On-Surface Integration and Test of the ATLAS Central Solenoid and Its Proximity Cryogenics

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***Abstract*—The ATLAS detector for the LHC at CERN requires a superconducting solenoid, which provides the magnetic field for the inner detector. The ATLAS Central Solenoid and its associated proximity cryogenics system has been designed by KEK in collaboration with CERN. Following construction and preliminary tests at Toshiba in Japan the equipment has been shipped to CERN. The system is being prepared for the integration in the common cryostat with the LAr calorimeter, whereafter a full on-surface test has to be completed before its final installation 100 m underground in the ATLAS cavern. For this purpose a provisional set-up for commissioning of the final proximity cryogenics, the connecting chimney and the solenoid has been established. A number of tests and simulations have been conducted in applying a new process control system to validate the cryogenics functionalities, the electrical powering scheme as well as the magnet control and safety systems. The present status of the solenoid project and the results of the various cryogenic and electrical tests are reported.**

***Index Terms*—Detector magnet, quench, superconducting.**

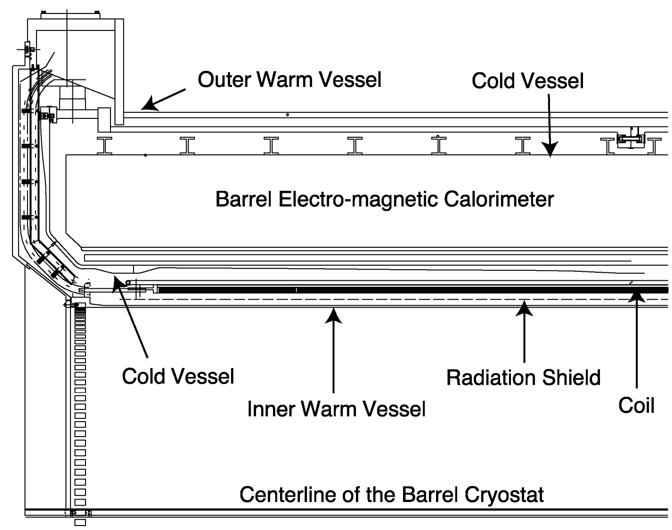

Fig. 1. Barrel cryostat cross section.

I. Introduction

The ATLAS collaboration is preparing a general purpose detector set-up for experiments with proton-proton collisions at the Large Hadron Collider (LHC) at CERN. The detector consists of four main parts: inner detector trackers, electromagnetic calorimeter, hadron calorimeter and muon spectrometer [1]. An essential part of the detector set-up is the magnet system which provides the bending power required for the momentum measurement of charged particle tracks. In this arrangement the Central Solenoid (CS) provides the volume of the inner detector trackers with an axial magnetic field of 2 tesla in a warm-bore diameter of 2.3 meters with a stored energy of 39 MJ [2]–[4]. The coil cold mass has a weight of 5.7 tonnes and a thickness of 45 mm equivalent to 0.66 radiation length. For the coil to be made this thin it is wound of specially developed high-strength aluminum stabilized superconductor [5]. The coil is installed in the same cryostat as the barrel electro-magnetic calorimeter, the so-called barrel cryostat. The coil is attached to the inner warm vessel of the barrel cryostat by 23 triangular supports made of GFRP. These are arranged in such a way that one side of the coil is fixed and the other sliding in axial direction [6]–[8]. The cryostat is surrounded by the hadron calorimeter which also serves as a return yoke for the magnetic flux.

The CS proximity cryogenics system consists of two major components: a control dewar and a valve unit. The control dewar contains a liquid helium dewar, cold control valves and services connections for the solenoid. The valve unit contains the warm control valves and monitoring equipment. The control dewar will be located on top of the detector set-up and is connected to the solenoid through a 10 meter long chimney which contains cryogenic transfer lines and superconducting bus-bars [9], [10]. The proximity cryogenics is supplied with liquid helium from a refrigerator common for the whole ATLAS magnet system [11].

The CS is developed in collaboration between KEK and CERN. The solenoid and its proximity cryogenics system were tested in Japan after fabrication [8], [12], and [13]. In 2001 all parts were shipped to CERN and the solenoid is now being integrated in the barrel cryostat.

