LINEAR & NONL. OPTICS CHECKS DURING LHC INJECTION TESTS

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Abstract

In early LHC commissioning, linear and "higher-order" polarity checks were performed for one octant per beam, by launching suitable free betatron oscillations and then inverting a magnet-circuit polarity or strength. Circuits tested included trim quadrupoles, skew quadrupoles, lattice sextupoles, sextupole spool-pieces, Landau octupoles, and skew sextupoles. A nonzero momentum offset was introduced to enhance the measurement quality. The low-intensity single-pass measurements proved sufficiently sensitive to verify the polarity and the amplitude of (almost) all circuits under investigation, as well as the alignment of some individual trim quadrupoles. A systematic polarity inversion detected by this measurement helped to pin down the origin of observed dispersion errors. Later, the periodic "ring dispersion" was reconstructed from the full first-turn trajectory of an injected off-momentum beam, by removing, at each location, the large incoming dispersion mismatch, forward-propagated via the optics model. Various combinations of inverted trim quadrupoles were considered in this model until reaching a good agreement of reconstructed dispersion and prediction.

INTRODUCTION

At the Large Hadron Collider (LHC), eight "interaction points" (IPs) are separated by eight long arc sectors. "Sector 12" (S12), for example, refers to the region between IP 1 and IP 2. Verifying the polarity of the large number of correction magnet circuits, in particular higher-order ones, has long been a subject of concern; e.g. see Ref. [1] and references therein.

In August 2008, the LHC beam commissioning started with a series of SPS-LHC synchronization and injection tests [2], which culminated in passing the beam around both LHC rings on 10 September. On 10 and 24 August as well as 6 September, polarity checks of trim quadrupoles and higher order correctors were performed for beam 1 in S23, and beam 2 in S78, respectively. Single-pass dispersion measurements were also conducted by changing the energy of the injected beam. The measurements revealed a few polarity discrepancies between the model and the actual machine, for some weak trim quadrupoles and several skew corrector circuits.

The beam measurements were conducted using single bunches of low emittance (about 1μm horizontally and 0.5 μm vertically) and with a low intensity of 2×10^9 protons.

STABILITY AND RESOLUTION

From repeated reference trajectory measurements (recorded for a frequency shift of 800 Hz) we can infer an upper limit on the BPM resolution at 2×10^9 bunch intensity and on the trajectory stability. Figure 1 shows the average and rms trajectory readings over a time period of 10 minutes and 3 hours. The 10-minute data indicate that the rms BPM resolution is better than 0.2–0.3 mm, while the rms variation over 3 hours is of the order of 0.5 mm.

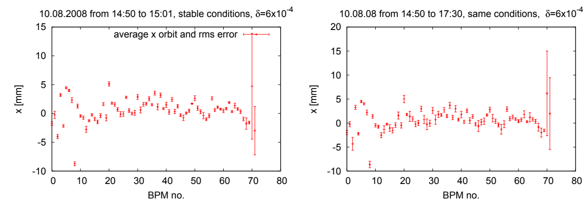

Figure 1: Average and rms reference trajectory in the horizontal plane computed from trajectory data taken over a 10-minutes (left) and 3-hours interval (right) in the very first injection test on 10 August 2008.

MEASUREMENT PROCEDURES

Polarity Checks

The procedure for the polarity checks was as follows: (1) a free betatron oscillation was launched along a sector with a suitable single orbit corrector, (2) the strength or the polarity of the circuit under investigation was inverted or, if initially zero, set to a finite value, and (3) four sets of data were taken, with two settings of the orbit corrector and the circuit under scrutiny, allowing a double difference trajectory to be calculated in order to remove or reduce the effect of an initial beam offset. For certain circuits the sensitivity was enhanced by introducing a momentum offset. The magnet circuits subjected to these tests were the QT and QTL trim quadrupoles, the MQS skew quadrupoles, the SF and SD arc sextupole circuits, the MCS b3 spool pieces, the OD and OF Landau octupoles, and the MSS skew sextupoles. For the quadrupoles, the two sets of measurements taken without orbit-corrector excitation, but at varying magnet settings, can also be exploited for a beam-based alignment of the quadrupoles with respect to nearby BPM readings.

