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DEPENDENCE OF THE STATIC AND DYNAMIC FIELD QUALITY OF THE LHC SUPERCONDUCTING DIPOLE MAGNETS ON THE PRE-CYCLE RAMP RATE

N.J. Sammut[1)], L. Bottura, G. Deferne, W. Venturini Delsolaro, R. Wolf
CERN, Geneva, Switzerland

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[1)] The University of Malta & CERN

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CERN,
CH-1211 Geneva 23
Switzerland

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N. Sammut[1,2], L. Bottura[1], G. Deferne[1], W. Venturini Delsolaro[1], R. Wolf[1]
1 - CERN, Geneva CH-1211, Switzerland; 2 - University of Malta, Msida MSD 2080, Malta

Abstract
The allowed multipoles in the Large Hadron Collider (LHC) superconducting dipole magnets decay whilst on a constant current plateau. It is known that the decay amplitude is largely affected by the powering history of the magnet, and particularly by the pre-cycle flat top current and duration and the pre-injection preparation duration. Recently, it was observed that the decay amplitude is also highly dependent on the pre-cycle ramp rate, which has an indirect effect also on the sample of data taken at constant field along the magnet loadlines. This is an important consideration to be included in the Field Description for the LHC (FiDeL), to cope with the difference between the test procedure followed for series tests and the expected cycles during the machine operation. This paper presents the results of the measurements performed to investigate this phenomenon and describes the method included in FiDeL to represent this dependence.

THE FIELD DESCRIPTION FOR LHC

The Field Description for the LHC (FiDeL) [1], currently being developed at CERN, is a feed-forward system designed to forecast the field variations during particle injection, acceleration and collision within a residual error comparable to commissioning beam control requirements. Once the machine is within the commissioning tolerances, it will be in a state that is controllable through beam based measurements, thus allowing the beam diagnostics to take over and reach the nominal beam parameters.

FiDeL is based on the decomposition of the magnetic field in static and dynamic field components, matched to the results of series tests performed at CERN from 2002 to 2007. The static components depend only on current. *Loadline* measurements were performed during series tests to study the static multipole variations and consist of taking two measurements on current plateaus, from injection current to nominal current. The loadline is preceded by a pre-cycle to put the magnet in a known magnetic state. For series measurements, the pre-cycle ramps up at 50A/s to nominal current (11850A), and then ramps down at the same ramp rate after a waiting time of 1000s at this current.

The dynamic components (decay and snapback) depend on current and time. They affect the machine mostly at injection and at the beginning of the acceleration. The decay amplitude is known to be strongly dependent on the magnet powering history [2,3] and especially on the pre-cycle flat top current, the pre-cycle flat-top duration and any waiting time before injection. Decay and snapback were characterised during series tests using measurements performed during *simulated LHC cycles* [2]. For series measurements, the LHC cycle was a ramp up at 10A/s to injection current (760A) with a duration of 1000s on the injection plateau. This was followed by a standard LHC PELP (Parabolic Exponential Linear Parabolic) ramp, a 1000s flat-top plateau at the nominal current of 11850A, and a ramp-down to minimum current (350A) at 10A/s. The measurement LHC cycle was preceded by a pre-cycle at 50 A/s as described above.

EFFECT OF PRE-CYCLE RAMP RATE

The powering conditions during series magnetic measurements were adjusted to minimise test time, and in some instances they could not be fully representative of operation in the LHC. One specific instance is the ramp rate used for the pre-cycle of dipole and quadrupole tests, 50A/s for series tests vs. 10 A/s in the LHC (limited by the maximum voltage available over the magnet string of a sector). A difference in pre-cycle ramp rate changes the pre-cycle duration, and we expect a variation of decay and snapback. To investigate the magnitude of this effect, we have performed dedicated measurements on 4 LHC dipole magnets. The measurements consisted of standard measurement LHC cycles preceded by pre-cycles of varying ramp-rate.

Figure 1 shows the decay of the sextupole harmonic (b_3) in dipole MB2598 (aperture 2) for three different pre-cycle ramp-rates. From the figure, it can be observed that the decay amplitude is a function of pre-cycle ramp-rate, and a fast pre-cycle yields a large decay. In addition, the starting point of the decay appears to be different for the three cycles. We focus on these two features next.

