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Training Tests on Single Superconducting Coils of Sextupolar Correctors for LHC

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The paper describes the design, construction and calibration of the testing device, the test instrumentation and the results of the first experiments with sextupolar coils. This work was realised in the framework of a collaboration between CERN and CEDEX/Spain.

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Abstract — **The precompression of the coils is considered to be one of the most important parameters to achieve good training performance in a superconducting magnet. In order to better understand and optimise precompression, a test device has been created that allows to test individual coils in a cryostat at 4.2 K exerting a variable precompression in situ. The paper describes the design, construction and calibration of the testing device, the test instrumentation and the results of the first experiments with sextupolar coils. This work was realised in the framework of a collaboration between CERN and CEDEX/Spain.**

I. INTRODUCTION

The coils in each of the superconducting LHC correction magnets, quadrupoles, sextupoles, octupoles and decapoles, are compressively pre-stressed by means of an aluminium shrinking cylinder, placed around the coils. The interference of this cylinder with respect to the outer diameter of the coil assembly determines the level of precompression obtained at the superconducting coils. Our purpose is to find the pre-stress conditions at which no noticeable training will happen.

One could test different magnets each assembled using different mechanical parameters. However, if a difference in training appears, it would be difficult to judge if it comes from the different pre-stress or from the fact that another fabrication of coils has been used. Therefore a special device has been designed and manufactured which allows to test individual coils under different conditions (like azimuthal precompression, winding tension and different main post materials) where the pre-stress can be changed during the test. Iron around the test coil allows to keep the magnetic field pattern similar to that of a complete magnet.

II. TESTING DEVICE

The device consists of a package of iron laminations assembled in the form of a pair of pliers.

Forces to close the pliers and compress the test coil are generated by two superconducting coils. These azimuthal actuators assure an adjustable azimuthal pressure on the test coil.

A second superconducting solenoid actuator was included in the testing device in longitudinal direction to study the influence of axial stress, arising from the winding conditions (Fig.1). During the test, the forces are measured by means of capacitive gauges and the pliers movements are measured with linear potentiometers as well as a simple electrostatic transducer.

A. The iron laminations

The laminations are made from Armco (Fe 99,9%), and shaped by laser cutting and electro-erosion to obtain the same magnetic field as in the corrector magnets.

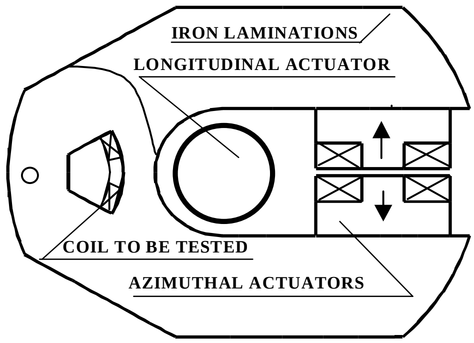


Fig. 1. The test device with the coil to be tested

B. The azimuthal actuators

1. Magnetic design

The azimuthal actuators use the repulsion of two coils with opposed fields. The coils are placed as shown in Fig. 2. In each conductor there is a net force in y direction given by (1) (h and s explained in Fig. 2.).

$$F_{iy} = \sum_{k=1}^{3} F_{kiy} = I^2 \frac{\mu_0}{2\pi} \frac{s^2}{h\left(h^2 + s^2\right)} \qquad (1)$$

The vectorial sum of forces in x direction is zero for each coil. Then the resultant force in the whole coil is:

$$F_y = \sum_{i=1}^{2} F_{iy} \qquad (2)$$

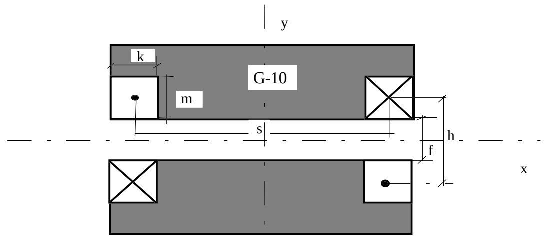


Fig. 2. Geometry of the azimuthal actuator

The sensitivity of the system is a function of the two geometrical parameters: s and h.

