K)					≤10	≤5.3	≤100	≤72.9
Inlet pressure (bara)	≥5.3	5.4	≥3.7	3.8				
Outlet pressure (bara)	≥3	3.22	≥3					
Mass flow (g/s)	≥450	454.9	≥200	≥215.9				
Test heater power (W)	≥1100	1110.4	≥800	≥808.6	≥250	259.7		
Casings:								
Inlet temp. (K)	3.4≤T≤3.9	3.37	3.9≤T≤4.5	3.87				
Outlet temp. (K)					≤10	≤5.6	≤100	≤72.9
Inlet pressure (bara)	≥3.4	3.51	≥3.1	3.19				
Outlet pressure (bara)	≥3	3.23	≥3					
Mass flow (g/s)	≥800	807.9	≥300	307				
Test heater power (W)	≥1820	1835.1	≥1820	≥1834.9	≥1820	≥1853.6	≥520	≥527
CVP:								
Inlet temp. (K)	3.4≤T≤3.9	3.38	3.9≤T≤4.5	3.86				
Outlet temp. (K)					≤10		≤100	
Inlet pressure (bara)	≥3.6	3.02	≥3.6	3.02				
Outlet pressure (bara)	≥3	2.52	≥3	≥2.49				
Mass flow (g/s)	≥250	253	≥250	255				
Test heater power (W)	≥500	508.5	≥500	508.5	≥500	≥513		
Current leads:								
Inlet temp. (K)	≤4.5	Ca. 4.5K	≤4.5	Ca. 4.5K	≤4.5	Ca. 4.5K	≤105	
Mass flow (g/s)	≥25	25.6	≥15	≥15.43	≥5	≥5.33	≥5	≥5.33

Table 2. Guarantee values (as specified) and measured average values of various parameters during PPM, SM (with and without LN2 precooling), SSM (with and without LN2 precooling and with PV baking) and LSM (with and without LN2 precooling) [3].

Parameter (Units)	Peak power mode (PPM)		Standard mode (SM)		Short standby mode (SSM)		Long standby mode (LSM)	
	Guarantee value	Measured average value	Guarantee value	Measured average value	Guarantee value	Measured average value	Guarantee value	Measured average value
CVP shield:								
Inlet temp. (K)	≤80	≤79.2	≤80	78.7	≤80			
Inlet pressure (bara)	2-8		2-8	1.35	2-8			
Vapor fraction (%)	≤0.9	≤0.9	≤0.9		≤0.9			
Test heater power (W)	≥6000		≥6000	6037	≥6000			
Thermal shield:								
Inlet temp. (K)	≥30	40.7	≥30	≥41.6	≥30	≥43		
Outlet temp. (K)	≤80	62	≤70	≤61	≤70	≤68.1	≤100	≤93.3
Outlet temp. with PV baking (K)					≤100	≤91.3		
Test heater power (W)	≥14100	14570	≥14100	≥14453	≥14100	≥14400	≥14100	
Test heater power with PV baking (W)					≥28100	28526		
He liquefaction (g/s):								
w/o LN2 precooling					≥9	18.7	≥20	26.9
with LN2 precooling					≥21	31.84	n.a.	37.75
LN2 precooling+ PV baking					≥11	20.39		
LN2 consumption (g/s):								
Normal operation			≤31.5	27.4	≤103	115.2		
with PV baking					≤126	91.1		
LHe consumption (g/s)								
w/o LN2 precooling	≤69	54	≤22.5	18.65				
with LN2 precooling			≤15	14.35				
Compressors (HP+LP) electrical power (kW)*	≤1640	≤1554.2	≤1640	≤1521	≤1640	≤1614.6	≤1640	≤1585.8
Cooling Water System cooling power (kW)	≤1500	≤1349.9	≤1500	≤1362.2	≤1500	≤1447.1	≤1500	≤1485.7

* HP: High Pressure, LP: Low Pressure

3.6. Cool-down and warm-up

It was foreseen that it must be possible to cool-down and warm up the refrigerator alone as well as together with the W7-X cooling applications. The cool-down of all the applications including the thermal shield and the current leads must occur simultaneously by restricting the temperature difference between the return and supply temperatures to 40 K. For the actual operation with W7-X it is planned to maintain a cool-down rate of about 1 K/h, however for the tests the cool-down time was limited to 5 days. Without the actual cold mass, it was planned to provide the heat capacity by using heaters with the power varying with the following formula:

$$Q_{max} = 20 * Min\left\{\frac{T_{Return}}{50}, 1\right\}$$

Here Q_{max} is the electrical power (kW) to be applied to heaters and T_{Return} is the return temperature (K) from the applications. Until the return temperature of 50 K is achieved, full 20 kW heating power is to be used. Below 50 K, the power applied is reduced by a factor of $T_{Return}/50$ down to the specified loads for short standby modes conditions when the cool-down operation is to be considered completed. The cool-down and warm-up operations were completed satisfactorily. In order to avoid the stresses within the heat exchanger block, it was not possible to use the LN2 until the temperatures of 120 K were reached. For the warm-up operation, the warm gas from high pressure (HP) stream was added to control the supply temperatures to the applications. While warming up until 100 K in the applications, the 80 K adsorber was kept in operation to capture the impurities release.

3.7. Interchanging between modes

One of the important features of the refrigerator is automatic switch over between the four operating modes i.e. LSM, SSM, SM and PPM. After the cool-down is achieved SSM remains the basic operating mode. From SSM it was demonstrated that any other selected mode could be reached. Once the mode is deselected then the refrigerator returns to the SSM. As mentioned above, the starting and stopping of cold compressors, cold circulators, turbines, adjusting the JT stream and pressure levels, generating the SHe flow etc. take place automatically by selecting / deselecting the mode.

3.8. Emergency signals and utility failure

During the emergency signals generated from the W7-X main controls i.e. coil quench, vacuum failure, CVP failure and emergency stop, the refrigerator isolates the respective application or all the applications automatically. The refrigerator remained in operation ready to be reconnected once the signals were reset.

For the utility failure i.e. electrical, instrument air, cooling water, the refrigerator shuts down. The cabinets and controls are supplied with uninterrupted power supply to remain in operation for the data archiving.

3.9. Purging operation

Before starting the cool-down of the W7-X applications, it is necessary to purge these with pure He. The impure helium in the return lines needs to be purified using the dryer and cold adsorbers. This operation was demonstrated satisfactorily with 80 K adsorber being in operation with 300 K helium to be circulating through the applications.

4. Summary

For the acceptance tests during all the specified modes, the measured average values of various parameters were found to be within the guarantee values. The incorporation of emergency signals were done appropriately. The automatic changeover of modes and the purging operation were also demonstrated successfully. After the successful completion of the final acceptance tests, the refrigerator was handed over to IPP.

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References

[1] Kuendig A., Schauer F., Bozhko Y., Dhard C.P., Helium Refrigeration System for Wendelstein 7-X, Proc. of International Cryogenic Engineering Conference -20, Beijing, China (2004) 677-680.

[2] Dhard C.P., Raatz S., Nagel M., Nuesslein U.G., Progress of Helium Refrigerator System for Wendelstein 7-X, Proc. of International Cryogenic Engineering Conference – 24, Fukuoka (2012) 555-558.

[3] Ressel M. Pruefprozedur Abnahmetest der Kaelteanlage (KATUN), IPP internal document no. 1-BCA11-S5065.12, dated 26.04.2013.