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Report

Conclusion of the Electrical Conformity Assessment Panel on the Installation of the MBH Magnet S2 in the LHC

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Abstract

In this report we assess the feasibility for installation of the Nb_3Sn MBH S2 magnet in the LHC and conclude on possible performance limitations.

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Contents

1 Executive summary

As part of the HL-LHC Project, it was planned to install 11 T, Nb3Sn dipoles within an assembly combining two double aperture magnets and a collimator in between with a common cryostat during LS2. In the test programme dedicated to qualifying the magnets for operation in the tunnel, one of the 11 T dipole magnets named S2 (type A – the type containing the cold bypass diode and the trim leads) showed abnormal electrical signals during fast discharges after quenching (usually triggered by quench heater firing) on the test bench. The origin of these signals was not understood.

A panel was called by the HL-LHC Project Management with the aim of investigating the situation together with WP11 of HL-LHC and the TE-MSC management. The panel's task was to assess whether the magnet was suitable for the installation despite these signals, and what special procedure or conditioning were required for the installation and hardware commissioning of the magnet to minimize the risk of poor performance under the LHC operating conditions. The panel was invited to issue any other recommendation deemed appropriate for further investigation or additional qualification testing in view of tunnel installation.

The members of the panel were A. Siemko (Chair), A. Devred, F. Rodriguez Mateos, R. Schmidt, A. Verweij and J. Wenninger. A series of meetings were organized between April and October 2020 to ensure proper follow up of the studies. A vast amount of data was collected and analysed. Several experts were invited to present their interpretations so that conclusions could be drawn. Proposals for additional tests were discussed by the panel and feedback was given to the panel once the analysis of the tests were available.

The signals from voltage taps and quench antennas recorded during the quench process were analysed. A typical signal pattern from voltage taps was observed (see paragraph 4.1): 1) a smooth increase and decrease of the voltage during the quench process for about 500 ms, 2) voltage bumps / wiggles on top of the smooth signal with a duration of approx. 10 ms, and 3) fast spikes with a duration of less than 1 ms. Fast spikes are only observed during a fast current discharge following quench heater firing when the initial magnet current is in a range between 7.5 and 10.5 kA. Analysis of the signals together with a number of simulations led to a partial understanding of the signal pattern.

The signals recorded during the quench process from quench antennas (see paragraph 4.2) are provided by six sets of coils in each aperture of the magnet. Each set contains three coils. The differences in induced voltages between various coil combinations are recorded. A clear correlation is found between voltage spikes and signals from four sets of quench antennae. The amplitude of their signals is approximately proportional to the amplitude of the coil voltage spikes.

Another source of signals are from voltage taps across the splices (see paragraph 4.3), both from internal magnet splices and the splices required for the connection of the magnet to the current leads of the test bench. Voltage peaks with fast rise and decay with an amplitude of up to more than 0.2 V are observed across individual splices, similar to the spikes inside the coil. Voltage spikes across splices of aperture 1 have the same polarity as the spikes in the upper coils, and spikes across splices of aperture 2 have the same polarity as the spikes in the lower coils.

Paragraph 4.4 summarizes the main observations regarding the range of magnet current and its derivative for the occurrence of spikes, the time scale of spikes, the symmetries, the amplitude, the dependence on quench heater polarity or powering pre-history, the correlation between signals, etc.

Possible explanations for the voltage spikes are described in paragraph 5. Possible sources for the spikes can be divided into different groups: effects external to the magnet, intermittent shorts, inductive coupling of various kind (flux jump, coupled loops) and capacitive effects. No satisfactory explanation could be determined from the observations presented in paragraph 4.1 to 4.4

To improve the understanding of the phenomena, different types of tests were carried out (see paragraph 6): TFM (Transfer Function Measurement) and TDR (Time Domain Reflectometry), tests in which a short circuit was artificially introduced between the potential points were the spike signals initially appeared, and a test with a lifted voltage to ground introduced between coils and ground in order to mimic the situation of the magnet when connected to the series of LHC dipoles in a sector with energy extraction activated after a quench.

Different simulation models (electro-magnetic, thermal, mechanical) were developed and simulations were performed with boundary conditions corresponding to those during the tests of the magnet (see paragraph 7). The comparison of the measured values with the results from the simulations did not allow to clearly identify the origin of the spikes, except to point out that their occurrence seems to be correlated with asymmetries in the quench evolution between the magnet coils.

The panel concluded that the origin of the spikes is most likely inductive and due to the different effect of magnetization in Nb3Sn compared to NbTi. The panel also concluded that the presence of spikes is no reason to block this magnet for an installation in the tunnel. The panel recommended that additional high voltage tests be included in the magnet test plan to better reflect the operating conditions in the magnet string in LHC.

The test of the S2 magnet was finally terminated due to a short circuit between quench heater and coil. Recommendations for future tests and investigations (paragraph 8) and summary and conclusion (paragraph 0) close the document.

2 Introduction

This is the final report of the Electrical Conformity Assessment Panel for the Installation of the 11 T Nb3Sn Magnet MBHA-001 (also called S2). The task of the panel was to evaluate if phenomena observed during magnet quenches such as unusual voltage spikes could impact on the operational performance of these magnets. Two intermediate reports were presented to ATSMB [1] and to TCC [2].

For installation of collimators in two locations of the LHC arcs on both sides of IP7, two LHC dipole magnets (MB) will be replaced by assemblies of Nb3Sn magnets with a central field of 11 T. One assembly, replacing one MB dipole magnet, houses two 6 m long Nb3Sn magnets, each one producing an integrated field of 119 Tm at a nominal current of 11.85 kA. In total, six Nb3Sn magnet assemblies are required, four for installation into the LHC and two as spares. Each Nb3Sn magnet has two apertures and four coils.

There are two variants of Nb3Sn dipole magnets, type MBHA and type MBHB. MBHA is slightly different from MBHB and includes trim leads, a cold diode, busbars for the connection to MBHB and a larger number of instrumentation wires. Both magnets of an assembly are connected electrically in series with the MB dipole magnet circuit.

One of the 11 T dipole magnets named S2 (MBHA-001) showed abnormal electrical signals during fast discharges following quenching on the test bench. The panel was asked to assess whether the 11 T dipole magnet S2 is suitable for installation in LHC, despite the presence of these electrical signals. If so, what special procedure or conditioning is necessary for the installation and hardware commissioning of the magnet in order to minimize the risk of performance degradation under the LHC operating conditions? The panel was encouraged to make any other recommendation considered appropriate for the recovery of the magnet in the event of unsuitability for installation.

Originally, it was proposed to install two assemblies in the LHC during LS2. During 2020 this was reduced to one assembly, mainly to gain experience with operating for the first time Nb3Sn magnets in an accelerator. Later, after the Panel had already started its work, it was decided that the installation of the assembly will be postponed to another shutdown due to non-conformities of the available magnets observed during the cold tests, in particular, quench performance limitation after a thermal cycle to room temperature.

3 MBH Magnets and Electrical Circuits in LHC and on the test bench

In the LHC, an MBHA magnet will be installed inside a cryostat, followed by a by-pass cryostat housing a collimator, and connected to an MBHB magnet inside another cryostat [3]. The Nb3Sn magnet assembly will be connected between the M3 busbars from the preceding and the following MB dipole magnet. As shown in Figure 1, the magnet current flows from the M3 busbar into aperture 2 of MBHA, to aperture 2 of MBHB, to aperture 1 of MBHB, to aperture 1 of MBHA and then to the M3 busbar. The go/return M4 busbars, passing through the connection cryostat, connect MBHA and MBHB. A diode is installed in MBHA (not shown in the Figure).

Initially it was planned to first cold test each magnet individually, followed by a test of the full assembly with two magnets on a test bench. For scheduling reasons, the test of the full assembly was postponed, with a plan to perform the assembly test only on the two spare magnets. The electrical scheme for the individual magnet tests is therefore different from the one in Figure 1. The connection between the two apertures is done inside the feed box. Each aperture has one upper and one lower pole (coil). The poles of each aperture are connected as shown in Figure 2 for the MBHA magnet.

