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*Large Hadron Collider Project*

**LHC Project Report 534**

# MODELING OF COIL PRE-STRESS LOSS DURING COOL-DOWN IN THE MAIN DIPOLES OF THE LARGE HADRON COLLIDER

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# Modeling of Coil Pre-stress Loss During Cool-down in the Main Dipoles of the Large Hadron Collider

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*Index Terms*— **Superconducting coil, pre-stress losses, mechanical properties, elastic modulus, thermal contraction**

## I. Introduction

The mechanical behaviour of a superconducting magnet is an important feature to ensure good performance. Finite element models of the dipole cross-section are used both to optimise the mechanical structure, and to figure out the tolerances of the dipole components [1], [2], [3]. The modeling of these structures is not trivial [4]: this is mainly due to the complex behaviour of the blocks of conductors, that feature a large mechanical hysteresis, a non-linear stress-displacement relation, and difficulties in defining a thermal contraction factor [5], [6], [7], [8].

The aim of this work is to predict coil deformations induced by loads during assembly and cool-down in the main dipoles of the Large Hadron Collider (LHC). In particular, we are interested in modeling stresses and displacements at ambient temperature and at cryogenic temperature, having as input the dimensions of the collared coil components. In [9] we evaluate the influence of the obtained deformations on the magnetic field-shape, showing that they are consistent with magnetic measurements and that they cannot be neglected for the LHC beam dynamics.

Here, we show how to build the mechanical model of the collared coil at 300 K and at 1.9 K, based on the mechanical properties of stack of cables and on the collaring procedure. The model is validated by experimental measurements of the dependence of pre-stress and of collar deformations on the dimension of spacers between coil pole and collars (shims). The final cross-check is given by the comparison between simulations and experimental data of the azimuthal pre-stress loss in the coil from 300 K to 1.9 K.

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## II. Mechanical behaviour at 300 K

### A. Coil mechanical properties

In [7] we presented measurements of the mechanical properties of the LHC main dipole coils. Stacks of conductors have been analysed. As it has been observed in several types of insulated cables (see for instance [2]), the stack features a large elongation in a loading-unloading cycle. In Fig. 1 we plot the measured stress-displacement curves of a stack of the insulated cable of the inner layer. Five cycles of loading-unloading are shown, with peak stresses ranging from 70 to 120 MPa.

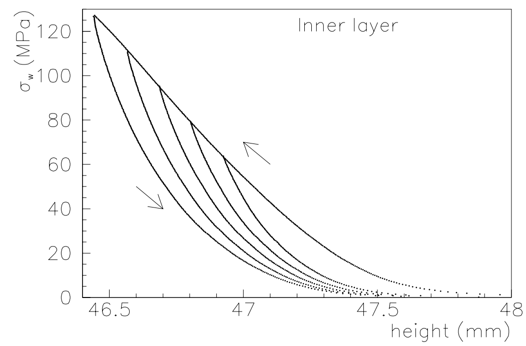


Fig. 1. Stress $\sigma_w$ (MPa) at ambient temperature versus total height of a stack of conductors for the inner layer, loading and unloading curves from different peak stresses (experimental data of Ref. [7]).

For a linear stress-strain relation, elastic modulus is the ratio between stress and strain. In the general case, it can be defined as the derivative of the stress with respect to the strain; therefore, it depends on the stress. Elastic modulus can be evaluated from the stress-displacement experimental curve shown in the above figure according to

$$E(\sigma) = \frac{d\sigma}{d\epsilon} = \frac{d\sigma}{dl} l_0. \quad (1)$$

where $l_0$ is the stack height. One obtains values that considerably vary according to the pressure and to the cycle: between 40 and 100 MPa the elastic modulus is around 5.5 GPa in loading, and is between 6 GPa and 18 GPa in unloading (see Fig. 2).

