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Innovative method for quench localization in superconducting high-order magnets

S. Mariotto(1)(2) and M. Sorbi(1)(2)

(1) *Dipartimento di Fisica Aldo Pontremoli, Università degli Studi di Milano - Milano, Italy*
(2) *Laboratorio di Acceleratori e Superconduttività Applicata (LASA), Istituto Nazionale di Fisica Nucleare, INFN Sezione di Milano - Segrate, Italy*

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Summary. — The quench event is the transition into the normal resistive state of superconducting magnets. Since this critical event can damage the magnet and limit its performance, huge efforts in the scientific community are spent to localize its development and study the relevant causes. Conventional methods for quench detection, such as voltage taps, are embedded in the magnet, representing a potential risk of short circuits during the coil operation. Less invasive methods, such as quench antennas, have many advantages but can be applied to few magnet designs. During my PhD research, I developed an innovative idea based on the analysis of the magnetic field perturbation induced by superconducting hysteresis magnetization. Using standard field measurement technologies, I demonstrated that the residual superconducting magnetization of the high-order corrector magnets for the CERN High-Luminosity LHC upgrade allows the quench position reconstruction with high efficiency and accuracy. With these techniques, we found different quench developments not measured by standard methods. The excellent results encouraged the implementation of this analysis for future superconducting magnets.

1. – Introduction

The constant development of the high energy particle colliders research requires the technological improvements of modern superconducting magnets increasing the magnetic field values produced and, consequently, the stored energy density. When the superconductor state of the magnet material is lost, the electromagnetic stored energy turns into heat deposition inside the coil causing damages if the magnet is not quickly discharged. Knowing the position of the initial quench development deeply improves the design optimization of the magnet and allows the evaluation of possible weakness during the construction process. Diagnostic technologies like voltage taps and quench antenna are extensively used during the prototype development of a magnet. However, during the series production, these technologies are less implemented to simplify the construction process affecting the ability to precisely reconstruct the quench development location.

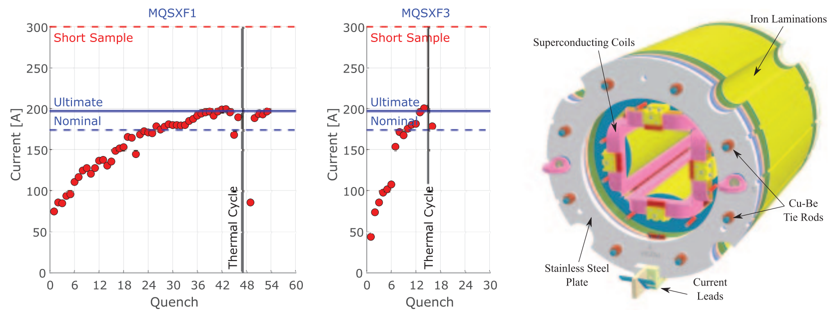

Fig. 1. – Comparison between different training behaviours of the skew quadrupole magnets MQSXF1 and MQSXF3 of the HO series production (left). Sketch (right) of the skew quadrupole magnet with details of the assembly elements.

To retrieve this capability, an innovative method, based on standard magnetic measurements and suitable for every magnet order, has been developed by INFN LASA and already applied to the series production of the High Order Corrector magnets for the High Luminosity LHC program [1]. An extensive analysis of the quench reconstruction results is reported and discussed in this paper, confirming this method as a powerful tool to improve the diagnostic technology of superconducting magnets.

2. – The residual harmonic field method

The 5 types of high-order corrector magnets [2], designed from the skew quadrupole up to the dodecapole order, will compensate for the imperfection of the main focalizing magnets in the Interaction Region and are based on a superferric configuration to minimize their dimensions in the collider ring. The NbTi superconducting coils are used to excite the iron poles and their precise shapes tune the magnetic field quality. All the coils are connected in series through a Printed Circuit Board under the closing iron lamination plates and are powered through the external current leads, see fig. 1. During the series production phase, only the two halves of each magnet are instrumented with voltage taps, thus losing the ability to retrieve the exact position of the quenched coil for each event of the magnet training [3]. However, after current discharge, only the not quenched coils still in the superconducting state deform the residual field quality due to the hysteresis magnetization of the superconductor filaments. Therefore, analyzing the 2D harmonic component of the residual magnetic field in the magnet cross-section, the number and positions of the quenched coils can be uniquely retrieved. The magnetic

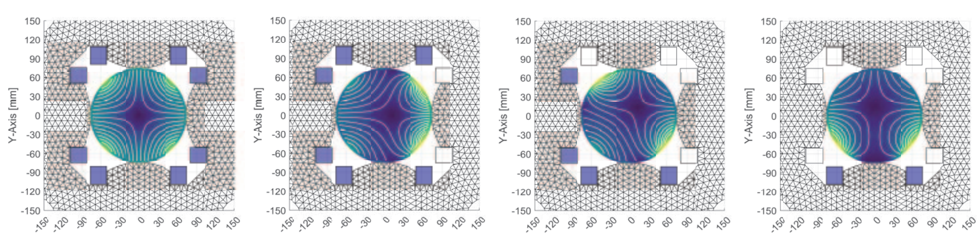

Fig. 2. – Magnetic Field Map inside the skew quadrupole bore for different quenched coil configurations. The quenched coils (white cross-sections) do not present residual superconducting magnetization introducing different harmonic components in the field map representation.

