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Quench Protection Study of the Updated MQXF for the LHC Luminosity Upgrade (HiLumi LHC).

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***Abstract*— In 2023, the LHC luminosity will be increased, aiming at reaching 3000 fb-1 integrated over 10 years. In order to obtain this target, new Nb3Sn low-β quadrupoles (MQXF) have been designed for the interaction regions. These magnets present a very large aperture (150 mm, to be compared with the 70 mm of the present NbTi quadrupoles), and a very large stored energy density (120 MJ/m^3). For these reasons, quench protection is one of the most challenging aspects of the design of these magnets. In fact, protection studies of a previous design showed that the simulated hot spot temperature was very close to the maximum allowed limit of 350 K; this challenge motivated improvements in the current discharge modeling, taking into account the so-called dynamic effects on the apparent magnet inductance. Moreover, quench heaters design has been studied going into more details. In this paper, a protection study of the updated MQXF is presented, benefitting from the experience gained by studying the previous design. A study of the voltages between turns in the magnet is also presented during both normal operation and most important failure scenarios.**

***Index Terms* — Niobium compounds, quench protection, superconducting accelerators.**

I. INTRODUCTION

THE Large Hadron Collider (LHC) in 2010-2013 has produced collisions between proton beams with up to 4 TeV energy per beam. Now, LHC is producing collisions at 6.5 TeV per beam, and it will run until 2023. It is expected that in 2023 the integrated luminosity of 300 fb^{-1} will be reached; beyond this value, running the machine will not lead to significant statistical advantage, maintaining the present peak luminosity of 1.5-2×10^{34} cm^{-2}s^{-1}. Then, a luminosity upgrade program, named High Luminosity LHC (HL-LHC), has been planned, aiming at reaching 3000 fb^{-1} in 10 years after 2025. The main action will be reducing the beam size, and this can be achieved with more performing magnets in the interaction regions. In particular, the present low-β triplet NbTi superconducting quadrupoles are planned to be substituted with new Nb$_3$Sn magnets, called MQXF. It is one of the first Nb$_3$Sn superconducting magnets designed in order to be inserted in a particle accelerator, and many challenges have been faced.

The quench protection of MQXF has been one of the most challenging aspects in the design, because of the large magnetic energy stored into the coils (~0.12 J/mm^3, a factor 2 larger than in the present NbTi LHC low-β quadrupoles), and of the high magnetic field (~12 T) needed for the beams focusing. In fact, the first quench protection studies showed that the magnet safety could not be ensured, because the hot spot temperature was very close, or even larger than the maximum allowed of 350 K [1]. For this reason, new protection studies have been carried on, improving the quench heaters design, and studying with more detail the behaviour of the current decay, adding the simulation of dynamic effects on the magnet inductance, due to the coupling currents between the filaments. This study led to better results, showing that the magnet protection was possible [2].

Nevertheless, in the last year, the main magnet operation parameters have been upgraded, for example reducing the current and the cable dimensions, and some uncertain parameters have been established. The upgraded parameters are reported in Table I.

TABLE I MAIN PARAMETERS OF MQXF

Aperture diameter	150 mm
Gradient	132.6 T/m
Nominal current	16470 A
Magnetic stored energy	1.17 MJ/m
Inductance	8.3 mH/m
Magnetic length (Q1/Q3)	2 x 4.2 m
Magnetic length (Q2a/Q2b)	7.15 m
Conductor peak field	11.4 T
Operating temperature	1.9 K
Strand diameter	0.850 mm
Bare cable width	17.86 mm
Bare cable thin/thick edge thickness	1.462/1.588 mm
Insulation thickness	0.145 mm
Number of strands	40
Cu/Sc	1.2
Copper RRR	100

Moreover, the option of protecting the whole triplet with a single protection system is under discussion. The triplet is constituted by four cold masses (Q1, Q2a, Q2b and Q3), and until now one protection circuit for Q1/Q3 and another one for Q2a/Q2b were foreseen. The option of Q1, Q2a, Q2b and Q3 in series could reduce costs, because only one power supply and just one dump resistor could be needed instead of two.

In this paper, the protection study of the upgraded version of MQXF is discussed. The analysis of the hot spot temperature is showed together with the analysis of the peak voltages during a quench. Nominal cases are analysed and compared to some quench heaters failure scenarios.

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Also, the option of protecting the triplet with a single protection circuit is compared to the nominal case of two circuits. The option of protecting MQXF using CLIQ [3] is not discussed in this paper; nevertheless, it is a solution under discussion [4]. CLIQ is a novel passive method for the quench protection, which take advantage of coupling currents in order to induce the quench in the whole magnet.