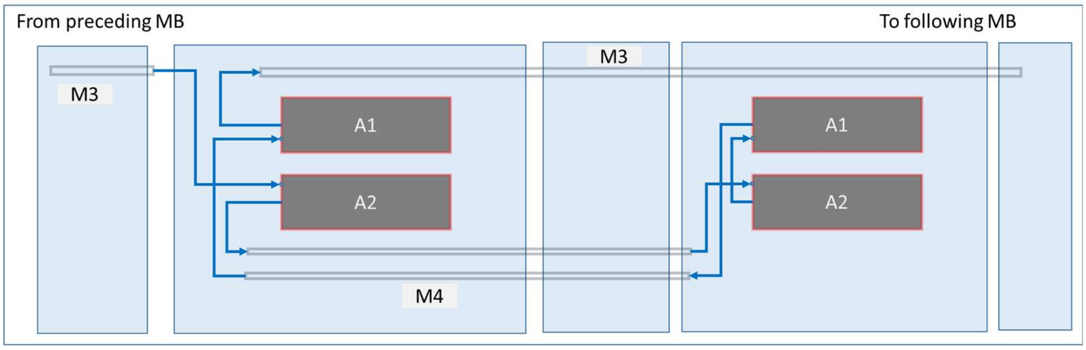

Figure 1: Simplified drawing of the electrical scheme for an Nb3Sn assembly with MBHA and MBHB in the LHC tunnel

The magnet is instrumented with a large number of voltage taps. Voltages across each pole and each aperture are recorded, as well as the voltages across many of the splices between superconducting cables.

Tests of the MBHA-001 magnet started in Q4 of 2019. During the first series of cold tests, two problems were observed: (1) degradation of the dielectric strength to ground and (2) the occurrence of spikes on some of the coil voltages during ramp-down after a quench or a heater-induced discharge from a current between 7.5 and 10.5 kA. The origin of the degradation of the dielectric strength to ground was found and the fault was repaired, and cold testing was resumed after the 2nd cool-down in February 2020. The spikes on individual coil voltages were still present with the same characteristics.

The magnet performed as expected. The dielectric strength tests were fully conform. The electrical performance was as specified. A nominal current of 11.85 kA + 100 A was achieved and the magnet operated for 12 hours at this current without problems. Without presence of the observed voltage spikes during quenching, MBHA-001 would have been qualified for installation in LHC.

Since voltage spikes might be an indication of an inter-turn or inter-coil short in the magnet, understanding of their origin and monitoring whether or not they degrade is important. For the MB-3004 dipole magnet tested in SM18 more than ten years ago, voltage spikes during a discharge were preceding the appearance of an inter-turn short. During the following discharge, the coils were damaged and a hole in coil and cold bore was created. A similar event with an Nb3Sn magnet in the LHC would be very serious. Although the voltage spikes measured before the MB dipole was damaged were up to two orders of magnitude larger than the spikes observed on MBHA-001, it is required to exclude the presence of a similar non-conformity in MBHA-001.

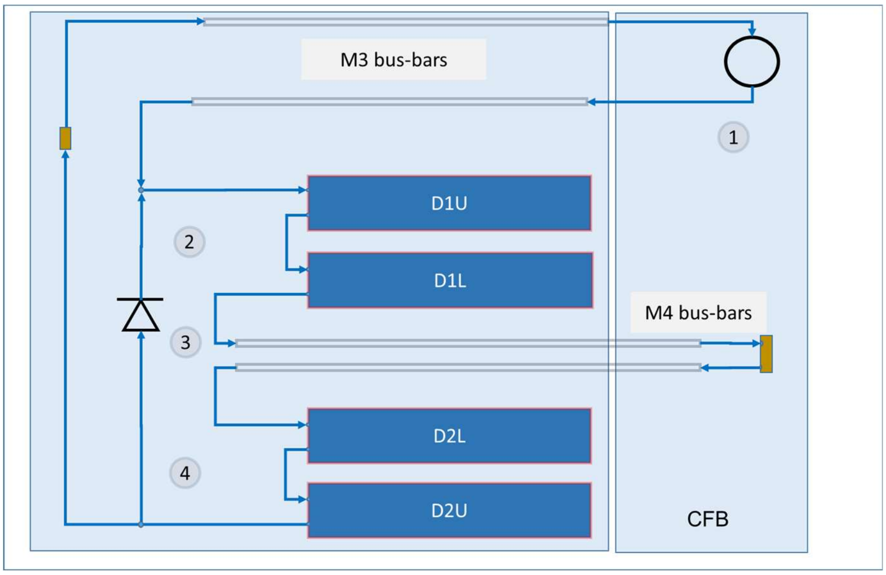

Figure 2: Simplified drawing of the electrical scheme for the MBHA magnet on the test bench

4 Experimental observations for the 11 T Nb3Sn magnets

In this section we present the observations during commissioning and dedicated tests of the 11 T Nb3Sn magnets.

4.1 Voltage tap signals and spikes

Most quenches (also called discharges) are induced by firing quench heaters. Quench heaters (QH) are installed on all four coils. During the quench, the voltages across the two apertures and the four coils (poles) are recorded (see an example in Figure 3). Typically, three signatures are observed in the voltage signal: 1) a smooth increase and decrease of the voltage during the quench process that takes in total about 500 ms, 2) voltage bumps / wiggles on top of the smooth signal with a duration of about 10 ms, and 3) fast spikes with a duration of less than 1 ms.

4.1.1 Signature 1

If all coils would quench in the same way, the inductive and resistive voltages over each coil would cancel and the total voltage across each coil would be very low. Due to variation of RRR, Cu/SC ratio and Jc between the four coils, the inductive and resistive voltage do not fully cancel and voltages are building up over each coil during the quench process, up to about 120 V for quenches at 9 kA and up to 200 V for quenches at 12 kA. By delaying the quench heaters on one of the apertures, the maximum coil voltage measured during the magnet discharge could be reduced from about 120 V to 40 V [4].

4.1.2 Signature 2

During quenching, in some voltage signals additional bumps with a duration of about 10 ms and an amplitude of up to a few volts are observed. In each coil, the inner layer quenches by the combined heating effect of coupling currents and thermal diffusion from the outer layer [5]. The voltage bumps can be explained by slightly different quench onset in upper and lower coil. The position of the bumps changes with quench current and with the delay of the quench heater firing.

A number of simulations for the discharge of the MBHA-001 magnet were performed with the STEAM-LEDET framework that includes an electro-magnetic and a thermal 2D model [5]. The simulations manage to reproduce the measured voltages for the effects with signature 1 and 2 (see Figure 4), as well as for discharges performed by delaying the firing of some of the quench heaters.

4.1.3 Signature 3

On top of the voltage signals, fast voltage spikes with a duration of less than 1 ms are visible. Spikes are observed for many discharges but especially pronounced for discharges with a current around 9 kA. For discharges from higher current and lower current, less spikes are present, and their amplitude is smaller. During discharge from nominal current, during current ramps and during a plateau, spikes do not appear. Most spikes appear when dI/dt is between 30 and 50 kA/s.

The amplitude of the voltage spikes is about 1 to 3 Volts. The spikes become more apparent when using a filter with a band-pass from 250 Hz to 10 kHz (see Figure 5). This allows to analyse and compare the spikes for different coils / apertures. The voltage spikes of the upper coils of the apertures have the same sign, opposite to the sign of the lower coil voltage spikes (see an illustration of the magnet coils and the spike symmetry in Figure 6). Voltage measurements across the two apertures show only small signals, because the voltage spikes between upper and lower coil compensate.

Voltage spikes are only appearing during part of the discharge, starting after about 100 ms from the start. In this part, the aperture voltages show also an increased activity but of much smaller amplitude (0.3 to 0.4 V). Some activity is also visible on the derivative of the magnet current with an amplitude of about 200 A/s with a good correlation with the voltage spikes. This leads to a change of current of about 100-200 mA during a spike. An important observation is that the decrease of the voltage during the discharge with delayed quench heater firing from 110 V to 40 V had no impact on the voltage spikes.