Single-Pass Dispersion Measurements

The "first-turn dispersion" was measured by changing the momentum of the injected beam, through a shift in the frequency of the LHC 400-MHz master reference, which then led to a corresponding change in the SPS RF frequency. The maximum RF frequency shift which could be applied during the first test on 10 August corresponded to +/-800 Hz of the LHC 400 MHz master, limited by the available hardware set-up. With the SPS momentum compaction of $\alpha_c = 1.9 \times 10^{-3}$, this frequency shift corresponded to about -/+1 per mill relative momentum change.

For subsequent studies, from 24 August onward, the accessible range was increased and stable extraction from the SPS was possible for momentum offsets up to -/+2 per mill. The slope from a linear fit of the measured horizontal or vertical position data against the different momentum offsets represents the measured "first-turn" dispersion, computed at each beam position monitor (BPM).

In case the incoming dispersion is mismatched in the transfer line, the ring dispersion cannot directly be confirmed. We can however fit the incoming dispersion oscillation over a certain selected (and adjustable) region of the ring, for example one sector, to a model optics, and then propagate this incoming dispersion around the entire ring, using the same optics model. Subtracting the propagated incoming contribution from the measured "first-turn" dispersion at each BPM, we obtain a "quasi-measurement of the ring dispersion" that we can compare with the ring dispersion predicted by the same model as used for the removal of the incoming dispersion. The "quasi ring dispersion" and the model ring dispersion should agree if the optics model corresponds to the actual situation.

QUADRUPOLES

Polarity-check trajectories were recorded for the trim-quadrupole circuits (QT11, QT12, QT13) right of IR2 and left of IR8, and for the skew-quadrupole circuits.

Measurements for QTL11R2B8 in Fig. 2 (left) indicated a polarity error for this trim quadrupole circuit. Based on additional evidence, e.g. electrical drawing and earlier Hall-probe measurements on warm magnets, it was pointed out that the polarity error of the QTL11 could reveal a more general problem of polarity convention affecting half of the trim correctors, namely those attached to the arc QDs of a given beam [3, 4].

Checking this hypothesis for first-turn dispersion data recorded the same day, it was found that the model with inverted polarity of QTL7, QTL9, and QTL11 could also explain a dispersion error found at the end of S23, and indeed reproduce the measured dispersion, as is illustrated in Fig. 2 (right).

Difference trajectories for QTL11.L8B2 are shown in Fig. 3 (left). The reconstructed amplitude is almost two times smaller than the measured value which could indicate an initial trajectory offset or misalignment for this quadrupole. Indeed, a vertical offset of approximately 3 mm would explain the discrepancy; see Fig. 3 (right). The BPM reading closest to the magnet, BPM.11L8.B2, showed a beam offset of only -0.18 mm, which seems to imply that the center of this trim quadrupole is about 3 mm offset with respect to the zero reading of the nearest BPM. Further downstream the measured offset increased to -1.13 mm (BPM.10L8.B2) and -4 mm (BPM.9L8.B2).

Similar polarity checks were also performed for the skew-quadrupole corrector circuits, of which there are one or two per beam and per sector. The trajectories for both MQS23.B1 and MQS78.B2 show a disagreement between the MADX model and the measurements, as is illustrated in Fig. 4, pointing to a convention difference between the control system and the MADX optics model.

