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Abstract

After the long shut down of 2013-2014, the LHC energy will be pushed toward 7 TeV. In this range of energy, the main magnets will enter a new regime. For this reason, this paper will present a detailed study of the performance of the FiDeL model that could be critical for the operation in 2015. In particular this paper will study the saturation component and its precision in the model, the errors due to the hysteresis, and an estimate of the dynamic effects for the 7 TeVoperation.

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THE FiDeL MODEL AT 7 TeV

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Abstract

After the long shut down of 2013-2014, the LHC energy will be pushed toward 7 TeV. In this range of energy, the main magnets will enter a new regime. For this reason, this paper will present a detailed study of the performance of the FiDeL model that could be critical for the operation in 2015. In particular this paper will study the saturation component and its precision in the model, the errors due to the hysteresis, and an estimate of the dynamic effects for the 7 TeVoperation.

INTRODUCTION

The Field Description of the LHC (FiDeL) [1] is the magnetic model which describes the relation between the current and the magnetic field of the numerous families of magnets in the LHC. It is the main tool to establish the currents to be fed in the circuits of the LHC magnets, given the fields and gradients required by the beam dynamics. FiDeL is based on a series of equations (field vs current fits), a list of parameters for the fits, plus a recipe for cycling the magnets to ensure reproducibility [2-4].

Until now, the LHC magnets at collision energy of 4 TeV were operating in a linear regime, which is the easiest operational condition. Going towards 7 TeV many families of magnets will operate at a current level where the saturation effects are in the range of 10 – 500 units (i.e. up to 5%). For each magnet family the expected value of saturation component and the precision that is associated to the model is given.

Hysteresis errors are also analysed. This is done mainly for the quadrupole magnets installed in the matching section and dispersion suppressor. An estimate for the error induced due to the hysteresis branching is given for the most critical magnets.

Finally, the relevance of dynamical effects is discussed. It is well-known [3] that the amplitude of the dynamical effects on the top energy, and will increase when this energy is increased. During the 2010-12 operation dynamic effects were clearly visible in operation both in the tune and in the chromaticity as decay and snapback [5, 6], with typical decay values of 0.02 of tune [7] and 25 units of chromaticity [8].In this paper a review of the knowledge of the scaling law is made together with a forecast for the 7 TeVoperation.

SATURATION COMPONENT OF THE FiDeL MODEL

In both superconducting and normal conducting magnets, when the iron plays a relevant role and when the field in the iron is larger than 2 T one has a non-linearity due to saturation. The saturation contribution is always given with respect to the geometric component, this is defined as the average ramp-up and ramp-down value at the current value at which the effect of the persistent currents and DC magnetization is over and the saturation contribution is not yet present.

The present version of the FiDeL model, built over the large set of measurements carried out during the LHC magnet production, was used to obtain the saturation component for each family of magnets at 7 TeV energy. This is given in Table 1, together with the uncertainty [9] associated to the model, when available.

From Table 1it was concluded that the saturation component and its uncertainty should not pose any problems for operation except for; the main dipoles where they can produce a small amount of beta-beating due to mismatch with the quadrupoles and the inner triplets where they are very critical during the squeeze, especially at very low β^* values.

Table 1: Saturation components in the transfer function for 7 TeV operation. The numbers in the parenthesis next to the magnets' name stand for the IP number in which they are installed.

Magnet	Current (A)	μ (units)	σ (units)
MB	11850	-59	1.87
MQ	11870	-13	0.12
MQXA (1,5)	6800	-442	-
MQXA (2,8)	7180	-472	-
MQXB (1,5)	11400	-179	-
MQXB (2,8)	11960	-187	-
MQM @ 1.9 K	5390	-11	0.10
MQM @ 4.5 K	4310	-6	0.13
MQY	3610	-53	0.51
MBX (2,8)	5800	-578	2.16
MBRC (1,5)	4400	-4	0.19
MBRC (2,8)	6000	-53	0.79
MBRS (4)	5860	-621	-
MBRB (4)	6150	-64	-
MBW (3,7)	640	-86	0.61
MBXW (1,5)	690	-222	11.28
MCBW (3,7)	500	-107	6.00
MQWA (3,7)	710	-631	24.25
MQWB (3,7)	600	-74	16.77
MCBM	55	-195	-
MCBC @ 1.9 K	100	-357	-
MCBC @ 4.5 K	80	-110	-
MCBY	72	-342	-
MCBXH	550	-180	-
MQT/MQS	550	-665	-
MQSX	550	-130	-
MSM	550	-165	-

