# Assessment of MQXF Quench Heater Insulation Strength and Test of Modified Design

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*Abstract-* **The HL-LHC interaction region magnet triplets (Q1, Q2, and Q3) will be composed of superconducting $Nb_3Sn$ quadrupoles. The MQXF quadrupole protection system is based on CLIQ (Coupling-Loss Induced Quench system) and outer layer quench heaters. This paper reports a summary of quench heaters to coil high voltage tests performed on MQXF short and long coils in air after fabrication, and in air and He gas after magnet training. Breakdown voltage values demonstrate good margin with respect to the Electrical design criteria for the HL-LHC inner triplet magnets. A modification in the quench heater installation- with an extra layer of fiber glass between the coil and the quench heater trace- has been proposed and tested in a mirror magnet to further increase electrical margins. Results demonstrated improvements of high voltage margin at the expense of a clear increase of hot spot temperature. The baseline heater to coil insulation was assessed to be able to guarantee safe operation for the $Nb_3Sn$ quadrupole magnets for the interaction regions of HL-LHC.**

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

## I. Introduction

THE US HL-LHC Accelerator Upgrade (US HL-LHC AUP) project and CERN are fabricating superconducting quadrupole magnets for the interaction regions of the High Luminosity Large Hadron Collider (HL-LHC). The HL-LHC interaction region magnet triplet consists of three optical elements: Q1, Q2, and Q3. Q1/Q3 cold masses contain two 4.2 m quadrupole magnets (MQXFA) whereas Q2a and Q2b consist of a single unit MQXFB ~7.5-m-long quadrupole magnet and high order multiple corrector magnets [1]. The $Nb_3Sn$ quadrupole magnets operate in superfluid He at 1.9 K with a nominal field gradient of 132.2 T/m. The MQXF quadrupole protection system is based on CLIQ and outer layer quench heaters [2].

The quench heaters are made of stainless-steel strips with copper plated section to lower the resistance between the heating stations (trace) [3-6]. The heating stations consist of 25 µm thick resistive layer of 316L stainless steel. The quench heater trace is photoetched on a layer of 50 µm thick polyimide and 10 µm thick glue. The trace design is shown in Fig. 1. The quench heater is embedded in the coil before epoxy impregnation. The $Nb_3Sn$ cable insulation is a 145 µm braided S2-fiber glass that generates a layer of G11 when impregnated with epoxy. This makes the heater to coil distance 200 µm [3]. An extra layer of 50 µm polyimide between coil and heaters is added at the ends of MQXFA and MQXFB coils [5]. Each polyimide layer is expected to withstand more than 10 kV

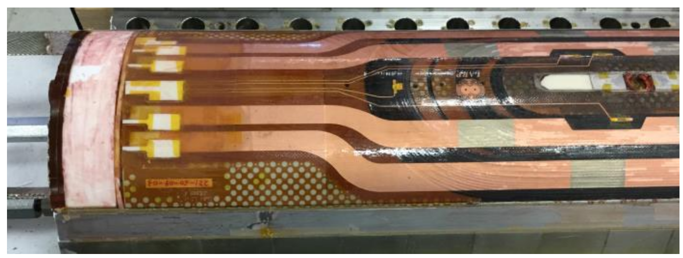

Fig.1: MQXFA coil with epoxy impregnated quench heater trace.

Holes are added to the polyimide to facilitate epoxy impregnation. The minimum distance of those holes from the heaters is 4 mm in the short MQXFS magnet [5], 5 mm and 10 mm in the MQXFA and MQXFB magnets respectively.

The presence of epoxy bubbles represents a potential weakness and has driven the investigation of the quench heater insulation strength. This paper reports the results of such investigation. The manuscript presents a summary of quench heaters to coil high voltage tests performed on MQXF short and long coils in air after fabrication, and in air and He gas after magnet training.

The specifications of the coil to quench heater insulation are given in Table I. In this paper we will review the data relative to the short model phase, and the prototype and pre-series long coils, showing how these specifications are met for the numerous statistics of manufactured coils (hundreds of heater strips tested). We then discuss how to assess the margin over the requirements with destructive tests on few selected cases. Finally, we consider a modification of the heater layout to further increase electrical margin. This modification has been

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implemented in a short coil and, tested in a mirror magnet configuration.

