Mechanical Characteristics of the ATLAS B0 Model Coil

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Abstract—The ATLAS B0 model coil has been tested at CERN to verify the design parameters of the Barrel Toroid coils (BT). The mechanical behavior of the B0 superconducting coil and its support structure is reported and compared with coil design calculations. The mechanical stresses and structural force levels during cooling down and excitation phases were monitored using strain gauges, position sensors and capacitive force transducers instrumentation. In the ATLAS magnet test facility, a magnetic mirror is used to reproduce the electromagnetic forces present in the BT coils, once these are assembled in toroid in the underground cavern in 2004.

Index Terms—ATLAS magnet system, capacitive force transducers, cold mass, FEA stress calculations, strain gauges measurements, toroidal coil.

I. INTRODUCTION

THE COMPLETION of the B0 model coil is a major technical milestone within the ATLAS Magnet Design Activity, which started in 1996. The main objectives of the B0 model coil testing are: validation of the coil production techniques, determination of operational margins, and verification of the design criteria. An extensive campaign of measurements, aimed to characterize the mechanical, thermal, electrical and magnetic properties of the coil, was performed in the period April–Dec. 2001. In this document, the focus is on the mechanical measurements made on the B0 coil facing the iron magnetic mirror, which reproduces the electromagnetic stress levels reached in the final Barrel Toroid.

The main mechanical objectives of the test program are:

- 1) Demonstrate correct rotation in tie rod system during cooling down, warming up and energization;
- 2) Reproduce Barrel Toroid peak radial electromagnetic forces;
- 3) Demonstrate the “cold mass supports” operation during thermal cycling.
- 4) Validate local stress calculations on the cold mass.

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Fig. 1. Overall view of assembled barrel toroid.

Fig. 2. Cross section of a Barrel Toroid Coil. The cold mass is suspended by titanium tie rods and react the force.

II. ATLAS BARREL TOROID SYSTEM

A. ATLAS Barrel Toroid Design

The Barrel Toroid, part of the ATLAS magnet system [1], is composed of 8 flat racetrack coils (Fig. 1), each consisting of two double pancake windings housed in a common aluminum alloy casing that guarantees rigidity and transfer of the magnetic forces. The coils are indirectly cooled by cooling LHe pipes mounted on the coil casing. The dimensions of each coil are: 26 m long and 5 m wide, racetrack shape.

During operation of the ATLAS detector, each BT coil undergoes large resultant radial electromagnetic centering forces up to 11 MN which are reacted by the “warm structure” via Titanium tie rods. The ATLAS Magnet System, which consists of 8 Barrel Toroid (BT) coils, 2 End Cap Toroids (ECT) and the

Fig. 3. Layout of B0 coil testbench: (1) Support units, (2) Ribs, (3) Vacuum vessel, (4) Busbars system, (5) Vacuum line, (6) Cryogenic service turret, (7) Current lead turret, (8) Magnetic mirror.

Central Solenoid, is one of the largest superconducting magnet systems, in the process of being built, with total stored energy of 1.5 GJ [2].

B. Purpose of the B0 Model Coil Mechanical Test

The B0 model coil has been mechanically characterized using a magnetic mirror [3]. The electromagnetic external forces, produced by the magnetic mirror, are reacted by three titanium tie rods, anchored to the casing and the vacuum vessel via pivot mechanisms. The choice of titanium for the tie rods allows for a light, slim and low heat leak structure. Its high mechanical strength facilitates to sustain forces up to 2000 kN at each tie rod.

On the test stand, each tie rod head, at the vacuum vessel end, is rigidly bolted to the magnetic mirror via massive steel supports (Fig. 3).

Calculations were performed on the configuration B0 coil plus magnetic mirror. At the nominal current, of 20.5 kA, the total forces (auto plus external forces) reach a maximum of force per unit length of 1750 kN/m, in the corners of B0 coil. In B0 an increase of current to 24 kA develops a maximum total force of 2250 kN/m, which matches the peak force on the BT system (Fig. 4) at 20.5 kA. The B0 mechanical test is needed to validate the mechanical operating conditions of the BT system, and for this reason B0 was tested up to 24 kA, which overload the titanium tie-rods by 40%.

