Vacuum Tests of a very large Component: The Final Test Cryostat System for the ITER Central Solenoid Modules

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Abstract. The ITER Central Solenoid system is composed of 6 individual Central Solenoid Modules (CSMs) that are assembled together at the ITER site to form a 18 m high superconducting magnet. General Atomics (GA) is currently under contract to fabricate and test the ITER Central Solenoid Modules (CSMs). The contract is managed by the US ITER at Oak Ridge National Laboratory, under the sponsorship of the Department of Energy Office of Science. The Final Test Cryostat System (FTCS) is used in conjunction with other subsystems to perform final testing of the CSMs before shipping. In particular, final testing includes testing under vacuum conditions including leak testing at ambient and cryogenic temperatures and electrical tests under vacuum and cryogenic conditions. In order to satisfy the different boundary conditions and requirements of the test program, the FTCS components need to conform not only to the usual requirements but must also be suitable for an environment in which high magnetic fields occur. The major steps in design and fabrication of the FTCS are described and results of the test during commissioning are provided.

1 Introduction

The ITER fusion experiment reactor includes three main magnet systems for confining the plasma, which has a temperature of about 100 000 000 K: The toroidal field (TF) coils, which mainly create the magnetic cage that confines the plasma, the poloidal field (PF) coils and the central solenoid (CS) coils, which induce a current in the plasma that is necessary to create the final helical magnetic field configuration of the total arrangement.

The responsibility for the supply of the TF coils is shared between Europe and Japan, the PF coils are shared between Europe and Russia and the CS coils are supplied by the US–ITER administration.

The central solenoid coils – 6 modules which will form one single giant solenoid in the final installation – are fabricated using Nb3Sn superconductors in order to create the large necessary magnetic field of 13.1 T. This conductor needs to be wound to its final shape before a heat treatment takes place that forms the superconducting alloy. It is therefore not possible to test the conductor in advance with respect to its superconducting
properties. Even more it is necessary to test the coil modules at the superconducting state before their final shipment to the site located in Cadarache (France).

The superconducting state is reached only at very low temperatures, which are below 18 K (−255°C) for the Nb₃Sn, while the necessary temperature for the use within this coil is 4.7 K (-269°C), the temperature of liquid Helium. Cooling machines for such low temperatures require an enormous amount of power, thus one of the main tasks for a test facility is the reduction of thermal loads to the coil under test.

2 Main Components of the Final Test Cryostat System (FTCS)

The FTCS consists of the vacuum vessel, the hood lifting system, an actively cooled thermal shield, the vacuum pumping system, the leak detection system, the Paschen test system and auxiliary mechanical systems. These components will be described in the following subsections:

2.1 The vacuum vessel

The vacuum vessel forms the boundary between the environment and the vacuum space and is designed to withstand the mechanical loads due to
- the weight of the tested module including its supports and loading system,
- the pressure difference between the vacuum inside the vessel and ambient pressure outside
- seismic acceleration
- static and dynamic electromagnetic forces during current operation of the tested module.

The vacuum vessel is fabricated from austenitic stainless steel. Its wall thickness is in the range between 15 mm and 25 mm depending on the load requirements. The hood shell (see Figure 1) is equipped with stiffening ribs in order to reinforce the system against the loads resulting from the pressure difference. Its main seal consists of 2 Viton o-rings whose intermediate space is connected to a dedicated pump for evacuation of the interspace region.

For raising and lowering of the hood shell, the system is equipped with a lifting system mounted on a massive structure. The movement is carried out with an electric motor mounted atop the horizontal bar of the gantry-like structure.

2.2 The thermal shield

The thermal shield serves primarily to reduce radiative heat load to the coil. During cryogenic operation it is cooled by the use of liquid nitrogen to a temperature of about 80 K (-193°C) which reduces the radiative load by more than 99%. The shield is made up of one actively cooled layer and one passive layer.

The choice of materials and the design were strongly influenced by contradicting requirements: Low permeability to minimize ferromagnetic forces caused by the static magnetic field and lightweight design called for aluminium, eddy current resistance, economics in fabrication and durability preferred stainless steel.