HYSTERESIS

Hysteresis effects are present in all the superconducting magnets at low current when cycling between low and high current. The branching of the transfer function curve due to hysteresis is not implemented inFiDeL as it creates singularities in the current functions (or in its time derivatives) generated for the power converters. For magnets which after ramping up to nominal current have to be ramped down, e.g., during squeeze, an error equivalent to twice the hysteresis component is introduced as the model is on the wrong branch, as shown inFig.1.

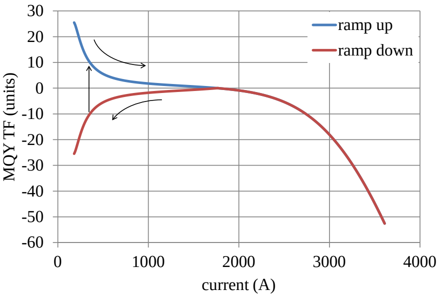

Figure 1: Transfer function of the MQY magnets.

This effect is present during the squeeze process in some insertion quadrupoles, also called independently powered quadrupoles (IPQs). The β* during the squeeze in the four experimental IPs starts at 11/10/11/10 m (values in metres for IP1/IP2/IP5/IP8, respectively) corresponding to the optics configuration used from injection to the end of acceleration, during the 4 TeV operation this was squeezed to a value of 0.6/3/0.6/3 m. For the 7 TeV operation, the estimate of the minimum β*, based on available mechanical aperture and collimators settings, is 0.4/10/0.4/3 m. In Table 2the IPQs which enter in the hysteresis regime at β* of 0.4/10/0.4/3 m for the 7 TeV operation are listed together with the error due to the hysteresis effect. In most cases the error is a few units, with the exception of a few Q6 where it reaches the value of 25 units, and a few Q5 where it reaches 10 units. The strategy will be to implement this correction as a trim at the very end of the squeeze process.

Table 2: IPQs operating in the hysteresis region at 7 TeV. The powering and corresponding magnetic errors for both apertures (named ap1 and ap2) are shown in the four columns.

Magnet	**Location**	**Current (A)**		**Error (units)**	
		ap1	**ap2**	**ap1**	**ap2**
MQY	Q5.R8	na	1543	na	1.1
MQML	**Q5.R1**	**1219**	**1553**	**9.1**	**6.7**
	Q6.R1	**388**	**505**	**25**	**23**
	Q8.L2	2400	na	3.9	na
	Q6.L2	2554	2582	3.7	3.7
	Q6.R2	2650	2660	3.7	3.7
	Q6.L5	**389**	**471**	**25**	**24**
	Q5.L5	2225	**1539**	4.2	**6.7**
	Q5.R5	**1554**	**1219**	**6.7**	**9.1**
	Q6.R5	**507**	**389**	**22.8**	**25**
	Q8.L6	2121	na	4.4	na
	Q8.R6	na	2102	na	4.5
	Q6.L1	**472**	**388**	**24**	**25**
	Q5.L1	**1540**	2227	**6.7**	4.2
MQM	Q6.L2	2554	2582	3.7	3.7
	Q5.R2	na	2670	na	3.7
	Q6.R2	2650	2660	3.7	3.7

IMPACT ON OPTICS

The impact of hysteresis and saturation effects on the beta-beating has been studied via numerical simulations. The effect of the uncertainty due to the saturation errors fromTable 1was studied together with the hysteresis errors from Table 2. This was done by simulating 60 cases with random gradient errors following a Gaussian distribution within the saturation uncertainty in order to estimate the impact on the beta-beating. The resulting histograms of the beta-beating for the squeezed optics are shown in Fig.2. It can be concluded that the peak beta-beating is around 1%, which is a negligible value, even if compared with the 5-10% beta-beating obtained after correction in the LHC [10].

