Quench Evolution and Hot Spot Temperature in the ATLAS B0 Model Coil

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Abstract—The 9-m long superconducting model coil B0 was built to verify design parameters and exercise the construction of the Barrel Toroid magnet of ATLAS Detector. The model coil has been successfully tested at CERN. An intensive test program to study quench propagation through the coil windings as well as the temperature distribution has been carried out. The coil is well equipped with pickup coils, voltage taps, superconducting quench detectors and temperature sensors. The current is applied up to 24 kA and about forty quenches have been induced by firing internal heaters. Characteristic numbers at full current of 24 kA are a normal zone propagation of 15 m/s in the conductor leading to a turn-to-turn propagation of 0.1 m/s, the entire coil in normal state within 5.5 s and a safe peak temperature in the windings of 85 K. The paper summarizes the quench performance of the B0 coil. Based on this experience the full-size coils are now under construction and first test results are awaited by early 2004.

Index Terms—Detector magnets, hot spot temperature, quench, racetrack coil.

I. INTRODUCTION

THE B0 Model Coil was built to verify the design concepts of the ATLAS Barrel Toroidal Magnet for the ATLAS Detector which is currently under construction at CERN [1], [2]. Even being a model, the 9-m long B0 coil belongs to the group of large superconducting magnets. The main parameters of the B0 coil are listed in the Table I. It consists of two double pancakes wound with NbTi cable in a pure aluminum cladding. The double pancakes are bonded into an aluminum alloy coil casing. The coil casing is indirectly cooled by liquid helium circulating through cooling lines glued on the surface of the coil casing. The coil was well instrumented with voltage taps, pickup coils and temperature sensors to study the normal zone propagation and quench evolution along and across the coil windings. An extensive test program was performed during June–December 2001 [3].

II. QUENCH INITIATION AND DATA ACQUISITION

A. Quench Initiation Heaters

Quenches were induced by firing different heaters which were placed near the conductor. Quench protection heaters

are installed on each double pancake to guarantee smooth temperature distribution after a quench. As a part of the Magnet Safety System they are able to initiate a quench in both layers of the double pancake at the same time. Spot heaters are mounted directly on the conductor situated on the most inner turn of the magnet. They have a low thermal inertia compared to the quench protection heaters and the quench is initiated by a short heat pulse of a few milliseconds.

B. Instrumentation and Data Acquisition

As a model, the B0 is equipped with different sensors to control mechanical, electrical and thermal behavior of the coil. In total about two hundred sensors have been installed on the cold mass [4]. In order to investigate the normal zone propagation after a quench the coil windings are instrumented with pairs of voltage taps. Because of design constraints the taps are mounted only on the external layers of the double pancakes. In addition a few pick up coils are allocated close to the pairs of voltage taps on the inner turns of the pancakes. In the framework of the ATLAS project INFN-LASA has developed a specific data acquisition system dedicated to electrical measurements on the B0 coil. The signal from a pick-up coil is linked to magnetic flux variations. In order to have detailed information from pick-up coils a sampling rate of the acquisition system must be of the order of milliseconds. At the same time, due to the fact that the resistance of the conductor in the normal state is very low, the resolution of voltage measurements has to be a few micro-volts. These features are successfully realized and the data acquisition system is successfully used to measure quench evolution in the B0 coil.

C. Quench Initiation and Normal Zone Propagation

There was only one spontaneous quench, which happened in the interconnection area between the coil and current leads

TABLE I
MAIN CHARACTERISTICS OF THE B0 MODEL COIL

Characteristics	Value
Dimensions	9 × 5 m
Operating temperature	4.8 K
Current	24 kA
Critical current at 4.8 K	> 35 kA
Stored energy at 24 kA	64 MJ
Peak field on conductor at 24 kA	4.4 T
Dimensions of conductor	12 mm × 57 mm
RRR of Aluminum stabilizer at 0 T	1100
Number of strands in cable	40
Diameter of strand	1.3 mm
Mass of insulated conductor	6450 kg
Total mass of cold mass	25000 kg

Manuscript received October 21, 2003.