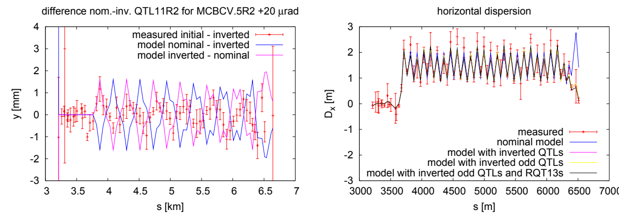

Figure 2: Difference trajectory for the nominal and inverted polarity together with predictions from the nominal model and from a model with inverted QTL11R2 demonstrating better agreement — a phase advance error developing in the arc was independently traced back to an error in the QTF/D settings (left). Horizontal and vertical dispersion in S23 measured on 10 August 2008, compared with various models in which all odd-numbers QTLs [7, 9 and 11] right of point 2 and left of point 3, plus optionally also the even-numbered quadrupoles QTLs and QT13, are inverted — the measured dispersion at the end of the arc is reproduced by all models with inverted odd QTLs (right).

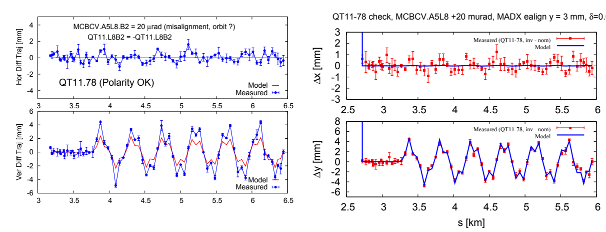

Figure 3: Difference of trajectories recorded for QTL11.L8B2 at nominal and inverted strength with orbit corrector MCBCVA.5L8 excited (left). The same as on the left but with MADX predictions including a 3-mm vertical misalignment of QTL11.L8B2 (right).

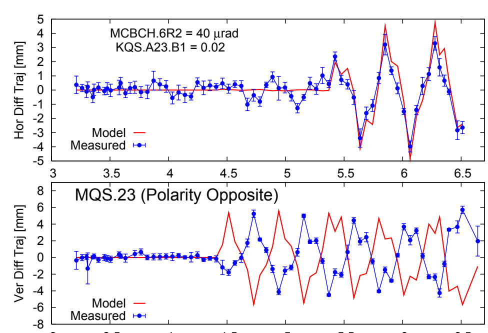

Figure 4: Horizontal and vertical difference trajectories for skew quadrupole circuit MQS23.B1 with its nominal and inverted strengths using the dedicated corrector MCBCH.6R2. The polarity of the corrector was verified independently.

On 10 September, the first turn dispersion was measured for beam 2. The horizontal measurement is shown in the left picture of Fig, 5, where a comparison with the model indicates a large incoming dispersion oscillation with 1–2 m amplitude. An attempt was made to extract the "ring dispersion" by taking out the incoming dispersion oscillation, following the procedure described in section . We recall that this type of "measured" quasi ring dispersion changes with the underlying model. It represents the true ring dispersion only if the model describes the real optics. A standard dispersion measurement performed with circulating beam would not have this type of ambiguity. Nevertheless the correctness of the quasi ring dispersion can be confirmed by constrasting it with the model forecast.

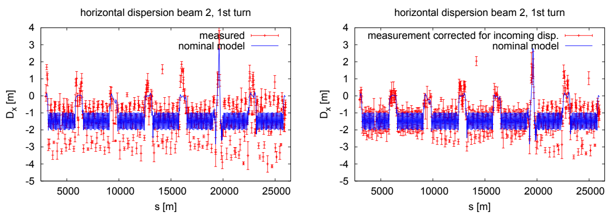

Figure 5: "First-turn dispersion" of beam 2 measured on 10 September 2009 (left), and "quasi ring dispersion" inferred from the former by taking out incoming dispersion oscillation after fitting over the first 10 km (right).

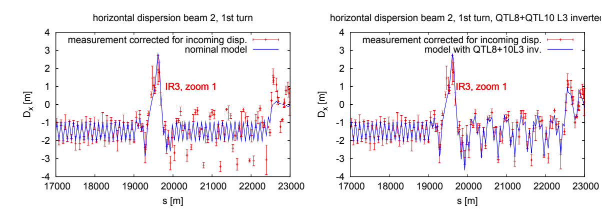

Figure 6: Zoomed view of "quasi ring dispersion" around IR3, after correcting for dispersion mismatch observed in preceding arc (left), and the same "quasi ring dispersion" computed after inverting QTL8 & 10 left of IP 3 (right).

