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**QUENCH INDUCED PRESSURE RISE IN THE COOLING PIPES
OF THE ATLAS BARREL TOROID MODEL**

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ABSTRACT

The ATLAS superconducting magnet system consists of a Barrel Toroid, two End-Cap Toroids and a Solenoid. Eight individual racetrack coils will be assembled to form the Barrel Toroid with overall dimensions of 26 m length and 20 m diameter. In order to verify the design concept a 9 m long short version of a single Barrel Toroid coil was built. A test program was conducted at the CERN cryogenic test facility which included the evaluation of the pressure rise in the helium cooling channels during quenches of the coil. A specific experimental set-up with cold pressure transducers and capillaries was installed for online measurement of the pressure signals. In addition a computer model was used to simulate these events. The data obtained are presented.

INTRODUCTION

ATLAS is one of four high energy physics experiments of the LHC collider currently under construction at CERN. The magnetic field required by the muon particle detectors of ATLAS will be produced by eight 25 m x 5 m superconducting air-core coils symmetrically arranged around the central axis forming the Barrel Toroid (BT) magnet with 20 m diameter and, in the forward region of the detector, by two End Cap Toroidal (ECT) magnets, FIG 1, [1]. FIGURE 2 shows the cross section of an individual BT magnet. The aluminium casings of all the superconducting coils are indirectly cooled via attached pipes with a forced flow of 1200 g/s of two-phase helium at 4.5 K circulated by a common centrifugal pump. This flow is split half between the ECT's and the BT magnet, hence, an individual BT coil is supplied with 75 g/s distributed over 8 parallel cooling pipes. Following detection of a quench the entire BT is made resistive with quench heaters and the stored energy of 1.1 GJ is dissipated into the cold mass which will rise in temperature. The helium vaporises in the cooling pipes with subsequent pressure increase. This pressure rise is unknown and, therefore, of concern. This applies to all toroid magnets (BT, ECT's) having the same cooling principles and similar circuit design.

FIGURE 1. ATLAS Toroidal Magnet System (Barrel Toroid and two End Cap Toroids). Overall dimensions: 26 m length, 20 m diameter.

FIGURE 2. Cross section of an individual Barrel Toroid (BT) magnet.

Preliminary computer code simulations were carried out for an ECT. The results obtained indicated unexpected small pressure rise [2]. It was hence felt that a more detailed evaluation was needed. With the construction of the Barrel Toroid magnet model [3], mainly serving to validate the technical design concept for the BT coils, a test object was available for experimental investigations of quenches. It was decided to equip this test magnet with adequate instrumentation for the recording of pressure rise in the cooling channels. We describe here the test set-up and the pressure rise curves obtained experimentally. One dimensional computer codes were applied to simulate the transient effects which are reported.

MODEL MAGNET AND EXPERIMENTAL SET-UP

The so-called “B0” magnet [3] is a test model for the Barrel Toroid (FIG 2) with corresponding design except for its reduced length of approximately 1/3. The racetrack shaped coil is 5 x 9 m. The cold mass consists of two double pancakes of aluminum stabilized superconductor housed in an aluminum casing integrated in a stainless steel vacuum vessel. The cooling pipes are glued onto the casing for indirect cooling of the cold mass. From the inlet manifold at one of the short legs of the coil the flow of 75 g/s 4.5 K liquid helium is split over the 8 parallel cooling pipes (4 on each long leg of the coil) with 12.0 m length each and re-collected at the outlet manifold at the opposite short leg. The operating temperature is 4.5 K and the stored energy 46 MJ at nominal current of 20.5 kA.

The B0 test coil is equipped with instrumentation such as temperature sensors, voltage taps, foil type quench heaters, point heaters, strain gauges, etc. permitting the testing and recording of a variety of parameters during the excitation of the coil and slow or fast discharge (quench). Four foil type protection heaters are integrated, one at each short leg of a double pancake.

