W7-X Superconducting Coils Cooling

at the CEA Saclay Cryomagnetic Test Facility

B. Renard[1], L. Genini[1], H. Viebke[2], J.-L. Duchateau[3]

1. CEA, Irfu, SACM, centre de Saclay, F-91191 Gif-sur-Yvette cedex France
2. Max-Planck Institute für Plasma Physik, EURATOM Association, Wendelsteinstr. 1, D-17491 Greifswald Deutschland
3. Association EURATOM-CEA, CEA/DSM/IRFM, F-13108 St Paul-lez-Durance France

Abstract

An extensive acceptance test program for the WENDELSTEIN 7-X (W7-X) confinement coils is presently being carried out in the CEA Saclay cryomagnetic test facility. Over half of the 50 non-planar coils and 20 planar coils have already been subject to a cool down to liquid helium temperature, allowing current tests in the superconducting state.
This paper presents a description of the cooling protocol observed at CEA. In-depth background information about the helium refrigeration technology limitations, the coil active cooling procedure and its control are given. The cryogenic power extraction is estimated through mass flow rate and enthalpy balance of the winding and casing helium circuits, which are derived from various coil and facility sensors.
Coils geometry and material thermal properties are given, as well as a simple modelling of the coil cooling. The observed coil thermal behaviour can help to better understand the role of the casing cooling loop on the cooling inertia and on the total cooling time. Finally, the cooling down process is projected into the future operation of the W7-X stellarator under construction.
More generally, data and experience gained from the cooling tests operated at the CEA Saclay cryomagnetic test facility provide practical knowledge to foresee the thermal behaviour and cryogenic challenges of other large magnets for thermonuclear fusion.

Topic and Keywords

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authors contact: bertrand.renard@cea.fr
CEA, Irfu, SACM ; bat. 123 pc. 11 ; Centre de Saclay
F-91191 Gif-sur-Yvette cedex
tel +33 (0)1 69 08 13 82/95 75
fax +33 (0)1 69 08 49 50

Introduction

The WENDELSTEIN 7-X (W7-X) stellarator magnetic confinement system is a torus made of fifty (50) non-planar coils (NPC). Additionally, twenty (20) planar coils (PLC) surrounding the torus allow field adjustment and magnetic configuration modification. The coils system is assembled in a subdivision of five modules and ten half-modules. Each half module holds 5 NPC and 2 PLC. Given the complexity of the stellarator mounting, a confinement coil failure is an unacceptable risk and a systematic extensive test for the W7-X coils is carried on, including current tests in the superconducting state [1]. Cold tests are being carried on in the CEA Saclay cryomagnetic test facility. 75% of the coils have already been subject to a cool down to liquid helium temperature [2].

The cryogenic equipment, procedures and measures of temperatures and cooling power are here depicted.

1. Experimental protocol

1.1 Coils geometry and properties

The W7-X coils are wound from superconducting NbTi cable-in-conduit conductor (CICC). The heat loads can be safely removed by a controlled helium circulation. A unique W7-X conductor is used for PLC and NPC, although the nominal current value is respectively 16 kA and 17.6 kA. Casing cooling circuits are made of external stainless-steel pipes thermally connected to the coil case by copper strips. Differences among the two types of PLC [3] and five types of NPC characteristics [4] are neglected for simplification from the cryogenic point of view, and PLC are differentiated simply from NPC (see Table 1). The cooling down of coils AAC52 and AAB10 have been used as examples in Fig. 3 to 6.

Table 1: Coil geometric properties

Figure 1: PLC (left) & NPC (right) heat capacity

The total coil energy to be extracted during cool down is not evenly distributed in temperature (Fig. 1). In the stellarator fourteen cryogenic distribution loops will be providing supercritical helium to the seven modules each with winding and casing circuits [5].

1.2 Saclay cryo-magnetic test facility

The Saclay cryomagnetic test station [6] comprises four principal parts:

1.2.1 Two cryostats: each hosting simultaneously two coils suspended under their support ring, in order to optimize the long cooling and warming time for the high number of coils. Current tests are however conducted separately;

1.2.2 The cryogenic plant: it comprises a collecting helium network, a variable volume surge tank, high pressure compressors, pressurized helium storing gas cylinders, a purifying system, a cycle compressor, oil traps and dehumidifiers, a refrigerator-liquefier, a 5000 l LHe reservoir, LHe helium supply lines to the distribution satellite, a valve box with current leads for each cryostat, a LN_2 network (Fig. 2);

1.2.3 The Electric supply (stabilized DC Current Transformer) of 25 kA, with ambient temperature copper conductors, actively cooled flexible conductors to the current lead heads and discharge resistors;

1.2.4 The control-command system, with a hardware coil security quench system and the data acquisition system.

Figure 2: Cryogenic systems of the test facility

Testing of the coils begins before insertion into the cryostat, because any intervention or instrumentation on a coil is checked, tested and recorded. The cryogenic test itself begins after vacuum pumping and leak proof detection of all circuits in the cryostat. After a flush of clean helium and the control of low pollution levels in the coils, the cooling down may start. The cryostat actively cooled shields and coil supports are filled with LN_2 within 12 hours. The temperature of these circuits rapidly sinks and radiation contribution to the cool down is significant when temperatures are still high. LN_2 consumption during operation is about 2500 l/day, corresponding to an evaporation power of 4.5 kW for a cryostat with two coils. Only the coils are cooled with the helium circulation. The helium cryogenic power is provided in part with LN_2 through heat exchangers in the cold box of the refrigerator. The insulation vacuum in the test cryostat is better than 10^{-5} mbar, therefore residual gas heat conduction can be neglected.

