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ABSTRACT

The large ATLAS toroidal superconducting magnet made of the Barrel and two End-Caps needs extensive testing at the surface of the individual components prior to their final assembly into the underground cavern of LHC. A cryogenic test facility specifically designed for cooling sequentially the eight coils making the Barrel Toroid (BT) has been fully commissioned and is now ready for final acceptance of these magnets. This facility, originally designed for testing individually the 46 tons BT coils, will be upgraded to allow the acceptance tests of the two End-Caps, each of them having a 160 tons cold mass. The integrated system mainly comprises a 1.2 kW@4.5 K refrigerator, a 10 kW liquid-nitrogen precooler, two cryostats housing liquid helium centrifugal pumps of respectively 80 g/s and 600 g/s nominal flow and specific instrumentation to measure the thermal performances of the magnets. This paper describes the overall facility with particular emphasis to the cryogenic features adopted to match the specific requirements of the magnets in the various operating scenarios.

INTRODUCTION

The ATLAS detector is the largest experiment of the Large Hadron Collider (LHC) and will be installed 100 m underground in a 50 000 m^3 cavern located at collision point 1. The ATLAS magnet system is based on a thin superconducting Central Solenoid (CS) which generates a uniform longitudinal field for the inner tracker, and three superconducting toroid magnets (a Barrel and two End-Caps) producing a tangential field around the central axis for the muon spectrometer.

The CS is 5.3 m in length with an inner diameter of 2.5 m and has a cold mass of 5.4 tons. The Barrel Toroid (BT), surrounding the CS, is made of 8 superconducting coils symmetrically placed around the beam axis of the detector. The BT has an axial length of 25.3 m, an outer diameter of 20.1 m, a stored energy of 1080 MJ and a total mass of 830 tons with a cold mass of 370 tons. Two identical End-Caps Toroids (ECT), each of them also made of 8 coils, are inserted at the two ends of the BT in order to provide the required magnetic field configuration in the forward areas of the detector. The inner bore of an ECT has a diameter of 1.7 m, the outer diameter is 10.7 m and its axial length is 5 m. The stored energy of each ECT is 250 MJ, its total mass is 239 tons of which 160 tons are the cold mass.

Because of the exceptional dimensions, it was not feasible to assemble and test on the surface the entire BT and then move it as a whole to its final underground area. Therefore, it was decided to test individually at the surface the eight coils forming the BT and the ECTs in two dedicated facilities providing, as closely as possible, the real operating conditions from both magnetic and cryogenic points of view.

CRYOGENIC TEST FACILITY CONCEPT

The BT cryogenic test station was designed and set-up with a helium distribution system allowing three test benches, with two of them holding one of the eight rectangular coils forming the BT [1]. This facility has been successfully commissioned with prototype magnets in 2001 [2]. After a subsequent decision of the ATLAS Collaboration to test also the ECTs in the same area (Fig. 1), it became necessary to substantially upgrade the capabilities of the BT test station.

In fact, a thermal analysis of the entire facility showed that the cooling capacity of the existing refrigerator (1.2 kW@4.5 K) was not sufficient to cope with the higher ECT thermal loads. Table 1 summarizes the main thermal characteristics of the ATLAS toroids and indicates that for a single ECT, thermal loads on both 4.5 K and shield circuits are almost three times larger than for a single BT.

