LHC Performance Note 002

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Trim Magnet Polarities, Dispersion, and Response Data in Sector 23

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Summary

During the first LHC injection test, on 10 August 2008, the horizontal dispersion measured with beam 1 at the end of Sector 23 differed from the model prediction close to point 3. Beam-based polarity checks performed during the same period indicated an inversion of the trim quadrupole QTL11.R2. Combined with other evidence, like electrical drawings and earlier Hall-probe measurements of warm magnets, this gave rise to the hypothesis of a systematic error. Indeed a model inversion of all trim quadrupoles (QT or QTL) attached to a defocusing main quadrupole (actually the odd-numbered trim quadrupoles in Sector 23) reproduced the dispersion measurement. An analysis of kick-response measurements independently revealed an optics error left of point 3, and confirmed the inversion of the odd-numbered trim quadrupoles in this sector. After changing the polarity of the suspected set of quadrupoles prior to the second injection test on August 24, the measured dispersion nicely traced the model prediction.

1. Introduction

During the LHC injection tests beam was injected into the LHC and dumped on the first turn, either on collimators (or as in the case of beam 2 for the third injection test from 5 to 7 September on the LHC beam dump itself). Off-momentum beam for single pass dispersion measurements and other off-energy optics studies can be obtained by trimming the frequency in the SPS during the flat top before extraction.

In the morning of 10 August the SPS RF frequency shift controlled by the LHC as master was made operational. The beam measurements were conducted using single bunches of low emittance (~ 1 μm horizontally and ~ 0.5 μm vertically) and with a low intensity of 2×10^9 protons. During part of the studies, the bunch intensity was further dropped to explore the BPM intensity threshold. The maximum RF frequency shift which could be applied during the first test corresponded to +/-800 Hz of the LHC 400 MHz master reference. It was limited by the available hardware set-up. With the SPS momentum compaction of $\alpha_p = 1.9 \times 10^{-3}$ a frequency shift of +/-800 Hz in the LHC (+/-400 Hz in the SPS) corresponds to about -/+ 1 per mill. The range was increased by a factor 4 for the second test on August 24. Nevertheless, even then

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stable extraction from the SPS turned out to be only possible for frequency shifts within +/-1.6 kHz of the LHC 400 MHz reference.

2. Beam Measurements and Model Predictions

In the following we report on the dispersion measurement on 10 August, the results of the QTL11R2 polarity check indicating an inversion, the model dispersion with inverted odd-numbered QTLs, i.e those attached to the main quadrupoles in Sector 23 which are defocusing for beam 1, and the analysis of kick-response data, both confirming this inversion, and a verification measurement after the polarity changes had been implemented.

2.1 Orbit Stability and BPM 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. Figure 2 displays similar results over a larger interval of 3 hours. Figure 3 presents the horizontal rms variation seen at different BPMs in histogram form. The 10-minute data indicate that the rms BPM resolution is better than 0.2-0.3 mm, while the variation over 3 hours is of the order of 0.5 mm.

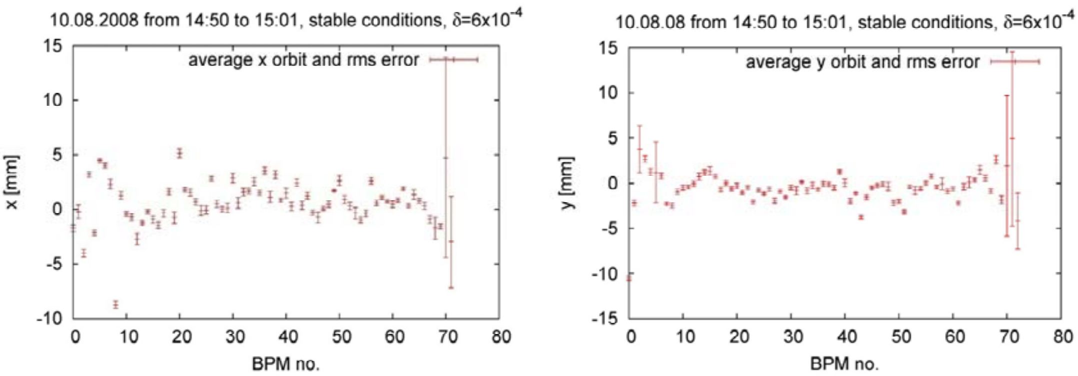

Figure 1: Average and rms reference trajectory in the horizontal (left) and vertical plane (right) for a -800 Hz frequency shift, computed from trajectory data taken over a 10-minute interval.

