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Hysteresis Effects of MCBX Magnets on the LHC Operation in Collision

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The Large Hadron Collider beams are brought into collision by superconducting orbit corrector magnets which generate the parallel separation and crossing angles at the interaction points during the different cycle phases. Unfortunately, the magnetic field errors that result from hysteresis effects in the operation region of these magnets lead to unwanted orbit perturbations. In a previous paper, it has been shown that these effects are within the perturbations coming from beam-beam interactions for the MCBC and the MCBY magnets but are significant in the case of the MCBX magnets. This paper presents a refined model of their field in the frame of the Field Description for the LHC (FiDeL); the results obtained from new magnetic measurements in cold conditions to test the model; the powering mechanism employed to maximize their field reproducibility; and the impact the modelling error is predicted to have on the LHC orbit in phase 1.

INTRODUCTION

Key beam parameters in the Large Hadron Collider (LHC) now under the final consolidation phases at CERN, are trimmed with superconducting corrector magnets. The MCBX [1], used to generate the LHC crossing scheme and to bring the beams into collision, are placed in the part of the accelerator where the beams share the same vacuum chamber. Even though there are clear advantages in having superconducting magnets perform these trims, there is also the disadvantage that these magnets suffer from persistent current effects that cause magnetic hysteresis [2]. This affects the instantaneous value of the field generated by the magnet and makes it dependent on the powering history. In the case of the MCBX, if hysteresis effects are not taken into account, they could jeopardize the collapsing of the separation bumps. Moreover, they can be the source of orbit distortions all around the ring. It is therefore important to provide a good understanding and model for these magnets in order to prevent any unwanted situation that could be critical for machine efficiency. The width of the magnets' hysteresis loops place the upper limit on the uncertainty of the magnetic field and therefore is usually taken as the worst case for the magnetic reproducibility. In this paper we discuss the detailed results for operation without crossing angles as planned later this year. The model and tolerances are different compared to the ones presented in [3] as only one coil of the magnet is powered and there will be no parasitic beam-beam interactions. The criteria used to judge how good the model is, is therefore the LHC closed orbit which is limited by the mechanical aperture. We also looked at how well we can bring the beams into collision using this model.

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MODELLING

To provide a field forecast of the magnetic elements of the machine [4], the LHC control system will rely on the Field Description for the LHC (FiDeL). This basically consists of a series of equations, based on magnetic measurements performed at warm and cold conditions, which 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. At low field they are dominated by the dc magnetisation and residual magnetisation effects. Therefore, in addition to what was modelled in [3], the latter two effects were also included in the modelling. As a result, the geometric component ($TF^{\mathrm{geometric}}$), the iron saturation contribution (TF^{sat}), the residual magnetisation (TF^{residual}) and the dc magnetisation (TF^{dc}) are included in the MCBX modelling [5]. In this way, the major hysteresis loop is modelled to correct the effect. Note however that this model only takes into consideration powering scenarios where the magnet is previously pre-cycled in such a way that it follows the major hysteresis loop.

The model chosen for the transfer function of the MCBX orbit correctors is:

$$TF = TF^{geometric} + TF^{dc} + TF^{residual} + TF^{sat}, \quad (1)$$

where

$$TF^{geometric} = \gamma_m^{geometric} \quad (2)$$

$$TF^{dc} = \mu_m \frac{|I|}{I}\left(\frac{I_{inj}}{|I|}\right)^{2-p_m}\left(\frac{I_c-|I|}{I_c-I_{inj}}\right)^{q_m}\left(\frac{T_{c0}^{1.7}-T^{1.7}}{T_{c0}^{1.7}-T_{meas}^{1.7}}\right)^{h_m} \quad (3)$$

$$TF^{residual} = \rho_m \frac{|I|}{I}\left(\frac{I_{inj}}{|I|}\right)^{r_m} \quad (4)$$

$$TF^{sat} = \sum_{i=1}^{N} \sigma_m^i \Sigma\left(I, S_m^i, I_{0m}^i, I_{nom}\right) \quad (5)$$

where

$$\Sigma(I, S, I_0, I_{nom}) = -\frac{1}{2}\left[1 + erf\left(S\left(\frac{|I|-I_0}{I_{nom}}\right)\right)\right], \quad (6)$$

and erf(x) is the error function:

$$erf(x) = \frac{2}{\sqrt{\pi}}\int_0^x e^{-t^2}\,dt \quad (7)$$

I is the excitation current. The symbols description and their values for the MCBX modelling can be found in Table 1.

