SINGLE-PASS BEAM MEASUREMENTS FOR THE VERIFICATION OF THE LHC MAGNETIC MODEL *

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Abstract

During the 2009 LHC injection tests, the polarities and effects of specific quadrupole and higher-order magnetic circuits were investigated. A set of magnet circuits had been selected for detailed investigation based on a number of criteria. On or off-momentum difference trajectories launched via appropriate orbit correctors for varying strength settings of the magnet circuits under study - e.g. main, trim and skew quadrupoles; sextupole families and spool piece correctors; skew sextupoles, octupoles - were compared with predictions from various optics models. These comparisons allowed confirming or updating the relative polarity conventions used in the optics model and the accelerator control system, as well as verifying the correct powering and assignment of magnet families. Results from measurements in several LHC sectors are presented.

INTRODUCTION

During the synchronization tests performed in November 2009 in the LHC, polarities of certain circuits in question from previous measurements [1, 2] in the Beam 1 & 2 were verified. Polarities of magnets which indicated a discrepancy in the polarity convention either from single pass difference trajectories or from optics measurements in 2008 were compared to those in the MADX model. Misalignments inferred from the past measurements were also verified. Difference trajectories for two different settings of each circuit were recorded while launching a betatron oscillation (see Fig. 1). The effect of the initial orbit was removed with baseline trajectories without the corrector but for both polarities of the circuit under verification. Individually selected orbit correctors with optimum phase advance to the magnets of interest are used to launch the betatron trajectory. The oscillations were launched and recorded with the help of the YASP on-line steering program [4]. For higher order circuits (sextupoles and octupoles), trajectories with finite momentum offset $\Delta p/p = 2.5 \times 10^{-3}$ were used to increase the sensitivity.

The beam measurements were conducted using single bunches of low emittances ($\sim 1\,\mu$m) and with intensities of 2×10^9 protons per bunch. The inclusion of b_2, b_3 and a_2 components in the dipoles with the aid of PTC [3] significantly improved the agreement between the model and measurements in most cases. The inclusion of b_2, b_3 and a_2 components (10^{-4} relative units at 17 mm) into the "thick" model (exact) is only possible using PTC.

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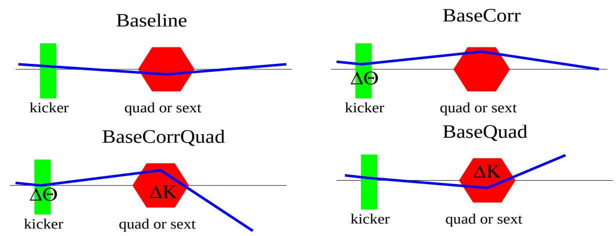

Figure 1: Sketch of the single pass trajectory measurements with nominal and inverted magnet polarity.

MEASUREMENTS

All orbit correctors used were initially verified for polarity convention with difference trajectories and found consistent with the model. The magnet circuits checked during these tests are listed in Table 1 along with the corresponding corrector magnet. Only trajectories of selected circuits are shown in graphic form to depict as a representative example. Optics measurements in 2008 showed a large beta-beat. The error sources were traced to potential polarity issues or a cable swaps between beam 1 and 2 in the dispersion suppressor regions. Some of the potential candidates (Q4.L6B2, Q4.R2B1 and QT5.L7B2) were tested using difference trajectories computed from nominal and inverted strengths of the magnet with their corresponding correctors (see Table 1) and found to be con-

Table 1: The model strengths of the circuits and the corresponding correctors strengths used for betatron trajectories. Note that the nominal values of skew circuits and octupole circuits were zero.

