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# On the Use of Wavelet Transform for Quench Precursors Characterisation in the LHC Superconducting Dipole Magnets

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## Abstract

Premature training quenches are caused by transient energy released within the magnet coil while it is energized. Signals recorded across the so-called quench antenna carry information about these disturbances. A new method for identifying and characterizing those events is proposed, which applies the wavelet transform approach to the recorded signals. Such an approach takes into account the time of occurrence as well as frequency content of the events. The choice of the optimal mother wavelet is discussed, and the results obtained from the application of the method to actual signals are given. The criteria to recognize the interesting events are presented as well as the methodology to classify their global behavior.

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# On the Use of Wavelet Transform for Quench Precursors Characterisation in the LHC Superconducting Dipole Magnets

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*Abstract*— **Premature training quenches are caused by transient energy released within the magnet coil while it is energized. Signals recorded across the so-called quench antenna carry information about these disturbances. A new method for identifying and characterizing those events is proposed, which applies the wavelet transform approach to the recorded signals. Such an approach takes into account the time of occurrence as well as frequency content of the events. The choice of the optimal mother wavelet is discussed, and the results obtained from the application of the method to actual signals are given. The criteria to recognize the interesting events are presented as well as the methodology to classify their global behavior.**

***Index Terms*—LHC, Superconductivity, Quench Precursors, Wavelet Transform.**

## I. INTRODUCTION

The main target of the signal analysis is to extract remarkable information from a waveform through its transformation. Singularities, irregular structures and rapid point variations, often carry the most important information in signals. Until recently, the *Fourier Transform* has been the main mathematical tool for analyzing singularities. The Fourier transform breaks down a signal into basic sinusoids of different frequencies and it is the most natural transformation for static signals, i.e. signals which properties do not change in the time domain. The Fourier transform provides a description of the overall regularity of the signals, but it is not well adapted for finding the location and the temporal distribution of the singularities. This was the main motivation for study the *Wavelet Transform* [1][2] in mathematics and in applied research. By decomposing signals into elementary building blocks that are well localized both in space and frequency, the wavelet transform can characterize the local regularity of signals. This feature makes this transform highly efficient in the analysis of the non static signals, i.e. signals characterized by many distinct variations during their temporal evolution. It has been proved that the maxima of the absolute value of the continuous wavelet transform (CWT) provide enough information for analyzing singularities and rapid point variations. The CWT has a particular behavior when singularities have fast oscillations, too. The local frequency of the oscillations can be measured from the points where the absolute value of the wavelet transform is at maximum, both along the scale and temporal variable.

In the following, the method developed for the characterization of quench precursors (spikes) based on wavelet transform is described in details and examples of data analysis are presented based on tests performed on the LHC superconducting dipole magnets. The experimental technique used is based on the so called quench antenna (QA) and the details are presented in [3].

## II. THE METHOD

The non-static and transitory nature of the spikes strongly indicates the wavelet transform as the natural tool for their analysis, both in its continuous and discrete version. With this technique it is possible to isolate and study the different parameters of the spikes. The analysis is carried out on signals acquired with the QA during the current ramp, up to the magnet experience a resistive transition (quench). The method proposed consists of three different phases.

In the first phase a statistical analysis of the signal spectrum is performed to define one or more *characteristic frequencies* which characterize the specific test. This is a range of frequencies inside which an elevated occurrence of spikes is observed. Thanks to its location capability on the time-frequency plane, in this phase the continuous wavelet transform is adopted, with the aim of estimating the spectral content of the spikes. The events which belong to the interesting interval are afterwards used in the following steps of the analysis. In the second phase the spikes energy is estimated and only the events with energy larger than a given threshold are selected. In the third phase the discrete wavelet transform is used to extract the spikes identified in the previous phases from the background noise. Thus the spike parameters in the time domain can be finally estimated from the resulting waveforms. Studying the signals relative to the same magnet it is possible to characterize the spikes present in these signals. Thus a classification of the spikes with common features, such as oscillation frequency, duration and amplitude is performed and characteristics of *spike families* relative to the specific test are identified. In the following the three phases of the proposed method are described in detail.

