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Electrical Integrity Tests during Production of the LHC Dipoles

G. de Rijk, M. Bajko, M. Cornelis, P. Fessia, J. Miles,
M. Modena, G. Molinari, J. Rinn, F. Savary, J. Vlogaert

Abstract

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***Abstract*— For the LHC dipoles [1], mandatory electrical integrity tests are performed to qualify the cold mass (CM) at four production stages: individual pole, collared coil, CM before end cover welding and final CM. A description of the measurement equipment and its recent development are presented. After passing the demands set out in the specification, the results of the tests are transmitted to CERN where they are further analyzed. The paper presents the most important results of these measurements. We also report a review of the electrical non-conformities encountered e.g. inter-turn shorts and quench heater failure, their diagnostic and the cures.**

***Index Terms*— Superconducting Accelerator Magnets, Production Control**

I. Introduction

The mandatory electrical tests, performed during four production stages, are done with standardised equipment provided by CERN to the Cold Mass Assemblers (CMAs). The tolerances on the various electrical parameters are stated in the Technical Specification [2] and it is up to the CMAs to verify that they are met. The results are communicated to CERN in fixed format Excel files where they are verified to catch errors and to see trends.

II. Electrical Test Methods

Four sets of equipment are employed for the tests.

A. *Measurement of DC quantities.*

The DC measurements at fixed current are done with a DC power supply and a digital voltmeter. The HV tests are performed with a Megger™.

B. *Impedance measurements.*

The impedance measurements are performed via a frequency scan with a Schlumberger™ gain-phase analyzer. The analyzer is controlled and read out via a GPIB interface into a PC. The coil is put in series with a reference impedance. The measured quantities are the ratio of the voltage drop over the coil and the reference impedance and its phase. The scan is done from 1 Hz to 10 KHz. From this the inductance values at 3 frequencies are extracted. In Fig. 1 an example can be seen of the result of a frequency scan on a pole in a collared coil. The operator compares the impedance curves with the curves made on a reference coil to assess the quality of the coil. The reference coils are approved coils from the pre-series production.

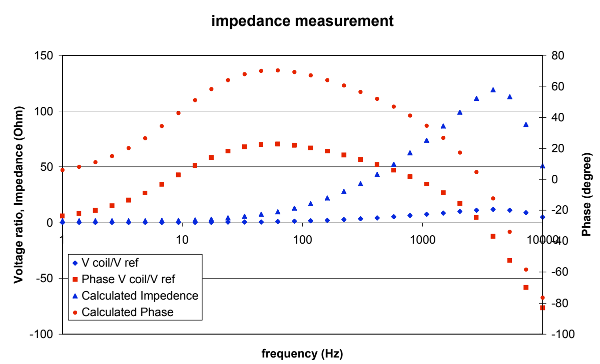

Fig. 1. Example of an impedance measurement with a gain phase analyzer. The impedance and its phase are calculated from the measured voltage ratio and phase between the coil and the reference impedance.

C. *Discharge measurements.*

The discharge measurements are done with a capacitance bank. The voltage and current as function of time are read out with a NI™ scope card in a PC.

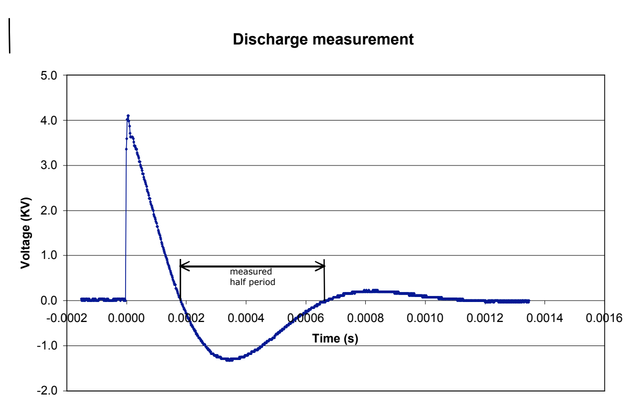

Fig. 2. Example of a discharge measurement on a pole in a collared coil.

