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Impact of the First Powering Cycles on the LHC Superconducting Dipole Coil Geometry

M.Calvi, E.Todesco, L.Bottura, S.Sanfilippo and A.Siemko

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Index Terms—**LHC, Superconductivity, Field Quality.**

I. INTRODUCTION

DURING the powering of a superconducting magnet [1], the magnetic field interacts with the current flowing in the cables, generating strong Lorentz forces that tend to deform the structure. Such deformations give rise to two effects that can be measured with the standard instrumentation used during tests:

- The conductor displacement affects the magnetic field shape, which is measured through rotating coils [2,3]. This measurement is very sensitive, having a relative precision on field harmonics of the order of 1 ppm. Simulations show that coil movements of the order of 10 micrometers can already give a signal which is well above the noise level.
- The conductor displacement in the strong magnetic field generated by the magnet induces a voltage across the magnet, which can be measured by the voltage taps that are routinely used during the power tests [4]. The amplitude of the signal depends on the amplitude of the movement, its velocity, and the number and position of the conductors involved in the movement.

In this paper we present experimental evidence of the coil deformation that take place during the first powering cycles of the main dipoles of the Large Hadron Collider [5]. These dipoles have NbTi cables cooled at 1.9 K, carrying a current of 11.85 kA, and providing a nominal magnetic field of 8.33 T. Data relative to the magnetic measurements at room temperature and in operational conditions (1.9 K), and the voltage taps signals are presented. The aim is a phenomenological description of the mechanism that rules the dynamics of the deformation of the coil during the first powering cycles [6].

II. ROOM TEMPERATURE MEASUREMENTS

The magnetic field in a dipole is expressed as a power series

$$B_y(x,y) + iB_x(x,y) = B_1 \sum_{n=1}^{\infty} (b_n + ia_n)\left(\frac{x+iy}{R}\right)^{n-1}, \qquad (1)$$

where (x,y) are the transverse coordinates, R is the reference radius (17 mm in our case), and B_1 is the main dipole component. The harmonic terms b_3, b_5, b_7 …, are generated by a coil lay-out that satisfies the dipole symmetry (allowed components), whereas the other harmonic terms are due to a break of the dipole symmetry (un-allowed components). The main component and the field harmonics are measured at room temperature with rotating coils of 750 mm length. 20 consecutive positions are measured, along the 15 m dipole. Position 1 and 20 cover the heads of the magnet, and 2 to 19 the so called straight part.

Measurements are carried out at the manufacturer at two different stages of the assembly procedure, namely after the collaring (superconducting coils clamped in the collars), and after the welding of the shrinking cylinder (the so called cold mass, i.e. the collared coil inside the iron yoke and the stainless steel cylinder).

The shape of the magnetic field at room temperature is determined by the position of the conductors, and is a powerful indicator of the actual geometry of the coil inside the magnet. Anomalies in the magnetic field can be traced back to assembly errors, missing or faulty components [7].

In May-June 2004, important anomalies in the un-allowed components (~0.5 units of a_6 and ~0.3 of b_8) have been detected in the dipoles produced at one of the dipole assembly firm. Such anomalies could be traced back to an inward radial shift of 0.3 to 1.0 mm of the conductor block in the inner layer close to the pole in one quadrant (the so-called block6, see Figure 1, left). Such field errors were not uniform along the magnet axis, but localized in some spots of length 0.02 to 2 m. In June-July 2004 another trend appeared, affecting this time the allowed components (~-2 units of b_3 and ~0.5 units of b_5). This second trend could be traced back to an inward radial shift of block6 in all quadrants of 0.3 mm (see Fig. 1, right). In this case, the field anomaly was uniform along the magnet

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axis, affecting all the positions relative to the 13.5 m of the straight part. Since this second trend was pushing the average b_3 out of the beam dynamics targets, before taking any corrective actions a measurement campaign has been launched to understand if this feature was wiped out by the first powering of the magnet or not. For this reason, 8 magnets with these field anomalies plus 6 'normal' magnets were measured at room temperature after the cold tests. Both trends disappeared after August 2004, without a clear indication of the cause.

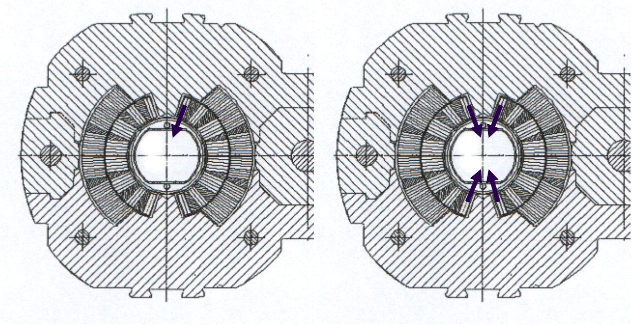

Figure 1 Inward displacement of block6 in one quadrant only (right) and in all quadrants (left)

The comparison of the field harmonics measured before and after the cold test has shown that

- All the anomalies, both in a_6 and b_8, and in b_3 and b_5 are still visible after cold test.
- The cold test is inducing a small systematic shift of the allowed components (~0.25 units of b_3 and ~-0.16 units of b_5) in the whole straight part of all magnets, both 'normal' and anomalous (see Table I).

