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ASG is deeply involved in the manufacturing and testing of the poloidal field coils at the Fusion for Energy (F4E) Poloidal Field coils factory, located at the ITER site.

If results of the preliminary tests are positive, the coil is cooled down to a temperature of 80 K, where the following additional tests are performed and/or repeated: pressure drop test and vacuum leak test of the helium circuit, high voltage DC test and current test.

IT'S COLD TEST TIME FOR THE POLOIDAL FIELD COILS OF THE ITER FUSION DEVICE BY THE ASG TEAM!

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with the collaboration of
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Poloidal field coil #6 — the located at the bottom of the ITER machine and the first in line for installation — has completed all testing on site in the factory of Fusion for Energy. (Courtesy of ITER)

Six poloidal field coils positioned horizontally around the ITER vacuum vessel and D-shaped toroidal field coils will help with the shape of the plasma and keep it in suspension away from the walls. The top poloidal field coil (PF1) will be supplied by Russia; the five lower ring coils are under the procurement responsibility of Fusion for Energy which is the European domestic agency in-charge of the procurement of the European in-kind contribution to ITER. Four of these will be produced on site. (PF6 has been produced by Europe and China.) ASG is involved in the supply of the ITER Poloidal Field Coils PF2, PF3, PF4 and PF5 and the cold testing of PF6, the provision of both the engineering integration services and Project management for the supply of the Poloidal Fields Coils PF2, PF3, PF4 and PF5. This includes definition, description and management of the interfaces between the various contractors participating in the Project.

The Poloidal Field Coils are fundamental components of the ITER experimental fusion device. Together with the toroidal field coils of which we have produced 10 of 19 at our La Spezia workshop, the poloidal field coils shape the plasma and contribute to its stability. Six poloidal field coils are installed in the ITER machine: PF1 to PF6. Four of them, the PF2, PF3, PF4 and PF5 are so large that they have to be manufactured in the ITER site at Cadarache, in France; the remaining two, PF1 and PF6, are comparably smaller and they are manufactured respectively in Russia and in China. The largest coil has a diameter of 24 m, while the heaviest weighs as much as 400 tons. These coils are manufactured using NbTi superconducting cables, due to the lower magnetic field to which they are exposed in comparison with the toroidal field coils which require the higher performing Nb3Sn material. In all cases, supercritical helium is needed in order to reach the operating temperature of both sets of coils. ASG is deeply involved in the manufacturing and testing of the poloidal field coils at the F4E factory, Cadarache. Despite the difficult times due to the covid-19 pandemic, we have not stopped our activities, while taking all safety precautions.

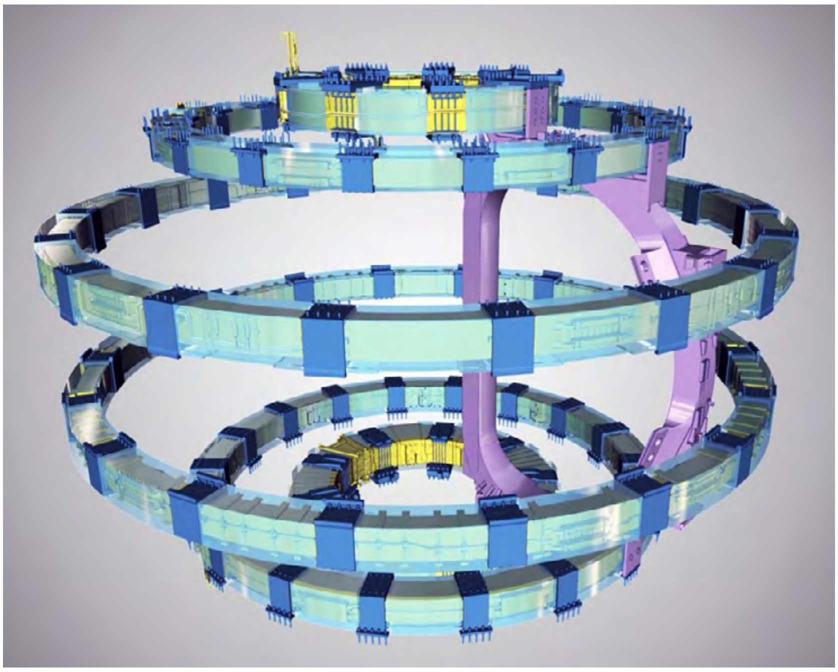

Figure 1 Poloidal field coils of ITER with one toroidal field coil.