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Digital Object Identifier 10.1109/TASC.2004.829709

Fig. 1. Signal behavior of pairs of voltage taps and corresponding pick up coils as function of time. Sensors are placed on the inner turns of both double pancakes. The quench was initiated by a spot heater at 24 kA.

during the first energizing of the B0 coil. The reason is a mechanical movement of the superconducting bus bar. A few quenches were induced by heat losses in the conductor during the coil discharge into a high dump resistor.

About forty quenches were initiated with the heaters at applied currents from 5 kA up to 24 kA. The normal zone propagation velocities are calculated using the time information between two pickup coil signals or signals from two pairs of voltage taps placed at a known distance. An example of a registered quench at 24 kA is shown in Fig. 1. The quench is initiated by the spot heater placed on one double pancake and it takes about four seconds until the normal zone is reaching the similar area of the second pancake. The detailed analysis of the longitudinal and transverse propagation velocities is given in [5], [6]. From 8 to 24 kA, typical values vary respectively from 0.3 to 15 m/s for the longitudinal propagation along the conductor and from 0.01 to 0.1 m/s for the transverse propagation within the layer of the quenched pancake.

III. HOT SPOT TEMPERATURE

The temperature sensors which are used in the B0 coil, are placed on the coil casing and are therefore not useful in determining the hot spot temperature. During a quench the voltage measured by a pair of voltage taps will rise. This is mainly caused by an increase of the resistivity of the pure aluminum cladding because of the temperature rise. This correlation between the voltage and the temperature makes the voltage useful to obtain local temperatures, if the resistivity of the conductor can be extracted from the measured voltage. The total voltage measured by a pair of voltage taps consists of three contributions:

$$V_{Total} = V_{resistive} + V_{Ind} + V_{Diff},$$

where $V_{resistive}$ is the component that is caused by the resistance, V_{Ind} is an inductive voltage induced in the loop formed by the wires of the two voltage taps. The last one, V_{Diff} is also an inductive voltage, which is the result of current diffusion and transverse propagation of the normal front. This last contribution will not be taken into account because it has barely any

Fig. 2. Measured and calculated voltages of a pair of voltage taps, where the quench was initiated, as function of time. The Magnet Safety system has detected the quench and interrupted the current after 5 s.

effect. In order to differentiate the remaining two components of the total voltage, V_{Ind} has to be determined. V_{Ind} is defined by:

$$V_{Ind} = k_i \frac{dI}{dt} + c_i,$$

where k_i and c_i are a coefficient and a constant respectively, which are voltage tap pair specific. These two figures can be obtained from cases when there is a slow discharge of the current without a quench. Since the conductor is still in the superconductive state, the measured voltage is caused by induction only. This way the necessary coefficient and constant can be determined for each pair of voltage taps. The correction of the inductive component of the measured voltage is shown in Fig. 2. The remaining part of the voltage is now totally resistive and can be used to calculate the local resistivity of the aluminum cladding in the conductor.

During the warming-up of the B0 magnet the temperature change is sufficiently homogenous to rely on the temperature sensors placed on the casing. When a constant current of 1 kA is applied growing voltage is seen, due to rising resistivity caused by an increase of the temperature. The warming-up data are fitted to values for the resistivity of aluminum measured separately on conductor samples. This results in a slightly different RRR compared to the one determined earlier in the experiment. Now the temperature and the resistivity can be related, which makes it possible to determine the temperature from the resistivity.

The resistivity does not only depend on temperature but is influenced by magnetic field. For the resistivity to be useful for temperature calculations this magnetic field dependence has to be corrected for. The influence of the magnetic field on the resistivity ρ is given by:

$$\rho(B) = \rho_{B=0} (1 + \beta(T))$$

In order to correct for the magnetic field, $\beta(T)$ has been determined from existing data for $\rho_{B=0}$ and $\rho(B)$ for pure aluminum with the RRR mentioned above. $\beta(T)$ is temperature dependent, therefore the magnetic field correction had to be done in an iterative process. The resulting resistivity is totally temperature-dependent, and hence can be used for temperature calculations.

Fig. 3. The algorithm for calculating temperatures from the voltage measured across the conductor.

Fig. 4. The time evolution of the electrical resistivity and calculated temperature of the hot spot area of the conductor at a 17 kA quench.

The method (Fig. 3) described above is used to calculate temperature distributions and hot spot temperatures in the B0 coil, with an accuracy of ± 2 K (Fig. 4).

