Study of Quench Protection for the Nb₃Sn Low- β Quadrupole for the LHC Luminosity Upgrade (HiLumi-LHC)

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Keywords: Niobium compounds, quench protection, superconducting accelerators

Abstract

The HiLumi program is aiming to develop and build new Nb₃Sn, high-field (12 T) and large aperture (150 mm) superconducting quadrupoles, which will be inserted in the LHC interaction regions and will provide the final focusing of the beam, in the program of the luminosity upgrade. The quench protection of these magnets is one of the most challenging aspects, mainly because of the large value of the magnet inductance (160 mH for the configuration with two 8 m long magnets in series), of the large value of the stored magnetic energy density in the coils (0.12 J/mm³, a factor 2 larger than in the conventional NbTi quadrupoles) and of the use of Nb₃Sn as conductor, which has never been used for large accelerator magnets. Previous works have demonstrated that a “standard” conservative analysis, assuming quench heaters only on the coils outer layer, gives high hot spot temperature, close to the design limit (350 K). In this paper, a new study of quench protection is presented. The benefic effects of large dI/dt during the discharge and other dynamic effects are discussed together with options for having a partial coverage of the inner layer by quench heaters. The analysis is validated by experimental data from R&D Nb₃Sn quadrupole magnets.

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Abstract— The HiLumi program is aiming to develop and build new Nb₃Sn, high-field (12 T) and large aperture (150 mm) superconducting quadrupoles, which will be inserted in the LHC interaction regions and will provide the final focusing of the beam, in the program of the luminosity upgrade. The quench protection of these magnets is one of the most challenging aspects, mainly because of the large value of the magnet inductance (160 mH for the configuration with two 8 m long magnets in series), of the large value of the stored magnetic energy density in the coils (0.12 J/mm³, a factor 2 larger than in the conventional NbTi quadrupoles) and of the use of Nb₃Sn as conductor, which has never been used for large accelerator magnets. Previous works have demonstrated that a “standard” conservative analysis, assuming quench heaters only on the coils outer layer, gives high hot spot temperature, close to the design limit (350 K). In this paper, a new study of quench protection is presented. The benefic effects of large dI/dt during the discharge and other dynamic effects are discussed together with options for having a partial coverage of the inner layer by quench heaters. The analysis is validated by experimental data from R&D Nb₃Sn quadrupole magnets.

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

I. INTRODUCTION

THE Large Hadron Collider (LHC) at CERN has produced proton-proton collisions up to 8 TeV centre-of-mass energy in the period 2010-2013. After the commissioning towards 14 TeV in 2015, and towards a designed luminosity of $1\text{--}2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, it is expected to reach 300 fb^{-1} at the horizon of 2021. Running the accelerator after this date without a significant luminosity increase will lead only to marginal statistical gain; therefore a luminosity upgrade, named High Luminosity LHC (HL-LHC), has been planned, with the target of accumulating 3000 fb^{-1} in the successive 10 years. This can be achieved with a more intense beam and by using superconducting magnets with better performance than the present Nb-Ti,

specifically replacing the low- β triplet quadrupole magnets with larger aperture magnets. The selected quadrupole design, called MQXF, presents a very large aperture (150 mm in magnet bore diameter) and a peak field on the conductor of 12.2 T, thanks to a Nb₃Sn conductor. Table I lists the main parameters of the magnet, and Fig. 1 represents the cross section of the magnet in the 1st quadrant.

Because of the high magnetic field and of the large magnetic energy density in the coils (about 0.12 J/mm³, compared to 0.05–0.06 J/mm³ in the current Nb-Ti low- β triplet magnets), the quench protection is one of the most challenging aspects of these magnets, requiring a detailed study to verify the safe working conditions [1].

