New Measurement Techniques Used for the Electrical Quality Assurance of HL-LHC Superconducting Magnets

Jaromir Ludwin, Mateusz Bednarek, and Tiago Catalo Da Rosa

***Abstract*—In preparation of the Large Hadron Collider (LHC) upgrade to High Luminosity LHC (HL-LHC), a number of new Nb_3Sn magnets, including short model and prototype magnets, had to be electrically qualified. The process included a number of well-established Electrical Quality Assurance (ELQA) tests, such as electrical continuity checks of the magnet instrumentation, High-Voltage (HV) insulation tests of the magnet and quench heater circuits, and impedance measurements. In certain cases, in order to fully understand the observed effects, we needed to introduce new measurement techniques, in particular both an impedance measurement at specific frequency and a HV insulation test of the quench heaters during high-current quenches of the magnet. Furthermore, in order to localize possible insulation faults, we performed HV insulation tests using an additional multichannel acquisition system with high sampling rate. In this contribution we present in detail the used measurement techniques, explain the safety aspects, and discuss the results and possible further work.**

***Index Terms*—Circuit testing, insulation testing, large hadron collider (LHC), superconducting magnets.**

I. Introduction

The Electrical Quality Assurance tests of superconducting magnets and circuits are typically performed to check the continuity of electrical connections and the quality of the electrical insulation. Additionally, measurement of complex impedance proves to be a useful tool to assess the health of the superconducting magnet or the entire superconducting circuit including busbars, current leads, and instrumentation. Those standard tests were described in depth in [1], [2], [3], [4], [5], [6], [7]. Some of the effects observed in new Nb_3Sn based dipole magnets required the following additional tests and measurements:

A magnet impedance measurement during high-current quench (see Section II) was carried out to detect possible intermittent internal short-circuits, which could have appeared during a quench.

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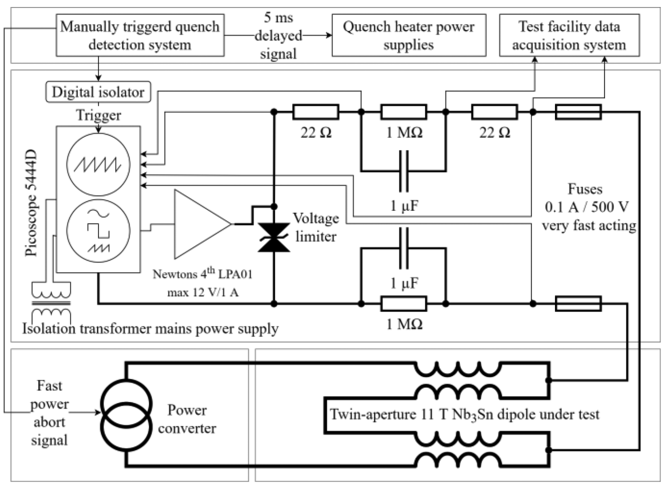

Fig. 1. Setup of the magnet impedance measurement during a quench.

Furthermore, a HV insulation test between the quench heaters and the coil (see Section III) was performed during high current quenches, in order to investigate the impact of helium-filled voids within the insulation layer. For these tests additional instrumentation was needed, to exclude or confirm that detected insulation faults are located in-between the quench heater circuit and magnet circuit.

The proposed measurement techniques were used during magnet test campaigns carried out at CERN in 2020.

II. Magnet Impedance Measurement During High-Current Quench

A. Measurement Setup

The magnet under test was a twin-aperture 11 T Nb_3Sn dipole magnet [8], made of four coils connected in series as shown at the bottom of Fig. 1. Details related to the quench detection, quench protection, and test stand data acquisition system are purposely omitted in the schematic, as they are mostly irrelevant to the way the described impedance measurement works. Upon quench detection, the power converter effectively puts the terminals of the magnet in a short-circuit. The middle points of the two apertures become then electrically the most distant points in the magnet. Analysis of the powering events resulted in hypothesis about the intermittent short-circuit located between the voltage taps connected to those two points, hence this is where the impedance was measured during the quench of the magnet.