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II. Integration

The solenoid coil is mounted on the inner warm vessel of the barrel cryostat. Fig. 1 shows a cross section of the barrel cryostat. Besides the solenoid the cryostat also contains a cold vessel for the liquid argon electro-magnetic calorimeter. This cold vessel serves as a radiation shield for the solenoid faced toward the support cylinder. It contains a liquid argon

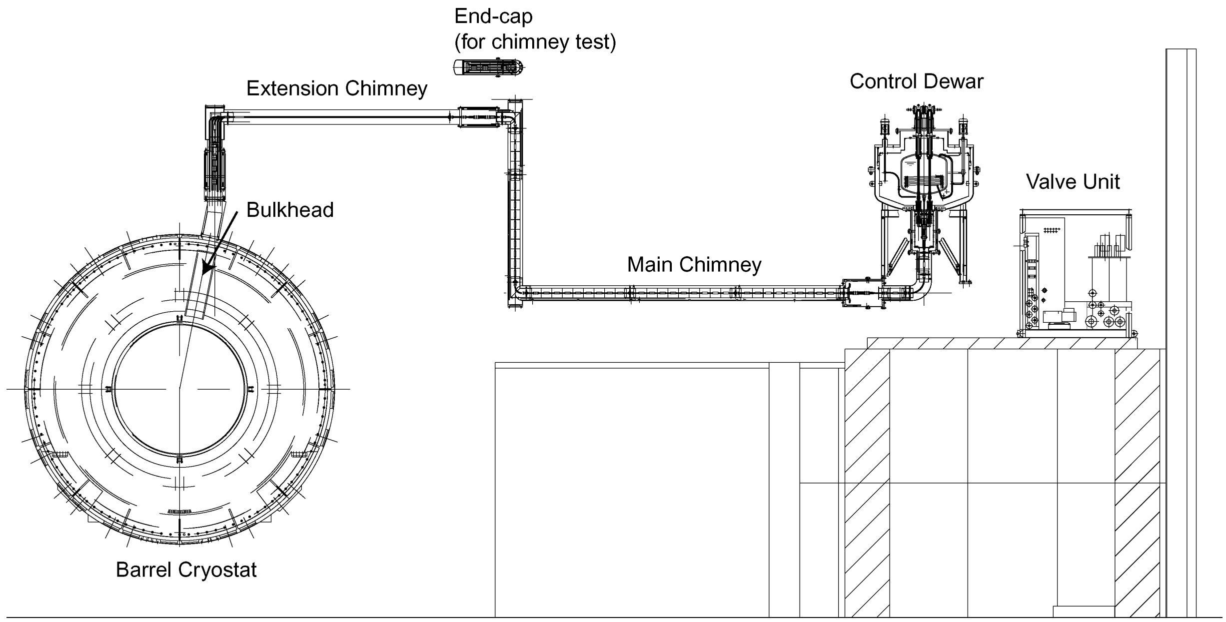

Fig. 2. Layout of the on-surface test setup.

electro-magnetic calorimeter and is cooled with liquid nitrogen. In the cryostat integration procedure, first the calorimeter will be installed in the cold vessel. The cold vessel will then be closed after which the inner warm vessel with solenoid will be installed. Then the connections between solenoid coil and chimney will be made in the cryostat bulkhead and through the cryostat feedthrough. Finally the end flanges of the cryostat will be closed.

Some of the final transfer-line connections have to be made on-site. This includes the connections between the chimney and proximity cryogenics and between chimney and cryostat. As the amount of work space is limited, especially in the cryostat bulkhead area, an automatic orbital welding machine has been developed. Initial problems in the welding of the aluminum tubes have been overcome and we are now in the process of fine tuning the welding parameters. We are confident that we can satisfy the ATLAS requirement of the ISO 10 042 standard class B. A mock-up of the cryostat bulkhead has been prepared to verify the assembly procedure.

All joints to be welded during on-site field work with the automatic welding machine contain an intermediate center piece. The center piece simplifies the on-site length adjustments of the tubes. Also no additional filler material has to be used in the welding process as the center piece will do as filler. The center piece is aluminum A5083 while the main tubes are made of A6063. The main tubes are either 18 or 24 mm in outer diameter with a thickness of 2 and 3 mm respectively. The center pieces are 21 and 27 mm in outer diameter with a thickness of 3.5 and 4.5 mm respectively. All connection surfaces are prepared with an edge of 30°. Most tubes have to be welded in vertical position causing a slightly different parameter optimization between the weld at the top and the bottom of the center piece. For the welds to be made in the cryostat bulkhead, the tubes will be inclined by 11.25° from the vertical position. This also requires slightly different parameter settings.