This systematic shift is small with respect to the spread of the multipoles along the production (1 unit of b_3 and 0.5 of b_5), but is well above the level of noise of the measuring system, which is 0.024 units for b_3 and 0.008 units for b_5 (one sigma). The measured effect is therefore at 10 sigma for b_3 and 20 sigma for b_5. If we subtract from the measured shift the expected multipole change due to a block6 *outward* radial movement in all quadrants, one can find an optimal amplitude of the displacement that brings the field shift within 3 standard deviation for all multipoles. This is a very strong numerical evidence that the source of the small systematic shift in the allowed multipoles is a block 6 movement. The amplitude of these movements is 0.01 to 0.03 mm (see Table II), for all magnets. Note that other block displacements and modes of deformation of the coil have been tried, without finding any match with the measurements.

TABLE I
AVERAGE AND STANDARD DEVIATIONS OF THE SHIFT IN FIELD HARMONICS DUE TO THE FIRST POWERING AT 13 KA, MEASURED AT ROOM TEMPERATURE.

	b3	**b5**	**b7**
average	0.26	-0.16	0.03
stdev	0.09	0.05	0.07

The conclusion that can be drawn by this measurement campaign is that the magnet powering does not put block6 back in the right position for the magnets that showed expected misplacements of 0.1 to 1 mm.

Indeed, a relevant result was found as an unexpected fall-out of this campaign:

- The first powering gives rise to a plastic like deformation of the coil in a four localized spots of the cross-section (the position of block6, i.e. close to the poles of the inner layer).
- The amplitude of the deformation is of some tens of micrometers, and there is evidence that it is independent of the initial condition, i.e. on the absolute position of block6 after the coil assembly at the manufacturer.

TABLE II
MAGNETS MEASURED AT ROOM TEMPERATURE AFTER THE FIRST COLD TEST, FIELD ANOMALIES DETECTED BEFORE COLD TEST, AND RADIAL OUTWARD DISPLACEMENT OF BLOCK6 DUE TO THE COLD TEST

		Block6 movement after thermal cycle (mm)	
name	**field anomaly**	**Ap1**	**Ap2**
1140	absent	0.020	0.021
1168	absent	0.013	0.013
1170	absent	0.015	0.012
2065	a6,b8 spots	0.027	0.024
2075	a6,b8 spots – b3,b5 average	0.013	0.012
2089	a6,b8 spots – b3,b5 average	0.027	0.024
2090	b3,b5 average	0.016	0.021
2091	a6,b8 spots – b3,b5 average	0.019	0.021
2093	b3,b5 average	0.024	0.027
2096	b3,b5 average	0.022	0.028
3239	absent	0.017	0.013
3259	absent	0.020	0.007
3261	absent	0.020	0.020

III. MEASUREMENTS AT 1.9 K

A. *Magnetic field harmonics versus powering history*

The field harmonic change during the first powering is a phenomenon that has been observed since the beginning of the dipole production. To improve the understanding of this effect special measurements have been performed in operational conditions at 1.9 K during the mass production. LHC dipoles are working from current of 0.76 kA (injection plateau) to 11.85 kA (nominal energy). The special current cycles used during this investigation are sketched in Figure 2. After connection, cool down and insulation tests, the magnet has been powered for the first time up to current I_1 of 6 kA. Then, the magnetic field harmonics are measured using the so called *mini-load line*, where the maximum current is 6kA. The geometrical component of the multipoles is estimated as the average of the measured value at 5 kA after the ramp-up and the value after the ramp down [3],

$$b_i^{geo} = \tfrac{1}{2}\left[b_i\left(5kA,\Uparrow\right)+b_i\left(5kA,\Downarrow\right)\right]. \qquad (2)$$

This is the standard way to measure the geometrical component at 1.9 K, since this level of current is high enough to wipe out the major part of the contribution of persistent current, and at the same time is sufficiently low not to have magnetic effects due to the iron saturation, and due to the deformation induced by Lorentz forces.

After this first measurement, a second pre-cycle is done at I_2=8 kA, followed by the same mini load line to measure the geometric components. Seven cycles of this type are performed, with increasing I_i up to 12.85 kA. In this way one can measure the geometrical component of the harmonics as a function of the highest current (and therefore of the highest Lorentz force) applied to the coil.