C. Mechanical Instrumentation

The B0 coil was mechanically instrumented [4] using strain gauges and capacitive force transducers [5]. Five strain gauges (thermally compensated) were located on each titanium tie rod; enabling to calculate the tie rod stress and the resultant radial EM forces. Two displacement transducers monitored the thermal contraction of B0 aluminum cold mass during cooling down. The fiber glass cryogenic supports were instrumented with compensated strain gages to calculate axial loading share and bending stress due to the cold mass sliding. Capacitive force transducers were installed on each support unit in compression between the support and the magnetic mirror. These sensors were read out by an LCR meter.

Fig. 4. Comparison of calculated total forces on BT system and B0 model coil with magnetic mirror.

TABLE I
B0 MODEL COIL MAIN FEATURES

Dimensions	5m x 9m
Cable Cross Section	57 x 12 mm ²
Current	24 kA
Stored Energy	63 MJ
Operating Temperature	4.4 K
Critical Current (@4.2K, 5T)	67 kA
Maximum magnetic Field	3.65 T
RRR (Al)	> 1000
Total weight	40 tons

III. MECHANICAL DESIGN CALCULATIONS

Electro-magnetic force calculations and structural calculations were performed to estimate the deformations and stress levels on different support parts of the B0 coil. The electro-magnetic calculations made with TOSCA OPERA software (Fig. 5) is used to determine the distribution of the radial resultant EM forces [6]. The mean calculated radial force at 20.5 kA is 420 kN/m, with a distance of 385 mm to the magnetic mirror and the total radial force is 3800 kN (Table II). The overall distribution of EM forces is input for the FEA structural model to calculate stress levels in the coil casing and tie-rods of the coil.

At 20.5 kA the resultant displacement varies from 0.8 to 2.7 mm, the maximum value is reached at the central tie rod position. The corresponding maximum Von Mises stress level in the middle of long side of the coil casing was 25 MPa.

1) *Calculations on Cryogenic Stop Support:* The overall weight of cold mass and thermal shield is supported by the cryogenic stop supports, which allow for relative movement of cold mass and vacuum vessel. During loading of the 20 tons cold mass onto the cryogenic stops, the expected maximum strain is around 910 $\mu\text{m/m}$, which corresponds to 43 kN in compression. The relative sliding of the cold mass is inducing bending strain in the cryogenic stop up to 600 $\mu\text{m/m}$ due to some 3 kN transverse force (Fig. 6).

2) *Calculations on Tie Rod Support System:* The titanium tie rod system is reacting EM radial forces exerted on the coils to the vacuum vessel. The B0 coil is equipped with three tie rod and BT coils with 8 [6]. During cooling down to 4.2 K, the

Fig. 5. Tosca Opera model of B0 coil model with magnetic mirror.

TABLE II
FEA EM FORCES CALCULATIONS AT 20.5 kA

Mean magnetic force on coil	420 kN/m
Mean magnetic force on straight length	950 kN/m
EM Tensile force in Ribs	1080 kN
Resultant EM radial force	3800 kN +/- 10%

Fig. 6. Bending strain calculation on the cryostat for 1 kN transverse load.

cold mass is thermally shrinking with respect to the fixed point, which displaces the anchored feet of the tie rods.

The head of tie rods accommodates this movement by a pivot link mechanism on the tie rod head. In B0 coil, the movement of tie rod feet is estimated from 5.2 mm to 19.9 mm maximum toward the fixed point.

As shown on Fig. 7, a 10 mm displacement results in a maximum longitudinal strain of 300 $\mu\text{m/m}$ in the thinner section of the tie rod during cool down (see Material properties in Table III). The FEA calculations on the cold mass model predict some deformation from 0.3 to 2.8 mm on the central tie rod area (Fig. 8).

