FERMILAB-PUB-18-580-TD

Analysis of the short-to-ground event in the LARP-AUP MQXFAP1 magnet, and its implication on the production and tests of the series magnets

Vittorio Marinozzi, Giorgio Ambrosio, Joseph Muratore, Piyush Joshi, Emmanuele Ravaioli, Stoyan Stoynev, Peter Wanderer

***Abstract*— Starting from 2022, the Large Hadron Collider (LHC) at CERN will be shut down to increase the luminosity of the machine. One of the main interventions will be inserting more performing low-β quadrupoles, called MQXF, in the interaction points.**

The US is involved in this activity with the US HL-LHC Accelerator Upgrade Project (AUP), and is responsible of the production and test of the Q1 and Q3 cryo-assemblies (each one containing two 4.2-m magnets in a single cold mass) of the triplet. After completing the US short model phase, the prototyping phase has started with MQXFAP1 (1st prototype, 4m long) test at the Brookhaven National Laboratory vertical test facility. However, after the magnet reached nominal current, a short-to-ground event stopped the test when the magnet was at 97.5% of acceptance current.

In this paper, an analysis of this event is presented. We present how the short event can be modeled, and we base our conclusions on simulations and experimental evidence, trying to explain the mechanism that led to the short-to-ground formation. The short-to-ground has occurred in a coil that was known to have a previous coil-to-heater short. Therefore, we explain the connection between these two events, the possible risks for the future magnets, and how to prevent this issue from happening again in the series magnets.

***Index Terms* — Quench protection, Low-beta quadrupoles, Superconducting magnets, Nb_3Sn, Electrical Insulation**

I. Introduction

The United States contribution to High-Luminosity LHC (HL-LHC) consists, among other duties, to produce, test, and deliver the quadrupoles for the Q1 and Q3 regions of the low-β triplet of the interaction regions, called MQXFA [1]. The main parameters can be found in Table I.

United States are today in the prototyping phase, and the test of the first prototype has been concluded in February 2018 [2] at Brookhaven National Laboratory. During training, magnet has reached nominal current (16470 A), while it was not able to reach ultimate current (17890 A) due to a short to-ground event during training quench 18. Training curve can be observed in Fig. 1.

In this paper, an analysis of this event is presented. Together with a quick analysis of the possible mechanism that caused the short, that is treated with more details in other referenced technical documents, the main purpose of the work presented here is to verify and prove the integrity of the electrical design of the magnet, in order to avoid future similar issues during production and tests of the series magnets.

V. Marinozzi, G. Ambrosio and S. Stoynev are with Fermi National Accelerator Laboratory, Batavia, IL, USA, email: vitmar@fnal.gov

J. Muratore, P. Joshi and P. Wanderer are with Brookhaven National Laboratory, Upton, NY, USA, email: muratore@bnl.gov

E. Ravaioli is with CERN, Geneve, Switzerland, email: emmanuele.ravaioli@cern.ch

TABLE I Main MQXFA Design Parameters

Material	Nb_3Sn
Aperture	150 mm
Peak field	11.4 T
Nominal current	16470 A
Length	4 m
Stored energy	1.17 MJ/m
Inductance	8.21 mH/m

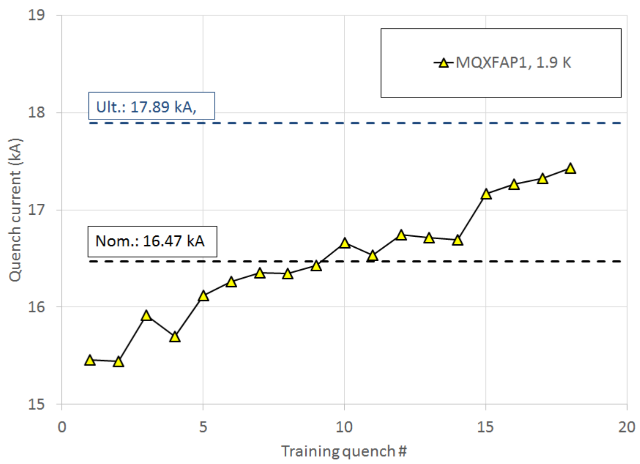

Figure 1: training curve of MQXFAP1

II. Cause of The Short Circuit To-Ground

Short circuit to-ground occurred in the coil QXFAP5, that was known to have a short circuit coil-to-heater, happened between quench 1 and quench 2 in the outer layer, low field region. Visual inspections confirmed that the short to-ground occurred in the region above the quench heater strip, where a clear burnt of the insulation can be observed (see Fig. 2).