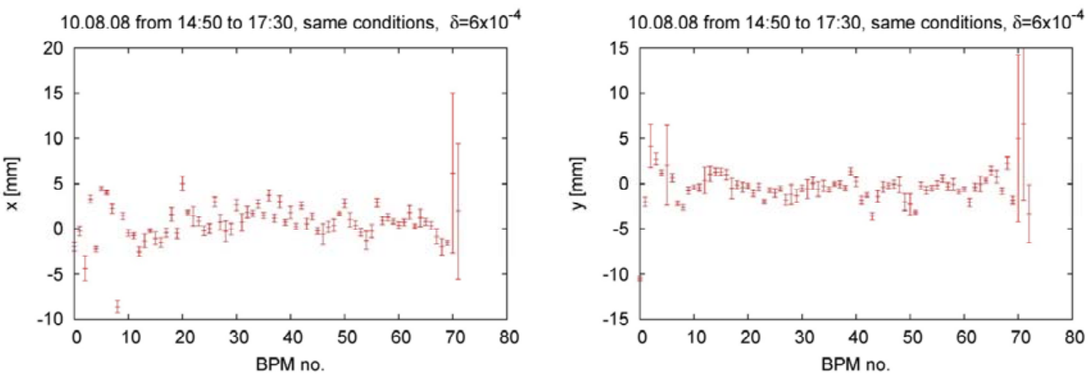

Figure 2: Average and rms reference trajectory in the horizontal (left) and vertical plane (right) for a -800 Hz frequency shift, computed from trajectory data taken over a 3-hour interval.

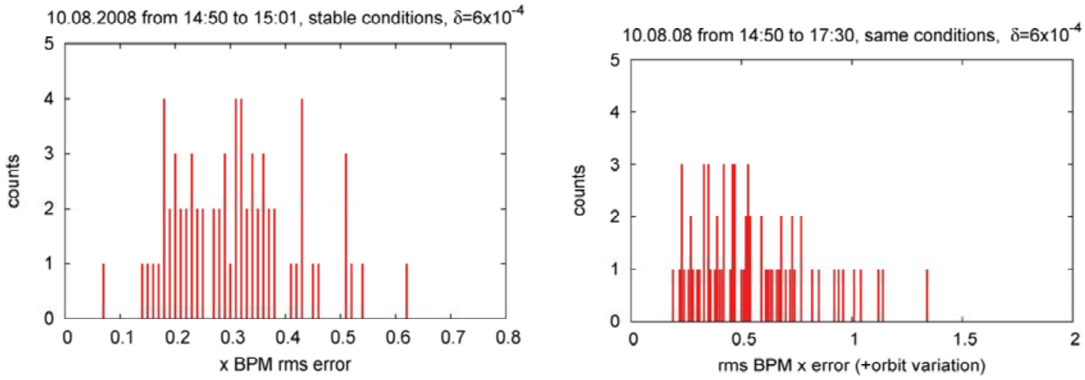

Figure 3: Histogram of measured horizontal trajectory variation at all BPMs over 10 minutes (left) and over 3 hours (right).

2.2 Dispersion in Sector 23 during the 1st Injection Test

The dispersion was obtained by subtracting trajectories measured with frequency shifts of +800 Hz and -800 Hz, the largest available range, corresponding to momentum offsets of approximately -/+1.1×10^{-3}. While the measured dispersion follows the model relatively well throughout the arc, a large horizontal dispersion error was revealed close to point 3; see Figure 4.