Fig. 7. Strain levels in the titanium tie rod when displacing of 10 mm by rotating tie rod head.

TABLE III
MATERIAL PROPERTIES

Titanium	$E_{(293K)} = 115 \text{ GPa}$ $E_{(4K)} = 131 \text{ GPa}$ $\int \alpha \Delta T (293K-4K) = -1.51 \text{ mm/m} \cdot$
Aluminum 5083 alloy	$E_{(293K)} = 70 \text{ GPa}$ $E_{4K} = 80 \text{ GPa}$ $\int \alpha \Delta T (293K-4K) = -4.19 \text{ mm/m} \cdot$
Stainless Steel	$E_{293K} = 200 \text{ GPa}$ $E_{4K} = 210 \text{ GPa}$
Fiber Resin Epoxy cylinder	$E_{4K} = 11.5 \text{ GPa}$

Fig. 8. Global deformation FEA calculation on the cold mass.

Fig. 9. Slip and stick sliding of cryogenic interfaces.

IV. MECHANICAL MEASUREMENT

Cooling down and energization of the B0 model coil have provided the deformation and stress levels in the different coil supports.

A. Cooling Down Phase

The B0 model coil is indirectly cooled down by He flowing in pipes that are glued on the coil casing. To minimize the differential thermal stresses, the cooling down is performed by controlling the temperature gradients on both coil casing and thermal shields to less than 40 K [8]. It was necessary to verify the mechanical behavior of force transfer systems, like cryostops, tie rods and fixed point, during the thermal contraction of the coil.

1) *Measurements on Cryogenic Stops:* During thermal contraction, the total displacement of 37 mm of the cold mass induces some bending on the Fiber Resin Epoxy (FRE) cryostops. The maximum strain recorded is below the material design limit of 1500 $\mu\text{m/m}$ corresponding to 30 MPa. The maximum increase of strain during cooling down is 240 $\mu\text{m/m}$ which is due to 2.75 kN sliding force (Fig. 9). Considering a maximum loading on a cryostop of 45 kN, the maximum static friction coefficient is 0.061 for the Teflon coated SS/Aluminum interface.

2) *Measurements on Tie Rods:* A spring washer based system is used to keep minimum compressive forces applied during cooling down on the tie rods, once they reach the median position. The critical buckling load is given by $P_c = m \cdot (\pi^2 \cdot E \cdot I / L^2) = 26 \text{ MPa}$ ($m = 1$ if both ends are articulated). The maximum axial compressive strain measured on tie rod A is $-180 \mu\text{m/m}$ which corresponds to 21 MPa compressive load. A 19.9 mm displacement of the tie rod foot, anchored into the cold mass yields some bending strain up to 550 $\mu\text{m/m}$ providing that the tie rod head is rotating as shown in Fig. 10. below.

B. Coil Energization—Radial Force Measurement

The coil has been energized up to the nominal current of 20.5 kA and a peak value of 24 kA.

The net radial force was derived from strain gauges on tie rods and capacitive force transducers.

At 24 kA, a net radial force of 2280 kN was measured on the middle tie rod, 1700 kN on side A, and 1530 kN on side B which gives a total resultant radial force of $5520 \text{ kN} \pm 10\%$ (Fig. 11). This value is consistent with the prediction from Table II made at 20.5 kA.

Maximum bending stress of 25 MPa in the cold mass occurs at the middle of the long branch opposite side to the mirror. No

Fig. 10. Bending strain on tie rod A during cooling down phase with rotating head.

Fig. 11. Radial forces measurements in the B0 coil supports with capacitive force transducers up to 24 kA.

additional vertical forces due to floor permeability were measured on capacitive force transducers.

V. CONCLUSION

The successful completion of the B0 coil mechanical test at 24 kA was a major step in demonstrating the feasibility and mechanical reliability of the ATLAS Magnet System, which for its exceptional size represents a unique challenge in magnet technology.

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