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**Comparison between Electromagnetic Models and Magnetic Measurements
in the LHC Magnets**

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Abstract—We present a comparison between the electromagnetic model of the main LHC magnets and the magnetic measurements carried out during production. The goal of this study is to test the validity range of the model and to uncover discrepancies between models and reality. We decompose the field computation into several parts: geometry (coils, collars, and yoke), persistent currents in the superconducting cables, and saturation of the iron yoke. For each component we give the agreement between model and measurements. This gives an indication about the precision one can expect to obtain from a simulation code - this information is particularly relevant for future upgrades of the LHC.

Index terms— Accelerator magnets, BEM-FEM numerical code, magnetic analysis, simulation of magnetic models

I. INTRODUCTION

THE operation of the LHC accelerator depends upon accurate knowledge of the magnetic field integrals as function of currents and of some major field errors [1]. This knowledge is acquired from magnetic measurements during the magnet production and complementary information is obtained through beam measurements [2]-[4].

The magnetic behavior for superconducting electromagnets depends on different physical phenomena and three main ranges can be defined: *low field*, *linear*, and *high-field* [5]. In the linear range the magnets produce a field proportional to the current, given by the coil geometry in the superconducting magnets. The low field range is perturbed by the presence of significant magnetization in the superconducting strands. The high field region is where the iron yoke saturates, and the iron permeability drops significantly. For the so-called transfer function T_f , i.e. the field divided by the current one can write

$$T_f(I) = \gamma + F_s(I) + F_m(I) \quad (1)$$

where γ is the nominal linear part (including coil geometry without structural deformations and with linear iron contribution), F_s is the saturation and F_m the magnetization of the cables. For high order harmonic components one has a similar decomposition, for instance for normal multipoles

$$b_n(I) = \gamma_n + F_{s,n}(I) + F_{m,n}(I) \quad (2)$$

The aim of this paper is to review the degree of agreement between the magnet model and the magnetic measurements

for the main LHC superconducting dipoles and quadrupoles [6]. We have omitted most of the corrector magnets due to space limitations. For the same reason we have favored the use of tables instead of figures.

The experimental data are the magnetic measurements carried out during the production [2], [3]. All magnets have been measured at room temperature, and a fraction of them in operational conditions (1.9 or 4.2 K). Measurements often provide the detail of the field variation along the magnet axis: here we only consider the integral values.

The electro-magnetic design of most LHC magnets was done with the in-house developed software ROXIE [7]. Therefore a library of 2D models (cross-section) has existed since the beginning of the magnet design period. Two years ago a new major version of ROXIE was released (version 10). The new version has a different input data format, so the existing models had to be converted. We profited of this change to make a final comparison of the magnetic measurements with the existing models, add a few models that were missing, and cross-check against the final version of drawings. We found a few differences which were incorporated in the models.

The main sources of errors in electromagnetic modeling are (i) Geometrical modeling, due a limited knowledge of the magnet, and to the deformation of the coil during assembly, cool-down and excitation; (ii) 3D effects: here we compare integrated measurements, including heads, with 2D simulations; (iii) Material data, i.e., the iron B-H curve, and the critical current used to estimate the magnetization in the superconductor; (iv) Approximation errors in the description of the persistent currents; (v) Numerical errors associated to the solution of the equations, which are in general negligible w. r. t. to the other sources.

The work described in this paper is important to ensure the best knowledge of the machine for the next 20 years operation. It allows us to assess the discrepancy between predictions and measurements. Furthermore, it is particularly relevant for future projects, such as the LHC upgrade [8], as it allows judging the feasibility and/or the tightness of beam dynamics requirements.

The simulations documented in this paper have been carried out with a continuous series of discrete evaluations of field as function of current. This feature has been used to mimic the actual LHC machine cycle: we use a pre-cycle, followed by a ramp to nominal current.

Reference radius for high orders is usually set at 1/3 of the magnet aperture diameter. Please note that in our case, following the LHC convention [6], all fields and harmonics are given for the reference radius of 17 mm: this is 30% of the 56 mm aperture main dipoles and quadrupoles, 24% of the 70 mm aperture triplet MQXA and MQXB, and 21% of the 80 mm aperture separation dipoles. Therefore all high orders appear much smaller than if they were expressed using the 1/3 convention.

