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Analysis of the heater-to-coil insulation in MQXF coils

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VITTORIO MARINOZZI, GIORGIO AMBROSIO, MARIA BALDINI, STEVEN KRAVE, FRED NOBREGA — Fermilab, USA
PIYUSH JOSHI, JOSEPH MURATORE, JESSE SCHMALZLE — Brookhaven National Lab, USA
PAOLO FERRACIN, EMMANUELE RAVAIOLI, EZIO TODESCO, SUSANA IZQUIERDO BERMUDEZ — CERN, Switzerland

Abstract

In the framework of the HiLumi project, the present LHC low-β superconducting quadrupoles will be substituted with more performing ones, named MQXF. MQXF will have high peak-field on the conductor (~11.4 T), therefore the Nb_3Sn technology is needed in order to reach the target performance. One of the main technological challenges for the Nb_3Sn magnets is the coil fabrication: due to the brittleness of Nb_3Sn, coils needs to be impregnated with epoxy resin in order to improve mechanical properties and avoid conductor damage. MQXF magnets are using quench heaters impregnated with the coil in order to reach the required efficiency. Quench heaters are insulated from the coil by a 50 µm layer of polyimide and a 145 µm layer of S2 Glass® filled with Epoxy resin. The test of the first MQXFA prototype (with 4 m long coils) was interrupted due to a heater-to-coil short circuit caused by an Hipot test after helium exposure. Electrical testing procedures were revised, and a thorough analysis of the heater-to-coil insulation was performed.

MQXF QUENCH PROTECTION

The quench protection of MQXF is based on Outer Layer quench heaters and CLIQ (coupling Loss Induced Quench). The triplet is made of 6 magnets in series (four 4.2 m MQXFA magnets, two 7.15 m MQXFB magnets). Each magnet has a dedicated CLIQ unit [4] (40 mF, 600 V/ 1000 V for MQXFA/B). Each coil is protected by 4 heater strips on the outer layer (16 strips per magnet). 8 HFUs are provided per each magnet (7.05 mF, 900 V).

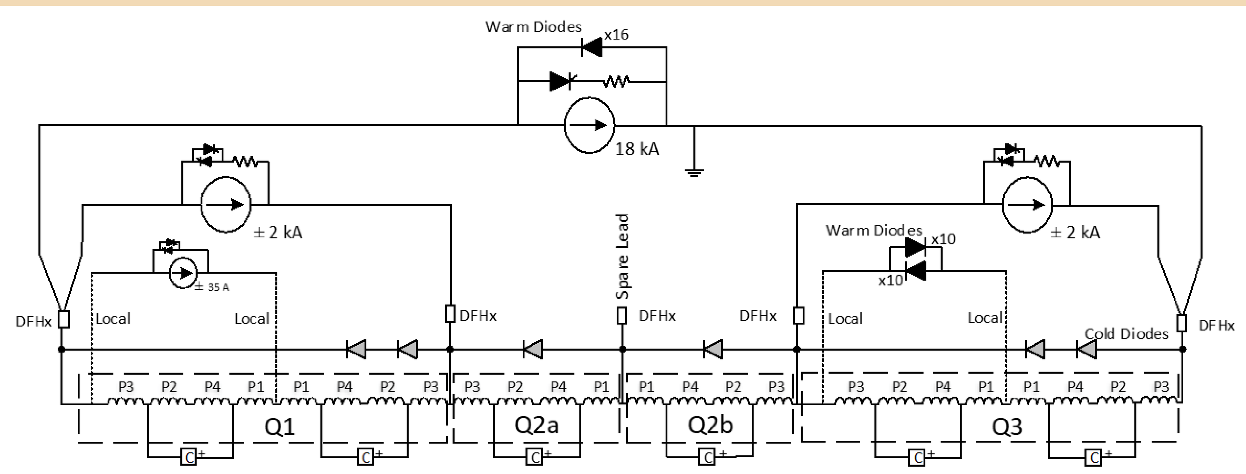

Fig. 1 Triplet quench protection circuit

TABLE 1 Main MQXF parameters

Material	Nb_3Sn
Aperture	150 mm
Peak Field	11.4 T
Nominal Current	16470 A
Length MQXFA/MQXFB	4.2 m / 7.15 m
Stored Energy	1.17 MJ/m
Inductance	8.21 mH/m

