CEA/SACLAY
DSM

SERVICE TECHNIQUE DE CRYOGÉNIE ET DE MAGNÉTISME

DAPNIA/STCM 99-12 December 1999

SYNTHESIS OF TECHNOLOGICAL DEVELOPMENTS FOR THE B0 MODEL COIL AND THE ATLAS BARREL TOROID COILS

C. Berriaud, R. Berthier, D. Cacaut, A. Daël,
B. Gallet, B. Gastineau, F.P. Juster, C. Lesmond,
C. Mayri, Y. Pabot, J.M. Rey, H. Van Hille, Z. Sun
Et al.

DAPNIA

Presented at the 16th International Conference on Magnet Technology, Tallahassee (USA), September 26-October 02, 1999

Département d'**A**strophysique, de Physique des **P**articules, de Physique **N**ucléaire et de l'**I**nstrumentation **A**ssociée
CEA/Saclay F-91191 Gif-sur-Yvette Cédex

COMMISSARIAT A L'ENERGIE ATOMIQUE

DSM/DAPNIA/STCM

Rapport n° 12
le 15 décembre 1999

E. ACERBI, F. ALESSANDRIA, G. AMBROSIO
C. BERRIAUD, R. BERTHIER, F. BROGGI
D. CACAUT, A. DAËL, B. GALLET
B. GASTINEAU, F.P. JUSTER, C. LESMOND
C. MAYRI, Y. PABOT, J.M. REY, L. ROSSI
M. SORBI, H. VAN HILLE, G. VOLPINI, Z. SUN

SYNTHESIS OF TECHNOLOGICAL DEVELOPMENTS FOR THE B0 MODEL COIL AND THE ATLAS BARREL TOROID COILS

16th International Conference on Magnet Technology, Tallahassee - Florida
26/09/1999 au 02/10/1999

Synthesis of technological developments for the B0 model coil and the ATLAS barrel toroid coils

E. Acerbi (**), F. Alessandria (**), G. Ambrosio (**), C. Berriaud (*), R. Berthier (*), F. Broggi (**), D. Cacaut (*), A.Daël (*),B. Gallet (*), B. Gastineau (*), F.P. Juster (*), C. Lesmond (*), C. Mayri (*), Y. Pabot (*), J.M. Rey (*),L. Rossi (**), M. Sorbi (**), H. Van Hille (*), G. Volpini (**), Z. Sun (*).

(*)CEA/DSM/DAPNIA/STCM, CE Saclay, 91191 GIF-SUR-YVETTE - FRANCE
(**)INFN, LASA via Fratelli Cervi 201, 20090 Segrate MILANO - ITALY

***Abstract* - The Barrel Toroid Magnet is part of the Magnet System of the ATLAS Detector for the LHC. It provides the magnetic field required by the muon spectrometer. It consists of eight flat superconducting coils and will extend over a length of 26 meters with an inner bore of 9 meters and an outer diameter of 20 meters. The general design (pancakes, coil casing, tie rods, circular cryostats and warm voussoirs) has been presented in MT15. The present paper concentrates on the technological developments for the B0 model coil and for the BT coils : industrial production of conductor, welding technique for the coil casing, prestress of the coil with bladders, cold to warm supports, construction and assembly of the cryostat.**

Introduction

The Very Early Design of the Barrel Toroid (BT) was reported in 1993 [1] and further developed in 1995 [2].

The BT consists of eight flat race track coils assembled radially around the beam axis (see Fig.1). The main parameters are listed in table I.

The motivation and the main aspects of the present technical design have been presented in 1997 [3][4]. No major changes of the basic design took place in between. Practical solutions have been developed mainly within the B0 prototype coil project.

