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STUDY OF MECHANICAL DISTURBANCES IN SUPERCONDUCTING MAGNETS USING PIEZOELECTRIC SENSORS AND QUENCH ANTENNA

B. Dezillie, K. Artoos, A. Siemko, R. Mompo, D. Tommasini

Abstract

Mechanical disturbances in superconducting magnets were studied by recording and characterising the signals induced in piezo-electric ceramic sensors (piezos) and accelerometers by spontaneous acoustic emission (AE) during magnet excitation. The localisation of AE sources as recorded by the piezos corresponds to the localisation obtained by another, indirect technique, the so-called Quench Antenna. Dominant acoustic wave velocities along the magnet were measured by using selected piezos as active actuators. A mechanical disturbance energy calibration is shown and a way to estimate the minimum energy needed for quenching is proposed. A statistical approach is given in order to estimate the most probable amplitude of AE.

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Administrative Secretariat
LHC Division
CERN
CH - 1211 Geneva 23
Switzerland

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Study of Mechanical Disturbances in Superconducting Magnets using Piezoelectric Sensors and Quench Antenna.

B. Dezillie*, K. Artoos, A. Siemko, R. Mompo, D. Tommasini

CERN, European Organisation for Nuclear Research, Geneva, Switzerland

ABSTRACT Mechanical disturbances in superconducting magnets were studied by recording and characterising the signals induced in piezo-electric ceramic sensors (piezos) and accelerometers by spontaneous acoustic emission (AE) during magnet excitation. The localisation of AE sources as recorded by the piezos corresponds to the localisation obtained by another, indirect technique, the so-called Quench Antenna. Dominant acoustic wave velocities along the magnet were measured by using selected piezos as active actuators. A mechanical disturbance energy calibration is shown and a way to estimate the minimum energy needed for quenching is proposed. A statistical approach is given in order to estimate the most probable amplitude of AE.

KEY WORDS: Acoustic emission, spikes, piezos, accelerometers, superconducting magnets, quench

1. INTRODUCTION

Magnet reliability and magnet protection against quench are important issues for the development of the large superconducting magnets for the Large Hadron Collider (LHC) project at CERN[1]. The sources of quenches can be conductor motion, structural disturbances (such as epoxy cracking, acoustic emission from the magnet structure) and strain in the superconductor or in the winding substructure. Quenches were localised by Quench Antenna (Qloc) and Voltage Taps (Vtaps) techniques. While the Vtaps can detect the zone where the first resistive transition occurred, the quench antenna will indicate and localise a change in the current distribution inside the cable and/or sudden cable displacements[2]. Numerous disturbances can take place during the ramping of the magnet before the actual quench occurs. If a disturbance does not release more energy than the minimum quench energy at given temperature and field, it will not result in a quench. The disturbance will however show a rapid variation in the signals of voltage taps and quench antenna. Such precursors to quenches, also called “spikes”, showing a rapid variation in the voltage, can be detected and characterised using these techniques.

In this paper the localisation of spikes detected by acoustic emission sensors is presented and compared to the results obtained by quench antenna. An array of 20 piezo-electric ceramics (piezos) was installed in the coil and collars of a twin aperture dipole model magnet. The propagation time of acoustic waves through the magnet is presented and finally, a statistical approach is given in order to estimate the most probable spike amplitude.

2. EXPERIMENTAL

The PXE5 piezos from Philips® used for this study were made of a polycrystalline ferro-electric material with perovskite crystal structure (ABO_3)[3] and a Ni electrode. The piezos were placed as close as mechanically possible to the coil in order to minimise the attenuation of the acoustic wave modes. Figure 1 (left) shows the position of the eight piezos in the coils of Aperture 1 (A1) of a twin aperture magnet. Four piezos were placed in A2 and eight piezos were fixed on two collars common to both apertures.