In Fig. 2 an example can be found of a discharge measurement. The measured period is deduced from the time

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between the first and second zero crossing of the voltage. With a short circuit of one turn on a single pole, this time is typically reduced by a few tenth of a millisecond.

D. Quench Heater circuit discharge test.

The 8 Quench Heater circuits are subjected to a discharge test after the collaring operations. This test was added to the program during the pre-series production. The value of the discharged energy was increased during the series production, to augment the significance of the test. The equipment used for this is similar as for the tests on the coil but with a larger capacitor bank.

III. Electrical Tests on the Poles

Electrical tests are done on the individual coil layers and, after assembly of the layers, on the poles. The aim is to detect insulation problems with respect to the exterior of the coil, inter-turn shorts inside the coil and to validate the splice between the layers. The recorded quantities are:.

- DC resistance of coil layers and poles at a current of 1 A.
- Inductance at 10 Hz, 100 Hz and 1 KHz of coil layers and poles.
- The oscillation period during a discharge test of 120 V/turn on layers and 100 V/turn on poles.
- The insulation resistance of the copper wedges in the layers with respect to each other at 500 V.
- The insulation resistance between inner and outer layer in each pole at 1 KV.

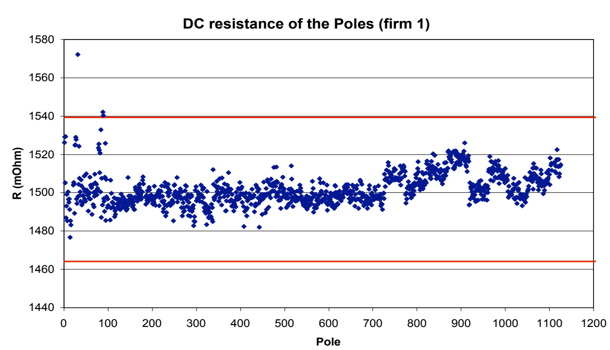

Fig. 3. The DC resistance of the poles at firm 1. The lines indicate the acceptance limits.

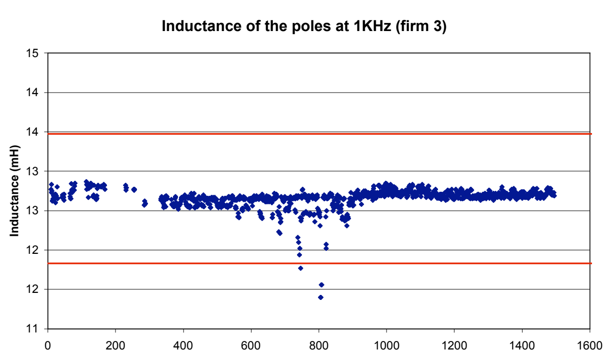

Fig. 4. The Inductance of the poles at Firm 3. The lines indicate the acceptance limits.

- The resistance of the splice between inner and outer layer at a current of 10 A.

In Fig. 3 the values of the pole resistance are shown for all the poles at Firm 1. The resistance depends on the cable types used for the inner and outer layers. The lower limit is set such that it corresponds to the reduced resistance of a missing turn in case of an inter-turn short circuit. An inter-turn short circuit should thus show up as a out of limit low resistance.

In Fig. 4 a graph can be found of the inductance as measured on the poles at firm 3. The presented results are final ones on accepted poles, the low values are recognized measurement problems.

IV. Electrical Tests on the Collared Coils

After the collaring operations, the collared coils (CC) are subjected to a number of electrical tests. The recorded quantities are:.