The total change of the geometric component from a first powering at 6 kA to the last at 12.85 kA is rather similar to the effect measured at room temperature. Average and standard deviations over a sample of 26 apertures are given in Table III. Note that the sample is not the same of that one used for room temperature measurements.

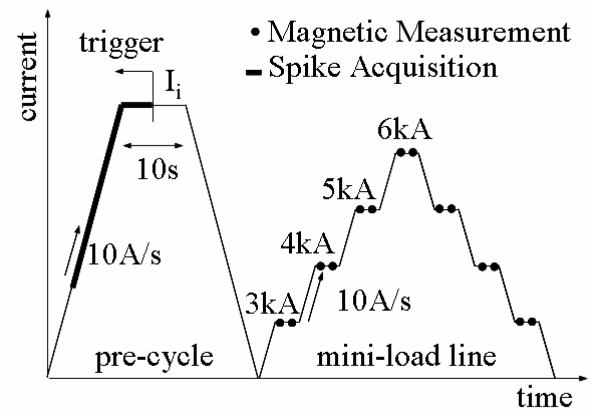

Figure 2 Special cycles implemented during dedicated cold tests performed to measure the changing in the geometric components of the allowed multipoles and to monitor the possible cable displacement during the powering.

TABLE III
AVERAGE AND STANDARD DEVIATIONS OF THE SHIFT IN THE GEOMETRICAL COMPONENTS OF FIELD HARMONICS DUE TO THE FIRST POWERING AT 12.85KA, MEASURED AT 1.9 K.

	b3	**b5**	**b7**
average	0.30	-0.16	0.02
stdev	0.14	0.05	0.01

A typical example of test results is given in Fig. 3, where the allowed multipoles smoothly change as a function of the highest applied current. The multipole change versus the highest powering current I_i can be fitted with

$$\Delta b_n^{geo}(I) = C_n (I - I_o)^2 \tag{3}$$

where I_0~6 kA, i.e. not far from the value of 5kA that would be expected for a multipole change proportional to the applied Lorentz force. This suggests that the shift in the block6 position estimated from the room temperature measurements takes place progressively as the magnet is experiencing an operating current that has not been reached before.

The good agreement between the multipole change observed at room temperature and at 1.9 K suggests that the deformations due to the thermal cycle are reversible and therefore do not play a relevant role in the subject of our analysis.

If a pre-cycle with a lower current is done after the 12.85 kA powering, the geometric measurement gives the same results of the 12.85 kA powering: this means that the coil geometry ‘remembers’ the highest Lorentz force which it has been undergone. The effect of an additional cool down on this memory has been preliminary investigated: some of the tested magnets have been cooled down and warmed up several times (one magnet up to four times) and re-measured following the same procedure. The results show that the cool down may lead the magnet to lose a fraction of its memory, which is recovered after the full powering. However it has never been observed, even after several thermal cycles, that the magnet goes back to a lower or equal level with respect to the previous cycle. The understanding of such phenomenon requires further investigation.

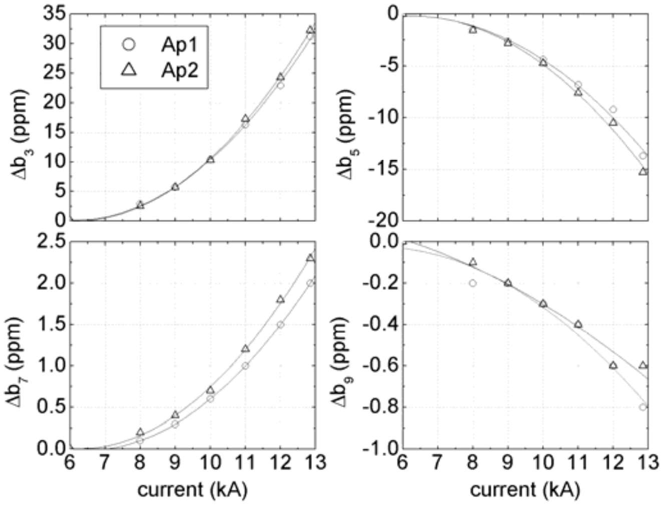

Figure 3 Geometrical components of the first four allowed multipoles as a function of the highest current seen by the magnet: measurements (markers) and parabolic fit (solid line).

B. Voltage Noise as a Function of the Powering History

If the movements of the conductors in block6 that take place during the powering are sufficiently fast, they can induce a voltage in the magnet coil that can be measured by the voltage taps. It is important to point out that, for current values below the nominal one, the energy released by these movements is not large enough to quench the magnet.