The refrigerator is used both as a circulating loop refrigerator, and also but subsequently as a liquefier storing LHe in a 5000 l tank. The helium refrigerator is designed to admit extremely clean compressed helium at 16 bars, serving it at a pressure up to 12 bars, at a temperature down to 4.7 K depending on the return vapor temperature. The refrigerator technology is based on a LN_2 exchanger, a series of four heat exchangers and a mono-turbine. The heat exchangers thermally connect cooling high pressure and warming low pressure helium. External cryogenic power above 150 K is provided on the first heat exchanger by LN_2 (77 K), most simple and efficient. As the heat exchange progressively becomes a limiting factor, cryogenic power must be extracted directly from the pressurized helium. A single cold turbine rotating at up to 2500 Hz draws a portion of the mass flow, depressurizing it to cool the remaining mass flow on the third heat exchanger. The coldest heat exchanger is used only when helium returns below a threshold temperature. The temperature in this last heat exchanger is controlled by helium pressure and thermodynamic properties through a Joules-Thomson valve.

2. Coil cooling procedure

2.1 Mass flow rate in the coil circuits

Helium mass flow rate is precisely measured at cryogenic temperature through Venturi flow meters specially adapted to the density and viscosity of He under 10 K. These Venturi diaphragm flow meters would bring a high pressure drop and reduce the mass flow rate during cool-down therefore the flow is diverted into a bypass for cool-down circulation. This means the observation of pressure drop is the only valid measure recorded during the cool-down. The mass flow rate is calculated from the pressure drop using the formula:

$$m^2(T) = m^2{}_{cryo} \frac{f_{cryo}}{f(T)} \frac{\rho(T)}{\rho_{cryo}} \frac{\Delta P(T)}{\Delta P_{cryo}}$$

Figure 3: PLC and NPC mass flow rate and pressure drop

The coils winding and casing inlet pressure regulation is an important cooling down parameter. Near ambient temperature, helium pressure drop is high and the cryogenic power transferred to the coils is limited by the mass flow rate. A high inlet pressure, up to 12 bars, is necessary to push a significant mass flow through the hydraulic circuits (Fig. 3).

2.2 Cooling control

The cooling down of the coils is controlled by maximal ramp and gradient laws (Table 2). The mass flow rate and cryogenic power of the cooling loop may also limit the cool down (see § 2.3).

Table 2: Cooling down statutory laws

Figure 4: PLC and NPC inlet and outlet cooling down temperatures (left scale) and temperature ramp (right scale) Inlet pressure, turbine start or turbine velocity adjustment events are marked with p or T signs.

Fig. 4 presents the cooling down temperatures and the temperature ramp limiting factor. The inlet temperature setpoint follows the 2 K/h temperature derivative ramp (clearly in Fig. 4 PLC up to 70 hours) by small steps unless the maximal gradient is reached. In this case (in Fig. 5 NPC between 40 and 70 hours) the setpoint remains constant until the gradient is below the maximal value, and the setpoint can step down again.

Figure 5: PLC and NPC casing temperature (left scale), in-out He temperature difference and maximal casing temperature difference (right scale)

2.3 Cooling down limiting factors

The cool-down of the coils is limited by the following factors:

2.3.1 Pressure and mass flow rate

The mass flow rate through the casing and winding circuits is defined independently by the inlet pressure and the pressure drop. The inlet pressure is reduced especially when other factors are limiting the cool-down.

2.3.2 Speed of inlet temperature decrease (ramp)

The rate of inlet temperature decrease, calculated as the derivative of temperature over time, is a statutory rule (Table 2) visible in Fig. 4.

2.3.3 Maximum admissible temperature gradient

The maximum temperature difference in the coil between any two points, or more practically between the inlet and a casing temperature most distant from the cooling circuit, is a statutory rule limited to 40 K (Table 2). This gradient is not a limiting factor for PLC but only for more massive NPC (Fig. 5).

2.3.4 Available cryogenic power (nitrogen, turbine and turbine velocity)

The cryogenic power available is strongly dependant on the temperature range of the cold box, on the thermodynamic properties of helium and on the velocity of the turbine that may be raised manually by steps.

