THE DEPENDENCE OF THE FIELD DECAY ON THE POWERING HISTORY OF THE LHC SUPERCONDUCTING DIPOLE MAGNETS*

N. Sammut[#], L. Bottura, S. Sanfilippo, CERN, Geneva, Switzerland
J. Micallef, University of Malta, Malta

Abstract

The decay of the allowed multipoles in the Large Hadron Collider (LHC) dipoles is expected to perturb the beam stability during the particle injection. The decay amplitude is largely affected by the powering history of the magnet and is particularly dependent on the pre-cycle flat-top current and duration as well as the pre-injection preparation duration. With possible prospects of having different genres of cycles during the LHC operation, the powering history effect must be taken into account in the Field Description Model for the LHC and must hence be corrected during machine operation. This paper presents the results of the modelling of this phenomenon.

INTRODUCTION

The Large Hadron Collider (LHC) at CERN can only be controlled adequately if the main magnetic field and its harmonics are known to the required accuracy. Unfortunately, a control system solely based on measurements of beam perturbations produced by the field inhomogeneities may be too demanding for the instruments available. Therefore, in order to reduce the burden on the beam-based feedback, a feed-forward system will be used to predict the behaviour of the field errors during the machine cycle. This feed-forward system is known as the Field Description for the LHC (FIDEL) [1]. The latter is primarily based on a field model which separates the effects that together contribute to the total field in a magnet aperture.

One of the main error components that largely affects the field during the injection plateau is the systematic decay of the allowed harmonics. It has now been established that this phenomenon is mostly a consequence of field changes in the strands caused by current redistribution in the superconducting cables [2], [3]. Unless the small changes of the local magnetic field are overwhelmed by a change in the transport current, they affect the magnetisation of the filaments in the strands causing it to decrease. This therefore results in a net magnetisation decrease in the aperture i.e. a field decay. As described in [4], the decay drift can be modelled well enough with a double exponential function of the type:

$$\Delta(t, t_{inj}, \tau, d) = d\left(1 - e^{-\frac{t - t_{inj}}{\tau}}\right) + (1 - d)\left(1 - e^{-\frac{t - t_{inj}}{9\tau}}\right) \quad (1)$$

which is a direct consequence of current diffusion through the cable.

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

Measurements have shown that the harmonic decay is not reproducible from cycle-to-cycle [4], [5]. The decay amplitude is strongly dependent on the magnet powering history. It has been shown in [6] that this dependence can be formulated by a composition of current imbalance redistributions from previous cycles which partially cancel. In the first approximation, these redistributions can be modelled in the same way as a charging-discharging L-R circuit.

POWERING HISTORY DEPENDENCE

Studies performed on short LHC dipole models based on a single powering cycle [7] have shown that the decay amplitude is mostly dependent on the pre-cycle flat-top current I_{FT}, flat-top duration t_{FT} and the pre-injection plateau duration time $t_{preparation}$. The powering pre-cycle can therefore be characterised by these three parameters as shown in Figure 1. In practice, measurements have shown that the powering history of the magnet can be condensed into a single powering pre-cycle.

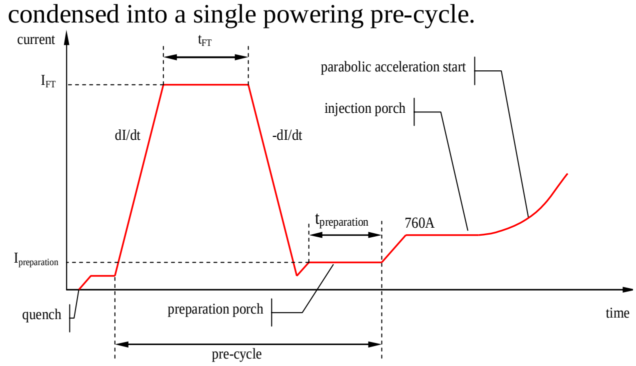

Figure 1: Parameters affecting decay during injection

MEASUREMENT PROCEDURE

Powering history dependence measurements performed at cold on series dipole magnets were each preceded by a quench to erase all persistent currents. A pre-cycle with its parameters varied was then followed by an LHC cycle. A standard pre-cycle (I_{FT}= 11850 A, t_{FT} = 1000 s, $t_{preparation}$= 0 s) as used in series decay measurements was used as a reference.