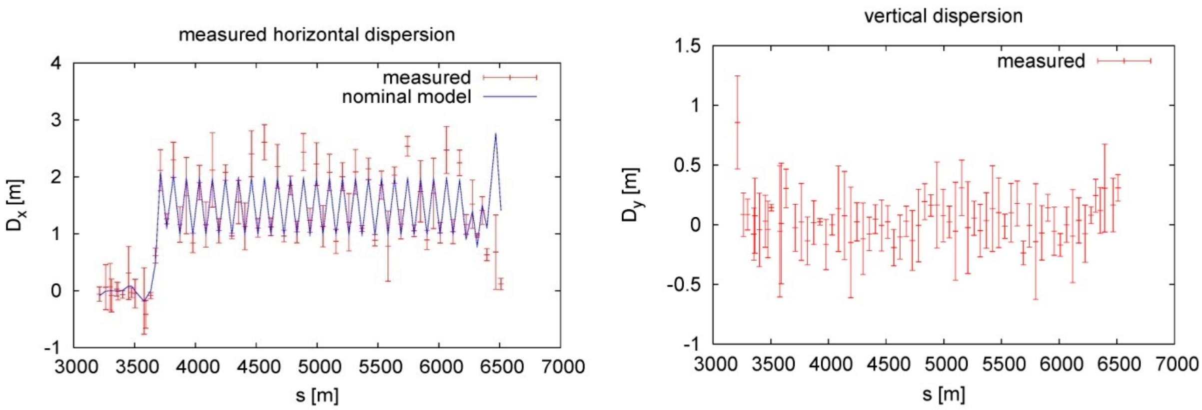

Figure 4: Horizontal and vertical dispersion in Sector 23 measured on 10 August 2008. The horizontal measurement is compared with the model. The vertical design dispersion is zero.

Good online diagnostics is available in the control room with tools like the steering program YASP, by which the measurement can be analysed immediately. The measured dispersion obtained from YASP on 10 August is shown in Figure 5.

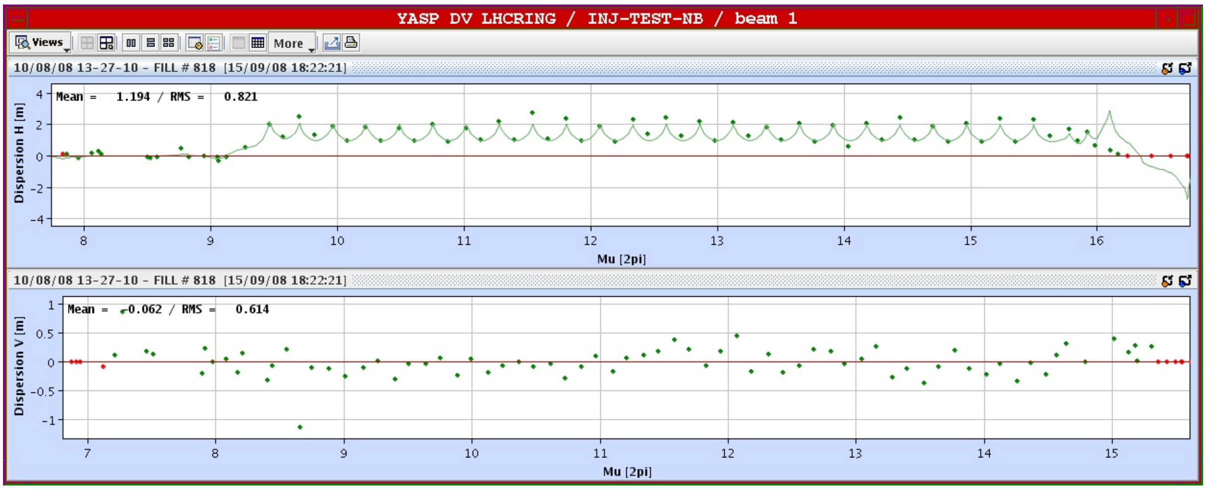

Figure 5: Horizontal and vertical dispersion in Sector 23 measured on 10 August 2008 analysed online with the steering program YASP.

2.3 QTL11R2 Polarity Error

Also on 10 August, free betatron oscillations were launched with various correctors on the right side of IP 2. The maximum deflection angle applied was 20 μrad. Together with the low bunch intensity, the moderate deflection angle resulted in limited sensitivity. (For similar studies during the second injection test, the deflection angles were increased.) The measured vertical betatron oscillations and their difference to the model prediction revealed a repeating conspicuous pattern as is illustrated in Figure 6.

