Protection Strategy and Quench Study of MCBXF Magnets

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***Abstract*—Nested combined orbit correctors are needed for the upgrade of LHC. They are developed at CIEMAT, in collaboration with CERN in the framework of HL-LHC project. There are two types of magnets, so-called MCBXFA and MCBXFB, with different lengths (2.5 and 1.5 m, respectively), but sharing the same cross section. The coils of both magnets are wound with the same Rutherford-type NbTi cable, composed of 18 strands of 0.48 mm diameter, insulated with a braided glass fiber sleeve. Various magnet protection schemes were considered for MCBXF magnets. In this work, self-protection, energy extraction resistor and quench heaters are discussed emphasizing advantages and disadvantages of each strategy. This analysis is supported by quench calculations performed with Squid (CIEMAT in-house developed code) and Roxie. Selected quench simulation results are presented and compared with measurements done on magnet prototypes. Based on the presented study, a protection scheme with energy extraction resistor was selected for the series magnets. The value of the resistor was optimized and related quench calculations are also included.**

***Index Terms*—Nested superconducting magnet, quench simulation, superconducting accelerator dipole, superconducting magnet test.**

I. Introduction

THIS paper is focused on the protection strategy of the nested orbit correctors of HL-LHC project [1]–[3], which will replace the equivalent magnets presently installed at LHC. Four 2.5 m long magnets, so-called MCBXFA, and eight 1.5 m long magnets, MCBXFB, are needed for the machine. They share the same cross section (Fig. 1).

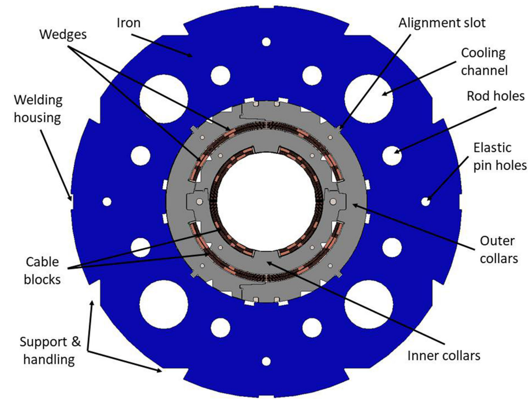

Fig. 1. Cross section of MCBXFB magnet. MCBXFA one is the same, but with smaller cooling channels (61 mm vs. 77 mm diameter).

CIEMAT, in collaboration with CERN, developed two MCBXFB prototypes [4]–[8]. They were equipped with inner and outer nested dipole coils of the same length. They were wound with a NbTi Rutherford cable of 18 strands of 0.48 mm diameter, 1.75:1 as copper to superconductor ratio, insulated with a 0.135-mm-thick braided glass fiber sleeve, and vacuum impregnated. The results of the power tests showed long training to reach nominal operation during the first ramp and after each change in torque direction. Although those prototypes were valid for HL-LHC optics requirements, it was decided to implement a fine tuning of the inner dipole design in the first MCBXFB series magnet [9]. This magnet showed excellent performance in the power test, with short training, good memory after the thermal cycle and allowing operation in all different powering scenarios [10].

Tables I and II show the magnet parameters relevant for the protection study, both for the prototypes and the series magnets. In the first design, the integrated field was slightly above the requirements. This paper is focused on the protection strategy of these magnets. Three alternatives are evaluated: self-protection, dump resistor and quench heaters.

II. Discussion on Protection Strategy

The following strategies were considered to guarantee the safe operation of MCBXF magnets.

TABLE I
MCBXFA PARAMETERS: FIRST DESIGN / FINAL

Parameter	ID	OD	Units
Nominal individual field	2.12 / 2.18	2.18 / 2.12	T
Field integral	4.61 / 4.5	4.61 / 4.5	Tm
Nominal current	1584 / 1617	1402 / 1353	A
Ultimate current	1702 / 1737	1502 / 1457	A
Pole length	1946 / 1828	1828	mm
Coil length	2342 / 2224	2342	mm
Differential inductance at nominal current	107.4 / 101.3	231.7 / 234.1	mH
Stored magnetic energy at nominal current	134.7 / 132.7	240.2 / 224.8	kJ
Stored magnetic energy at ultimate current	155.5 / 153.1	272.4 / 257.8	kJ

TABLE II
MCBXFB PARAMETERS: PROTOTYPE / SERIES

Parameter	ID	OD	Units
Nominal field	2.18 / 2.36	2.30 / 2.24	T
Integrated field	2.56 / 2.5	2.56 / 2.5	Tm
Nominal current	1625 / 1755	1474 / 1435	A
Ultimate current	1755 / 1885	1594 / 1545	A
Pole length	946 / 828	828	mm
Coil length	1342 / 1224	1342	mm
Differential inductance at nominal current	58.4 / 52.5	124.3 / 125.4	mH
Stored magnetic energy at nominal current	77.3 / 81.1	143.6 / 136.7	kJ
Stored magnetic energy at ultimate current	90.1 / 93.5	165.4 / 138.5	kJ

A. Self-Protection

The stored magnetic energy is dissipated by induced losses in the coils and near metallic parts. The power supply is turned off when the quench is detected. The crowbar is equipped with a 7 mΩ resistor, which also contributes to dissipate the stored magnetic energy.