Circuit Circuit	k_n $[m^{-n}]$	Corrector	Kick $[\mu rad]$
Q4.R2.B1	0.00492	MCBHX3.R2B1	40
Q4.L6.B2	0.00493	MCBCH9.R6B2	40
QT5.L7.B2	-	MCBCH6.R7B2	40
QTL11.L7.B2	0.0000387	MCBCH9.L7B2	40
QT12.L7.B2	0.00168	MCBCV10.L7B2	30
QT13.L7.B2	-0.000686	MCBCH11.L7B2	30
MQS.A23.B1	0.02	MCBCH6.R2B1	30
MQS.A78.B2	0.02	MCBXV3.L8B2	30
MQS.A56.B2	0.02	MCBYH5.R6B2	30
SD1.A23.B1	-0.1065	MCBCV5.R2B1	30
KOF.A23.B1	50.0	MCBCH6.R2B1	30
MCS.A67.B2	0.1568	MCBCV6.L7B2	30
MSS.23.B1	3.0	MCBCH6.R2B1	20
MSS.78.B2	3.0	MCBCV5.L8B2	20
MSS.56.B2	-3.0	MCBCV5.L8B2	20

sistent with the model. Inclusion of b_2 component in the dipoles improved the agreement between the measured and model trajectories (see Fig. 2). Measurements in 2008 in-

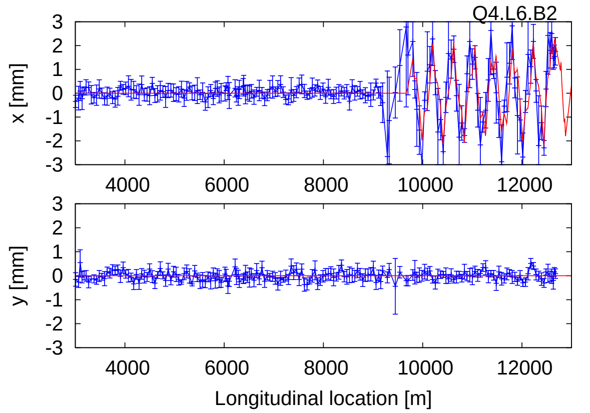

Figure 2: Difference trajectories with a finite value of Q4.L6B2 and corresponding inverted strength.

dicated trajectory discrepancies in QTL11.L8B2 polarity check which was reproduced by a 3mm misalignment in the model. However, measurements in 2009 were consistent with the MADX model. The discrepancy in 2008 measurements could perhaps be explained due to unintentional orbit changes during the measurements for this specific circuit, but the discrepancy is not reproducible. In addition, QT13.L8B2 measurements in 2008 were inconclusive due to noisy data. In 2009 they were confirmed to be consistent with the model. Additional trim quadrupole circuits in sector 78 (QTL11.L7B2, QT12.L7B2, QT13.L7.B2) were also tested in 2009 and found to be consistent with the model (Fig. 3).

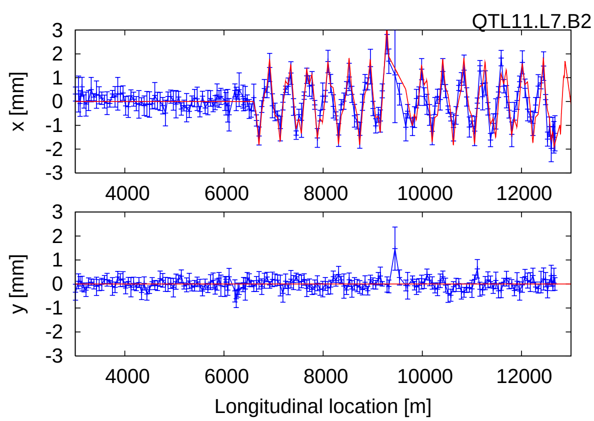

Figure 3: Difference trajectories of QTL11.L7B2 with nominal and inverted strengths.

For skew quadrupoles, difference trajectories for MQS23.B1 (beam 1), MQS78.B2 and MQS56.B2 (beam 2) circuits are shown in Fig. 4 using the associated correctors MCBCH6.R2B1, MCBXV3.L8B2 and MCBYH5.R6B2. All three circuits show a disagreement between the MADX model and the measured values similar to the 2008 measurements, pointing to a wrong polarity or a systematic convention difference between online LSA database and the MADX model.

