TRAINING STUDY ON SUPERCONDUCTING COILS OF THE LHC SEXTUPOLE CORRECTOR MAGNET

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Abstract

A study on a single sextupole coil, working under the same conditions as the full magnet, has been made to evaluate the effect of the azimuthal pre-compression and the longitudinal pre-tension on the training of superconducting coils. A testing device has been used that allows to test individual sextupole type coils in a cryostat at 4.2 K by exerting variable pre-stresses in situ. The paper describes the tests made with this device and discusses the results obtained for different pre-stress conditions and for different central island materials, in particular G-10 and stainless steel.

INTRODUCTION

The coils of the superconducting corrector magnets for the LHC are pre-compressed by means of an aluminium shrinking cylinder in order to avoid tensile stresses in the coil and possible movements of the cables which can generate enough heat to provoke premature quenches.

In order to experimentally optimise the pre-compression level in superconducting sextupole corrector magnets, a special testing device was built, that allows to test individual coils under different pre-compression and with a field distribution as in a complete magnet. The pre-compressions can be changed in situ during the test.

1 DESCRIPTION OF THE TESTING DEVICE

A detailed description of the special testing device can be found in [1]. The device acts like a superconducting press able to exert an azimuthal pressure in the range of 0 to 60 MPa and a longitudinal tensile force of 4kN. Powered with a current of 100A an azimuthal pressure of 60MPa is applied to the test coil.

The longitudinal actuator consists of a superconducting solenoid attracting an iron core. A current of 21A in the solenoid brings some 110MPa of longitudinal tensile stress in the test coil.

2 PARAMETERS OF THE TEST COILS

The coils have all been wound from the same monolithic enamelled wire with a rectangular cross section. The technique is that of wet-winding around a central post which is part of the coil. The common parameters of the test coils are listed in Table 1 and can be found in more detail in [2].

Table 1. Common parameters of the tested coils

Type	sextupole
Nominal current	600A
Critical current	1050A @4.2K
Peak field	2.17T
Nr. of turns	2x13 (double pancake)
Overall wire dimensions	$1.25x0.75mm^2$
Enamel thickness	6μm

There are some mechanical differences between coils such as the type of material used for the main post, and the presence or not of a supporting liner.

Table 2 gives the number of tested coils for each combination of central post material and supporting layer of G-10. The upper support is a G-10 liner between the coil and the yoke, the lower support is the same on the inside of the coil (see Fig. 1).

Table 2: Number & Type of tested coils

Main post / Support	G-10	St. steel	Hybrid *	None
None	10	2	1	2
Lower	2	-	-	-
Upper	2	-	-	1
Upper (ends only)	2	-	-	-
Upper & Lower	1	-	-	-

*(St. steel core in a G-10 matrix)

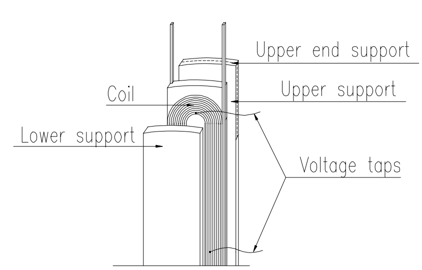

Figure 1: Location of the supporting layers of G-10 Shown is also the location of the voltage taps for quench detection.

3 THE MEASUREMENT SYSTEM

During the test electrical and mechanical measurements were made. The quench current and voltages are recorded with a Digital Storage Oscilloscope. The origin of the quench can be localised thanks to voltage taps dividing the coil into upper and lower layer and inner and outer part. The force measurements are made with capacitive gauges [1,3]. The data acquisition system for those measurements is based on an RCL meter and a GPIB card controlled by a Labview program. In the case of simultaneous measurements a Scanner is used. The maximum frequency of 4 sample/sec is achieved when only one gauge is measured. For the detection of displacement, two potentiometers are placed at the extremities of the arms of the device.

4 THE MEASUREMENTS

The aim of the experiment was to find the optimum level of pre-compression i.e. the level at which the behaviour of the magnet was best. As can be noticed from Table 2, most of the work was done on the so called “standard coil” with G-10 main post and no supports. The typical measurement consisted of first testing the coil in free conditions (the laminations not touching the coil), then applying current to the azimuthal actuator until the contact was fully established (3-5MPa) and finally to increase the pressure gradually from 10 to 60MPa. Between each load step, the actuator was completely unloaded to have the same starting conditions. At each pressure step quenches were made until the coil reached the critical current. A typical example is shown in the Fig.2.

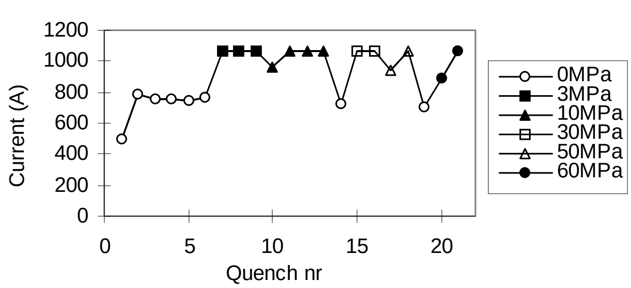

Figure 2: Typical quench history for a standard coil at different pre-compressions

In order to compare the results obtained under different conditions a quality factor f_{qp} was defined as:

$$f_{qp} = \frac{I_1}{I_c} \quad (1)$$

The ratio between the first quench current I_1 and the critical current I_c as is given in Table 1. The evolution of f_{qp} for the standard coil as well as for the stainless steel (ss) main post case is shown in Fig.3.

