First Cool-Down and Test at 4.5 K of the ATLAS Superconducting Barrel Toroid Assembled in the LHC Experimental Cavern

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***Abstract*—The large ATLAS superconducting magnets system consists of the Barrel, two End-Caps Toroids and the Central Solenoid. The eight separate coils making the Barrel Toroid (BT) have been individually tested with success in a dedicated surface test facility in 2004 and 2005 and afterwards assembled in the underground cavern of the ATLAS experiment. In order to fulfill all the cryogenic scenarios foreseen for these magnets with a cold mass of 370 tons, two separate helium refrigerators and a complex helium distribution system have been used. This paper describes the results of the first cool-down, steady-state operation at 4.5 K and quench recovery of the BT in its final configuration.**

***Index Terms*—ATLAS barrel toroid, large helium refrigerator, LHC experiment, superconducting magnet.**

I. Introduction

THE underground assembly of ATLAS, the largest general-purpose detector of LHC, is now in its final stage for a first operation scheduled for May 2008.

The ATLAS magnet system consists of four superconducting magnets [1]: one Central Solenoid (CS), one Barrel Toroid (BT) and two End-Cap Toroids (ECT).

The CS, which is aligned on the beam axis, provides a 2 T magnetic induction for the inner detector and has been thoroughly tested in its final location in May 2006 [2].

On the other hand, the BT and the two ECTs provide a useful tangential field of 1 T with a maximum peak value of 4 T for the muon spectrometers. Fig. 1 shows the BT when its underground integration was completed in November 2005.

The complete magnetic system is 22 m in diameter and 26 m in length with total cold mass of 660 tons and a stored energy of 1.6 GJ when the toroids are powered up to 20.5 kA.

Four cryogenic operational modes have been identified for these magnets; namely, the cool-down from ambient temperature, the steady-state operation at 4.5 K, the thermal recovery (from 58 K) after a fast dump and the warm-up [3].

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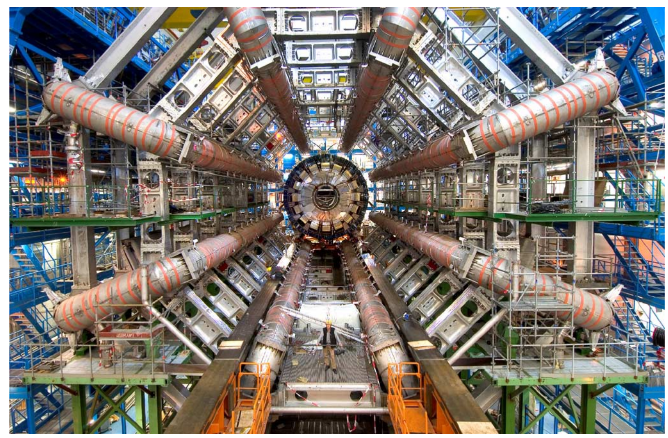

Fig. 1. Barrel Toroid fully assembled in the ATLAS cavern (Nov. 2005).

To cope with these cryogenic tasks, two separate helium refrigerators have been installed and commissioned in a side-cavern close to the detector [4]. The main refrigerator (MR) has an equivalent cooling power of 6 kW at 4.5 K. It is used to cool-down the magnets from 100 K to 4.5 K and then ensure their steady-state operation at 4.5 K which also includes the cooling of the current leads. The second machine, the shield refrigerator (SR), is used to cool-down the magnets from 300 K to 100 K and then maintain the thermal shields between 40 K and 80 K. Its cooling capacity is 20 kW for the normal shield cooling (40 K–80 K) but can be boosted, by liquid nitrogen (LN_2), up to 60 kW during the one-month magnet cool-down phase. Fig. 2 presents a simplified process flow diagram of the complete ATLAS magnets cryogenic system.

Detailed description of these various cryogenic components can be found in [2] and [4].

II. First Cool-Down of the Barrel Toroid

On 04th July 2006, we started the cool-down of the BT made of 8 identical coils and with a total cold mass of 370 tons.

Fig. 3 shows the evolution versus time of the minimum and maximum cold mass temperature measured on the eight individual BT coils.

During the first phase of cool-down, i.e. from ambient temperature to 100 K, only the SR was in operation with its LN_2 precooler, to supply in parallel through the 8 coils, a total helium mass flow of about 0.20 kg/s.