In this section, we show how a short coil-to-heater can degrade into a short to-ground. We refer to the quenches occurred in MQXFAP1, that are the worst cases. Details on the quench protection system used for MQXFAP1 can be found here [3].

This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.

A. Single short

The first reasonable assumption that can be made is that the heater and the coil have a single contact short, which can be represented in terms of resistance. In this scenario, the heater acts as a capacitance during a quench. Even though the heater is not connected, its voltage grows with that of the shorted turn, with a certain delay that is dependent on the short's resistance and on the heater capacitance. Due to the voltage difference among involved turn and quench heater, a current will flow between the heater and the coil. We try to estimate this current in order to verify whether it could be dangerous for the magnet during a quench.

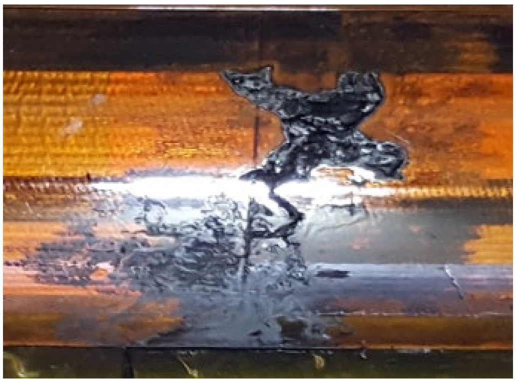

Figure 2: picture of MQXFAP1 short circuit location

The unknown parameters are the coil-heater resistance and the heater capacitance. Short resistance cannot be measured, so we can perform the analysis for two extreme values, that we have chosen to be 10 mΩ and 100 Ω. The heater capacitance can be measured, instead, and it resulted to be ~10 nF for coil QXFA107. Knowing these parameters, it is easy to model the short, to solve the circuit and to compute the power dissipated inside a single short between coil and quench heaters. More details on this analysis can be found in [4]. Maximum expected dissipated power is ~ 10 μW, so we conclude that a single short between quench heater strip and coil can be considered not worrying.

B. Double short

Another possibility is having more than one short between coil and quench heater. In this case, an alternative path for the current exists: current can therefore flow through the quench heater instead than through the coil, going through the insulation, and degrading it. The larger is the voltage across the involved turns during a quench, the larger is the current flowing through the short. In this case, more complex quench simulations are needed, cause quench resistance and turns self and mutual inductances are involved in the process; for this reason, this situation becomes critical during a quench. Simulations have been performed with STEAM [5], allowing to solve a complex circuit involving quench protection circuit and shorts with PSPICE, together with a reliable quench simulation software using LEDET [6]. More details on these simulations can be found in [7]. The conclusion is that, in this case, large current can flow through this alternative path, and constantly degrade the insulation, leading gradually to a short to ground. Indeed, such as shown in [7] it is possible to observe signs of shorts starting from quench 2 of the magnet, until a clear short to-ground is visible in quench 18.

C. Heater-to-coil short formation mechanism

Since a heater-to-coil short can pose a risk for the magnet, it is important to understand the mechanisms that can lead to its formation. Here we present a hypothesis to explain the formation of such a short, that we think finds its origin in the test procedure.

Figure 3 shows the test procedure adopted for MQXFAP1 during the cold vertical test [2], together with the quench history, focusing on the Hi-Pot tests performed on the coil QXFAP5. The Hi-Pot tests were performed according to the procedures used for cold tests of MQXFS (short models) by LARP and CERN.

