**DATA ANALYSIS OF TRANSIENT ENERGY RELEASES
IN THE LHC SUPERCONDUCTING DIPOLE MAGNETS**

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Data Analysis of Transient Energy Releases in the LHC Superconducting Dipole Magnets

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Abstract – *Premature training quenches are caused by transient energy released within the LHC dipole magnet coils while it is energized. Voltage signals recorded across the magnet coils and on the so-called quench antenna carry information about these disturbances. The transitory events correlated to transient energy released are extracted making use of continuous wavelet transform. Several analyses are performed to understand their relevance to the so called training phenomenon. The statistical distribution of the signals amplitude, the number of events occurring at a given current level, the average frequency content of the events are the main parameters on which the analysis have been focalized. Comparisons among different regions of the magnet, among different quenches in the same magnet and among magnets made by different builders are reported. Conclusions about the efficiency of the raw data treatment and the relevance of the parameters developed with respect to the magnet global behavior are finally given.*

Keywords – LHC projects, Superconducting magnets, training quenches, wavelets, CWT

I. INTRODUCTION

The Large Hadron Collider (LHC) [1], now under installation at CERN in Geneva Switzerland, will provide proton-proton collisions with a centre-of-mass energy of 14 TeV. In order to achieve this design energy within the constraint of the 27 km LEP tunnel, the main bending magnets must provide a dipole field of 8.33 T. The choice of NbTi superconducting cables operating at 1.9 K was made and the main twin aperture dipoles were designed to have the superconducting limit at 9.7 T.

Like most large scale superconducting magnets, the LHC dipoles exhibit *training quenches*, i.e. a progressive improvement of the maximum field level after repeating quenching. These types of premature resistive transitions, *quenches*, are mainly originated by conductor motion and associated transient energy released inside the magnet coil. All of these mechanical events produce in general a rapid variation of the voltages, called *spikes*, across the magnet coil (voltage taps, VT) and in the so-called quench antennas (QA i.e. array of pick-up coils [2]). A dedicated study on the LHC cable stability has been performed to estimate the energy needed to induce a quench as a function of the duration of the energy release, the length of the cable region affected and the

cables parameters, like the thermal and electrical coupling among its components [3]. A new instrumentation has been also developed to finely localize the origin of the resistive transition, to estimate its dimension and to study the beginning of its expansion [4]. Finally dedicated field quality measurements have been performed to estimate the impact of the first powering cycles on the allowed multipoles components of the field to reconstruct the permanent changes on the coil geometry due to the Lorentz forces [5].

In this paper an improved analysis of the raw signals from VT and QA is presented. These signals are the only source of information about the undergoing dynamic which is responsible for the macroscopic behavior of the magnet coil structure previously summarized. A preliminary analysis of such signals was discussed in [6] when high frequency resolution signals and long recording time were not available. Later a new acquisition system with unlimited recording duration and 50 kHz sampling frequency has been used during the tests of some LHC dipole magnets to provide this additional information and the first results have been presented in [7], where the use of wavelets has been originally introduced. In the following an improved method to analyze those data is described in details which makes combined use of wavelets and Fourier analysis. The increased number of magnets tested since then gives also same preliminary information to compare this analysis on different magnet builders (for the LHC dipole three firms has been chosen for the construction which in the following are called for simplicity family 1,2 and 3).

II. THE TRANSIENT SIGNALS

During the powering of the LHC dipole magnets several pulsing signals of typical duration of few milliseconds are present across both VT and QA channels. Examples of both signal families are presented in Fig. 1. The first one from the top has been recorded on a VT channel (the difference between the voltage across the two apertures of the magnet) and the other two on the QA, relatively on pick-up coils located respectively in the first and second aperture of the magnet coil. Even though they appear at the same time and very luckily triggered by the same mechanical event, they have different features and magnitude. The mechanisms which induce voltage are different between the two signal

families. In case of VT the cable displacement induces an abrupt variation caused by magnetic coupling between the moving windings and the coil itself, while for pick-up coils the signal is induced by field distortion generated by the conductor displacement.

The VT signals are less sensitive to conductor motions with respect to the QA ones because they are more affected by the noise of the power converter. Also the electronic amplifier cards used in this study have not been designed for high frequency acquisition and this cause an additional undesired filtering of the data. In case of more sensible QA signals, because each pick-up coil is located in a particular region of the magnet coil it is possible to acquire information relatively to the behavior of a specific region.