As it was the first BT cool-down, and to minimize the thermal stresses induced by large temperature gradient inside the cold

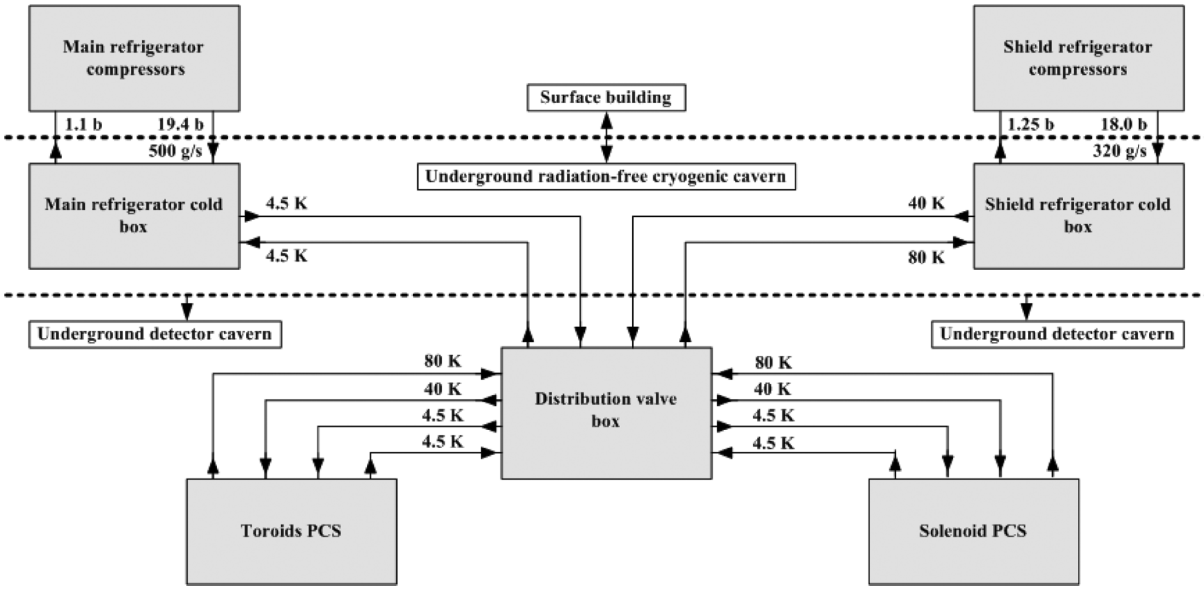

Fig. 2. Simplified flow scheme of the ATLAS magnet cryogenic system.

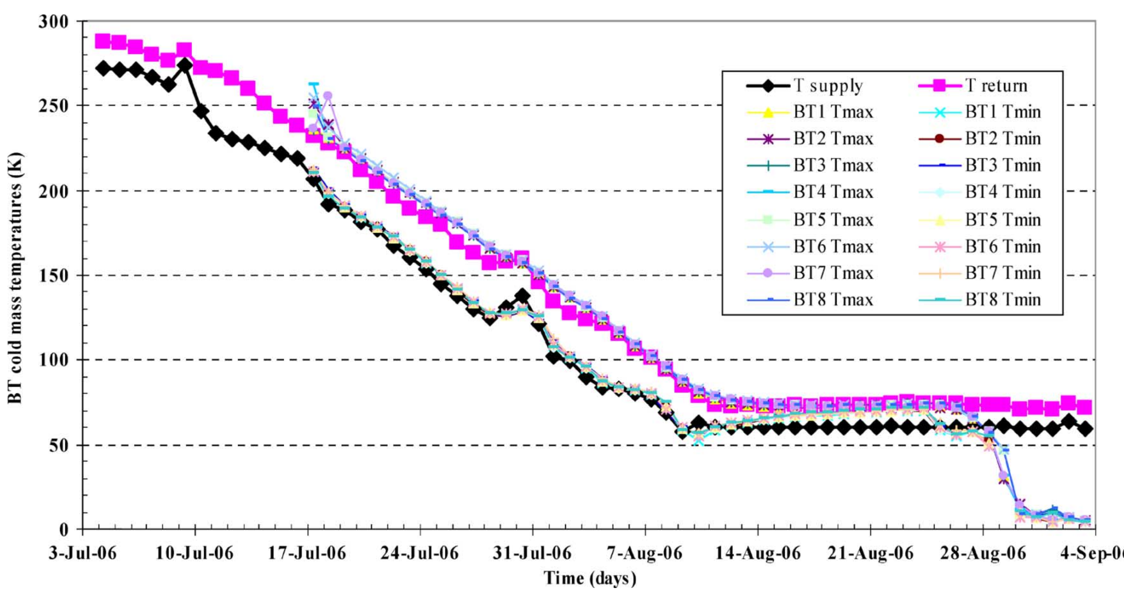

Fig. 3. Parallel cool-down of the 8 Barrel Toroid coils.

masses, the temperature of helium provided by the SR was maintained only 20–25 K lower than the magnets temperature. For the subsequent cool-down, this ΔT will be increased to 40 K in order to accelerate the cool-down rate.