Once the manufacturing process is completed, each PF coil undergoes a test campaign inside a cryostat designed and produced for this purpose. While such tests are not performed at the final operating temperature, they nevertheless provide valuable information both to the manufacturing team and to the quality inspectors, and largely increase the general confidence in assembling the tested coils in its final position in the tokamak
Initially, before cooldown, a vacuum leak test and a pressure drop test of the helium cooling circuit are performed, together with an electrical DC current test and an electrical insulation (or Paschen) test of the ground insulation at room temperature.
If results of the preliminary tests are positive, the coil is cooled down to a temperature of 80 K, accordingly to the technical specifacation requirements where the following additional tests are performed and/or repeated: pressure drop test and vacuum leak test of the helium circuit, high voltage DC test and current test. Scope of the cold tests is to detect any possible malfunction that may appear after cooldown, that could originate e.g., from the different thermal contraction of materials.
At the end of the tests at low temperature, the coil is warmed up and the previous tests at room temperature are repeated.
All the PF coils will be tested in Cadarache by ASG Superconductors, inside the above-mentioned facility, following the technical specification issued by ASG.
To date, both PF6 and PF5 coils have been fully and successfully tested.

The Cold Test Facility

The Cold Test Facility provides the set of equipment and machinery to perform the cold test of the PF coils at the target temperature of 80K. The facility has been designed to cool down the magnet while minimizing the risk of insulation breakage due to thermal contraction/expansion: for this purpose, the machine is able to decrease the temperature of the magnet with a maximum cooling rate of 1 K/h and can maintain the maximum instantaneous temperature difference between any parts of the coil to less than 50 K at all times during the cool-down and warm-up phases.

The Cold Test Facility (CTF) is composed of two main systems: the cryogenic plant and three cryostats to host the different size of the PF coils.

The cryogenic plant creates the pressurized cold helium gas flow that will circulate through the PF coils. The 80 K temperature regime is reached by passing helium gas through a heat exchanger in direct contact with liquid nitrogen at 77 K.

The cryogenic plant is also able to supervise the cooldown and acquire additional information by interfacing with auxiliary devices installed on both the cryostat and on the PF coil during the whole thermal cycle. An acquisition system monitors the data of temperatures, pressures, flows, etc..; a video recording system of 40 vacuum video-cameras monitors the coil under Paschen conditions; a leak detector performs leak testing of the coil at room and cold temperature and a power supply and electronics are used to measure the coil resistance by applying an electrical current of 500 A at low temperature.

The cryostats are stainless-steel vacuum chambers designed to host the coil and to reduce thermal losses during the test by conduction, convection and radiation. To mitigate these effects, the chambers employ thermal shields, superinsulation material, fiberglass supports and provide a vacuum level of 10^-5 mbar.

From a geometrical point of view, the dimensions of the cryostats have been determined by the size of the different PF coils, their diameter ranging from 12 m for the smallest PFs to 27 m for the largest ones Each cryostat is designed to withstand the coil weight (up to nearly 400 tons) and it is constructed out of modules of stainless-steel. The modules are joined together and welded, creating the complete donut-shape vacuum chamber that contains the coil during the tests.

Figure 2 The dedicated area for the cryostats: On the right, the smaller cryostat is assembled and cold testing of the PF6 coil is in progress. On the left, the medium sized cryostat is about to be assembled for the final cold test of PF5.

Cool down of the coils

As explained in the previous section, through the CTF we control the cooling rate and the temperature gradient along the coil. The coil is instrumented with Cernox and Pt100 thermometers and the electrical resistance of each double pancake is measured and converted into an average value of temperature.
The coils are cooled by a flow of He gas that is circulating along the cooling circuit of the coil, by means of temporary piping that connects the inlet and outlet of the coil to the valve box.
Two other circuits, in parallel with the main one, provide the He gas for cooling down the coil clamps and the thermal shield of the cryostat.