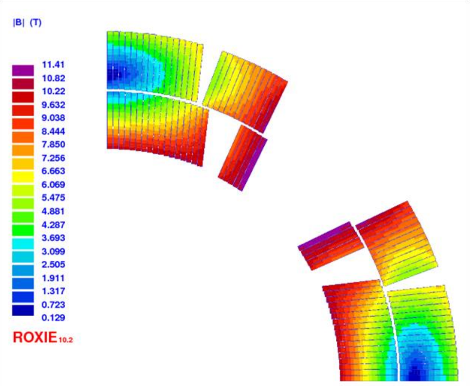

Fig. 1. One quadrant cross section of MQXF with magnetic field map.

II. Quench Heaters Design

MQXF stores very high magnetic energy at operation current (see Table 1). Moreover, it is a long magnet (magnetic length of Q1 and Q3 is 2x4.2 m, Q2a and Q2b 7.15 m), therefore it has a large inductance. For these reasons, it is impossible to protect it using just a dump resistor, which is limited by the maximum voltage across the coil ends, and efficient quench heaters are needed. Previous studies [1] showed that heaters only on the outer layer are insufficient to assure magnet safety, therefore various designs for the inner layer heaters have been proposed. The heater designs used for the protection analysis showed in this paper are described below.

A. *Outer layer quench heaters*

The outer layer protection heaters are constituted of a set of simple straight strips that span along the coil and across each (pole and mid-plane) winding block. There are stainless steel heating stations, which have a width of 40 mm and are separated by 120mm long copper-plated bridges. The design layout is showed in Fig. 2.

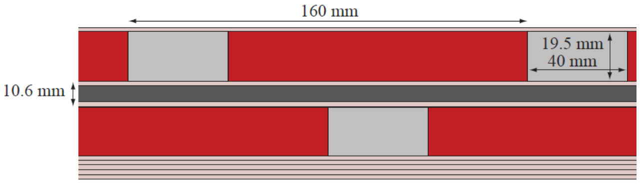

Fig. 2. Design of the MQXF outer layer protection heaters.

B. *Inner layer quench heaters*

The inner layer protection heaters are constituted of copper-plated narrow bridges, which connect wide stainless steel heating stations. This design is optimized in order to avoid as much as possible the helium bubbles issue [5]: the magnet inner layer is in direct contact with super-fluid helium, which could penetrate between the heaters strips and the coils; during a quench, the helium evaporates, and it generates bubbles, which reduces the thermal contact between the heater and the coil surface, reducing the heater efficiency. The design with narrow bridges should allow for more spacing for perforations, which should help the helium gas to evacuate the coil. The "snake" shape allows covering both the mid-plane and the pole blocks. This design is showed in Fig. 3.

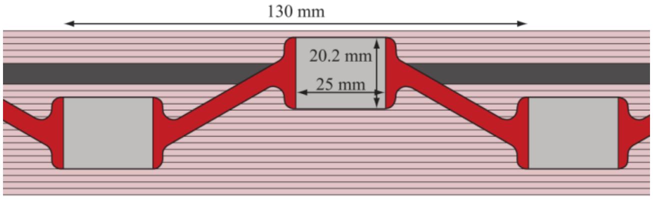

Fig. 3. Design of the MQXF inner layer protection heaters.

C. *Protection heaters delay time*

The protection heaters efficiency is related to how fast they can induce quench within the coils after being fired. The delay time depends on the firing voltage, and on the thickness of the insulation (typically kapton) between the heaters strips and the coils surface, which is 50 µm in the case of MQXF. The heaters delay time from firing to induced quench are used in this protection study are showed in Fig. 4. The values are computed using CoHDA [6]. For each layer, two average values are reported: one is related to the high magnetic field (HF) zone (pole block), one is related to the low magnetic field (LF) zone (mid-plane block).