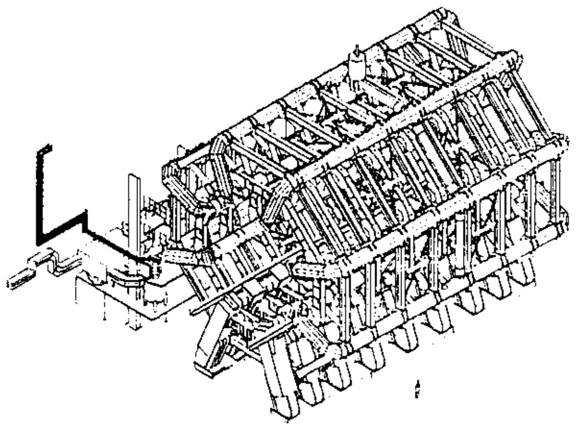

Fig.1. General view of the Barrel Toroid

Many specific developments have been undertaken such as electron beam welding of the massive coil casings, proof test of the suspension rod behaviour, impregnation and prestressing of the coil winding, helium flow characterization of cold pumps etc. A first important step in the ATLAS R & D has been done with the energizing of the so called race-track mock up.

TABLE I
Updated Main Parameters of the Barrel Toroid

Overall characteristics :	
Inner bore	9.4 m
Outer diameter	19.5 m
Axial length	26 m
Cold mass (incl. conductor)	8 x 47 tons = 376 tons
Coil (incl. cryostats)	8 x 87 tons = 696 tons
Total weight	832 tons
Winding :	
Pancakes/coil	4
Turns/pancake	30
Operating current	20.5 kA
Operating temperature	4.8 K
Total ampere turns	19.68 MAT
Stored energy	1080 MJ
Peak field	3.8 T
Conductor :	
Size overall	57 x 12 mm^2
Insert cable :	22. x 2.3 mm^2
Number of strands	38
Strand diameter	1.3 mm
Design current at 5 T	58 kA
RRR alu-stabilizer (at B=0T)	800
Total length	56 km

I. Race Track Mock Up Experiment

A race-track coil, 2.7 m long and 0.7 m wide has been built to verify the operational characteristics of the superconductor in the thermal, mechanical and cryogenic environment of ATLAS magnets. In particular it is subject to the same peak field and the same level of magnetic force. The race-track magnet is a multi-turn superconducting magnet, with indirect cooling, built with fully bonded aluminum coils. Various experiments have been performed to check the validity of the main technical options for the magnet. The mechanical deformations of the magnet during the energezing and the induced quenches are monitored at 12 points. The overall tranversal deformation of the magnet is measured by 6 strain gages placed on measuring clamps connecting the two arms of the magnets ; other sensors are placed on the casing of the magnet.

Removable reinforcing clamps are present between the arms. The displacements measured with and without the reinforcing clamps are respectively 0.30 mm and 1.mm and are presented in detail in [ ].

Another study focuses on thermal stability and quench propagation measurements. For a 70 x 7 mm^2 aluminum-stabilized conductor carrying a 20 kA current, a 4-5 Joule minimum quench energy and a 20 m/s longitidunal quench propagation velocity were found. The quench was initiated by inclusive heaters.

A new method based on pickup coils has been tested for measuring the quench propagation velocity. The current diffusion from the cable to the aluminum can be observed. The spatial distribution and the time constants are checked. The sensitivity of this method illustrated in fig.3 permits also to observe the quench propagation in successive turns.

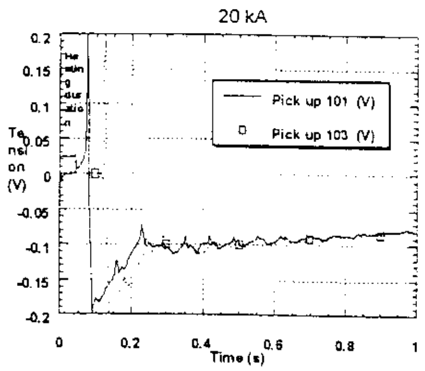

Fig. 2 Propagation velocity measurement.

A field reconstruction method based on 3 D Hall probe measurements has been tested and gives a precision better than 1 mT for the field in all the toroid.

II. Conductor Production

The conductor consists of a flat superconducting cable inbedded in a high purity aluminum stabilizer. The characteristics, shown in Table 1, are based on both stability and protection criteria. The operating temperature is estimated at 4.8 K, which leads to set the superconductor rating at 6.7 - 6.8 K at nominal current and peak field. The aluminum content and RRR are specified accordingly, together with the adopted quench protection scheme.