Similar spikes were also observed on other 11 T magnets. For most magnets the spikes are hardly visible, with an amplitude about one order of magnitude lower. Magnet MBHB-003 was cold tested after the tests of MBHA-001 had finished and showed similar voltage spikes as MBHA-001.

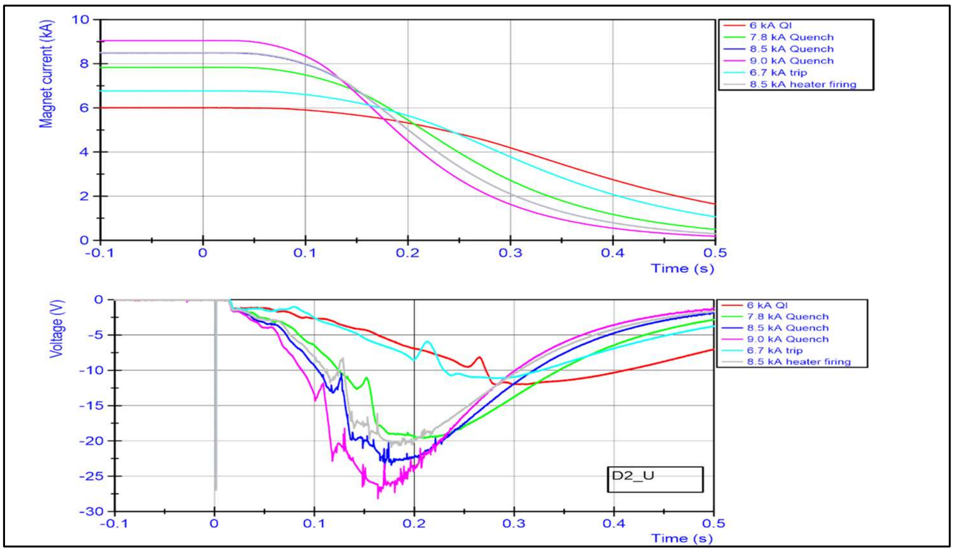

Figure 3: Example of magnet current and voltage across the lower coil of aperture 2 for different discharges [4]

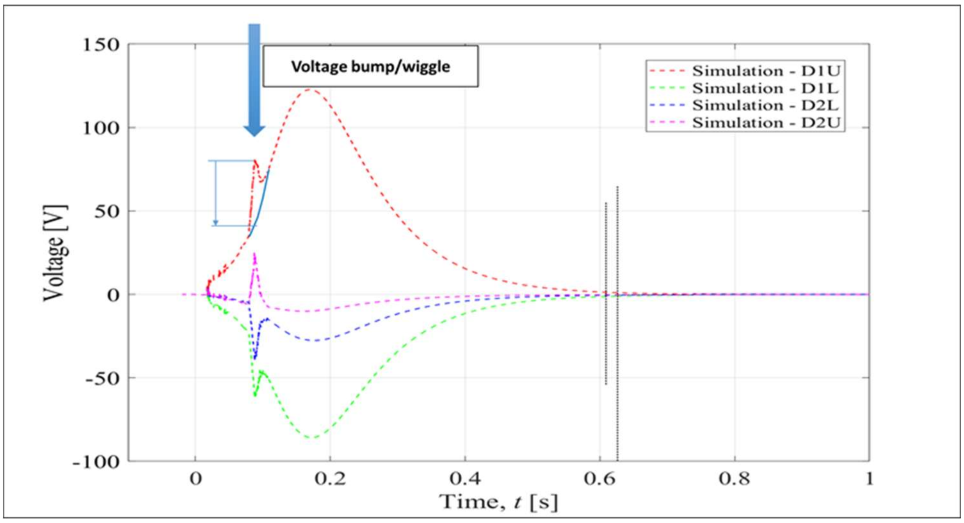

Figure 4: Simulations to reproduce the voltage development across a coil during the discharge (Effect 1 and 2) [5]

4.2 Quench Antenna signals

The quench antenna is a very powerful instrument detecting magnetic field perturbation caused by current redistribution among the strands of the cable. At the same time it can also detect very small differences in transport current between the upper and lower coil, possibly caused by an inter-aperture short.

Six sets of coils QA1 to QA6 are installed in each aperture of the magnet, each set at a different longitudinal position [6]. One set has three coils, in the mid-plane of the magnet (C), above (A) and below (E). QA2 – QA5 are installed along the central field region, QA6 in the connection side opposite of the feed box and QA1 in the non-connection side in a region with low magnetic field (see Figure 7).

The differences of induced voltages between various coil combinations (A-E, A-C and C-E) are recorded. An example is the difference between the voltages of the coils above and below the mid plane, V(A)–αV(E), with the parameter α to compensate for the small differences in the processing electronics.

The value α is set individually for each quench antenna and has a value close to one. In case of a perfect compensation between A and E and a perfect dipole field, the signal V(A)–αV(E) should be zero.

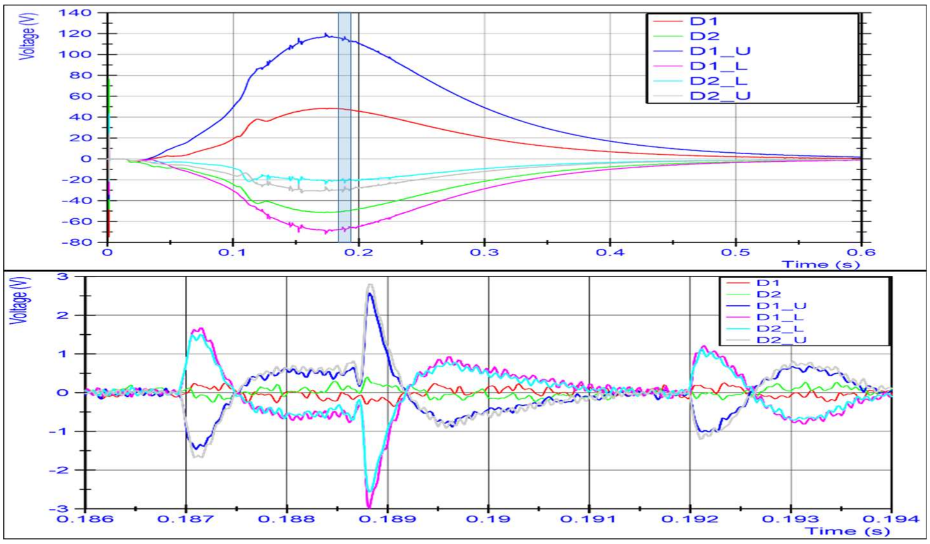

Figure 5: Symmetry of the voltage spikes across coils. The lower figures show the signals between 0.188 s and 0.194 s after the start of the discharge, using a band pass filter 250 Hz – 10 kHz.

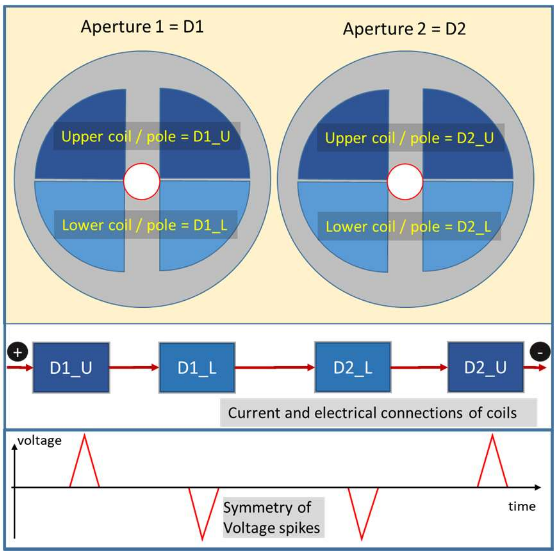

Figure 6: Illustration drawing to show the magnet apertures, coils (poles) and the symmetry of the observed voltage spikes