Obviously, it is the most simple and cheap protection system, but the expected peak temperature and voltage are the highest. This system would not allow a reliable protection of the bus bars, because redundancy is not guaranteed [11].

B. Dump Resistor

An external resistor can be connected in series with the magnet when the quench is detected. The assumed time for quench detection, validation and insertion of the resistor is 100 ms (conservative). Redundancy is not considered. To keep moderate voltages at current leads, the dump resistor could have up to 0.3 ohm. As the coils are double layered, the voltage at current leads will be the maximum turn-to-turn voltage in this protection scheme. It will yield a voltage below 530 V for any powering scenario (Tables II and III). The maximum test voltage will be twice the maximum voltage to ground at nominal current plus 500 V multiplied by two, that is, 3120 V [12].

The switch is an expensive component, but the expected peak temperature and voltages are moderate.

TABLE III
MCBXFA PROTECTION STUDY: INNER DIPOLE (NOMINAL) / OUTER DIPOLE (NOMINAL) INNER DIPOLE (ULTIMATE) / OUTER DIPOLE (ULTIMATE)

Strategy	Initial current (A)	Peak temperature (K)	Peak voltage (V)
Self- protection	1584 / 1402	282 / 344	346 / 534
	1702 / 1502	303 / 370	425 / 638
Dump resistor	1584 / 1402	102 / 155	475 / 421
	1702 / 1502	123 / 187	511 / 451
Quench heaters	1584 / 1402	115 / 126	380 / 601
	1702 / 1502	126 / 136	469 / 727

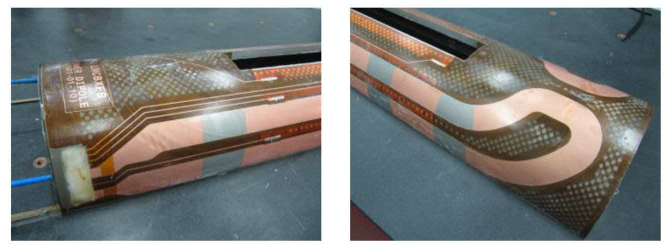

Fig. 2. Quench heaters on the first MCBXFB coil: connection side on the left and return side on the right. Traces for voltage taps can be noticed.

C. Quench Heaters

Strip heaters can be used to warm up the coils when a quench is detected. MCBXFB coils are fully impregnated with CTD-101K resin. Strip heaters could be integrated before the coil impregnation, on top of the outer layer (Fig. 2).

One heater will be placed on each side of the coils, both inner and outer dipoles, that is, two heaters per coil. Quench heaters will be powered by the discharge of 7.05 mF capacitors charged at 450 V. Each power supply is connected to two heaters, one on each coil, for redundancy. Therefore, two power supplies are required per dipole.

The heaters are made of a 25 μm stainless steel foil plated with 50 μm copper, glued on top of a 25 μm thick polyimide foil. Copper plating is removed at some sections, which act as heater stations when the capacitors are discharged. The resistivity in those areas is much higher. Some simple calculations [13] are made to design the strips, concluding that the copper plating must be removed from 50 mm long sections, with a distance of 150 mm between them. The width of the strips is 27 mm. The estimated developed resistance is 0.65 ohm per strip. Assuming 1.5 ohm of cable resistance, two heaters per power supply, an initial current of 160 A would warm up the strips, dissipating about 80 W/cm^2 at the heat stations. During discharge, the dissipated energy per strip in adiabatic conditions would be 714 J, reaching a peak temperature of about 210 K. A simple FEM model in ANSYS [14] allows computing the delay till cables become resistive. In adiabatic conditions, one cable of each layer are modeled separated by the interlayer insulation. The power density provided by the heater is applied at the top, computing the time necessary for the bottom cable to surpass the critical temperature, yielding about 14 ms. MCBXFA quench heaters are designed following the same guidelines.

