Mechanical Commissioning of the ATLAS Barrel Toroid Magnet

A. Foussat, H. H. J. ten Kate, A. Dudarev, H. Bajas, P. Védérine, C. Berriaud, Z. Sun, and M. Sorbi

Abstract—ATLAS is a general-purpose detector designed to run at the highest luminosity at the CERN Large Hadron Collider. Its features include the 4 T Barrel Toroid magnet, the largest superconducting magnet (25 m long, 20 m diameter) that provides the magnetic field for the ATLAS muon spectrometer. The coils integrated at CERN, were tested individually at maximum current of 22 kA in 2005. Following the mechanical assembly of the Barrel Toroid in the ATLAS underground cavern, the test of the full Barrel Toroid was performed in October 2006. Further tests are foreseen at the end 2007 when the system will include the two End Cap Toroids (ECT). The paper gives an overview of the good mechanical test results achieved in comparison with model predictions and the experience gained in the mechanical behavior of the ATLAS Toroidal coils is discussed.

Index Terms—ATLAS, mechanical tests, superconducting coils, toroidal field coil.

I. INTRODUCTION

THE barrel toroid magnet is part of the system of ATLAS (Apparatus Toroidal Large Aperture Spectrometer) large air-core toroid magnets that provide the magnetic field needed for the ATLAS muon spectrometers [1]. The Barrel Toroid (BT), see Fig. 1, is composed of eight superconducting coils each housing two double pancakes with in total 120 turns of Aluminum stabilized NbTi/Cu superconductor carrying up to 20.5 kA in nominal operation at 4.6 K. Each double pancake is inserted and glued in an Al5083 casing under pre-stress to limit interfacial shear stress to 10 MPa. The aluminum casing provides a stiff mechanical structure to the coil. The cold mass is housed in a stainless steel 304 L vacuum vessel. The Barrel Toroid structure (22 m diameter and 25 m length) is assembled symmetrically around the colliding beam axis. The eight coils are interlinked and supported by an aluminum alloy warm structure unique in size, design and manufacturing. This novel structure is challenging as it should guarantee reliable toroid operation during the next 15 years.

The warm structure supports not only the eight coils but also about 340 tons of muon detectors, services and access structures

Fig. 1. Overall view of ATLAS barrel toroid magnet installed in the underground ATLAS cavern at CERN.

in ATLAS which constitutes a total mass of 1400 tons. During excitation of the Barrel Toroid, each coil is reacting in-plane centering magnetic forces of maximal 15 MN. Due to the size of the individual Barrel Toroid coils as well as the infeasibility of repairs once installed, a representative test of the single coils on surface at nominal current of 20.5 kA is mandatory.

The comparable electromagnetic forces were generated by testing the coil in close contact with a magnetic mirror. These tests in years 2004–2005 allowed qualifying both magnet design choices and the mechanical operation of the cold mass suspension system up to 1800 kN in a single tie rod [2]. The mechanical assembly of the Barrel Toroid started in the underground ATLAS cavern at the end of 2004 and lasted up to autumn 2005 [3]. The mechanical installation was followed by the completion of the electrical system, cryogenic connections and the Magnet Control system. Finally in autumn 2006, the completed Barrel Toroid was gradually powered up to the nominal current of 20.5 kA.

II. OPERATIONAL LOADS OF THE BARREL TOROID COILS

A. Mechanical Load and Shape of the Barrel Toroid

The Warm structure is composed of eight inner and outer radius supporting rings made of aluminum alloy beams assembled using high strength tensioning studs [4]. The 10 mm thick vacuum vessel is made of stainless steel 304 L. The cold mass is

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A. Foussat, H. H. J. ten Kate, A. Dudarev and H. Bajas are with the European Center for Nuclear Research—CERN 1211, Geneva CH, Switzerland (e-mail: Arnaud.Foussat@cern.ch).

P. Védérine, C. Berriaud and Z. Sun are with CEA, Gif-sur-Yvette, France.

M. Sorbi is with INFN—Laboratorio LASA, Milano, Italy.

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Fig. 2. Cross section of the BT cryostat showing the vacuum vessel, cold mass and the cold mass suspension system onto inner ring: tie rods and cryo-stops.

