EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
European Laboratory for Particle Physics

Large Hadron Collider Project

LHC Project Report 1107

MEASUREMENT AND EFFECTS OF THE MAGNETIC HYSTERESIS IN THE LHC CROSSING ANGLE AND SEPARATION BUMPS

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(1) UOM: The University of Malta & CERN

Presented at
EPAC'08, 11th European Particle Accelerator Conference, Genoa, Italy - June 23-27, 2008

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MEASUREMENT AND EFFECTS OF THE MAGNETIC HYSTERESIS ON THE LHC CROSSING ANGLE AND SEPARATION BUMPS*

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Abstract

The superconducting orbit corrector magnets (MCBC, MCBY and MCBX) in the Large Hadron Collider (LHC) at CERN will be used to generate parallel separation and crossing angles at the interaction points during the different phases that will bring the LHC beams into collision. However, the field errors generated by the inherent hysteresis in the operation region of the orbit correctors may lead to unwanted orbit perturbations that could have a critical effect on luminosity. This paper presents the results obtained from dedicated cryogenic measurements on the orbit correctors and the resulting simulations performed to quantify the impact of the hysteresis on the LHC orbit.

INTRODUCTION

The Large Hadron Collider (LHC) now under construction at CERN, relies on superconducting orbit corrector magnets to trim key beam parameters. During high luminosity LHC operation, three types of dipole magnets [1] will be used to generate the parallel separation at injection and the crossing angles at top energy. As shown in Figure 1, the MCBC and the MCBY are placed before the triplets and are controlled independently for both beams. The MCBX are placed in the part of the accelerator where the beams share the same vacuum chamber.

Along with clear advantages, the superconducting magnets suffer from persistent current effects [2] and are therefore hysteretic. Hysteresis affects the instantaneous value of the field generated by a corrector and it makes it dependent on the powering history.

Field errors due to hysteresis in the orbit correctors are expected to affect the orbit position at the IP as well as the crossing angle. The purpose of the crossing angle is to avoid unwanted long-range collisions. It is therefore important to know how big this effect will be in order to control the magnets appropriately.

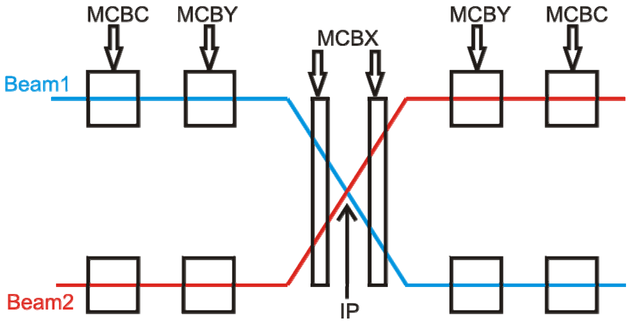

Figure 1: Magnet configuration around the interaction point.

The maximum uncertainty on the value of the magnetic field corresponds to the width of the hysteresis loops of the magnets. Therefore we can set the upper estimate of the reproducibility to be the width of the hysteresis loop.

MAGNET CONTROL

The LHC control system will rely on the Field Description for the LHC (FiDeL) to provide a field forecast of the magnetic elements of the machine [3]. This system is based on magnetic measurements performed at warm and cold conditions together with a series of equations that describe the different contributions of the magnetic field.

The magnet transfer functions are used to generate the magnetic field trims and are highly nonlinear at high field due to the saturation of the iron. Hence to a first approximation, the geometric component and the iron saturation contribution must be modelled to generate the magnet transfer function [4]. Note that the hysteresis is not modelled so as to calculate the relevance of the effect. Therefore the model chosen for the transfer function of the orbit correctors is:

$$TF = \gamma_m + \sum_{i=1}^{N} \sigma_m^i \Sigma\left(I, S_m^i, I_{0m}^i, I_{nom}\right) \tag{1}$$

where

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

and where erf(x) is known as the error function:

$$erf(x) = \frac{2}{\sqrt{\pi}}\int_0^x e^{-t^2}\,dt \tag{3}$$

γ is the geometric parameter which can be obtained from a warm/cold correlation as shown in [3]. I is the excitation current and N is typically 1 or 2 depending on the complexity of the geometry of the iron yoke. I_{nom} is the nominal current used to normalize the equation whilst σ, S and I_o are the fitting parameters.

MCBC AND MCBY

Magnetic Measurements

The orbit correctors were tested in the dedicated test facility used for the corrector magnets (Block 4) [5]. One MCBC magnet and one MCBY magnet were measured in cryogenic conditions to obtain their transfer function.