When testing the influence of one parameter (e.g. the flat-top current) the second and third parameters (e.g. the flat-top duration and the pre-injection duration) were held constant at the value corresponding to the standard pre-cycle. The measurements were performed with the twin rotating coil system [8]. The I_{FT} dependence was measured on 18 apertures, the t_{FT} dependence was measured on 24 apertures and the $t_{preparation}$ dependence was measured on 14 apertures.

MATHEMATICAL FORMULATION

The powering history dependence in the decay amplitude δ_n of the harmonic n can be modelled by:

$$\delta_n^{I_{FT}} = \delta_{std}^{I_{FT}} \left(\frac{E_0^n - E_1^n e^{-\frac{I_{FT}}{\tau_E^n}}}{E_0^n - E_1^n e^{-\frac{I_{FT}^{std}}{\tau_E^n}}} \right) \tag{2}$$

$$\delta_n^{t_{FT}} = \delta_{std}^{t_{FT}} \left(\frac{T_0^n - T_1^n e^{-\frac{t_{FT}}{\tau_T^n}}}{T_0^n - T_1^n e^{-\frac{t_{FT}^{std}}{\tau_T^n}}} \right) \tag{3}$$

$$\delta_n^{t_{preperation}} = \delta_{std}^{t_{preperation}} \left(\frac{P_0^n + P_1^n e^{-\frac{t_{preparation}}{\tau_P^n}}}{P_0^n + P_1^n e^{-\frac{t_{preparation}^{std}}{\tau_P^n}}} \right) \tag{4}$$

where δ_{std} is the decay amplitude measured for a standard pre-cycle, i.e. with flat-top current equal to the nominal current of I_{FT}^{std} = 11850 A, flat-top time t_{FT}^{std} = 1000 s and pre-injection time $t_{preparation}^{std} = 0$ s. τ_E^n, τ_T^n and τ_P^n are the time constants for the magnet memory for flat-top current, flat-top duration and pre-injection time respectively. E_0^n E_1^n T_0^n, T_1^n, P_0^n and P_1^n are the fitting parameters. These three equations are a direct consequence of the assumption of exponential decay during constant current excitation, i.e. Eq 1, where only the longest time constant has been retained for simplicity.

RESULTS

The average dependence was obtained by first fitting Eq 2, 3 and 4 to the data. Figure 2 shows the measurement results of the b_3 decay amplitude vs. I_{FT} (top), t_{FT} (middle) and $t_{preparation}$ (bottom). Considering the average curves of the measurements, the importance of the three parameters can be determined for the main field and the harmonics being considered. The difference between the maximum and minimum value of the curves is shown in Table 1. This table therefore shows that the most important dependence is I_{FT} since variations of this parameter cause the largest change. Table 1 also indicates that all the three parameter dependencies for b_3 are important for modelling. The I_{FT} and $t_{preparation}$ dependence for b_1 and b_5 is relatively small and is comparable to the twin rotating coils measurement system uncertainty. For this reason we choose not to model these effects.

Table 1: The average effect of each powering history parameter on the allowed harmonics

parameter	b_1 (units)	b_3 (units)	b_5 (units)
I_{FT}	0.9	1.29	0.21
t_{FT}	0.02	0.46	0.03
$t_{preparation}$	0.49	0.6	0.02