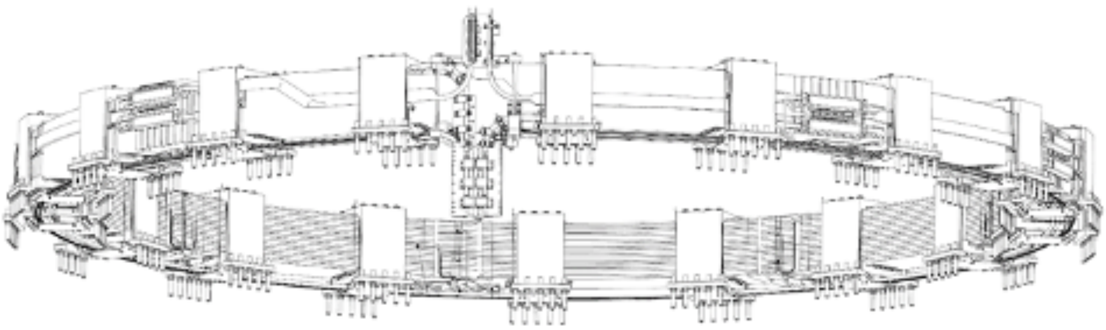

Figure 3 PF5 isometric view.

The cooldown is controlled by the mass flow of helium which circulates in the circuits, and the nominal cooling rate stays between 0.8 and 1 K/h. Thus, for a cooldown of a coil to 80 K, about 13 days are needed, including an initial transient time and time for the final stabilization of the temperature.

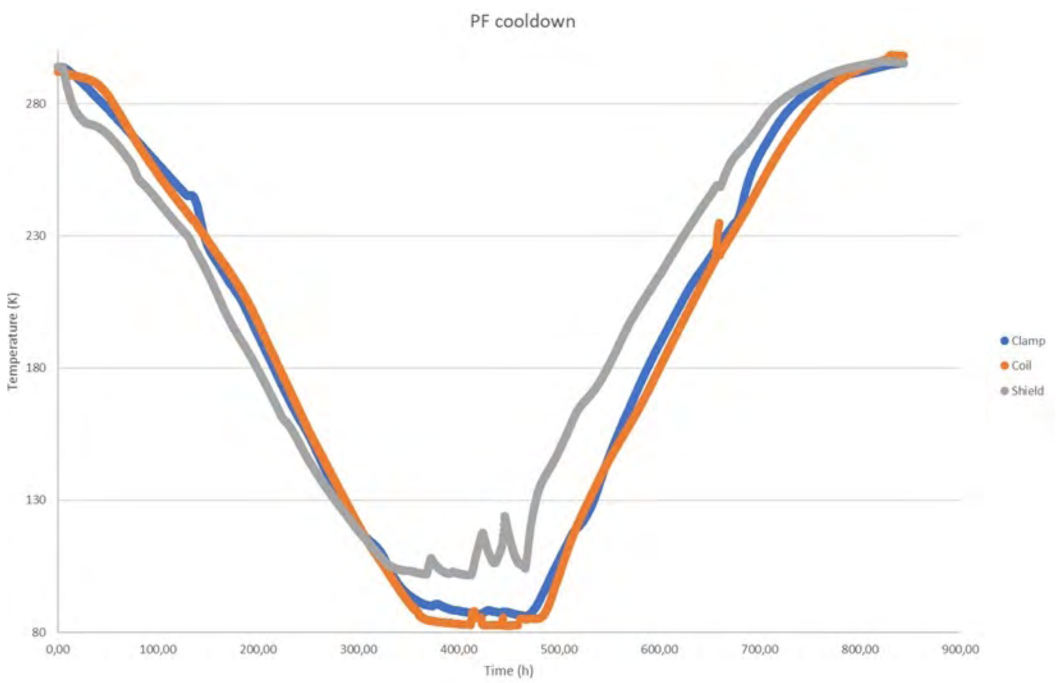

Figure 4 Cooldown and warm up of PF6.

At the end of the tests at cold temperature, the coil is warmed up again controlled by the flow of He gas.

Tests performed on the PF coils

Several tests are performed on each coil. The following tests are carried out at room temperature before and after the cooldown: pressure drop test, leak test, high voltage DC test and Paschen test.
The following tests are performed at 80K: pressure drop test, leak test, high voltage DC test and current test.

Pressure drop test

The pressure drop test confirms the performance of the hydraulic circuit that is used to refrigerate the coil at cryogenic temperatures. Any leak, bottleneck, or increased friction against the cold helium flow would result in an increase in pressure drop. As the pressure drop is compensated by the cooling system, it cannot exceed certain values otherwise the coil will not be able to maintain the appropriate operating temperature.
In this experiment, a dry helium gas mass flow (g/s), which is circulated in the coil by a compressor, is set at different values so that the flow rate can be correlated to the difference between the measured inlet and outlet pressures (pressure drop). Indeed, the magnet offers a hydraulic impedance, an "opposition" to the helium flow and the higher the gas mass flow, the higher the pressure loss that will arise. This test is performed controlling the helium gas mass flow and monitoring the pressure of the gas which enters and exits the magnet through dedicated pipes. It is successfully passed when the results are compliant with research studies that can be found in literature, along with the results of previous tests performed on ITER superconducting magnets.