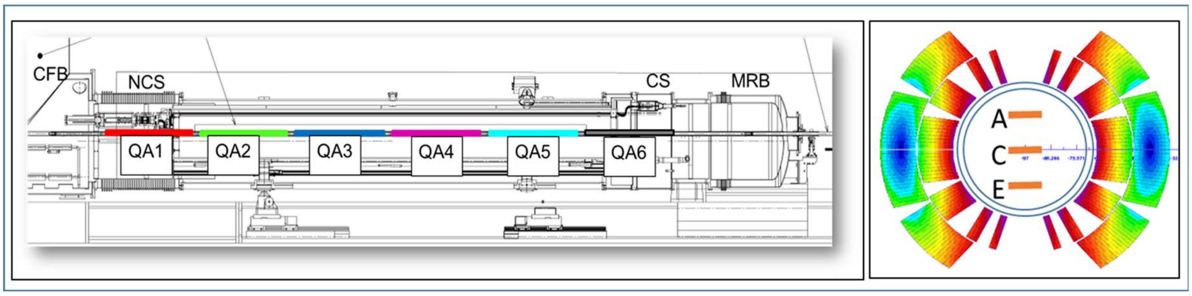

Figure 7: Quench antenna with 6 coil sets along the magnet (left) and position of three coils at one longitudinal position [6]

There is a clear correlation between voltage spikes and signals from four quench antennas (see Figure 8). Only QA1 in the stray field region shows no signal correlated with the voltage spikes. Signals from QA6 were not recorded. The antennas from the two apertures show spike signals with opposite polarity and similar amplitude, indicating that the source is located in one aperture.

When the signals of all quench antennas from both apertures are averaged (after changing the sign of the signals from one aperture), the correlation becomes very clear (see Figure 9). The amplitude is about proportional to the amplitude of the coil voltage spikes.

The sensitivity of the antenna can be derived by integrating the voltage during a discharge from 9 kA to zero [7]. From the magnetic field and surface of the QA coil, the magnetic flux seen by the QA coil at the start and the end of the discharge can be calculated, assuming that the QA coil is correctly aligned with respect to the dipole field.

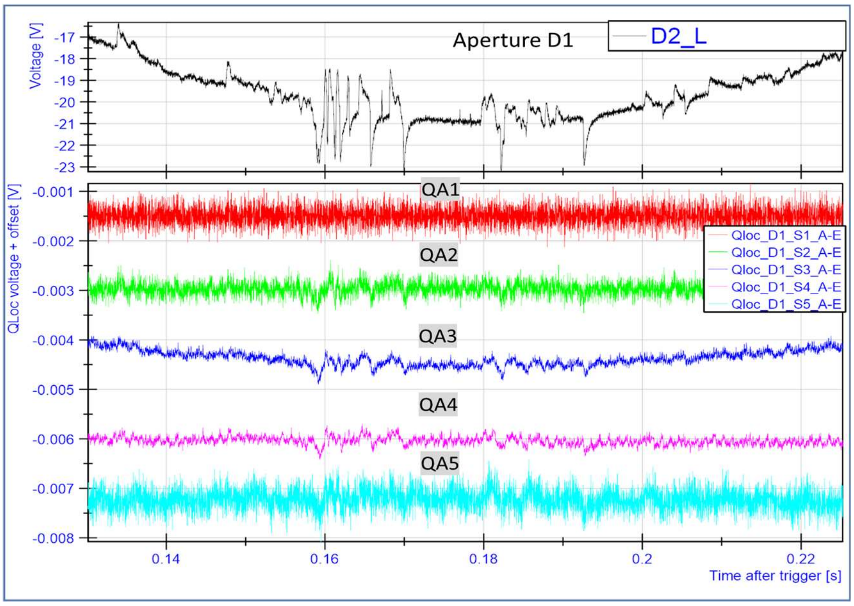

Figure 8: Signal from voltage taps across one coil and signals from quench antennas, for one discharge

The difference between the voltage across two QA coils in different vertical positions in the aperture ("A" and "E") is used to measure the magnetic gradient in the aperture. Assuming a current imbalance in lower and upper coil of +/-1 A at a magnet current of 9 kA, an expected field component a2 (skew quadrupole) of 0.3 units is calculated using ROXIE [8].

When a spike measured by the antenna is analysed and the integral of the spike signal calculated, an effective current imbalance between upper and lower pole to generate such spike can be deduced. For one of the large spikes, this yields an effective current imbalance of about +/-0.4 A. If it is assumed that there is no current imbalance, a fast change of the current through both coils of 40 A would be required to generate such spikes. Such a change is not observed.

4.3 Electrical signals from splices

About 15 splices are present inside the magnet and for the connection of the magnet to the test bench. The connection between lower pole and upper pole includes three splices, two between Nb3Sn and NbTi cables, and one between two NbTi cables.

Across individual splices, voltage peaks with fast rise and decay with an amplitude of up to more than 0.2 V are observed, similar to the spikes inside the coil (see Figure 10) [9]. Voltage spikes across splices of aperture 1 have the same polarity as the spikes in the upper coils, and spikes across splices of aperture 2 have the same polarity as the spikes in the lower coils. Signals across three splices show a much slower decay and a maximum amplitude of only about 0.025 V, a factor of 10 less than the individual voltages.

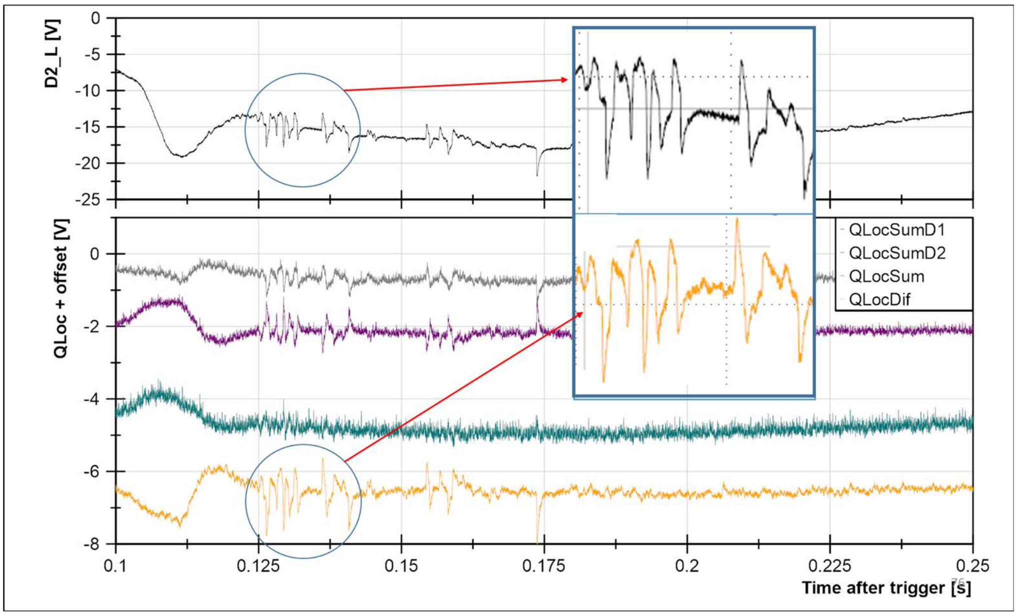

Figure 9: Signal from voltage taps across one coil and averaged signal from 10 quench antennas. The correlation between the signals is remarkable (shown in the zoom) [6]

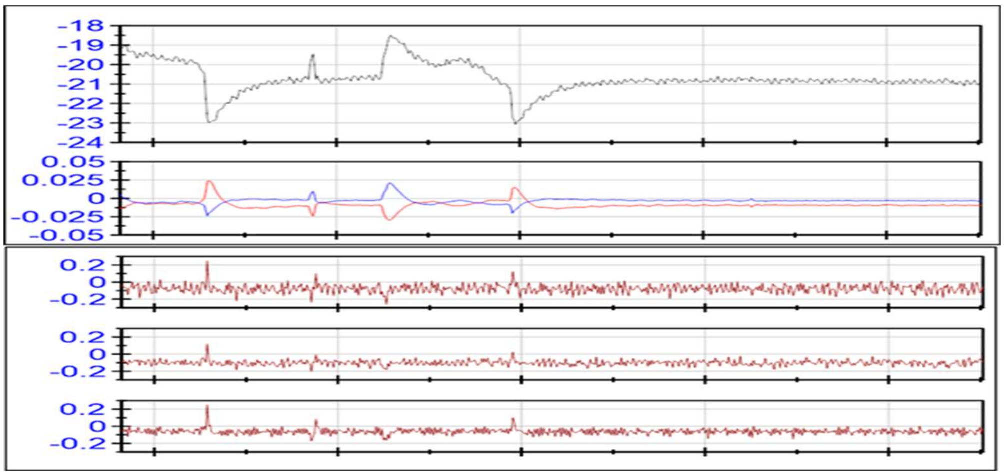

Figure 10: Signals across coil and across splices. Top: Coil signal, below: signals across three splices, bottom: signals across 3 individual splices [9]

