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Models by Field Perturbation Measurements**

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Abstract

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QUENCH OBSERVATION IN LHC SUPERCONDUCTING ONE METER LONG DIPOLE MODELS BY FIELD PERTURBATION MEASUREMENTS

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Abstract - A new method to localize and characterize the origin of a quench in a superconducting dipole has been developed during the tests of the LHC 1 meter long superconducting dipole models. It consists of an extended analysis of the voltage signals generated at the onset of a quench in pick-up coils distributed along the inside of the magnet bore in conjunction with the pole voltage signals. In this paper, we discuss the measurement method and the main results obtained during the training of these magnets, reaching a bore field of 10 T.

I. INTRODUCTION

The first LHC twin aperture 1 m long models suffer from premature quenches [1]. A program was started to localize the sources of the quenches, without having the possibility of connecting more voltage taps on the coils already assembled. Particular peaks that initiate the resistive transition have been observed on the voltage taps [2]. These peaks suggest sudden movements of the conductors due to the Lorentz forces, and their analysis helps to understand the causes of the quenches of such magnets [3]. Coils, mounted originally in both apertures to measure the field harmonics, were connected as well to the quench recorder to pick up the flux changes linked to these fast movements. The resulting sharp signals allowed to locate longitudinally the quench. Surprisingly, slower perturbations were also observed, even for quenches not induced by mechanical movements, but due to fast ramp rates or at the short sample limit. Calculations using the ratios between the signals observed on the various coils located in the same cross-section of the magnet, can also indicate which block of conductors induces this flux change. The pick-up coil system was gradually improved for these studies.

II. THE MEASURING SYSTEM

Fig. 1 schematizes the location of the pick-up coils inside the magnet. Table 1 gives the main dimensions of the coils. The three flat radial triple-coil assemblies are designed for harmonic measurements of the magnetic field and can therefore be placed at any angular position before ramping to quench. A gap of about 0.1 m separates the two assemblies measuring the ends from the one on the middle of the magnets.

Dedicated tangential coils were deposited on polyimide foils using printed circuit technology. These foils are wrapped against the inside of the magnets bores. They are divided in 7 lengths and allow full longitudinal coverage, hence better resolution for the longitudinal localization of the quenches. Different cross-sectional geometries were tried.

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The positioning was less accurate than for the harmonic coils due to the small space available between the magnet conductors and the rotating shaft. Fig. 1 shows the latest version in use.

Fig. 1 The pick-up coil system in the magnet winding

Clean signals are obtained by connecting in opposition coils located symmetrically in both apertures. Recent measurements show that the method can also be applied on a single aperture magnet: the noise on a short coil (for ex. H1) is suppressed by comparing it to the average reduced signal across the full length coil (the sum of H1 to H7).

Table 1: Characteristic data of pick-up coils

Coil type	Number of turns	Length (m)	Width (m)
Harmonic	44	0.30	0.008
Tangential, middle	12	0.25*	0.02*
Tangential, ends	12	0.15*	0.02*

* average values.

A 64 channel acquisition system with a time resolution of 10 μ sec measures accurately the duration of a peak, corresponding to a mechanical movement, and lasting of the order of 100 μ sec. This system stores at the same time the signals coming from the voltage taps of the magnet (1). The small number of taps on the magnets tested up to now did not allow to verify the validity of the model for localizing the quench within the cross-section.

III. THE ABRUPT FLUX CHANGES

The sharp "peak" signals seen simultaneously on the voltage taps and on the pick-up coils are attributed to mechanical movements responsible for the premature quenches (Fig. 2). The linearly rising shape of the signal is due to the

limited bandwidth of the electronics (20 KHz), and measures the duration and amplitude of the movement.

Fig. 2 Typical event with peak, oscillations, and bump

Oscillations follow these peaks. Their characteristics, measured by the different coils of the detection system, confirm that these peaks result from a sudden movement in the structure. The observations hereafter are deduced from signals taken with the harmonic coils assemblies.

- The damping time of these oscillations depends strongly on the magnet structure. A coil-collar assembly was tested without iron yoke, resulting in almost no damping. Later on, these collars were squeezed into the iron yoke, and the oscillations were heavily damped (Fig. 3).
- Records were taken from the three assemblies of harmonic coils placed along the magnets bore: two at the ends and one in the central part of the magnet. Coils were oriented perpendicular to the field. After the spike, low frequency oscillations with opposite phases are measured by the end coils while the central coil gives a negligible signal. It could be explained by longitudinal motion of the support of the coils along the magnet bore.
- Hitting violently the cryostat excites oscillations with the same frequencies.

Fig. 3 Peak and consecutive oscillations with and without iron yoke

These peaks can be measured even if they do not initiate a quench. Their longitudinal localization along the magnet's bore, and the measured frequencies of the oscillations are a valuable tool to understand the behaviour of the magnet. In most cases, peaks reflect a global movement in the winding cross-section:

- the pulses detected by the harmonic coils assemblies being perpendicular to the magnet field have the same polarity and similar amplitudes;
- when the detection system is rotated to be insensitive to the main field component, the peaks amplitude vanishes but the consecutive oscillations remain. This is illustrated in Fig. 4.