TABLE I MAIN PARAMETERS OF MQXF

Aperture diameter	150 mm
Gradient	140 T/m
Maximum length	2 × 4 m
Nominal current	17500 A
Magnetic stored energy (2 × 4 m)	10.6 MJ
Conductor peak field	12.2 T
Operating temperature	1.9 K
Strand diameter	0.850 mm
Bare cable width	16.638 mm
Bare cable thin/thick edge thickness	1.462/1.673 mm
Insulation thickness	0.150 mm
Strand N.	40
Copper/non-copper ratio λ	1.2
Copper RRR	≥ 100

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

In a previous paper [2] the MQXF quench protection was analysed with two different codes, and the conclusion was that the minimal target to keep the peak temperature below 350 K was hardly achieved. This was not leaving margin for any uncertainties, such as material properties or additional temporal delays in the protection activation. Further studies on the quench protection have been done to explore the presence of hidden margins. One of the most important was the possible gain due to the reduced value of the apparent inductance, probably caused by rapid dI/dt effects; this lower inductance was experimentally observed

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during the test of HQ magnets with fast current decays, which was more rapid (~30%) than in the simulations. In this paper we discuss some models to explain the faster current decay that has been experimentally measured. These models are used to update the simulation scenario for MQXF, where also inner layer quench heaters are considered.

II. COUPLING WITH METALLIC COMPONENTS

A first explanation of the apparent inductance decrease during a fast decay has been envisaged by electromagnetic coupling of the coils with the metallic parts of the magnet, such as the collar or the shell: during the discharge, because of the high dI/dt , eddy currents flow in these metallic parts and extract part of the stored energy.

As a first approximation, the collar or the shell can be represented as an infinitely long external thin cylinder. In this cylinder, assuming that the main coils are a perfect $\cos 2\vartheta$ magnet, $\cos 2\vartheta$ eddy currents flow during the decay, with an intrinsic time constant τ [3]. As a consequence, the coupling of the cylinder with the quadrupole is equivalent to the coupling of a primary circuit (the circuit of the coils) with a secondary circuit (the circuit of cylinder with equivalent current I_2 , inductance L_2 and resistance R_2), with mutual inductance M . The equivalence between magnetic-energy/power-dissipated in the cylinder and magnetic-energy/power-dissipated in the secondary circuit gives the following values for the electrical parameter of the secondary circuit [4]:

$$R_2 = \frac{\pi \varrho}{4ad} \quad (1)$$

$$L_2 = \frac{\pi}{16} \mu_0 \quad (2)$$

$$M = \frac{\pi}{32} \mu_0 \frac{c_2^2 + c_1^2}{a^2} N_1 \quad (3)$$

where ϱ is the cylinder resistivity, a is the cylinder radius, d is the cylinder thickness, c_2 and c_1 are respectively the outer and inner radius of the main coils, and N_1 is the total number of the main turns.

The solution of the equation of the current in the coil coupled with the equivalent circuit gives a current decrease faster than a pure exponential.

III. DYNAMIC INDUCTANCE FOR INTER-FILAMENT COUPLING CURRENTS

Under changes of the external field, the superconducting strands are affected by Inter-Filament Coupling Currents (IFCC). During the quench process, the field variation is so large that the field flux produced by these currents could not be negligible, therefore it should be taken into account in the calculation of the magnet differential inductance during the current discharge.

The total field B_i on the strand follows the equation [5]:

$$B_i = B_e - \dot{B}_i \tau \quad (4)$$

where B_e is the external field, and τ the IFCC decay time constant [5]. Even if the copper resistivity is not constant (in space and in time) because of the magneto-resistivity, τ has been considered constant and corresponding to an average field value. Assuming that B_e decreases exponentially, the solution of (4) is

$$B_i = \frac{B_0}{\tau - \tau_e} \left(\tau e^{-\frac{t}{\tau}} - \tau_e e^{-\frac{t}{\tau_e}} \right) \quad (5)$$

where τ_e is the external field time constant and B_0 the field at $t = 0$. The IFCC produce a magnetization M :