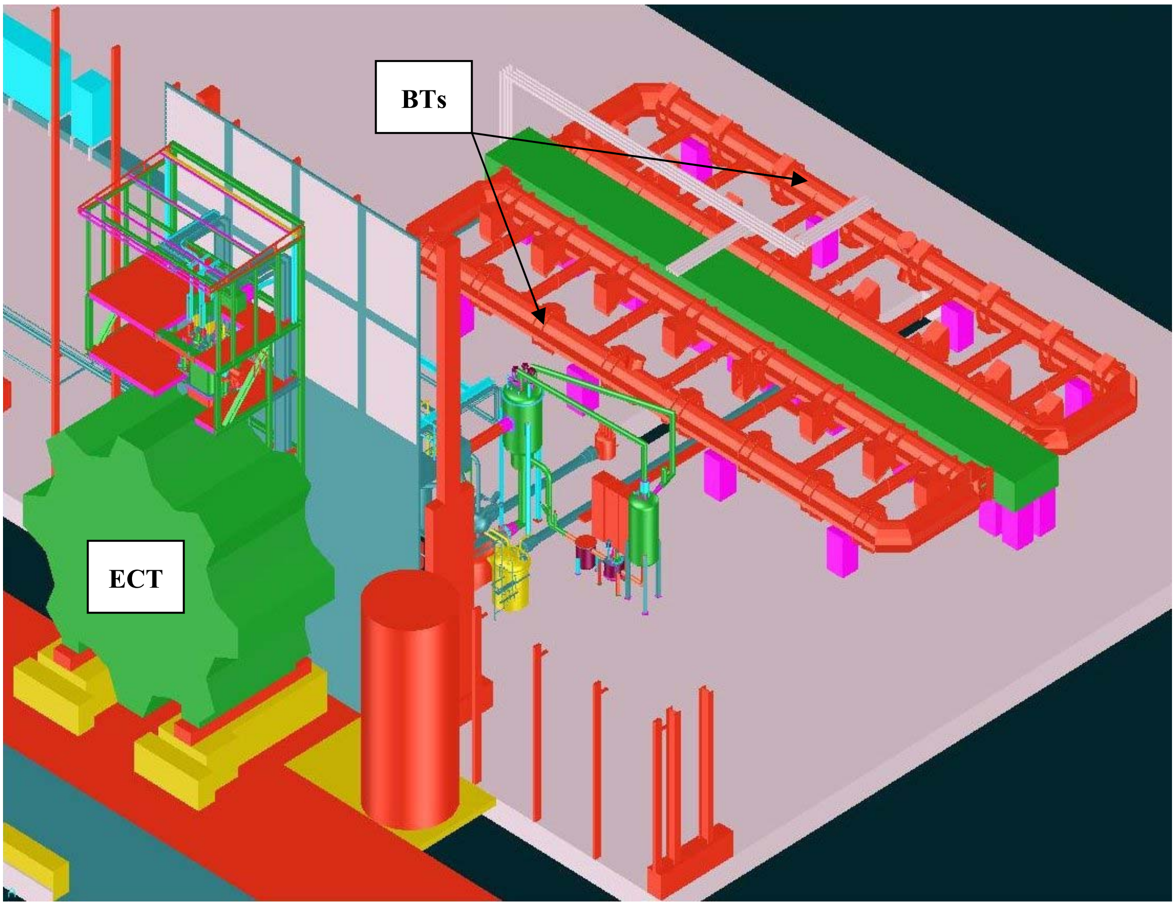

FIGURE 1: Three-dimensional view of the test facility with two BTs and one ECT installed.

TABLE 1: Thermal loads and main characteristics of the ATLAS toroid magnets.

	For a single BT	For a single ECT
Static isothermal load at 4.5 K, with an average shield temperature ≈ 60 K	80 W	180 W
Dynamic isothermal load at 4.5 K (current ramp up/down)	44 W	110 W
Liquefaction load at 4.5 K (current leads)	3.1 g/s	3.1 g/s
Thermal shield load between 40 K and 80 K	740 W	2250 W
Pump-flow required at 4.5 K during surface test	80 g/s	300 g/s
Precooler helium flow required during cool-down in surface test	50 g/s	50 g/s
Total assembly mass	104 tons	239 tons
Cold mass	46 tons	160 tons

The third test bench will be used for the ECTs. The corresponding simplified cooling scheme is shown in Fig. 2 and the following solutions will be adopted in order to boost the overall performance of the existing facility.