TABLE IV
MCBXFB PROTECTION STUDY: INNER DIPOLE (NOMINAL) / OUTER DIPOLE (NOMINAL) INNER DIPOLE (ULTIMATE) / OUTER DIPOLE (ULTIMATE)

Strategy	Initial current (A)	Peak temperature (K)	Peak voltage (V)
Self- protection	1625 / 1474	234 / 298	201 / 334
	1755 / 1594	250 / 322	253 / 411
Dump resistor	1625 / 1474	81 / 108	487 / 442
	1755 / 1594	93 / 129	526 / 478
Quench heaters	1625 / 1474	122 / 138	223 / 379
	1755 / 1594	134 / 150	279 / 469

Protection based on quench heaters is cheaper than using dump resistors, but coil fabrication is more difficult, and there is an additional risk of coil insulation failure. Additionally, voltage taps can be integrated into quench heater foils to locate the quench origin and measure the propagation speed.

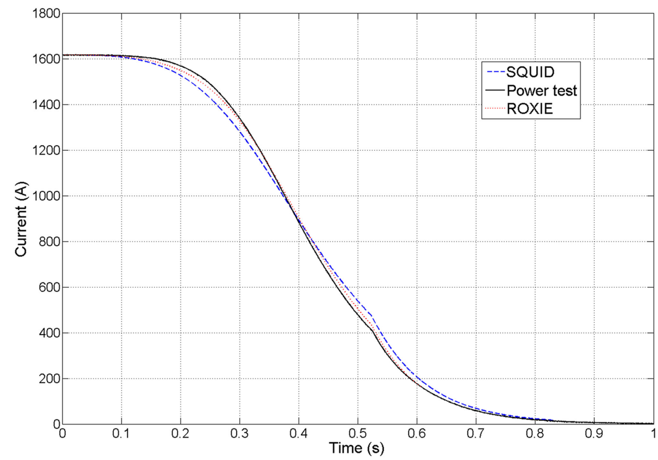

Fig. 3. Comparison between measured and simulated current decay for the inner dipole with a delay of 500 ms to connect the dump resistor.

III. PROTECTION STUDY ON MCBXF MAGNETS

The next step is to simulate the different scenarios to choose the most adequate protection system. The aim is to know the peak temperatures and voltages during the quench propagation. Both dipoles are in quadrature, so the mutual inductance is negligible. However, the self-inductance of each circuit is affected by iron saturation, which is different if the other dipole is powered. Higher inductance yields a slower current decay, which leads to a higher peak temperature. Since iron saturation decreases the inductance, the self-inductances are computed when only one dipole is powered, which is the worst case scenario. This is a pessimistic assumption, but it eases the simulation.

Quench propagation was simulated with the help of the dedicated code developed at CIEMAT, so-called SQUID [15]. It is based on a finite-difference method. There are some assumptions for this calculation:

- AC losses are neglected: the current decay is in the order of 1 to 2 seconds, so its contribution to the energy dissipation is not very significant.
- Heat transmission through the copper wedges is neglected because they are much thicker than the cables.
- The real field map at each cable is not implemented. The magnetic field is modeled as uniform for all the cables, decreasing with current.
- The location of the quench start is the pole turn of the inner layer, which is pessimistic. This turn features the peak field in the case of individual powering, but not in combined operation.
- The RRR is assumed to be 120.
- Data are not available on the physical properties of the glass fiber insulation impregnated with CTD-101K resin [16]. G-10 data is used instead.

Tables III and IV show the simulation results for MCBXFA and MCBXFB magnets, respectively. Peak voltages are computed by SQUID as the overall resistive voltage in the transited coil. Due to the high number of turns (140 for the inner dipole, 191 for the outer one), the turn-to-turn voltage will be low. In the case of dump resistors, the initial voltage computed as the value of the resistance times the current will be higher than the resistive voltage developed inside the coil, and that is the one reported in the Tables. It is agreed that the hot spot temperature should be below 250 K for magnet reliability. In the case of self-protection, there are some scenarios with temperatures above that threshold, but the use of dump resistors or quench heaters would achieve that goal.

IV. DECISION ON PROTECTION STRATEGY

The first MCBXFB magnet prototype was equipped with quench heaters to check the fabrication feasibility and to check the simulations. It was decided not to fire the heaters to avoid risking the electrical integrity of the coils, since the magnet should be installed in a cold mass. At least, the voltage taps integrated in the heater traces helped to locate the quench origin.

Due to the simulation assumptions, there was some uncertainty on the accuracy of the quench simulations, mainly for the case of self-protection, which relies on the natural propagation of the resistive state. Therefore, it was decided to delay the triggering of the dump resistor progressively, up to 500 ms, to get that information without risk to the magnet.

Fig. 3 shows the measured current decay for a quench in the inner dipole, starting with a current of 1616 A. The delay to switch on the dump resistor is 500 ms, allowing the study of natural quench propagation in the coil. Cables were not thermal treated and measured RRR is only 76. Due to the voltage taps, the quench origin can be located in the midplane block of the outer layer. The simulation was also performed with ROXIE [17] as a reference. ROXIE takes into account the real field map at each conductor, but only that created by the dipole which quenches. The predicted peak temperature by SQUID is 184 K, compared to 173 K by ROXIE. The measured integral of the squared current is 920 k(A^2s), compared to 896 k(A^2s) computed by SQUID and 913 k(A^2s) by ROXIE.