## II. High Voltage Tests in MQXF Magnets

TABLE I
COIL-QUENCH HEATER HIGH VOLTAGE TEST LEVELS

| Electrical component | HV at 300 K before He | HV at 1.9 K in LHe | HV at 300 K after He | HV at 100 K in GHe gas at 1.2 bar after He |
|---|---|---|---|---|
| Coil-heater | 3.7 kV | 2.3 kV | 460 V | 850 V (MQXFB) 425 V (MQXFA) |

### A. MQXF Electrical Design Criteria

The voltage withstand levels for each component of MQXF magnets are described in [7]. Quench heater insulation strength is tested with a coil-to-heater high voltage test that is performed over four stages, see Table I.

Coil to heater high voltage tests are performed in air at 300 K after coil fabrication, in liquid He at 1.9 K and again at 300 K after He exposure. A very conservative test at 100 K in 1.2 bar He gas was added in 2019 to assure margin after training and thermal cycle and it is further discussed in detail in section II B. The voltage test levels are defined from simulations of peak voltages to ground for MQXFA and MQXFB. Those voltage values have been calculated considering the failure of two quench heaters at nominal and ultimate current plus margins (16.5 kA and 17.8 kA respectively) [7]. The worst cases were found at 100 K at 353 V for MQXFA and 657 V for MQXFB [8, 9]. More details about high voltage test levels determination can be found in Ref. [7].

### B. High voltage test data

In this section, a summary of the high voltage tests is discussed. A detailed report of all the high voltage test data collected so far on MQXF magnets can be found in Ref. [10].

Up to September 2020, 33 MQXFS short model, 27 MQXFA and 24 MQXFB coils have gone through high voltage tests in air at 300 K after fabrication. This means that 336 heater strips have undergone high voltage tests. Only one of the heaters of coil 114 of MQXFB failed the test due to a heater to coil short. This coil is not going to be assembled in any magnet. It is also important to point out that the test voltage level was officially determined by US-AUP and CERN in 2018 and voltage tests performed before this date had been done to lower voltage levels.

Among those fabricated coils, 41 have been assembled in magnets and tested at 1.9 K. In Tab. 2 a list of the short and long magnets is displayed together with the number of quenches and thermal cycles [10]. Short models have seen up to 350 quenches and 8 thermal cycles. MQXFA magnets have seen up to 50 quenches and three thermal cycles.

This means that 157 strips have experienced cooldown, powering and quenches. All of them have successfully passed the high voltage test in liquid He at 1.9 K and the one at 460 V in air at room temperature after training (see Tab.1), demonstrating that the quench heater baseline design meets electrical specifications.

A destructive test was then carried out on 109 heater strips at ambient temperature after training and He exposure. Those hi-pot tests to failure were performed on several short and long MQXF magnets. In Fig. 2 the first heater to coil voltage failure is shown as a function of the number of quenches sustained by the magnet prior hi-pot testing.

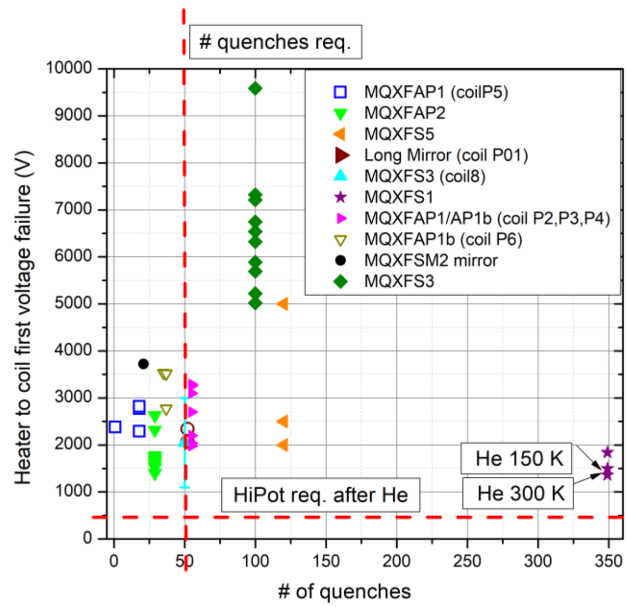


Fig.2: Heater to Coil first voltage failure in air at 300 K after cold test. The dashed lines identify the number of quenches that correspond to a magnet life time based on MQXFA Functional Requirement Specification [8] and the High voltage test requirement after He reported in the MQXFA electrical design criteria [9]