The first-turn "ring dispersion" reconstructed in this way is presented in Fig. 5 (right). It shows only two regions where significant errors might be present: IR3 (near 20 km) and perhaps IR6 (near 10 km). Figure 6 shows a zoomed view of IR3. The dispersion is sensitive to polarity errors in the IR3 region. By introducing various polarity changes in our model, we found strong evidence for a wrong polarity of the trim quadrupoles QTL8 and QTL10 in L3, as demonstrated by Fig. 6, which also illustrates that the "measured" quasi ring dispersion changes with the model.

HIGHER-ORDER CIRCUITS

Concerning higher-order polarity checks, trajectories were recorded for focusing, defocusing and skew sextupoles, as well as for focusing and defocusing Landau octupole circuits. A relative momentum offset of 0.0025–0.003 was introduced to enhance the effect of the polarity inversion on the difference trajectory. Example results are shown in Fig. 7. Good agreement was obtained for all sextupole circuits, including spool piece windings, MCS. The skew sextupole circuit was found to have a polarity opposite to the MADX convention. For the Landau octupoles ROF in S78 both amplitudes and polarity agree. For the ROD circuits, the data point to a wrong polarity (S23), and to the effect of incoming dispersion or to a different momentum offset (S78), respectively [5].

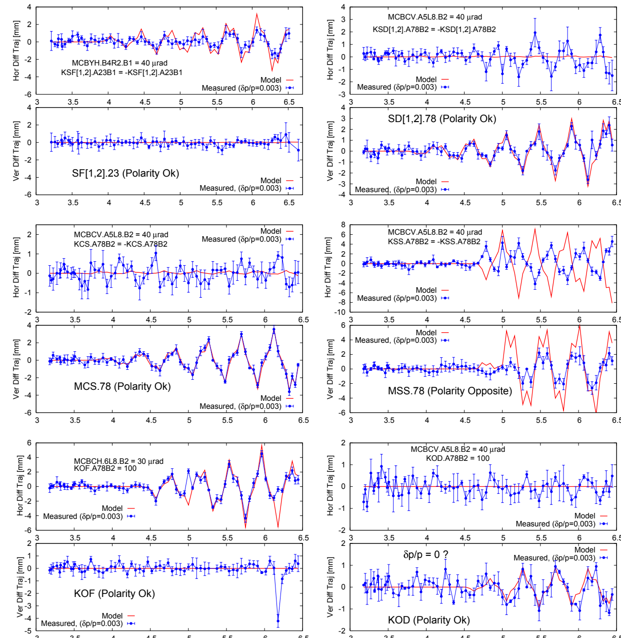

Figure 7: Difference of trajectories recorded at nominal and inverted strength for higher-order polarity checks compared with model predictions. Focusing (SF1&2.A23B2, top left) and defocusing lattice sextupoles (SD1&2.A78B2, top right). Sextupole spool-piece circuit (MCS.A78B2, center left). and skew-sextupole circuit (MSS.A78B2, center right). Focusing (ROF.A78.B2, bottom left) and defocusing Landau octupole circuit (ROD.A78.B2, bottom right). The orbit corrector polarities were also verified.

CONCLUSIONS

A procedure for polarity checks of trim quadrupoles and higher-order circuits has been established. The measurements in August and September 2009 demonstrate the possibility to verify the polarity and strength (at the 10% level) of trim quadrupoles, sextupoles, skew sextupoles, b3 spool pieces, and Landau octupoles, using trajectory data for a few single passes of single bunches with 2×10^9 protons. A number of discrepancies were found, in particular for the polarity of several trim quadrupoles, skew quadrupoles, and skew sextupole circuits. Processing of the single-pass dispersion measurement provides a model-dependent "quasi ring dispersion," which has helped to pin down two polarity errors. The trajectory measurements also allow for beam-based alignment. In one case the data suggests a 3 mm misalignment of a trim quadrupole.

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