$$M = 2\lambda\tau \frac{\dot{B}_i}{\mu_0} \quad (6)$$

which can be written also as

$$M = \frac{\chi}{1 + \chi} \frac{B_i}{\mu_0} \quad (7)$$

where χ is the magnetic susceptibility and $\lambda < 1$ is the product of the metal fraction in the strand and the conductor packing factor. Combining equations (5), (6) and (7), the susceptibility χ related to the IFCC can be obtained:

$$\chi = \frac{2\lambda\tau \left(e^{-\frac{t}{\tau_e}} - e^{-\frac{t}{\tau}} \right)}{\tau e^{-\frac{t}{\tau}} - \tau_e e^{-\frac{t}{\tau_e}} - 2\lambda\tau \left(e^{-\frac{t}{\tau_e}} - e^{-\frac{t}{\tau}} \right)} \quad (8)$$

The dynamic inductance, defined as:

$$L_d = \frac{d\phi}{dI} = \frac{1}{I} \frac{dU}{dI} \quad (9)$$

can be found through the expression of the stored energy variation per unit volume du :

$$du = HdB = \mu_0 H dH + \mu_0 \chi H dH + \mu_0 H^2 \frac{d\chi}{dI} \quad (10)$$

The dynamic inductance variation due to the IFCC can be found integrating over the coils volume the last two terms in (10), and substituting the result in (9)

$$L_d = \int \left\{ (1 + \chi) \frac{\mu_0}{2I} \frac{dH^2}{dI} + \frac{\mu_0 H^2}{I} \frac{d\chi}{dI} \right\} dV \quad (11)$$

The first term in (10), integrated over the whole space, gives the static inductance, assuming that the magnetization does not affect the magnetic field H .

IV. DYNAMIC INDUCTANCE EXPERIMENTAL VALIDATION

It has been experimentally observed that during a quench the current decreases faster than expected [6], [7], already at the very beginning of the discharge.

Fig. 2. Comparison between an experimental current decay from HQ02 (solid green), a pure exponential (dashed blue) and a current decay obtained considering the coupling with an external cylinder (pointed brown).

The experimental data in Fig. 2 are from HQ02 [8], a Nb₃Sn quadrupole magnet, with an external dump resistor R_d of 60 mΩ, starting from 13 kA (70% of the short-sample-limit at 1.9 K). Considering the nonlinear inductance of 5.8 mH at 13 kA, one gets an exponential decay (blue curve, with a time constant of 97 ms). On the other hand, the experimental curve has an initial time constant about 30% smaller; this cannot be explained as a quench back since it happens at the very beginning of the decay, whereas the quench back needs some time to act.

In Fig. 2 the result of the model described in section II (coupling with the external cylinder) is shown, considering

the following values: $R_2 = 4.5 \mu\Omega$, $L_2 = 0.2 \mu\text{H}$, $M = 19.3 \mu\text{H}$. for the resistance calculation, the nominal aluminium resistivity at 2 K has been used, from the MATPRO database [9]. Actually, the magnet collar is laminated, therefore an effective, higher resistivity could be used in order to take into account the surface resistance of the laminations; for lacking of reliable data, nominal value of bulk material has been used. The obtained current decay fits well at the beginning (from $t=0$ to $t=30$ ms), but later the current decays again much slower than the experimental curve.

For the model described in section III (inductance variation for the IFCC), an extension to the quench simulation code QLASA [10] has been implemented, and the results have been compared with the experimental data in Fig. 3. In the code at each time step the inductance is recalculated, assuming (8) for the permeability in the coils, and a $\cos 2\theta$ magnetic field for the volume integration (11).

Fig. 3. Comparison between an experimental current decay from HQ02 (solid green), a pure exponential (dashed blue) and a simulation made considering the dynamic effects described in section III (pointed red).

The simulation [11] has been performed considering $\lambda = 0.7$ and $\tau = 15$ ms [5]. Also in this case, the simulation which considers the IFCC fits the experimental one at the beginning, until about 10 ms; then, the experimental curve decays faster. However at this time a quench back can be supposed to occur: in Fig. 4 the power per unit volume dissipated by the IFCC ($p = \frac{2B^2\tau}{\mu_0}$) is represented and compared to the joule effect dissipation ($p = \rho J^2$). The presence of fast quench back starting after about 5-10 ms has been also confirmed by the results of the CLIQ [12] tests performed on the same magnet at CERN.