The value of h must be as small as possible to achieve the highest force for a given geometry and current. However, (3) and (4) show that, if h is small, a very little variation provokes a large variation of the force and this is not desired as we wish to maintain a constant force.

$$\frac{\partial F}{\partial h}=\frac{\mu_0 I^2 s^2}{\pi}\left[-\frac{3h^2+s^2}{h^2\left(h^2+s^2\right)^2}\right]<0 \qquad (3)$$

$$\lim_{h\to 0}\frac{\partial F}{\partial h}=-\infty \qquad (4)$$

The parameter s must be as large as possible but it is limited by the dimensions of the construction. The system is not very sensitive to the variation of variable s. The final geometry was defined considering all those arguments.
Table I. lists the geometrical parameters of the azimuthal actuators.

TABLE I.
PARAMETERS OF THE AZIMUTHAL ACTUATORS

Coil	
k	17.15 mm
m	10.00 mm
s	32.85 mm
f (depends of the initial position of the device)	1.5 mm (min value)
h	f+2m/2
Coil length	135 mm
Number of turns per coil	852
Wire	
Type	VACRYFLUX $F54_{1.35}$
Diameter	0.400 mm
Insulated diameter	0.438 mm
Filament diameter	27µm
A_{Cu}/A_{Sc}	1.35
Copper cross section area	0.0722 mm^2
Critical current at 8Tesla	60A

Fig. 3. shows the load line of the actuator coil, calculated with a F.E.M. code, versus critical current of the wire at a temperature of 4.2 K. The operational current of 107 A is approximately at 80% of the critical current

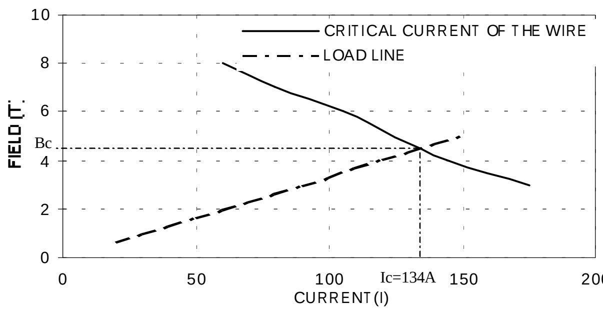
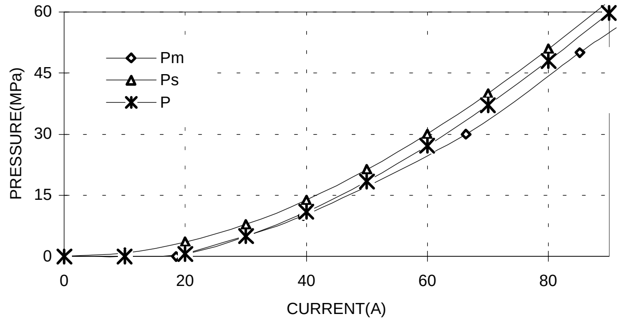


Fig. 3. Load line of the actuator and critical current of the wire

2. Mechanical design

The maximum azimuthal pre-compression requested in the test coil is 60MPa. Considering the actual lever arm of the actuator (4.62) this corresponds to an overall force of 3900N at the azimuthal actuators.
An electromechanical calculation was carried out, with F.E.M. software (qField) to define the relationship between the force on the test coil and the current through the azimuthal actuators.

The Ps curve in the Fig.4. represents the theoretical variation of the azimuthal pressure (MPa) on the test coil with the current *I* in the azimuthal actuator. In practice it appeared



that a current of 18A is needed to overcome the initial friction. The P curve shows the theoretical Ps curve shifted by 18A. The Pm curve was obtained by experiment.