Fig. 2 MQXFA quench heater trace

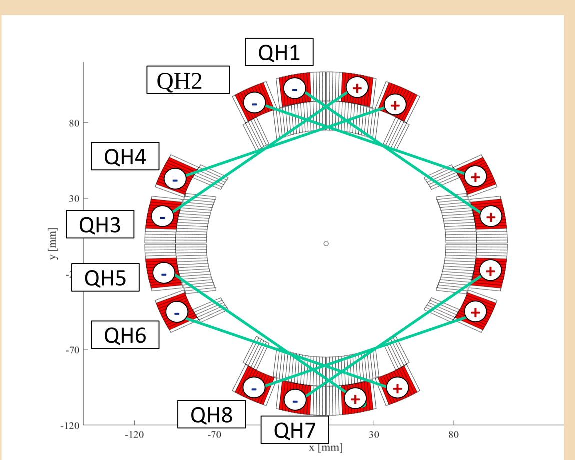

Fig. 3 Quench heater locations and connections

ELECTRICAL REQUIREMENTS AND QUALITY CONTROL

Electrical requirements are defined by the HiLumi Electrical Design Criteria [1], based on peak voltages expected during quench. Test values are reported in Table 2. All coils produced up to now passed all electrical QC tests after production.

TABLE 2 MQXF coil electrical QC levels

Component	V_test (1.9 K)	V_test (air, 300 K)	V_test (air, 300 K, after He)
Coil-Ground	1840 V	3680 V	368 V
Coil-Heater	2300 V	3680 V	460 V

MQXFAP1 FAILURE

First MQXFA prototype had a coil-ground failure during training (quench 18). The failure occurred in a coil which previously had a heater-coil short. The current flowing through the heater-coil short degraded the ground insulation. The heater-coil short was caused by a 2.5 kV heater-coil test performed after magnet had already been in superfluid helium. The threshold for this test is now set to 460 V by EDC, Table 2 (not available by AUP at the time of MQXFAP1 test).

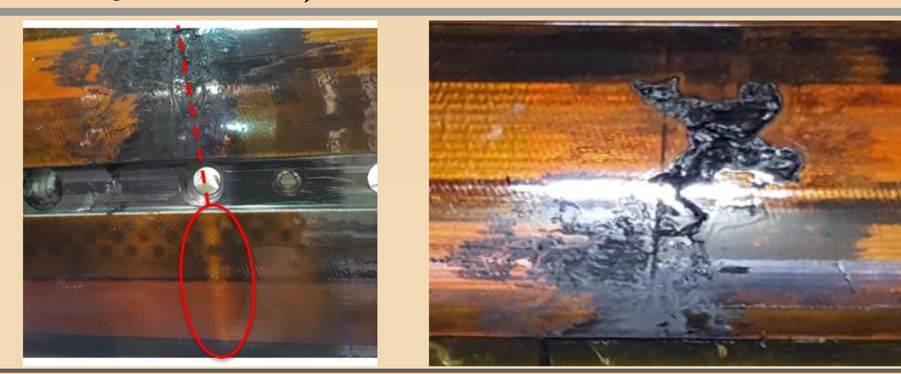

Fig. 4 Pictures of the short location in MQXFAP1

VOLTAGE FAILURE LEVELS IN MQXF COILS & MARGIN

The heater-coil insulation of several prototype and short MQXF magnets have been tested up to failure. Results were compared to the QC voltage after contact with helium (460 V according to EDC), in order to understand the electrical design margin. The result is that MQXF coils have a factor 3 margin (Fig. 5). Similar test made in helium (Fig. 6) can be compared with peak voltages expected during a quench (Fig. 8-9)

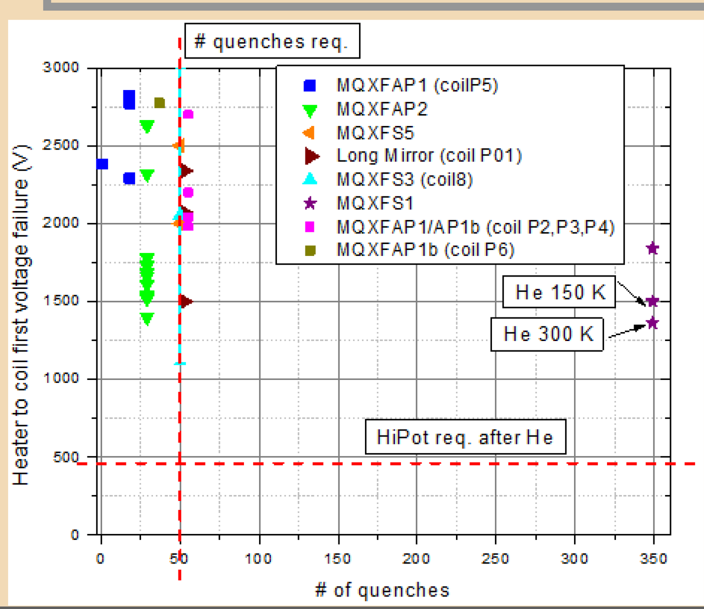

Fig. 5 Heater-coil insulation voltage in MQXF coils: first failures and requirement