Table 1: FiDeL symbols and modelling values for the MCBX corrector magnets

symbol	*Units*	*Description*	*Inner Coil*	*Outer Coil*
γ^{geo}	Tm/A	geometric parameter	0.0029201	0.0031014
μ	Tm/A	d.c. magnetisation	-0.00338	-0.00232
T	K	temperature	1.89	1.89
T_{meas}	K	measurement temperature	1.89	1.89
$T_{c\emptyset}$	K	critical temperature	9.5	9.5
p	-	pinning exponent	0.93205	0.88633
q	-	pinning exponent	2	2
h	-	pinning exponent	2	2
ρ	Tm/A	residual magnetisation parameter	0.0003715	-0.0000328
r	-	residual magnetisation exponent	1.7198	0.74033
σ	Tm/A	saturation parameter	0.0856	0.0009406
I_o	A	saturation current	1648.46	883.88
S	-	iron saturation current range	1.38981	1.8774
N	-	number of saturation curves	1	1
I_{nom}	A	nominal current	550	550
I_{inj}	A	injection current	1	1
I_c	A	critical current	1240	1240
I_{geo}	A	geometric current	200	200

Table 2: Measurement sequence phase 1

1	Outer @ 0.7 max	Inner @ 0.7 max
2	0 A	Pre-cycle Inner
3	Pre-cycle Outer	0 A
4	0 A	Inner major hysteresis
5	Outer major hysteresis	0A
6	0 A	Inner IR5
7	0 A	Pre-cycle Inner
8	0A	Inner IR8
9	0 A	Pre-cycle Inner
10	Pre-cycle Outer	0 A
11	Outer IR1	0 A
12	Pre-cycle Outer	0 A
13	Outer IR2	Inner not powered

MEASUREMENT SETUP

Magnetic Measurements

One MCBX magnet was measured in detail in the dedicated test facility used for corrector magnets (Block 4) [6]. The measurements were performed in cryogenic conditions at 1.89 K in vertical cryostats. The magnets were only measured in the so called phase 1 machine operation conditions, where there is no crossing angle i.e. when only the inner coil or the outer coil (but not both) are powered.

MEASUREMENT RESULTS PHASE 1

The magnets were first both cycled to 70% of their maximum current. As the two coils are nested, this value was chosen so as to ensure that no quench occurred. The major hysteresis curves for the two coils were then obtained and modelled as shown in Figures 1 and 2. The model was then used to calculate the excitation current needed to obtain the magnet strength as determined by the simulations, performed with optics V6.503 at injection, pre-collisions and collision from MAD-X [7].

The simulation values were used as a reference, and FiDeL was employed to power the magnets such that they approached these values. The resulting difference and the ΔB/B obtained can be seen in Table 3. The effect on the orbit was computed using MADX [7].

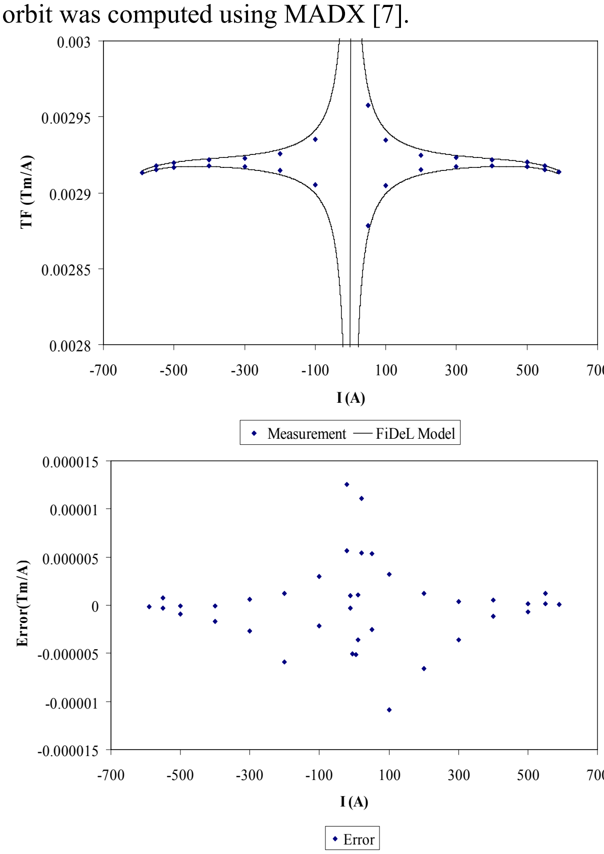
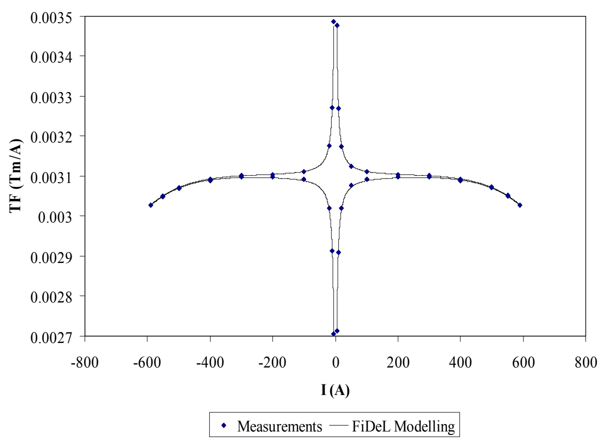