II. DIPOLES

A. Main characteristics

The primary function of the dipoles is to bend the two LHC beams into closed orbits [6]. This is done through the double-aperture, 8.3 T MB magnets – the workhorse of the LHC. MBR and MBX separation dipoles are used to change the nominal beam separation from 194 mm to zero in the interaction point, to 224 mm for the beam cleaning by collimators, and to 420 mm in the zone for RF cavities. The MCB corrects the orbit locally. The main magnet parameters are shown in Table I.

TABLE I
MAIN DESIGN PARAMETERS OF THE LHC DIPOLES

Magnet	Aps	mag len (m)	T op (K)	ap dia (mm)	B nom (T)	I op min (A)	I nom (A)	beam sep (mm)
MB	2	14.3	1.9	56	8.33	757	11850	194
MCB	2	0.647	1.9	56	2.93	0	55	194
MBRB	2	9.45	4.5	80	3.8	395	6050	194
MBRC	2	9.45	4.5	80	3.83	284	6050	188
MBRS	2	9.45	4.5	80	3.84	350	5750	414
MBX	1	9.45	1.9	80	3.84	345	5750	0

B. Transfer function

We define the transfer function as the central field divided by the current. Data relative to the transfer functions of the main dipoles are shown in Tables II-IV. The linear part is shown in Table II: the agreement is expressed in units, where 10000 units = 100% of the main field. One can observe that the agreement is better than 50 units, i.e. 0.5%. The MB was produced with three different cross-sections (XS1-2-3), to optimize the allowed field harmonics; we show data for all cases.

In Table III we have expressed the saturation component relative to the geometric value in Table II. The difference shows how many units the model differs from the average of the measurements. In the main LHC dipole, MB, saturation at nominal current is about 60 units, and the agreement with the model is within 15 units. Similar results are found for the MBRB and MBRC, with 50-70 units of measured saturation and 70-90 units in the model. The magnets MBRS and MBX are in a different range: here saturation is 10 times larger, i.e., 6-7%. The model is in agreement within 1.5%. A plot of the saturation component versus current for the main LHC dipoles is given in Fig. 1. Discrepancies in saturation have two main sources: the limited knowledge of the iron B - H curves, and neglecting the magnet head contributions in the model.

TABLE II MODEL VERSUS MEASUREMENTS FOR THE LHC
DIPOLES: TRANSFER FUNCTION, GEOMETRIC PART

Magnet	I (A)	measured (T/kA)	model (T/kA)	Diff (units)
MB XS1	5000	0.70798	0.70743	-8
MB XS2	5000	0.70759	0.70734	-4
MB XS3	5000	0.70720	0.70735	2
MCB	25	53.52039	53.77072	47
MBRB	3000	0.63272	0.63488	34
MBRC	3000	0.63276	0.63473	31
MBRS	2000	0.70715	0.70867	21
MBX	2000	0.70619	0.70856	34

TABLE III MODEL VERSUS MEASUREMENTS FOR THE LHC
DIPOLES: TRANSFER FUNCTION, SATURATION COMPONENT

Magnet	I (A)	measured (units)	model (units)	Diff (units)
MB	12000	-62	-78	-15
MCB	55	-194	-191	2
MBRB	6200	-67	-87	-20
MBRC	6000	-52	-69	-17
MBRS	6000	-650	-782	-132
MBX	6000	-619	-754	-135

In Table IV we express the magnetization component relative to the geometric value. In all cases, contrary to the case of high orders, the magnetization has a low impact on the transfer function: it is below 20 units and the model is in agreement within 10 units.

TABLE IV MODEL VERSUS MEASUREMENTS FOR THE LHC
DIPOLES: TRANSFER FUNCTION, MAGNETIZATION COMPONENT

Magnet	I (A)	measured (units)	model (units)	Diff (units)
MB	760	0	-5	-4
MCB	10	1	-5	-5
MBRB	400	-6	-4	2
MBRC	300	-9	-16	-8
MBRS	300	-17	-11	7
MBX	300	-12	-22	-10

Fig. 1. MB transfer function (TF): the geometric component has been removed and what remains has been expressed as units of geometric

C. Multipoles: b_3 and b_5

The allowed multipoles b_3 and b_5 , whose values are not set to zero by the symmetries of the coil, are shown in Tables V, VI and VII and Fig. 2 and Fig 3. The sextupole b_3 is a source for chromatic errors in the accelerator, and therefore it is important to know this multipole with high precision (0.1 units) [11]. The MB geometric value is optimized to partially compensate the magnetization component. The agreement for b_3 in the MB is about 1 unit for all three cross-sections, but it is much worse (up to 5 units) for the separation dipoles. We believe this is due to our inaccurate knowledge of the coil geometry. The agreement for b_5 in the MB is within 2 units. It is known that part of this discrepancy comes from coil deformation under assembly, which is here neglected [9]. The agreement for b_5 in the separation dipoles is about 1 unit.