Fig. 4. Calibration curve (azimuthal stress in the test coil as function of the current in the azimuthal actuator)

C The longitudinal actuator

To study the influence of axial stresses in the test coil arising from winding tension or from thermal differential contraction, a supplementary actuator was included to exert an axial force on the test coil.
This actuator uses the principle of minimum reluctance of a magnetic circuit consisting of an iron core (Fig.5.) in a superconducting solenoid .

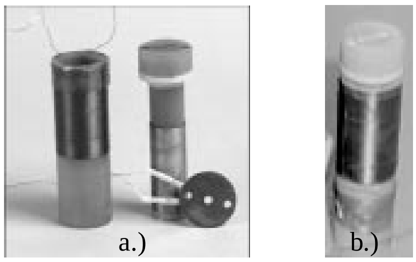


Fig. 5. The longitudinal actuator a.)The solenoid and the iron core b.) The two parts together

The maximum force in the test coil as computed with F.E.M., is 4000N (which is the fracture limit of the glue). The wire characteristics are those of Table I. With 1264 turns the critical current is 170A corresponding to a 3.13T peak field in the solenoid.

III. FORCE MEASUREMENT

To know precisely the force in the test coil we used special capacitive force transducers developed and manufactured at CERN.
The gauges are made of several stainless steel foils (50µm thickness) interleaved with poly-imide films. The layers are glued together using M610 bond and then cured under pressure at a temperature of 140°C during 2 hours. The development, construction and test of these gauges have been described by I. Vanenkov [1], [4].

The calibration curves at 4.2K have a good linearity and no hysteresis during load-releasing cycles (see Fig.6).

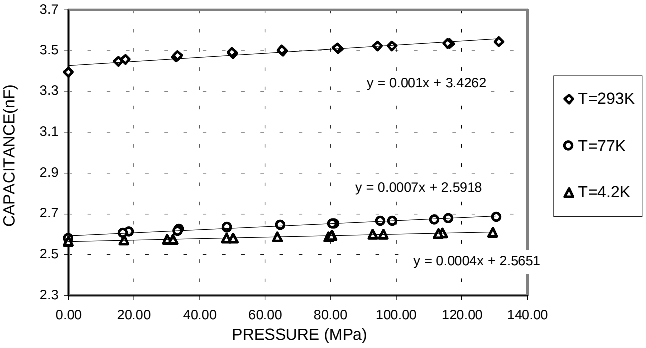


Fig. 6. Typical calibration curve for the capacitive gauges at T293K, T=77K and T=4.2K

Another way to know the azimuthal force at the actuating coil is to measure the separation (f) between the actuators and compute the force from this value.

We have used two methods to measure this separation: (i) linear potentiometers placed at each end of the special scissors laminations and (ii) simple capacitance transducers made from two parallel plane electrodes, which were glued to the face of each azimuthal actuator. For both cases the main problem is the calibration, but although we did not obtain a precise absolute values, it gave useful information on the relative movements of the laminations during the tests.

IV. The Tests

A. *Test coil*

The device has been designed to test coils of the type used in the MCS sextupole corrector magnet for the Large Hadron Collider (LHC). This corrector magnet has been designed for a nominal current I=600A corresponding a peak field of 2.17T at the end of the coil. The coil has 26 turn/coil in two layers. Using a wire with a cross-section of s=1.65mm×0.75mm over the insulation the computed critical current is 1200A. [2]

Table II summaries the main parameters of the coil.

From a magnetic point of view, the test device guarantees very similar conditions to that of a complete sextupole magnet (see Fig.7.).