Out of 109 strips tested, 100% successfully reached ≥ 1.4 kV demonstrating a factor of 3 margin and 74% went up to 3 kV. Autopsy of coils was performed after the hi-pot destructive test. Failures were all located where blistering of polyimide was observed. This mechanism can be described as a thinning of the

TABLE 2
MQXF SHORT AND LONG MAGNETS

| | SHORT MIRROR MQXFSM2 | MQXFS1 US-AUP | MQXFS3 CERN | MQXFS4 CERN | MQXFS5 CERN | MQXFS6 CERN | MQXFAP1/b US-AUP | MQXFAP2 US-AUP | MQXFA03 US-AUP | MQXFA04 US-AUP | MQXFBP1 CERN | LONG MIRROR US-AUP |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| # of quenches | 21 | 349 | 100 | 160 | 120 | 25/60 | 18/37 | 29 | 9 | 8 | 21 | 52 |
| # of thermo-cycles | 3 | 8 | 5 | 8 | 3 | 4 | 4 | 1 | 2 | 1 | 1 | 1 |

polyimide insulating layer due to the rapid expansion of helium gas trapped in epoxy bubbles during a quench. More details about coil autopsy and blistering can be find in Ref [11].

Long term behavior was also investigated with those tests. Voltage breakdown values are found to be similar for magnets after hundreds or dozens of quenches. Indeed, the first heater to coil failure in MQXFS1 magnet, where 350 quenches and 8 thermal cycles took place, displays the same level of margin. The first failure was observed in He gas at 1.5 kV at 150 K, and at 1.36 kV at 300 K. Those tests were performed in He gas and are more conservative than those performed in air. No failures at requirement levels (460 V) are observed in MQXFS4 after 8 thermal cycles and 1000 power cycles. Those results show that the baseline quench heater insulation provides long term reliability.

As mentioned in section IA, the higher values of heater to coil voltages are expected during operation at 100 K, at 353 V for MQXFA and 657 V for MQXFB [8, 9]. Based on those computational data, a high voltage test in He gas at 100 K was introduced to guarantee margin after training and thermal cycles and to assure that no breaching of polyimide is present in the MQXF magnets. The voltage level has been fixed to 450 V for MQXFA and to 850 V for MQXFB.

All magnets passed this additional test since its introduction [10]. A total of 94 heater strips have been successfully tested: high voltage tests were performed on MQXFS4 up to 850 V. MQXFS4 passed the test after each cooldown and after 1000 current cycles; MQXFS6 passed the 850 V test at 100 K after three cooldowns; the first MQXFAP1 prototype successfully reached 800 V at 150 K; MQXFA03 and MQXFA04 were hipotted to requirements levels (425 V at 100 K) with no issues and the first CERN prototype MQXFBP1 successfully reached 850 V.

The analysis of the failure of the insulation has shown that in case of polyimide breaching the increase of gaseous He pressure at quench provides additional margin [11, 12]. Since the high voltage test is performed at 1 bar there is an additional margin provided by the pressure of the GHe.

### C. *Design modifications*

Two modifications of the quench heater insulation were taken into consideration to reduce risks that some of the coils may fail the 100 K test in He gas. Those alternative solutions have been developed by CERN and by US-AUP respectively. A short MQXFS7 magnet with non-impregnated quench heaters is being assembled at CERN and will be tested at 1.9 K by the end of 2020.

A second modification was developed and tested by US-AUP. The main idea was to swap one of the two layers of fiber glass which sit by design [3] between the coil and the structure and to add it between the heater and the coil. Swapping a fresh (i.e. not exposed to coil heat treatment) layer of fiber glass from above to below the heater does not introduce any significant deviation to the coil fabrication process and, contrary to the non-impregnated heaters, to magnet assembly. The heater to coil distance was thus extended by 100 µm, increasing the breakdown voltage. The added extra layer of G11 separating the epoxy bubbles from the polyimide should help to prevent the blistering mechanism. A short coil (S10) was fabricated according to this procedure, was assembled in a short mirror magnet MQXFSM2 and tested at 1.9 K at the vertical magnet test facility [13] of the Applied Physics and Superconducting Technology Division at FNAL.