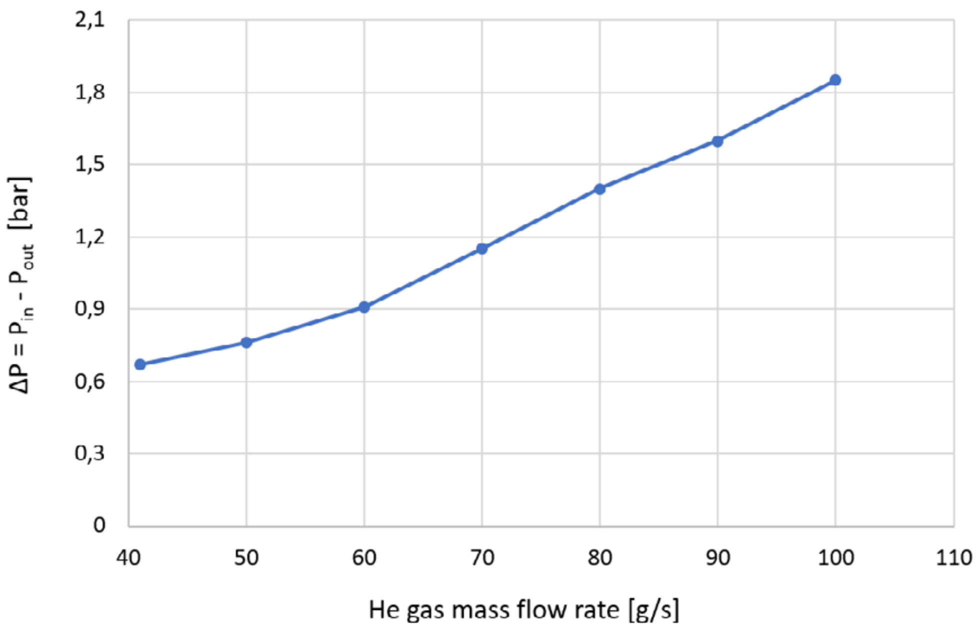

Figure 5 Pressure drop test on PF6 after cool-down at 80 K.

High voltage DC test

When the current in a superconducting magnet is ramping up and down, and in an unlikely case of a quench, a voltage appears on the superconducting coil. A high voltage DC test is therefore required to be sure that no significant leakage current appears through the electrical insulation material.

In this experiment, a maximum voltage of 15 kV is applied across the magnet, reaching this value after a ramp of about 17 V/s, and is held constant for 5 minutes. The test is passed if the insulation resistance at 15 kV is higher or at least equal to 500 MΩ, which corresponds to a leakage current lower than 30 μA.

Leak test

The cooling process down to cryogenic temperature can produce considerable thermal stresses which can cause the formation of leaks. Therefore, it is necessary to perform a leak test before and after this process. First of all, the helium flow rate in the magnet is set to zero and its pressure is set to 15 bar. The leak rate measured at this pressure is then recorded by means of a helium leak detector which is connected to the cryostat. Given a certain volume, the helium leak rate provides a measurement of the change of pressure over time, due to the flow of some amount of the noble gas. Should a leak be present, helium would flow out of the magnet and its circuit and into the cryostat and would be measured by the leak detector.

Then, a calibrated leak into the cryostat is opened in order to check if a leak of known magnitude can be detected and correctly measured. Subsequently, the calibrated leak is closed and the helium inside the coil is pressurized at 30 bar. After waiting for one hour in this configuration, the leak rate is measured again, and then the calibrated leak is opened. The helium leak rate measured at 15 bar is then subtracted from the rate at 30 bar and if the result is lower than 10^{-6} mbar*l/s the test is passed successfully.

Figure 6 Leak detector, on left side, and vacuum pumping system connected to PF5 cryostat.

Current test

The current test is undertaken to ascertain the homogeneity of the electromagnetic architecture of the superconducting coil.
This test, performed only at low temperature, consists of feeding the coil with 500 A and recording, from the voltage taps that are installed on the coil, the voltage drops across each double pancake. The voltage drop across a shunt resistor is also measured in order to calculate the actual current flow in the coil. All these signals are then acquired using a fast acquisition measurement device at a sample rate of around 100k sample/s. The results are analysed and the test is considered successful if the modulus of the difference between the resistances of each double pancake is lower than 5%.

