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Mechanical Tests on the Prototype LHC Lattice Quadrupole

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A prototype twin superconducting quadrupole magnet for the Large Hadron Collider (LHC) is being developed and built at CEN/Saclay in collaboration with CERN. This paper describes the mechanical tests performed to validate the main concepts of the mechanical design in order to meet the requirements of prestress while maintaining a precise geometrical shape of the coils. Moulding tests on samples of superconducting cables have been made in order to evaluate the final size of the coils after curing and under stress. Collaring tests have been made on small length models to verify the process and the resulting prestress. The principal results and conclusions of the tests are summarized.

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Abstract - A prototype twin superconducting quadrupole magnet for the Large Hadron Collider (LHC) is being developed and built at CEN/ Saclay in collaboration with CERN. This paper describes the mechanical tests performed to validate the main concepts of the mechanical design in order to meet the requirements of prestress while maintaining a precise geometrical shape of the coils. Moulding tests on samples of superconducting cables have been made in order to evaluate the final size of the coils after curing and under stress. Collaring tests have been made on small length models to verify the process and the resulting prestress. The principal results and conclusions of the tests are summarized.

I. INTRODUCTION

A prototype of a twin lattice superconducting quadrupole magnet has been developed at the CEN/Saclay for the Large Hadron Collider. The first cold tests are planned for the month of October 1993. The design of this magnet has been described elsewhere [1]. Its main characteristics are summarized in the Table 1. The manufacturing of the magnet is described in [2]. A major concern for the quench performance of a superconducting magnet is the coil prestress. This prestress is required to avoid displacement of strands during the magnet energization. The prestress is applied with rigid laminations called collars, stacked and clamped around the coils with tapered keys .

TABLE 1
MAIN PARAMETERS OF THE MAGNET

Nominal gradient (T/m)	252
Inner coil aperture (mm)	56
Magnetic length (m)	3.055
Overall current density (A/mm^2)	530
Peak field (T)	7.76
Nominal current (A)	15060
Designed Prestress (MPa)	50
Cable bare dimension	(1.70-2.16)x13.05 mm^2

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On the other hand, the designer needs to give to the coils after collaring the calculated geometry in order to achieve the requirements of the field quality. The final shape of the coils depends on the final geometry of the collar, which in turn comes from the manufactured profile of the collar and the balance between the elastic behaviour of the collar and the deformation of the coil under stress. It was anticipated that the final shape of the coils under stress could be controlled by the curing process with the size of the cavity formed by the mould and mandrel of the curing press.

II. MECHANICAL DESIGN PHILOSOPHY

One solution to achieve the prestress within the collar cavity is to add shims in the polar plane of the coils during the collaring. We wished to avoid the use of these shims during the manufacturing of the magnet for several reasons. The first reason is the alteration of the field quality due to the presence of the shims . A second reason is the process of shimming, in our quadrupole design. Contrary to the dipole case, the way to clamp the collars in a quadrupole (alternated stacking at 90°) doesn't give an easy way to measure the prestress. Furthermore, one has to fully remove the tapered keys to dismantle the assembly to insert the shims, with the risk of damaging the coils and the collars. A third reason is that the control of the coil prestress by shims, inserted at the collaring time, is not a good solution for mass production.

The method we have chosen to control coil pressure is to control the cavity formed by the mould, the mandrel and the pressing bars of the curing press. We use shims to adjust the size of the pressing bars. The objective is to obtain after the curing phase a "good" coil; that means a coil having the size of the collar cavity when one applies to it the azimuthal pressure of 50 MPa.

The choice of the thickness of the shim is made with a series of compressive tests on cured samples of small-length stacked conductors. To validate this method, we have performed collaring tests with small length samples (200mm) cut from the first cured coil and equipped with stress sensors.