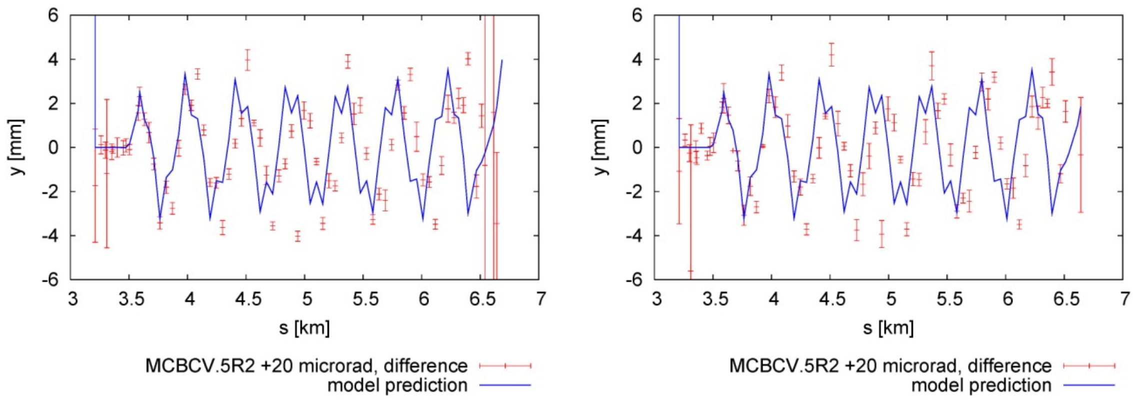

Figure 6: Two sets of vertical oscillation data taken with a 2-hour interval, at 15:00 (left) and 17:00 (right). The oscillations were launched by exciting the corrector MCBCV.5R2 at 20 μrad. Displayed are the difference trajectories with respect to the reference, as well as the model prediction. A repeating conspicuous pattern of deviation from the model is visible.

Figures 7 shows that the vertical oscillation measurement with inverted QTL11R2 (green dots) was closer to the nominal model (red line) and that, conversely, the measurement with the initial QTL11R2 polarity (pink dots) resembled the model with inverted polarity (blue line). A possible polarity error is still more clearly revealed by the corresponding difference trajectories, in Fig. 8.

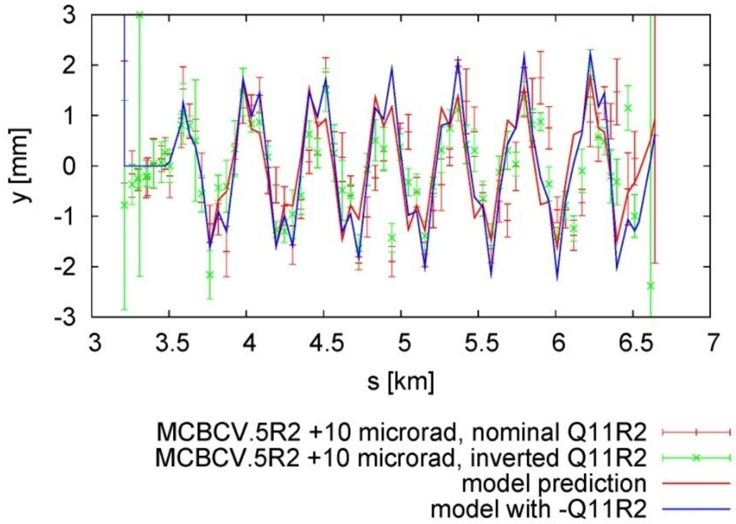

Figure 7: Vertical betatron oscillation measured for the initial and the inverted polarity of QTL11R2 together with the two corresponding model predictions, indicating a polarity error for this trim quadrupole.

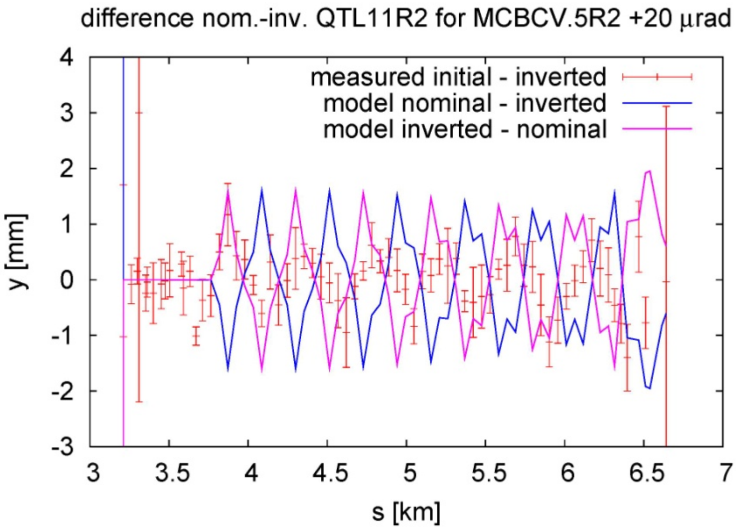

Figure 8: The difference trajectory computed from BPM data taken for the nominal and inverted polarity together with the predictions from the nominal model and from the model with inverted QTL11R2, demonstrating that the latter is consistent with the nominal measurement. (A phase advance error developing in the arc was independently traced back to an error in the QTF/D settings).