## III. MQXFSM2 MIRROR MAGNET TEST AND ANALYSIS

The MQXFM2 mirror magnet reached 17890 A in 15 training quenches. It was able to hold 18 kA with no quench both at 1.9 K and at 4.5 K. Quench heater delay studies were performed to estimate the increase of the hot spot temperature due to the extra 100 µm layer of insulation thickness. Minimum power density studies were also performed to assure that the magnet could be protected at low current (2000-6000 A) when CLIQ is not efficient. Finally, heater to coil high voltage tests were carried out at selected temperature and voltage values to verify electrical requirements and evaluate margins. In Fig. 3, the current dependence of measured time delays is shown.

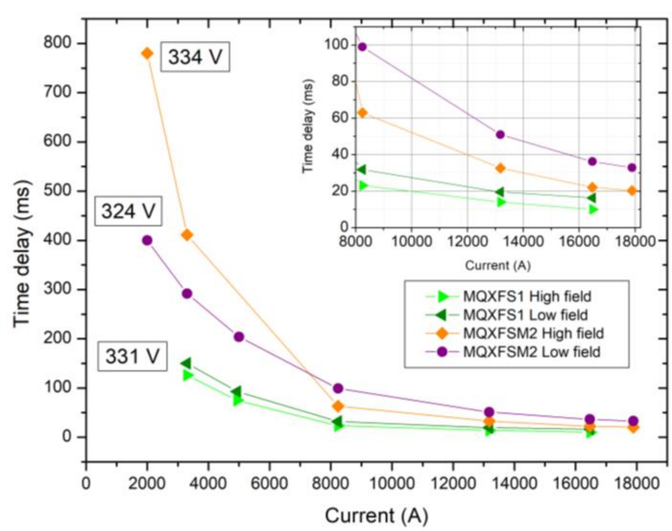


Fig. 3.Current dependence of time delays for MQXFSM2 mirror magnet and MQXFS1 short magnet. High field data are collected from a quench heater circuit that consists of the two pole strips connected in series whereas low field circuit is made by the two midplane strips in series. Heater firing unit voltage values used during the test are also displayed.

The MQXFSM2 time delay data were compared with those collected for the first short model MQXFS1. High field and low field quench heater circuits consisted of the two pole and midplane heaters connected in series, respectively. Time delays were found to increase by a factor of 2 at high current (see inset of Fig.3) as it was expected by adding an extra layer of insulation.

The relative hot spot temperature difference given by adding 100 um of fiber glass between the heater and the coil was computed using STEAM-LEDET for several current levels [14]. The entire conductor block below the quench heater was assumed to quench and no failures of the quench protection system were considered in the simulations. Time delays obtained from the MQXFSM2 and MQXFS1 cold tests were used and detection times and quench propagation velocities were calculated with QLASA [15], using the quench detection voltage thresholds employed for the MQXFA vertical test at BNL. The relative temperature difference was added up to the hot spot temperature calculated using default conductor parameters and several protection systems. The worst-case scenario corresponds to a CLIQ failure, where the hot spot temperature is found to be around 360 K at 17890 A [16]. The modification tested in the mirror magnet results in a 76 K increase of the hot spot temperature in case of CLIQ failure (up to 450 K). The safe limit for the hot spot temperature value was established at around 360 K [17].

Hi-pot tests in He gas were carried out up to 2.0 kV at 100, 150, 200 and 300 K. Results are discussed in section IV where a throughout discussion on margin for the test in He gas is reported.

High voltage tests were also carried out up to 6 kV in air at 300 K after Helium exposure. One failure was observed in one of the heater strips at 3.7 kV whereas the remaining strips reached successfully 6 kV. It is worth mentioning that the breakdown voltage value is higher than the one used to assess the insulation strength after fabrication (3.68 kV). Visual inspection and autopsy confirm that the addition of an extra layer of insulation reduces blistering but does not fully eliminate the phenomenon. The autopsy confirmed that the high voltage test failure location coincided with the presence of a polyimide blister.