TABLE I
BARREL TOROID MAIN PARAMETERS

Dimensions	20m diameter x 25 m length
Conductor cross section	57 x 12 mm ²
Nominal current	20.5 kA
Stored energy	1.1 GJ
Operating temperature	4.4 K
Critical current (@4.2 K, 5 T)	67 kA
Peak magnetic field in windings	3.65 T
RRR (Al)	> 1000
Total weight	1100 tons

suspended by eight titanium alloy Ti 5Al2.5Sn tie rods, which react the resultant electromagnetic radial forces on conductors, see Fig. 2. The glass fiber reinforced epoxy resin cryogenic stops support the cold mass weight of 45 tons and accommodate the 51 mm total thermal shrinkage of the cold mass with a sliding system. The Barrel Toroid assembly with a weight of 1100 tons stands on stainless steel feet. The main magnetic parameters are summarized in Table I.

In order to approach the ideal cylindrical shape under self weight and service loads, the Barrel Toroid was assembled with an ellipse shape with eccentricity parameters of $\Delta y = +29$ mm and $\Delta x = -15$ mm based on design calculations [5]. A global ANSYS model was developed at CEA and CERN (Fig. 3) to derive the deformations and resultant forces through the warm structure components and bolted connections [6]. The boundary conditions included gravitational loads, vacuum pressure, muon services load and in-plane radial magnetic forces. Survey measurements have shown an overall vertical down displacement of 27 mm due to the self weight, which is in good agreement with calculations. The expected additional deflection of the warm structure towards the center during powering is 2 mm.

B. Electromagnetic Force Distribution

A 3D TOSCA model of the Barrel Toroid and calorimeter was developed (Fig. 4) to calculate the electromagnetic forces acting on the coils.

When operated alone, the Barrel Toroid is subjected to in-plane radial electromagnetic specific forces of 840 kN/m

Fig. 3. Global ANSYS FEA model of the barrel toroid warm structure.

Fig. 4. View of ATLAS toroid magnet electromagnetic model.

acting on the inner coil legs and 560 kN/m on the outer ones. At nominal operation the presence of the End Cap Toroids introduces a dissymmetry in the specific force along the BT cold mass extremities. The end corner regions at inner radius are subject to a maximum specific total force of 2200 kN/m defined as $F_t = (F_r^2 + F_z^2)^{1/2}$. The specific forces are plotted in Fig. 5 over half of the BT coil perimeter. By integrating the axial specific force F_z , the resultant interaction force between BT and ECT is found equal to 2320 kN. The Hadronic Tile calorimeter includes a central and two end cylindrical parts which are modeled as iron annular blocks with different equivalent permeability values. Its contribution to the electromagnetic force acting on the BT conductor is limited to 15% up to 2200 kN. This result is checked analytically with the image current method.

C. Mechanical Load on the BT Titanium Tie Rods

When energizing the BT coils the magnetic loads are reacted by the eight tie rods, which are part of the coil suspension system [7]. Two BT test configurations are considered for further calculations and comparison with measurements: (1) single BT test completed with Tile calorimeter in place and (2) full BT-ECT test. In order to extract the resultant forces on the tie rods an

Fig. 5. Expected specific force distribution along half perimeter of BT conductors in the BT-ECT test configuration.

Fig. 6. FEA model of the BT cold mass for calculation of tie rods em loads.

TABLE II
BARREL TOROID MECHANICAL LOAD

Test configuration	BT + Tile	BT + ECT + Tile
FEA calculation		
Expected load on tie rod 1,2,3,4 (tons)	132, 115, 103, 60	139, 142, 178, 181
Experimental test results		
Load measurement on tie rods (tons)	114, 100, 98, 55	N/A
Comparison test results wrt prediction	-15 %, -15%, -5%, -9%	

ANSYS model of the cold mass was built (Fig. 6). The calculated distribution force is input into the FEA model, which includes the operational 10 MPa pre-stress between windings pack and casing. The resultant expected forces are compared with the readings of the strain gages on the tie rods during the BT test with the end cap tile calorimeter in open configuration as summarized in Table II.

