MAGNETIC-FIELD MEASUREMENTS AND PRELIMINARY MODELLING FOR THE OPERATION OF THE HIGH-ORDER CORRECTOR MAGNETS FOR HL-LHC

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Abstract

High-order corrector magnets will be required for the magnetic system of the HL-LHC inner triplets. These magnets are based on a superferric design thus the saturation of the iron poles affects the field generated in the aperture, i.e., the magnetic transfer function shows a nonlinearity. One of the challenges for the operations of these magnets is to find a suitable fit of the magnetic transfer function able to predict the field generated, given the current, within the acceptable level of 1%. In the LHC, the magnet operations rely on a magnetic field model (FiDeL) for deriving the current level from the required field strength. This paper presents a first iteration of the field modelling for the new high-order corrector magnets.

INTRODUCTION

A new set of superconducting magnets, including several correctors, is required for the HL-LHC at CERN. The high-order correctors, developed by the LASA laboratory (INFN-Milano), are the first superferric magnets to be installed in a high-energy collider [1].

A total of 54 correctors, divided in six families, will cover different harmonic orders, namely: the skew quadrupoles MQSXF [2], the sextupoles MCSXF and MCSSXF [3], the octupoles MCOXF and MCOSXF [4], the decapoles MCDXF and MCDSXF [5], the normal dodecapole MCTXF, and the skew dodecapole MCTSXF [6]; see Fig. 1.

As for normal conducting magnets, the field shape is given by the iron poles. The magnetomotive force, instead, is provided by Nb-Ti superconducting coils. Both iron yoke and coils are cooled to 1.9 K.

For the operations in the accelerator, an accurate prediction of the magnetic field generated by the magnets is required in order to apply the required correction strength. A suitable model of the magnetic transfer function, defined as the ratio of the generated field and the operating current, must be developed for each family of magnets. This is to provide an estimate of the value of the excitation currents to be used according to the required correction on the beam.

In this paper, we analyze the results of magnetic measurements and discuss the main aspects to be considered in view of the development of the magnetic field model for the high-order corrector magnets.

RESULTS OF MAGNETIC MEASUREMENTS

The series production magnets for the high-order correctors have been tested at LASA. The integral transfer function has been measured at a cryogenic temperature by using a rotating coil system. The tests have been carried out in vertical cryostats and with the rotating coil immersed in the helium bath [7].

The standard powering test of each magnet consisted of a pre-cycle with the current ramp up to the positive nominal current and then negative nominal current, followed by a stair-step ramp up again to the positive and then negative nominal current with plateaus at which the magnetic field is measured.

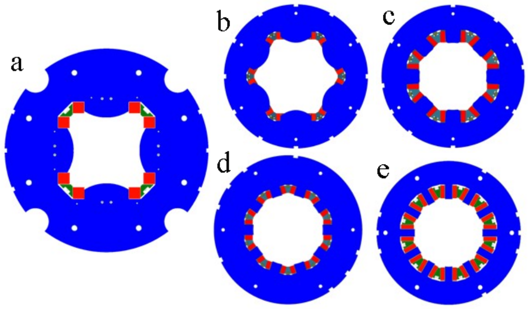

Figure 1: Cross-sections of the high-order corrector magnets [8]: a) the skew quadrupole, b) the sextupole, c) the octupole, d) the decapole, and e) the dodecapole. The coils are depicted in red and the iron yoke in blue.

The results of the magnetic measurements performed on a first batch of magnets are reported in Table 1 [7]. The integrated strength, defined as the main field measured at the 50 mm reference radius times the magnetic length, is compared to the computed value from FEM simulations. In addition, the saturation and the magnetization hysteresis are given. The saturation is evaluated as the difference of the measured transfer function between the value at low-field linear regime and the value at nominal, normalized by the value at low-field. The hysteresis is evaluated as the difference of the measured main field between up-ramp and down-ramp, normalized by the field at nominal level. Figure 2 shows the magnetization hysteresis for the normal dodecapole MCTXF.

From the results of the magnetic measurements we can deduce: i) the magnetization hysteresis is within an acceptable range for all magnets, and ii) the saturation varies from 16% for the MCSXF to 67% for the MCTSXF; therefore it

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has to be taken into consideration in the magnetic model. Furthermore, the absolute calibration of the field strength should be cross-checked with a more accurate measurement system, such as the stretched wire.