The main part of the measurement setup was a Pico Technology Picoscope 5444D, which combines a four-channel oscilloscope and an arbitrary waveform generator (AWG). The signal from the AWG was then amplified by Newtons 4th LPA01 Laboratory Power Amplifier. The output of the amplifier was connected to the magnet under test through two 22 Ω current readout resistors and two DC blocking 1 µF capacitors. The 1 MΩ resistors, connected in parallel to the DC blocking capacitors, were installed to slowly discharge the capacitors, in case they were charged during the measurement. The second current readout resistor was installed to provide a redundant stimulus current measurement by the test station data acquisition system. The value of the current readout resistors was selected based on expected current levels, input range of measurement devices, and availability of the components. The oscilloscope was connected to the tested circuit such that the difference between the first and second channel gives the voltage across the current sensing resistor, and the difference between the third and fourth channel provides the voltage across the tested circuit. It must be noted that with the setup as in Fig. 1, the impedance of fuses and wiring is included in the measured impedance.

The generator and oscilloscope were configured such that the one-second-long sinewave generation and the acquisition were started simultaneously upon an external trigger generated manually through the quench detection system. The same trigger signal, with additional 5 ms delay, was used to fire the quench heaters, causing a quench of the magnet. As a result, we obtained a measurement starting approximately 5 ms before the quench of the magnet and lasting for 1 s.

The measurement frequency can be chosen arbitrarily, as long as it remains within the bandwidth of used components.

B. Safety

Several safety aspects had to be considered, with personnel safety being the most important one. The entire measurement setup remains at the magnet potential with possibly lethal voltages present. No direct manipulation can be allowed once the power converter is connected to the magnet and switched on. The oscilloscope/generator was controlled using a laptop computer, which during the measurement was accessed using Remote Desktop Protocol.

Also, equipment safety had to be considered, concerning the tested magnet as well as the measurement equipment. The measurement system was connected to the magnet via two very fast acting fuses Mersen MI6FA50V01 to protect the voltage tap wires in case of a short-circuit in a measurement system. The tripping current of those fuses is 0.1 A with voltage rating of 500 V and interrupt rating of 200 kA. The output of the amplifier was protected using a 1.5KE33CA bipolar transient voltage suppressor (TVS) diode against the overvoltage generated by the magnet. The standoff voltage of the TVS is 28.2 V and the peak pulse power dissipation is 1500 W. The measurement devices were installed on an insulated table, covered with a Kapton sheet, and powered using an isolation transformer to avoid unwanted ground loops.

Particular care was taken to make sure that the AC generator does not affect the operation of the quench detection system. This goal was obtained by assuring that the stimulus is applied only after triggering the quench heater power supplies. If the measurement was to be done during normal operation, the amplitude of the stimulus should be low enough not to affect the quench detection system or the power converter. A similar measurement method was later proposed in [9], where this specific safety aspect is also addressed.

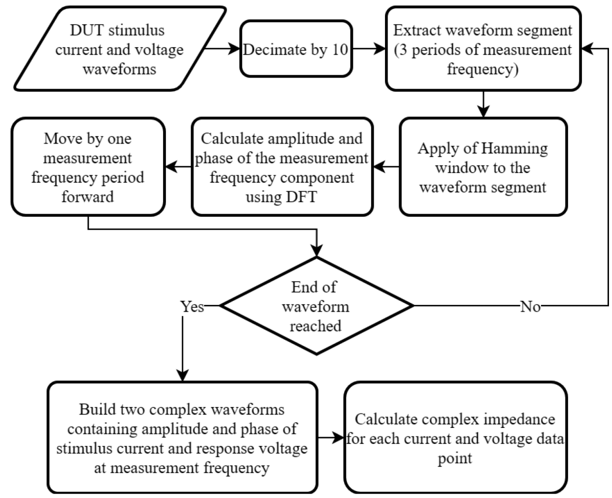

Fig. 2. Signal processing for the magnet impedance measurement during a high-current quench.