- DC resistance of the 4 poles at a current of 1 A.
- Inductance at 10 Hz, 100 Hz and 1 KHz of the 4 poles.
- Resistance of the 8 quench heater circuits.
- Capacitance of the dipoles.
- The oscillation period during a discharge test of 100 V/turn on the poles.
- Insulation resistance between poles and dipoles to the CC and quench heaters at 1 KV; between the poles in a dipole at 1 KV.
- Leakage current between the poles and dipoles to the CC at 6 KV; between poles to quench heaters and between the poles in a dipole at 3 KV.
- A discharge test of 850 V, 2.5 KJ on the quench heaters circuits, followed by a re-measurement of their resistance and insulation with respect to the CC and the poles.

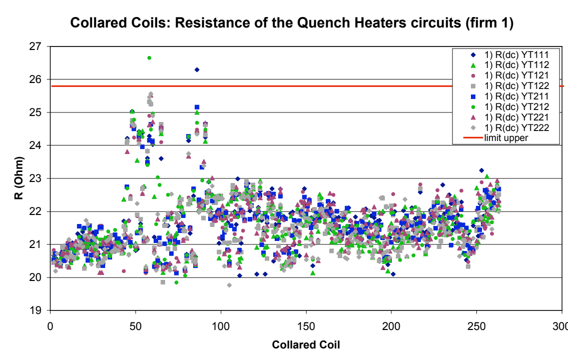

Fig. 5. Collared coils; the resistance of the 8 quench heater circuits. The line is the tolerance value.

In Fig. 5 the trend in the resistance of the quench heater circuits at firm 1 can be found. Around CC 50 the resistance values increased. This problem occurred at all 3 CMAs simultaneously and was not due to electrical problems but to material problems. Corrective action in the production of the quench heater strips, made of austenitic stainless steel, brought the values back to normal.

The results for the discharge test in the CC of firm 3 can be found in Fig. 6. The presented results are from accepted CCs.

CCs with defects were repaired before the final measurements were made.

V. Electrical Tests on the CMs

A. Electrical tests before end cover mounting.

During the assembly of the CMs, just before the two end covers are welded onto the CM, a full set of electrical tests is performed. These tests consist of:

- DC Resistance of the 4 poles, the 2 dipoles and the CM at a current of 1 A.
- Inductance at 10 Hz, 100 Hz and 1 KHz of the 4 poles, the 2 dipoles and the CM.

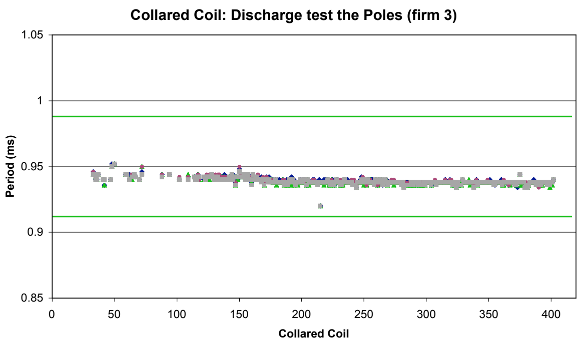

Fig. 6 Discharge test on the CCs at firm 3. The period of the first oscillation is recorded.

- The continuity of all the voltage tap connections.
- The resistance of the 8 quench heater circuits.
- The resistance at 20 A of the splices between the poles and between the dipoles.
- The resistance of the spool pieces.
- The capacitance of the CM.
- The oscillation period during a discharge test of 70 V/turn on the poles.
- Insulation resistance at 1 KV and 1.5 KV of the poles with respect to each other, the quench heaters and the CM.
- Leakage current between the poles, the quench heaters and the CM at 5 KV.
- The resistance of the temperature sensor and the cryo heater.