The concept adopted for the BT tests, i.e. to cool-down the magnet from 300 K to 100 K with a 10 kW liquid-nitrogen (LN_2) precooler and then to switch off this precooler and continue the cooling with solely the 1.2 kW refrigerator down to the operating conditions is abandoned for the ECT and we keep on duty the LN_2 precooler, even when the ECT temperature is below 100 K. With this concept, the 1.2 kW refrigerator provides the 4.5 K and current leads cooling while the precooler is coping with the ECT thermal

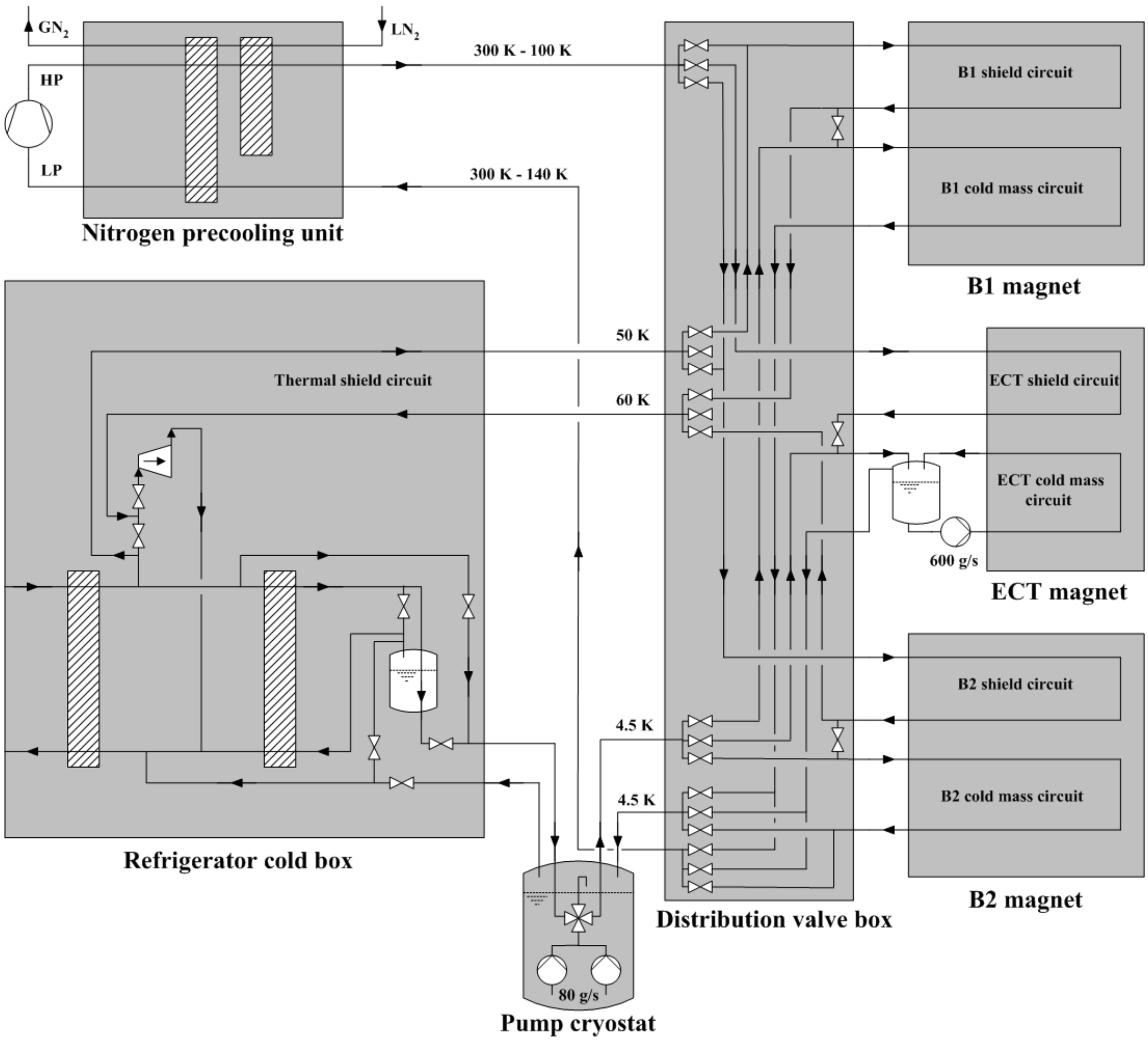

FIGURE 2: Simplified Process Flow Diagram of the cryogenic test station.