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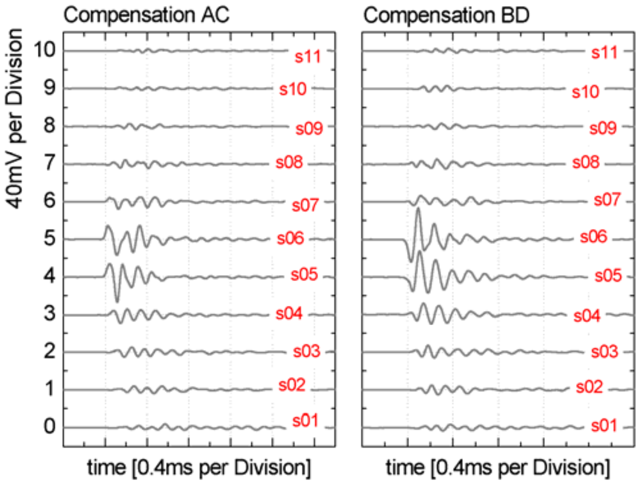

Figure 1 Example of spike recorded on the local quench antenna. Two different signal types are represented which correspond to different pick-up coil compensation schemes.

### A. *Frequency characterization of the Spikes*

The CWT is applied to the full set of signals recorded during the magnet test and it is mathematically defined as follows:

$$CWT_{a,b} \equiv \int_{-\infty}^{+\infty} f(t)\, h\left(\frac{t-b}{a}\right), \tag{1}$$

where $f$ is the actual signal and $h$ is the so-called mother wavelet. For each signal the maximum of the absolute value of the CWT is evaluated and the critical frequency ranges defined. The CWT is an effective tool for first investigation of signal properties, useful for developing algorithms and concepts. It produces a time-frequency representation of the signal, with the additional property of the so-called *zooming*. Thus the spectral resolution is a function of scale, i.e. small-scale structure has higher resolution (frequency bandwidth) than large-scale structure. The CWT can zoom in the signal to display detailed, fine features (high frequency) and zoom out to display large, coarse trends (low frequency). For signals in which spectral characteristics or statistical properties are likely to change over time, the CWT can be used to identify those features potentially usable by signal processing. This is the main motivation for study the spikes through the CWT. In this first step all the available signals from different tests of the same magnet are treated.

The number of octaves $J$ to be used for the CWT calculation is established by the following relationship:

$$J = [\log_2 N] - 1 \tag{2}$$

where $N$ is the number of samples. The *mother wavelet* chosen for the study of these signals is the so-called *Morlet wavelet* [3] which can be formalized analytically as follows:

$$h(x) = e^{-x^2/2}\cos(5x)\,. \tag{3}$$

In Figure 2 the Morlet wavelet is plotted in time and frequency domain. The values of the continuous wavelet transform are orderly in a matrix CWT [$a$, $b$], where $a$ is the scale ($2 \rightarrow J+2$) and $b$ the discrete time ($1 \rightarrow N$). The number of scale is $J{\cdot}M$, where $M$ is the number of voices per octave. The scales and the frequencies are joined with the following formula:

$$F = \frac{F_c}{a \cdot \Delta} \tag{4}$$

where $F$ is the pseudo-frequency related to the scale $a$, $\Delta$ the sampling period of the signal and $F_c$ the frequency which corresponds to the maximum of the spectrum of the mother wavelet. The maxima of the absolute value of the CWT are related to signal samples characterized by rapid variation. Thus spike identification corresponds to the search of these maxima. Starting from the matrix CWT[$a$, $b$] the maximum value for both the rows and the columns is located. It is, thus, possible to find the scale factor (or frequency) which corresponds to the maximum of the absolute value achieved by CWT. Such a value is used for the estimation, by means of the relationship (4), of the oscillation frequency of the spike. The next step consists in the estimation of the occurrences of the maxima in the scale factors.

From the histogram of the occurrence number , through a statistical analysis, one or more ranges of scales, inside which an elevated number of spike occurrences exists, are identified. Such ranges of scales are defined as the characteristic scales of the magnet under test.