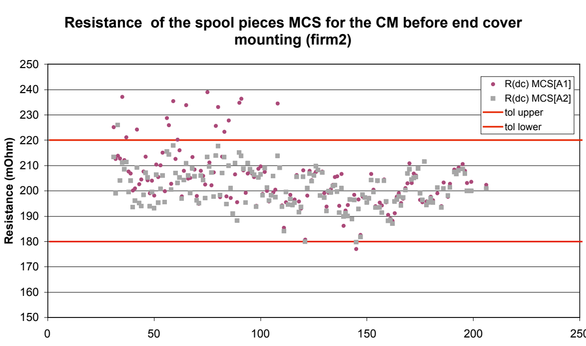

Fig.7. The resistance of the sextupole spool pieces on the CMs before end cover mounting at firm 2.

In Fig. 7 the resistance of the sextupole spool pieces on the CM before end cover mounting (firm 2) can be found. The higher, out of tolerance, values were traced back to the production of the spool pieces and were accepted.

B. Electrical tests on the finished CM before delivery.

At the end of the production line just before delivery, a final set of tests is done by the CMA. These tests consist of:

- DC resistance of the 2 dipoles and the CM at a current of 1 A.
- Inductance at 10 Hz, 100 Hz and 1 KHz of coil of the CM.
- Resistance of the 8 quench heater circuits.
- The continuity of all the voltage tap connections.
- The voltage drop over each spool piece measured on the voltage tabs when a 1 A current is passed.
- Leakage currents inside the CM at 1.5 KV and 5 KV
- Capacitance of the CM.
- Insulation resistances at 1 KV and 1.5 KV inside the CM.
- The oscillation period during a discharge test of 25 V/turn on the CM.
- The resistance of the temperature sensor and the cryo heater.
- The resistance of the connections on the protection diode.

Fig. 8 shows the results of the discharge tests at firm3 on the finished CMs.

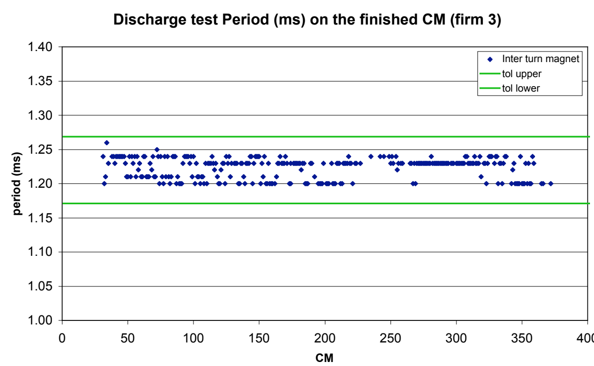

Fig. 8. Inter-turn short circuit test with a 25V/turn discharge for the finished CMs at firm 3.

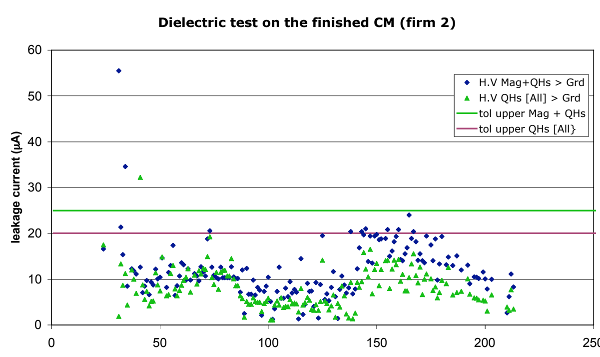

Fig. 9. Dielectric tests on the finished CMs in firm2: coils (Mag) + Quench Heaters to CM at 5 KV, Quench Heaters to CM at 3 KV.

In Fig. 9 the leakages currents from the dielectric tests on finished CMs at firm 2 can be found. The ambient humidity at firm 2 is suspected to be the cause of systematically higher leakage currents when compared to those of the other two firms (average value: 12μA compared to 1 μA).