On 10th August 2006, all maximum cold mass temperatures were below 90 K. We could then stop the LN_2 precooler and start the refrigerator's turbines to be able to switch the SR into its normal shield-cooling mode.

Between 10th August and 25th August 2006, several electric and magnetic checks were done at 80 K level on the 8 BT coils before starting the final cool-down to 4.5 K.

On 24th August 2006, the MR was started and took over the BT cool-down, supplying gaseous helium in parallel into the 8 cold masses.

On 31st August 2006, once we had accumulated more than 3'000 liters of liquid helium in the phase separator located at the outlet of the coils [4], [5], we could start the centrifugal pump providing a total circulation of 0.6 kg/s ($\sim$5 L/s) of liquid helium through the 8 coils.

The BT was then ready for current ramp-up.

III. Barrel Toroid Quenches

Before starting to power up the Barrel Toroid at nominal energy level, the commissioning of the Magnet Safety and Control Systems (MSS and MCS respectively) were done at reduced energy, i.e. with 1 kA and 5 kA current. Once both MSS and MCS were operational, several successive powering tests were gradually performed at 5 kA, 6 kA, 10.2 kA, 14 kA, 18 kA and finally at nominal current of 20.5 kA on 09th November 2006. Each of these powering tests was followed by a provoked energy fast dump of the magnet system.

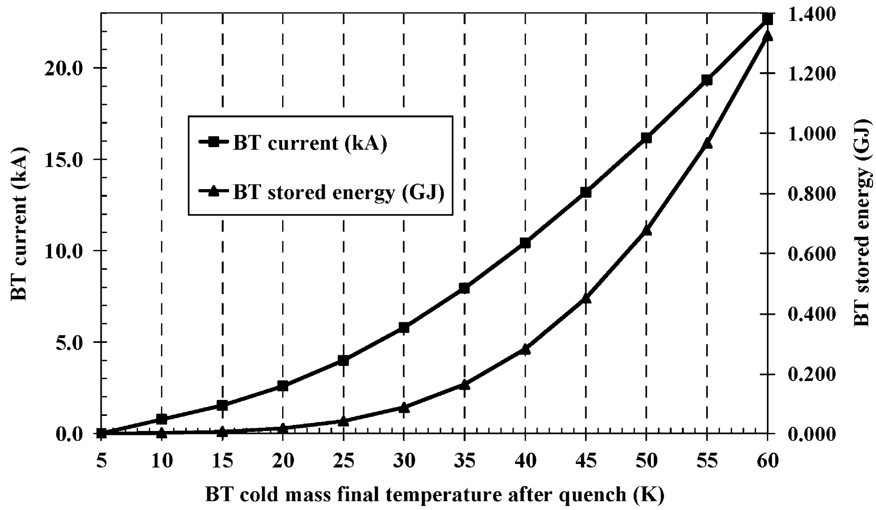

Fig. 4. BT final cold mass temperature as function of coil current.

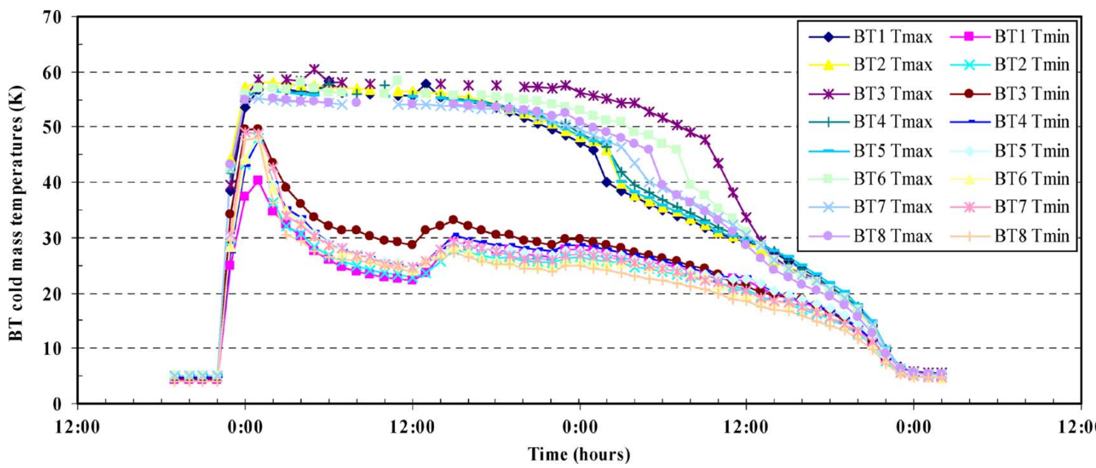

Fig. 5. Barrel Toroid recovery after a fast dump at 20.5 kA.