Fig. 1 Example of signal samples recorded on both VT and QA during the same time interval. A relevant event correlated to an energy released is present on both families of signal but it is better represented in the QA channels. The amplitude ratio between VT and QA has been artificially changed to better fit in the graph.

Table 1. Channels descriptions

Family	channels		definition
VT	D1-D2		Difference between the two magnet apertures
	D1_L-U		Difference between lower and upper pole of the first aperture
	D2_U-L		Difference between upper and lower poles of the second aperture
QA	Aperture 1	D1_S01	Extremity (CS ¹)
		D1_S07	Straight part
		D1_S08	
		D1_S13	Extremity (NCS ¹)
	Aperture 2	D2_S01	Extremity (CS)
		D2_S07	Straight part
		D2_S08	
		D2_S13	Extremity (NCS)

In the data analysis process the VT signals are mainly used to estimate the global mechanical activity inside the magnet coil because they are the only signals which monitor the

¹ CN and CNS are respectively the so called connection and non connection side of the magnet which are independently analysed because of their different mechanical structure.

whole magnet coil. While the information on the fine structure of the events can only be derived from the analysis of the QA signals, better compensated.

Each signal of both VT and QA, can be modeled by this expression,

$$ch(t) = n(t) + \sum_n A_n \cdot \cos(\omega_n t + \varphi_n) + \sum_k \sum_j B_{jk} \cdot s_k(t - t_{jk}), \quad (1)$$

where the first term is the white noise, the second is the signal periodicity and the third one the signals correlated to transient energy released. This last term is composed of compact support functions s_k . If the events are the scaled replica of a base function, only shifted in time, the index k should be omitted. The Fourier analysis (see example in Fig. 2) indicates the presence of different frequency components which may change among events. For sake of generality we leave the possibility that more families of events exist. The main goal of the data analysis, explained later in the paper, is to extract from the raw signals the third term of (1) and to represent the associated parameters to better describe the perturbation spectrum and reconstruct useful information on the magnet properties based on the regularities of the signal.

Fig. 2 Example of an event recorded on QA channel (upper) and its power spectrum evaluated by FFT (lower) where dominating frequency picks are visible.

III. DATA ANALYSIS METHOD

The data analysis method developed in this study provides parameters to estimate the global mechanical activity inside the magnet coil, the memory of the system with respect to the powering history, and the fine structure of the events (QA) towards a physical model of the coil.

The continuous wavelet transform (CWT) has been implemented to recognize the presence of relevant events. The efficiency of this approach has been tested against different techniques. The simple method based on a voltage threshold presented in [6] has the disadvantage of strong dependence on the estimation of the signal mean value and on its standard deviation. Both these parameters vary as a function of time since they depend on the presence or not of

relevant events in the time interval where the parameters are evaluated. On the contrary the wavelet technique is not affected by the mean value of the signal, since it is the projection of the signal on a zero mean value base function. The two channel families have been treated with different mother wavelets, the VT ones have been analyzed with the Mexican-Hat and the QA with the Morlet [8]. In Fig. 3 examples of CWT and window Fourier transform (WFT) are presented. The CWT is very efficient to identify event in time domain, improving the signal to noise ratio, while the WFT gives information about their frequency content.

Fig. 3 Example of typical signal recorded across QA (a), its WFT transform with a step window of 50ms (b) and the CWT (c).

A. The time domain analysis

The relevant events recorded on VT and QA correlated to energy released have been identified in time using the CWT with the procedure previously described. The time distribution of such events during the ramp up to ultimate field (or up to quench) is represented as the total number of events occurring before a given current, $N(I)$. An example of such analysis is given in Fig. 4 where the data of the first

quench and the second quench recorded on the VT have been used. This representation of the mechanical activity gives information about the number of the events, their rate at a given current level and about the beginning of the activity. We have defined also a criterion to measure the memory of the system between different powering cycles as the mean distance (measured in current axis) between $N(I)$ during two different ramps to quench (see Fig. 4, arrows). The amplitude of the events on the contrary cannot be inferred from such representation and this analysis should be integrated with the following representation of the signal in amplitude domain.

Fig. 4 The total number of relevant events occurred after reaching a given current level is represented.