Finally aluminium was selected as the shield material for the upper part (hood part) of the system and stainless steel for the bottom part. Details of the design phase have been discussed in [1] and [2]. The aluminium parts of the shield can be seen in Figure 1.
Stainless steel was selected for fabrication of the lower part of the shield. The main reasons were the better mechanical properties of stainless steel, as it was necessary to design it in a way that it can be removed for room temperature Paschen tests. Also the coil support structure (CSS) is part of the bottom shield. The CSS is a frame construction resting on 4 posts. These posts are part of the active cooling circuit and are equipped in addition with G10 insulating plates to minimise heat conduction on both temperature boundaries (300 K / 80 K and 80 K/ 4K). The CSS can be seen in the background of Figure 2.

The main properties of vessel and shield are summarised in the following Table 1

<table>
<thead>
<tr>
<th>Table 1: System Parameters of the FTCS</th>
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<tbody>
<tr>
<td>Total height</td>
</tr>
<tr>
<td>Total mass of FTCS</td>
</tr>
<tr>
<td>Total mass of CS coil module + support</td>
</tr>
<tr>
<td>Maximum considered seismic horizontal acceleration</td>
</tr>
<tr>
<td>Cryostat height</td>
</tr>
<tr>
<td>Cryostat inner diameter</td>
</tr>
<tr>
<td>Cryostat volume</td>
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Figure 1: Hood shell (hanging in crane) lifted over hood shield (on bottom) during assembly

2.3 The vacuum system

The vacuum system is designed to evacuate the chamber to 0.01 mbar within 4 hours after start and a 5·10⁻⁴ mbar after 24 hours of pumping.

A special challenge for the design of the vacuum system was the presence of strong magnetic fields in the vicinity of the test vessel during current operation of the coil. The roughing pumps needed to be placed at a safe distance due to their components consisting of magnetic steel. The same is necessary for the vacuum gauges because their reading would be influenced by the fields.

For the roughing system we have chosen an Oerlikon Leybold DRYVAC 5000 system which technically is a serial combination of a screw pump providing a start–up pumping speed of 630 m³/h and a roots blower which increases the pumping speed to a maximum value of 3800 m³/h with decreasing pressure [3].
The sealing interspace is pumped by a two stage rotary vane pump with a maximum pumping speed of 65 m³/h. Besides its task to evacuate the space between the o-rings of the main flange, this pump is used to pump the forelines of the installed diffusion pumps (see below) during their start-up and shut-down phases.

Another smaller pump of the same type is installed for permanent evacuation of the installed calibrated leak which is part of the leak detection equipment (see section 2.4).

All these components, as well as the vacuum gauges necessary for monitoring and control of the machine, were installed in an adjacent building connected to the vessel by piping having a length of about 35 m.

For the fine vacuum system it is not possible to use the same approach. In the molecular flow range, the conductance of piping systems is strongly dependent on the diameter and length of the pipe connecting the pump and the vessel. Therefore it is necessary to place the fine vacuum pump as close as possible to the vessel. As turbomolecular pumps are highly sensitive to magnetic fields, even in the low millitesla range [4], it is not possible to operate them during the presence of strong magnetic fields. We installed 3 diffusion pumps of the type Oerlikon Leybold DIP 8000– especially fabricated using non–magnetic stainless steel parts – having a nominal pumping speed of 8000 l/s each (Figure 2). Due to the installed water-cooled baffles and their geometrical distance to the vessel of 1.3 m, we expect that about half of the nominal speed is available at the vessel.

2.4 The leak detection system

The main requirement for the leak detection system is the ability to detect a leak of at least $5 \cdot 10^{-7}$ mbar-l/s on the coil module in vacuum. Due to the large volume of the vessel of 160 m³ it is not practical to attach even the most powerful conventional leak detector directly to the vessel, because the response times would become extraordinary long. Therefore a turbopump is arranged in the flow path between vessel and leak detector in order to take advantage from its significantly higher pumping speed.