III. CURING AND COMPRESSIVE TESTS

A. Principles of the test

We have designed a special fixture (Fig. 1) which can be used to simulate the curing process for small length reproduction (85mm) of the first and second layers of the coil. The curing cycle uses the identical temperature and pressure profile of the cycle of the full-length prototype. During the curing phase we can adjust the mould size with three different thicknesses of shims. The same apparatus is used to make the compressive test so as to obtain the curve of stress vs. coil size. The calibration of the coil size is determined with a steel master which reproduces the theoretical size of the collar cavity. The elastic deformation of the compressive mould, measured separately, is subtracted from the results.

B. Experimental results [3]

We used for the tests two cables, one made of Cu strands with a filling factor of 88.6%, the other one made of NbTi/Cu composite strands, used for the manufacturing of the coils, with a filling factor of 93%. We have varied also the overlapping of the Kapton insulation between 38% and 48%, and changed the thickness of the insulation for reasons explained in [2]. These different conditions have allowed us to study the influence of the materials on the ability to reach the target point. A summary of these influences is presented below.

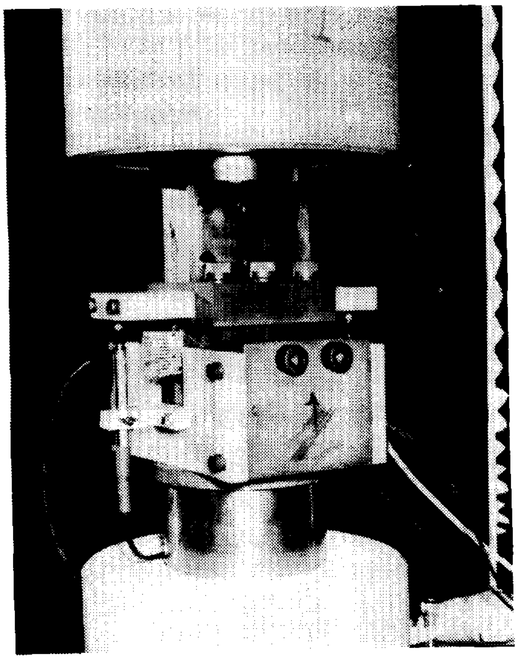

Fig. 1. Curing Fixture used for the test

The curves obtained from the cured coils with the three shims are shifted with regard to the others by a certain amount proportional to the difference of sizes between the shims. So the coil size at prestress is roughly a linear function of the mould size. We can interpolate from the experimental curves the theoretical curve which passes through the target point (design prestress and size) (Fig. 2). From the statistical study of the results, the uncertainty in the displacement for one compressive test of one sample is estimated at +/- 10 μm. A typical set of curves is shown Fig. 3

1) Mould Cavity Size: All along the tests, the deviation of the final mould cavity from the theoretical one (i.e. the collar cavity) is between -143μm and +48 μm. These variations are strongly dependant on the thickness of the insulation in its free state. The elastic modulus of the samples is around 12 GPa and decreases with the increase of the mould size (between 15 GPa and 10 GPa).

2) Change of cable : The properties of the cable are very important. During the early stage of the design of the magnet we have changed the diameter of the strands within the tolerance imposed by the specification. But the resulting increase of the filling factor (from 88.6% to 93%) has increased the pressure required to close the mould above the maximum pressure allowed for the press. In fact, the variation of filling factor, allowing more or less room for the insulation to creep between the strands, pilots the final size of the cable stack. The shift on the coil size between the two cables, is about 0.1 mm. The change of the elastic modulus is about 20%.