Fig. 4. Comparison between the power per unit volume dissipated by the eddy currents (solid orange) and the power dissipated by the joule effect during a quench in a high field zone (8 T) (dashed blue).

A quench back after 10 ms and the additional power due to the IFCC have been introduced in the model, in order to fit the curve; quench back is modelled as a widespread quench in the whole magnet after 10 ms. The simulation is now almost coincident with the experimental curve, as

represented in Fig. 5. A curve which considers only the dynamic effects is also shown, in order to point out that the quench back (with the additional power dissipation for IFCC) affects the decay more than dynamic effects.

Fig. 5. Comparison between an experimental current decay from HQ02 (solid green), a simulation made considering the dynamic effects (pointed red), one considering dynamic effects plus quench back after 10 ms (dashed black) and one considering quench back after 10 ms, but no dynamic effects (point-dashed purple).

On the other hand the 10 ms quench back alone cannot justify such a sudden change of the current slope at the very beginning of the discharge, as shown in Fig. 5, where the point-dashed purple curve represents a current decay with 10 ms quench back at the magnet nominal inductance.

The computed dynamic inductance during the discharge, according to the model of the IFCC described in section III, is shown in Fig. 6, and it is compared to the HQ nominal inductance (measured at low dI/dt [13], a high current value is used for reference).

Fig. 6. Comparison between the nominal HQ inductance (dashed blue) and the differential inductance obtained considering the dynamic effects described in section II (solid orange).

It can be noted that the dynamic effects appreciably affect the curve at the beginning of the decay, when $t \lesssim \tau$, where the dynamic inductance is $\sim 30\%$ lower than the nominal one. Then the dynamic inductance saturates, because the IFCC decay within $2-3 \tau$. Note that the dynamic inductance saturates to a value slightly lower (about 1 %) than the magnet nominal inductance: this is due to the fact that the magnetization due to IFCC continues to change since for large values of t the susceptibility given in (8) saturates to a not null, negative value, therefore in (11) there is always a small reduction.

In conclusion, this study shows that faster current decays during a discharge can be predicted by inductance variation due to the IFCC, as shown in section III; this model is also consistent with a very rapid quench back, because of the additional power dissipated in the conductor. Instead, the variation of inductance due to coupled current in metallic components, as in the model described in section II, allows to fit experimental data at the very beginning of current decay, but it cannot justify a fast quench back in the coils.

V. MQXF QUENCH HEATERS

MQXF protection is relying on quench heaters on the outer layer [2], [14]. A possible way to improve protection is to add protection heaters also on the inner layer (IL). Various designs for the IL protection heaters have been proposed and are here summarized

A. Stainless steel-only design

This layout comes from the earlier design used in Long Quadrupoles (LQ) [15]. It involves regularly spaced heating stations separated by wider bridges (Fig. 7 up-left). The material is uniform stainless steel (SS304) with thickness $d = 25 \mu\text{m}$.

Fig. 7. Top-Left: a sketch showing a period of heating station stainless steel-only design. Top-Right: IL heater layout for copper-plated heater design 1. Bottom: IL heater layout for copper-plated heater design 2.

B. Copper-plated heater designs

The copper plating allows to better protect a long magnet w.r.t the heating stations technique: in fact, the resistance of the copper part is negligible and heating stations can be made longer without exceeding the maximum voltage. The design 1 is shown in Fig. 7 top-right. In the design 2 the copper-plated bridges are made narrower with respect to the design 1, to allow further space for cooling the coils and also to allow more space for perforation, avoiding the formation of helium bubbles that have been observed in the HQ program. The distance between heating stations is in both cases of the order of 100 mm; having a longitudinal propagation speed of 20 m/s [13], the locations between heating stations get quenched 2.5 ms later, which is considered as an acceptable delay. Terminals of the heating stations are copper-plated to improve current flow uniformity. The design is shown in Fig. 7, bottom.