B. The amplitude domain analysis

Knowing only the current level of the event does not give a complete picture of the background mechanical activity since the energy associated with each event is mandatory information to conclude about the stability of the coil winding. This last is not easy information to obtain since all signals available are not only proportional to the energy but also to the location and to the dimension of the sub-part of the coil which is moving. Establishing a correlation between the amplitude of the signal and the actual energy released is a hard problem which may not have clear answer and it is nevertheless out of the scope of the present work. In the following we pragmatically use the amplitude of the signal to estimate in first approximation the energy released. Furthermore we use not only the maximal amplitude of the signal (which may look the most representative parameter of the event) but all the available samples identified within the time duration of an event because the shape of the signal indicates the presence of multiple motions associated to one event. This is revealed by the not monotonous decay of the envelope observed in many events, which can only be explained by a sort of creeping dynamics.

Finally the absolute value of all samples associated to an event is used for the analysis of the amplitude. We represent this information with cumulative statistical distribution, which reads as the number of samples associated to a mechanical event with an amplitude bigger than a given value. Results of this analysis are presented in Fig. 5 where

two examples are reported relatively to one VT channel and one QA channel. The analysis has been performed for all events identified during the first ramp to quench. Formally these distributions can be described as:

$$NP_{>}(A) = N \int_A^{+\infty} p_A(x) dx, \quad (2)$$

where $p_A(x)$ is the probability density function associated to the variable A (in this case the sample amplitude) and N is the total number of signal samples associated to mechanical events. Another example is presented in Fig. 6 where the analysis is performed on sub-parts of the VT signal. This may be used to study the shape of the distribution and its stability at different level of mechanical forces. In this particular example the decay of the large event can be well fitted with an exponential but while the characteristic amplitude is about the same for low currents it is larger for the high currents.

Fig. 5 The signal is represented using non normalized statistical distributions $NP_{>}$. Both example of VT and QA are presented.

Fig. 6 The non normalized cumulative distribution $NP_{>}$ is used to represent the VT signal. In this analysis the signal has been divided into four sub intervals of 3kA duration windows. To be noticed that there is no activity for the interval 0-3kA.

C. The frequency domain analysis

The analysis relative to the occurrences of mechanical events, $N(I)$, and their associated amplitude, $NP_{>}$, gives

information about the global mechanical behavior, the rate of the events and their magnitude. With the frequency analysis we try to investigate their shape to better understand the undergoing mechanics. For such investigation we use only the QA signal which are more reliable as already explained in section II.

To estimate the frequency context of the events the Fast Fourier Transform (FFT) is adopted since the CWT does not provide enough accuracy at high frequency value. The spectrum of the whole signal does not provide relevant information about the frequency content of single events because the power spectral density of the periodic signal is much higher (the duration of the recorded signal is about five orders of magnitude higher than the characteristic duration of an event). For such reason we divide the signal in sub-parts which are compatible both with the mean duration of the events and the desired frequency accuracy. Time windows of 50 milliseconds have been chosen which guarantees 20 Hz resolution and limits the density spectrum of the main periodicities to reasonable values. An example of such analysis is given in Fig. 7 (left). The procedure adopted is to make the FFT of all signal sub-parts independently and afterwards to average together the spectrum of the intervals in which at least one event was identified and doing the same for the remaining ones. The difference between the two average spectra obtained in this way (so called the signal spectrum and the noise spectrum) gives a good quality representation of the average frequency excited during cable motion. As already done for the amplitude distribution, we analyze the signals separately for different current intervals (see Fig. 7 right). In the example reported the frequencies of the events do not change at increasing current levels. What is obviously changing is the associated peak amplitude, in agreement with the increasing amplitude of the events.

Fig. 7 On the left side an example of average FFT for QA signal (the signal, the noise and their difference). On the right the average FFT, already cleaned from the noise, as a function of the current level.

IV. DATA ANALYSIS RESULTS

The signal amplitude and the occurrence of events recorded on VT signals show that the magnet of family 1 has a significantly different global mechanical activity with respect to the others. In Fig. 8 the $NP_{>}$ relative to the first

quench of three magnets belonging to different families is represented. The amplitude distribution relative to family 1 is significantly lower with respect to the other ones. The amplitude distribution of the second quench presented in Fig. 9 confirms this trend. In general during the second ramp lower amplitudes are observed, even if in the range of rare events (about 1% probability) deviations can be observed, as it is the case of magnet number two. These deviations are inside of what is usually referred to as statistical fluctuation. We interpret this global attenuation of the background mechanical activity as an improvement of the stability of the coil winding after repeating powering cycles to quench.

