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PRESTRESSING CONCEPTS AND RELATED MATERIALS QUALIFICATIONS FOR THE ATLAS BARREL TOROID COIL

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ABSTRACT

The Barrel Toroid Magnet is part of the Magnet System of the ATLAS Detector for the LHC. 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 whole magnet structure is made of aluminium or aluminium alloys, and is subjected to a high level of strain induced by the Lorenz forces. In order to ensure the reliability of the magnet an innovative process for the prestressing of the windings in the coil casing has been develloped at DAPNIA/STCM Saclay. The paper explains this process and reviews the developments undertaken at Saclay to qualify the materials and predict the remaining level of stress at the operating temperature (4.8 K).

INTRODUCTION

The Barrel Toroid Magnet is part of the Magnet System of the ATLAS Detector for the LHC[1]. 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 eight flat superconducting coils of the ATLAS Barrel Toroid have a race track shape of 26 meters length and 5 meters width. In order to ensure the reliability of the magnet an innovative process for the prestressing of the windings in the coil casing has been developed at DAPNIA/STCM Saclay. This process will be qualified during the assembling of the B0 coil[2] which is a shortened racetrack coil, having a length of only 9 meters.

Although the process mainly consists in putting strain in one part of the structure the expression "prestressing", being more usual, will be used in the article.

REQUIREMENTS

Each of the coils consists of two double pancakes of insulated conductors in a coil casing. The conductor is a pure aluminium stabilised cable obtained by a coextrusion process. After winding the double pancakes are insulated using a vacuum impregnation technique, and inserted in the coil casing. Since the conductor carries a 20500 A current, each stack of conductors takes 2.46 10^6 A in a region where the magnetic field increases from –2.15 T to +2.8 T, and from -2.6T to +3.85T in the peak field region. Therefore due to the Lorenz forces the stack of conductors is strongly compressed on itself during the energisation of the magnet. The compressive stress appearing on the stack of conductors can be expressed as:

$$F_x(B) = \Sigma\, B_{yi}\, I_{zi} \quad \text{per unit length}$$

$$\sigma_x(B) = F_x / S_{coil} = I_{zi}\, \Sigma\, B_{yi} / S_{coil}$$

$$\varepsilon_x(B) = \sigma_x(B) / E_{coil} \qquad (1)$$

Where X, Y and Z are the directions as expressed in figure 1, S_{coil} represents the surface of coil per unit length in the XY plane, (B) indicates a function of the magnetic field and i the conductor number in the stack.

The indirect cooling technique requires a good bonding of the double pancake coils on the coil casing. The shear stress appearing between the double pancake coil and the coil casing would represent a very unsafe design for a magnet that stores 1.2 GJ.

Moreover a displacement of the conductors may produce a quench of the coil, and any debonding could irremediably damage the magnet by reducing the efficiency of the conductive cooling.

In order to avoid shear stress at the double pancake/coil casing interface the prestressing technique developed by DAPNIA/STCM creates tensile stress in the coil casing during the assembling of the magnet. Therefore during the energising of the magnet, the tension in the coil casing will be released by the magnetic compression of the stack of superconductors, but no relative movement can appear and shear stress is not induced at the interface.

The technique retained to impose the prestress is to use inflatable bladders on each side of the superconducting winding. The bladders 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. This can be expressed as putting a mechanical strain in the coil casing corresponding to the following expression:

$$\varepsilon_x(M) = F_{bladder} / S_{casing}\, E_{casing} \qquad (2)$$

$$\varepsilon_x(M) = P_{bladder}\, S_{coil} / S_{casing}\, E_{casing} > \varepsilon_x(B)$$

Which leads to a value of the applied pressure in the liquid resin that corresponds to:

$$P_{bladder} = S_{casing}\, E_{casing}\, \mathrm{Max}[\varepsilon_x(B)] / S_{coil}$$

Where S_{casing} represents the surface of Casing in tension per unit length in the XY plane, (M) indicates a function of the bladder pressurising system.

In the case of B0 it is foreseen to use 48 bladders placed on each side of the two double pancakes. For the eight race track coils of the Barrel Toroid 832 bladders will be necessary. The bladders will have a length of 2.2 meters and a width of 122 mm. After pressurising and curing their thickness will be comprised between 8 and 11 mm. The picture 1 gives an idea of the size of a bladder.