The fact that the full gas flow is led into the leak detector is an advantage and a disadvantage of this arrangement at the same time. The advantage is obvious: The system has the maximum possible sensitivity and this is limited only by the Helium background present in the main vessel. The downside is that the gas flow has to be limited in a way that the leak detector still is able to process the full flow without losing the sensitivity. This is not a trivial condition because the large inner surfaces (about 800 m² of metallic surfaces and about 130 m² of epoxy surface) will create a significant source gas flow due to degassing. The type of turbopump as well as the leak detector model therefore has to be chosen such that both requirements are obeyed.

In the end we decided to use a 600 l/s turbopump, which will theoretically correspond to a response time constant (defined as volume divided by pumping speed) of 4.5 min.

Due to the flow restrictions caused by both the angle valve between turbopump and vessel and the inner components of the vessel like the shield elements we expected a response time between 5 and 10 minutes corresponding to a complete test time between 15 and 30 minutes based on 3 time constants.

The gas load forced the use of a leak detector having the ability to process high gas loads. This led to selection of the Oerlikon Leybold PhôniXL500 [5], which appeared on the market in 2014 and is able to operate in its fine mode already with an inlet pressure of 1.2 mbar [5].
The control of the vacuum system also allows to operate the leak detection unit in parallel mode to the diffusion pumps which allows fast leak detection in case of large leaks, where a precise determination of the leak rate is not necessary.

Figure 2: Diffusion pumps and Leak detector. In the background one can see the CSS.

The leak detector is equipped in addition with a sniffer probe having a 20 m tube to be able to access any possible leak location on the system and the coil module.

2.5 The Paschen Test System

Paschen tests are high voltage tests carried out on the coils at different vacuum levels. These tests are very sensitive to detect insulation weaknesses on electromagnetic systems and were used in the production of large superconducting coils since the Wendelstein 7-X project [6]. They are based on the fact that the discharge voltage of gases is strongly dependent on the pressure of the gas (more precisely the product of pressure and distance between electrodes). For a detailed discussion of the processes see e.g. [7].

Figure 3: Camera Frame with control monitors; Upper right corner: Detail of camera assembly
The Paschen tests system consists of a set of 42 cameras (Figure 3) whose field of view covers the complete outer surface of the coil module. In case of an insulation weakness typically a flash is created on the outer surface of the coil. The cameras help to locate the position of the flash foot points. These positions are essential for determination of the fault location. The type of the foreseen cameras has been tested before assembly extensively with respect to its performance in vacuum conditions. It must be ensured that overheating due to the lack of cooling by the surrounding air does not occur.

The cameras are assembled on a structure made of aluminium profiles which are designed for easy assembling and disassembling, as this camera frame (Figure 3) needs to be installed for the Paschen test and removed for the cold test. The video signal cables are collected in 3 feedthroughs which are arranged in 120° distances around the circumference of the vessel. The whole frame can be rotated by ± 30° remotely controlled.

2.6 Auxiliary mechanical systems

In order to enable the loading of the coil module, a dedicated bridge connecting the vessel bottom and the surrounding facilities has been installed. The air cushion carrier transporting the coil module and its supports moves over this bridge, thus it is necessary that no gaps are present along the complete transport path.

For easing the installation of the coil as well as the assembly and disassembly of the components, a walkway is erected around the complete vessel.

3 Fabrication

The main components were fabricated at several subsuppliers which were chosen because of their special qualifications. Final assembly of the vessel and its components took place in a dedicated facility in the port of Duisburg in which it was possible to lift the heavy components and to load them directly onto a ship after completion.

3.1 Vessel

The vessel is a fully welded structure made of austenitic stainless steel. It has been prefabricated in 3 parts:
- The bottom part including all mechanical stiffeners that are necessary to withstand the gravitational loads
- The hood lower part and
- The hood upper part.

As the vessel was designed following the rules of the AD-2000 standard, also nearly all the required non-destructive testing has been carried out. As the vessel will form a vacuum barrier, the dye-penetrant test was waived in order to avoid the closure of possible leaks by the indicator fluid. This kind of problem is well known in the framework of pressure tests carried out with water on pressure vessels [8].