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*Work supported by CERN [#]nicholas.sammut@cern.ch

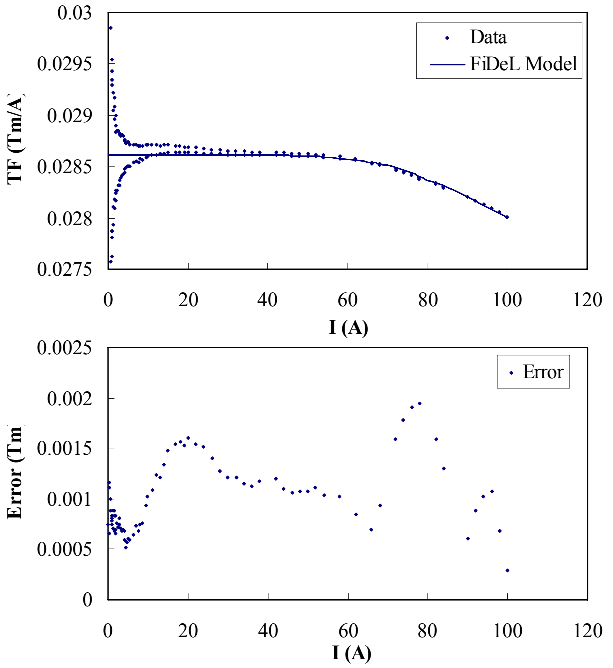

Figure 2: (top) the measured TF and the FiDeL model for the MCBC (bottom) the modelling error for the MCBC.

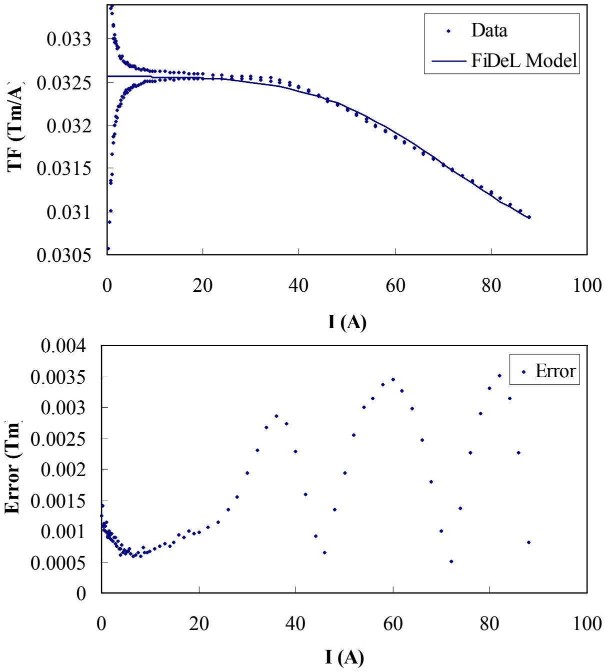

Figure 3: (top) the measured TF and the FiDeL model for the MCBY (bottom) the modelling error for the MCBY.

Table 1: Errors Due to the Hysteresis in MCBC & MCBY Magnets

	Vertical Plane		Horizontal Plane	
	Position (Beam σ)	Angle (μrad)	Position (Beam σ)	Angle (μrad)
IP1	0.04	1.5	0.06	1.3
IP2	0.04	0.4	0.05	0.3
IP5	0.04	1.3	0.05	1.5
IP8	0.05	0.3	0.03	0.4

The magnets were first pre-cycled so as to obtain the main hysteresis loop. The TF was then modelled using the equations shown above and the modelling error was hence obtained and used in the MAD simulations to calculate the relevance of the hysteresis effect. Figure 2 shows the measured and modelled TF of the MCBC as well as the difference between the two. Figure 3 shows the same for the MCBY.

MCBC and MCBY Simulation Results

The simulations to study hysteresis effect were performed for the MCBC and MCBY at the four LHC interaction points for Beam 1 (all at the same time) by using the FiDeL model error. All simulations were performed with the nominal collision optics V6.500 from MAD-X [6] and the dipole strength file from a dedicated algorithm generating the errors ΔB(I) with random signs. Table 1 summarizes the results obtained.

The error in position is approximately 5% of a beam σ whilst the angle of the order of 1.5 μrad. These values are very small and well within the errors originating from beam-beam effects the latter being about 0.1 to 0.2 σ offset and an angle of about 5 μrad [7]. Therefore in this case, the hysteresis effect is negligible and can be ignored.

MCBX

Magnetic Measurements

8 MCBX (inner coil) and 13 MCBX (outer coil) magnets were measured in the dedicated test facility used for corrector magnets (Block 4). The magnet TFs are shown in Figures 4 and 5 together with the FiDeL model that was obtained by considering the geometric and saturation contribution as shown above.