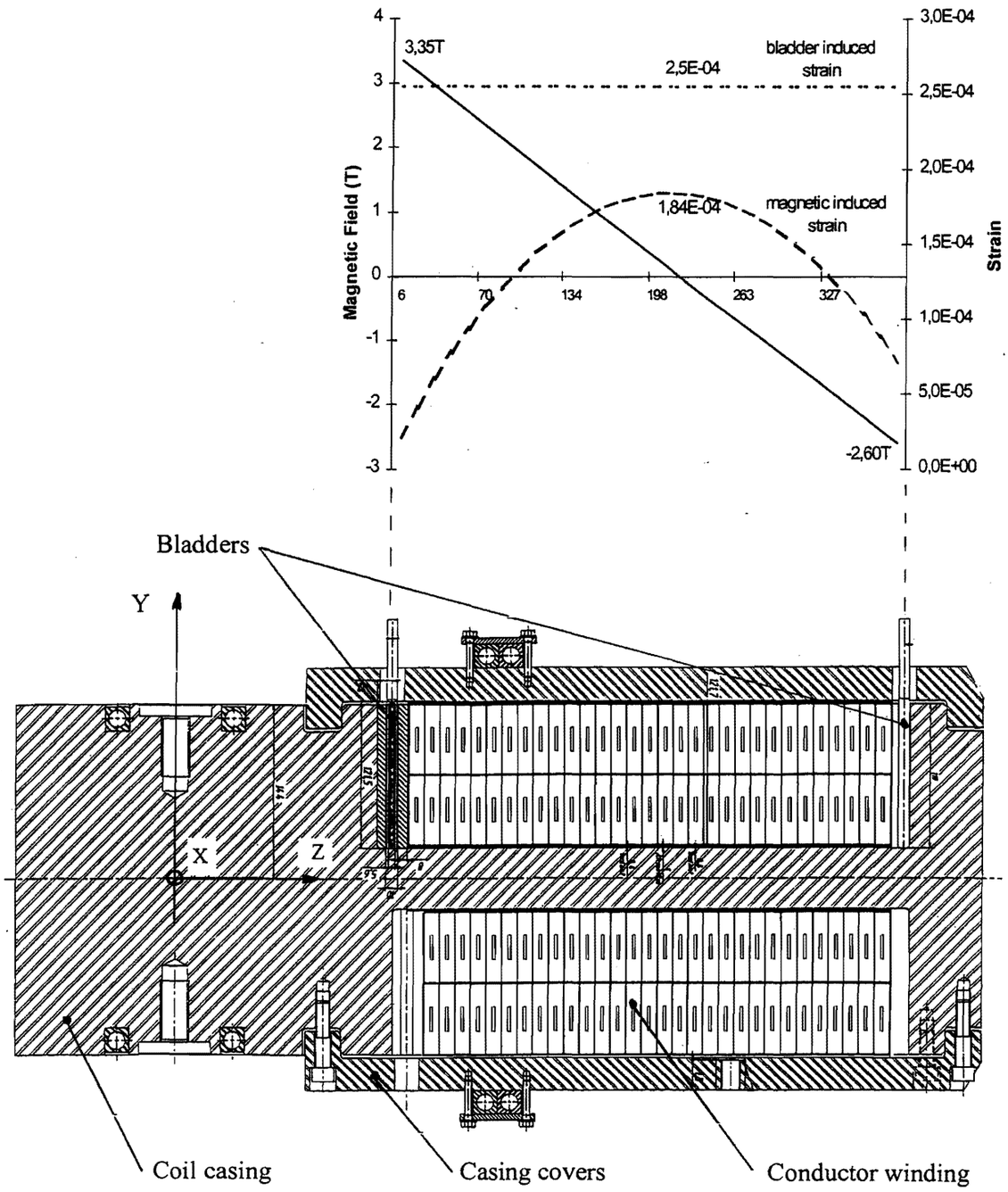


Figure 1: Upper part: Magnetic field and magnetic induced strain and bladder induced strain as a function of the conductor location along the coil casing width (along X axis). Lower part: Cross section of the ATLAS race-track coil. The bladders are located on each side of the conductor windings. The bladders of the lower coil are not represented.