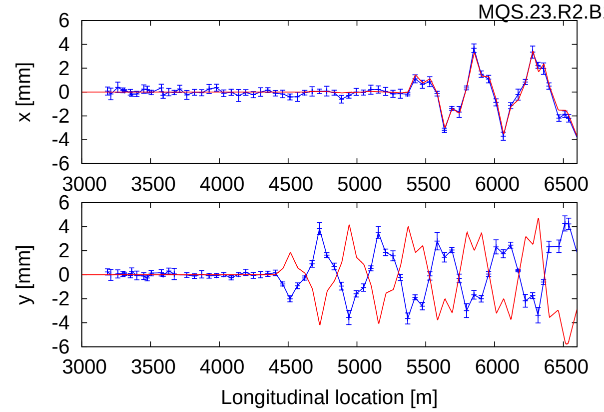

Figure 4: Difference trajectories with a finite value of MQS23.B1 and corresponding inverted strength.

For normal sextupole and octupole circuits tested in 2008, the polarity convention measured was found to be consistent with the model. However, inclusion of b_2 and b_3 components in the dipoles and initial trajectories help improve agreement between the measured and model trajectories as demonstrated for SD1.A23B1 and KOF.A23B1 (see Fig. 5) For the b_3 spool pieces, MCS circuits, only the

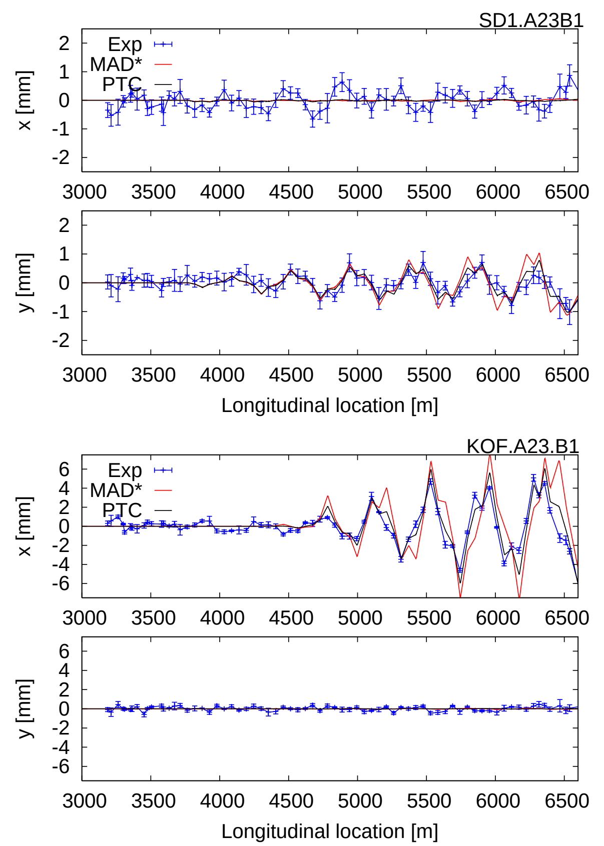

Figure 5: Difference trajectories for SD1.A23B1 and KOF.A23B1 (right) with finite nominal value and corresponding inverted strength.

polarity for MCS.67B2 (beam 2) was tested. The difference trajectories in Fig. 6 show good agreement for both polarity and amplitudes between the model and measurements. A comparison with a model including the b_2 and b_3 components with the aid of PTC (black) gives a significantly improved agreement as opposed to the bare model (red). For the skew sextupole magnets, trajectories for

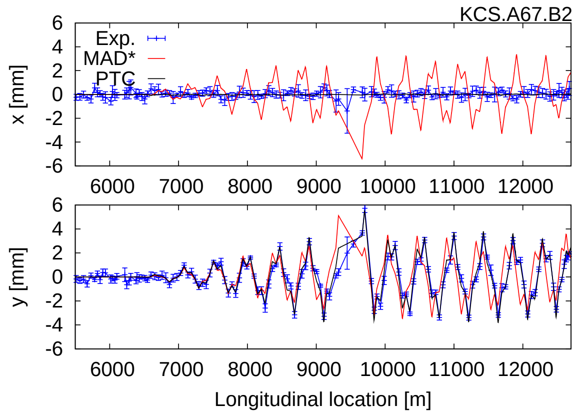

Figure 6: Difference trajectories of KCS.A67.B2 with nominal and inverted strength using MCBCV6.L7B2 corrector.