TABLE II.
COILS PARAMETERS

Coil	
Inner/outer radius	28 /30.5 mm
Magnetic/overall length	104/135 mm
Turn per coil ("double pancake")	2*13
Winding tension	30 MPa
Main post	G10
Wire	
Cable dimensions bare	1.13*0.606 mm^2
Insulation thickness(PVA)	0.06 mm
Cu/Sc ratio	1.6
Critical current density (⊥ to the broad side) at 5T	2671A/mm^2
Critical current density (|| to the broad side) at 5T	3052A/mm^2

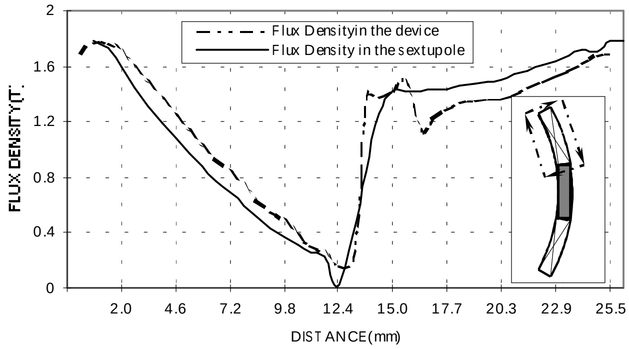


Fig. 7. Magnetic field around the periphery of the coil block compared to that in the sextupole at I=600A (results from a 2Dcalculations)

B. Tests description

For each coil several training test were made using different values of azimuthal (0-60MPa) and longitudinal (0-45MPa) pre-stress all during the same session thus without intermediate warming up and cooling down. Between two training tests the coil pre-stress is released and a training test performed in the unstressed condition to check whether anything has changed in the coil. It appeared that the limiting quench current with the coil "free" lies typically between 600-700A and this value remains constant even after many tests under different pre-stress conditions at the much higher critical current. That shows that during a test the same initial conditions are assured. For each combination of pre-stress a complete training up to critical current has been made.

Voltage taps for detection of the quench were used to distinguish between quenches starting in the lower or upper layer or in the inner or outer part of the coil.

In addition the current, the pre-stresses and voltages have been registered.

To record the signals from the 7 different gauges simultaneously a multichannel data acquisition system was used. This system together with a LabView program for the control of this system, was developed at CERN [1].

C. The first results of the tests

The usual sextupole coils are wound around a central post of G-10 fiberglass-epoxy using a winding tension of 30 Mpa. After assembly of the coils a pre-impregnated glassfiber bandage is wound around the assembly and cured. Finally circumferential pre-stress is achieved by shrinkfitting an aluminium tube around the assembly. To judge the effect of the parameters such as winding tension and the glassfiber bandage some test coils were prepared without a glassfiber backing, others with this glassfiber backing and some with a central post of stainless steel to see the influence of this element. It appeared from the results that the coils can be ranged in three main groups: coils with G-10 main post and no G-10 backing, coils with G-10 main posts and G-10 backing and coils with stainless steel main posts.

a) *Coils with G-10 main post, with or without winding tension; no G-10 backing*

The G-10 central post is relatively flexible as it has a low modulus and therefore the winding tension nearly disappears in the compression of the G-10 post. This type of coil, trained without any pre-compression reaches after one or two training quench a plateau typically situated at a stable 600-700A. Adding a very low azimuthal pre-compression of 2-5MPa the coil reaches the critical current of 1060 A almost without training quench (see Fig. 8). In all these cases the quenches starts in the inner layer and close to the central post where the peak field is found. Bringing the pre-compression to a higher level has the result that some training quenches may be needed to go to the critical current. The most surprising aspect of the test of these coils was that a release of pre-compression brought the coil back to its virgin condition, meaning that the "training" may have the origin in phenomena happening outside the coil and not in mechanisms like cracks of the coil insulation or serrated yielding of the superconductor inside the coil. For curiosity we tested a coil where the main post had been taken away and this appeared to behave in the same way.