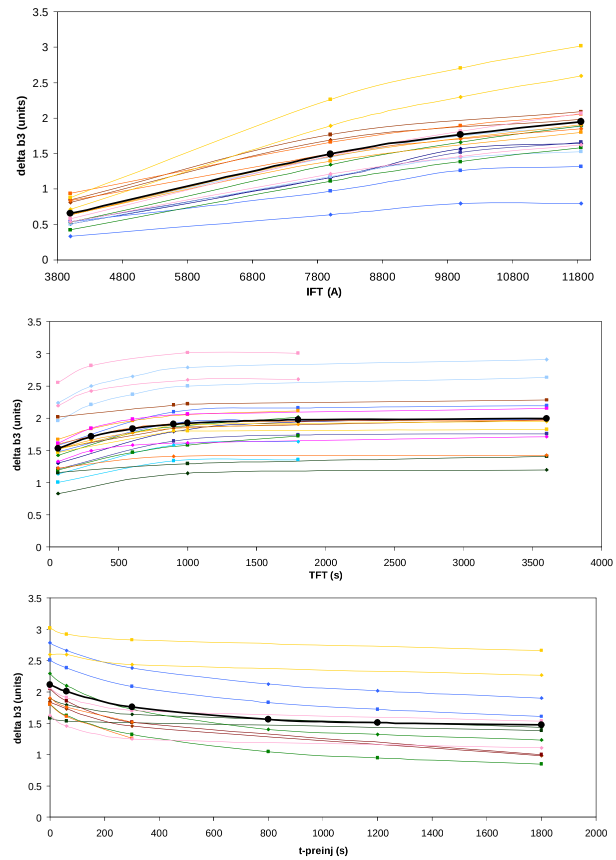

Figure 2: The effect of a variation of I_{FT} (top), t_{FT} (middle) and $t_{preparation}$ (bottom) on the decay amplitude at the end of injection. (bold black line is the average dependency)

EXTRAPOLATION OF THE PARAMETER SPACE

Eqs. 2, 3 and 4 can be joined together to yield an equation that extrapolates the powering history dependence to a 3d parameter space:

$$\delta_n = \delta_{std} \left(\frac{E_0^n - E_1^n e^{-\frac{I_{FT}}{\tau_E^n}}}{E_0^n - E_1^n e^{-\frac{I_{FT}^{std}}{\tau_E^n}}} \right) \left(\frac{T_0^n - T_1^n e^{-\frac{t_{FT}}{\tau_T^n}}}{T_0^n - T_1^n e^{-\frac{t_{FT}^{std}}{\tau_T^n}}} \right) \left(\frac{P_0^n + P_1^n e^{-\frac{t_{preperation}^{std}}{\tau_P^n}}}{P_0^n + P_1^n e^{-\frac{t_{preperation}^{std}}{\tau_P^n}}} \right) \tag{5}$$

The reference cycle is a pivot point that is common for all three powering history parameters. However, this pivot point has different values for the three parameters due to the limited sample of measurements taken. To homogenise the pivot point and to have a powering history prediction for the entire magnet population, a scaling law is used to scale the average curves of Figures 2. Eq. 5 is then used to fit the three scaled average curves to a 3-dimensional parameter space. The fit yields the parameters reported in Table 2. The corresponding surface plots are shown in Figure 3. For b_3, the parameterization is found to produce an extrapolation with a maximum error of 0.15 units with a median error of 0.035 units.