### B. Collaring procedure

The large hysteresis shown in the stress-displacement plot is an important feature of our model: indeed, during the collaring, the coils are compressed up to a peak pre-stress and when the pressure is released only a fraction of it is left. This is due to the elasticity of the collars,

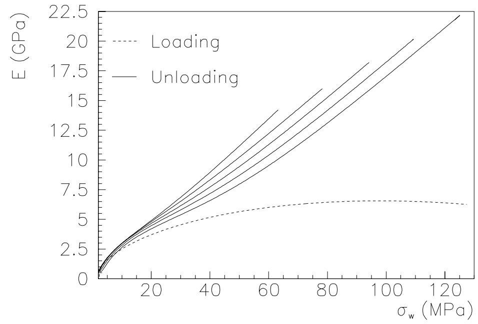


Fig. 2. Elastic modulus $E_w$ (GPa) versus stress $\sigma_w$ (MPa) at ambient temperature of a stack of conductors for the inner layer, loading and unloading curves from different peak stresses (experimental data).

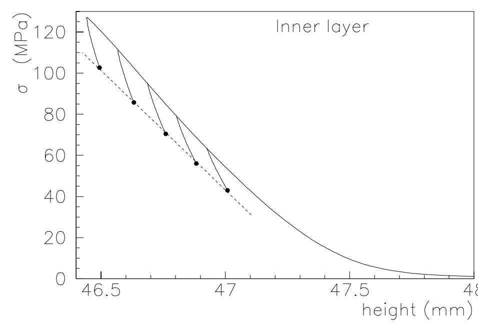


Fig. 3. Equivalent stress-displacement curve (dashed line) for the coil inner layer.

that are pushed up and deformed by the pre-stress (the so-called spring-back). Moreover, to insert the collaring rods one also needs some clearance between the holes and the rods that provokes an additional loss of pre-stress. Stress measurements made with capacitive gauges [10] placed on the coil poles have been taken for the LHC dipole prototypes; a ratio of 0.6 between the residual pre-stress after collaring and the peak pre-stress during collaring provides a good fit of experimental data.

### C. *Modeling coil elasticity at 300 K*

The aim of our finite element model is to compute loads and displacements, having in input the geometry of the components of the collared coil at 300 K. Since the collaring procedure is not modelled explicitly and loads are applied through interferences of contact elements, the mechanical properties of the coil must include informations on the path followed in the stress-displacement graph (see Fig. 1). For instance, if the pole shims are larger than the nominal ones, during the collaring a higher peak pre-stress will be reached, and the unloading will take place along a different branch of the curve (see Fig. 3, solid lines). Therefore, the elastic modulus of the coil to be input in the model is neither the loading nor the unloading, but an 'equivalent' modulus taking into account the peak pre-stress [11]. The equivalent stress-displacement curve is shown for the inner coil in Fig. 3 (dashed line). Its slope is smaller than both the unloading and the loading curve. Values for the loading, unloading and equivalent elastic moduli of the inner and outer coil are given in Table I.

### D. *Results: model vs experiments*

The mechanical behaviour foreseen by the model has been tested at 300 K with a dedicated experiment on a 1-m long prototype [11]. The magnet has been assembled five times with different pole spacer (shim) dimensions to vary the pre-stress and the azimuthal coil length in the collared coil. A 'central' setting with nominal shims plus four other configurations with either inner or outer shims thicknesses different by ±0.15 mm were tested. In each case, pre-stress at coil poles and vertical diameter of the collars were measured. Post-processing of experimental data show that a 0.1 mm thicker shim provokes a pre-stress increase of 12 to 13 MPa on the corresponding layer. Results from the model are in agreement with experimental data (see Table II). Our model underestimates the outer layer pre-stress sensitivity of 2 to 4 MPa; this could be due to slight differences in the mechanical behaviour between conductor stacks and conductor arcs. Indeed, one can point out that if the unloading elastic modulus at 70 MPa (around 12 GPa) had been used, we would have obtained a sensitivity of 25 MPa.