4.4 Summary of main observations

1) Voltage spikes appear only during discharges from a current in the range of about 7.5 kA to 10.5 kA. For discharges from nominal current, hardly any spikes are observed.
2) Voltage spikes appear after about 100 ms from the start of the discharge, with the most intense spike activity when the current decreased to a value between 4 kA and 8 kA, and when the current decay rate is about 40 kA/s.
3) Symmetry: The voltage spikes of the upper coils for both apertures have the same sign and about the same amplitude. The sign of the lower coil voltage spikes have an opposite sign

and about the same amplitude. Across the apertures, voltage spikes are small due to a compensation from the lower and upper coil spikes.

4) The amplitude of the voltage spikes does not depend on the voltage differences in the magnet.
5) The polarity of the quench heaters has no impact on the voltage spikes signature.
6) The occurrence of the spikes is affected by the powering history, i.e. pre-cycles (e.g. ramp to 11.85 kA prior to standard quench heater discharge at 9 kA, or V-shape cycle to nominal prior to standard quench heater discharge at 9 kA, degaussing cycle prior to standard quench heater discharge at 9 kA).
7) The signal from the quench antennas in the central-field region of the magnet are correlated with voltage spikes. The signals in the two apertures have similar amplitude and opposite polarity.
    a. Aperture 1: Signals observed with the quench antenna have the same polarity as the voltage measured across the lower coils
    b. Aperture 2: Signals observed with the quench antenna have opposite polarity to the voltage measured across the lower coils
8) Voltage spikes were also observed in other MBH magnets. In MBHB-002 and MBHA-002, only few spikes with much lower amplitudes were observed, but with the same symmetry as in MBHA-001. The Nb3Sn magnet MBHB-003 was tested after the investigations of MBHA-001 were finished. Spikes very similar to MBHA-001 were observed.
9) The measured voltages across splices show are correlated with the coil voltage spikes.
10) Dedicated impedance-measurements during the discharge show no significant change of the impedance and do not provide any evidence for an intermittent short (see section 6.1).

5 Possible explanations for the voltage spike signals

To understand the origin of the voltage spikes, a number of possible explanations can be grouped in several categories.

1. Source of the voltage spikes external to the magnet.

2. Intermittent electric shorts could produce voltage spikes (electrical shorts should never be present in a healthy magnet and are considered a serious non-conformity):
    - Intermittent short between apertures, as a result from damaged insulation of the instrumentation wires in the capillary tube.
    - Intermittent short between apertures, possibly resulting from a combination of three insulation defects, namely between coil and quench heaters in aperture 1, between quench heaters of aperture 1 to quench heaters of aperture 2 (through wiring), and between coil and quench heaters of aperture 2.
    - Unwanted contacts between leads / bus bars. Mechanical movements of leads/bus bars combined with damaged insulation.
    - Inter-turn short.
    - Short between quench heater and coil.
    - Short between coils to ground.

3. Voltage spikes from inductive effects:
    - Flux jumps in the superconductor.
    - Motions or vibrations in current leads, connections and bus-bars, resulting in local variations of flux.
    - Inductively coupled loops.

4. Voltage spikes from capacitive effects:

- Intermittent parasitic capacitance.
- Variation of capacitance and electrical insulation resistance between the coil and the loading plate.

Apart from the possible sources of voltage spike signals originating in the instrumentation and equipment external to the magnet (see 7.1), the possible spike signal mechanisms that were considered are summarised in Table 1.

Table 1 Possible mechanisms for voltage spike signals

id	Type	Mechanism
M1a	Resistive	Intermittent short between apertures, possibly resulting from damaged insulation of the IFS wires in the capillary tube
M1b	Resistive	Intermittent short between apertures resulting from insulation defects coil to QH, then QH Ap1 to QH Ap2 through wiring, then QH Ap2 to coil
M2	Resistive	Unwanted contacts between leads / bus bars. Mechanical movements of leads/bus bars combined with damaged insulation (transport current)
M3	Inductive	Flux jumps
M4	Inductive	Inductively coupled loops
M5	Inductive	Vibrations or motions of leads / bus bars resulting in local variations of flux
M6	Capacitive	Intermittent parasitic capacitance. A link between the apertures is needed to provoke spikes as observed (shown per modelling)
M7	Resistive / Capacitive	Variation of capacitance and electrical insulation resistance between the coil and the loading plate. Same remark as for M6 as to the necessary link
M8	Resistive	Inter-turn short
M9	Resistive	Quench heater to Coil short
M10	Resistive	Coil-to-ground short

From the observations presented in section 4, the correct explanation could not be clearly determined. The analysis of a series of additional tests was presented to the panel to provide further data to better understand the voltage spikes and to demonstrate that the dielectric strength of the MBHA-001 magnet is adequate for installation in LHC.

6 Tests to understand voltage spikes and dielectric strength of the magnet

The motivation for the tests was to better understand the origin of the voltage spikes as well as to qualify the magnet for installation in LHC.

6.1 Transfer function measurements

The impedance of the magnet was measured with a transfer function measurement. In case of a non-conformity, e.g. an intermittent short between apertures, the impedance should change. The impedance is measured with different stimulus amplitudes of 1 V, 10 V and 140 V and a frequency between 1 Hz and 100 kHz [10].

Measurements were performed at zero current in periods between quenches, at high current as well as during discharges provoked by firing the quench heaters. The measurements at zero current did not reveal any change of the magnet impedance

Transfer function measurements after firing quench heaters were performed at current levels of 0 kA, 1 kA, 6 kA and 9 kA with a frequency of 6 kHz. For an intermittent short between apertures, the impedance between aperture midpoints should vary during the spikes. During the tests, it is observed that the magnet impedance strongly depends on current and quench process. For quenches at 6 kA and 9 kA, the resistance changes between about 80 and 120 Ohm. Some spikes are visible in the impedance measurements, roughly correlating with the coil voltage spikes, however, the expected level of impedance change during the spikes is not observed.

6.2 Reflectometry measurements

In case of an intermittent short, the results of reflectometry measurements should vary slightly from one test to another, assuming that the resistance of the short would change during a quench. A number of measurements between six powering cycles with discharges were performed on all V-taps, but no measurable difference was detected.

6.3 Tests with artificial intermittent shorts

The objective of these tests was to understand if the signature of the observed voltage spikes could be generated by an intermittent short circuit.

6.3.1 Test description

To create an intermittent short between the midpoint of aperture 1 and the midpoint of aperture 2, an electronic switch was connected to two corresponding voltage taps [11]. Closing the switch changed the resistance from 1 kΩ to 25 Ω, followed by opening the switch to change the resistance from 25 Ω back to 1 kΩ. Switching was done with a frequency of 11 or 6 Hz during multiple current ramps with a ramp rate of +50 A/s, -50 A/s and -100 A/s. Amplitude and shape of the recorded voltages can be compared with the voltage spikes registered during 9 kA quenches.

During closing of the switch, the voltage rises in a time of about 128 µs, during opening of the switch in about 100 µs. As expected, the voltage measurements across the coils are correlated with the switch closing and opening, with the same symmetry as observed in the voltage spikes for discharges from 9 kA.

The observed coil voltage signals after closing and after opening of the switch are consistent with results from simulations, both from a polarity and symmetry point-of-view. The amplitude of the observed signal is lower than from simulations by a factor of about 2.5 to 3.5. It is suspected that the PSPICE model, which considers a constant magnet inductance, is not adequate for this type of modelling and the discrepancy is likely due to magnetization effects.