The first Hi-Pot test, at room temperature, showed that the heater-to-coil insulation was robust. However, after just one quench and one thermal cycle, the second room temperature Hi-Pot test showed a 2.38 kV breakdown, the first evidence of a heater-to-coil short. After cooling the magnet without any quench, the Hi-Pot showed a 0 V breakdown, clearly indicating a heater-to-coil short. The coil QXFAP5 outer layer low-field quench heater was therefore insulated. Then the magnet had quench 2 and 3, and a complete thermal cycle. After 14 more quenches, it showed a short-to-ground, and the test campaign was stopped.

It is evident that the heater-to-coil short occurred immediately after quench 1. We hypothesize that it was caused by the second hi-pot test at room temperature. Indeed, after the first quench and thermal cycle, cracks in the epoxy resin can occur due to thermal contractions and electromagnetic forces; superfluid helium can infiltrate into these cracks and become trapped within the resin.

At room temperature, helium gas is a "good" conductor, at least compared with air. Figure 5 shows the breakdown voltage of air and helium gas at different temperatures and pressures [8]. It can be seen that the breakdown voltage is compatible with a ~10 mm path from the coil to the quench heater, considering that the hi-pot test was performed at room temperature (>275 K), but that there was not only helium gas, but some air too.

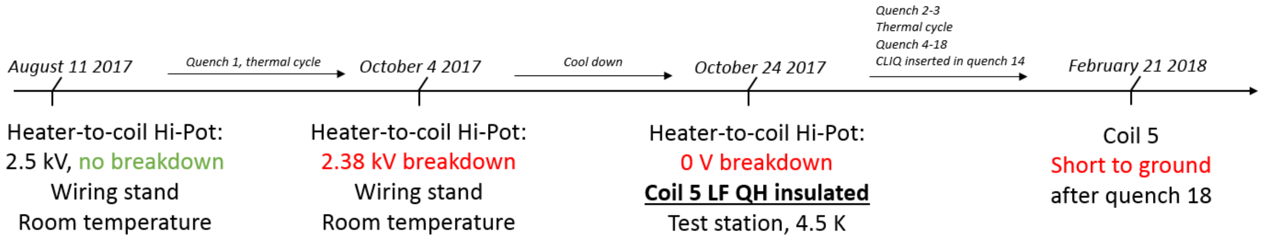

Figure 3: History of quench and hi-pot tests on the coil QXFAP5, low-field zone

Figure 5 shows the outer-layer quench heater trace. Since the quench heater trace contains holes that are about 5 mm away from the heater strips, it is possible to foresee a path from the coil to the quench heater through a crack in the epoxy filled with helium gas, and then through one of these holes. As a result, the electric arc can damage the polyimide insulation, creating a direct path from the coil to the quench heater that is just 200 µm long. This may explain the 0 V breakdown after the cool-down. It is not clear whether, in the specific case of coil QXFAP5, the heater-to-coil short had been in multiple turns since the beginning. It cannot be excluded, therefore that the insulation to-ground was exposed to heat deposition for 17 quenches.

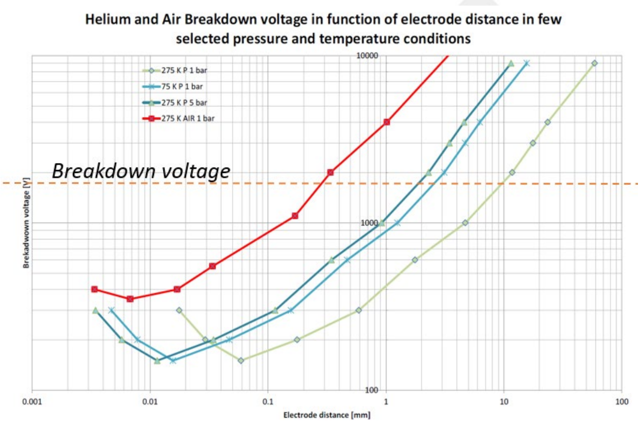

Figure 4: Helium and Air breakdown voltage, for different distances and pressures