Paschen Test

In order to minimize the probability of an electrical breakdown at operating voltage, for example in case of an accidental pressure-rise, the electrical equipment has to be Paschen-tight, meaning that no breakdown may occur across a range of pressures. Figure 7 shows the heavy dependance of the breakdown voltages of various gases on the product of the gas pressure and the distance between two electrodes at different electric potential.

The Paschen test is performed at room temperature before and after cooldown.
A DC high voltage is applied to the coil at different levels of nitrogen gas pressure from 10-2 mbar to 100 mbar in the cryostat. At each pressure step, a voltage of 15 kV is applied for 1 minute. An electrical breakdown would cause an increase in the leakage current, detected by the high voltage generator and a flash, hopefully located by the cameras in the cryostat. The criteria for passing the test are having a leakage current lower than 20 µA and not observing any discharge.
Once this last test is passed after the cooldown and warm-up, the cold testing of the coil is completed and the magnet is ready for the final operations before being delivered to ITER for assembly in the tokamak.

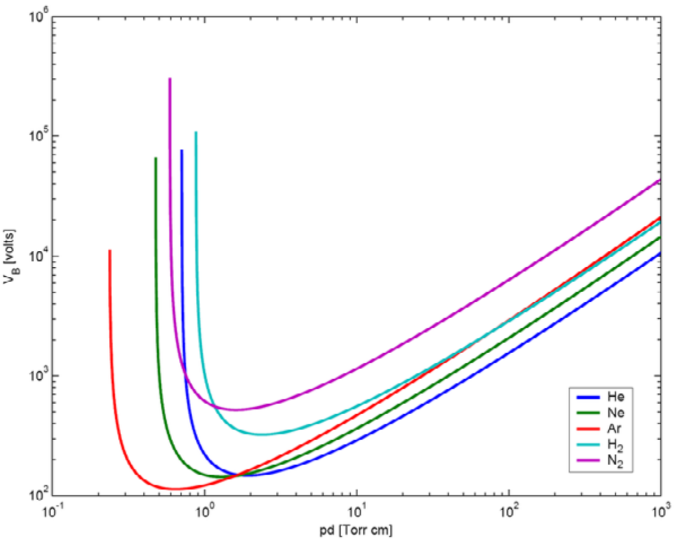

Figure 7 Paschen curves for different gases. He and N2 plots are relevant f or the tests on ITER superconducting magnets.

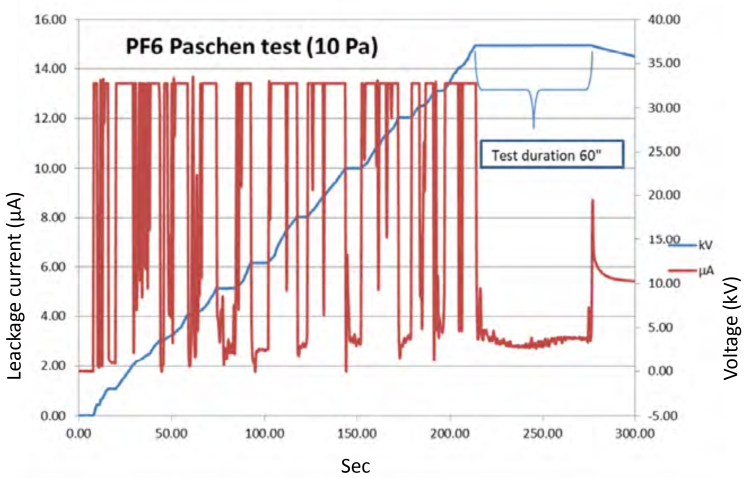

Figure 8 : Paschen tests on PF6.

Conclusions

The poloidal field coil cold test represents an exciting moment for the ASG team to verify that the lengthy manufacturing work of the huge superconducting systems was carried out successfully.
The cold tests on the PF6 confirmed the integrity of the coil, which passed all the tests carried out. The tests performed so far on the PF5 have also been successfully passed. The Cold Test Facility operated correctly during all the phases of the activity, with no noteworthy problems. The activities have been supervised 24 hours a day by the ASG team, both on-site and remotely, with support from Fusion for Energy and other personnel.
This activity was made possible by a remarkable effort of coordination and teamwork between different entities from all around the world with a common goal: to build the ITER device.