MSS.23B1 (beam 1), MSS.56B2 and MSS.78B2 (beam 2) circuits were tested for magnet polarity. The initial values of the skew sextupoles were zero. They were powered to finite values for the experiment (see Table 1). The difference trajectories are shown in Fig. 7 indicating opposite polarities or convention for all three circuits as compared to the MADX model.

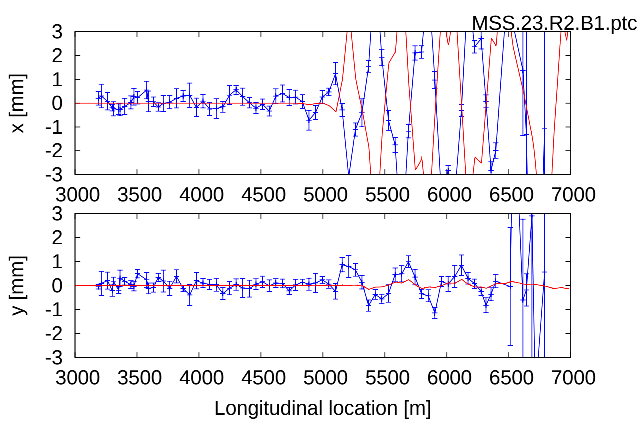

Figure 7: Difference trajectories with a finite value of MSS.23.B1 and corresponding inverted strength using MCBCH6.R2B1 corrector compared with model prediction.

CONCLUSIONS

Polarities for linear and higher order circuits in question from 2008 measurements were verified in the 2009 tests and listed in Table 2 and Table 3. The polarity verification of the magnet circuits tested indicate all normal circuits to be consistent with the model. Measurements for the skew quadrupole and sextupole circuits indicate either an opposite polarity of a systematic convention problem between the MADX model and LSA online database. Inclusion of b_2 and b_3 components of the dipoles in the model significantly improve the agreement to the measured values.

Table 2: Status of the circuits tested in 2008 and 2009 in Sector 23, Beam 1. B, H, T correspond to candidates with polarity issues found from β-beat, hardware or trajectory measurements in 2008 respectively.

Name	Sector 23	
	2008	2009
Q4.R2.B1	Opposite (B)	Correct
Q6.R2.B1	Opposite (B)	Correct
Q6.L3.B1	Opposite (H)	Correct
QT11.R2.B1	Opposite (T)	Correct
QT12.R2.B1	Correct (T)	-
QT13.R2.B1	Correct (T)	-
MQS.23.B1	Opposite (T)	Opposite
SF[1,2].23.B1	Correct	-
SD[1,2].23.B1	-	Correct

Table 3: Status of the circuits tested in 2008 and 2009 in Sector 78, Beam 2. B, H, T correspond to candidates with polarity issues found from β-beat, hardware or trajectory measurements in 2008 respectively.

Name	Sector 78	
	2008	2009
Q4.L6.B2	Opposite (B)	Correct
Q5.L8.B2	Opposite (B)	Correct
QT5.R7.B2	Opposite (B)	Correct
QT[11-13].L7.B2	-	Correct
QT11.L8.B2	Misaligned (T)	Correct
QT12.L8.B2	Correct (T)	-
MQS.56.B2	-	Opposite
MQS.78.B2	Opposite (T)	Opposite
SF[1,2].78.B2	Correct (T)	-
SD[1,2].78.B2	Correct (T)	-
MCS.78.B2	Correct (T)	-
MCS.67.B2	-	Correct
MSS.56.B2	-	Opposite
MSS.78.B2	Opposite (T)	Opposite
KOF.78.B2	Correct (T)	-
KOD.78.B2	Correct (T)	-

ACKNOWLEDGMENTS

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REFERENCES

[1] F. Zimmermann et al., PAC09, Vancouver, Canada, 2009.
[2] R. Calaga et al., LHC performance note.
[3] P. Skowronski et al., LHC Project Report 1016.
[4] J. Wenninger, YASP, *Yet Another Steering Program.*