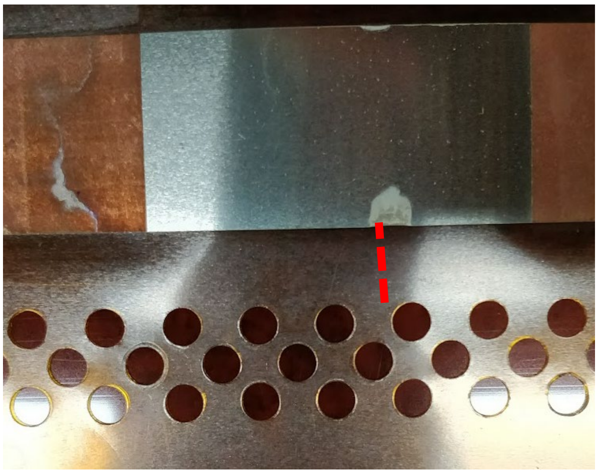

Figure 5: picture of the quench heater trace used for MQXFAP1.

In addition, figure 6 shows that the impregnation of the coil in the short zone was poor, increasing the chances of shorts. The sign of poor impregnation is the “white” area evidenced by a circle.

We can conclude that performing hi-pot tests at room temperature, after the magnet has been in contact with superfluid helium, can pose a hazard. This procedure can cause a multiple heater-to-coil short, which, as we have seen, can pose risks to the safety of the magnet. After the magnet has been exposed to helium, the document “Electrical Design Criteria for the HL-LHC Inner Triplet Magnets” [9] (not available at the time of MQXFAP1 first and second cooldown) recommends decreasing warm Hi-pot to 1/5 of the minimum design to withstand the voltage at nominal operating conditions. In the future, these guidelines will be strictly followed for short models and prototypes tests, and this issue will be avoided.

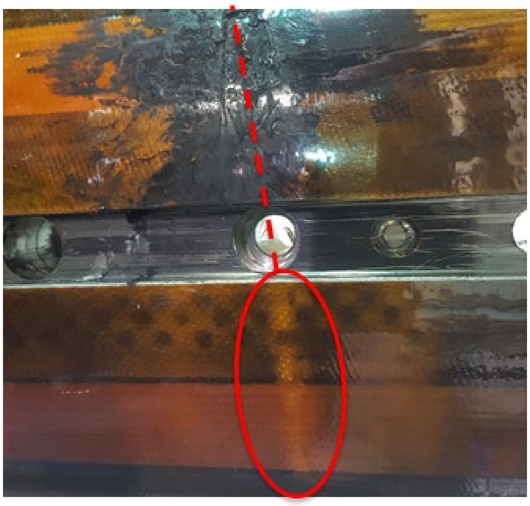

Figure 6: Evidence of poor impregnation (white zone) in the MQXFAP1 short location

III. Analysis of An Insulation Failure

In the previous section, we have understood that high voltage tests after helium exposure can damage the insulation of the coil, and lead to short circuits. However, this does not indicate that the insulation is poor, and that it cannot sustain the peak voltages that will occur during a quench. In this section, we verify that, in standard conditions, the electrical design of the magnet is robust, and suitable to withstand the peak voltages that will occur during a quench.

In this section, we assume that a direct path from heater to coil is caused by damage of the insulation and crack of the epoxy; we estimate the peak voltage from heater to coil, and verify if the magnet can withstand it without causing a discharge, and damaging the coil.

A. Peak voltages during a quench.

Due to thermal contractions and electromagnetic forces, cuts in the polyimide insulation of the heaters may occur. These cuts, together with epoxy cracks, may create a direct path from the coil to a quench heater. In the worst case the locations of these failures may coincide, and the heater be separated from the conductor only by a 200 µm deep crack, that is filled by superfluid helium. The minimum distance is 200 µm since the minimum cable insulation is 140 µm thick, the polyimide insulation is 50 µm thick, and there is a ~10 um layer of glue between the heater and the polyimide.