Fig. 4 shows a similar comparison for a quench in the inner dipole, starting with the nominal current (1625 A). The delay to connect the dump resistor is 300 ms. This case is useful for studying the current decay when the dump resistor is connected

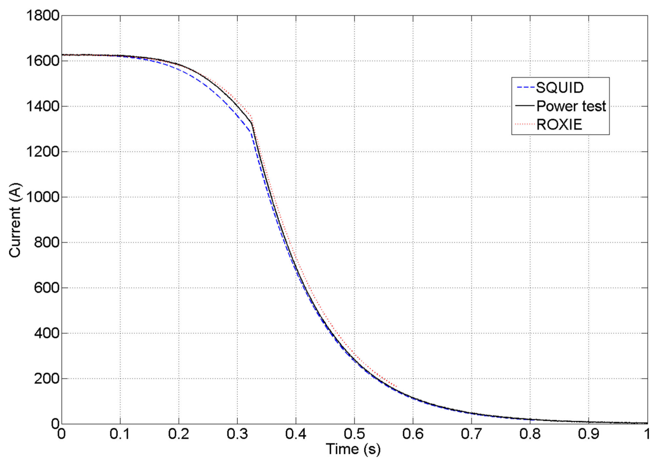

Fig. 4. Comparison between measured and simulated current decay for the inner dipole with a delay of 300 ms to connect the dump resistor.

for a longer time. The quench origin is at the pole turn, outer layer, non-connection side. The simulation of the current decay with SQUID and ROXIE is again close to the measured one. The predicted peak temperature is 185 and 208 K, respectively. Based on the information provided by the voltage taps at the pole turn, the initial measured longitudinal propagation speed is 17 m/s, while SQUID yields about 7 m/s. This comparison is challenging because SQUID results are dependent on the length of the initially transited cable.

Similar results were collected for other currents. Both the SQUID and ROXIE models reproduce quite closely the experimental data, validating the simulation results compiled in Tables III and IV. In consequence, magnet self-protection was discarded because of the high predicted temperatures, mainly for the long magnets, and the impossibility to protect reliably the bus bars in case of a quench starting there. Quench heaters are difficult to implement safely in impregnated coils. It was finally decided to choose dump resistor as the protection system for all MCBXF magnets, despite the high cost of the switch, as the more balanced solution.

V. Quench Simulation for MCBXF Series Magnets

A fine tuning of the inner dipole design has been implemented for series production. The coil length has been decreased, so the nominal and ultimate currents have increased. Therefore, the peak voltages at coil current leads when the dump resistors are connected would also rise. The values collected in Tables III and IV suggest that there is some margin to reduce the dump resistor, which has finally been fixed at 0.15 Ω. In this way, the electrical checks during production and tests will be done at a maximum of 2 kV. Table V shows the peak temperature and voltages computed for the series magnet design with that dump resistor. According to the experience accumulated in the power tests, the dump resistor can be connected 50 ms after quench detection. In fact, the usual timing in the power tests is as follows: 10 ms for quench detection, 10 ms for validation and 2 ms to open the switch. Some values of peak temperature are around

TABLE V
MCBXF Series Magnets Protected with 0.15 ohm Dump Resistors: MCBXFA / MCBXFB

Dipole	Initial current (A)	Peak temperature (K)	Peak voltage (V)
Inner (nominal)	1617 / 1755	154 / 112	243 / 263
Inner (ultimate)	1737 / 1885	183 / 132	261 / 283
Outer (nominal)	1353 / 1435	219 / 155	203 / 215
Outer (ultimate)	1457 / 1545	252 / 182	219 / 232

250 K, but taking into account the conservative assumptions for the calculations, they do not imply a real risk for the magnets.

VI. Conclusion

Three alternatives have been studied for the protection of MCBXF magnets (A and B-type): self-protection, dump resistors and quench heaters. Quench propagation has been simulated with SQUID, a dedicated code developed by CIEMAT, and cross-checked with ROXIE.

The data recorded during the power tests have validated the simulation results. The predicted peak temperature and voltages for self-protected magnets are too high. The first MCBXFB prototype was equipped with quench heaters, but they are difficult to implement. It is finally decided to use dump resistors to protect both types of magnets, as the more reliable solution, in spite of the high cost of the switch.

A fine tuning of inner dipole design has been performed for the series magnets. Additional simulations with the updated design parameters allow fixing the value of the dump resistors as 0.15 Ω, so reducing the peak voltages during quench propagation and, additionally, voltage test levels for quality assurance.

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