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Field Quality of the Main Dipole Magnets for the LHC Accelerator

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Abstract

Short and long dipole model magnets for the LHC are measured in detail to optimize the field quality to the different operation phases of the accelerator. We will report on recent progress to understand and quantify effects related to the magnetization of the superconductor, to time dependent effects at fields corresponding to beam injection and to behaviour during acceleration. A parametrization for the measurements is proposed. The contributions from any misalignment of the dipoles and correctors magnets is compared to expected field quality of the dipoles.

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ABSTRACT

Short and long dipole model magnets for the LHC are measured in detail to optimize the field quality to the different operation phases of the accelerator. We will report on recent progress to understand and quantify effects related to the magnetization of the superconductor, to time dependent effects at fields corresponding to beam injection and to behaviour during acceleration. A parametrization for the measurements is proposed. The contributions from any misalignment of the dipoles and correctors magnets is compared to expected field quality of the dipoles.

1 INTRODUCTION

The LHC accelerator will produce head on collisions between beams of 7 TEV protons [1]. Beam optics calculations indicate that the performance of the LHC will be limited by the field quality mainly at low energy through a limitation of the dynamic aperture. Experience from the Tevatron [2] and Hera [3] machines have shown that time dependent effects on the field errors can lead to unstable beams during the injection and at the beginning of the acceleration where an abrupt “snap-back” to the field errors at start of injection takes place. Field ramps necessary for the beam acceleration create coupling currents between the strands of the superconducting cables of the winding, resulting in degradation of the field quality.

The field expansion used is relative to the main field, B_1,of the magnet at x = R_{ref} = 10 mm. Here n=1 is a dipole field, n=2 is a quadrupole field etc. The b_n and a_n represent the normal and skew relative field errors.

$$\mathbf{B}_y + i\mathbf{B}_x = \sum_{n=1}^{\infty} C_n \left(\frac{z}{R_{ref}}\right)^{n-1} = B_1 \sum_{n=1}^{\infty} \frac{(b_n + i a_n)}{10^4} \left(\frac{z}{R_{ref}}\right)^{n-1}$$

This paper will concentrate on field errors that could dominate the behaviour of the LHC at low energy.

2 ALIGNMENT OF THE DIPOLES AND THE END CORRECTORS

The harmonics allowed by the symmetry of the dipole are large at injection field due to the cable magnetization. A misalignment of the dipole containing a multipole of order n+1 produces an additional one of order n. Table 1 compares the errors generated by a misalignment of 0.5 mm to the expected random errors $\sigma(b_n)$ and $\sigma(a_n)$ of the dipole field. Moreover, the decapole and sextupole correctors mounted at each end of the main dipoles will produce similar quadrupole and octupole terms if misaligned with respect to the dipoles. Some care will therefore be needed to avoid systematic misalignment of the end correctors with respect to the main dipoles.

Table 1. Comparison for even harmonics (in units of 10^{-4} of injection field at 10 mm radius), between the errors resulting from a misalignment of 0.5 mm of the dipole and the standard deviation (σ) of the field errors expected in the dipoles.

n	b_{n+1} expected in the dipole	$\sqrt{b_n^2 + a_n^2}$ for 0.5mm mis.	σ (b_n)	σ (a_n)
2	-3.9	0.4	0.4	1
4	0.25	0.05	0.1	0.1
6	-0.026	0.008	0.06	0.01

3 INTERSTRAND EDDY CURRENTS

Current ramps induce field distortions for all harmonics. These effects are dominated by coupling currents inversely proportional to the interstrands resistance of the superconducting cables [4]. Table 2 shows, for three different 10 m long models, that the deviations are important for all harmonics. Systematic field errors due to this effect could happen for instance due to the bending of the dipoles to the radius of curvature of the LHC.

A tight control of the LHC dynamic aperture is required. A systematic study based on these measured values was performed on the resulting loss of dynamic aperture at the beginning of the acceleration [5]. It makes the assumption that an exponential increase of the acceleration rate gives a constant perturbation all over the acceleration.

Table 2. Field errors due to cable coupling currents (in units of 10^{-4} of the injection dipole field at 10 mm) at 8T/20min ramp-rate, in four 10 m long dipole models. Also reported the average interstrand resistance as deduced from loss measurements.

n	MTP1A1	MTP1A2	MTP1A3	MTP1N2
b_1	88	10.8		9.8
b_2	-0.96	-1.11	-0.052	1.32
a_2	10.8	0.89	1.052	1.06
b_3	4.6	0.95	0.3	0.55
a_3	-0.16	-0.19	-0.035	0.14
b_4	0.45	-0.13	0.019	-0.047
a_4	0.82	0.08	0.13	0.24
b_5	2.08	0.05	0.002	-0.09
a_5	-0.34	-0.02	-	0.026
R_{cable}(μΩ)	1.6	6.8	14	6.7

This study shows that a spread comparable to the imperfections of MTP1A1 would significantly reduce the LHC dynamic aperture during the ramp. What matters is really the spread of all harmonic terms for the whole population of dipoles, the average b_3 and b_5 can indeed be corrected with the end correctors. A spread comparable to the imperfections of MTP1A2 or even better of MTP1A3 would not degrade significantly the dynamic aperture. MTP1A2 might be seen as an acceptance limit at the expense of a significant increase of the already long ramp time. These conclusions should be confirmed by further tracking studies.

