First Full-Size ATLAS Barrel Toroid Coil Successfully Tested up to 22 kA at 4 T

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Abstract—The Superconducting Barrel Toroid is providing (together with the two End-Cap Toroids not presented here) the magnetic field for the muon detectors in the ATLAS Experiment at the LHC at CERN. The toroid with outer dimensions of 25 m length and 20 m diameter, is built up from 8 identical racetrack coils. The coils with 120 turns each are wound with an aluminum stabilized NbTi conductor and operate at 20.5 kA at 3.9 T local field in the windings and is conduction cooled at 4.8 K by circulating forced flow helium in cooling tubes attached to the cold mass. The 8 coils of 25 m $\times$ 5 m are presently under construction and the first coils have already been fully integrated and tested. Meanwhile the assembly of the toroid 100 m underground in the ATLAS cavern at CERN has started. The 8 coils are individually tested on surface before installation. In this paper the test of the first coil, unique in size and manufacturing technology, is described in detail and the results are compared to the previous experience with the 9 m long B0 model coil.

Index Terms—Detector magnets, superconductors, toroid.

I. INTRODUCTION

THE BARREL Toroid (BT) of the ATLAS magnet system which is currently under construction at CERN [1] consists of eight racetrack coils. Each individual coil will be tested on surface before final assembly underground. The separate BT coils (1), already unique in size, are installed in a test station (see Fig. 1), with a magnetic mirror (3) next to them. The attractive force between the mirror and the coil is transferred to eight tie-rods via a support unit (2). Due to the presence of the end cap toroids in the ATLAS magnet system the force of the tie rods will increase toward the ends of the coil. In order to simulate this situation in the test station extra magnetic plates are placed toward the extremity of the magnetic mirror. The force on the titanium tie-rods in the test station is representative for the force in the final toroidal arrangement.

The design and fabrication of the coils is already described in several papers dealing with the 9 m long B0 model coil [2]–[5].

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Fig. 1. The coil in the test station in its vacuum vessel (1), support unit (2), magnetic mirror (3) and current lead turret (4).

For clarity a cross-section of the coil and a top view of the cold mass are shown in Fig. 2(a) and Fig. 2(b) respectively. The main parameters of the coil are summarized in Table I.

This paper focuses on the results of the test of the first full size racetrack coil. The test program includes ramp up to nominal current, test of quench heaters, fast discharge and monitoring of the mechanical behavior. The results are discussed briefly.

II. COOL DOWN & WARM UP

In Fig. 3 the temperature during the cool down period is shown (solid lines) as well as the temperature gradient over the cold mass (broken line). During cool down till 100 K a regulated temperature difference of maximum 40 K over the coil is maintained in order to control the cooling and keep the mechanical stress below an acceptable level.

Under normal operating conditions the coil is cooled with forced flow liquid helium flowing through pipes attached to the cold mass. From room temperature to 100 K a pre-cooling system is used where helium gas, cooled with liquid nitrogen in a heat exchanger, is flowing through the cooling pipes. The change from pre-cooling to the final cooling system is visible in Fig. 3 as the kink in the temperature curves on the 26th of August.

After 12 days of cooling the operating temperature is reached. The temperature of the cold mass varies between 4.5 and 4.9 K. The side of the coil connected to the tie-rods is the hottest spot due to the heat leak through the rods. The measured cryogenic

Fig. 2. (a) Cross-section of the coil. We see from inside out, the two double pancakes with 2×60 turns enclosed in an aluminum coil casing. The cold mass is connected (to the right) to the vacuum vessel with tie-rods that take the Lorenz forces (about 150–180 tons per rod at 22 kA) and cryogenic stops (to the top and the bottom halves of the vessel) that block the cold mass in the round vacuum vessel. A thermal shield at 60–80 K is positioned in between the cold mass at 4.6 K and the vacuum vessel at 300 K. The cryogenic stops have sliding surfaces in order to accommodate the thermal shrinkage of the cold mass. (b) Top view of the cold mass with rib and tie-rods. Sizes are 25 m length, 5 m width.