Fig. 7. Expected specific forces distribution along ECT conductors in the full system BT-ECT test configuration.

In the single BT test the current was ramped up to 14, 18, 19 and 20.5 kA corresponding to 46, 77, 86 and 100% of the maximum electromagnetic load respectively. A maximum load was measured on inner tie rods up to 114 tons. The measured load levels on tie rods are up to 15% lower than predicted. The differences can be explained since part of the BT stray field is also magnetizing some surrounding iron structure, which reduces the effective radial load on the tie rods. The electromagnetic interaction between ECT and BT increases the peak total specific force on BT conductor by 55% up to 2380 kN/m with respect to the case of BT alone. This force corresponds to a maximum load on the extremity tie rod number of 181 tons. The total specific force on the ECT conductors raises up to 3800 kN/m as shown in Fig. 7.

III. ANALYSIS OF TEST RESULTS

The cooling down of the barrel toroid to 4.6 K caused a cold mass thermal shrinkage of 51 mm inducing a total displacement of 45 mm on the extremity tie rod as expected. The corresponding bending strain in the tie rod was monitored during cooling using strain gages as shown in Fig. 8 in order to check the displacements. It is observed that the tie rod feet move symmetrically around the fixed point as expected with maximum displacement of 45 mm.

At nominal current in presence of the ECT magnets, each coil reacts a large expected centripetal force up to 1200 tons. In the last single BT test each coil has seen around 60% of this load level without the ECT coils in place. The Tile calorimeter was opened with 3.5 m gaps between central and end caps modules. Some full bridge cryogenic epoxy phenolic backing strain gages Vishay types WK-06-120NB were used to monitor the tensile load on each tie rod during the current ramp up. The displacement of BT warm structure was also recorded with mechanical comparators CX, CY and optical instruments on top sector and side ones.

A. Displacement Measurement

Considering the equivalent stiffness of warm structure supports it was calculated that BT would deform uniformly inwards by $dy = dx = -2$ mm. The measurements shown that the top sector raised by $dy = +3$ mm and the side ones moved inwards

Fig. 8. Relative displacement of 8 tie rods on each coil during cool down.

Fig. 9. Displacement measurement of BT structure during coil excitation.

by $dx = -2$ mm (Fig. 9). This non-uniform deformation of the Barrel Toroid is characteristic of the combination of constrained displacements on bottom coils in ATLAS feet and an initial non circular assembly shape.

B. Magnetic Load Measurement

The maximum load measured on the inner central tie rods is 114 tons (Fig. 10). No hysteresis is visible, which denotes the mechanical reversibility of the BT suspension system. The analysis has shown a maximum load difference of 20% between tie rods of same category. This difference can be explained by the different azimuthal position of the BT coils.

C. Fixed Point Measurement

The fixed point installed on each central rib is made of fiber glass reinforced epoxy, PermaglassFE29, 50 mm diameter rod

Fig. 10. Load measurement on tie rods during current ramp up to 21 kA and followed by a fast dump.

with tensile modulus of 30 GPa and provides a reference contact point during the BT cold mass thermal shrinkage. When energizing the BT coils a relative movement of 1.7 mm of the aluminum rib with respect to the fixed point introduces bending strain with a dynamic range of $2250 \mu\epsilon$. This deflection is about the same as observed at the on-surface test.

IV. CONCLUSION

An extensive testing program is performed to test and qualify of the ATLAS Barrel Toroid mechanics. The achieved load and stress levels are those of the fully assembled ATLAS Barrel toroid coil without presence of the End Cap Toroid. The good agreement found between the predictions based on a finite element model and the mechanical measurements performed during the tests demonstrates that the coil mechanical behavior is understood. The reproducibility of the evolution of the stresses on tie rods and the warm structure deformation during testing including cycling tests showed that no measurable degradation of coil mechanics occurred.

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