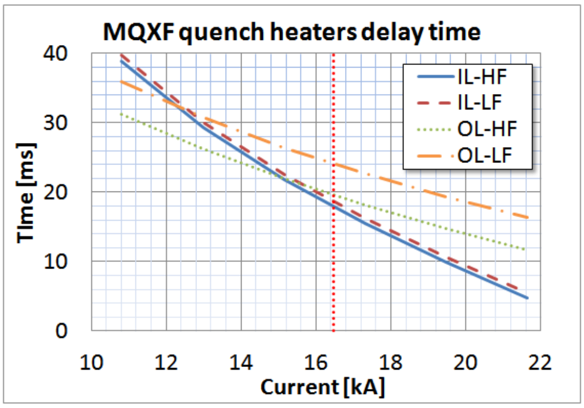

Fig. 4. MQXF quench heaters delay time as a function of the magnet current. The solid curve shows the inner layer high-field delay time, the dashed curve shows the inner layer low-field delay time, the pointed curve shows the outer layer high-field delay time, the dashed-pointed curve shows the outer layer low-field delay time. The operational values are on the pointed vertical line.

III. Hot Spot Temperature

The hot spot temperature calculation is very important in order to ensure the magnet safety. In fact, during a quench, the temperature of the first resistive zone should not exceed 350 K [7]. This limit temperature has been established observing experimentally that, below it, there is not permanent degradation in superconducting magnets. Actually, the hot spot temperature could theoretically reach 420 K, beyond which the epoxy impregnation starts to melt; nevertheless, a further 70 K temperature margin in simulations allows taking into account uncertainties on the protection parameters or material properties.

The hot spot temperature is strongly related to the current decay. Assuming adiabatic conditions the energy per volume unit dissipated by the resistive zone is absorbed by the heat capacity:

$$\varrho J^2 dt = \gamma C_p dT \qquad (1)$$

where ϱ is the resistivity, J the current density, γ the cable density and C_p the specific heat. From the eq. (1), it is possible to relate the current time integral to a quantity

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which depends only on the conductor material properties, called $MIITs$:

$$MIITs(T) = \int_0^\infty I^2 dt = \frac{A^2}{10^6}\int_{T_0}^{T} \frac{\gamma C_p(T)}{\varrho(B,T,RRR)} dT \qquad (2)$$

where A is the cross section area, and T_0 is the magnet operating temperature. This means that, knowing the conductor dimensions and materials, it is possible to calculate the hot spot temperature simulating and integrating the current decay; then, the hot spot temperature is given by the $MIITs$ vs T curve. Note that the $MIITs$ depend on the copper RRR and on the magnetic field where the quench starts, because of the copper magneto-resistivity, which is very effective at low temperatures.

The MQXF conductor parameters can be found in Table 1, and the conductor $MIITs$ calculated at the peak field, considering the cable insulation, are showed in Fig. 5.

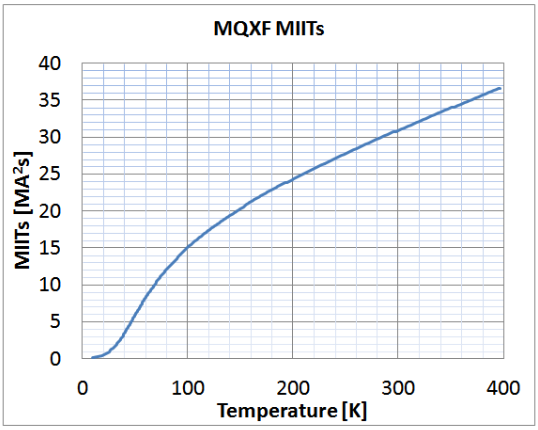

Fig. 5. $MIITs$ vs T curve of the MQXF conductor at peak field (11.4 T).

The material properties used for the calculation are from the MATPRO [8] database. It's easy to see that the limit of 350 K corresponds to ~34 $MIITs$.

The simulations of the current decays have been performed using QLASA [9]. It is a program born for quench simulation in solenoids, but it can be used for accelerator magnets such as quadrupoles with some precautions [10]. The protection parameters used for the simulations are reported in Table II. The main assumptions made are listed below:

- the initial quench is a point (initial size equal to 0) located in the peak field zone (pole turn);
- the detection time is computed according to the propagation velocities computed by QLASA, which are based on the Wilson model [11]. It results to be ~7 ms in order to reach the 100 mV threshold at nominal current;
- the quench heaters delay times are showed in Fig. 4. It is assumed that the quench is induced at a different average time in the high-field and in the low-field blocks of each layer. The quench has null radial dimensions, and it is induced only in the turns actually covered by quench heaters. The heating stations are simulated, but pre-heat from the copper-bridges is not considered (conservative assumption). The induced quench propagates in the radial, azimuthal and longitudinal directions according to the propagation velocities computed by QLASA;
- heat exchange between layers is neglected;
- dynamic effects on the magnet inductance due to the inter-filament coupling currents are taken into account. These effects have been experimentally observed in the HiLumi experience [1-2]. More details on the electromagnetic model developed and implemented in QLASA can be found in [12];
- quench-back is neglected (conservative assumption).