Effect of Finite Measurement Time at Injection

The different starting point of the decay is not related to

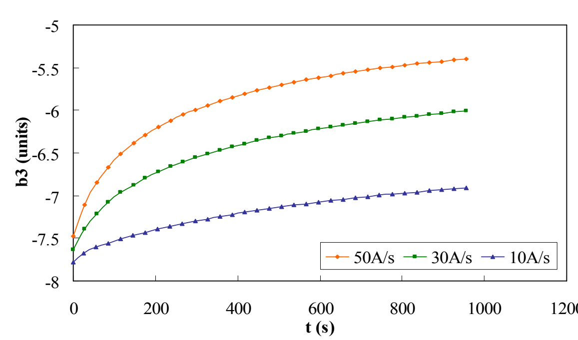

Figure 1: b_3 decay at injection following pre-cycles with different ramp rates in dipole MB 2598 (aperture 2).

*Work supported by CERN. #nicholas.sammut@cern.ch

the magnet, but is rather due to the measurement technique. The rotating coils [4] used to take these data perform a measurement in approximately 30 seconds. In addition, a measurement delay is present at the beginning of the injection plateau to make sure that constant current is reached after the parabolic roll-off from the ramp.

The blind time at the beginning of the injection plateau, associated with a fast decay with an amplitude that is a function of the pre-cycle ramp-rate, results in an apparent different decay starting point for the three cycles. To demonstrate this feature, we have applied the decay model presented in [2] to each curve and extrapolated backwards in time as shown in Figure 2. At a time of 26 s before the first data point, the standard deviation between the curves is less than 0.02 units, which is comparable to the reproducibility of the rotating coils. Assuming that this is the real start of the injection, the three curves have in practice the same starting point, showing that the pre-cycle ramp rate has no effect on the value of sextupole at the beginning of injection, as expected.

This measurement artefact has been removed from the measured curves of Fig. 1 (and other magnets) for the analysis of the influence of pre-cycle ramp rate on decay. As discussed later, this effect has an impact also on data taken in steady state during loadlines, which also require correction.

Ramp Rate Scaling of Decay and Snapback

We have drawn in Figure 3 a summary of the pre-cycle ramp rate dependence of decay in the first allowed harmonics (dipole b_1, sextupole b_3 and decapole b_5) of the LHC dipoles measured. The pre-cycle ramp rate largely affects the decay amplitude, defined as the change in harmonic between the beginning and end of injection, corrected as described in the previous section. Pending a more refined analysis, we have defined a *scale factor* to correct the data taken during series measurements and make them applicable for LHC operating conditions. The scale factors are reported in Table 1. The decay in LHC can be obtained multiplying the decay from series measurements by the scale factor, which corresponds to making the assumption that the decay is a linear function of the pre-cycle ramp rate. Specifically, we expect an average b_3 decay amplitude in LHC of about 0.9 units (10 A/s pre-cycle), vs. an average of about 2 units established during series measurements (50 A/s pre-cycle).

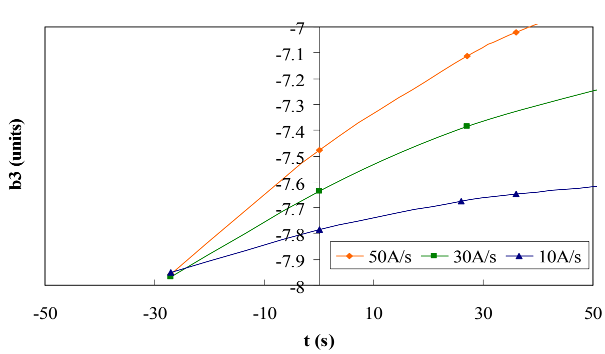

Figure 2: Decay **e**xtrapolation to the start of injection

Table 1: Scaling Factor and Uncertainty (at 1 σ) Required to Compensate for the Pre-cycle Ramp-rate Effect

b1	b3	b5
-0.034 ± 0.306	0.437± 0.058	0.300 ± 0.095

Correction of Static (Loadline) Data

The finding discussed above led us to re-examine the data taken during loadline measurements and at the basis of the characterization of the static field components. This measurement is taken at a number of constant current plateaus (about 20 along a ramp), few seconds after reaching each plateau. For each plateau, two data points are taken and averaged to produce curves of static harmonics vs. current. Although the static field component should not depend on the pre-cycle ramp rate, we expected that the decay on each plateau could affect the final average (over a finite measurement time) and induce an artificial dependence. We have verified this hypothesis, performing three loadline measurements in one dipole, with a different pre-cycle ramp rate. The results are shown in Figure 4, reporting b_3 vs. current.