TABLE I. – *Examples of reconstructed quench from different high-order corrector magnets.*

MQSXF2 Quench N	Current [A]	Meas. C_3 Φ [°]	σ [°]	Sim. C_3 Φ [°]	N Coil	Va/Vb QDS	Va/Vb MM
1	44	88.8	1.6	90	1	Vb	Vb
3	86	357.3	0.7	360	2	Va	Va
4	98	296.7	0.7	270	3	Va	Va
5	102	226.4	0.8	225	3/4	Va	Va/Vb
9	168	185.3	1	180	4	Vb	Vb
13	196	28.4	7.1	-	All	Vb	Va/Vb
MCSXF05 Quench N	**Current [A]**	**Meas. C_4 Φ [°]**	**σ [°]**	**Sim. C_4 Φ [°]**	**N Coil**	**Va/Vb QDS**	**Va/Vb MM**
1	113	32.1	5.5	30	3	Va	Va
MCTXF3 Quench N	**Current [A]**	**Meas. C_7 Φ [°]**	**σ [°]**	**Sim. C_7 Φ [°]**	**N Coil**	**Va/Vb QDS**	**Va/Vb MM**
1	97	126.8	2.30	120	1	Vb	Vb
2	97	182.7	2.40	180	5	Vb	Vb
3	83	142.2	12.30	150	6/8	Va/Vb	Vb

field harmonic content produced by a magnetized coil can be analytically calculated by approximating the superconducting magnetized volume to an equivalent dipole moment with amplitude m and orientation θ in the magnet cross-section reference frame, see [4]. The phase of the different harmonic components are functions of the magnetized coil angular position, the magnet symmetry rotational order b and the harmonic order n. As already described in [5], it can be proved that the phase value of the not allowed harmonic components with an order $n = b \pm 1$ are directly correlated with the single quenched coil position inside the magnet. If multiple coils lose magnetization at the same time, the quench localization is still possible with the comparison of the phase pattern of multiple harmonics. The analytical model results have been also validated through finite element simulations and better evaluate the effect of the iron permeability saturation on the harmonic coefficient phase and amplitude, see fig. 2. The results of the simulations show that iron has no effect on the not allowed harmonic phase values, while, on their amplitudes, the hysteretic behaviour of iron has to be taken into account to properly model the residual field quality.

3. – HO series production results and discussion

All the magnets of the series have been already produced in 2022 and, by the end of January 2023, magnet testing at 4.2 K will be completed. Most of the quench events (192/247 equal to 77.73%) have been observed in the 6 skew quadrupoles produced largely due to the bigger stored energy and to the dimensions of the coil increasing the probability of mechanical instabilities of the superconducting wires. All 247 quench events have been analyzed with the harmonic field analysis method, and all the reconstructed quenched coil positions are in agreement with the voltage tape results of the quench detection system (QDS). An example of the comparison between the measured and simulated $n = b+1$ harmonic phase values is reported in table I. All the measured values, in case of single coil quench event, can be considered compatible with a simulated phase because their mis-

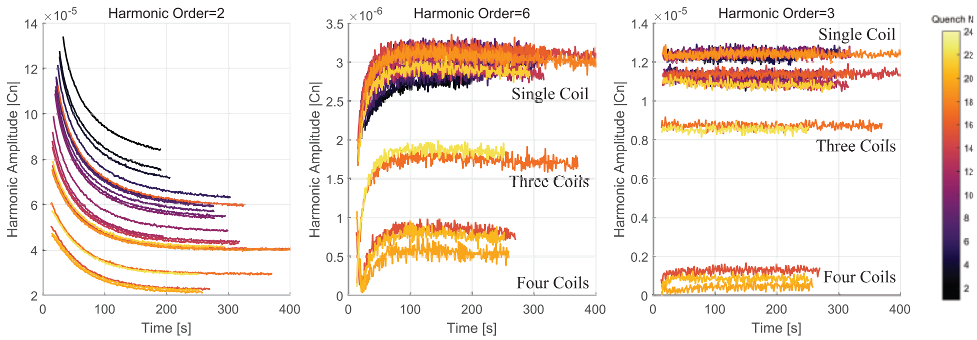

Fig. 3. – Time development of different harmonic components amplitude after several quench events occured in the MQSXF5 magnet. Here are reported the main field harmonic (left), the first allowed harmonic (center) and the first one not allowed (right).

match is of the order of 5.1σ, whereas all other possible match would give a discrepancy at least larger than 30σ in case of the dodecapole and up to 80σ for the quadrupole. In case of multi-coil quench events (event 5,13 of the MQSXF2 and event 3 of the MCTXF3 in the table I), to retrieve their positions in the magnet, the phases of different harmonic components have been considered. Among all the quench events occurred in the skew quadrupole magnets, 33% of them have been registered as multi-coil quench events. Besides the phase evaluation of the different harmonic contents, also their amplitude can be used to evaluate the number of quenched coils during an event, see fig. 3. The amplitude of the harmonics coefficients is discretized according to the number of quenched coils in the magnet and decreases as it increases. Since measurement is performed "post-mortem" after the magnet discharge, no information on the timing of the quench development in the different coils can be obtained. However, it is interesting to point out the time dependence of the harmonic coefficients after current discharge. The magnetic measurement system performs the harmonic analysis with a 1 Hz frequency and the acquisition is performed until the coils are thermalized and the magnet powered. During this period, the power supply is shut down and no current flows in the coils. The exponential variation of the allowed harmonic components, with a time constant of $\tau \sim$100 s, is not compatible with typical superconducting transient effects or eddy currents in the wires or filaments. Moreover, the constant behavior of the not allowed harmonics, created only by the superconducting magnetization lost, suggests the source of this effect to be attributed to the domain magnetization relaxation of the iron laminations that compose the magnet. Further analysis is still ongoing to study the dynamic effect properties and confirm our hypothesis on iron behavior. The harmonic field analysis method, validated through the comparison with the QDS quench reconstruction, proved to be an important diagnostic technique in the characterization of superconducting high order magnets, also showing multi-coil quenched events not previously observed with conventional voltage taps analysis.

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