TABLE II MQXF PROTECTION PARAMETERS

Dump resistor (maximum voltage between ends)	46 mΩ (800 V)
Voltage threshold	100 mV
Validation time	10 ms
Switch opening delay time after validation	5 ms

The hot spot temperature results are reported in Table III and Table IV. The simulations compare two possible scenarios: in the "1PS" scenario all the triplet magnets are protected in series by one dump resistor and powered by one power supply; in this situation, the total magnetic length is 31.1 m. In the "2PS" scenario Q1 and Q3 are powered and protected separately from Q2a and Q2b;

TABLE III MQXF HOT SPOT TEMPERATURE / 1PS SCENARIO

Nominal	No IL-QH	Fail OL-QH HF
28.3 MA^{2}s	33.6 MA^{2}s	30.7 MA^{2}s
261 K	346 K	299 K

TABLE IV MQXF HOT SPOT TEMPERATURE / 2PS SCENARIO

Nominal	No IL-QH	Fail OL-QH HF
28.1 MA^{2}s	33.3 MA^{2}s	30.5 MA^{2}s
257 K	341 K	295 K

For each scenario three columns are reported: the first column ("Nominal") shows the hot spot temperature obtained if the protection system (inner and outer quench heaters plus dump resistor) performs as expected; the second column ("No IL-QH") shows the hot spot temperature obtained if there are not Inner Layer Quench Heaters; the last column ("Fail OL-QH HF) shows the hot spot temperature obtained in an unlikely failure scenario, where all the quench heaters of the high-field (pole) blocks do not work, which means that the magnets resistance is ~30 % less than in the nominal case.

Analyzing the results, the first conclusion is that, in the nominal case, the protection of the magnets is ensured; in fact the temperature is well below the limit of 350 K. Then, it is evident that quench heaters on the inner layer are needed in order to ensure protection. A good redundancy is ensured, because removing ~30 % of the magnets resistance gives a temperature of ~300 K, 50 K less than the maximum limit, and this is a very unlikely event. Finally, comparing the results with one or two power supplies, it's easy to note that the two scenarios are very similar. In fact, in both the scenarios the starting decay time constants $\tau = L/R_d$ are high (τ = 2 - 4 s for 2 PS - 1 PS, the total decay time is ~300 ms), therefore the current is almost constant when the quench heaters are not yet effective. Then, the decay is dominated by the quench heaters, and the discharge time depends on the resistance per unit length, which is the same in both the scenarios. In conclusion, looking at the hot spot temperature, the option of using just one power supply and one dump resistor for the low-β triplet protection circuit should be considered.

Repeating all the simulations without the dynamic effects on the inductance gives ~20 K more, in all the studied cases. Nevertheless, these effects have been experimentally observed [1-2], the model developed for their simulation using QLASA has been experimentally validated [12], and they are confirmed by an innovative method of magnet inductance measurement during a fast

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current decay [13], therefore they have been included as nominal. Moreover, the reported numbers are probably yet conservative, because it has been showed that quench back, which is not included, strongly affects the fast decays [2].

IV. PEAK VOLTAGES

In this section an analysis of the peak voltages during a quench in MQXF is showed. The study has been performed using ROXIE [14-15], which is a program originally written at CERN for electromagnetic modelling, with a quench simulation subroutine that has been implemented later. ROXIE allows analysing the voltages of each turn during a quench, depending on the current and its derivative, on the resistance, and on the magnetic field. The analysis of peak voltages is very useful in order to dimension and test the insulations of conductors and coils. The assumptions are basically the same made for the hot spot temperature calculation (see Section III), except that heating station are not simulated, and dynamic effects on the inductance are not taken into account. The simulations compare the scenarios considering one or two power supplies. Nominal case is compared to a good amount of possible quench heaters failure situations. The results are listed in Table V and Table VI. In the 2 PS scenario, numbers are reported only for Q2a/Q2b, which is the worst case (longer magnetic length).