Development of this type of conductor has been carried out over the last five years at several european manufacturers, all based on the coextrusion process. Full qualification is now completely established, as well as reproducibility and reliability in long unit lengths. The necessary quality assurance measures to be implemented during full production have been extensively applied [ ].

III. Cold Mass Construction

III. 1 Winding

The concept of coil manufacturing is based on winding the double pancake on a temporary mandrel and impregnating it within a mould (at 5 MPa prestress).

A specific and very efficient winding tool has been developed in industry. The preparation line, which includes the wrapping of the insulation ribbon is now separate from the winding. No straightening device appeared to be necessary. The double pancakes, after winding, are extracted from the winding mandrel and receive a wrapped ground insulation before insertion in the impregnation vacuum vessel. The impregnation is done under 5 MPa.

III.2 Coil Casing

The design of the casing has been carried out with finite element calculations using the measured longitudinal elasticity modulus of the coil obtained with a 2 m sample of 10 conductor impregnated block (Fig. 3).

For the construction of the B0 coil casing, elements made of 7-ton rolled billets are premachined and assembled by electron beam welding. The depth of this welding is limited to 120 mm. Extensive tests of the welding procedure have been made in industry.

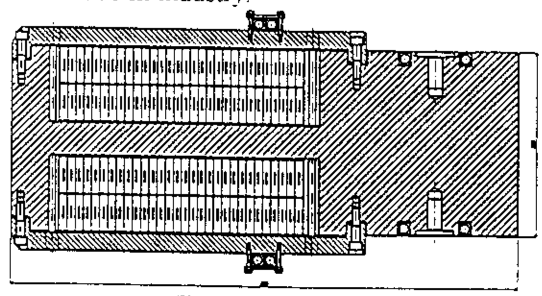
Fig.3. Cross section of the cold mass

III.3 Integration n°1

After impregnation, the insulated double pancakes are transferred into the coil casing where they are glued under radial precompression (15 MPa). The reason for this design is that, in the conductor region, the magnetic field increases from − 2.6 T to + 3.85 T. Therefore, due to the Lorentz forces, the stack of conductors is strongly compressed on itself at full current ; in order to avoid shear stress at the double pancake/coil casing interface, a prestressing technique has been developed [ ]. During the assembly of the cold mass, a tensile stress is created in the coil casing. The technique retained to impose the prestress is to use inflatable bladders on each side of the superconducting winding. The bladders are made of aluminum and are filled with glass microballs and impregnated with liquid epoxy resin, then pressurised and cured under pressure. Once filled with resin and pressurised the bladders act as hydraulic jacks, putting the double pancake coils in compression and the coil casing in tension. After curing under pressure, the bladders work like shims under the compression due to the tensile strain stored in the coil casing.

A full scale short model of the cold mass cross section has been recently tested and the tooling for B0 is under construction.

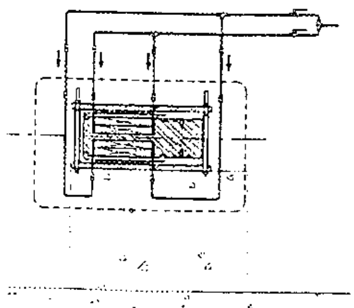
Fig. 4 Precompression technique

IV. Cryostat

IV.1 Tie Rods

The cold mass (Fig.5) is suspended by eight articulated titanium rods from vacuum vessel reinforcements onto which the voussoirs are tightened. These rods withstand net radial magnetic forces on the cold mass up to 180 kdaN.

A big effort has been made for producing and qualifying the tie rods : 3 prototypes have been forged and premachined for B0, in the TA5E ELI grade. Two other tie rods have been produced by stamping and forging. A special cryostat is being built for testing them under load in cryogenic conditions.