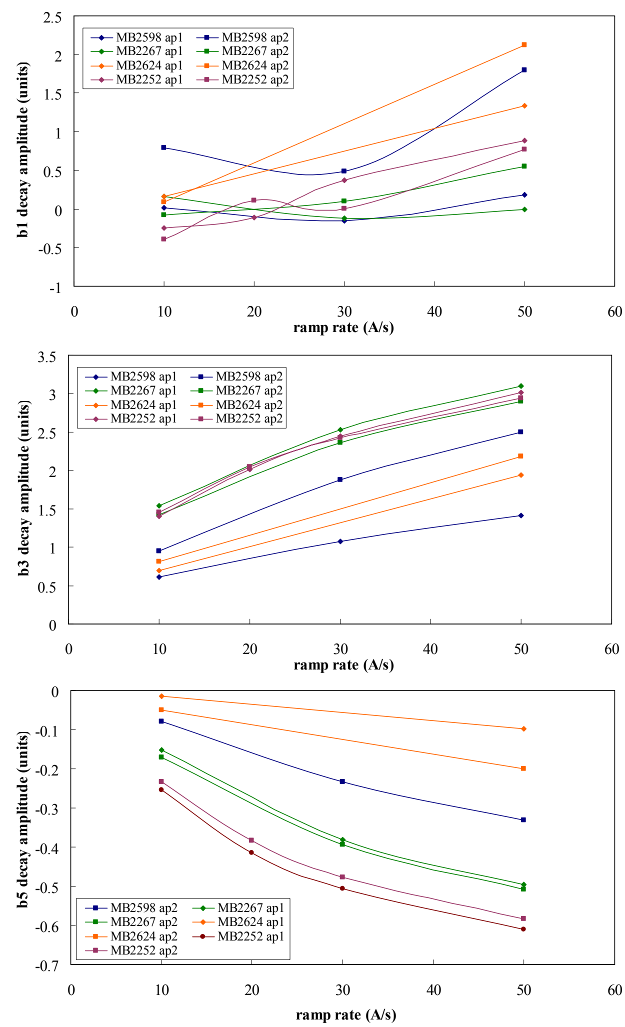

Figure 3: Decay dependence on b1, b3 and b5 on the pre-cycle ramp-rate. The average is normalized to the decay average of the magnet population sampled in series tests.

There is a decay between the two measurements on each plateau that depends on the pre-cycle ramp rate and reduces with increasing current. Using the technique described earlier, it is possible to extrapolate the decay back to where the plateau is assumed to start, thus correcting for the different decay amplitudes at different currents. Once corrected, the loadline measurements become practically identical, see bottom of Figure 4. The maximum standard deviation between the three corrected cycles is 0.03 units, negligibly small. Without the above correction, the b_3 value at injection would have been taken -7.37 units, i.e. the average of the two points at 760 A for the pre-cycle at 50 A/s. The correct extrapolation yields a b_3 value of -7.96 units i.e. a difference δb_3 of 0.59 units which is significant. A correction δ is hence required also for all static data from series measurements.

To avoid re-processing all series measurements, we apply a global correction to the average of cold data. Detailed measurements of a few magnets, fully characterised as described above, provide a correction $\delta(I)$ to be applied to loadline (static) data as a function of current. To make $\delta(I)$ representative of the average of the population of cold tested magnets, we note that there is a correlation between the correction to be applied and the decay amplitude. This correlation is demonstrated in Figure 5 for b_3. The decay amplitude, in turn, is readily available for all magnets cold tested. The average b_3 decay for all magnets cold tested is 2.05 units at 760 A, which corresponds to a correction $\delta(760)$ of 0.56 units. Using the correlation of Figure 5, it is hence possible to scale the correction $\delta(I)$ at each current to produce values representative of the average of the whole magnet population. The final result is shown in Figure 6.