VI. Integrity of the Quench Heater Circuits

During the production several CMs developed a continuity breakdown in a quench heater circuit during the cold test at CERN. To detect this type of defect at an earlier stage, an additional discharge test was added, during the pre-series production, on the quench heater circuits after the collaring operations. This test has however not detected any quench heater circuit problems up to now. Recently, in order to better understand the quench heater problems, a series of tests were done at CERN on partially sectioned quench heater strips. Only when a strip is sectioned for more than 90% of its width, will the 850 V, 2.5 KJ discharge sever the connection. A spark accompanies the severing of the connection. The curve of the voltage as function of time shows only over a limited time span a noise signal. The carbon, originating from the effect of the spark on the polyimide, provides a contact bridge between the two sides, complicating the detection of the broken connection by DC means afterwards. Moreover a re-test by discharge does mostly behave as for an intact strip.

The quench heater problems have been addressed by improving the quality control and the assembly procedures during the CC fabrication.

VII. Inter-turn Short Circuits in the Coils

On 15 CCs and one CM an inter-turn short was detected during the production up to now.

A. Static inter-turn shorts

In addition to the mandatory checks, the CMAs also perform specific checks during the various production steps. During the collaring operation, with the CC in the collaring press and under pressure, the resistance values of the 4 poles are constantly compared with each other. If an unbalance is detected, this can be the signal for an inter-turn short circuit. The DC mandatory checks and the specific checks have up to now yielded 13 CCs with in indication for an inter-turn short circuit. These short circuits we indicate as 'static'. For one of the CMAs, 9 such cases occurred in a time span of a few months. Short circuits can be localized using a magnetic measurement system, which employs a 'mole' with rotating coils [3]. An inter-turn short circuit will cause a re-distribution of the current in the cables, as one turn will be shorted. The current will be different between the cable sections in front and behind the defect. In this way short circuits in 12 CCs were localized up to now (on one case no localization was done), 9 at one firm and 3 at another. Of the 9 short circuits at one firm, 7 were at the same spot (between turn 3 and 4, counted from the top angle of the coil, on the inner layer at the connection side). From the three cases at the other firm, 2 were at the same spot (between turn 7 and 8 on the inner layer at the connection side). The single case in a CM was localized with the magnetic measurements but is still waiting to be disassembled for confirmation and repair.

B. Dynamic inter-turn shorts

After the collaring operations, on 4 CCs an inter-turn short circuit was detected with the discharge test at the same firm where a series of 'static' cases were seen. These are indicated as 'dynamic'. By visually observing a spark on the inside of the inner layer through the air gap between the coil and the cold bore tube of the CC, a precise localization was possible. This localization was in the same area as for the 'static' cases. After opening of the CC burn spots were found at this location (Fig. 10).

The cause for both the 'static' and 'dynamic' cases at one firm was the non-optimal filling of the coil end by an end spacer. During collaring, due to the pressure in the collaring press, the CC is longitudinally stretched. Open spaces in the coil end can cause the cable to be deformed and the insulation wrappings to open up. Adding strips of pre-preg insulation at the requisite places during the coil winding cured the problem.

Fig. 10 Short circuit on the inside of the inner layer. The scratched arrow points to the spot between turn 3 and 4 on the connection side.

VIII. Conclusion

The electrical integrity of the dipoles is guaranteed by an extensive set of electrical tests prescribed by CERN and executed with standardized CERN supplied equipment. The tests are done at all production stages in order to detect any problem as early as possible. The large majority of electrical problems are intercepted with this method.

Acknowledgment

The effort for the dipoles is the work of a large number of people in many institutes and firms. The authors would like to thank all people involved in setting up, executing and analyzing the electrical tests since the very beginning of this project. We would like to thank B. Caserza, M. Kühnberg, M. Schweitzer and M. Zehner of the CMAs for their work on the tests. We would like to thank Lucio Rossi and Lyn Evans for their lasting support on the dipole project.

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[3] B. Bellesia, G. Molinari, C. Santoni and E. Todesco, *Short circuit localization in the LHC main dipole coils by means of room temperature magnetic field measurement,* submitted *to IEEE Trans. On Applied Superconductivity* for publication (this conference).