shield load. Furthermore, we will use LN_2 in the first heat exchanger of the 1.2 kW cold box to increase its liquefaction capacity. A drawback of this solution is that the ECT will be tested in worse thermal conditions than in its final position since the temperature of the thermal shield and the conductive heat intercepts will range from 90 K to 100 K whereas the real operating conditions will range from 40 K to 80 K [3]. The influence of the shield and intercepts temperature on the 4.5 K load have been already measured with a prototype magnet [4].

The additional important modification to cope with the higher heat loads at 4.5 K is to increase the two-phase helium flow provided by the centrifugal pump to satisfy the adopted hydraulic stability criteria in the cooling pipes, i.e. to keep a vapor mass fraction at the outlet of the coils less than 10% and to have a mass flow rate per unit area greater than 4 $g.s^{-1}.cm^{-2}$. An existing centrifugal pump prototype of 600 g/s nominal flow, already tested by CEA-Saclay [5], will be re-used at a reduced mass flow of 300 g/s to fulfill the hydraulic stability criteria. Since the existing pump cryostat and associated distribution valve box and transfer lines were built for 80 g/s required by the BTs, the increased pump flow obliged us to re-design these components and upgrade the associated instrumentation (Fig. 3).

All of this equipment is actually designed and constructed not only to operate the 600 g/s pump required for the ECT surface test but also the 1200 g/s pumps that have to be tested before their installation in the ATLAS final system.