TABLE I

Equivalent, loading and unloading elastic moduli (GPa) of the coil at 70 MPa.

| | Inner layer | Outer layer |
|---|---|---|
| $E_w^e$ (equivalent) | 5.5 | 5.1 |
| $E_w^u$ (unloading) | 12.0 to 14.0 | 11.0 to 13.0 |
| $E_w^l$ (loading) | 6.6 | 6.4 |

TABLE II

Additional pre-stress (MPa) due to a 0.1 mm thicker shim.

| | Inner layer | Outer layer |
|---|---|---|
| Measurements | $12 \pm 1$ | $13 \pm 1$ |
| Finite element model | 12 | 10 |

Another ingredient necessary to obtain a correct mechanical model is the collar deformation due to the coil pre-stress. This is a combined effect of the elastic modulus of the collar material, i.e., austenitic steel 316LN, and of the two-in-one collar geometry. The change in the collar vertical diameter due to a pre-stress variation of 10 MPa on both layers was evaluated in the same experiment. The finite element model results give 0.036 mm, in agreement with the experimental data of 0.037 ± 0.006 mm.

## III. Behaviour at 1.9 K and pre-stress loss

### A. *Coil elasticity at 77 K*

We measured the stress-displacement curves at 77 K for the inner and outer layer stacks; elastic moduli were worked out using the same scheme outlined for 300 K (see section II.A). Results are shown in Fig. 4: the unloading modulus is similar to the ambient temperature case, whilst the loading modulus is increased by a factor 1.5. For this reason, the difference between loading and unloading is less pronounced with respect to 300 K, but the dependence of elastic modulus on pre-stress is still rather strong. These measurements have been used to model coil rigidity at 1.9 K, since the variation of elasticity between 77 K and 1.9 K is negligible.

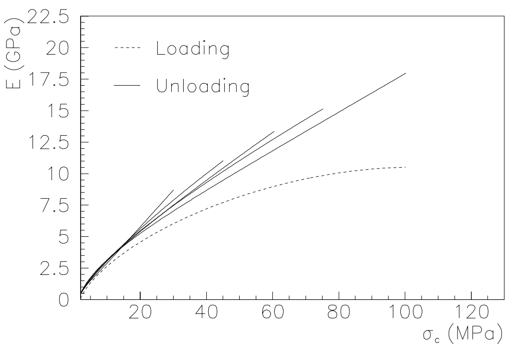


Fig. 4. Elastic modulus $E_w$ (GPa) versus stress $\sigma_w$ (MPa) at 77 K of a stack of conductors for the inner layer, loading and unloading curves from different peak stresses (experimental data).

### B. Pre-stress loss equation

Let us consider a conductor stack closed in a infinitely rigid mould, under a pre-stress $\sigma_w$ at 300 K. If the whole system is cooled down at 1.9 K, the difference in the coil deformation $\epsilon_w - \epsilon_c$ between 300 K and 1.9 K is equal to the difference in the integrated thermal contraction coefficients of the coil $\alpha_b$ and of the mould $\alpha_c$:

$$\epsilon_w - \epsilon_c = \alpha_b - \alpha_c. \tag{2}$$

Here, we neglect terms of the order of $\epsilon\alpha$ with respect to $\epsilon$ and $\alpha$. Using a linear relation between deformation and stresses $\sigma_w = E_w\epsilon_w$, and $\sigma_c = E_c\epsilon_c$, where $E_w$ and $E_c$ are the elastic moduli of the coil at 300 K and 1.9 K respectively, we obtain the equation for the pre-stress loss [4]

$$\sigma_c = \frac{E_c}{E_w}\left(\sigma_w - E_w(\alpha_b - \alpha_c)\right). \tag{3}$$

### C. Coil integrated thermal contraction

The pre-stress loss of a stack of cables in a closed mould is the usual technique to derive a measurement of the integrated thermal contraction of an insulated Rutherford cable [8]. A direct measurement of the thermal contraction is not possible, since the stack dimension when no load is applied shows a large indeterminacy. In [8], we measured five pre-stress losses of the inner and outer layer stacks, starting from different values of the pressure at room temperature $\sigma_w$. Results are shown in Table III.