Identifying the characteristic scales (or frequencies) of the magnet, a first selection of the identified spikes is performed. Only those signals with maximum of the absolute value of the CWT in the characteristic ranges are considered. This selection of spikes is used in the second phase of the analysis.

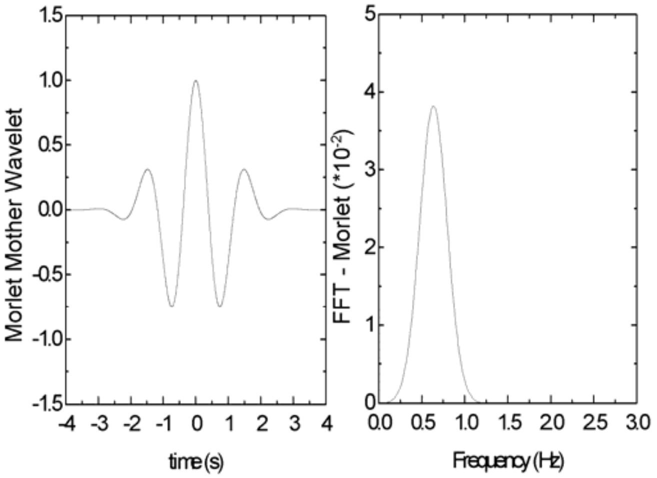

Figure 2 The morel mother wavel on the left and its spectrum of amplitude on the right panel.

### B. *Spikes Energy*

In the second phase the energy of the selected spikes is estimated. It is evaluated as the sum of the square of absolute values of CWT coefficients, belonging to the selected scale and time ranges. The energy of the selected spike can be expressed as follows

$$\sum_{a,b} \left| CWT_{a,b} \right|^2 . \tag{5}$$

The scale and time ranges have been empirically chosen from the analysis of the absolute value of the CWT performed on several signals. Finally the following criteria have been implemented:

scale_max–2 → scale_max+2,

time_max–0.4ms → time_max+ 0.4ms

where *scale_max* and *time_max* are, respectively, the scale factor and the time instant which corresponds to the maximum of the absolute value achieved by CWT. The values of the energy are plotted in two different histograms for signal type. This division is useful for the second selection of the signals. A second selection of the signals is produced in order to concentrate the study on the most meaning spikes. Only those spike with energy superior to a threshold, are chosen. The choice of the threshold for the selection has been matched for the signal type since it has been observed a systematic difference among them.