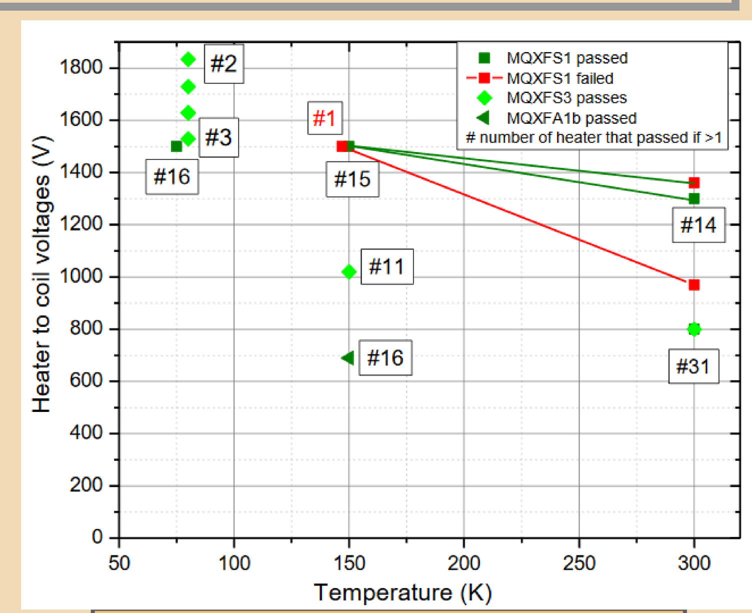

Fig. 6 Heater-Coil HiPot in He gas (1 bar) after magnet training

QXFP1 AUTOPSY

A 50 µm polyimide layer is expected to withstand up ~12 kV. The polyimide layer where heaters are photoetched has holes, used to allow epoxy flow during impregnation, which are set at a minimum distance of 4 mm from the heaters. If epoxy has multipole cracks during cooldown the minimum heater-coil distance is therefore ~4 mm. Helium at 1 bar and 300 K has 1 kV voltage breakdown for 4 mm distance (Fig 8). This threshold is consistent with the heater-coil voltage failures reported in Figure 5. Nonetheless autopsy was performed on QXFP1, first 4 m prototype coil for MQXFA, tested in a mirror structure. The autopsy showed that in failure zones there are bubbles on the polyimide layer under the heaters. These bubbles may have been formed by blistering caused by helium expansion in micro-voids of the impregnation during a quench. The bubbles reduce the thickness of the polyimide, and therefore also its dielectric properties.

Fig. 7 QXFP1 autopsy, and areas with reduced thickness of heater-coil polyimide insulation

PEAK VOLTAGES DURING A QUENCH

Heater-Coil voltages change significantly during a quench because of CLIQ oscillations and the development of inductive and resistive components. Figures 8 and 9 show the peak heater-coil voltages in MQXFA and MQXFB magnets at nominal current. The peak heater-coil voltage in MQXFA magnets (computed using STEAM-LEDET [2-3]) is ~ 350 V, and it is reached when coil temperature is ~ 100 K; in MQXFB magnets the peak heater-coil voltage is ~ 650 V, and it is reached when coil temperature is ~ 100 K. The difference is due to different magnet lengths (4.2 m and 7.15 m). Peak values are compared with the Polyimide and Helium breakdown voltages. The helium breakdown voltages are reported for a 0.2 mm path, that is the minimum distance between heaters and coil in case of complete polyimide failure, and for a 4 mm path, that is the minimum distance between the heater and the holes in the polyimide (Fig. 2). During a quench helium may act as insulator, since its pressure grows with the increasing temperature (in isochoric expansion, helium should reach 530 bar at 100 K), and provide enough insulation to prevent a heater-coil discharge also in case of complete polyimide failure [4-5]. An option to increase the electrical robustness of the design is to increase the heater-coil insulation. However, in this case hot-spot temperature will exceed the 350 K threshold in case of CLIQ failures (Fig. 10), increasing the risk of damaging a magnet during a quench. The choice of increasing electrical insulation should be made only if strictly needed.