The b_3 magnetization component is 7-8 units in the MB and the agreement is within 1 unit (see Table VI). From the computational point of view this is a challenging task, and the only case in which the inaccuracy of the physics model can play a relevant role: a 15% agreement (i.e., 1 unit out of 7-8 units) is a good result. The b_3 in the separation dipoles is in a rather wide range from 1 to 6 units. The large difference between model and measurements is not understood, and further analysis is ongoing. On the other hand, the agreement for b_5 magnetization is better than a fraction of unit for all dipoles.

Saturation is typically small for multipoles (see Table VII), i.e. not more than one unit. The only exceptions are MBRS and MBX where the model predicts 5-6 units and measurements give less than 1 unit. This needs further analysis.

TABLE V MODEL VERSUS MEASUREMENTS FOR THE LHC
DIPOL: b_3 AND b_5 , GEOMETRIC COMPONENT

Magnet	I (A)	b_3 (units)		b_5 (units)	
		meas	model	meas	model
MB XS1	5000	6.6	6.8	0.6	-0.9
MB XS2	5000	4.0	3.5	0.1	-2.1
MB XS3	5000	2.1	3.3	-0.3	-2.1
MBRB	3000	-0.6	-5.7	0.2	-0.7
MBRC	3000	-0.8	-6.0	0.1	-0.8
MBRS	2000	-2.6	-4.7	0.1	-0.8
MBX	2000	-2.6	-5.0	0.1	-0.8

TABLE VI MODEL VERSUS MEASUREMENTS FOR THE LHC
DIPOL: b_3 AND b_5 MAGNETIZATION COMPONENT

Magnet	I (A)	b_3 (units)		b_5 (units)	
		meas	model	meas	model
MB	760	-7.2	-8.0	1.1	1.0
MBRB	400	-4.4	-1.0	-0.1	0.1
MBRC	300	-6.1	-5.8	0.1	0.5
MBRS	300	-6.4	-0.7	0.0	0.2
MBX	300	-6.0	-5.3	0.1	0.3

TABLE VII MODEL VERSUS MEASUREMENTS FOR THE LHC
DIPOL: b_3 AND b_5 SATURATION COMPONENT

Magnet	I (A)	b_3 (units)		b_5 (units)	
		meas	model	meas	model
MB	12000	0.6	0.4	-0.2	0.0
MBRB	6200	0.6	0.3	-0.1	-0.1
MBRC	6000	0.7	0.6	-0.1	-0.1
MBRS	6000	-0.3	-6.6	0.2	-0.1
MBX	6000	0.9	-4.8	0.2	-0.1

Fig. 2: MB b_3 model versus measurements. The offset between the curves, 1 uni, is considered as a good agreement.

Fig. 3: MB b_5 model versus measurements. The offset between the curves, 1.5 units, is assumed to be due to the neglected effect of coil deformation.

III. QUADRUPOLES

A. Main characteristics

The primary function of the quadrupoles is to provide the focus to the beam. The MQ arc quadrupoles provide the optical function of the arcs, the MQXA and MQXB provide the final focus, and the MQM and MQY magnets match the arc optics with the final focus optics.

The main magnet parameters are shown in Table VIII: apertures range from 56 to 70 mm. Peak field in the coils vary from 6 to 8 T. There are three types of the MQM magnets, only differing in magnetic length. In this paper we use the notation MQM* to refer to the common cross-section.

B. Transfer function

The geometric part of the transfer functions of the quadrupoles are given in Tables IX. The agreement for MQXA and MQXB are within 1%. The other magnets have similar agreements as the dipoles, i.e. within 0.5%. There are two different cross-sections for MQ with similar agreement. A

known issue is that the MQ and MQY collars had higher permeability than design value [10], [11].