This insulation failure is difficult to detect at cold (1.9 K), since superfluid helium is a good insulator. However, during a quench, the temperature of the coil, and therefore of the helium, can easily reach > 100 K. Trapped helium transit in the gas state, and it is therefore important to check whether the helium gas can sustain the voltage difference between the quench heater and the coil during a quench.

A detailed evaluation of the peak heater-to-coil voltages during a quench, in different scenarios and locations, is reported in [10], together with expected temperature of the turn. The worst situation in MQXFA is expected to be 350 V peak voltage between heater and coil, being the involved turn at 130 K.

B. Comparison with helium breakdown voltage

Now, we assume that the helium gas that is in the crack is at the same temperature as the involved turn. This is a conservative assumption, since the helium is a better conductor at higher temperature.

Helium gas breakdown voltage for a 200 μm path can be estimated to be ~330 V at 75 K and atmospheric pressure, as it can be seen in figure 7 [8]. Therefore, the expected peak voltage [10] (350 V at 130 K) is comparable to or larger than the helium voltage breakdown, and a discharge could be expected in case of a failure, with subsequent damage of the coil.

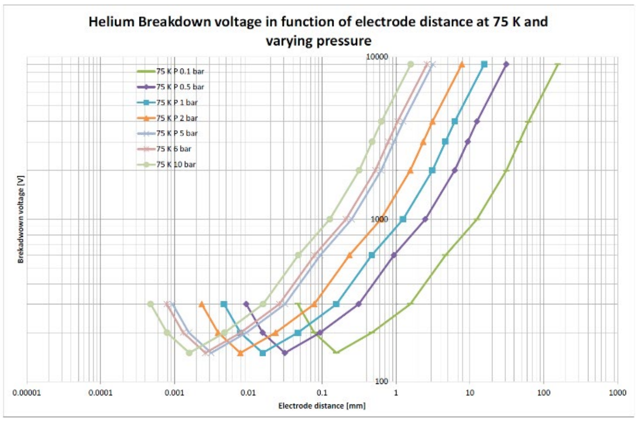

Figure 7: Helium breakdown voltage, for different distances and pressures

However, it is difficult to imagine that helium will stay at 1 bar pressure during the process. Indeed, helium gas tends to expand significantly at cryogenics temperature when subject to temperature increase, and being trapped inside the cracks, its pressure should likely increase.

For example, making the simple assumption that the helium gas is trapped within the epoxy resin, and that it preserves volume and mass during quench, the resulting pressure can be easily computed. For instance, starting from 1 atm pressure at 1.9 K, the helium pressure grows to ~530 atm at 100 K. This is a huge pressure, and some helium is expected to flow away. Modelling this scenario in order to estimate the actual helium pressure is unfortunately not trivial.

Nonetheless, it is important to point out that the outer layer of the MQXFA coils is in direct contact with the structure. It is pushed by very strong magnetic forces against the structure, and the polyimide ground-insulation should act as seal: indeed, the roughness of the insulation surface and of the structure surface is really low.

Figure 8 shows the contact pressure between the coil and the structure, in two different paths. It can be seen that it is always beyond 100 MPa (or 100 bar).

Since the roughness of the two surfaces in contact is low, we could assume that they act as a good seal, able to sustain helium pressure of ~ 100 bar.

Moreover, assuming that just a fraction of this pressure can be actually taken by this seal, for instance 10% (~10 atm), the helium breakdown voltage would be > 1 kV (see Figure 7). Therefore, in this more realistic case, we can conclude there is some margin to prevent shorts between the coil and the outer layer heater of the longest coils, although it could be assessed by more accurate modelling. The robustness of the electrical insulation can be therefore considered good by this analysis.