The cases considered, from the top to the bottom, are: nominal case; only outer layer quench heaters; failure of all the quench heaters of the first coil (in the coils connection series); failure of all the quench heaters of the third coil; failure of the all the outer layer quench heaters of the high-field (pole) blocks, in all the coils; failure of the inner layer quench heaters of the first coil; failure of the inner layer quench heaters of the third coil; failure of the outer layer quench heaters of the high-field (pole) block of the first coil, just one side (one octant); failure of the outer layer quench heaters of the high-field (pole) block of the third coil, just one side; failure of the outer layer quench heaters of the low-field (mid-plane) block of the first coil, just one side; failure of the outer layer quench heaters of the low-field (mid-plane) block of the third coil, just one side. For each case, five values are reported: the first is the nominal voltage to ground, computed considering symmetric grounding, i.e. ground positioned in the middle of the magnets chain; the second is the voltage to ground with a short circuit ("sc") of the symmetric ground, i.e. with one of the current leads to ground; the third is the voltage between adjacent turns of the same layer; the fourth is the voltage between adjacent turns of different layers (layer to layer voltage); the fifth is the voltage between the mid-plane turns. It is evident that the two scenarios are almost equivalent, except to the mid-plane voltage, which doubles in some of the 2 PS scenarios. For this reason, using a suitable mid-plane insulation, the choice of one power supply is convenient also on the peak voltages point of view. The "To Ground" columns need a comment: presently, ROXIE allows simulating only one magnet in a series. This means that the simulations have been performed considering a magnet alone, with a dump resistor dimensioned in order to have the right voltage fall across the magnet ends. Then, the voltage to ground is obtained adding the actual magnet ends input voltage, considering the magnet is inserted in the chain, to the simulated voltage. For this reason, the failure scenarios represent the magnet with a failure in a series of well working magnets, and the case of failures in different magnets cannot be simulated. This causes an error on the to-ground voltage evaluation, of the order of the resistance difference between failure scenario and nominal case.

TABLE V MQXF PEAK VOLTAGES / 1PS SCENARIO

	TG [V]	TG (sc) [V]	T-T [V]	L-L [V]	M-M [V]
Nominal	638	838	46	454	148
OL-QH	757	1007	86	549	146
Coil 1 fail	1862	2092	62	1734	1701
Coil 3 fail	1463	1693	63	1747	1832
OL-HF fail	738	958	66	239	148
Coil 1 IL fail	662	872	49	522	356
Coil 3 IL fail	663	873	50	527	482
Coil 1 OL-HF fail 1 side	608	813	48	487	159
Coil 3 OL-HF fail 1 side	608	813	47	490	275
Coil 1 OL-LF fail 1 side	597	802	47	472	147
Coil 3 OL-LF fail 1 side	582	787	47	472	176

TABLE VI MQXF PEAK VOLTAGES / 2 PS SCENARIO

Nominal	659	859	44	421	313
OL-QH	798	1048	81	509	311
Coil 1 fail	1810	2020	59	1674	1513
Coil 3 fail	1335	1565	59	1686	1769
OL-HF fail	833	1053	62	223	312
Coil 1 IL fail	754	964	47	486	342
Coil 3 IL fail	755	965	47	490	494
Coil 1 OL-HF fail 1 side	704	909	45	452	314
Coil 3 OL-HF fail 1 side	704	909	45	455	314
Coil 1 OL-LF fail 1 side	680	885	45	439	312
Coil 3 OL-LF fail 1 side	681	886	45	439	313

It is also possible to calculate the maximum coil-to-heaters voltage: in the case of grounded heaters, it is equal to the voltage to ground, because the maximum is reached when the heaters are discharged; in the case of floating heaters, the maximum voltage is half of the heaters charge (500 V) plus half of the voltage between coil ends, because both have a symmetric ground; it is therefore ~650 V. In the case of failure of both the grounds (short-circuits), the maximum coil-to-heaters voltage can reach ~1300 V.

V. CONCLUSIONS

The protection of MQXF has been a significant challenge in the first stage of the design process. A first series of studies showed that a standard protection approach (energy extraction and OL heaters) was not sufficient to ensure magnet safety. This result led to improve the design of quench heaters, including them on the inner layer, finding different ways to avoid helium bubbles issue. The current decay behaviour has been studied in deep, leading to develop an electromagnetic model for the simulation of the inductance dependence on the inter-filament coupling currents. The magnet parameters have been upgraded, increasing the margin to the short sample limit. This work shows that, with all these innovations, MQXF protection is possible, with a good margin on the uncertainties (such as material properties), and with a good redundancy because of possible failure scenarios. Moreover, it shows that the option of using only one power supply for the protection of the whole triplet is safe (both hot spot temperature and peak voltages are acceptable), and it could be considered in order to reduce costs. The last open issue is the inner layer quench heaters reliability because of the helium bubbles. If not solved, the option of using CLIQ with outer layer and no inner layer quench heaters should be taken into account.

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