III. Test Set-Up

Before underground installation in the ATLAS cavern a full scale on-surface test is being prepared to verify the overall performance of the Central Solenoid, its proximity cryogenics and control systems. Except refrigerator and power supply, all final components will be used. This includes proximity cryogenics, control and safety systems. The layout of the on-surface test is shown in Fig. 2. Due to height restrictions the control dewar is located aside of the cryostat instead of on top of it. An extension chimney is added to connect the main chimney and cryostat (Fig. 3). At present the proximity cryogenics, main chimney and extension chimney have been installed as shown in Fig. 4. The cryostat is waiting for the installation of the last detector components after which the solenoid will be installed and connected to the chimney.

The cryogenic system used for the on-surface tests is based on a BOC cold box with four turbines and a Sulzer 3-stage four piston compressor. It has a refrigeration power of 320 W and a build-in dewar for helium liquifaction with a volume of 100 l. The dewar has two heaters for liquid level control with a power of 300 W each.

The 6.5 V/24 kA magnet power supply is shared with the ATLAS toroid test facility [14]. In order to connect the power supply to the solenoid, an additional 120 m of aluminum power cables ($40 \times 240~\mathrm{mm}^2$ per pole) and 31 m of aluminum bus-bars ($4 \times 4050~\mathrm{mm}^2$ per pole) have been installed.

The proximity cryogenics system has been installed and connected to the chimney during the Spring of 2002. Two test programs were executed in Summer 2002 and in Spring 2003. For these tests the chimney cap (as shown in Fig. 2) was used which contained a shortcut for cryogenic cooling lines and superconducting bus-bars. The time in between the test programs was used for minor modifications and updates of the proximity cryogenics system. During the Summer of 2003 the

Fig. 3. Mock-up of the cryostat bulkhead and feedthrough.

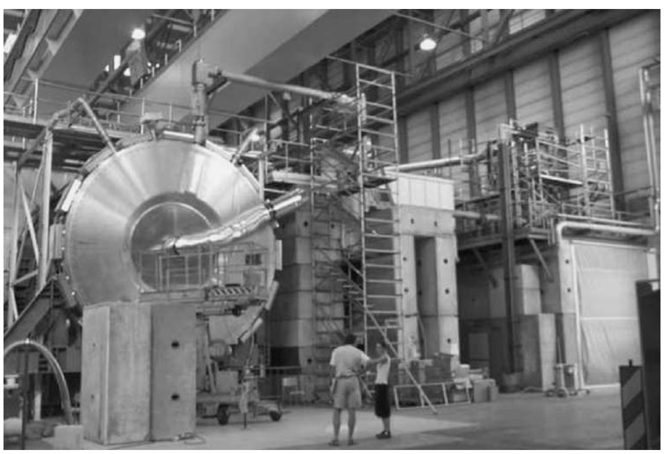

Fig. 4. On-surface installation (August 2003).

extension chimney has been connected. Now the integration of the solenoid coil into the cryostat is under preparation.

The control system is being developed according to LHC standards. It consists of Schneider PLC hardware with Unicos as process control system. The user interface is based on a software package called PVSS. There are two separate control systems. One for the proximity cryogenics and one for the magnet including control of the magnet power supply. A fully independent magnet safety system provides an interlock for the two control systems. It will switch off the magnet power supply and initiate an energy dump of the magnet in case it identifies a problem such as a quench. The magnet safety system (MSS) consists of two identical systems operating in parallel.

IV. Test Results

As a preparation for the on-surface test of the solenoid, a commissioning test of the proximity cryogenics and chimney

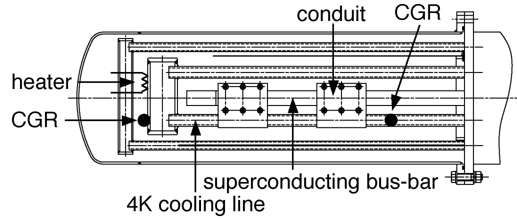

Fig. 5. Layout of the end-cap used for chimney thermal load test.

have been executed. This included the final proximity cryogenics control system. The superconducting bus-bars inside the chimney were powered up to 9 kA. Thermal load tests were performed as well as a cooling mass flow stop in the chimney. An end-cap, which is shown in Fig. 5, with cryogenic and superconducting short-cuts was installed at the end of the main chimney instead of the connection to extension chimney and solenoid.