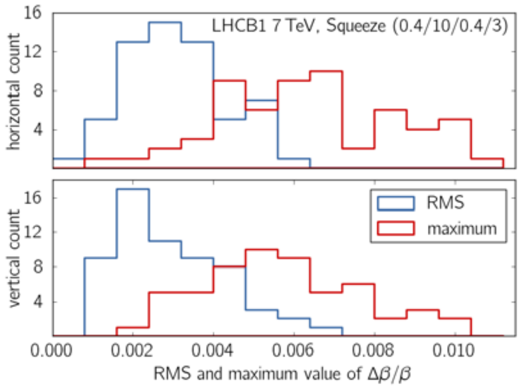

Figure 2: Distribution of the rms and maximum beta-beating for the squeezed optics.

TUNE DECAY AT 7 TeV

After 1000 s on the injection plateau, an average tune decay of -0.005 ± 0.002with a time constant τ = 1000 s has been observed in the LHC through measurements of the tune.The LHC has five different quadrupole types: one in the main arc cell (MQ), two (MQY and MQM) in the dispersion suppressor (DS) and matching section (MS), and two (MQXA and MQXB) in the interaction region (IR) [11]. All of these contribute to the tune value and therefore to the tune decay. Table 3summarises the decay amount as expected by each family of magnets based on the magnetic measurements for the 4 TeV and 7 TeV. The expected average total tune decay is of -0.0045 units at 4 TeV and -0.0094 units at 7 TeV, an increase by a factor of 2.

Table 3: Decay of the transfer function (TF) as expected at 4 TeV and 7 TeVoperation based on magnetic measurements.

Family	Average decay after 1000 s at 4 TeV		Average decay after 1000 s at 7 TeV	
	TF	tune	TF	tune
MQ	0.10	6×10^{-4}	0.17	1×10^{-3}
MQM	-0.80	-8×10^{-4}	-2	-2×10^{-3}
MQML	-0.80	-8×10^{-4}	-2	-2×10^{-3}
MQMC	-0.80	-8×10^{-4}	-2	-2×10^{-3}
MQY	-3.40	-1×10^{-3}	-3.4	-1×10^{-3}
MQXA	-0.75	-4.5×10^{-4}	-1.5	-9×10^{-4}
MQXB	-2.1	-1.26×10^{-3}	-4.2	-2.5×10^{-3}
Total		-4.5×10^{-3}		-9.4×10^{-3}

CHROMATICITY DECAY AT 7 TeV

Chromaticity decay was studied through the use of magnetic and beam-based measurements. This consisted of the series measurements, which are all the magnetic measurements which were done before the installation of the magnets before 2008 [12]. Following the first operation of the LHC, further measurements on spare magnets were required to simulate the LHC operational conditions. During the operation of the LHC it has been possible to perform beam-based measurements, from which the equivalent magnetic behaviour was deduced. A summary of the different type of measurements available together with the measured decay is given in Table 4.

The series measurements were used to obtain the first estimates of the decay amplitude. From these measurements, the b_3 decay amplitude was observed to be equal to 2.5 units at infinity with a time constant of 200 s [3].During the 2011 and 2012 operation, the flattop current was limited to 6/6.8 kA (3.5/4 TeV). From magnetic measurements performed at such operating conditions, it was found out that the b_3 decay amplitude was around 0.5 units at infinity, i.e., a factor of 5 less than that observed in the series measurements. This reduction factor is in line with the scaling given by the powering history scaling law [3]. The decay amplitude observed in the 4 TeV magnetic measurements was confirmed through beam-based measurements. In this case a b_3 decay amplitude of 0.4 units with a time constant of 600 s was observed. Following the long shut down, the LHC will be working at an energy of 6.5 to 7 TeV. This is equivalent to a flattop current of 11 to 11.8 kA. Magnetic measurements performed in these conditions gave a decay amplitude of around 0.6 units. This means that the decay amplitude of chromaticity (and the associated snapback) is expected to increase by a factor of 1.4 when compared to the 4 TeV operation.