Fig. 4 Two quenches made with harmonic coils perpendicular ($\phi = 90^\circ$) and parallel ($\phi = 0^\circ$) to the field, showing presence and absence of peaks, and presence of oscillations

IV. THE SLOW FLUX CHANGES

Quenches with no peak, characteristic of a conductor movement, induce slower signals on the pick-up coils, indicating another type of local field change, related to a current redistribution in the conductor (Fig. 6). Their observation can be difficult when their signals are mixed with the voltage oscillations consecutive to a peak.

The most probable cause for these bumps is that the current is transferred from the quenching strand of the cable to the surrounding strands. Their observation leads to the two following analysis to try and localize the quench, as described below.

A. Localization along the length of the magnet

The various coils located longitudinally see these bumps propagating along the magnet axis (Fig. 5). The signal on the coils placed in the central part appears simultaneously with the resistive transition recorded on voltage taps. A few msec later, the signal appears on coils located at the magnet ends. The respective measured delays allow a longitudinal resolution better than the length of the detection coil in the case where a constant velocity of the quench propagation can be assumed. The velocity, estimated in this way, is between 10 and

50 m/s, and corresponds to the measured voltage rise on the magnet taps. When the quench starts in the end of the winding, as was observed in most cases, the longitudinal resolution is limited to the length of the pick-up coil.

Fig. 5 Longitudinal propagation of the quench as seen along the different coils

B. Localization in the magnet's cross-section

In some cases, it seems possible to determine the start position of the quench in the magnet cross-section, assuming the model for the current redistribution, as described in section V.

The amplitude of the signals of the coils located in the same cross-section differ from each other, sometimes with opposite polarities. This is the case both for coils parallel and perpendicular to the field, and suggest that the sources of these bumps is localised. The model for localizing the quench in the magnets cross-section will concentrate on two types of quenches taken in the following conditions:

- "natural" quenches during training: the current went afterwards to higher values with the same temperature and ramping conditions;
- quenches of lower current values due to a fast ramp of the current in the magnet, inducing eddy current losses: the quench is expected to start in the internal winding layer and in the mid-plane where the magnetic field is perpendicular to the wide side of the cable.

V. MODELLING OF THE CURRENT REDISTRIBUTION

We will suppose that a quench begins with a redistribution of the transport current in the strands of the superconducting cable of the magnet winding. In first approximation we can model this by a magnetic moment changing with time. Calculations made with several longitudinal positions of the magnetic moment along the magnet cable show that the ratio of the flux changes in the pick-up coils are insensitive to the position. However, it is not clear how shielding currents in the magnet cable can influence the result. Using this model with the three harmonic coils signals we get a range of possible solutions.

Two ratios are available to find three unknowns: the radial and azimuthal position of the magnetic moment, and its direction. An example of such a calculation is given in Fig. 6, for a training quench, and for a quench induced by eddy currents at high ramp rates.

Using the signal ratios of the tangential coils for supplementary information usually shows that these are consistent with signal ratios of the harmonic coils. The quantitative agreement between harmonic coils and tangential coils was however poor, possibly due to eddy currents in the magnet coils.

Often, the voltages observed for a training quench are consistent with the field distribution resulting from a magnetic moment located at the edge of conductor and direction perpendicular to the conductor plane and are in most cases in the region of the highest field of the magnets.

Fig. 6 shows such a quench on the inner turn of the inner layer.

Fig. 6 Calculation of the quench location for a training quench and a quench induced by rapidly ramping the magnet. The location was derived from the inductive voltages measured in 3 harmonic coils across the magnet cross-section

The best confirmation that the model is reasonable comes from the quenches recorded at high ramp rates, and expected to occur in the mid-plane of the magnet (Fig. 6). The ratios of voltages measured by the coils located in the same symmetry plane are in fact often consistent with the location of a magnetic moment at the inner conductor edge in the horizontal plane. Quenches provoked by the heaters surrounding the outer winding layer also give compatible amplitudes on the pick-up coils.

In some cases for the quenches at the end of the magnet, the measured voltages are not consistent with the model described and the location of the quench could be only made with respect to the longitudinal direction.

VI. CONCLUSION

It is possible to localize the origin of a quench with the help of assemblies of pick-up coils, placed along the magnet apertures. Voltage taps give clearer results but are delicate to mount in large numbers in a magnet winding. The proposed method is simpler for localizing the quench along the magnet axis, for instance at the ends. The quench localization within the magnet cross-section should be verified, by inducing quenches in known positions, or by a cross-check with enough voltage taps on a dedicated magnet. The fact that a field perturbation is measured at the onset of a quench is interesting for an experimental study of quench phenomena. This method could therefore become extremely useful during the production tests of a large series of magnets.

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