Fig. 8 The not normalized cumulative distribution $P_>$ for VT signals is presented for the first quench of magnets built by different firms.

Fig. 9 The not normalized cumulative distribution $P_>$ for VT signals is presented for the second quench of magnets built by different firms.

The total number of events at a given current level for the three families extracted from the VT signals is presented in Fig. 10 for the first two ramps to quench. It indicates again that the family 1 differs with respect to the others in terms of the lower number of events identified during the first ramp to quench and lower memory during the second ramp. The analysis of the QA signals confirmed this trend. An example of QA analysis done for one aperture of magnet belonging to family 2 is presented in Fig. 11. The differences in number of events between the straight part (S) and the extremities (E) is

due to the different dimension of the coil region monitored by the two systems; in the extremities is about four times shorter than for the straight part. The differences on the contrary observed indicate a different mechanical behavior and consequently a different perturbation spectrum between the two end types.

Fig. 10 The relevant events identified in VT signals are presented as the total number of occurrences at a given current level during the ramp to quench.

Fig. 11 The relevant events identified in QA signals are presented as the total number of occurrences at a given current level during the ramp to quench. The signals recorded during the first and the second ramp to quench are presented.

The analysis of the mean frequency components of the events associated to energy released has been performed on all magnets tested with high resolution. An example of this analysis for the QA signals recorded during the first quench of family 2 magnet is presented in Fig. 12. Clear peaks in the power spectrum are present. The summary of the observed frequency is presented in Table 2.

Table 2. Summary of the frequency peaks observed with the FFT analysis on different magnet families

Frequency (kHz)	Family 1		Family 2		Family 3	
	S	E	S	E	S	E
4	X		X	X		X
6.5	X	X	X	X		X
10.5	X				X	
13.5	X					
14.5			X	X

Fig. 12 The average value of the FFT is presented for all signals recorded on the QA for magnet of family 2.

V. CONCLUSIONS

An improved method to analyze high resolution signals recorded in the LHC dipole magnets based on the Continuous Wavelet Transform analysis has been presented. Signals both from Voltage Taps between the magnet coil and Quench

Antenna have been analyzed. Optimized mother wavelets have been used for the two types of signals, since the efficiency of the method is strictly related to the similarities among the events and the mother wavelet. An improved description of the undergoing mechanical activity in the coil winding during excitation has been provided. Differences and similarities among the three magnet builders have been addressed. Family 1 has a globally lower mechanical activity while it has a lower memory of previous cycles with respect to the others. Family 1 and 3 have a sensibly different power spectrum between straight part and extremities, as expected from different mechanical structures, while family 2 has significant similarities between these two regions.

In order to conclude these preliminary results more magnets are expected to be tested with high resolution acquisition system, up to the end of 2006 when the series tests are expected to be completed.

REFERENCES

- [1] LHC DESIGN REPORT, Vol.1 THE LHC MAIN RING
- [2] J. Billan et al. Twin rotating coils for cold magnetic measurements of 15 m long LHC dipoles. IEEE Transaction on Applied Sup. Vol.10, No 1, pp.1422-1426, March 2000.
- [3] L. Bottura, M. Calvi, A. Siemko "The LHC cable stability" Cryogenics 2006.
- [4] M. Calvi et al. Improved Quench Localization and Quench Propagation Velocity Measurements in the LHC Superconducting Dipole Magnets. IEEE Transaction on Applied Sup. 15 (2005) no. 2 pt.2, pp.1209-12.
- [5] M. Calvi et al. The impact of the first powering cycles on the LHC superconducting coil geometry. IEEE Transaction on Applied Sup.
- [6] M. Calvi et al. Statistical Analysis of conductor motion in the LHC dipole magnets. IEEE Transaction on Applied Sup.
- [7] M. Calvi et al. On the Use of Wavelet Transform for Quench Precursors Characterization in the LHC Superconducting Dipole Magnets. IEEE Transaction on Applied Sup.
- [8] J. Morlet, G. Arens, I. Fourgeau, D. Giard, Wave Propagation and Sampling Theory, Geophys. 47, 203-236, 1982.