3. Cooling power and projection to cryoplant design

The W7-X magnets cooling down data base can be helpful at a moment when several superconducting fusion machines are starting their operation (EAST, KSTAR) or envisaging the acceptance tests (JT-60SA, ITER). For the imperative acceptance tests, one main point in discussion is how to design the cryoplant according to the required cooling down duration: How to proceed for a facility working mainly in cool-downs, what is the required cryogenic power at low temperature, is LN_2 necessary, what is the required mass flow rate, what are the respective roles of the casing and of the winding pack to extract the enthalpy?

3.1 Extracted power

From the mass flow rate and temperature difference between coil inlet and outlet, the enthalpy balance can be produced and plotted for the casing and winding circuits (Fig. 6).

Figure 6: PLC and NPC actively extracted power as a function of coil temperature

Plotted as a function of temperature, the cryogenic power clearly shows the limit of nitrogen-cooled helium, before the turbine is activated. These curves show the power extracted on one coil through He circulation Power extracted or added from the supports and cryostat is also present:

$$W_{coil\ cooling} = mass.\Delta h_{\text{winding}} + mass.\Delta h_{\text{casing}} + W_{N2\ \ radiation} + W_{N2\ \ conduction}\ .$$

The total refrigerator power (200 W at 5 K) corresponds to the enthalpy extraction from two coils and from the facility busbars circuits. The comparison between the enthalpy to be extracted and the available cryogenic power integrals over temperature will provide an estimate of the cooling down duration. Cooling down time is a fundamental design parameter for schedule planning and cryogenic facilities design.

3.2 Discussion and lessons for cryoplant design

Although the uncertainty of PT100 temperature sensors is less than 1% of the total range, the cooling-down curves cannot be observed below 30 K. The curves are plotted from PT100 sensors between 300 and 50 K, from cernox sensors below 40 K, and as a linear interpolation of PT100 and cernox in-between. Sensors were paired according to their proximity, but the artificial sensor transition between 50 and 40 K corresponds to sensor reading differences up to 1 K.

Given the geometric complexity of unique coil casing geometries, the assumption of simple geometry with temperature homogeneity is rough. The thermal gradients in the coil can be subdivided into a circumferential gradient along the hydraulic circuits, precisely the temperature difference between inlet and outlet on one hand, and a transverse thermal gradient on the other hand, to be evaluated on a coil cross-section. A 3D thermal model however, would be much more complicated for a limited gain in precision. The isothermal casing hypothesis provides only basic thermal analysis of global diffusivity, inertia and time response properties.

A modelling of the helium refrigerator cryogenic power as a function of T, united with the control-command laws can lead to a full cool-down prevision. This experimental data base can be very useful to control the concept and dimensioning of the cryoplant. Combined with heating and quench scenarii, the cool down and power measurements provide highly valuable information that can help validate the helium mass flow rate, instantaneous power, heat exchangers and volume capacity of the W7-X cryogenic plant. Such an analysis is considered at present time in the case of the W7-X project, but the possibility of application is interesting for any large magnet with high field.

Heat extraction through the casing is efficient close to room temperature as observed in Fig. 6, while helium circulation in the CICC is difficult. On the opposite, near lowest temperature, the casing heat extraction is limited by the pipe area. The casing mass flow rate is hence reduced and heat extraction is more efficient through the winding circuit.

The coil cooling time is a parameter helpful to design new large superconducting coils. It will help understanding and justifying the role of the case cooling circuit when starting the cooling process, while the winding channels cannot carry their nominal mass flow rate.

Conclusion

During the cooling down of the W7-X superconducting magnets for their cryogenic acceptance tests before assembly, a large data base has been collected regarding temperature, pressure drop and mass flow. This CICC data base has been used to better understand manufacturing homogeneity, cooling down process and control. The result of this investigation can be very helpful to dimension the cooling test facilities which are foreseen

for ITER and JT-60SA future acceptance tests. Moreover this data base can help to prepare for the coil thermal behaviour and cooling down of the W7-X machine long before reactor operation, with adapted thermal shield conditions.
Further work is needed to investigate the respective role of the casing, the winding pack and the shield along the cooling process.

Nomenclature and abbreviations

CICC		Cable-In-Conduit Conductors
cp	[J/kgK]	calorific capacity
f	-	European friction coefficient
Δh	[J/kg]	inlet/outlet helium enthalpy variation
Δp	[Pa]	inlet/outlet pressure drop
ΔT	[K]	inlet/outlet helium temperature variation
EAST		Experimental Advanced Superconducting Tokamak (China)
ITER		International Thermonuclear Experimental Reactor
JT-60SA		Japan Tokamak – 60 Super Advanced
KSTAR		Korea Superconducting Tokamak Advanced Reactor
mass	[kg]	(winding, insulation, casing or total) mass
m	[kg/s]	mass flow rate
NPC		Non-Planar Coil(s)
PLC		PLanar Coil(s)
ρ	[kg/m^3]	fluid density
W	[W]	Power
W7-X		Wendelstein 7 stellarator X

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