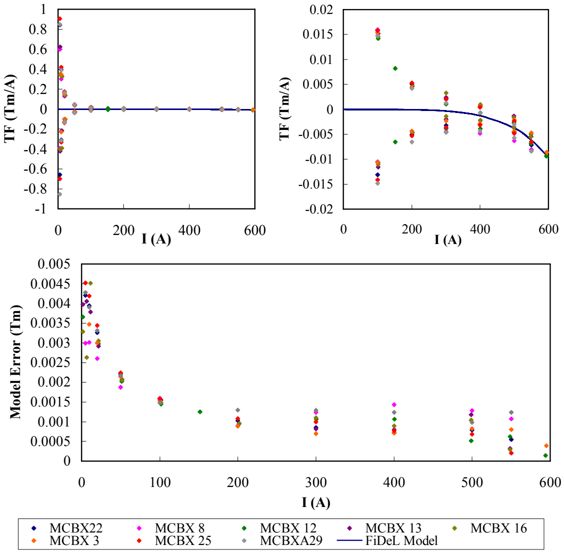

Figure 4: (top left) the measured TF and FiDeL model for the MCBX inner coil (top right) the measured TF and FiDeL model for the MCBX inner coil zoomed in to show the saturation, (bottom) the FiDeL modelling error for the MCBX inner coil.

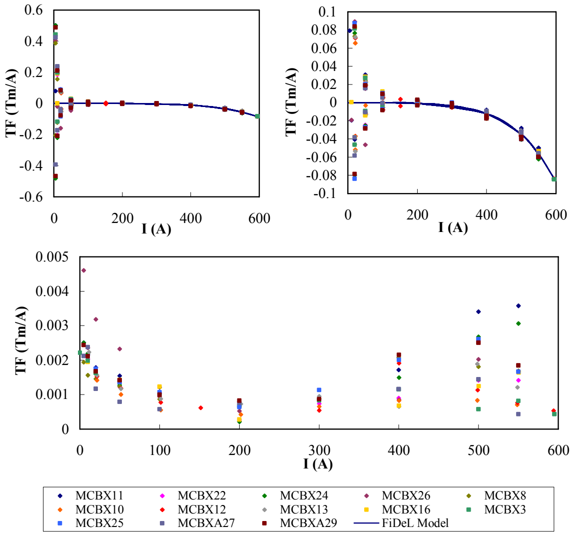

Figure 5: (top left) the measured TF and FiDeL model for the MCBX outer coil (top right) the measured TF and FiDeL model for the MCBX outer coil zoomed in to show the saturation, (bottom) the FiDeL modelling error for the MCBX outer coil.

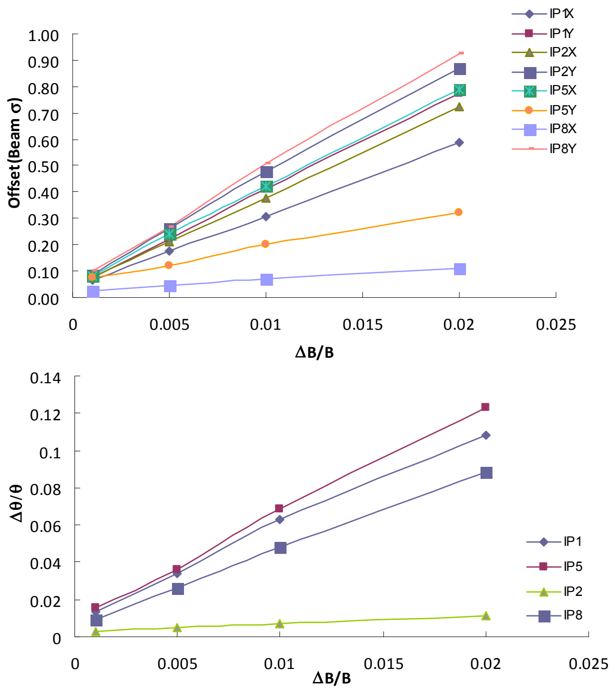

Figure 6: (top) Beam offset versus the field error and (bottom) crossing angle versus the field error.

MCBX Simulation Results

As the MCBX magnets are situated where the two beams share the same vacuum chamber, a field error in these magnets affects both beams at the same time. Using the same simulator for these magnets results in an error much larger than that obtained for the MCBC and the MCBY due to the magnetic hysteresis. The error can be of the order of 1 σ for the offset and 15 μrad for the angle. This large error demonstrates that the hysteresis effect cannot be neglected in this case. It can be shown how precise the hysteresis model should be to minimize the errors to an acceptable level.

Figure 6 (bottom) shows that the highest error is at IP5 where the half crossing angle is 142.5 μrad. In order to obtain an error of the same order as that obtained from beam-beam effects, a $\Delta\theta/\theta \sim 0.03$ is needed and therefore a model for the field with a precision of 0.2% (i.e. $\Delta B/B \sim 0.002$) is required. This would also correspond to an offset of about 0.15 σ.

CONCLUSION

This paper presents the effect of the hysteresis in the magnets that are used to generate the crossing angles and the separation bumps. It also presents the impact of the hysteresis effect on the orbit at the different interaction points. The simulation results show that for the MCBC and MCBY, the errors generated at the IP by the hysteresis is within the beam-beam effect and therefore shouldn't be an issue. However, for the MCBX, the errors are well above this limit and can reach values that would be critical for LHC operation. Due to this, it has been shown that it is necessary to build a better hysteresis model for the MCBX magnets to reduce this unwanted effect.

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