4 MAGNETIZATION DECAY AND "SNAP-BACK"

LHC superconducting dipoles are characterized by a significant drift of the magnetic field when the current is constant, with typical time scales in the order of several minutes to several hours [4]. At the restart of the ramp (beam acceleration phase) the field quickly bounces back, "snaps back", reaching within 25 to 40 A (approximately 20 to 30 mT of field change) the original value at the start of the injection plateau. This can be of concern for the start of beam acceleration. All harmonics are subject to the field drift. On allowed harmonics the drift is systematic in the direction decreasing the contribution from the filaments magnetization, while it is random on non-allowed harmonics.

In accordance with previous measurements on Tevatron[2], HERA[3] and SSC[6] magnets, we have found that the amount of decay on all harmonics (and thus the snap-back) depends on the time spent at high current, and on the number of operating cycles. Typically, for the LHC dipoles, the decay requires very long flat-tops at high current to saturate (times longer than _ hour). A few cycles (of the order of 5) to nominal operating current produce an asymptotically stable situation. Quenching resets previous history effects. For machine operation this implies that magnets who have followed different histories will have a different behaviour at injection field.

We speculate that the long term drift and the snapback are associated with the interaction between the changing cable internal field associated with the strand current distribution and the magnetization of the single strands. We have started measurements of typical field decays and snap-back amplitudes, investigating on the influence of several parameters such as pre-cycles and temperature drifts in order to establish suitable procedures to minimize this effect. The main findings of these studies are listed below.

- Snap-back is associated with field change rather than with field change rate. This is shown in Fig. 1 where measurements in a 10 m long prototype are shown in the case of different ramp-rates after the injection plateau. The magnitude of the snap-back is approximately the same in all cases, but the time span for the snap-back scales inversely with the current ramp-rates.
- A pre-injection plateau at a lower current reduces the amount of field decay and snap-back at injection. A ≈25 % smaller snap-back was measured on b_3 after a 15 minutes pre-injection plateau. The reduction is not a critical function of the pre-injection current.
- The magnitude of the snap-back on the allowed harmonics at different temperatures scales as the ratio of the contributions of DC magnetization to the harmonic at the same temperatures. This demonstrates the relation between field decay, snap-back and DC magnetization.

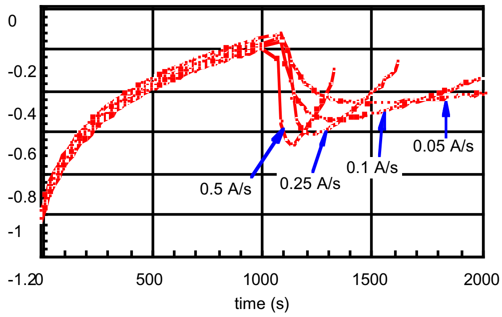

Figure 1. Snap-back in a 10 m long dipole prototype (MTP1N2) at different ramp-rates after the injection plateau.

In summary, a pre-injection plateau before the injection phase decreases the snap-back. The residual magnitude can be accommodated by slow ramps giving time for the corrector scheme to react. Typical magnitudes for the snap-back of the first harmonics in the LHC 10 m long prototypes, measured after several days of operation, are reported in Tab. 3. Systematic effects are expected only on the allowed harmonics.

Table 3. Change of multipoles due to snap-back for the LHC dipoles, estimated from the measured snap-back in 10 m long prototypes. All quantities in units of 10^{-4} of the main field, at 10 mm reference radius. The standard deviations expected from geometrical errors in the magnets series are quoted as a reference.

component	Δ (Snap-Back)	σ(geometric)
b_2	±0.1	0.4
a_2	±0.5	1
b_3	+0.8	0.5
a_3	±0.2	0.15
b_4	±0.5	0.1
a_4	0.0	0.1
b_5	-0.1	0.05
a_5	0.0	0.04

5 PARAMETRIZATION OF THE MEASUREMENTS

In a most general way, we can write that the field **B** produced by a magnet in arbitrary operating conditions is approximated by:

$$\mathbf{B} = \mathbf{B}_{geom} + \mathbf{B}_s + \mathbf{B}_{\Delta x \Delta y} + \mathbf{B}_{AC} + \mathbf{B}_M + \mathbf{B}_{\Delta M}$$

where we have evidenced the various contribution of winding geometry $\mathbf{B}_{geom}$ (including the linear iron contribution), iron saturation $\mathbf{B}_s$, winding movements $\mathbf{B}_{\Delta x \Delta y}$, coupling current $\mathbf{B}_{AC}$, filaments magnetization $\mathbf{B}_M$ and long term magnetization drift and snap-back $\mathbf{B}_{\Delta M}$. For each of them we are testing suitable parametric dependencies based on existing models or empirical fits.