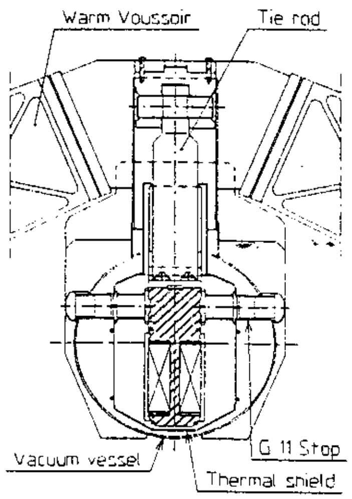

Fig 5 Cryostat and tie rod cross section

IV.2 Cryogenic stops

For the ATLAS BT, 256 cryogenic stops (Fig. 6) have to be built. Each stop comprises a cold ferrule, between the coil and the shields, a warm ferrule, between the shields and the vacuum vessel, and a sliding system including a swivel.
The assembly procedure is one of the delicate aspects of the integration of the coil and consists of four stops.

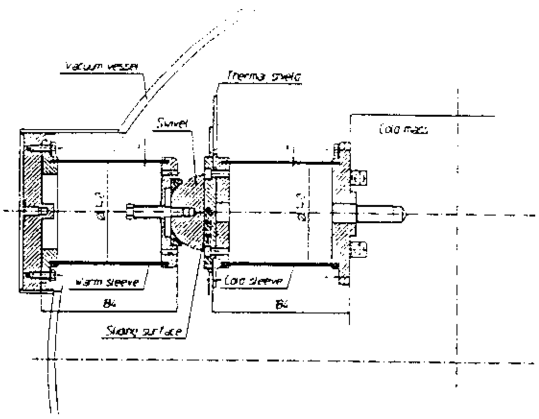
Fig.6 Cryogenic stop

1 – The "lower" warm ferrules are adjusted in position and welded on the "lower" half vacuum vessel.

2 – The cold mass, with its cold ferrules and its shields, is placed onto the warm ferrules, the shields being secured onto the cold ferrules.

3 – The upper half vacuum vessel is welded onto its "lower" homologue.

4 – The "upper" warm ferrules are placed onto their cold homologue and secured. The clearance between the two ferrules, warm and cold, during this operation, is controlled.

Once the toroid is assembled, its cooling down induces a sliding between the warm ferrule and the cold ferrule. This sliding is performed by the swivel. During this phase only the "lower" stops which support the weight of 40 tons are loaded. The clearance provided for assembling is increased by the thermal shrinkage that must let the cold mass free to move. The maximum shifting is observed on the end stop on the strut side. (see fig. 7)
During the current ramping up, the coil lengthens by 3 mm on each side of the fixed point. That induces a relative shifting of the ferrules in the opposite direction to the shifting caused by the cooling down.

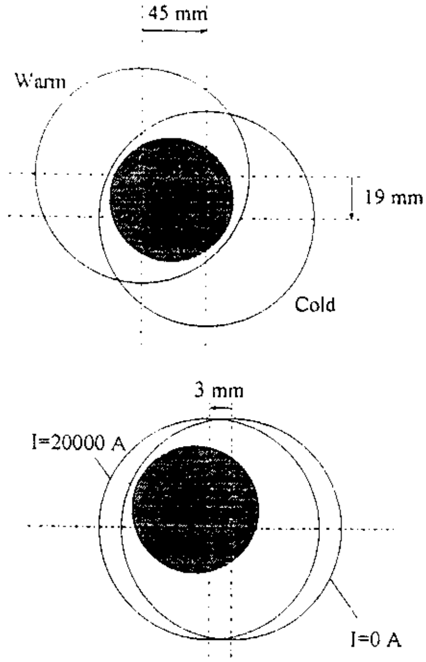

Fig. 7 Mouvements of the cryogenics stops

During a rapid discharge, eddy currents are generated in the shield panel, and create a Laplace force on the shields.
This force of typically 1 ton is picked up by the cold ferrules which support the shields and creates shear stress.
A prototype and a special test facility will be available soon to test the cryogenic stops.

V. Quench Analysis and Heater Efficiency

The magnet protection relies on Heaters.
The propagation of quenches distance along conductor as a function of the turn has been extensively studied.
A quench heater is located in the middle of the first conductor turn. For a 20 500 A current circulating in one ATLAS BT coil, the overall quench propagation time is about 4.5 s, according to this simulation ; it includes the time due to current diffusion inside the conductor. This

time is dominated by the transverse propagation, which is about twice slower than longitudinally in the first turn. At very low current (2 000 A), the conductor margin is large and the Joule effect is small. Hence Helium evaporation is playing the major role. About 150 s are needed to evaporate the helium and to start the quench propagation. The full quench of the coil requires 150 s + 160 s = 310 s. The protection Heater power supplies must be able to heat up the coil during that time (UPS requirement).