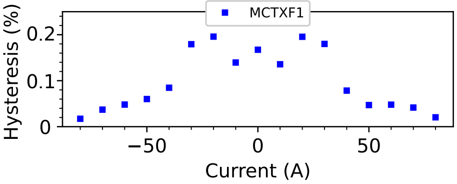

Figure 2: Hysteresis evaluated for the MCTXF magnet family based on magnetic measurements of a single magnet.

MODELLING OF THE TRANSFER FUNCTION

The FiDeL Model

For the LHC, the *Field Description for the LHC* (FiDeL), a semi-empirical and parametric model, is used to determine, for each main magnet or for families of corrector magnets, the level of current for the required field strength [9]. FiDeL is based on fitting the magnetic measurements with functions that keep the physical meaning of the different components contributing to the total field in the magnet aperture. The model uses different levels of complexity, starting from a geometric component that describes the linear dependence of the magnetic field on the current, on top of which other terms describing the nonlinear effects can be added.

For corrector magnets, the magnetic transfer function must be typically provided with an accuracy of 1%, relative to the nominal level. As discussed in the previous Section, the high-order corrector magnets for HL-LHC show a considerable nonlinearity at high field due to the saturation of the iron yoke. Hence, with an approximation suitable for this purpose, the main field of order m can be modelled by considering the geometric component and the contribution from iron saturation [9]:

$$B_m(I) = \gamma_m I + \sum_{i=1}^{N} \sigma_m^i I \sum(I, S_m^i, I_{0m}^i, I_{\text{nom}}), \qquad (1)$$

where:

$$\sum(I, S, I_0, I_{\text{nom}}) = -\frac{1}{2}\left[1 + \text{erf}\left(S\left(\frac{|I| - I_0}{I_{\text{nom}}}\right)\right)\right]$$

$\text{erf}(x)$ is the error function, γ_m is the geometric term, I is the excitation current, N is typically 1 or 2 depending on the shape of the iron yoke, I_{nom} is the nominal current while σ, S and I_0 are the fitting parameters.

Fit of the Saturation Component

The first set of results from magnetic measurements have been analysed considering only the data-points measured at the plateaus. For each magnet, a geometric term has been calculated by adjusting the linear fit for selected data points of a reference cycle and within the linear range below saturation. Then, the saturation contribution has been modelled using the second term in Eq. (1). The averaged fit for each magnet family is then reported.

The first analyzed case is the sextupole, the least affected by saturation. The transfer functions, measured on the magnets MCSXF01 and MCSXF04, and the proposed FiDeL model are shown in Fig. 3. The maximum error between the measured data and the proposed model is ±0.3%, as shown in Fig. 4, which is well within the acceptable range.

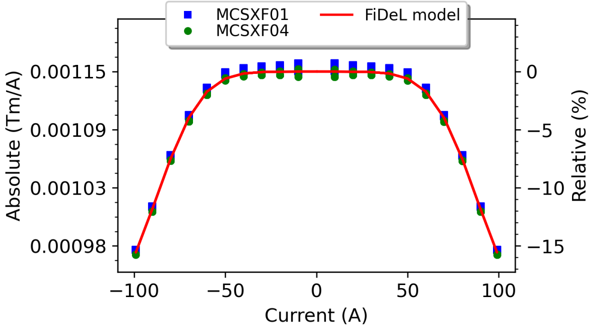

Figure 3: The measured transfer function of two sextupole magnets and the FiDeL model for the MCSXF magnet family.

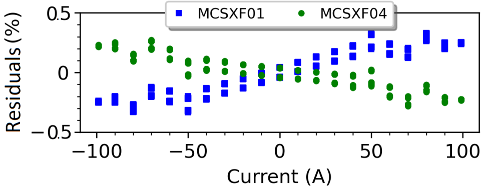

Figure 4: Modelling residuals for the MCSXF magnet family.

The second case is the decapole which shows, among the high-order correctors, an intermediate level of saturation. The comparison of the transfer function, measured on the magnets MCDXF01, MCDXF05 and MCDXF06, and the proposed FiDeL model is shown in Fig. 5, whereas the residuals of the fit are shown in Fig. 6. The model is accurate within ±1.0%, which is within the acceptable range.