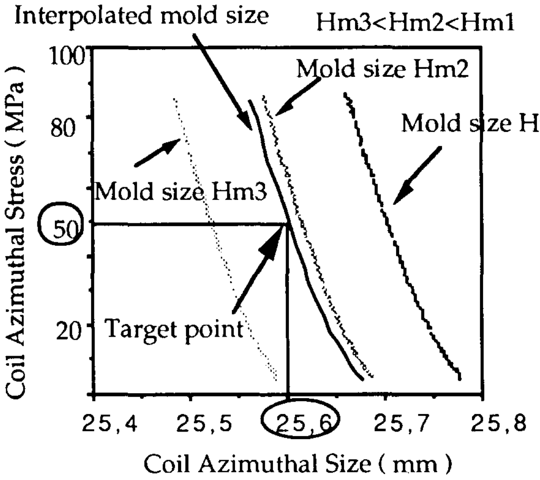

Figure 2 : Example of curves

3) *Change of thickness of insulation* : To accommodate the change of cable described above, we have reduced the thickness of the Kapton insulation from 75 µm (25 µm with 48% overlap + 12.5 µm with 48% overlap) to 62.5 µm (12.5 µm with 48% overlap + 12.5 µm with 60% overlap). The pressure to close the mould is decreased from 80 MPa to 10MPa. The decrease in the coil size is about 0.16 mm, half of the change in the thickness of the insulation (0.3 mm). The decrease of the elastic modulus is about 25%.

4) *Change of the overlap* : For a given thickness of insulation the change of the overlapping percentage doesn't affect the transverse mechanical behaviour of the cable stack. The variation on the coil size is about 10 µm and on the coil modulus less than 10 %.

5) *Qualification test on small length samples taken from a full-length cured coil* : We have taken 6 samples on both left and right sides of a dummy cured coil in the mould cavity defined by the procedure mentioned above. The tests have shown that the mean dimension of the six samples deviated less than 10 µm from the target with a standard deviation of 23 µm. This result confirms the validity of the concept of adjusting the size of the curing mould to control the coil size.

6) *Double curing effect* : We have cured twice some stacks to simulate the double curing of the first layer of the coil, and the test of compression doesn't show any difference in their mechanical response compared to cured only once samples.

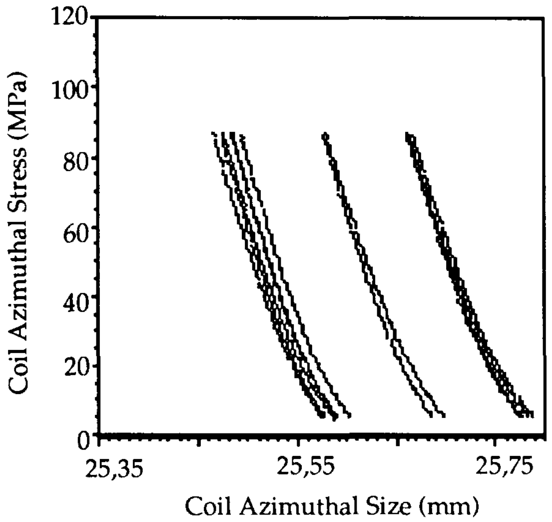

Fig . 3. Typical results of the compressive test with three mould sizes

IV. COLLARING TESTS

A. Principles of the test

The study of the collaring process is made on a small scale model (200 mm length and full scale section) (Fig. 4). We have instrumented the model with different sensors : strain gauges on the collars and on the coils, photoelastic coatings on the end collars, and pressure sensitive paper bundles (see below) developed by the SATIMAGE, a scientific image processing company [5]. We record also the force applied through the hydraulic jack to the tapered keys.

The strain gauges were glued on the "pole" of the collars placed in the middle of the model (Fig. 4) and also on the top of the section of the angular wedges of the coils. A calibration of the strain gauges has been made with the help of the pressure sensitive bundle. The location of the strain gauges doesn't disturb the mechanical behaviour of the cross section and we can record the real behaviour of the magnet during the collaring.

The photoelastic coatings on the two last collars of the stack give a global information about the distribution of the stress in the collars. This information is very helpful to study the stress distribution, in contrast to the localized information given by the strain gauges. Moreover, we can obtain an image of the stress concentration in the corner of the keyways and such high stress locations.