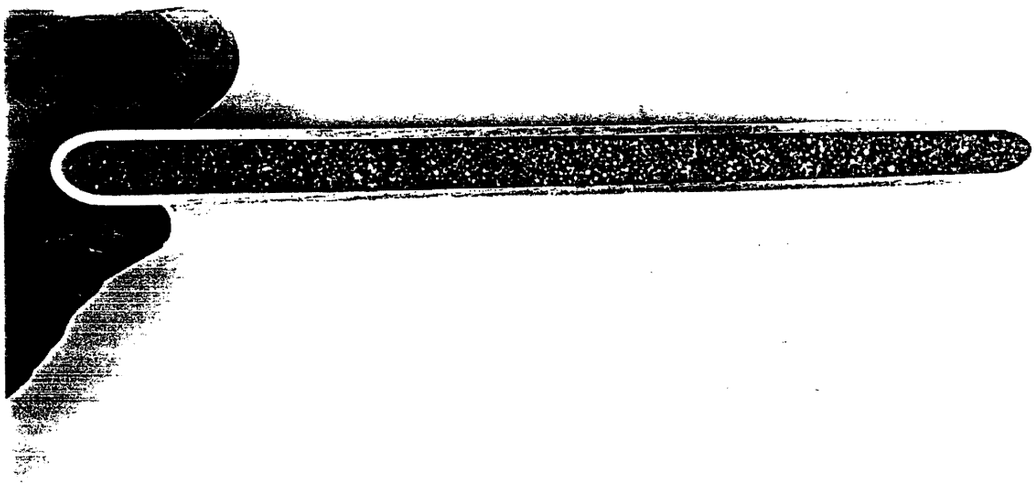
Picture 1: Full scale bladder hold by a human person.

PROCESSING

Since it is not possible to fill a bladder with a resin and microballs mixture because the compound did not flow easily, the processing operations comprise the following sequences:

- The bladders are inserted between the coil casing and the double pancake and the coil casing covers are fitted to close the coil casing.
- The bladders are inflated with gaseous nitrogen up to 20 bars (2 MPa) to expand and fill the gap between the double pancake and coil casing.
- The gaseous nitrogen is released and the bladders are filled with glass microballs.
- The remaining gas are evacuated from the bladder to a pressure of 5 mb.
- The bladder is impregnated with epoxy resin. The pressure applied on the resin is first increased to 2 MPa for two hours in order to impregnate completely the microballs in the bladder.
- The pressure is further increased to 20 MPa by steps of 2.5 MPa. The tubing and the unions are checked at each steps to prevent from leakage.
- The system is cured under pressure.

All this process is possible because the preimpregnated material that will glue the double pancake coil on the coil casing are cured during the same thermal cycle as the bladders. The prepreg, that will ensure the conductive cooling from the coil casing to the winding, is cured between one part in tension and one in compression but is not subjected to shear during the working life of the magnet.



Picture 2. View of a cut bladder.

MATERIALS QUALIFICATIONS

Bladder. The bladders are made of 5754 aluminium alloy tubes. The aluminium is first formed in a tube having an external diameter of 77.6 mm and a wall thickness of 1.15 mm. The tubes are flattened and one injection port is welded at each end of the bladder.

Microballs. The microballs used to fill the bladders have a spheric shape and a diameter varying from 430 to 850 μm. This size has been chosen to ease the filling of the bladders because the microballs can easily roll an each other. Their density, 2.5 at 25C, has been measured using a MICROMERITIC pycnometer type 1305.

Resin. The resin used to impregnate the bladder is a CIBA product referenced CY 192, and cured with the hardener HY 917. This resin has been chosen for its low viscosity, 250 to 450 mPa.s at 25C, and long pot life, two days at 40C. The properties of this resin have been published in a previous work[3]. These are a high density, 1.264 at 25 C, and a low chemical contraction during the curing, 0.24 %, compared to other epoxy resin. The thermal contraction between 300K and 4K is 0.114 mm/m.