TABLE I
MAIN PARAMETERS OF THE BT COILS

Coil type	$2 \times$ double pancake
Total number of turns	120
Racetrack dimension	25 m $\times$ 5 m
Weight of the cold mass/complete coil	42/84 ton
Operating temperature	4.6 K
Nominal current	20.5 kA
Self-inductance	0.56 H (with mirror)
Stored energy at 22 kA	133 MJ
Sizes of the Al/NbTi-Cu conductor	12 mm $\times$ 57 mm
RRR of the aluminium stabilizer at 0 T	> 1000
Peak field on the conductor	$\approx$ 4.0 T (with mirror)
Critical current margin I/I_c at 4 T	25%

heat loads are 85 W on the cold mass at 4.7 K and 800 W on the thermal shield.

A vacuum level of less than 10^{-7} mbar is reached after cool down. This value is maintained throughout the tests without any problem.

The shrinkage of the cold mass from room temperature to 4.7 K is 0.42%, which is 104 mm on the length of the coil (25 m). This value is in perfect agreement with the data for aluminum in this temperature range.

The so-called cryostops, see Fig. 2(a), block the cold mass in the vessel, but at the same time at the sliding interface they enable the movement of the cold mass compared to the vacuum vessel during cool down and warm up. Strain gages are attached

Fig. 3. Temperature (solid line) and temperature gradient (broken line) along the coil during cool down.

to the vacuum vessel near the cryostops to monitor the force due to friction between the sliding surfaces. No signs of stick-slip are observed.

The tie-rods are pre-bent at room temperature so that during cool down the bending strain is released and the tie-rod is in its neutral position. The signals from the strain gages show that indeed the tie-rods are in a stress free state after cool down.

The warming-up process is accelerated through active ohmic heating of the coil by using a coil current between 200 and 500 A. During warm up the RRR of the coil is measured. The values found for the two pancakes are 1600 and 2000. The difference is explained by the fact that conductors from two manufacturers are used with a slightly different purity of Al used for the co-extrusion of cable and the stabilizer.

Fig. 4. Force on the tie-rods and current during ramp to 22 kA.

Fig. 5. Force on the tie-rods as function of current squared, the lines are a guide to the eye.

After complete warming up the sensors on the mechanical parts of the coil are checked again. No signs of damage, yield or hysteresis are found meaning that the coil is mechanically seen healthy.

III. MECHANICS

Besides the question whether the coil would reach the nominal current, the mechanical behavior of the coil is of equal importance. In Fig. 4 the current in the coil and the load on the four tie-rods on the A-side of the coil, measured with strain gages, is shown.

The maximum test current of 22 kA (which gives the equivalent stress in the windings as in the complete and installed toroid) is reached at first cool down and without training. The load on the tie-rods increases accordingly to maximum 175 ton on tie-rod 3 A.

When the current is ramped down to zero all strain gage signals come back to zero, so no sign of hysteresis in the tie-rods is found. The same behavior is observed for the tie-rods on the other side of the coil (C-side).

In Fig. 5 the force load on the tie-rods is shown as a function of the square of the current. The lines deviate slightly from the expected quadratic behavior in current due to saturation effects in the magnetic mirror. The load on the tie-rods at 22 kA varies from 150 to 175 ton. Both the absolute and relative magnitude is as expected from model calculations. The load is also measured

Fig. 6. Barrel toroid coil quench at 22 kA. The current decays completely within 150 s after firing one protection heater.

with load cells which are placed between the support unit and the mirror, see Fig. 1. Within the uncertainty margin ($\pm 10\%$) the load measured with load cells and strain gages are in agreement.

IV. FAST DISCHARGE AND QUENCH BEHAVIOR

The nominal current of the Barrel Toroid coil is well below its critical value and it was reached without any training. The coil design is made safe and thus the mean current density in the Al stabilizer is about 30 A/mm^2 , a relatively low value. Consequently the single coil can survive a quench without active protection when the stored energy is dumped in the coil with only a moderate increase of temperature. This has been demonstrated during the test of the 9 m long B0 model coil [6]. About forty quenches were initiated in the model coil with the different internal heaters at applied currents up to 24 kA and the maximum hot spot temperature was about 90–95 K. The density of the stored energy in the full size Barrel Toroid coil is 3.2 kJ/kg at 22 kA, a value only 20% higher than in the B0 coil at maximum current. Based on this, no significant difference in temperature during the BT coil quench is expected.

In the final assembly eight Barrel Toroid coils are connected in series. Without any safety measures the temperature of the quenched coil may go up to 200 K. In the case of a quench event the stored energy must be distributed homogeneously between all coils. To achieve this, after quench detection the protection system fires the internal heaters which are placed close to the inner layers of the double pancakes. There are four quench heaters in each Barrel Toroid coil located at each end of the 25 m long coil.