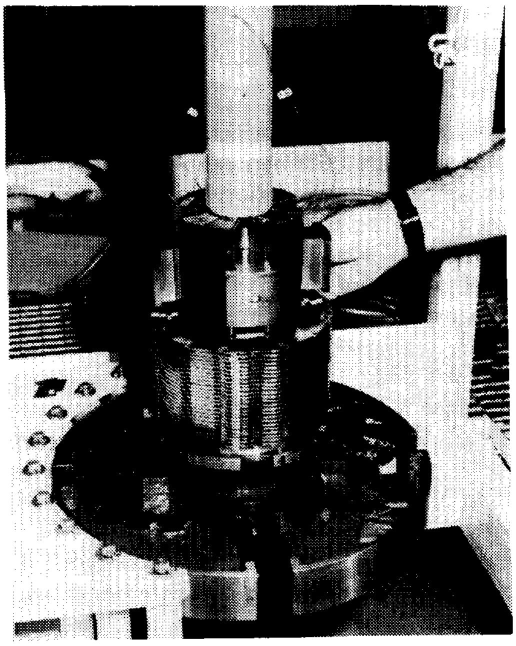

Fig. 4. Collaring Model

The pressure sensitive bundle is made with a sheet coated with ink, acting on a second blank sheet. These bundles are inserted between the contact surfaces of adjacent coils. The pressure generates a visible imprint, which is characterized by levels of grey. The imprint's intensity has a reproducible value, which is a function of the maximum pressure applied in the considered point. The imprint obtained can be treated by an image processing system, so as to provide a map of the exerted pressure-peaks. The range of pressure is 1-400 MPa with a spatial resolution of 0.1 mm. The thickness of the bundle is about 230 µm and special bundles are designed to eliminate the effects of relative sliding between the two faces. With this sensor we can measure the spatial distribution of the pressure in the middle plane of the magnet and also calculate the mean pressure applied (Fig. 5).

B. Experimental results [4]

Different tests have been made using samples coming from coils, in which the parameters of the insulation have been varied, and which then have been cured with different thicknesses of shims. The main results are summarized below.

1) Measured Prestress: The results of the different tests show a variation of the measured mean prestress from 50 MPa to 65 MPa. These variations correspond to a variation of 30 µm on the theoritical dimensions of the coils and/or collars.

2) Global homogeneity: The variation of the prestress between coils in the collared quadrupole at one axial position is around 20 % of the mean value.

3) Pressure distribution in the middle plane : From the map of pressure obtained with the pressure sensitive paper we can give the following results (Fig. 5):

- First of all, the outer layer is less compressed than the inner layer according to the calculations. The inner edge of each layer is more compressed. The ratio of pressure between the inner and outer edge is about two.
- The over pressure on the most stressed part of the inner edges is about 1.8 times the mean pressure.
- We can discriminate on the print the location of the cross-over of the tapes of prepreg and even the location of the overlapping of the cable strands.

4) Distribution of stresses in the collars : The data given by the photoelastic measurements show good agreement between the predicted and measured values. The stress concentration is more than 400 MPa in the corner of the keyway.

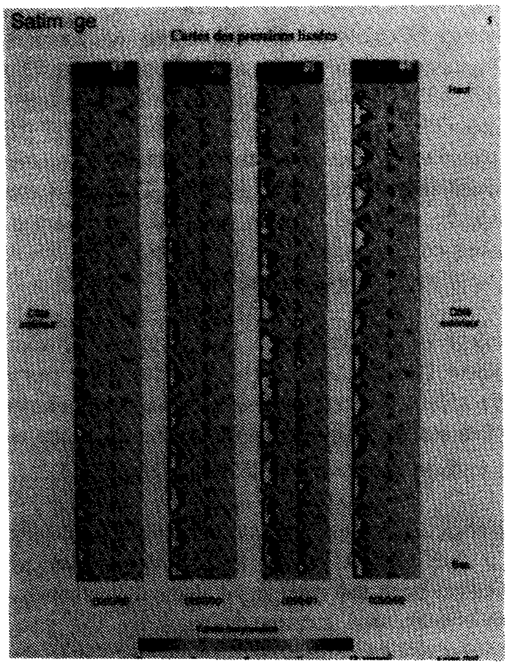

Fig. 5. Pressure Distribution Map in the middle planes of the coils

CONCLUSION

The results of the tests made on models of cured coils and collared coils, make us very confident in the method of shimming the pressing bars in the mould cavity to control both the prestress and the coil geometry within the collar cavity. The first cold tests, in which the magnet is instrumented with strain gauges, should give us a final confirmation.

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