For the particular investigation of pressure rise in the cooling circuits an additional set-up with instrumentation was needed. Two pressure measurement points were chosen; in the middle of an individual cooling pipe where the maximum pressure rise is expected and the second at the outlet manifold. Local tapping of the cooling pipe at its half length to connect a pressure transducer was not possible for construction and safety reasons. Instead

FIGURE 3. Cold mass of the B0 magnet model during installation of the capillary and pressure transducers.

FIGURE 4. Fixture with pressure transducers and capillary integrated in the B0 magnet helium circuits (manifold and cooling pipe).

a technical solution using a long capillary was adopted. A 6.0 m long stainless steel capillary with 4 mm i.d. and 6 mm o.d. was introduced in one of the cooling pipes such that its one end terminates at the cooling pipes' half length. This position corresponds also to the half length of the magnet.

FIG 3 shows the cold mass during installation of the capillary. The other end of the capillary terminates at the level of the outlet manifold in a small closed volume of a fixture (FIG 4). This permits the measurement of the pressure at the terminal of the capillary and at the same time of the manifold. In total 4 pressure transducers are connected, two are redundant. Under normal operating conditions the capillary and the fixture volumes are filled with liquid helium at 4.5 K and the pressure transducers are in direct contact with the fluid.

Capillaries are generally used to connect ambient temperature pressure transducers at a distance from the cold measurement point. In case of rapidly changing signals, however, the pressure transmission produces considerable delays and distortion of the physical signal. In contrary, cold pressure transducer arrangements where capillaries and transducers are filled with pure liquid and, hence, without presence of gas, show negligible measuring errors even in the millisecond range. Detailed studies on these phenomena using transducers of the Siemens KPY14 type are reported in [4].

This type of piezo-resistive absolute pressure transducer was used. They show an excellent sensitivity of approximately 5 mV/V/MPa at their linear range of 0 to 1 MPa with response times of one ms only. The delay of the pressure wave at the capillary terminus introduced by the 6.5 m long capillary is related to the velocity of sound and is, hence, negligibly small on the order of a few tenths of ms [4]. The disturbances due to the magnetic field of B0 are on the order of 2 to 3 percent.

The overall test station comprises a dedicated cryogenic system, a power supply, a magnet control system (MCS) and Magnet Safety System (MSS) [5]. At baseline operation a refrigerator cryoplant provides the required cooling capacity. Liquefaction is done in a common cryostat which houses two immersed centrifugal pumps one of which is redundant. A nominal coolant flow of two-phase 75 g/s helium is pumped via a distribution system into the cold mass cooling pipes and brought back to the cryostat which serves as a phase separator [6].

A specific data acquisition system for the recording of all fast signals was developed; "LASA-DAQ" [7]. A detailed list of the electrical signals is given in [8]. The acquisition system has no operational function and serves only for post test evaluations and studies. Active functions are provided by the Magnet Safety System (MSS) which detects quenches

and triggers subsequent functions on the Magnet Control Systems (MCS) and other components, e.g. to fire quench heaters and to provide for fast discharge. The pressure transducer signals were also read by this data acquisition system.

EXPERIMENTAL RESULTS

All experimental data on the pressure rise recorded derive from quenches initiated by heaters. The way the quench was initiated, i.e. either by point heaters or by the foil heaters, had no significance on the pressure curves registered. At quench detection the circulating pump was stopped. The stored energy was discharged in the magnet cold mass with subsequent temperature rise of the coils.

The recorded pressure rise curves for two quenches at 18 and at 22 kA, respectively, are discussed in this paper being representative for all other data obtained as the results all show quite similar behavior. In FIGURES 5a and 5b the pressure in the manifold and in the center of the cooling pipe is shown as a function of time. The pressure curves are normalized and presented as overpressure with respect to the operational pressure of 0.12 MPa. Following the initiation of a quench and discharge of current the average temperature of the coil casing rises which is also plotted in the graph. In both cases the pressure rise curves reach a maximum shortly after the initiation of the quench. The pressure increases from the normalized value (zero MPa) to approximately 0.05 MPa in around 10 to 15 seconds and then decays.