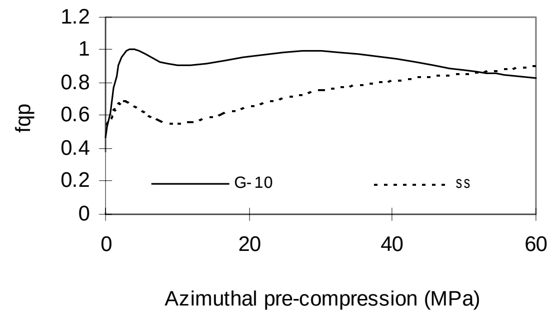

Figure 3: Evolution of the quality factor with the pre-compression

5 ANALYSIS OF RESULTS

For the “standard coil” with G-10 main post, the results given in Fig.2 and Fig.3 lead to the following preliminary conclusions:

The optimum pressure value is the condition of “contact”, where a very small force is exerted on the coil. Another optimum is achieved when the pressure is increased up to 30MPa approximately. For higher values of pre-compression the coil starts to train more. The worst behaviour of the coil is when it is free so the worst and the best conditions are very close. Nevertheless, in free condition almost all quenches occur at above the nominal current.

It seems that the coils do not "learn" and behave like virgin coils every new test.

For the coil with the ss main post, the preliminary conclusions are that the behaviour of the coil improves as the pressure increases up to 40 MPa. Beyond this point, there is also a degradation of the coil performance. No significant difference appears when going from the free to the contact condition. In general, the training of the coil with the ss. main post is worse than that of the standard coil with G-10 post. These coils seem to “learn” during the test.

For both cases the application of an axial force to the coil did not modify these results.

The typical stresses in the plane of the coil have been calculated and are summarised in Table 3.

Table 3: Equivalent stresses in coil materials during test

Condition	NbTi (MPa) G-10/St.Steel	Epoxy (MPa) G-10/St.Steel
4.2K	-130/-145	50/50
+40MPa prestress	-200/-230	100/120
+40MPa+Lorentz F.	-200/-230	100/120

They are not very different for the two types of coil. The prestress has a strong effect on the stress in the epoxy and in the NbTi.

6 INVESTIGATIONS

The two last conclusions for the standard coil with G-10 post led us to investigate further the quench origin. The fact that with just a slight pressure, the coil could reach critical current, on the one hand, and that without it, it quenched always at a relatively low current, on the other, suggested that for free condition there was a conductor movement which was always located in the inner part of the lower layer.

Two alternatives for the quench origin were considered:

- The debonding from the main post or
- Movements at the coil ends.

Coils without main post were tested without any significant improvement for the free condition, thus discarding the first possibility. On the other hand when a support was glued to the outside of the coil, its performance in the free condition became much better, whereas it did not improve when such a support was glued on the inner face.

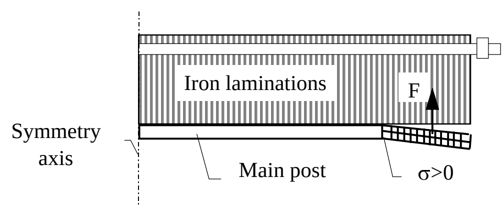

Figure 4: The bending effect in the coil end

A detailed inspection of the ends showed that the coil end was not in contact with the laminations and the magnetic forces would bend it towards the laminations (Fig. 4). When a local G-10 support was glued to the coil end the bending was avoided and the performance became comparable to that of the coils supported over the whole length (Fig. 5).

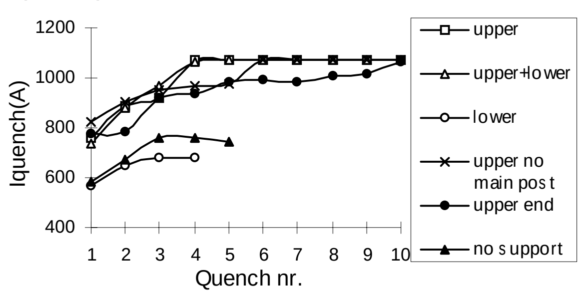

Figure 5: Training in free condition. Different coil supports.

7 A SPECIAL SEXTUPOLE

In order to check the results for the single coil test we decided to build a complete sextupole without any pre-compression on the coils. Each coil was glued onto a G-10 insulating support and the six coils were then bolted into an iron tube.

Fig. 6 shows the training behaviour of this magnet as well as the magnet itself. The training is slower than expected from the single coil tests although the current level is well above nominal.

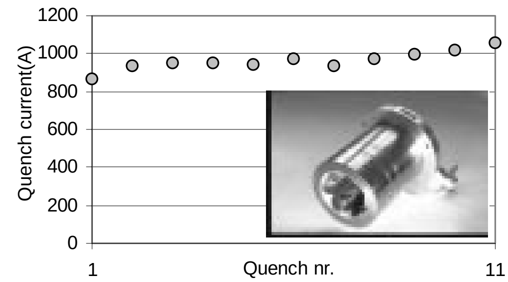

Figure 6: The special sextupole and its quench history

CONCLUSION

The influence of the pre-compression on the quench behaviour of sextupole coils has been experimentally studied using a special superconducting press built for this purpose. The results for the standard coil with G-10 main post and no external supports show that the coil reaches the critical current in the first quench when the pre-compression is close to zero. A similar behaviour is also achievable for higher pressures, up to a limit (40 MPa approx.) beyond which the training behaviour degrades. For coils with stainless steel main posts there is no such favourable condition of near-zero pre-stress and the optimum pressure is in the range of 30-40Mpa. In contrast to the standard coil these coils do learn. An investigation into the origin of the quenches points to badly supported coils or coil ends. When these problems were overcome, the behaviour of the coil was better. Even in free conditions a well supported coil can achieve the critical current.

A complete magnet has been manufactured without any pre-compression. It trained more than expected from the single coil tests but well above nominal current.

ACKNOWLEDGMENT

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