VI. MQXF HOT SPOT TEMPERATURE

The MQXF hot spot temperature has been calculated considering also the presence of protection heaters (PH) on the IL (see section V) and the dynamic effects described in section III. The results show that the three IL heater designs are almost equivalent for the hot spot temperature calculation (the hot spot temperature changes are about ± 5 K in the three designs). The PH delay time have been obtained using CoHDA [16]: the heaters-induced quench is assumed to occur at the same time in all the turns which are in direct thermal contact with the strip. The delay times shown in Table II are therefore averages. More details on the PH simulation using QLASA can be found in [2] and [11]. The simulations have been performed considering the case of two 8 m long magnets in series, according to the nominal protection parameters, which are reported in Table II. Table III reports hot spot temperature for four different cases, with/without IL heaters and with/without dynamic effects. The hot spot temperature calculation has been performed considering material properties from the MATPRO database [9].

TABLE II MQXF PROTECTION PARAMETERS

Dump resistor (maximum voltage to ground)	46 m Ω (800 V)
Voltage threshold	100 mV
Validation time	10 ms
Heaters delay time from firing (inner-layer)	12 ms
Heaters delay time from firing (outer-layer)	16 ms

The insertion of PH on the IL causes a decrease of ~ 40 K of the hot spot temperature; the dynamic effects give an additional ~ 25 K decrease. Although the dynamic effects are here less effective than in the previously examined HQ case, because in MQXF the initial di/dt is lower (~ 10 kA/s vs. ~ 100 kA/s), they appreciably affect the current decay, reducing the MIITs developed during the discharge and lowering the final magnet hot spot temperature. In conclusion, considering the dynamic effects on the inductance, magnet safety is ensured in both cases with or without IL PH.

TABLE III MQXF MIITs/HOT SPOT TEMPERATURE

No IL-PH no dynamic	IL-PH no dynamic	No IL-PH dynamic	IL-PH dynamic
35.5 MA ² s	32.8 MA ² s	39.9 MA ² s	31.1 MA ² s
330 K	290 K	306 K	266 K

VII. MQXF PROTECTION REDUNDANCY

Simulations have been repeated for the four cases previously examined, considering a failure of half of the PH. The results are reported in Table IV.

TABLE IV MIITs/HOT SPOT TEMPERATURE WITH HALF HEATERS

No IL-PH no dynamic	IL-PH no dynamic	No IL-PH dynamic	IL-PH dynamic
37.8 MA ² s	34.2 MA ² s	36.5 MA ² s	32.9 MA ² s
365 K	311 K	341 K	287 K

There is an increase of the hot spot temperature of ~ 20 K in the IL-PH case, and of ~ 35 K in the no IL-PH case, respect to Table III. According to this model, considering also the dynamic effects, redundancy is provided only if inner layer protection heaters are inserted.

VIII. CONCLUSIONS

Previous works on the MQXF quench protection showed that the hot spot temperature was too close to the design limit of 350 K [2]. On the other hand, experimental evidence of dynamic effects for the HQ quadrupole showed a faster current decay. Here we study these effects, developing two models described in sections II and III. The IFCC model described in section III allows to reproduce the observed faster discharge, and the additional power dissipation in the conductor explains rapid quench back. The model has been applied for the MQXF simulations in order to calculate the dynamic inductance during the discharge, according to the nominal protection parameters.

Additionally, quench heaters in the IL have been designed and implemented in the simulations. A faster discharge can be clearly observed, therefore less MIITs are produced and the hot spot temperature is now reasonably lower than the design limit of 350 K; therefore, under these assumptions, the magnet can be considered safe also without IL quench heaters. Anyway, redundancy is ensured in case of half heaters failure, provided that IL protection heaters are inserted. Further improvement to the MQXF protection supposed to come from quench back has not been considered in this work.

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