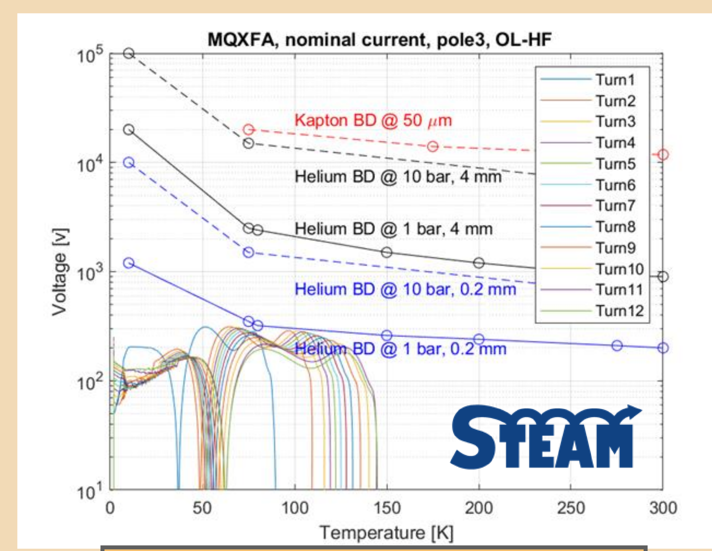

Fig. 8 Peak heater-coil voltages in MQXFA

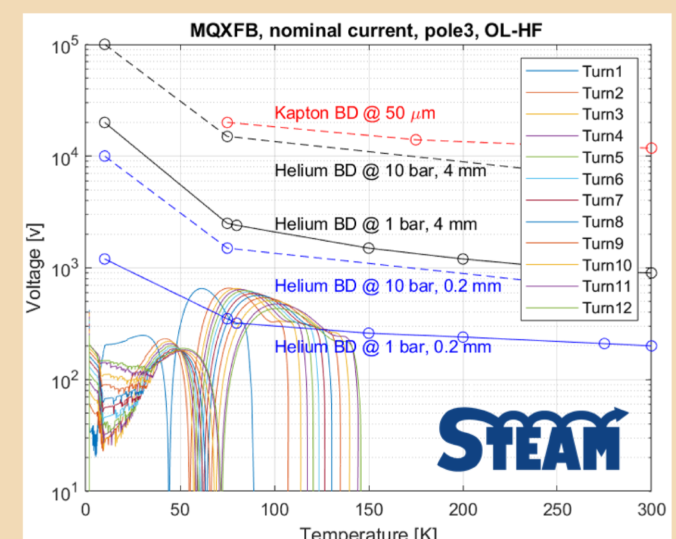

Fig. 9 Peak heater-coil voltages in MQXFB

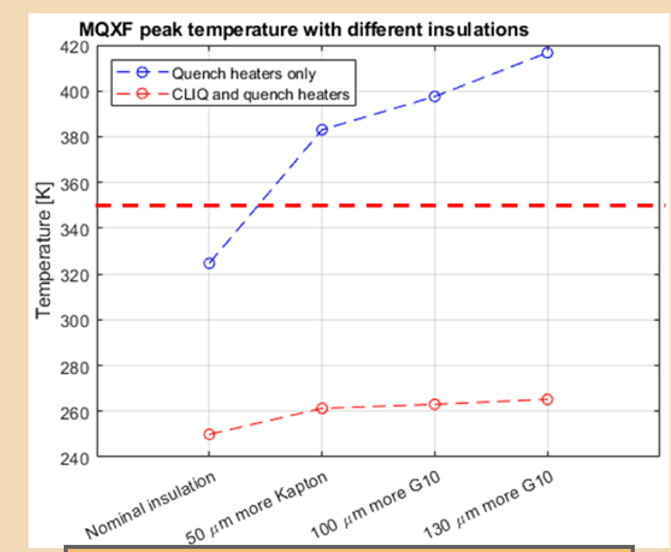

Fig. 10 Effect of alternative design on quench protection

CONCLUSIONS

This poster presents the analysis of MQXF Heater-Coil insulation.

A coil-to-ground short occurred during the test of the first MQXFA prototype is explained by a heater-coil high-voltage test (2.5 kV) performed after coils were exposed to helium. The HL-LHC Electrical Design Criteria [1] set a threshold of 460 V after helium exposure, which will prevent similar issue.

All coils fabricated so far passed all heater-coil QC tests showing no issue after manufacturing.

Test to failure of 106 MQXF heaters after cold magnet test showed heater-coil failures above 1.5 kV (Fig. 5). This threshold is three times above the requirement (460 V, Table 2) and is consistent with the holes in the polyimide for epoxy flow during impregnation.

Coil autopsy showed that after cold test there may be polyimide thickness reduction in some locations on top of micro-bubbles in the epoxy between turns. The dielectric strength of the polyimide may be reduced by this phenomenon. Nonetheless tests performed in He gas (Fig. 6) have shown sufficient margin with respect to expected peak heater-coil voltages during quench. On top of this margin there is the additional margin provided by the large pressure increase of helium during quench, which is going to increase the dielectric strength of helium trapped in epoxy bubbles/cracks.

Any increase of heater-coil insulation is going to cause hot-spot temperatures above 350 K in case of CLIQ failure.

Therefore the present design of MQXF heaters is a reasonable compromise and an acceptable solution for MQXF magnets.

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