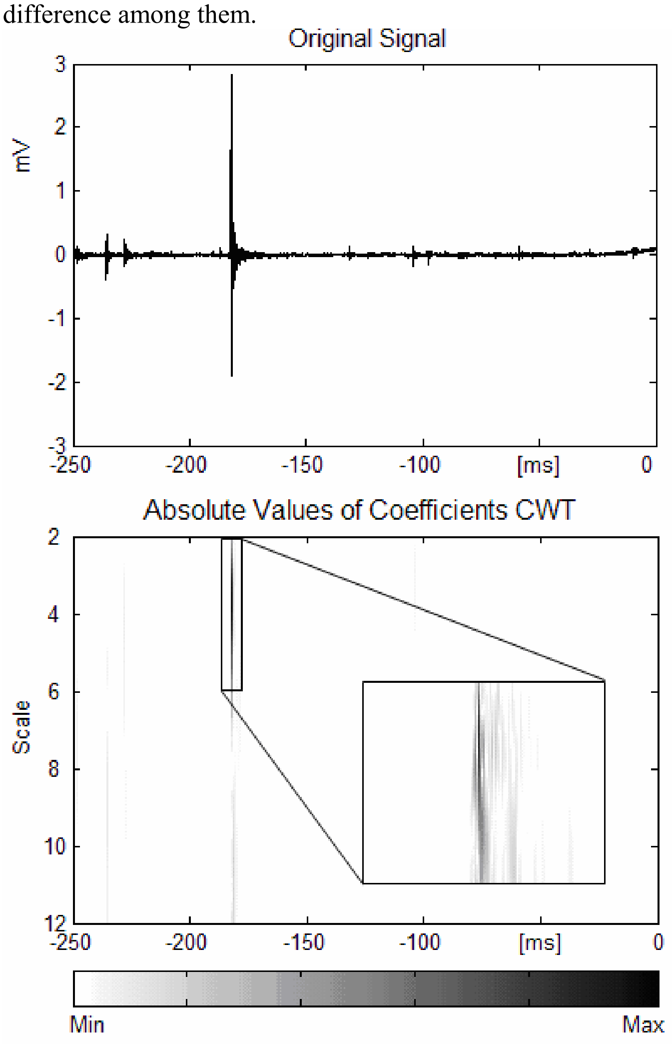

Figure 3 Example of CWT, scale versus time.

### C. *Time Characterization of the Spikes*

In the third phase the characterization in time domain of the remaining spikes is done. The signal spectrum is decomposed in frequency sub-band through the discrete wavelet transform (DWT). Only the sub-band containing the spike is reconstructed in the time domain. The analysis and synthesis phases of the DWT, performed in sequence, produce signal decomposition in many components in the time domain. Each component is characterized by a frequency sub-band. This sub-bands, separated each other, overlay the frequencies axis from zero to half of the adopted sampling frequency (Nyquist frequency).

The analysis phase is based on two digital filters: a high-pass filter (H) and its low-pass mirror version (L). The synthesis phase is also based on the same filters, turned over in the time domain. The decomposition is achieved setting up these filters in a tree-structure, as shown in Figure 4. The *mother wavelet* adopted for the study of the signals is the *Daubechies wavelet* with 8 coefficients that has globally shown the best results in the conducted tests. This wavelet has no explicit analytical expression, except for the Daubechies with one coefficient, which coincides with the *Haar* wavelet.

The number of decomposition levels *n* has been tuned experimentally. The original signal is decomposed in *n* sub-bands by this analysis stage of the DWT. The extraction of the spike from the signal is achieved reconstructing (synthesis stage of the DWT) only the sub-band containing the spike frequency, evaluated in the first phase of the analysis.

Finally measurements in the time domain can be performed on the reconstructed spike waveform, in order to estimate the characteristic parameters of the quench precursors like for instance the peak-to-peak amplitude, the starting time and the duration.

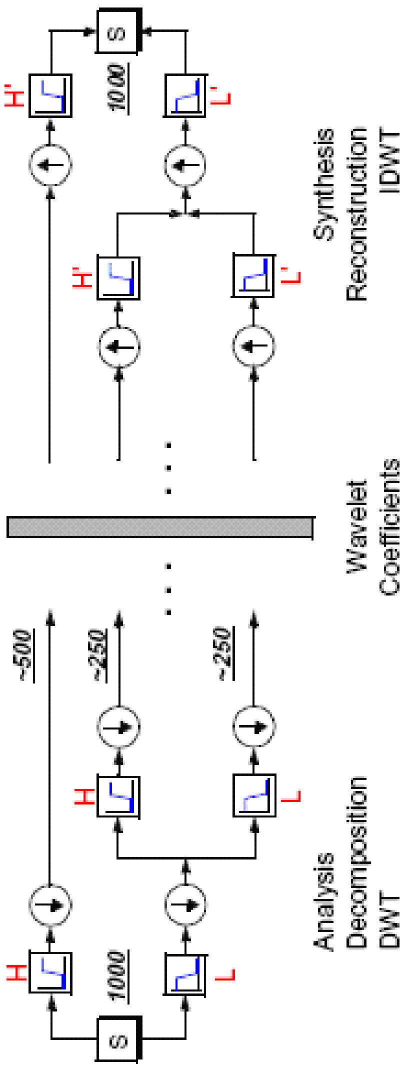

Figure 4 Schematic representation of the analysis and synthesis of the signals for the time characterization

From the analysis of signals recorded for the same magnet it is possible to characterize the spikes present in these signals. Thus an identification of characteristics "families of spikes" with common features, such as oscillation frequency, duration, and amplitude can be performed. The features of the spikes and the ranges of *characteristic frequencies* evaluated during the first phase of the method, are the keys to characterize the quench precursors related to the magnet under test.