C. Signal Processing

The oscilloscope was configured to acquire signals with a sampling frequency of 2.976 MS/s. This provides a significant oversampling. Already at the level of the oscilloscope control application two additional math channels were defined, one of them calculating the voltage across the Device Under Test (DUT) from the difference of voltages at the output of the system and a second one calculating the current flowing through the current sensing resistor. The waveforms from those two virtual channels are later used by the NI LabVIEW based analysis software, which calculates the amplitude and phase of the measurement frequency component in short segments of each waveform using the Discrete Fourier Transform (DFT) as shown in Fig. 2. The impedance is then calculated from the two complex waveforms containing information about voltage and current at the stimulus frequency. The time resolution of the impedance measurement depends on the stimulus frequency and number of periods used for the DFT calculation.

D. Example Measurement

The magnet was powered to 9 kA and the quench detection system was manually triggered, resulting in firing of the quench heaters. A stimulus with a frequency of 13 kHz and an amplitude of 10 V_{peak} was applied to the magnet. The measured complex impedance is shown in Fig. 3. The glitch visible at 0.055 s is the moment of quench heater firing. Then as the magnet is quenching, one can observe an increasing impedance modulus and decreasing phase due to increasing resistive component of the impedance. An intermittent short circuit would manifest itself as large temporary impedance drop – in the order of tens of ohms. Such effect was not observed.

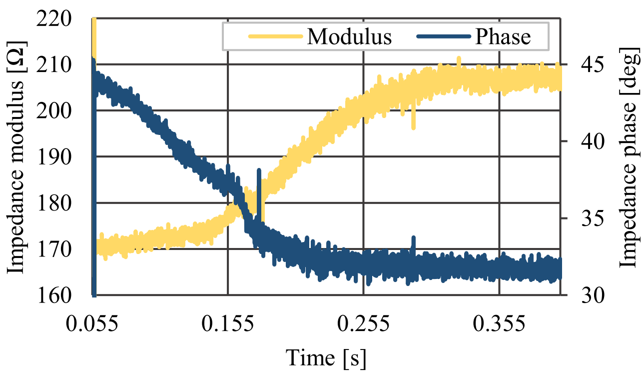

Fig. 3. Example measurement result. Complex impedance between midpoints of the two apertures at 13 kHz, magnet current before quench: 9 kA.

E. Further Work

The measurement described above is focused on the impedance between specific voltage taps of the magnet. In order to improve the accuracy of the impedance measurement of the magnet itself, the stimulus should be provided to the magnet with a separate pair of leads and a proper four-point measurement should be implemented. The measurement is conducted only at a single frequency, which is a limitation, that can be addressed by applying more than one stimulus frequency at once [9].

III. High-Voltage Quench Heater Insulation Test During a High-Current Magnet Quench

A. Measurement Setup

The goal of this measurement was to assess the quality of the quench heater to coil insulation in a single aperture short model of an 11 T Nb_3Sn dipole magnet [10] under realistic operation conditions. Such conditions assume that the magnet is installed in the accelerator as a part of a highly inductive magnet chain, that the quench causes evaporation of the liquid helium in which the magnet is immersed, and that high voltages generated by the energy extraction system and quench heater firing are present. The tested magnet was equipped with four quench heater circuits. During the measurement, two quench heater circuits were used to provoke the magnet quench or protect it in case of a spontaneous quench, one quench heater was brought to high potential to test the insulation, and one quench heater was excluded from tests and protection of the magnet due to earlier insulation failure and degradation detected during standard insulation tests in nominal operating conditions.

The magnet was grounded at the level of the negative terminal of the power converter. The high voltage was supplied via a resistor network from one channel of the multichannel insulation tester [1], as shown in Fig. 4. The figure also shows the configuration of the high-frequency acquisition part, realized using two interconnected oscilloscopes: Tektronix DPO5045 and Picoscope 5444D. The sampling rate was set to 200 MS/s and 125 MS/s respectively. The combined oscilloscopes were needed to provide the required number of measurement channels.