Table 4: Decay amplitude of the b_3 component as observed during magnetic and beam-based measurements.

Measurement name	Description	Decay amplitude at infinity (units of b_3)
Series measurements	dI/dt = 50 A/s I_{FT} = 12 kA	2.49
4 TeV magnetic measurements	dI/dt = 10 A/s I_{FT} = 6.8 kA	0.47
7 TeV magnetic measurements	dI/dt = 10 A/s I_{FT} = 12 kA	0.56
Beam-based measurements	dI/dt = 10 A/s I_{FT} = 6.8 kA	0.40
LSA settings	2012 control settings	0.39

CONCLUSIONS

At 6.5 - 7 TeV, which is the expected LHC energy in Run II, most of the main magnets will be operating in the saturation region of their transfer function. The errors stemming from a limited knowledge of this component, which can be of the order of 10-50 units, should be easily corrected by feedback system (orbit, tune) and through beta beating measurements (triplets and IPQ).

The present FiDeL model consists of the ramp up branch only, this cause an intrinsic error in the magnetic model. Such situation is encountered in some of the quadrupoles during the squeeze process. During this process, about 20 magnets are ramped down to current levels where the hysteresis is significant, with the worst case being the Q6 MQML magnets. For these magnets an error of 25 units in the gradient is expected, which would induce additional beat beating. This error can be compensated by subtracting ad hoc trims in these magnets.

The estimated hysteresis and saturation errors have been used to simulate the resulting beta-beating expected in the LHC. The results of the numerical simulations indicate that the peak beat-beating should be negligible (1%) if the contribution from MQXA/B is not taken into account.

In the LHC, decay was observed in both tune (due to the b_2 component) and chromaticity (due to the b_3 component). Tune decay is expected to double at 7 TeV w.r.t 4 TeVoperation, and to increase by 40% for chromaticity. In both cases an analysis of beam measurements will be needed to fine tune the corrections.

REFERENCES

[1] “FiDeL home: the Field Model of the LHC.” Internet: https://cern.ch/fidel, [Aug. 2013].

[2] N. J. Sammut, et al., Phys. Rev. ST Accel. Beams**9**, 012402 (2006).

[3] N. J. Sammut, et al., Phys. Rev. ST Accel. Beams **10**, 082802 (2007).

[4] N. Sammut, et al., Phys. Rev. ST Accel. Beams **12**, 102401 (2009).

[5] D. A. Finley, et al., in Proceedings of the 12th Particle Accelerator Conference (IEEE, Washington, DC, USA, 1987), pp. 151–153.

[6] L. Bottura, L. Walckiers, and R. Wolf, in *IEEE Transactions on Applied Superconductivity,* June 1997 vol. 7, no. 2, pp. 602-605.

[7] N. Aquilina, et al., “Expected and measured behaviour of the tune in the LHC operation at 3.5 TeV.” in Proc. IPAC, 2012, pp 3554-3556.

[8] N. Aquilina, et al.,“Chromaticity decay due to superconducting dipoles on the injection plateau of the Large Hadron Collider.” Phys. Rev. STAccel. Beams **15**, (2012) 032401.

[9] P. Hagen, private communication.

[10] R. Tomás, T. Bach, R. Calaga, A. Langner, Y. I. Levinsen, E. H. Maclean, T. H. B. Persson, P. K. Skowronski, M. Strzelczyk, G. Vanbavinckhove, and R. Miyamoto, “Record low β beating in the LHC”, Phys. Rev. ST Accel. Beams **15**, 091001 (2012).

[11] O. Brüning, et al., “LHC Design Report Volume I The LHC Main Ring,” CERN, 2004.

[12] L. Walckiers, et al., “Towards series measurements of the LHC superconducting dipole magnets”, *in Proc. of PAC*, 1997, Vol. 3, pp. 3377-3379.