During these tests, the transfer function was measured with frequencies of 6 kHz and 13 kHz [12]. The resistance change of the artificial short, from 11 kΩ to 1 kΩ, was clearly visible in the modulus and phase of both signals (see Figure 11). To understand the sensitivity of the measurement, the short resistance was also changed from 11 kΩ to 10 kΩ. This change could hardly be detected. A resistance of an intermittent fault of the order of few kΩ can easily be detected by the TFM measurement.

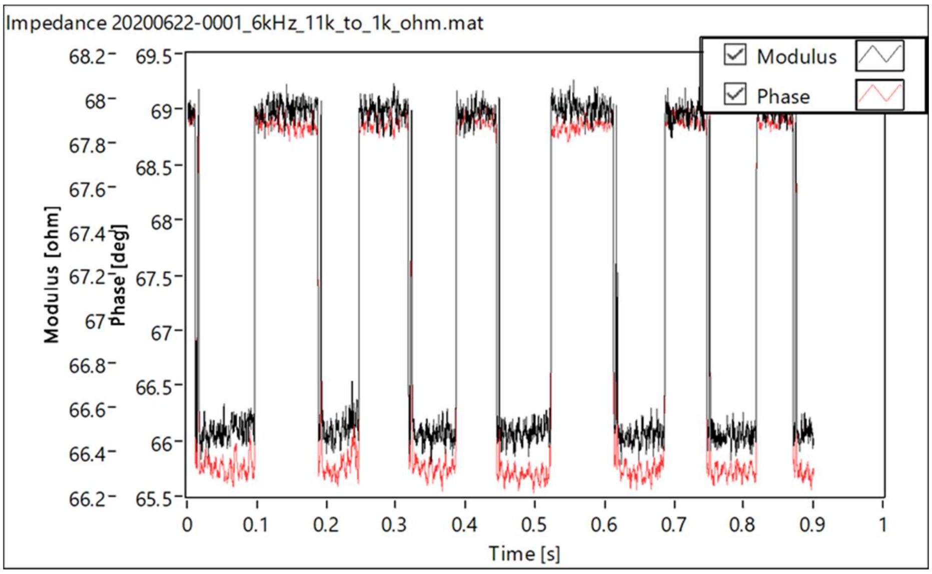

Figure 11: Impedance measurement when switching between short/no short with a frequency of 6 Hz during a current ramp. Modulus and phase show a clear dependence of the short resistance [12].

Measurement of the transfer function versus frequency shows a different impedance at temperatures of 1.9 K and 37 K. Using frequency-domain modelling, these results can be well reproduced up to frequencies of about 10 kHz. Already at a frequency of 1 Hz, the measured impedance modulus at 1.9 K is only 70% of the inductance at 37 K, i.e. the nominal magnet inductance.

6.3.2 Quench antenna signals for artificial short tests

During the tests with artificial short circuits between the midpoints of both apertures, the signals from the quench antennas were recorded. The signals from the antenna segments in the straight section have similar amplitude, while the amplitude of the signals from the antenna segments at the ends have significantly lower amplitude.

The signals of aperture 1 are opposite to the signals of aperture 2. For a ramp-down with -50 A/s, the flux changes measured by the antenna were compared with the expectation for a current of 74 mA through the short and showed excellent agreement. The signals recorded with the quench antennas during real quenches have the same characteristics in terms of polarities, amplitudes, signals in straight vs end sections as the signals induced by intermittent short circuits between the midpoints of both apertures.

6.4 Tests with lifted voltage to ground potential

Such test ensures an adequate electrical integrity of the magnet during a quench in the LHC tunnel. It is considered to be the most representative test in comparison to voltages appearing during a quench of an Nb3Sn magnet powered in series with the MB dipoles in the LHC tunnel. The magnet will experience not only the internal voltages caused by the quench, but also the voltages generated by the energy extraction system of the magnet circuit and the quench voltage imbalance caused by the serial connection of two MBH magnets with one common cold bypass diode. The voltage from the energy extraction system prevails when the temperatures in the magnet reach their maxima.

In the test, the voltage generated by the energy extraction system is simulated by artificially raising the voltage relative to ground during the quench process using a dedicated voltage generator. With such a lifted voltage test, the magnet can be tested under conditions that are representative to the LHC, hence avoiding possible voltage breakdown due to an insulation failure of the magnet that only activates under quench conditions and which could otherwise result in magnet damage and consequently long down-time of LHC.

The magnet was ramped to a current of 3 kA during the first ramp and to 9 kA during the second ramp. When the current plateau was reached, the voltage across the magnet was lifted in a few 10 ms to 988 V simulating the voltages generated by the energy extraction system [13]. When the voltage of 988 V was reached, the quench heaters were fired. After a delay of 0.5 s, the lifted voltage was ramped down.

The results from the test at 3 kA were as expected, without any anomaly. After this test, the insulation integrity was verified with a voltage of 3.3 kV between coil and ground, and 3.2 kV between coil and quench heaters.

During the following test with a discharge from 9 kA, a breakdown of the insulation between one of the quench heaters and coil was observed. After the test, a measured resistance of 100 Ohm between coil and quench heater demonstrated that the insulation between quench heaters and coil was permanently damaged. In the analysis after the event, the location of the short was determined by powering the magnet with a current of 2 A at a temperature of 36 K. The short is located in the outer layer of the upper pole of the left aperture, in turn 21-22 counted from the outer layer splice. It is important to underline that this test only revealed the weakest point of the insulation system.

6.4.1 Spikes during the tests with lifted voltage

The lifted voltage to ground as well as the insulation failure had no significant effect on the voltage spikes. This is another indication that the spikes are related to electromagnetic effects and not to a weakness in the electrical integrity of the magnet.

6.4.2 Lifted voltage test and short circuit simulations

The expected voltage and temperature distributions in the coils during the tests were simulated with the STEAM-LEDET magnet model [14]. The voltage-to-ground for the position of the short was very close to 988 V with the peak temperature in the coil between 70 K and 90 K at the time when the short appeared, namely at about 120 ms. At this time, the voltage of the quench heaters to ground is already down to several tens of volts, since the time constant for the discharge is 42 ms.

7 Consistency of models with the experimental observables

7.1 Possible mechanisms for spikes from equipment external to the magnet

A number of tests were performed to exclude that the voltage spikes are generated in the measurement wires, the data acquisition system, the quench protection equipment and the power converter.

Changing the wiring between magnet and acquisition system, disconnecting the electronics, modifying the wiring for DAQ and quench heaters, or changing the polarity of the quench heaters did not change the signature of the voltage spikes [10].

When a quench is detected and a fast power abort is generated, the main circuit breaker opens and disconnects the converter from the AC supply [15]. The magnet current continues to flow through part of the converter, first through a thyristor bridge, and after a short delay of some ms through a free-wheeling thyristor. After disconnection of the power converter from the AC supply, the structure of the voltage signal across the magnet is solely defined by the quench heater firing, quench process and voltage spikes. There is no indication that the power converter contributes to the creation of voltage spikes observed on the magnet voltage tap signals.

7.2 Intermittent shorts

Intermittent shorts were modelled [5], and a short between a mid-point of two neighbouring coils and a mid-point of two other neighbouring coils are assumed. There are four mid-points and six combinations for such shorts. Simulations were performed for these six combinations. The parameters for the short are a resistance between 600 Ohm and 10 kOhm, and a rate of resistance change dR/dt. Only a short between the midpoint of the upper and lower poles of aperture 1 and the midpoint of the upper and lower poles of aperture 2 is compatible with the observed symmetry of the voltage spikes. To explain the time dependence of the observed voltages, a specific time dependence of the short must be assumed. The decay of the voltage spike is not well reproduced by the model.

Mechanisms M1a and M2 (see Table 1) assume that the spikes are due to an intermittent short circuit occurring either in the capillary tube or between current leads / busbars. In both cases, the position of the supposed short would effectively be across the two aperture mid-points. There are several observations against the short-circuit hypothesis:

1. The spike amplitude is independent of the voltage across the supposed short position.
2. The occurrence of the spikes is influenced by current pre-cycling, which hints at an electromagnetic phenomenon.
3. A resistance of an intermittent fault of a few kΩ or less can be detected by the TFM measurement. However, TFM during discharges did not indicate an impedance change from a short circuit.
4. Similar spikes are observed in other magnets, in MBHB-003 with the same amplitude as in MBHA-001. It is very unlikely that both magnets suffer from the same type of insulation weakness.