TABLE VIII MAIN DESIGN PARAMETERS
OF THE LHC QUADRUPOLES

Magnet	Aps	mag len (m)	T op (K)	ap dia (mm)	Gnom (T/m)	I op min (A)	I nom (A)
MQ	2	3.1	1.9	56	223	686	11870
MQM	2	2.4	1.9 or 4.5	56	200 or 160	144	5390 or 4310
MQMC	2	3.4	1.9 or 4.5	56	200 or 160	205	5390 or 4310
MQML	2	4.8	1.9 or 4.5	56	200 or 160	134	5390 or 4310
MQXA	1	6.37	1.9	70	215	418	7150
MQXB	1	5.5	1.9	70	215	717	11950
MQY	2	3.4	4.5	70	160	134	3610

TABLE IX MODEL VERSUS MEASUREMENTS
FOR THE LHC QUADRUPOLES: TRANSFER FUNCTION,
GEOMETRIC COMPONENT

Magnet	I (A)	measured (T/kA)	model (T/kA)	Diff (units)
MQ XS1	5000	0.32012	0.31954	-18
MQ XS2	5000	0.31984	0.31930	-17
MQM* 1.9K	2000	0.63033	0.62820	-34
MQXA	2000	0.53452	0.53858	76
MQXB	2000	0.31238	0.31493	82
MQY	2000	0.75486	0.75690	27

Saturation is small in the MQ and MQM (less than 0.1%), larger for MQY (0.5%), and reaches 2% and 5% in MQXB and MQXA respectively (see Table X). The agreement is considered very good.

TABLE X MODEL VERSUS MEASUREMENTS FOR THE LHC
QUADRUPOLES: TRANSFER FUNCTION, SATURATION

Magnet	I (A)	measured (units)	model (units)	Diff (units)
MQ	11000	-9	-6	3
MQM* 1.9K	5000	-8	1	8
MQXA	7000	-457	-503	-46
MQXB	11500	-192	-183	9
MQY	3500	-45	-54	-9

TABLE XI MODEL VERSUS MEASUREMENTS FOR THE LHC
QUADRUPOLES: TRANSFER FUNCTION, MAGNETISATION

Magnet	I (A)	measured (units)	model (units)	Diff (units)
MQ	680	4	1	-3
MQM* 1.9K	200	27	-23	-50
MQXA	350	38	19	-19
MQXB	700	38	-2	-39
MQY	200	25	-24	-49

Magnetization effects are relevant but no agreement is found for the MQM, MQY and MQXB, and only half for MQXA (see Table XI).

C. Multipoles: b_6

The allowed multipole b_6 is shown in Table XII. The agreement for the geometric is within 1.5 units, with the exception of the MQM. The magnetization component is very variable (1 to 11 units) but one has a good agreement within 1 unit. The saturation effects are small and in good agreement.

TABLE XII MODEL VERSUS MEASUREMENTS FOR THE LHC
QUADRUPOLES: MULTIPOLE: b_6

PERSISTENT CURRENTS, GEOMETRIC AND SATURATION

Magnet	I geometric			I magnetisation			I saturation		
		meas	model		meas	model		meas	model
	(A)	(units)		(A)	(units)		(A)	(units)	
MQ XS1	5000	4.8	3.7	680	-3.8	-4.8	11000	0.1	0.2
MQ XS2	5000	2.7	1.5	680	-3.8	-4.9	11000	0.2	0.2
MQM*	2000	4.6	-1.0	200	-10.9	-8.3	5000	0.4	0.4
MQXA	2000	0.3	-0.2	350	-2.0	-2.2	7000	0.1	0.0
MQXB	2000	-0.1	-1.4	700	-1.2	-0.5	11000	0.2	0.4
MQY	2000	1.2	1.4	200	-2.8	-3.2	3500	0.1	0.1

IV. CONCLUSIONS

We presented a comparison between magnetic model and measurements for the LHC dipoles and quadrupoles. The measured linear part of transfer functions typically agrees with the model within 0.5% (both dipoles and quadrupoles, see Table II and IX). The saturation component can be modeled with a 20% error, also when it is several percent of geometric (see Tables III and X). For field harmonics, the first order geometric b_3 (dipoles) and b_6 (quadrupoles) is often modeled within 1-2 units (see Tables VI and XI), and the magnetization part within 20% (see Tables VI and XII).

The better understanding of the discrepancies between model and measurement is a work in progress. Main open issues are: better measurements of the B-H curve in operational conditions, better knowledge of the coil geometry under deformations, 3D modeling of heads. For some magnets the behavior at low currents is critically dependent on the precycle strategy: consistency between modeling and operation should be constantly verified. This will give an enhanced capability of forecasting magnetic behavior for future projects.

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