Two accelerometers Model 351B03 from ICP® were used in addition to the piezos as a second type of sensor. The accelerometers were fixed with studs to the bolts that transfer the axial end forces between the magnet end plate and the collar end plate. For the data taking a Bakker™ recording system in single ended mode was used, which is a high-speed, multi-channel, buffered data acquisition system with external triggering. As trigger signals for the piezos, the voltage Vtaps, and Qloc, the voltage

*Corresponding author., Ph.D. Address: CERN, LHC/MTA, CH-1211 Geneva 23, Switzerland.
Tel: +41-22-767-1767; fax: +41-22-767-6230.
E-mail address: britta.dezillie@cern.ch

difference between a Vtap in A1 and A2 were used. The trigger level for the first run was 20 mV and for the second run 10 mV. The sampling frequency was 300 kHz and the recording time was 5 ms pre-trigger time (1500 samples) and 15 ms post-trigger time (4500 samples).

3. RESULTS AND ANALYSIS

3.1 Spike localisation

The spikes have been detected by Qloc and a distribution of spikes versus magnet section has been plotted. The highest number of spikes is observed in the straight part of the magnet and not in the magnet ends (sections L01, L12, L78 and L89, cf. figure 1) where most of the natural quenches were observed. This result indicates that mechanical vibrations more likely take place near the centre of the magnet and that the energy released propagates towards the magnet ends where quenches are more likely to occur for mechanical reasons. Figure 1 illustrates the longitudinal signal distribution recorded by piezos and Qloc. A comparison of the three methods (including the Vtaps) shows a very good correlation and proves that the spike origin is purely mechanical. Statistically, the quench antenna spike locations correspond in 99% of all cases with the Vtaps and piezo spike localisation. Each piezo signal was always accompanied by a Vtaps. This indicates that in practice all spikes originated from conductor motion and not from structural motion, such as epoxy cracking, welded areas under stress and many other acoustic emissions from the magnet structure itself. Tsukamoto and Iwasa[4] presented a theory based on the frictional sliding of the conductors, which is induced by electromagnetic, elastic and frictional forces. Comparing the experimental data to this theory shows a good agreement, which proves that conductor motion is at spike origin.