The pressure rise curves measured at the center of the cooling pipe follows the same pattern as the one measured at the manifold and they basically do not differ from each other. The difference in pressure measured between them are within the range of uncertainty of the measuring equipment and read out system. These experiments indicate that there is no measurable pressure difference between the center of the cooling tube and the manifold.

We attribute the pressure rise to some 0.05 MPa above the normalised value in the coil to the dynamic effect of the vaporising and expanding fluid which expels (“pushes”) the two-phase volume in the rather long supply and transfer lines and the valve box internal lines towards the cryostat volume being at lower operation pressure. Some

FIGURES 5a. & 5b. Measured pressure in the manifold and cooling pipe as a function of time following a quench (fast discharge). The pressure curves are normalized and presented as overpressure with respect to the operational pressure of 0.12 MPa. The average temperature of the coil casing and the coil current are also plotted.

pressure rise in the pump cryostat was also observed. A pressure increase reaching a clear maximum plateau as in the case of an ideal isochoric system was not observed and measured as the cryostat volume was permanently level- and pressure controlled by the cryoplant refrigerator serving as kind of additional buffer during all test runs including quench and post quench phases. This explains the fast pressure recovery after some 2 to 3 minutes.

SIMULATION OF THE PRESSURE RISE

The computational analysis of the pressure transient during the quench of B0 has been split in two parts aimed at modeling separate phenomena that happen on different time scales: a detailed analysis of the pressure evolution inside the cooling pipes of the B0 coil, which establishes on the time scale of sound wave propagation along the pipe length, and an analysis of the pressure increase in the system, depending on the overall response of the plant. Details on the models used in the analysis are found elsewhere [9], [10].

In both cases we have considered that the average coil casing has a uniform temperature, obtained from an average of the readings of the temperature sensors located on the B0 casing during a 22 kA quench. The heat exchange from the casing to the helium is mainly limited by the thermal resistance between casing and pipe. We have estimated that the typical value for the equivalent thermal resistance per unit pipe length is of the order of 0.04 K m/W. The simulations show that the helium temperature follows with negligible gradient the temperature of the coil casing. The reason is that the time scale of the temperature evolution (tens of s) is much longer than the time constant for the heat exchange across the thermal resistance (few tenths of s to 2 s in the worst case).

As a first step we have computed the evolution of the helium outflow and pressure induced by the heat exchange with the coil casing in a pipe of 12.0 m length and 14 mm diameter. Two situations were considered: a pipe open to a constant pressure manifold which is the normal operation case and, for fault analysis, a fully obstructed pipe.

These results are summarized in the design chart of FIG 6, which is valid for the same cooling pipe geometry but different quench conditions. The chart reports the pressure rise computed as a function of the volumetric heating rate in the helium $\dot{Q}$. The solid lines are obtained in the limit of negligible friction (inertial limit) and negligible inertia (frictional limit). For comparison we have also reported in the graph (dashed line) the value obtained from the analytical approximation of Dresner for the maximum pressure in a pipe which holds in the frictional limit, and is found to correspond well to the computed friction dominated pressure increase. We have finally reported in the plot the values of the maximum pressure increase obtained simulating quenches in the range of 10 to 22 kA, either assuming that the pipe is open to a constant pressure manifold (triangles) or closed (circles).

The values for open pipe are small, of the order of 100 Pa, and in fair agreement with the expected friction dominated pressure increase, and about 10 times higher than the analytical expression of Dresner. Recalling that the expression of Dresner was developed for significant pressure rise, and given the extremely low values obtained, we do not believe that this is an issue. In the case of closed system the pressure increase is above 10 MPa, a dramatic difference. During the experiment there was no clear pressure rise inside the pipe, consistent with the results of the calculation with open ends. This result can be generalised to an individual full length ATLAS coil for which, as observed experimentally, pressure rise in the cooling pipes is not an issue provided that sufficient exhaust is available at the manifolds.