## IV. HIGH VOLTAGE TEST IN HELIUM GAS AT 100 K

Destructive tests were performed to investigate margin for the hi-pot at 100 K in helium gas [10]. Results are displayed in Fig.4 where high voltage data collected from several short and long model are reported.

Symbols in Fig. 4 refer to magnets that have successfully passed the high voltage tests. The few observed failures are represented by empty diamond symbols. The number of tested heater strips is also indicated for each magnet. Filled star symbols refer to the data collected from the mirror magnet. The temperature dependence of the He breakdown voltage for a 4 mm distance is also displayed (filled circles line).

The destructive test was performed on the short MQXFS1 magnet after 350 quenches and 8 thermal cycles. The first failure was observed at 1.5 kV at 150 K. The same strip experienced a second failure at lower voltage 970 V at 300 K. The observed breakdown values are compatible with He breakdown voltage for a path of 4 mm (heater to hole distance for short model traces) [18, 19]. A second strip was found to fail at 1.36 kV at 300 K. This test showed a factor of 4.2 and of 2.3 margin with respect to MQXFA and MQXFB peak voltages. Significant additional margin is provided by the increase of the He pressure due to quenching and by the 50 K reduction of He temperature at peak voltages (100 K) [12]. All the MQXFSM2 heater strips successfully reached 2 kV at each temperature levels, showing a larger margin with respect to the baseline.

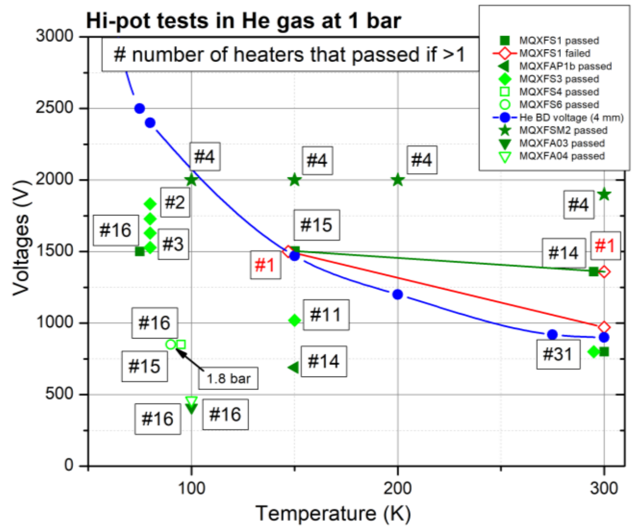


Fig. 4. Heater to coil voltage values for tests performed in He gas at selected temperature. The He breakdown curve for a 4 mm distance is shown (blue circles line) [12]. Red dots correspond to a high voltage test failure.

## V. CONCLUSION

The strength of the heater to coil insulation was assessed for MQXF magnets. The baseline quench heater design meets all specifications listed in the HL-LHC IT Electrical Design Criteria, including the new additional test performed at 100 K in helium gas. Failures observed above requirements were ascribed to the presence of blistering of polyimide. Degradation of the insulation strength due to a large number of quenches (after first few quenches), thermal cycles and powering has been excluded thanks to the high voltage tests made on short model magnets.

High voltage tests margin was explored with destructive tests: the first failure is at 1.4 kV demonstrating a factor of 3 margin for hi-pot at 300 K in air. The first breakdown in He gas is at 1.5 kV at 150 K which indicates a factor of 4.2 for MQXFA and 2.3 margin for MQXFB.

A modification of the quench heater layout has been investigated and tested in coil S10 assembled in the MQXFSM2 mirror magnet. This solution shows an increased margin, as expected. Due to the limited statistic (only one short coil was tested) it is difficult to quantify the gain in the margin of the voltage tests: for the available case it is order of a factor 8.0 at room temperature with respect to the high voltage test value of 460 V (the first failure at room temperature is observed at 3.7 kV instead of 1.4 kV).

However, the insulation improvement due to the presence of a 100 µm extra layer of insulation between the coil and the heater does not appear to be worth the hot spot temperature increase (up to 450 K) that is expected in failure modes. For this reason, the present baseline is kept in the production of the MQXF coils.

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