The two oscilloscope channels connected to the terminals of the tested quench heater via DC blocking capacitors were monitoring the difference in arrival time of the voltage wave generated by the insulation breakdown, as described in [11],

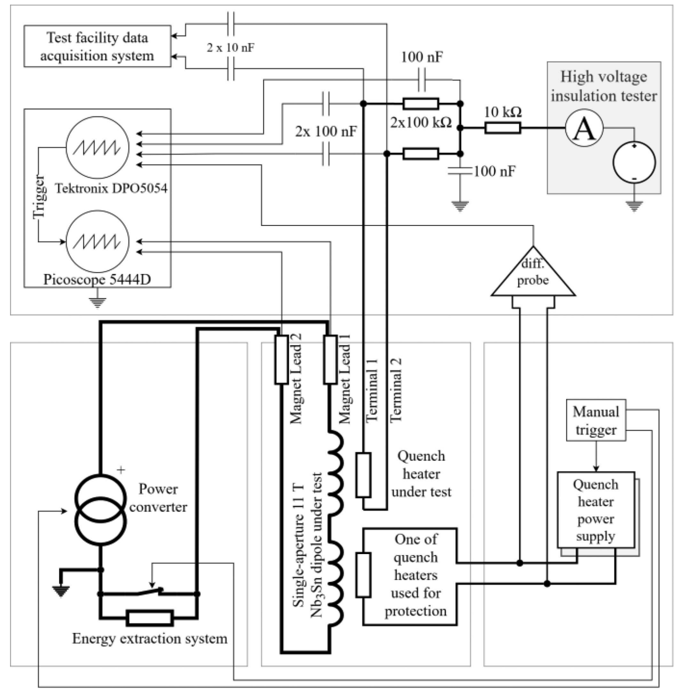

Fig. 4. Set-up of the HV test of a quench heater insulation during a high-current magnet quench.

therefore providing information about the location of the isolation fault along the quench heater circuit. The use of external capacitors instead of the AC coupling feature of the oscilloscope, provides reduced DC loading of the insulation tester, which is important when measured leakage currents are in the range of a few nA.

The two oscilloscope channels connected to the magnet current leads are part of the new development, with respect to the previously used techniques [11]. If the insulation between magnet circuit and quench heater circuit fails, the charge is transferred to the magnet circuit and the voltage recorded by the oscilloscope during the breakdown has a positive value. If any other part of the insulation fails, then the voltage-to-ground on the magnet terminals will drop below zero due to capacitive coupling between the tested quench heater and magnet coil, while the quench heater voltage-to-ground is being rapidly discharged.

The remaining two oscilloscope channels connected to the insulation tester output via the DC blocking capacitor and to one of the active quench heaters via differential probe are for monitoring purposes.

The magnet developed significant internal voltages-to-ground when quenching. These voltages, and their location in the magnet coil with respect to the tested quench heater must be accounted for when setting the target voltage of the HV tester. The insulation measurement was conducted as follows:

- The magnet was powered up to the target current – from 3 kA to 11.85 kA.
- The high voltage was applied to the tested quench heater circuit, up to a total quench heater to coil voltage of 1.6 kV including the voltage generated by the quench in the range of 66 to 250 V, depending on the quench heater.
- The high voltage was kept for about one minute in order to let the leakage current stabilize.