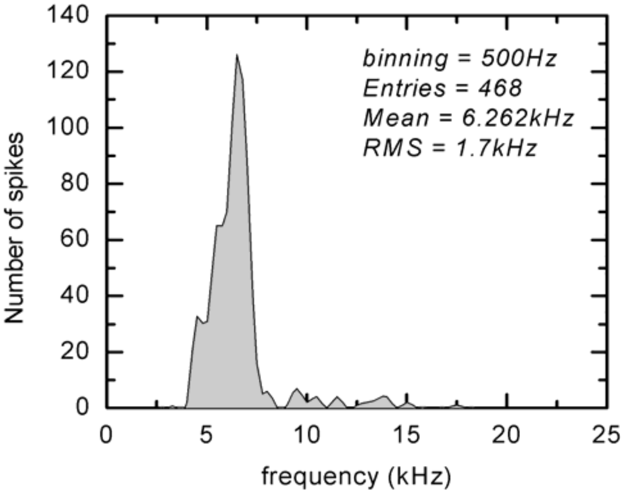

Figure 5 Histogram of the characteristic frequency of the spikes recorded during a special test on one particular magnet.

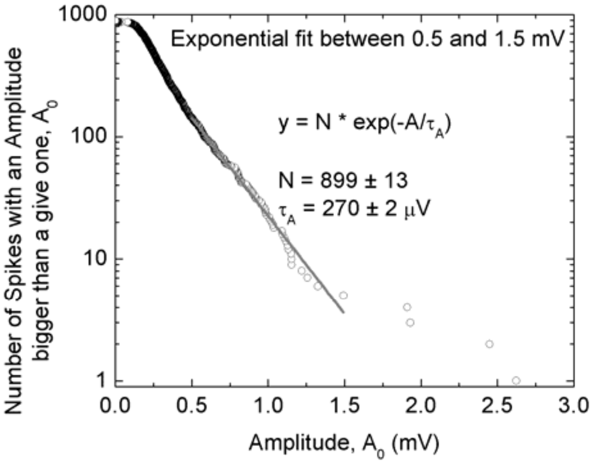

Figure 6 The cumulative distribution of spike amplitudes normalized with respect to the total number of events. The data can be well fitted with an exponential decay for intermediate value of the amplitude.

## III. EXPERIMENTAL RESULTS

Several sets of signals recorded during the standard powering cycles have been used to test the proposed method and to optimize its implementations. The existing data available are nevertheless not considered sufficient, neither for the short time recording (250 ms at 50 kHz), nor the long recording time (9s at 5kHz) due to either the small number of events or to low sampling. A dedicated test has been performed with a prototype acquisition system to record the QA signals all along the current ramp, up to the quench. Eight channels have been acquired simultaneously with a sampling frequency of 50kHz, considered high enough to have sufficient spectral resolution. The most promising parameter is the main frequency of the spike, which is supposed to carry information about the mechanical structure of the coil. The histogram of the identified frequency is presented in Figure 5. A clear peak around 6.5kHz has been identified. The cumulative distribution of the amplitude of the reconstructed spikes is presented in Figure 6. The data are normalized with respect to the total number of spikes detected. The intermediate values are best fitted with an exponential decay while the highest values deviate from such a distribution. Further investigation should validate these preliminary results.

## IV. CONCLUSIONS

The wavelet transform, in its versions both continuous and discrete, has been chosen as a tool for spike analysis. The use of the wavelet transform succeeds to identify quench precursors and characterizing them both in time and frequency domain. The proposed method has been tested on several signals recorded during the standard powering cycles performed on the LHC dipole magnets. As well a special test has been done with a prototype data acquisition system to record the quench antenna signals from the very beginning of the ramp up to the quench. The most promising and so far not yet exploited information is the spike frequency. This parameter is the less affected by the measurement method and strongly coupled to the mechanical properties of the coil. A systematic study of the spike frequency will be performed and its histogram will be used to compare magnets and correlate their global macroscopic behavior.

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