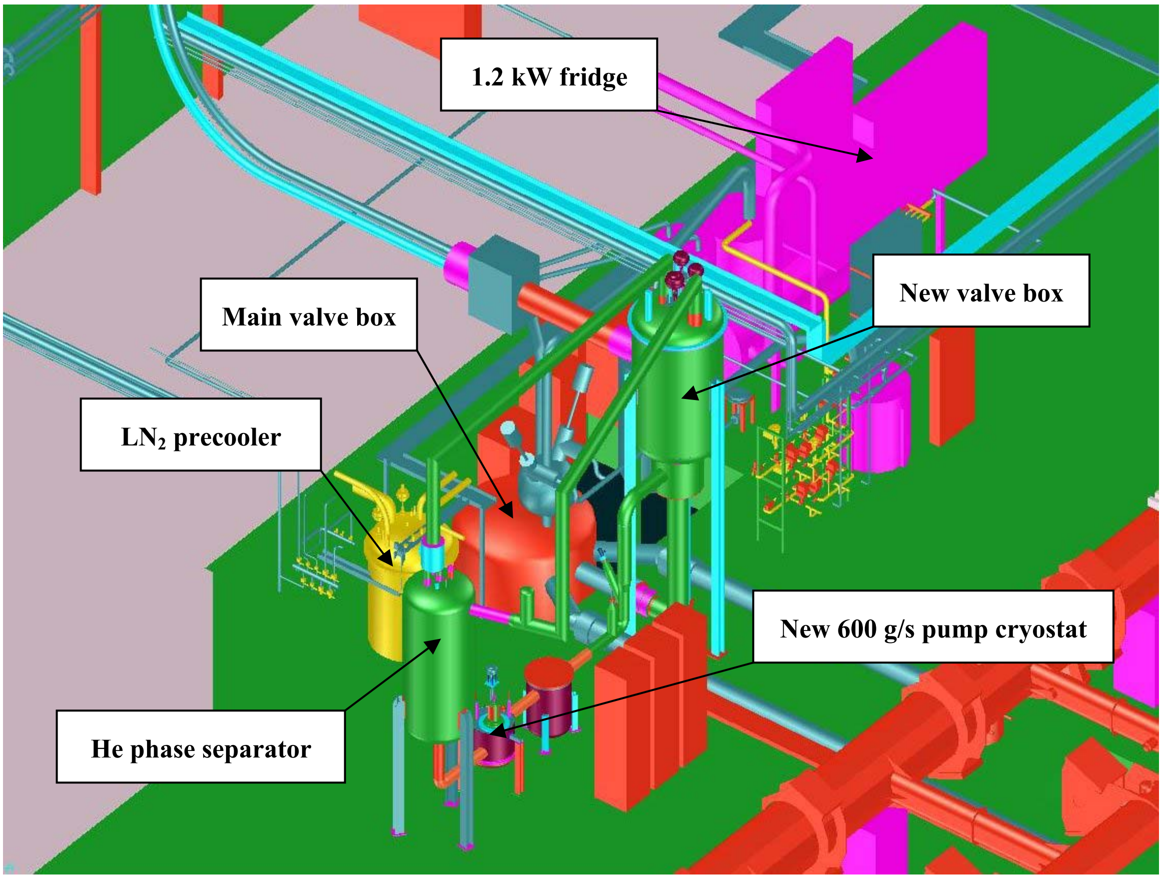

FIGURE 3: Three-dimensional view of the cryogenic equipments required for the ECT tests.

OPERATING SCENARIOS

From the cryogenic point of view, the complete test sequence of a single magnet (BT or ECT) consists of three main phases: cool-down from 300 K to 4.5 K, steady-state operation at 4.5 K and warm-up back to ambient temperature.

During the first part of the magnet cool-down, i.e. from 300 K to 100 K, it is very important to avoid excessive thermal stresses induced by a large temperature gradient between two points of the cold mass. A helium forced-flow of maximum 50 g/s will be provided by the LN_2 precooler which will constantly keep the supplied gas temperature 40 K lower than the cold mass average temperature.

Once the 100 K temperature level is reached, there are two different scenarios depending of the magnet type. In the case of a single BT coil, we can switch off the precooler and continue the cooling down to 4.5 K with solely the 1.2 kW refrigerator capacity, thus liberating the precooler for cooling a second BT from 300 K to 100 K. This will allow a considerable reduction of the BT overall test time. On the contrary, if the magnet is an ECT, we have to keep running the precooler which will be connected solely to the thermal shield. The 1.2 kW refrigerator will then only cope with the 4.5 K cold mass heat loads and the cooling of the current leads. From 300 K to 4.5 K, we expect a cool-down time of 3 weeks in the case of a single BT (limited by the temperature gradient) and 6 weeks for an ECT (limited by the available cooling capacity).

The steady-state operation for a BT will also differ from the ECT one. The BT operation at 4.5 K will not need the LN_2 precooler and will require 80 g/s of helium forced-flow. The ECT will require 300 g/s of helium forced-flow and the precooler on duty all through the test.

Similarly to the cool-down phase, the warm-up is also split into two parts. From 4.5 K up to 100 K, only direct electrical heating through the windings will be adopted for both BT and ECT. Between 100 K and 300 K, BTs will continue the warm-up solely via this electrical heating, whereas the complex mechanical structure of the ECT will require an additional forced-flow of gaseous helium to distribute the heat produced electrically and thus smooth the temperature gradients of the cold mass. The warm-up time from 4.5 K to 300 K for both BTs and ECTs is similar to the cool-down time.

From the schedule point of view, we have to test first the eight BT coils. Then, after the 8th BT, a short interruption to install the new equipment will be necessary prior to continue the testing of the two ECTs. This intensive test campaign will start with the first BT in January 2004 and should be finished within two years. To accelerate the ATLAS assembly in the cavern, once a BT has been fully tested on the surface, it will be moved underground and mounted on the final structure.

CONCLUSIONS

The cryogenic test facility for the eight BT coils is now fully operational and ready for final acceptance of these magnets. Concerning the test of the two ECTs that will come after the BTs, we have to build and integrate in the existing test station the 600 g/s pump cryostat and associated equipment. At the end of the two-year continuous test campaign, all the thermo-hydraulic, mechanical, electrical characteristics, including the magnet protection, will be thoroughly verified for every BT and ECT prior to their final underground installation in the ATLAS cavern.

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