Bladder Filling Material. The composite material of a bladder cured under pressure has been removed by cutting the bladder. The measurements done on this composite material gave a density of 2.024 which corresponds to a microballs volumic fraction of 0.62. The thermal contraction between 300K and 4K has been estimated using the mixing rule and the thermal contraction of pyrex glass [4,5]. The calculated thermal contraction from 300K to 4K is 0.48. A cut bladder, cured under pressure, is shown in picture 2.

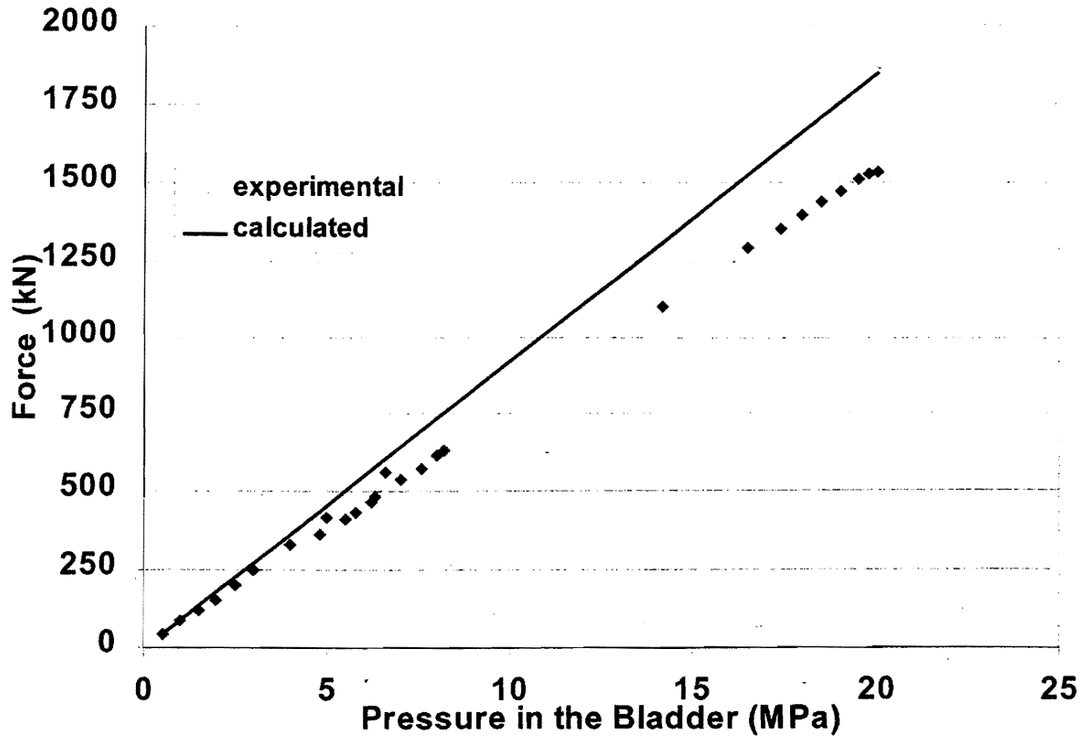


Figure 2: Measured bladder efficiency. The dots on the lower curve correspond to the experimental points. The upper line correspond to the calculated force considering an effective area equal to the overall surface of the bladder.

Superconducting Winding. A short model of the coil winding has been realised to measure its mechanical properties. A stack of pure aluminium conductors wrapped with glass fiber ribbons has been impregnated under vacuum with epoxy resin. The ratio between the conductor and the insulation were the same as in the ATLAS double pancake windings. The compression measurement made on this stack of conductors has given a modulus of 55 GPa.

EFFICIENCY OF THE BLADDERS

The efficiency of the bladder has been defined as the ratio of the measured force applied by the bladder to the calculated force applied by an hydraulic jack having the same external section as the bladder. This has been measured using a bladder of 758 mm length and 122 mm width pressurised with oil under a 2000 kN hydraulic press regulated at a fixed position. The force was recorded using the load cell of the press. The result of this test is presented in figure 2, showing the force measured in the load cell as a function of the pressure applied in the bladder. The calculated force corresponds to the resulting force for a pressure applied on the overall surface covered by the bladder. From the test the efficiency is 0.83. The difference between experiment and theory comes from the pressure used to deform the aluminium of the bladder and the reduced effective area due to the edges of the bladder.