Figure 1: (top) the measured TF and the FiDeL model for the MCBX inner coil (bottom) the modelling error.

Table 3: The test results of phase 1

IR	I (A)	Meas (Tm)	Simulation (Tm)	Difference (Tm)	ΔB/B
IR5 (inner)	21.5	0.0631868	0.060056	0.003130817	0.0521316
	320.3	0.9586375	0.93398	0.024657505	0.0264005
	-1.1	-0.000102	0	0.000102032	N/A
IR8 (inner)	-25.7	-0.0754925	-0.072596106	0.002896387	-0.0398973
	-387	-1.1585615	-1.129001445	0.029560041	-0.0261825
	1.1	6.228E-05	0	6.22779E-05	N/A
IR1 (outer)	-19.9	-0.0624364	-0.060056	0.002380351	-0.0396355
	-301.6	-0.9628069	-0.93398	0.028826893	-0.0308646
	0.7	-0.000165	0	0.000165024	N/A
IR2 (outer)	16.5	0.0507841	0.049338966	0.001445148	0.0292902
	247.8	0.7909379	0.767310632	0.023627277	0.0307923
	-0.7	5.453E-05	0	5.45275E-05	N/A



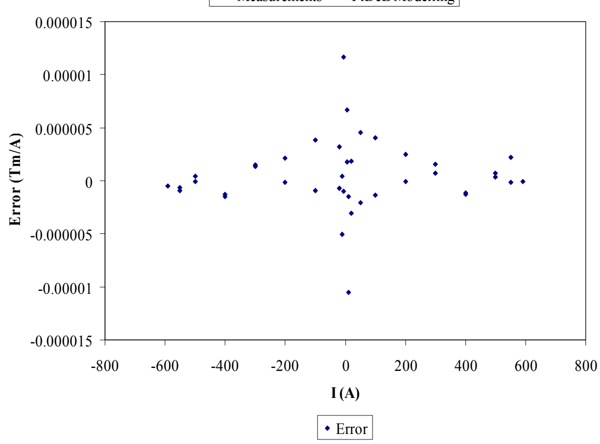


Figure 2: (top) the measured TF and the FiDeL model for the MCBX outer coil (bottom) the modelling error.

Considering only the worst error for all magnets (5% at injection and 3% at top energy) injection, pre-collisions and collisions were studied. The resulting maximum peak and RMS orbit are respectively 0.5mm and 0.09mm at injection and 0.08mm and 0.02mm at top energy. These values are well within the LHC tolerances (3mm at top energy and 4mm at injection for the peak orbit) and are not considered to be critical for operation.

Bringing the beams into collision consists of ramping down these magnets to a zero field. Due to the imperfect correction of the hysteresis, the remaining field results in orbit distortions at the IP of the order of a μm at most, which is within the BPM's precision [1].

CONCLUSION

This paper has shown the results obtained from a campaign to test FiDeL on the MCBX magnets for operation without crossing angle. In this paper, the dc magnetisation and the residual magnetisation were also modelled so as to obtain the major hysteresis loop of the MCBX. The modelling was used to power the magnets and the magnetic field was then compared to what was expected in the simulations. We looked at the resulting effects on the LHC orbit, which proved to be rather small and well within the tolerances. We showed that FiDeL can be used to control the MCBX and bring the beams into collision with the required precision for LHC phase I. Work is ongoing at CERN to understand the hysteresis of the MCBX for the full LHC crossing scheme with crossing angles, when both the inner and the outer coils are powered.

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