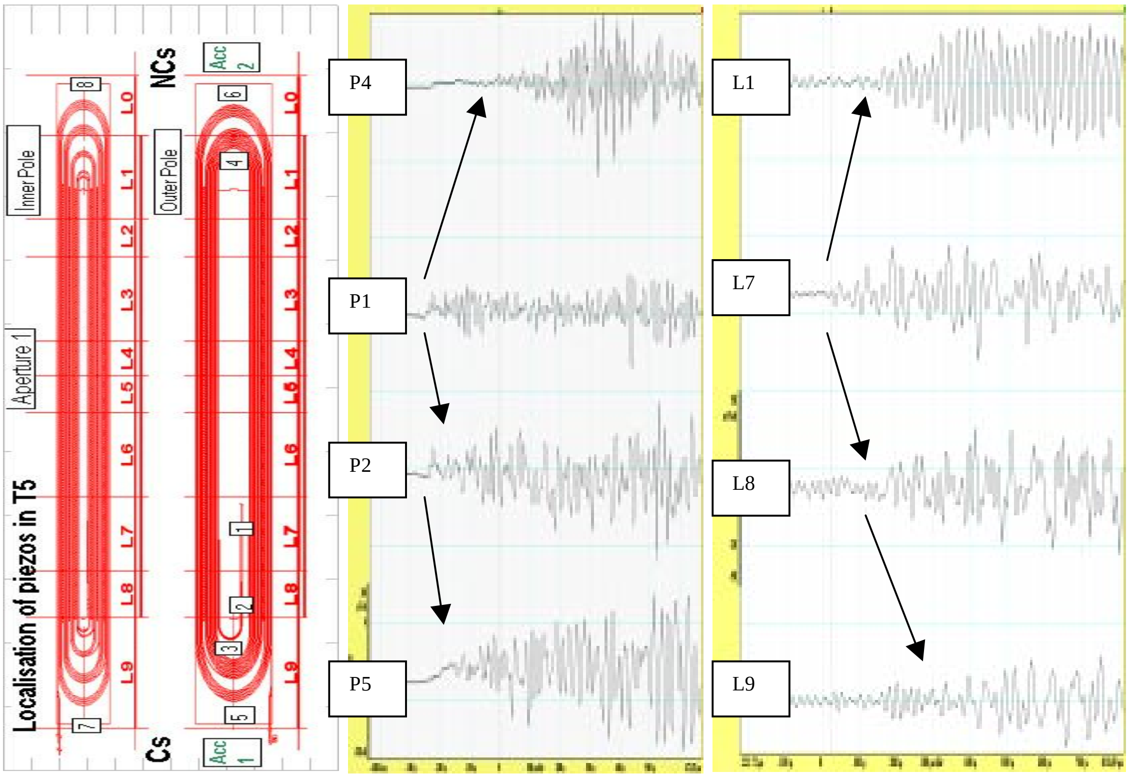

Figure 1. Piezo localisation (left) and Longitudinal signal distribution recorded by piezos (middle) and Qloc (right). Arrows indicate the detection of propagation.

3.2. Sensor calibration

For this test, each of the piezos one-by-one, was used as actuator with a sinusoidal input signal at a constant frequency of 2 kHz. In this way, the input signals were calibrated and reproducibility verified. Figure 2 (left) shows the result of this test performed at 1.8 K, zero current in the magnet and with a actuator (shaker) signal amplitude of 50 Vpp. On this 3-dimensional plot, the amplitudes of the signals from all sensors are plotted with the use of a different actuator as a parameter. Between all sensors, the most sensitive sensor (piezo 17) is situated on the collar of Aperture 2 on the non-connection side. The results of the same measurement performed at 1.8 K but with a magnet current of 13 kA and an actuator signal input amplitude of 250 Vpp is shown in figure 2 (right). The most sensitive sensor is now piezo 7, situated on the lateral side of the inner pole on the connection side of Aperture 1 demonstrating a change of mechanical properties of the magnet structure under the action of the Lorentz forces. The observed variation of the velocities of the sound waves from the collars at zero current to the coil at high magnet current, can be explained by the increase of the Young modulus of the coils under the Lorentz forces. Considering the amplitude of the sensors versus actuator input amplitude shows a linear energy calibration with an average input to output amplitude calibration coefficient of $0.2\ 10^{-3}$.

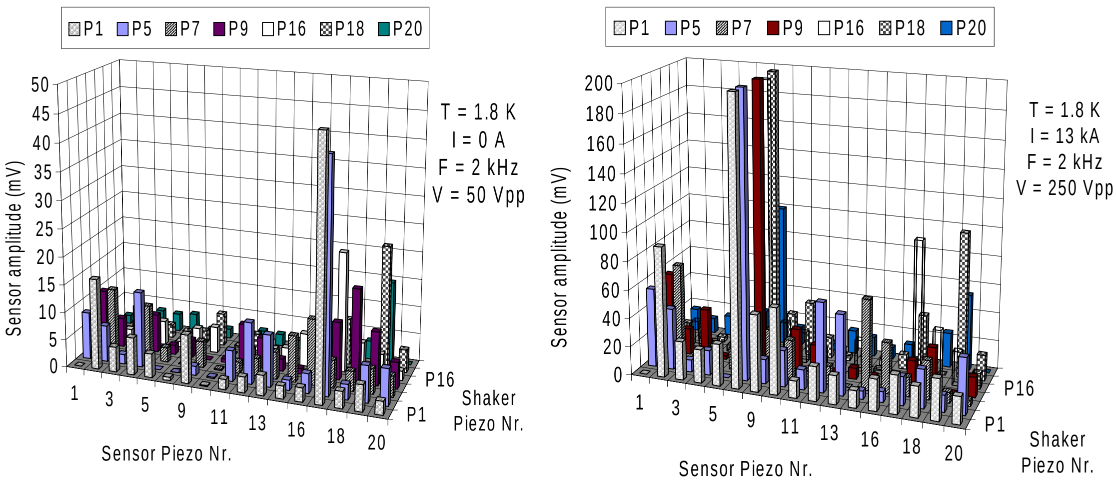

Figure 2. Sensor amplitude measured at 1.8 K for signals produced by different actuators and for I = 0A (left) and I = 13 kA (right)