In order to verify the reliability of the coil and efficiency of the quench protection heaters the fast dump has been initiated with only one heater at maximum current of 22 kA. Obviously the full-size Barrel Toroid coil has a minimum amount of sensors as compared to the model B0 coil. The main signals are the voltages across each double pancake. A quench was induced by the heater located in the double pancake with the lowest RRR value.

The current decay and calculated active voltages across the pancakes are shown in Fig. 6. Assuming that within one double pancake there are no large temperature gradients the average maximum temperature can be determined at the maximum value of the coil resistance.

The maximum average temperature of the quenched double pancake is about 75 K. It is very close to the maximum temperature observed in the B0 model coil quenched at 24 kA. As seen in Fig. 6, the normal zone propagates from one pancake to the other one within a few seconds. The average temperature of the second double pancake goes up to 66 K. It confirms that the magnet is safe for the quench event and the temperature gradient is low.

A few temperature sensors are mounted on the coil casing and they react to the coil temperature rise with some delay. Since the distance between two sensors is 30 m (positioned at each end of the long coil) and with 2–3 seconds delay in response time, we can conclude that the longitudinal normal zone propagation velocity is about 10–15 m/s which is in good agreement with the 12 m/s at the same current measured in the 9 m long B0 model coil [7].

During a quench the maximum internal voltage in the single coil is less than 110 V and it may rise to 700 V in the final 8-coils toroid assembly in the case of a complete failure of the magnet protection system.

The ground insulation has been tested at 2 kV. The value of the resistance to ground varies from 1.1 G Ω at low temperature to 230 M Ω after warming up. These numbers are fully acceptable.

V. B0 MODEL COIL VERSUS FULL SIZE BT COIL

The B0 model coil was built to validate the design concept and to test the manufacturing process. The B0 coil was fully instrumented with about 400 sensors.

The test results lead to many small and a few essential improvements. The main visible difference is the length: the BT coils are 25 m long instead of 9 m for B0. This corresponds to a factor 2.5 in volume of the vacuum vessel.

A few construction improvements are:

- The shape of the sliding interfaces in the cryostop has changed in order to reduce the stress, local bending and thereby reducing the risk of stick-slip motions.
- To prevent the blocking of a tie-rod feet in a critical position when it should slide and rotate, it was decided to avoid any sliding in the tie-rod to casing connections by pre-bending the tie-rods at room temperature and to let them relax to their stress free and straight condition after cool down; this worked fine.
- The technology for accommodating thermal shrinkage of the thermal shield panels with respect to the cold mass was changed. Completely new supports for the shield were designed and installed.
- In the B0 thermal shield a small leak was found, this triggered a redesign of the cooling line on the thermal shield by which the number of Al-Al tube welds is minimized in order to drastically reduce the risk of helium leaks. In addition a stringent quality control is implemented for controlling the welds as well as leak testing all lines under thermal shock and at 77 K.

TABLE II
COMPARISON BETWEEN B0 AND BT

Issue	B0 value	BT value	BT/B0 measured	Comments
5 K heat load	85 W	85 W	1	2.4 according to the surface
Cool down time	15 days	12 days	0.8	new cooling machine
Coil casing contraction	39 mm	104 mm	2.7	25/9.1=2.7
RRR Al	1400	1600 - 2000	1.1-1.5	different pure Al, manufactures
Slow dump time at 22kA	25 min	1 hr	2.4	different dump resistor
Stored energy	60 MJ	133 MJ	2.2	As expected

- Cooling lines were doubled everywhere so that in the case of leaks one can switch to a fully redundant set of lines in order to guarantee a continued operation of the magnet.
- In the B0 coil one training quench below the nominal current occurred, however, the quench was in the coil terminals. This triggered a redesign of the conductor supports outside the coil body which was implemented in the BT coil construction.
- Many minor modifications were accepted in the coil construction and various integration procedures.

A few scaling factors observed from the 9 m long model to the full size coil are listed in Table II. The coil width and cross section are the same (factor one) but the length has grown by a factor 2.5.

VI. CONCLUSIONS

The acceptance test of the first full-size Barrel Toroid Coil was successful. For the first time it was demonstrated that 25 m long racetrack type coils do work and can be built very reliable for use in large magnet systems. The coil went at first cool down, without training up to 22 kA (nominal current is 20.5 kA), survived slow dump and fast dump actions and showed no hysteresis in the coil mechanics.

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