During the previously described measurements, the signal across the main voltage taps of the magnet has been recorded. Here we analyze the difference between the two voltage channels across the magnet apertures. This differential signal has the advantage of being insensitive to the inductive component excited by the current ramp and less affected by the noise of the power converter. Examples of such signals recorded during the pre-cycle up to a current I_i, for successively increasing values of I_i are shown in Figure 4. For the sake of simplicity we only give the absolute of the signal, thus losing information about which aperture is inducing the spike. Indeed, our aim is to deduce from the average amplitude of the noise some qualitative information about the global mechanical activity within the magnet during the powering.

In the ramp going up to 9 kA, where the magnet was already powered up to 8 kA, the signal below 8 kA is pretty stable and due to the noise of the power converter (Fig. 4, upper left). Then, from 8 kA to 9 kA a signal that can be related to conductor movements is measured. For the successive ramp up to 10 kA, we observe no activity up to 9 kA, and activity from 9 to 10 kA (fig. 4, upper right). The same pattern is followed for the successive ramps to 11 kA and 12 kA: when the previous highest current is approached, the signal switches from the noise level to measurable random spikes. This pattern is compatible with the hypothesis that the spikes are due to fast cable motions induced by the Lorentz forces [8,9,10], that take place only when exceed the previous highest current.

This signal gives complementary information with respect to the global deformation previously estimated with the magnetic measurements, mainly on its temporal structure. Even though the geometrical changes of the magnet cross section can be considered as a smooth process in the time scale of several seconds, the voltage tap signals show that the undergoing dynamics is characterized by micro-motions of the conductor and the system evolves in between periods of quiescence interrupted by sudden activity, in the time frame of milliseconds.

This is not surprising, since this type of dynamics has been observed in several natural systems like for instance earthquakes, volcanic eruptions, solar flanges, gamma-ray burst and biological evolution [11]. This particular dynamics is usually called stick-slip motion and it is a characteristic of complex systems with a large number of coupled degrees of freedom, where friction is an important ingredient of the equation of motion. The 6th block could be schematically considered as a spring connected to the collar and pushed against it by the Lorentz force. The block does also experience a friction force against the collar and the copper wedge which try to inhibit the motion. This simple model can already well interpret both the changing geometry and the temporal structure of the cable motion. Similar modeling has been made in different domains with different mathematical approaches [12][13].

IV. CONCLUSIONS

Cold test campaign has been performed to investigate the impact of the first powering cycles on the geometry of the LHC dipole cross section. The main results from both warm and cold measurements are the following ones

- The first powering induces a small systematic shift in the allowed multipoles that is compatible with an outward radial movement of 20-30 micrometers of the block of conductors of the inner layer on the coil pole (block6), in a uniform way along the length of the magnet.
- Measurements at 1.9 K show that the multipole shift (and therefore the coil deformation) is proportional to the square of the intensity of the highest current experienced by the magnet. This is compatible with the hypothesis that the coil movement is induced by the Lorentz forces.

Additional information is given by the voltage taps recorded during the powering. When the magnet is experiencing currents that have never been seen before, there is a strong signal composed by spikes localized in the range of fraction of milliseconds, while the system can be quiescent for tens of milliseconds. This suggests that the temporal structure of the plastic like deformation of the coil is not continuous, but rather discrete on a time range of fractions of milliseconds.

We finally remind that these movements are not directly related to the quench of the magnet, which is usually localized in the coil heads, since their amplitude and the level of current are such that the energy release is too low with respect to the stability margin. Therefore these phenomena, however of the same nature, can be well distinct from the mechanisms that are at the origin of quenches and training in the LHC dipoles.

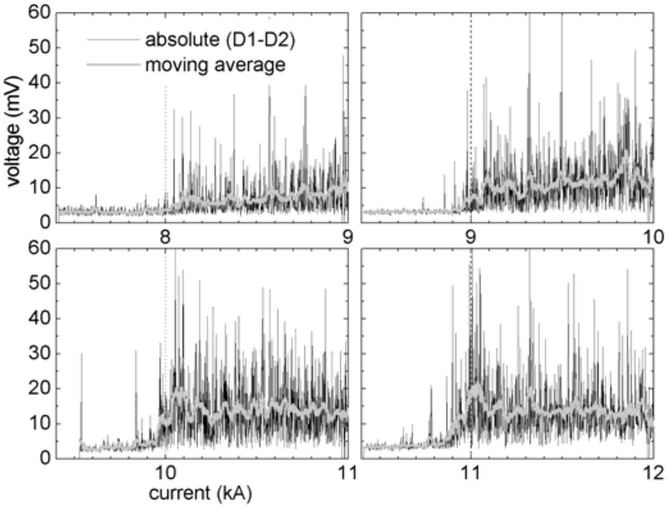

Figure 4 Voltage tap signals recorded in between the magnet apertures during different ramps. The first (top-left) corresponds to a ramp performed while the magnet cross section previously experienced already a current up to 8kA. The second (top-right) a current of 9kA. The third (bottom-left) a current of 10kA. The fourth (bottom-right) a current of 11kA.

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