Pre-stress losses $(\sigma_w, \sigma_c)$ provide through Eq. (3) the integrated thermal contraction $\alpha_b$ for a given choice of the

TABLE III
PRE-STRESS LOSSES (MPA) FROM 300 K TO 77 K FOR INNER AND OUTER LAYER STACKS IN A CLOSED MOULD

| $\sigma_w$ inner | $\sigma_c$ inner | $\sigma_w$ outer | $\sigma_c$ outer |
|---|---|---|---|
| 80 | 45 | 80 | 43 |
| 70 | 38 | 69 | 36 |
| 60 | 34 | 61 | 29 |
| 50 | 27 | 50 | 20 |
| 40 | 18 | 40 | 14 |

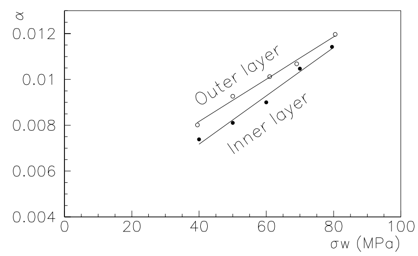


Fig. 5. Integrated thermal contraction coefficient from 300 K to 77 K versus pre-stress at 300 K and linear fit

elastic moduli $E_w$ and $E_c$. In our case at 300 K we use the equivalent elastic modulus $E_w^e$ defined in Section II (see Table I) to model the collaring. The elastic modulus at 77 K depends on the pressure (see Fig. 4). We use the elastic modulus at $\sigma_c = 37$ MPa, that is the pre-stress at 77 K reached by the stack from the nominal pre-stress at ambient temperature $\sigma_w = 70$ MPa (see Table III). We consider the average between loading and unloading, choosing $\sigma_c =$ 6.5 GPa for both stacks. Using these elastic moduli, we can evaluate the integrated thermal contraction factor $\alpha_b$ through Eq. (3), with a small correction to take into account the mould cavity rigidity. We find a dependence of $\alpha_b$ on the stress $\sigma_w$, obtaining results that range from 0.006 to 0.011 (see Fig.5). A linear fit

$$\alpha_b(\sigma_w) = \alpha_{b0} + \alpha_{b1}\sigma_w \tag{4}$$

provides an analytic approximation of the experimental data. An increase of 10 % in $\alpha_b$ has been applied to extrapolate these measurements from 77 K to 1.9 K.

### D. Finite element modeling of coil elasticity at 1.9 K and pre-stress loss

The dependence of the thermal contraction factor on the pre-stress [see Eq. (4)] cannot be included in the finite element code ANSYS$^{TM}$ that has been used in simulations. Indeed, the pre-stress loss equation that includes a linear dependence of $\alpha$ on $\sigma_w$ for an infinitely rigid cavity is

$$\sigma_c = \frac{E_c}{E_w^e}\left(\sigma_w - E_w^e(\alpha_{b0} + \alpha_{b1}\sigma_w - \alpha_c)\right). \tag{5}$$

One can group the dependence of $\alpha$ on $\sigma_w$ to the term that accounts for coil elasticity at cold

$$\sigma_c = \frac{E_c}{E_w^e}\left(\sigma_w(1 - \alpha_{b1}E_w^e) - (\alpha_{b0} - \alpha_c)E_w^e\right). \tag{6}$$