REMAINING PRESTRESS IN THE OPERATING CONDITIONS

In order to estimate the right pressure to put in the bladders during the curing cycle, the remaining strain in the coil casing at the operating temperature of the ATLAS coil has been calculated. These calculations consider successively the pressurising of the resin in the bladders, the curing of the resin, the cooling and the energising of the magnet. At each step the stresses and strains are calculated in the different materials. The values used are given in table 1. To be conservative the calculations have been done considering the bladder filling material could be pure resin. Figure 3 shows the remaining strain in the coil casing after energising as a function of the pressure applied in the bladder for the mean field and in the peak field region. The plotted values corresponds to the difference between the bladder induced strain and the higher value of the magnetic induced strain shown in the upper part of figure 1. For the prestressing of the double pancake windings in the coil casing the retained

Table 1. Materials properties used for the calculation of the remaining prestress

Material	Elastic modulus At 300K	Elastic modulus At 4K	Thermal contraction 300K to 4K
Coil Casing	71.5 GPa	77 GPa	0.43%
Conductor Winding	50 GPa	55 GPa	
Pure Aluminium	70 GPa	77 GPa	0.43%
Electrical Insulation			0.8%
Bladder Filling Material	9 GPa	10 GPa	1.14%

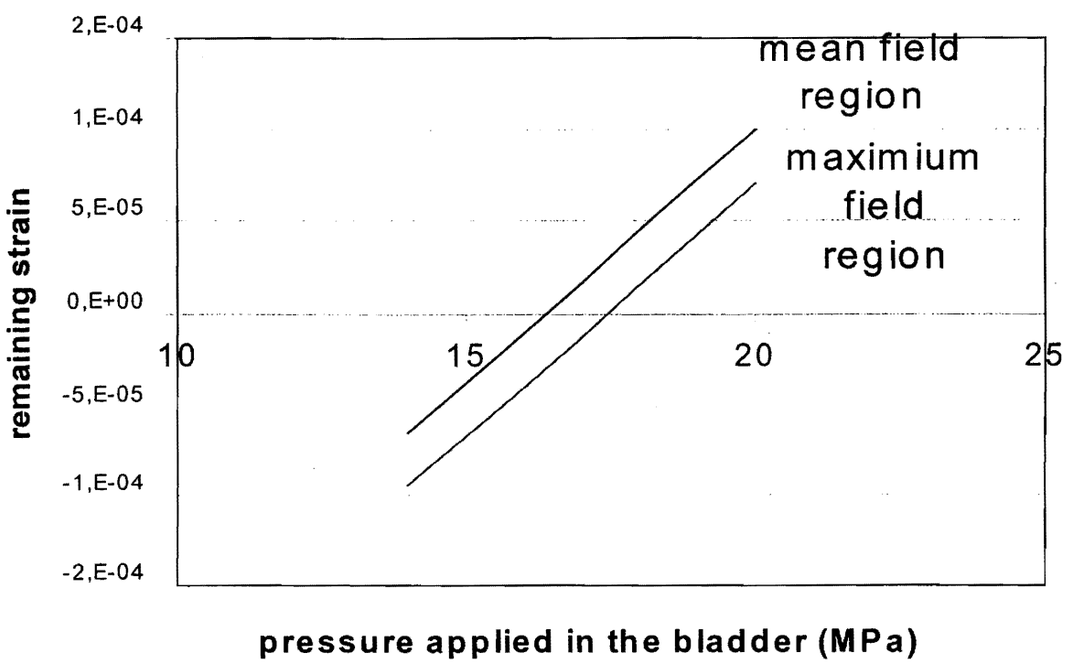


Figure 3: Remaining elastic strain stored in the coil casing as a function of the applied pressure during the curing cycle. The two lines correspond two the mean field region and to the maximum field region.

value of pressure to be applied in the bladder resin is 20 MPa which gives a satisfactory safety margin of 2 MPa at the peak field location.

CONCLUSION

A prestressing technique has been developed by DAPNIA-STCM at Saclay to ensure a stress free interface between superconducting windings and coil casing for magnet using conduction cooling technique. This technique uses bladders filed with glass microballs and epoxy resin. It will be used to realise the ATLAS B0 coil and later on the eight race-track coils of the ATLAS Barrel Toroid.

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