The present scaling for the coefficients C_n is given in Tab. 4, where C_m indicates the main field component.

Table 4. Scaling of the field contributions proposed for a parametric representation.

	Main field	Field errors ($n \geq m+1$)
$\mathbf{B}_{geom}$	$C_m^{geom} = \gamma_m I$	$C_n^{geom} = \gamma_n C_m$
$\mathbf{B}_s + \mathbf{B}_{\Delta x \Delta y}$	$C_m^{\mu} = \sigma_{m,2} I^2 + \sigma_{m,3} I^3 + \sigma_{m,3} I^4$	$C_n^{\mu} = \sigma_{n,2} C_m^2 + \sigma_{n,3} C_m^3 + \sigma_{n,4} C_m^4$
$\mathbf{B}_{AC}$	$C_m^{AC} = \tau_m \frac{dI}{dt}$	$C_n^{AC} = \tau_n \frac{dC_m}{dt}$
$\mathbf{B}_M$	$C_m^M = \mu_{m0} + \frac{\mu_{m1}}{I}$	$C_n^M = \mu_{n,0} + \frac{\mu_{n,1}}{C_m}$
$\mathbf{B}_{\Delta M}$	$C_m^{\Delta M} = \Delta_m \left[1 - e^{-(t-t_0)/\tau}\right]^{(\dagger)}$ $C_m^{\Delta M} = \Delta_m \left[1 - \left(I(t) - I_o\right)/\Delta I\right]^{(\ddagger)}$	$C_n^{\Delta M} = \Delta_n \left[1 - e^{-(t-t_0)/\tau}\right]^{(\dagger)}$ $C_n^{\Delta M} = \Delta_n \left[1 - \left(I(t) - I_o\right)/\Delta I\right]^{3\,(\ddagger)}$

(†) During a $I = I_0$ current plateau starting at $t = t_0$
(‡) At ramp restart, between starting current I_0 and current $I_0 + \Delta I$

6 IMPLICATION FOR THE SERIES MEASUREMENTS

A coils assembly able to measure the integral of the field is under construction [7]. It is composed of 14 measuring lengths separated for mechanical reasons by gaps equal to the twist pitch of the cable. It will allow much faster measurements for the series. The errors avoided by an integrated measurement are listed below.

- The residual error from a measuring coils having in average the length of the twist pitch that varies slightly between cable manufacturers is larger than thestandard deviation from magnet to magnet.
- Time dependent effects have a larger amplitude when approaching the ends of the magnets.
- Point like variations of eddy currents have been measured.
- The randomness of the snap back effects is not yet understood. We believe that the standard deviation measured along the 15 m of the magnets can be as high as the deviation between magnets.

The request to be able to measure the dipole axis and verify the centering of the spool piece correctors is not possible with a integral shaft. These measurements will be performed during warm tests of the final assemblies with the help of a short coil. Differences between the axis positions in warm and cold conditions will be verified on a reduced number of magnets.

7 CONCLUSION

Exploratory measurements of both short and long models of the LHC superconducting dipole magnets indicate the importance of methodically separating different effects. The reproduciblity of the time dependent effects and dynamic effects may dominate the low field quality with respect to superconductor magnetization and harmonics due to the conductors locations. We have defined a model for the magnetic measurements in order to quantify and eventually correct these effects that could limit the dynamic aperture of the LHC machine at low energy.

REFERENCES

[1] "The Large Hadron Collider, Accelerator Project", LHC Study Group, CERN/AC/95-05(LHC), Aug.1995.

[2] R.W. Hanft, et al., “Studies of Time Dependent Fields in Tevatron Superconducting Dipole Magnets”, IEEE Trans. Magn., **25**, (2), 1647-1651, 1989.

[3] H. Brueck, et al., “Time Dependent Field Distortions from Magnetization Currents in the Superconducting Hera Magnets”, Cryogenics, **30**, 605-609, 1990.

[4] J. Buckley, D. Richter, L. Walckiers, R. Wolf, “Dynamic magnetic measurements of superconducting magnets for the LHC”, IEEE Trans. Of Appl. Sup., **5**, (2), p 1024, 1995

[5] A. Faus-Golfe "Minimization of the ramp-induced non-linear field imperfections in LHC", LHC Project Note 9, May 1995.

[6] A. Devred, et al., “Time Decay Measurements of the Sextupole Component of the Magnetic Field in a 4-cm Aperture”, 17-m-Long SSC Dipole Magnet Prototype, Proc. of 14th Particle Accelerator Conference, San Francisco CA, May 6-9, 1991.

[7] P. Sievers, “Towards series measurements of LHC magnets”,CERN AT/94-11(MA), June 1994.