The first test was a functionality test of the proximity cryogenics and its control system. All cool-down sequences were performed under manual and automatic control. In the automatic cool down, the control system software is released step-by-step in order to follow the software sequences and hardware responses.

Another important step was a test with 150 m long capillaries (connection lines) between the pressure transducers and the proximity cryogenics. This included differential pressure transducers and is intended as a test to verify operation in the underground cavern. The (differential) pressure transducers will be installed in the experimental service cavern at some 150 m distance from the proximity cryogenic's control dewar in the experimental cavern. These pressure transducers worked without problems when the 150 m long capillaries were used.

Thermal load tests are done to check the dynamic heat balance of the system. It gives us the amount of cooling power available for the solenoid. An electric heater on the liquid helium cooling line at the end of the chimney was used for this purpose in combination with an electric heater inside the control dewar. The heater in the control dewar regulates its liquid helium level. The heater on the cooling line was powered up to its maximum of 70 W. Carbon glass resistors (CGR) were used to monitor the temperature of the cooling line and superconducting bus-bars inside the chimney. The layout of this set-up is shown in Fig. 5. The chimney temperature stayed constant as well as the liquid helium level in the control dewar. At the level of 70 W heater power on the cooling line, there was still a 3 W heater power for the level control heater. Thus a total cooling power of 73 W is available for the cooling of the solenoid. This is considered as being sufficient.

The system has been powered up to a maximum of 9 kA, which is at the voltage output limit of the power supply due to the long connection distance. Cooling of the superconducting bus-bars in the chimney and the copper current leads in the control dewar was tested up to a continuous period of 7 hours.

Mass flow stop tests are done in order to measure the warm-up speed of the chimney and verify the operation of the SQD's. The SQD's (Superconducting Quench Detectors) are small superconducting wires mounted along the superconducting bus-bars of the chimney. They are used as temperature switches and make

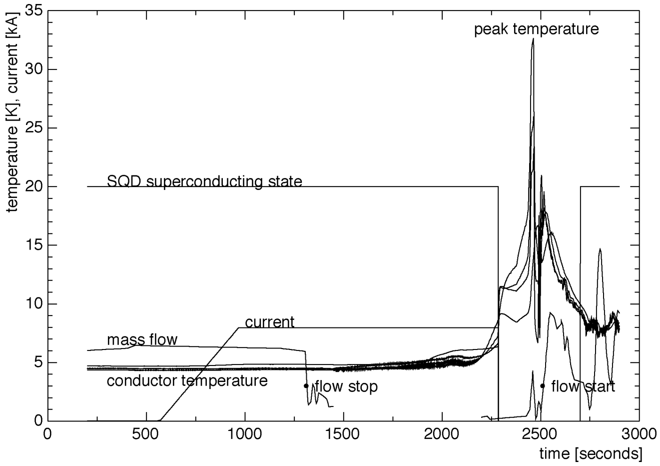

Fig. 6. Cooling mass flow test of the chimney at a current of 8 kA.

it possible to continuously monitor the superconducting state of the bus-bars [15]. The SQD's are connected to the MSS and will trigger an interlock signal as soon as they change state. In Fig. 6 the chimney temperatures and SQD states are plotted. After the SQD's triggered the MSS, the power supply, and thus the current, is immediately switched off. The cooling mass flow was restarted a few minutes later. This is marked by a peak in the chimney temperature as the flow front of relatively warm cryogen passes the temperature sensors. Note that the SQD on state (superconducting) is plotted at an arbitrary level. At a current of 8 kA it took 17 minutes from the time of stopping the cooling mass flow until the SQD's quench. At 6 kA it was 20 minutes, and at zero current 28 minutes.

The safety design of the system has been verified by simulating failure of the external services. This includes the main power, compressed air and cooling water. Failure of these services was simulated for the proximity cryogenics as well as its control system. A failure of the chimney cooling has been simulated by means of the mass flow stop tests described above.

V. Conclusions

The on-surface integration of the solenoid and installation of the test set-up is well under way and on schedule. An automatic orbital welding machine has been developed for the final on-site transfer line connections. The mass flow stop tests showed that there is enough time for a safe run-down of the solenoid after a cryogenics failure, as the run-down lasts less than 30 minutes. The proximity cryogenics and chimney, with cryogenic transfer lines and superconducting bus-bars, have successfully passed their commissioning. The performance of the cryogenic system has been confirmed.

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