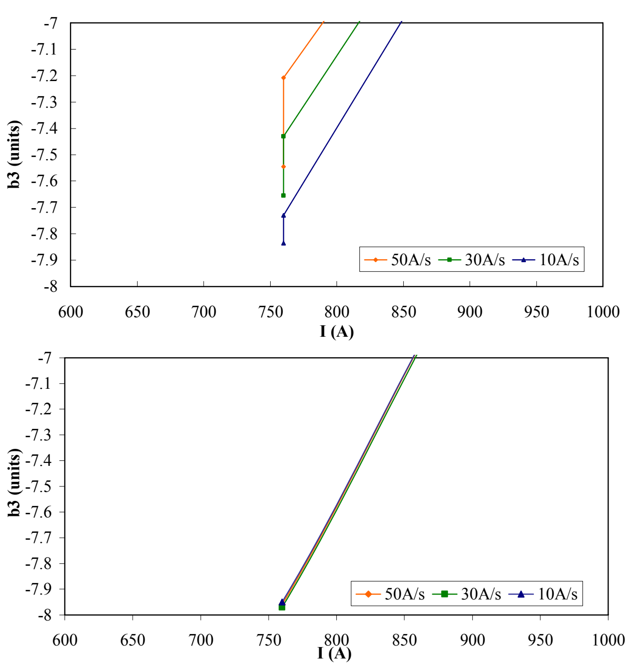

Figure 4: (top) Loadline measurement (MB2598 aperture 2) with different pre-cycle ramp-rates at 760 A, (bottom) Loadline measurements after correction.

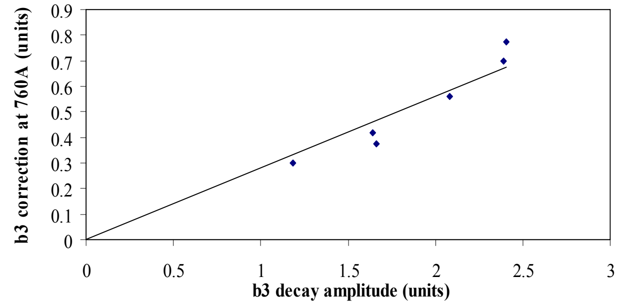

Figure 5: The b_3 correction at 760 A vs. the b_3 decay amplitude at 760 A.

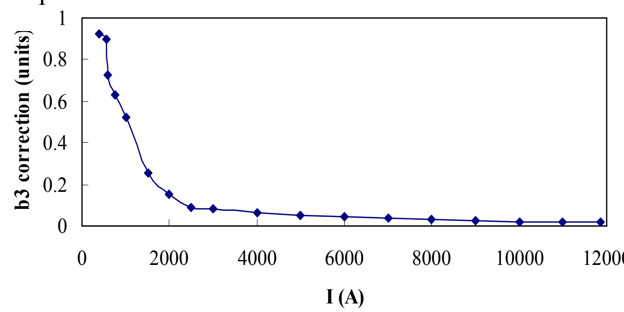

Figure 6: The b_3 correction to be implemented on the loadline ramp up measurements of the LHC dipole magnet population.

CONCLUSION

The effects caused by different pre-cycle ramp-rates were examined. It was determined that the pre-cycle ramp-rate does have a significant physical effect on the decay amplitude at injection. This is probably because the time constant of the decay as modelled in [2] is comparable to the time for the magnet to ramp down to minimum current and back up to injection current. It was also shown that the decay amplitude during machine operation is expected to be half as much as that found in series measurements. Scaling factors for this effect were found. It was also shown that the pre-cycle ramp rate affects the measurements on every plateau during the loadline hence a correction of the loadline measurements performed on the magnet population was obtained. To resolve this issue, apart from the above analysis procedure, a new fast measurement system has recently been developed at CERN to improve the time resolution of the measurements [5].

REFERENCES

[1] N. Sammut, L. Bottura, J. Micallef, Phys. Revs ST - Accel. Beams, Vol 9 No 1, 012402, 2006.

[2] N. Sammut, L. Bottura, P. Bauer, T. Pieloni, J. Micallef, Phys. Revs ST - Accel. Beams - Vol. 10, No. 8, 082802, 2007.

[3] R.W. Hanft et al, IEEE Transactions on Magnetics, vol. 25, pp. 1647-1651, 1989.

[4] J. Billan et al, IEEE Transactions on Applied Superconductivity, vol. 10, pp. 1422-1426, 1999.

[5] J. Garcia et al. International Magnetic Measurement Workshop XV, Fermilab, August 2007.