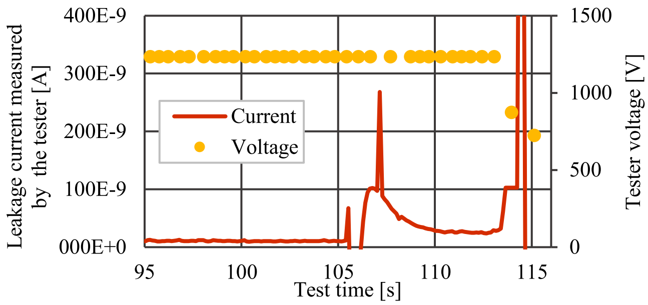

Fig. 5. Readout of the insulation tester during a quench heater circuit to magnet circuit insulation breakdown at 1.3 kV after a magnet quench at 11.85 kA. The three peaks in the leakage current from left to right are related respectively to: electro-magnetic disturbance caused by the quench heater firing, electro-magnetic disturbance related to the energy extraction switch opening, and breakdown of the insulation.

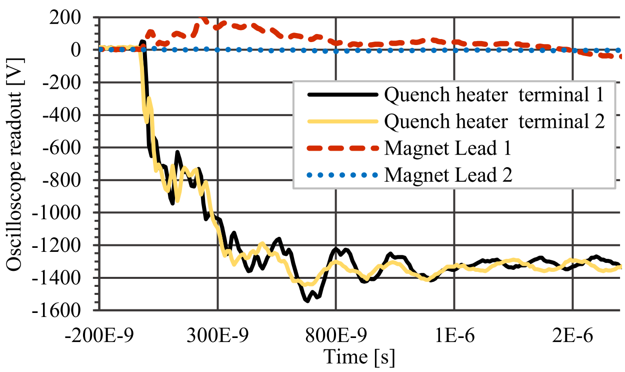

Fig. 6. Readout of the oscilloscopes during a quench heater circuit to magnet circuit insulation breakdown at 1.3 kV after magnet quench at 11.85 kA.

- The two active quench heaters were manually fired.
- The high voltage was still applied for another two minutes after the quench.

B. Safety

The standard safety measures for the HV insulation tests were applied regarding the personnel safety: the test area was fenced and proper signage was used. Additionally, all test equipment was operated remotely from the same control room, where standard quench tests are conducted.

The equipment safety was ensured by setting 1 mA current trip on the insulation tester and connecting the tested circuit via a resistor network as shown in Fig. 4. Particular attention was put on selecting the oscilloscope probes with voltage rating adequate to the HV measurement.

C. Example Measurements

A number of combinations of applied voltage and magnet current level were applied to all three available quench heater circuits in order to analyze the observed breakdowns. An example of a measurement which gives a very good insight on the functioning of the test is shown in Figs. 5 and 6. The measurement was conducted by powering the magnet to 11.85 kA and applying 1.3 kV to the quench heater. One can see that a breakdown occurs about 7 seconds after the quench. At this moment there is no current in the magnet. This effect may be explained by the existence of a liquid helium filled void in the insulation, providing sufficient electrical insulation. Also, during the quench when the void is filled with high pressure gaseous helium, the insulation is still sufficient. Only later, once the gas pressure drops, the insulation fails. The positive voltage on the ungrounded magnet terminal indicates an insulation failure between the quench heater circuit and magnet circuit.

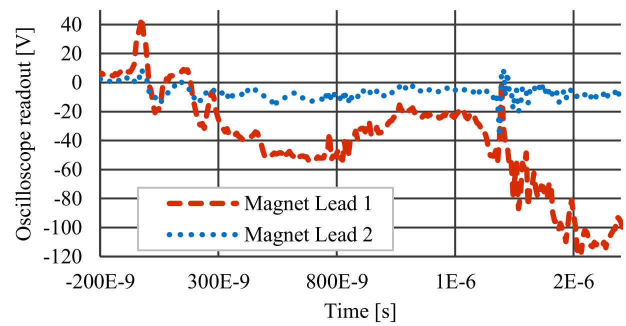

Fig. 7. Oscilloscope readout of a different quench heater insulation failure demonstrating insulation fault to a component other than magnet circuit. Measurement was performed without current in the magnet.

An example of the voltage readout from the magnet leads during HV test of a different quench heater in the same magnet is shown in Fig. 7. In this case the voltage-to-ground on the magnet leads becomes negative, indicating that the insulation is failing in a different location than between the tested quench heater circuit and magnet circuit.