The above equation can be cast in the form

$$\sigma_c = \frac{E_c^e}{E_w^e}\left(\sigma_w - (\alpha_b^e - \alpha_c)E_w^e\right) \qquad (7)$$

where we defined a coil equivalent elastic modulus at 77 K $E_c^e$ and an equivalent thermal contraction coefficient $\alpha_b^e$

$$E_c^e = E_c(1 - \alpha_{b1}E_w^e) \qquad \alpha_b^e = \alpha_c + \frac{\alpha_{b0} - \alpha_c}{1 - \alpha_{b1}E_w^e}. \qquad (8)$$

Now the thermal contraction of the coil does not depend on the pressure and therefore can be used in the finite element code. The same formalism can be used without assuming an infinitely rigid coil cavity: numerical values derived for $\alpha_b^e$ and $E_c^e$ are given in Table IV. The analytical model with a stress-dependent $\alpha_b(\sigma_w)$ has been compared to the implementation in a finite element model using these equivalent properties, finding an excellent agreement. This model can be used to compute the initial state of the system when the magnet is powered at 1.9 K. On the other hand, to compute deformations induced by electro-magnetic forces one has to use the measured stress-strain curves at 1.9 K.

TABLE IV

Equivalent thermal contraction and equivalent moduli defined in Eqs. (8) for the inner and outer layer

| | Inner | Outer |
|---|---|---|
| $E_c^e$ (GPa) | 2.7 | 3.0 |
| $\alpha_b^e$ | 0.0040 | 0.0067 |

### *E. Results: model vs experiments*

Several experimental results about pre-stress loss from collared coils at 300 K to cold mass at 1.9 K are available [4]. Data relative to both short and long prototypes are show in Fig. 6 (markers). Results from the analytical model based on Eq. (6) (plus the correction for the collar deformation) using the equivalent modulus at 300 K and the measured values of $E_c$ and $\alpha_b(\sigma_w)$ are shown in the same figure (solid line). The model overestimates the prestress at 1.9 K of 3 to 8 MPa in the validity range of our linear approximation (40 to 80 MPa at 300 K). This can be compared to a dispersion of the data around the best fit of 5 MPa (two sigma) in $\sigma_c$. This agreement can be considered satisfactory. We point out that a model that simply assumes a ratio $E_c/E_w$ equal to 1.5 (i.e., the usual hardening ratio) would predict a slope of the $(\sigma_c, \sigma_w)$ line of 1.5, against a measured value of $0.53 \pm 0.10$, whilst our model gives a slope of 0.50 for the outer layer and of 0.60 for the inner layer.

## IV. Conclusions

We have presented a finite element model of the dipole cross-section the aim of which is to evaluate the dependence of coil loads and deformations on the dimensions of magnet components at 300 K and at 1.9 K. The model is based on the measured mechanical and thermal properties of conductor stacks. Since the collaring procedure is not explicitly considered, we proposed to include it in the coil mechanical properties through the definition of equivalent elastic moduli. This also solves the ambiguity on the choice of the coil elastic modulus (loading or unloading) to be input in the model. We also propose coil equivalent properties at 1.9 K based on the measured stress-dependence of the coil thermal contraction factor. Numerical results of the finite element model are compared to experimental data. Dependence of coil pre-stress and collar deformations on shim size show a good agreement with the model. We finally explain the large pre-stress loss from ambient to cryogenic temperature observed in experimental data.

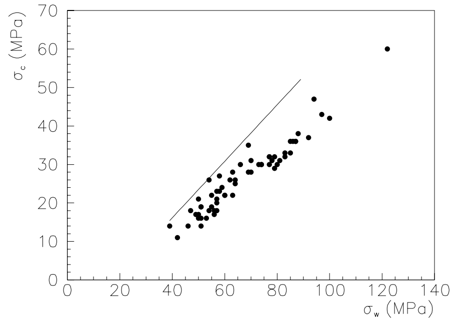


Fig. 6. Pre-stress at 1.9 K versus pre-stress after collaring at 300 K: experimental data (markers) versus analytical model (solid line).

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