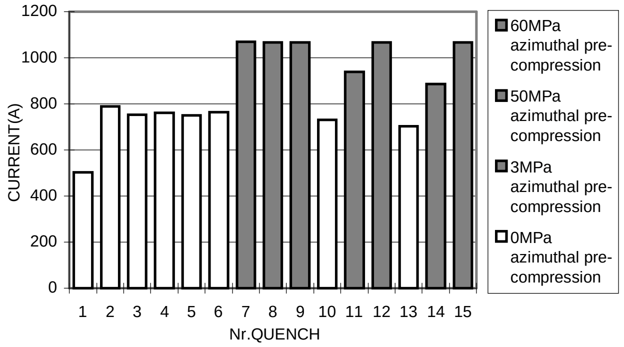


Fig. 8. Quench history for coil with G-10 central post and 30Mpa winding tension

b) *Coils with a G-10 backing layer*

The coils with a G-10 layer on the outer radius start training at the same level as before. However, thanks to the G-10 layer they train beyond the former 600-700 A and reach critical current even in the absence of pre-compression (see Fig. 9.).

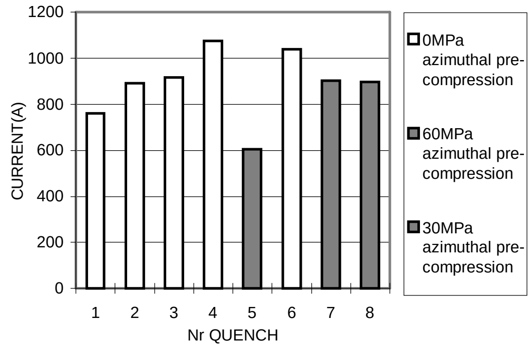


Fig. 9. Quench history for coil with G-10 central post and a G-10 backing layer

Continuing the training at different levels of pre-compression shows new training quenches. Coming back to the condition of no pre-compression it appeared that the coil had trained, did not repeat the training steps but went directly to critical current.

c) *Coils with stainless steel central post and no G-10 backing layer*

The coils with stainless steel post maintain a higher winding tension in the wires as the strong stainless steel post can resist the resulting compression. The training results show that in the absence of precompression the coils reach the same plateau as the one with G-10 central post and no backing layer at some 600-700 A. However quite some azimuthal pre-compression is now needed to bring the coil to critical current. The training originates in the coil and there is no noticeable re-training. Quenches start at the inner layer.

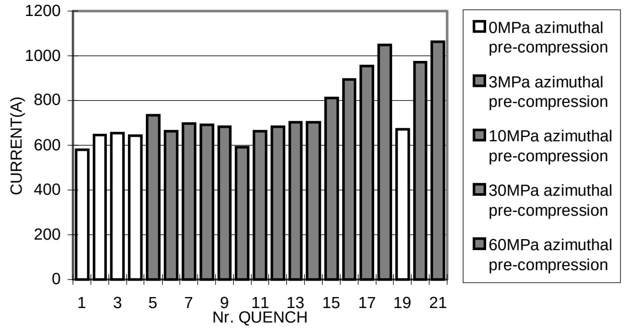


Fig. 10. Quench history for coil with stainless steel central post

V. Conclusions

A testing device has been developed to test the training of single coils under different pre-compression conditions which can be continuously adjusted during the test at 4.2 K. The device has been described and preliminary test results are given. The results seem to indicate that for coils with a central post of G-10 a minimum of pre-compression is the optimum condition for training free operation whereas coils wound around a central post of stainless steel need a larger amount of pre-stress to train to critical current. It appeared that in some cases the quench origin must be sought outside the coil and the coil itself stays virgin and retrains whereas in other cases the quench originates from inside the coil and the training does not give rise to re-training.

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References

[1.] I. Vanenkov "Using Capacitive Force Transduces for Measuring Stresses in Superconducting Magnet Coils for the LHC", Internal Note 96-14, CERN,Geneva, 1996.

[2.]J. Salminen, A. Ijspeert, A. Puntambekar "A Superconducting Sextupole Corrector Magnet for the LHC Main Dipoles " *5th European Particle Accelerator Conference '96*. Sitges, Publ. in: Proceedings

[3.] M. N. Wilson "Superconducting Magnets" *Clarendorn Press*. Oxford, 1986

[4.]T. Nakamoto "Preliminary Cable Test for Measurements of Capacitance Gauge", KEK, 96/10/17