A more complex case is the dodecapole which shows, among the high-order corrector magnets, the largest saturation. The measured transfer function of the MCTXF01 is shown in Fig. 7. As this magnet exhibits a strong saturation, 64% in relative terms, we tried two different models: i) with one saturation component $N = 1$ (model 1), and ii) with two saturation components $N = 2$ (model 2). Figure 8 shows the

Table 1: Computed and Measured Integrated Strength [7]

Magnet order		2	3	4	5	6	6
Magnet family		MQSXF	MCSXF	MCOXF	MCDXF	MCTXF	MCTSXF
Magnetic length	(mm)	401	168	145	145	469	99
Nominal current	(A)	174	99	102	92	85	84
Computed integrated strength	(mT m)	700	93.5	70.8	38.7	86.1	17.2
Measured integrated strength	(mT m)	719.6	95.27	71.55	39.59	88.51	17.36
Saturation	(%)	43	16	44	33	64	67
Hysteresis	(%)		0.08		0.10	0.14	

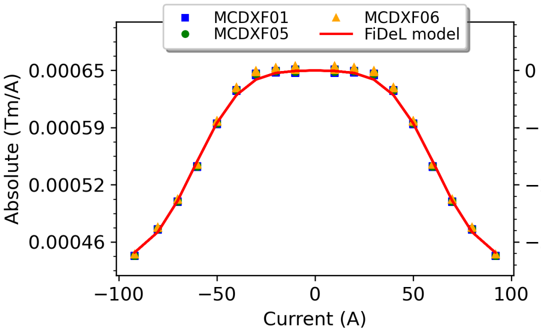

Figure 5: The measured transfer function of three decapole magnets and the FiDeL model for MCDXF magnet family.

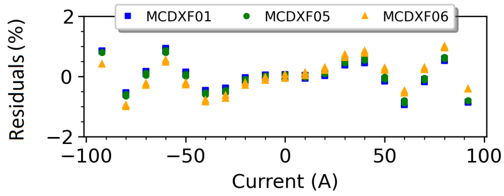

Figure 6: Modelling residuals for the MCDXF magnet family.

residuals of both fits. The maximum value of the residuals is ±4.5% for model 1 and ±1.5% for model 2. In the case of this magnet family, the accuracy of the model is limited by the complex shape of the transfer-function curve due to the large saturation.

Table 2 summarizes the parameters of the FiDeL models developed for the high-order corrector magnets using one saturation term ($N = 1$).

Table 2: FiDeL Fit Parameters for some High-Order Correctors

Param.	**Unit**	**MCSXF**	**MCDXF**	**MCTXF**
γ	Tm/kA	1.148	0.655	3.042
σ	Tm/kA	0.250	0.101	1.947
I_0	A	87.85	80.41	28.22
S	–	3.55	4.38	2.62
I_{nom}	A	99	92	85

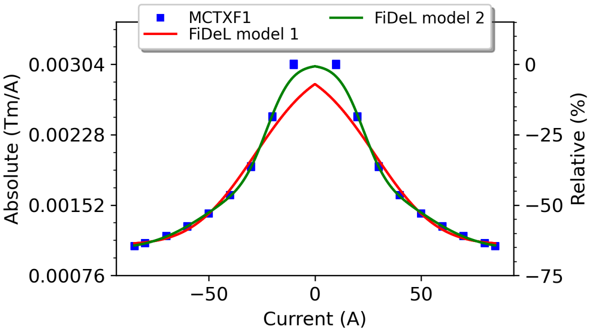

Figure 7: The measured transfer function of one dodecapole magnet and two FiDeL models for MCTXF magnet family.

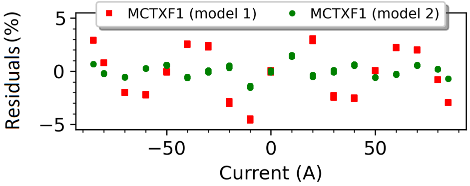

Figure 8: Modelling residuals for the MCTXF magnet family.

CONCLUSIONS

The magnetic transfer function of the high-order corrector magnets for HL-LHC has been analyzed in order to check the accuracy of possible FiDeL models. The preliminary studies show that for all families of magnets, a model composed of a linear term and one saturation component provides a suitable accuracy. The residuals are within ±1% except for the dodecapole magnets which show the largest saturation. For the dodecapole family of magnets the error is in the order of ±4.5% using a model with one saturation component.

In conclusion, for each magnet family the magnetic transfer function can be modelled in FiDeL by using:

- one geometric term from the fit of the measured average curve;
- one saturation component as well from the average on each family;
- no magnetization component since the measured hysteresis is in the order of 0.1%.

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