It was not possible to fabricate the hood at the subsupplier in one piece, because its size prohibited economical street transport within Germany.

3.2 Shields

The shield was fabricated in separate elements. 18 modules were fabricated for the active as well as for the passive part of the hood shield and 4 elements were fabricated for each of the bottom shields. All the welds on the cooling channels of these elements were
individually leak tested under operational pressure by the accumulation method to be tight to a level of at least $10^{-6}$ mbar l/sec.

3.3 Vessel Assembly and Testing

The vessel and shield parts were transported to the assembly site at Duisburg harbour as separate parts. There the final welds joining the parts of the hood were carried out. Following this weld, the hood and the bottom part jointly underwent a first leak test in order to verify the integrity of the outer shell and the proper functioning of the seals. Also the degassing behaviour was checked in order to verify sufficient cleanliness of the inner surfaces.

In parallel the modules of the hood shield were connected to form the hood shield assembly. The final welds on the cooling channels of the shield module underwent again a leak test using the accumulation method.

The hood then was lifted over the hood shield assembly and both components were fixed together. These connection elements were designed for minimizing the heat input by conduction. In the final step of the assembly, the relative position of shield and vessel shell was adjusted.

As a final step, the vessel was evacuated and integral leak tests were carried out on the shield assemblies and the outer shell. During these tests the response time was measured and found to be about 8 minutes, which is in good agreement with the expected value (see 2.4)

3.4 Transport and Site Assembly

All mechanical components were collected at the assembly site at Duisburg and these were shipped from there by river–transport to the overseas harbour in Vlissigen (NL). There the components were transferred to an overseas vessel and transported to the destination harbour San Diego (USA). After customs clearance, the parts were transported on the street to the final destination place at Poway. While the mechanical parts could be transported in standard shipping containers, the parts of the vessel were individually packed and protected.

On site, the first step was the placement of the vessel bottom to its final position. Thereafter the feet of the vessel were tack welded to respective anchoring plates on the ground.

In the next step, the lifting structure was erected, which later serves to raise and lower the vessel hood. To facilitate this, a large mobile crane was necessary for erection and lifting the structural parts. This step had a special delicacy as the assembly utilises the complete height of the building. Thereafter all the mechanical auxiliaries like the bridge and the walkway were installed, because these were necessary for the assembly of the hood.

This was the final step of the mechanical erection. The hood was transported using air cushions along the same way as later the coil. It was precisely positioned and then attached to the crossbeam of the lifting structure.

Parallel to all these steps the vacuum system was installed. About 20 m of the total 35 m length of the pipes had to be routed through a tunnel of 750 x 750 mm², in which also the cryolines for the test facility are present. Because connections inside the tunnel are not accessible after assembly, all electrical and pneumatic lines were installed without any joints. The joining of the vacuum lines was carried out using special seals made from aluminium (Oerlikon Leybold Ultra Sealing Disks), which were used in the past e.g. at CERN. All vacuum connections were leak tested to a level below $10^{-8}$ mbar l/sec during
this phase. The roughing pumps were installed at their foreseen position (see 2.3) in the adjacent building and the diffusion pumps were connected to the vessel bottom.

### 3.5 Commissioning

Commissioning activities are ongoing at present. The activities started with functional tests of the electrical controls of the machine. As soon as it was possible to precisely control the closure of the vessel, the initiating runs of evacuation took place.

It turned out, that the evacuation periods are well within the specification. This confirms the choice of the pumping speeds being suitable for the task. Also some minor leaks on ports of the vessel were identified and closed. It also turned out that some modifications on the control system of the vacuum equipment became necessary. Nevertheless the leak detection system showed its ability to perform within the specified properties as the installed calibrated leak – having a value of $2.4 \times 10^{-8}$ mbar l/sec – could be clearly seen against the background of the system.

Also the complete camera frame was erected and all 42 cameras were installed.

### 4 Acknowledgements

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### 5 References