Under adiabatic conditions the heat balance per unit volume of winding can be presented as follows [7]:

$$\int_{t_1}^{t_2} J^2(t) dt = \int_{T_0}^{T_{\max}} \frac{\gamma C_p(T)}{\rho(T)} dT,$$

where J is the current density, γ is density and C_p is the heat capacity. The quench starts at t_1 at temperature T_0 and the current is decayed completely at t_2 . Since all the remaining elements of this equation are material properties and known, this equation can be used to calculate the hot spot temperature under adiabatic conditions, by using the actual measured current density decay. As both C_p and ρ vary approximately linearly with temperature for temperatures above 50 K and more or less change at the same rate, one can expect a linear relation between J^2 and the hot spot temperature. It can be seen in Fig. 5 that the results are indeed in agreement with the expectations. In the same figure the hot spot temperatures are shown, which are calculated with the method described earlier in this paper.

IV. TEMPERATURE GRADIENTS BETWEEN PANCAKES

As mentioned before, the inner layers of the double pancakes of the B0 coil are not equipped with voltage taps in the same way as the outer layers. A few pick-up coils are mounted near the inner turn of the internal pancake. They are used to determine the propagation velocity. Only the overall voltage of each layer

Fig. 5. Hot spot temperatures and temperature calculated for adiabatic conditions versus I^2 .

Fig. 6. Measured voltage versus time across each layer in the double pancakes. At 18 kA, the quench is initiated by a spot heater located at the external layer (quenched).

in the double pancake is measured. The external ramp-down resistor has a very low resistance. During a quench, most of the stored energy is dissipated in the coil and its coil casing. The propagation of the normal zone from one double pancake to the next takes a few seconds. The quenched pancake absorbs more energy so its temperature must be higher than for the rest of the coil. As in the case of calculating the hot spot temperatures, the correction of the total voltage over the pancake is required to extract the active inductive component and to calculate the resistance.

Raw data of the voltages across the pancakes are shown in Fig. 6. The quench is initiated by a spot heater at 18 kA. The resulting resistances after the correction are calculated (Fig. 7). During warming up and cooling down the resistances are measured and it is confirmed that the pancakes are fully identical.

At temperatures above 50 K the temperature dependence of the resistance of pure aluminum is quite linear. It is found that within one pancake the temperature gradient is rather small (less than 10 K). Thus one can consider an “average” maximum temperature of the pancakes which can be calculated at the maximum value of the resistance. The “average” temperatures can be compared to the temperature calculated for the case of the homogenous distribution of the stored energy within the coil. The temperatures have been calculated for all cases of quench at the different currents (Fig. 8), and a few observations can be

Fig. 7. Resistance of each layer of double pancakes calculated with the correction of the inductive components of voltage. At 18 kA, the quench was initiated by a spot heater located on external layer (quenched).

Fig. 8. The dependence of the hot spot temperature, the average maximum temperatures of the pancake windings and the temperature at homogeneously distributed energy versus current. In all cases, the quench is initiated by the same point heater.

made. As expected, the maximum average temperature is at the quenched pancake. The hot spot temperature does not exceed the average temperature more than 10 K even at 24 kA. The temperature gradient of 10 K is within each double pancake.

The “average” temperatures of the pancakes are lower than the temperature calculated from the homogenous distribution

of energy. This can be explained by the heat dissipation into the coil casing. Also due to this dissipation the maximum temperature of the internal pancakes is always lower than the temperatures of the external pancakes. The maximum temperature gradient is about 30 K at the maximum applied current. It confirms that the quench in the B0 model coil is a safe event.

V. CONCLUSION

Detailed measurements of quench propagation, temperature gradients and hot spot temperatures, have confirmed that quenching the B0 coil, at any current up to 20% above the nominal operating current, can be handled safely. In particular, the average rise in temperature of a coil is less than that expected from the average dissipation of stored energy, confirming that heat is usefully diffused into the coil casing.

For the final Barrel Toroid coils, which are about three times longer but have the same cross-section as the B0 coil, the same quench behavior is expected. The coils are not equipped with the various diagnostics to control the quench evolution. Only the voltage over the double pancake will be monitored so the future analysis will be based on B0 voltage measurements presented in this paper.

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