V. Conclusion

Two new measurement techniques, suitable for superconducting magnet testing and failure diagnostics, were successfully and safely employed during the test campaign of the 11 T Nb_3Sn dipoles at CERN. The impedance measurement of the powered magnet with a similar setup to the one described here, was later proposed as a quench detection method by authors of [9]. The HV test of a quench heater insulation during a high-current quench contributed to our understanding of the effect of gaseous helium filled voids in the insulation layer on the voltage withstand levels during a quench. Additionally, monitoring of the voltage-to-ground on a magnet coil during a HV test of the quench heater to coil insulation greatly improves the possibility of fault localization, in particular when the limitations are imposed by external factors, like the test stand or cabling.

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REFERENCES

[1] D. Bozzini et al., "Automatic system for the DC high voltage qualification of the superconducting electrical circuits of the LHC machine," in *Proc. Eur. Part. Accel. Conf.*, 2008, pp. 2416–2418.

[2] A. Kotarba et al., "Automatic measurement system for electrical verification of the LHC superconducting circuits," in *Proc. Int. Part. Accel. Conf.*, 2011, pp. 1756–1758.

[3] M. Bednarek and J. Ludwin, "Software tools for the electrical quality assurance in the LHC," in *Proc. 8th Int. Conf. Accel. Large Exp. Phys. Control Syst.*, 2011, pp. 993–995.

[4] R. Kulaga, "Hardware and software upgrade of the High Voltage Crate for the ELQA, TE-MPE-TM meeting," Feb. 2013. Accessed: Oct. 1, 2020. [Online]. Available: https://indico.cern.ch/event/238924/

[5] J. Ludwin and P. Jurkiewicz, "Upgrade of the automatic measurement system for the electrical verification of the LHC superconducting circuits," *IEEE Trans. Appl. Supercond.*, vol. 26, no. 3, Apr. 2016, Art. no. 0600803, doi: 10.1109/TASC.2016.2520094.

[6] M. Bednarski, P. Jurkiewicz, J. Ludwin, D. Wojas, M. Bednarek, and G. D'Angelo, "Upgrade of the arc interconnection verification system for the large hadron collider," in *Proc. 26th Int. Conf. Mixed Des. Integr. Circuits Syst.*, 2019, pp. 106–110, doi: 10.23919/MIXDES.2019.8787158.

[7] J. Ludwin et al., "Preparation and execution of the electrical quality assurance program on the LHC superconducting circuits during the second long shutdown," *IEEE Trans. Appl. Supercond.*, vol. 31, no. 5, Aug. 2021, Art. no. 4002404, doi: 10.1109/TASC.2021.3065978.

[8] B. Bordini et al., "Nb_3Sn 11 T dipole for the high luminosity LHC (CERN)," in *Nb3Sn Accelerator Magnets. Particle Acceleration and Detection*, D. Schoerling and A. Zlobin, Eds. Berlin, Germany: Springer, 2019, pp. 223–258, doi: 10.1007/978-3-030-16118-7_9.

[9] M. B. B. Christensen et al., "Enabling real-time impedance measurements of operational superconducting circuits of accelerator magnets," presented at the MT28 Conf., Aix-en-Provence, France, Sep. 10-15, 2023, Paper 4PoM03-14.

[10] A. V. Zlobin et al., "Design and fabrication of a single-aperture 11 T Nb_3Sn dipole model for LHC upgrades," *IEEE Trans. Appl. Supercond.*, vol. 22, no. 3, Jun. 2012, Art. no. 4001705, doi: 10.1109/TASC.2011.2177619.

[11] D. Bozzini et al., "Detection and location of electrical insulation faults on the LHC superconducting circuits during hardware commissioning," in *Proc. Eur. Part. Accel. Conf.*, 2008, pp. 2413–2415. [Online]. Available: https://accelconf.web.cern.ch/e08/papers/wepd007.pdf