Therefore, models M1a and M2 are discarded.

Mechanism M1b assumes an intermittent short between apertures resulting from insulation defects coil to QH, then QH Ap1 to QH Ap2 through wiring, then QH Ap2 to coil. The very occurrence of a triple intermittent insulation defect is extremely unlikely. Moreover, during each quench heater discharge the quench heater current and voltage are monitored. No intermittent non-conformity is observed.

Therefore, model M1b is discarded.

7.3 Intermittent parasitic capacitance

In the simulation model reproducing mechanism M6, a series of parasitic capacitors was added between the centre of inner and outer layers of the lower coil of aperture 1 and the centre of inner and outer layers of aperture 2 [5]. Such parasitic capacitances are present due to the loading plates for each aperture. Two loading plates are installed for each coil, insulated from the magnet and from other parts of the structure and therefore these plates are at floating potential. The model M6 can reproduce the observed spike polarities and amplitudes by fast changes of the capacitance between two points of the apertures. Since this model requires the multiple intermittent insulation defects and direct electrical path between the apertures, it is unlikely that the hypothesis is the correct explanation for the spikes. Apart from the fact that the required parasitic capacitance changes are unlikely to occur, the transfer function measurements did not show such changes. Therefore, model M6 is discarded.

7.4 Sudden magnetic flux variations

A generic sudden magnetic flux variation is modelled as a sudden change in an R-L loop introduced in the circuit [5]. To achieve the symmetry of the spikes, the loop must be coupled to two of the four coils (either the two upper, or the two lower poles). Parameters are resistance R, inductance L and coupling k between loop and coils. Adjusting the parameters to R=7 mOhm, L=1.72 µH and k=4%, the amplitude, symmetry and decay time of the spikes are well reproduced. The time dependence of the spike is reproduced by changing R as a function of time between 7 mOhm and 40 Ohm. When R decreases, the spike has one sign, when R increases, the spike has the opposite sign. The current in the loop is in the order of mA.

An intermittent and nearly identical flux variation in two coils in two different apertures is difficult to imagine, except if it takes place at some particular locations (e.g. in the magnet interconnect outside the coils). This would not be consistent with the observations from the quench antenna.

7.5 Voltage spikes as consequence of global flux jumps

A main argument for a magnetic effect is the dependence of voltage spikes on the powering history of the magnet. An explanation for the voltage spikes can be the flux jumps that are symmetric with respect to the two magnet apertures and anti-symmetric with respect to the upper and lower coils [16].

Since the magnetic field change is picked up by quench-antenna coils at all locations along the magnet length, flux jumps causing spikes have to appear along the magnet. The ramp-rate of the magnet current could be a cause for this sudden magnetization change, since the conductor stability depends on dI/dt. Furthermore, inter-filament coupling loss, which in first approximation is proportional to the square of the ramp-rate, could cause sudden demagnetization and/or quench in an entire turn or more turns of certain coils.

In order to obtain the observed symmetry, the global flux jumps should occur with similar features in the upper coils of both apertures, and in the lower coils of both apertures, but with opposite features in upper/lower coils of the two apertures. This could be related to different coupling losses in the coil conductor, and in particular different effective transverse resistivity, which influences inter-filament coupling loss. The value of RRR of the conductor in the four MBHA-001 coils is relatively uniform [RRR=164, 173, 185, 206], and it is unlikely to be the cause of different coupling loss. The value of RRR is valid for the bulk Cu in longitudinal direction. The transverse resistivity that affects the coupling loss depends on the Cu resistivity in-between the filaments can be different. It is also unlikely that very different magnetization/persistent current losses are generated in the four coils, as their conductor has the same filament size and strand structure.

During quench discharges, a bump or wiggle in the coil voltages was observed (see chapter 4.1). Wiggles occurring in the coils of two different magnets were analysed. The coil voltage signals were filtered to show only their high-frequency component. The two magnets are MBHA-001, which exhibits the spikes and MBHA-002 with spikes of much lower amplitude. Provoked quenches at 9 kA and one training quench at about 9.7 kA were analysed for MBHA-001, and four training quenches between 8.3 kA and 10.4 kA for MBHA-002.

The features of the wiggle are similar in all tests of each individual magnet; but differ between the two magnets. For MBHA-001, the wiggles of the upper and lower coils from the same aperture are out of phase. For MBHA-002, the wiggles of the upper and lower coils from the same aperture are in phase.

Upper and lower coils of MBHA-001, which exhibit opposite bump polarities, could have a different sensitivity to dI/dt, i.e. their conductor might have different coupling loss or stability. This might explain why global flux jumps do not occur simultaneously in all coils, and spikes are generated.

Upper and lower coils of MBHA-002, which exhibit the same bump polarity and amplitude, could have similar dependence on dI/dt, i.e. their conductor might have similar coupling loss and stability. This might explain why spikes were not observed in the coils of this magnet.

Voltage spikes across the coils are observed after appearance of the bump. For discharges from 9 kA, spikes start to appear at about 110 ms after triggering the quench heaters. For most discharges, spikes are present until about 200 ms. For discharges following a pre-cycle to nominal current, spikes appear also in the region between 200 ms and 250 ms.

According to the simulations [17] [18], a bump indicates a slightly different onset of the quenching of the inner layer in two coils. It is estimated that all cables inside the coil are quenched after about 100-110 ms, with an error of about 20 ms. In the bus-bars and splices in the coil end regions, part of the conductor might still be superconducting. Flux jumps inside the coil can only be present if cables are not fully quenched, therefore the appearance of flux jumps inside the coil after about 150 ms is unlikely for an initial current larger than 9 kA.

If the variations of the magnetic flux are localised, the amplitude of the quench antenna signals should decrease with the square of the distance from the position of the flux jump. The effect from flux jumps in the interconnections outside the coil or appearing in the coil ends would lead to a signal that decreases strongly with the distance from the connection. This is not in agreement with the observations since the antenna signals correlated with the coil voltage spikes have about the same amplitude along the magnet.

7.6 Spikes due to possible vibrations of the bus-bars and interconnection elements

Mechanical vibrations of components outside the coils could generate voltage spikes [19]. Possible vibrations were analysed with an ANSYS finite element model of the half-moon and cable connection. The frequencies depend on the mechanical constraints and were found between several 10 Hz to some kHz. The natural vibration frequency of the long M4 busbar should be much lower than those for half-moon and connections.

The fast rise-time of the spikes is not compatible with the frequency spectrum of the vibrations. To explain the symmetry of the voltage signals, leads and splices should vibrate at the same damped natural angular frequency. A driving force for such oscillation during the decay of current is not present. To trigger movements that generate voltage spikes, a mechanism such as slip-stick would be required, but even if such vibrations existed the expected observations would not agree with the quench antenna signals. Therefore, it is very unlikely that mechanical movement are at the origin of the voltage spikes.

7.7 Consistency of mechanisms with the experimental observables

Table 2 gives an overview and is summarising the results of consistency analysis of all considered mechanisms of voltage spikes with the experimental observables. The most significant observation is the symmetry of the observed signals. To compare the mechanisms with the experimental data, several simulation models were developed [5] [17] [20] [21] [22].

Taking into account the symmetry of voltage tap and quench antenna spike signals, a number of explanations are not compatible with the observed symmetry. Models M5, M6, M7, M8, M9 and M10 are therefore discarded [23].

Assuming realistic assumptions, only two mechanisms were complying with the experimentally observed symmetry of voltage tap and quench antenna spike signals, namely the mechanism of intermittent short between apertures and mechanism of global flux jumps that occur with similar features in the upper coils of both apertures and in the lower coils of both apertures, but with opposite features in upper/lower coils of both magnet apertures.