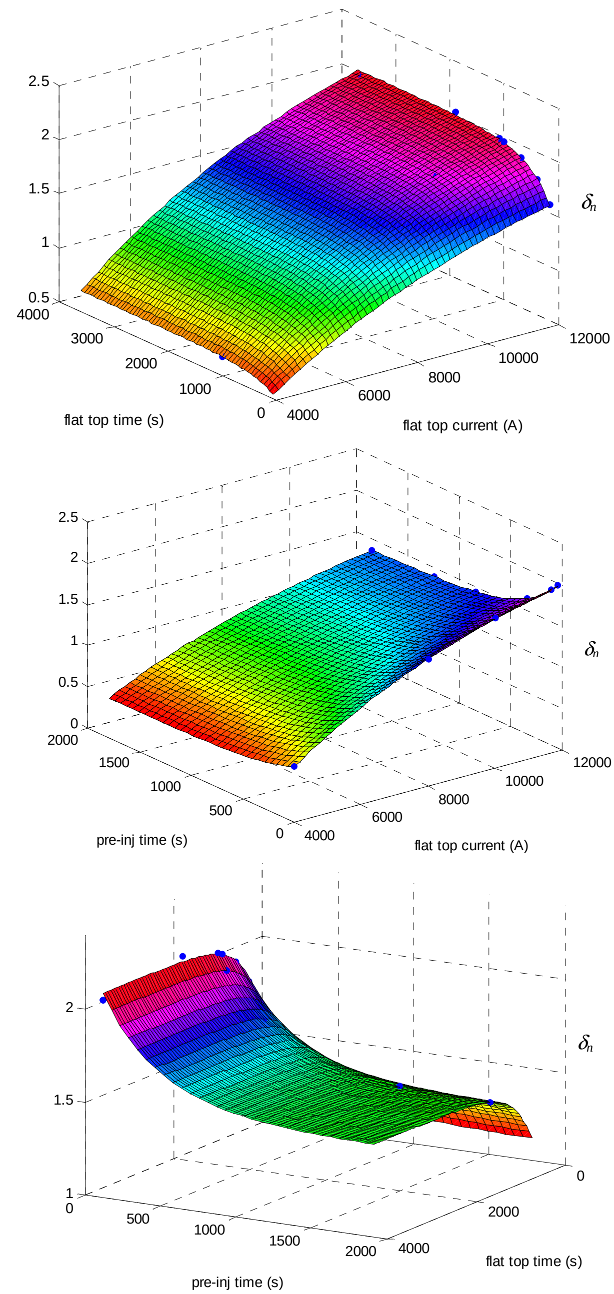

Figure 3: I_{FT} vs. t_{FT} (top), $t_{preparation}$ vs. I_{FT} (middle) $t_{preparation}$ vs. t_{FT} (bottom)

CONCLUSION

The decay amplitude dependence on the powering history of the LHC dipoles has been investigated by performing an extensive measurement program using rotating coils. The measurements were focused on the pre-cycle flat-top current, the pre-cycle flat-top duration and pre-injection duration which are known to have the largest effect on the decay. A model was constructed to interpolate the results obtained. The model was then extended to a 3d parameter space to extrapolate the powering dependence to magnetic states that were not measured. The results of the extrapolation were very satisfactory since the maximum error between the 3d model and the data was only 0.15 units @17mm. This 3d model is therefore quite powerful and will provide a good extension to FIDEL.

Table 2: the fit parameters of the 3-dimensional powering history dependence

	Coefts	b_1	b_3	b_5
I_{FT}	E_0	-0.467	16.981	-0.7025
	E_1	-1.027	22.984	-1.0329
	τ_E	4.665	0.658	5.8430
t_{FT}	T_0	-	8.18	-
	T_1	-	2.063	-
	τ_T	-	0.040	-
$t_{preparation}$	P_0	-	-8.779	-
	P_1	-	3.728	-
	τ_P	-	0.039	-
population decay amplitude	δ_{std}	0.986	2.004	-0.302

REFERENCES

[1] N. Sammut, L. Bottura, J. Micallef "Mathematical Formulation to Predict the Harmonics of the Superconducting Large Hadron Collider", Phys. Rev. ST Accel. Beams, 9, 012402, January 2006

[2] L. Krempasky, C. Schmidt, "Experimental Verification of 'Supercurrents' in Superconducting Cables Exposed to AC-fields", Cryogenics 39 (1999) 23-33

[3] R. Stiening, "A Possible Mechanism for Enhanced Persistent Current Sextupole Decay in SSC Dipoles," SSC Report SSCL-359 (1991)

[4] A.K. Ghosh, K.E. Robins, W. Sampson, "Time Dependent Magnetization Effects in Superconducting Accelerator Magnets", Proceedings to the 15th International Conference on High energy Accelerators, Vol. 2, 665-667, July 20-24, 1992

[5] R.W. Hanft, B.C. Brown, D. A. Herrup, M. J. Lamm, A. D. McInturff, M.J. Syphers, "Studies of Time Dependence of Fields in Tevatron Superconducting Dipole Magnets", IEEE Trans. Mag. Vol. 25, No. 2 (1989), 1647-1651

[6] T. Schreiner, "Current Distribution Inside Rutherford-type Superconducting Cables and Impact on Performance of LHC dipoles", Ph. D. thesis, Vienna University of Technology, 2002.

[7] M. Haverkamp, "Decay and Snapback in Superconducting Accelerator Magnets", Ph.D. Thesis, University of Twente, Netherlands, 2003

[8] J. Billan et al. "Twin Rotating Coils for Cold Magnetic Measurements of 15 m Long LHC dipoles", IEEE Trans. Appl. Supercond. 10, no.1, pp 1422-1426, Dec 1999