3.3. Wave velocities

The dominant wave velocity through the magnet can be estimated by measuring the time delays between a sensor near the actuator and another sensor (time of flight) and from the known distances between the piezos. For example, the time delay for the signals from piezos 13 (connection side) and piezo 17 (non-connection side) measured at 1.8 K is 146 μs. The distance between the collars on the connection end and non-connection end is 438 mm, which gives a velocity of 3 km/s at 1.8 K. This is the velocity of an acoustic surface wave in steel as published earlier[5].

3.4. Statistical estimation of the most probable spike amplitude

In order to check whether the spike amplitude plays an important role in the prediction of the field of the first quench as well as on the quench location, as stated in ref.[6], it would be interesting to estimate the most probable spike amplitude in an experiment. The most probable spike amplitude has been statistically calculated assuming that the spike distribution follows the truncated Rayleigh function. This assumption is based on the results of Barnett[7], who showed that the peak distribution conditional on a peak greater than a fixed threshold amplitude L is a function of power and for a peak magnitude X > L and L > 0, the truncated Rayleigh distribution function becomes:

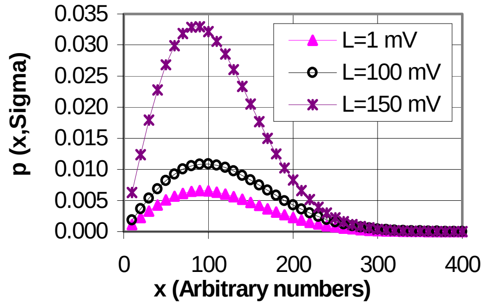

Figure 3. Power plot for radial coils following Eq. (1).

$$p(X,\sigma) = \frac{X}{\sigma^2}\exp\left(\frac{-1}{2\sigma^2}(X^2 - L^2)\right) \qquad (1)$$

where σ^2 is:

$$\sigma^2 = \hat{\sigma}^2 \pm 1.96\,\frac{\hat{\sigma}^2}{\sqrt{n}} \qquad (2)$$

with n the number of events and

$$\hat{\sigma}^2 = \frac{\sum_i^n X_i^2 - nL^2}{2n} \qquad (3)$$

The truncated density was fitted to the data from the experiment using a simple function φ(x) = x because the correlation between the input (actuator) voltage and the output (sensor) voltage is linear (see 3.2). Analysis was performed separately for the tangential and radial coils because of different coil sensitivity. The most probable spike amplitude is around 140 mV and 90 mV for the tangential and radial coils respectively (see figure 3). However this value does not take into account changes in systematic parameters as differences in temperature, coil sensitivity, etc. It has been shown as well that the spike amplitude together with the spike location is related to the coil pre-stress.

4. CONCLUSIONS

Many of today's efforts directed toward development of the large superconducting magnets call for the development of new techniques for the detection and control of potential quench sources. This paper demonstrates that monitoring of acoustic waves in coils can provide a record of disturbances. Piezo-electric ceramics have proven to be an appropriate tool for vibration measurements at 1.8 K and 9 T. There is a very good correlation between the piezo and quench antenna spike distribution, which proves the mechanical origin of the spikes. The fact that the conductor motion is at the origin of a spike is proven as well by the simultaneous observation of Vtaps and piezo signals. The spike distribution as measured by Qloc is the largest in the centre part of the magnet. The energy calibrations between the shaking and sensor piezos are linear functions and give directly the energy coefficient of the order of $0.2\ 10^{-3}$, corresponding to a displacement of about 5 μm. Using the Rayleigh function for Qloc spike signals, a statistical estimation of the signal amplitude can be made, which, together with the number of spikes, provides an estimation of the magnetic field for the first quench.

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B.Dezillie got her Ph.D. from the University of Grenoble in 1997 and is presently Fellow at CERN, Geneva.