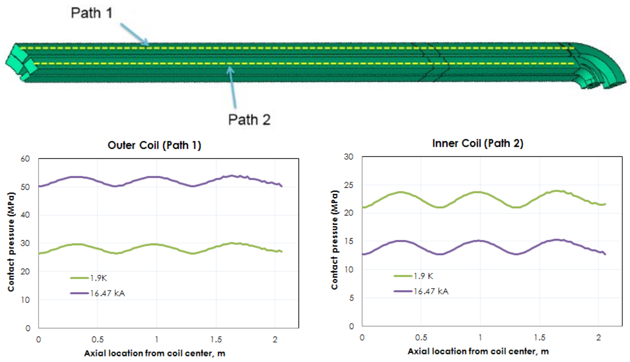

Figure 8: Contact pressure between outer layer of MQXFA coils and structure, at nominal current.

A completely different conclusion could be taken for the inner layer heaters: indeed, inner layer heaters are not pushed against any structure by magnetic forces. In this case, helium pressure in cracks, even though not trivial to compute, is expected to be considerably lower than the one on the outer layer surface. Inner layer heaters could be therefore considered even dangerous for the coil, and a deep analysis could be needed. However, inner layer heaters are not foreseen anymore for the protection of MQXF [11-12], therefore this analysis is not needed today.

IV. Conclusions

The test campaign of MQXFAP1 has been concluded after 18 quenches, due to a short to-ground event in coil QXFAP5. Previously, a short coil-to-heater had been found in the outer layer, low field region of the same coil, between quench 1 and 2. We have showed that, in case of multiple shorts between coil and quench heaters, a consistent current can flow through the short, and degrade the insulation, causing a short to ground. Instead, a single contact short can be considered not worrying, even though difficult to identify.

We have identified the mechanism that led to the short in MQXFAP1, that has been tested at high voltage after helium exposure. This procedure will not be repeated for future short models and tests.

We have shown that, however, this short event is not due to any weakness of the electrical design of the magnet: indeed, we showed that, in principle, coils can survive a quench even with a cut from the coil to the quench heaters, being just the helium gas the insulator.

The design of the magnet has therefore not been updated. The coil fabrication process has been kept unchanged, with the exception of adding a 25 μm layer of insulation between coil and structure just on the ends sections, in order to increase robustness of the insulation with coil parts. The test procedure for the series magnet has been revised, forbidding high voltage tests after helium exposure. The magnet design is considered electrically robust, and experience gained with MQXFAP1 will be useful to avoid mistakes in the future.

REFERENCES

[1] P.Ferracin, et al., "The HL-LHC Low-β Quadrupole Magnet MQXF: from Short Models to Long Prototypes", *IEEE Transactions on Applied Superconductivity*, presented at this conference.

[2] Joe Muratore, Reference for MQXFAP1 test results

[3] E. Ravaioli et al., "Quench protection of the first 4 m long prototype of the HL-LHC Nb3Sn quadrupole magnet", *IEEE Transactions on Applied Superconductivity*, presented at this conference.

[4] V. Marinozzi, "Analysis of MQXFAP1 Short-to-ground", Us-Hilumi-Doc-897, 2018.

[5] L. Bortot, et al., "STEAM: A hierarchical co-simulation framework for superconducting accelerator magnet circuit*", IEEE Transactions on Applied Superconductivity*, vol.28, n.3, 2018.

[6] E. Ravaioli, et al., "*Lumped-Element Dynamic Electro-Thermal model of a superconducting magnet*", Cryogenics, 2016.

[7] E. Ravaioli, "*Analysis of the short circuit in the MQXFAP1 magnet*", CERN-EDMS-2037314, 2018.

[8] P. Fessia, "*Guidelines for the insulation design and electrical test of superconducting accelerator magnets during design assembly and test phase*", CERN-EDMS-1264529, 2018.

[9] F. Menedez Camara, "*Electrical design criteria for the HL-LHC inner triplet magnets*", CERN-EDMS-1963398, 2018.

[10] V. Marinozzi, "*Failure Analysis of MQXF Heater-Coil Insulation*", Us-Hilumi-Doc-921, 2018.

[11] E. Ravaioli, "*Quench protection studies for the High luminosity LHC inner triplet circuit*" CER- EDMS- 1760496, 2017.

[12] E. Todesco "*HL-LHC: Decision Management WP3 – Protection of Q1/Q2/Q3 magnets*", CERN-EDMS-1972818, 2018.