VI. Thermal Behaviour

The BT cryogenics components are divided into three parts :

the external cryogenics which includes the refrigeration system and the cryogenic feed lines,

- the proximity cryogenics which includes the main valve box, a helium buffer dewar, the current lead cryostat, and at the top the two-phase separator,
- the internal cryogenics which concerns the coil equipment and instrumentation of the cryogenic ring (a common annular manifold routing the eight coils and including the superconducting bus).

A common cryogenic system is being studied.

The coils are cooled in the indirect mode by means of cooling pipes ∅ 14 mm glued onto the coil casing Thermal analysis in the steady state has been updated. A redundant circuit is presently under introduction according to CERN requirement and the positions of the cooling pipes have been optimized according to estimated thermal load. A 3 D study has been necessary to check the local over loading resulting from the local heating from to the tie rod.

VII. Warm Structure

When all the magnets are energized, the net radial magnetic force on each BT coil is 1 200 tons directed towards the axis ; each End Cap Toroid (ECT) is attracted towards the center with an axial force of 240 tons. These latter forces are taken at eight points by stainless steel mechanical supports located on the ECT vacuum vessel and on each BT coil vacuum vessel.

The warm structure constitutes the backbone of the ATLAS Barrel Toroid. Its general architecture is presented in Fig.1: the eight vacuum vessels are mutually supported by eight sets of voussoirs and struts distributed along the length of the toroid. Each set, in turn, consists of an internal ring of eight voussoirs and of an external ring of eight struts.

The whole assembly is supported on the feet.

The main functions of the warm structure are to transfer the gravitational load to ground, to take all the magnetic forces and to support the muon detector weight (400 tons). Additional constraints are seismic acceleration of 0.15g, accessibility for maintenance and specific assembly procedure.

Stresses and deformations have been calculated using a complete 3 D FEA model on ANSYS. A new design has made it possible to reduce the stress level in some critical regions and especially by increasing the stiffness of the voussoir ring, namely the rigidities of the voussoir and the tie rod box. The new tie rod box is no more like a box but more like a solid block. The stress level of the structure is acceptable. Typical deformations are presented in Table II. The deformations are mainly caused by the gravitational loads. They are increased by about 30 % as the muon chambers are installed. Compensation during assembly may reduce these deformations. Movements under magnetic loads are very limited.

TABLE II
DEFORMATION IN DIFFERENT LOADING CASES

Case 1 : own weight + cold mass
Case 2 : own weight + cold mass + muon chambers
Case 3 : own weight + cold mass + muon chambers + magnetic forces
Case 0 : only magnetic forces

Loading case	0	1	2	3
Deformations	2 mm	19 mm	24 mm	28 mm

VIII. Conclusion

The construction of the magnet has now started with many industrial partners from different countries. Considerable R&D work has been performed. The main parts of the B0 prototype are close to delivery.

Acknowledgment

The authors express their warm thanks to all the members of DAPNIA and LASA staffs.

These investigations are part of the ATLAS Detector development program for the LHC at CERN and are financed for the major part by the ATLAS Collaboration that includes about 145 institutes in 34 countries.

Références

[1] H. DESPORTES MT 13, IEEE Trans. ou Magnetics 1525, vol.30.

[2] A.DAËL et al MT14 IEEE Trans. ou Magnetics 2047,vol 32 (1996).

[3] A. DAËL et al.MT15 proceedings Beijing October 1997. Science Press. Beijing CHINA

[4] ATLAS Barrel Toroid TDR - CERN/LHCC/97-19 (1997)

[5] F. BROGGI et al. Mechanical Measurements on the Race-Track prototype for the ATLAS B0 an Barrel Toroid Magnet

[6] F.P. JUSTER et al. Stability and quench propagation velocities measurements on Race-Track mock-up of ATLAS toroid coil

[7] B. GASTINEAU-Saclay International Cryogenic Engineering. Conf. 1998 ICEC 17