Table 2: Consistency of considered mechanisms of voltage spikes with the experimental observables

id	Type	Mechanism	Consistency with observables and comments
M1a	Resistive	Intermittent short between apertures, possibly resulting from damaged insulation of the IFS wires in the capillary tube	Mechanism M1a assumes that spikes are due to an intermittent short circuit occurring in the capillary tube. There are several observations against this mechanism that is discarded (see 7.2).
M1b	Resistive	Intermittent short between apertures from insulation defects coil to QH, then QH Ap1 to QH Ap2 through wiring, then QH Ap2 to coil	Quench heater signals are fully conform to expectations. No intermittent non-conformity is observed. Model M1b is discarded. See 7.2.
M2	Resistive	Unwanted contacts between leads / bus bars. Mechanical movements of leads/bus bars combined with damaged insulation (transport current)	Mechanism M2 is discarded with the same arguments as applicable to mechanism M1a (see 7.2).
M3	Inductive	Flux jumps	Global flux jumps inside the coil can only be present if entire cable turns are not quenched, therefore the appearance of global flux jumps inside the coil after about 150 ms is unlikely for an initial current higher than 9 kA.
M4	Inductive	Inductively coupled loops	An intermittent and nearly identical flux variation in two coils in two different apertures is difficult to imagine, except if it takes place in particular locations such as magnet interconnect, but this would not agree with the observations from the quench antenna.
M5	Inductive	Vibrations or motions of leads / bus bars resulting in local variations of flux	Not compatible with observed voltage and quench antenna signal symmetry.
M6	Capacitive	Intermittent parasitic capacitance. A link between the apertures is needed to provoke spikes as observed (shown per modelling)	Not compatible with observed voltage and quench antenna signal symmetry. No short was detected during testing.
M7	Resistive / Capacitive	Variation of capacitance and electrical insulation resistance between coil and loading plate.	Same remark as for M6 as to the necessary link between apertures. No short detected during testing.
M8	Resistive	Inter-turn short	Not compatible with observed signal symmetry. No short was detected during testing.
M9	Resistive	Quench heater to Coil short	Not compatible with observed signal symmetry. No short was detected during testing.
M10	Resistive	Coil to Ground short	Not compatible with observed signal symmetry. No short was detected during testing.

An intermittent short would be the simplest explanation for the spikes, however several observations are not consistent with the hypothesis of a short circuit between magnet apertures:

- The spike amplitude is independent of the voltage across the supposed short position.
- Occurrence of the spikes is influenced by current pre-cycling.
- During the special tests at 9 kA quench discharges, no measurable impedance change was observed.
- Similar spikes are observed in other MBH magnets, in particular for one magnet where the same amplitudes were recorded.

The dependence of voltage spikes on the powering history as well as the very fast rise of the spikes are arguments for a magnetic effect. Experimental data show that voltage spikes appear also after the entire coil is expected to be normal conducting, which is contradicting the global flux jump mechanism.

Therefore, no explanation for the origin of the voltage spikes that is consistent with all observations has been found.

8 Recommendations

8.1 Future tests of Nb3Sn magnets

The HV test with lifted voltage to ground as described in paragraph 6.4 is judged to be the most representative HV test in comparison to the voltages and helium environment appearing during a quench of an Nb_3Sn magnet powered in series with the MB dipoles. During such tests the magnet experiences both the real internal quench voltages and simulated external voltages. Possible voltage breakdown due to an insulation failure in the magnet coil under quench conditions in the string of magnets can be identified by this type of test prior to the installation in the machine. Without this type of tests certain insulation failures could be omitted and could result in magnet damage once appearing under quench conditions in the LHC tunnel. Consequently, the tests with lifted voltage to ground are recommended to be included in the individual 11 T magnet acceptance procedure at cold condition.

Within the present baseline, the test of full 11 T magnet assembly is not planned. It is recommended to introduce such test into the baseline as a number of phenomena such as the quench voltage imbalance caused by the serial connection of two MBH magnets with one common cold bypass diode or real protectability and hot spot temperatures can only be assessed in the full 11 T magnet assembly. The assembly of two magnets should be tested together with the bypass diode, internal busbars, and trim converter. It is recommended as well to include in the acceptance procedure at cold condition the tests with lifted voltage to ground performed for the full assembly of 11T magnets.

8.2 Further investigations to understand the voltage spikes

A large number of voltage taps is installed in the 11 T magnets across coils, apertures, splices, bus bars etc. The present understanding of the voltages measured during discharges is not satisfactory. Further analysis of the signals during discharges is recommended:

- Select discharges without voltage spikes (e.g. at 9 kA after a pre-cycle).
- Select different time windows, before the magnet was fully quenched (e.g. at 100 ms), and when the magnet is considered to be fully resistive.
- Analyse the signals, in order to understand cross-talk, effects of electronics etc.

It is recommended to continue R&D on the voltage spikes and their origin, extending the analysis also to other Nb3Sn magnets, such as the MQXF.

8.3 Global flux jumps model and current redistribution between strands of a cable

Particularly puzzling are the voltage spikes that occur when the magnet coil is considered to be fully resistive. No realistic mechanism has yet been proposed to explain these spikes. A possible mechanism, equivalent to or extending the mechanism of global flux jumps, could explain such spikes when the current distribution in the pre-spike state is non-uniform before the magnet becomes resistive. With the rapid increase in temperature during the quench process and the corresponding increase in the resistance of the strands compared to the resistance between the strands, it is likely that current spikes may occur in the current transfers between the strands, harmonising the global current distribution throughout the cable. It is recommended that the suitability and plausibility of such a mechanism be investigated in more detail in connection with the mechanism of the global current jumps and the observed voltage spikes.

9 Summary and Conclusion

Magnet MBHA-001 (also called 11 T dipole S2) consists of two apertures (D1 and D2) each containing an upper and a lower pole (D1U, D1L, D2U and D2L). In SM18 the four poles were connected in series in the following way: D1U->D1L->D2L->D2U. During the tests in SM-18 magnet S2 showed unusual voltage spikes during fast discharges, mainly from currents between 7.5 and 10.5 kA. These spikes occurred after about 100 ms from the start of the discharge and had amplitudes of typically 1-3 V and duration of about 1 ms.

The sign of the spikes in D1U and D2U was the same and opposite of the sign in D1L and D2L.

The initial explanation for the observed spikes was an intermittent resistive short between the midpoints of both apertures. After excluding the instrumentation and equipment external to the magnet, the panel considered 11 possible mechanisms that could explain such voltage spikes. These mechanisms had resistive, inductive or capacitive origins. Various types of electrical shorts were considered, in-between different parts of the magnet or shorts to ground.

Additional diagnostics, besides voltage taps, was used namely pick-up coils in the apertures (also known as quench antenna measurements), transfer function measurements, and reflectometry.

Finally, several special tests were performed, namely tests with delayed firing of quench heaters, tests with a lifted voltage to ground, and tests with an artificial intermittent short.

In all the tests that were performed, the spikes only occurred during a fast discharge. So in case this magnet would be used in the LHC, the spikes would not affect beam operation since the beam is already dumped by the time the spikes occur.

The panel thinks that the most plausible mechanism has an inductive origin, and the amplitude of the spikes could therefore very well be correlated to the superconductor magnetization, meaning that the effect is much larger in Nb3Sn coils than in NbTi coils. The panel therefore recommended to continue the R&D on this topic, extending the analysis also to other Nb3Sn magnets, such as the MQXF.

Although the real physical explanation of this phenomenon is not understood, the panel concluded that the presence of the voltage spikes in S2 would not have prevented its qualification and subsequent installation in the LHC, since the signals were not the result of any kind of short (between coil and ground, or between coil and quench heater, or between quench heater and ground, or between two different poles, or in-between turns of the same pole) that could eventually damage the magnet in case of a quench.

The panel also stressed that the above conclusion should not be seen as a general conclusion for other magnet tests showing voltage spikes. In fact, voltage spikes occurring during any future magnet test should be carefully analysed since they could equally well be the result of an electrical fault which could result in magnet damage during a quench.

The panel finally concluded that individual acceptance tests of the two magnets of an 11 T assembly is not sufficient for qualification for installation in the LHC, but that the entire assembly of two magnets should be tested in SM18, including bypass diode, internal busbars, and trim converter.

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