Based on the observation above, we have examined the situation of the whole system using a much simplified model of the cryogenic test set-up. A schematic representation is reported in FIG 7. The model includes the helium volume in the cooling pipes, heated at the coil casing temperature, the helium collectors inside the B0 cryostat, transfer lines to the cold box (DN25 for the supply and DN32 for the return line), cold box circuitry simplified as two valves on the supply and return lines and the pump cryostat. In the model this last is connected through a relief valve to a large buffer at constant pressure that simulates the cryogenic plant. The characteristics of the pipes (friction factor) and valves (head loss) have been adjusted to match measured pressure drop in steady state operation at 75 g/s mass flow.

In FIG 8 we report the results of a simulation of the pressure transient during a 22 kA quench. To understand better the features of the transient process we have considered two cases, namely that of the isolated system at the pump cryostat (i.e. the relief valve remains closed) and that of open system at the pump cryostat. The initial pressure evolution is only marginally affected by the conditions at the pump cryostat, and the pressure rise is approximately the same in both cases. For times longer than 10 s, however, the closed system largely overestimates the pressure increase, while the results obtained in case that the pump cryostat is open to the constant pressure buffer, physically represented by the cryoplant refrigerator, are in much better agreement with the measured results, both in respect to the maximum pressure excursion computed as well as the time scale of the evolution. We attribute the residual discrepancy between the simulation and the experiment to the simplifications taken, especially with regard to the helium heating process and the actual geometry of the pipeworks and valves.

The pressure evolution in the system is determined by two terms: on one side the pressure increases due to the helium expansion induced by temperature excursion in the coil, while on the other hand the pressure relief to the buffer volumes represented by the pipework, the pump cryostat and the exhaust to the cryoplant tends to reduce the system pressure. In fact these two antagonist effects also interact with each other as explained below. In the case of open pump cryostat the helium can flow out of the coil without significant constrictions. The amount of helium heated in the volume then decreases once

FIGURE 6. Limits for the expected maximum pressure increase in the cooling pipe as computed in the inertial and frictional limits (solid lines), and analytically in the frictional limit (dashed) as a function of the helium volumetric heating rate. Also reported the simulations for the heating profile during quenches in the range of 10 to 22 kA for open-ends pipe and closed-ends pipe.

FIGURE 7. Schematic of the proximity cryogenics used for the simulation of pressure transients in B0.

FIGURE 8. Measured and simulated pressure rise in the coil cooling pipe. Simulations have been performed in the case of pump cryostat closed and open to a large buffer (exemplifying the cryoplant valve box).

the helium density drops due to phase transformation, thus also reducing drastically the term that tends to increase pressure in the system. In this case the pressure tends to decrease, driven by the pressure relief, right after the complete amount of helium in the coil has been vaporised. In the case that the pump cryostat is closed the helium outflow from the coil pipeworks is strongly suppressed and the system undergoes a process that is closer to constant density. The amount of helium in the coil cannot decrease as fast as in the case of open pump cryostat and the pressure rise is significantly larger.

CONCLUSIONS

The pressure rise experiments carried out on the B0 model magnet at quenches up to 22 kA showed no measurable pressure difference between the centre of the cooling pipe of 14 mm i.d. and the manifold, the two being apart by 6.0 m. We attribute this result to the comparatively large time constant of the temperature increase of the coil and its casing of quite large cold mass. The computer simulations using the measured temperature rise curves as input parameter confirm the experiments. The calculated pressure differences are at 100 Pa only. The rise of both the pressures at the manifold and at the centre of the cooling pipe to some 0.05 MPa overpressure with respect to the operational pressure is related to the cryogenic distribution system with transfer lines and pump cryostat volume. Simulations modelling the complete cryogenic system taking also the cryoplant refrigerator into account show similar pressure rise curves. The maximum pressure under isochoric conditions would approach 0.2 MPa of overpressure.

These investigations indicate that for the Toroidal Magnets of the ATLAS detector - even quite larger in size than the B0 magnet model - the pressure rise in their cooling channels at quench should be below values being potentially dangerous to the integrity of the pipes. In the unlikely case of a closed-end system, however, the pressure would rise uncontrolled to dangerously high values.

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