Since the initial toroid design, it was decided that in case of fast dump, the whole magnet energy will be dumped into the cold mass. Thus, knowing that the magnetic energy E stored is related to the coil current I by (1):

$$E = \frac{1}{2} \cdot L \cdot I^2 \quad (1)$$

where L represent the coil inductance $(L = 5.17\ \mathrm{H})$, we could easily estimate the cold mass final temperature after quench as a function of the coil current, i.e. the magnet energy.

For example, Fig. 4 predicts a final temperature of 56 K after a quench at 20.5 kA, corresponding to a stored energy of 1.08 GJ. This 56 K value is in good agreement with the average temperature of 58 K we measured on the 8 coils [6].

It should be mentioned that until now (August 2007), no accidental fast dump occurred during the BT's powering: all of them were intentionally provoked.

Fig. 5 shows the evolution of minimum and maximum cold mass temperatures during a 52-hour recovery time necessary to re-cool the BT down to 4.5 K after a quench at 20.5 kA.

During this quench recovery, since all temperatures are below 60 K, there is no constraint to keep a maximum temperature difference of 40 K in each cold mass, as it is necessary when cooling down from ambient temperature.

IV. Cryogenic System Particularity

Since December 2006, the BT cold mass cooling at 4.5 K by the MR has been interrupted. Nevertheless, thanks to a separate and continuous operation of the SR keeping cold the magnet shielding, all cold masses temperatures are floating below 80 K, i.e. the BT has not been warmed up since then.

V. Next Important Milestone

Among the four superconducting magnets making the ATLAS magnet system, the two ECTs have not been tested at 4.5 K, but only at 80 K in a dedicated surface test-facility in April and June 2007.

They are now (August 2007) under integration beside the BT in their final underground location and will be cooled down simultaneously to 4.5 K in October 2007 for different powering tests up to 20.5 kA in November 2007.

VI. Conclusion

The eight coils making the Barrel Toroid and the Central Solenoid have been fully tested with success in their final underground location.

The cool-down to 4.5 K of both End Caps is scheduled to start in October 2007.

Once both End Caps will be tested in the underground cavern, the cool-down of the complete ATLAS magnet system can be carried out and is now scheduled for spring 2008 to be ready for LHC start-up in May 2008.

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References

[1] ATLAS Magnet System: Technical Design Report CERN/LHCC/97-18, April 1997.

[2] F. Haug, N. Delruelle, Y. Doi, T. Haruyama, H. Ten Kate, M. Kawai, T. Kondo, Y. Kondo, Y. Makida, J. Metselaar, G. Passardi, O. Pavlov, M. Pezzetti, O. Pirotte, R. Ruber, and A. Yamamoto, "Commissioning of the ATLAS central solenoid cryogenics," in *Proc. of 21st International Cryogenic Engineering Conference (ICEC21)*, Praha, Czech Republic, 2006, pp. 47–50, Icaris Ltd.

[3] N. Delruelle, F. Haug, G. Passardi, and H. Ten Kate, "The helium cryogenic system for the ATLAS experiment," *IEEE Trans. Applied Superconductivity*, vol. 10, no. 1, pp. 1511–1513, March 2000.

[4] N. Delruelle, F. Haug, H. Ten Kate, G. Passardi, R. Pengo, M. Pezzetti, O. Pirotte, E. Baynham, T. Bradshaw, and J. Rochford, "Commissioning of the cryogenic system for the ATLAS superconducting magnets," in *Advances in Cryogenic Engineering*. New York: , 2006, vol. 51B, pp. 2018–2025.

[5] F. Haug, G. Passardi, R. Pengo, H. Ten Kate, E. Baynham, T. Bradshaw, G. Brown, D. Cragg, M. Crook, A. H. Orlowska, J. Rochford, and D. Sole, "The proximity cryogenic system for the ATLAS toroidal magnets," *Advances in Cryogenic Engineering*, vol. 47A, pp. 155–160, 2002.

[6] R. Pengo, K. Barth, N. Delruelle, O. Pirotte, G. Passardi, A. Dudarev, and H. Ten Kate, "Cryogenic characteristics of the ATLAS Barrel Toroid superconducting magnet," presented at the MT-20 Conference, Philadelphia, USA, 2007, to be published.