2.4 Systematic Error Hypothesis

After seeing the results reported in Section 2.3, and based on other evidence, e.g. electrical drawing and earlier Hall-probe measurements on warm magnets, Stephane Fartoukh pointed out that the polarity error of the QTL11 could reveal a more general problem of polarity convention affecting half of the trim correctors - i.e., trim quadrupoles, sextupoles or octupoles - attached to the defocusing main quadrupoles. The affected trim correctors correspond to the odd or even position numbers for the Sectors 23, 45, 67, and 81, or Sectors 12, 34, 56 and 78, respectively, for beam 1, and conversely for beam 2. Indeed all these trims have been apparently cabled such that a negative normalised strength in the model (the K parameter in MAD) actually corresponds to a positive current. The philosophy behind these polarity hardware conventions was that a positive current fed into these bi-polar trims should produce either a positive vertical tune shift (for the MQT/MQTL), a positive vertical chromaticity shift (for the defocusing lattice sextupoles) or a positive vertical amplitude detuning (for the Landau octupoles), while obviously corresponding to a negative K parameter in MAD conventions. Before the first injection test, this subtlety was not properly taken into account and 50% of the trims of each beam (namely those attached to the arc QDs of a given beam) had been set with the wrong sign.

2.5 Dispersion Data Revisited

Checking the hypothesis of Section 2.4, it was found that the model with inverted polarity of QTL7, QTL9, and QTL11 indeed reproduced the measured dispersion, actually independently of whether or not the even-numbered QTLs or the QT13 were inverted as well. This is illustrated in Figure 9.

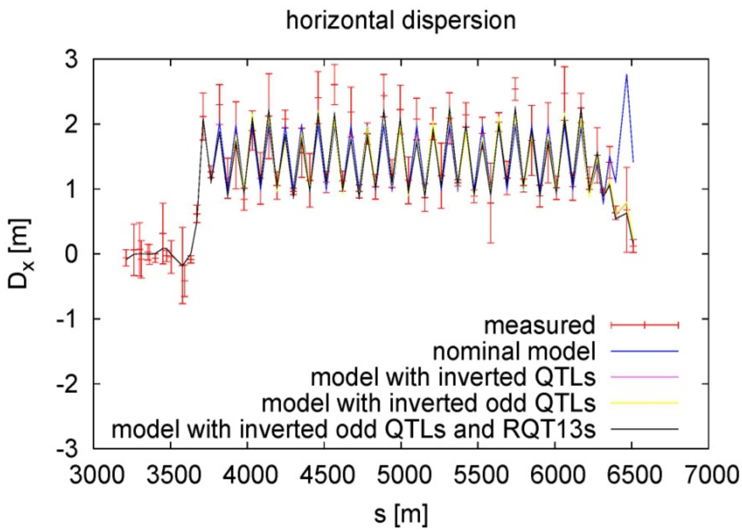

Figure 9: Horizontal and vertical dispersion in Sector 23 measured on 10 August 2008, compared with various models in which all odd-numbers QTLs (7, 9 and 11) right of point 2 and left of point 3, plus optionally also the even-numbered quadrupoles QTLs and QT13, are inverted. The measured dispersion at the end of the arc is reproduced by all models with inverted odd QTLs.

2.6 Dispersion Sector 23 during the 2nd Injection Test

Figure 10 shows the dispersion measured in the second injection test, after changing the polarity of (some of) the odd QTLs. [Incidentally, QTL11R2 for beam 1 was again found to have the wrong polarity in the third injection test on 7 September 2008.] The design model prediction is overlaid. The agreement between design model and measurement is much improved. In particular the measurement traces the horizontal design dispersion into the momentum-collimation insertion LSS3.

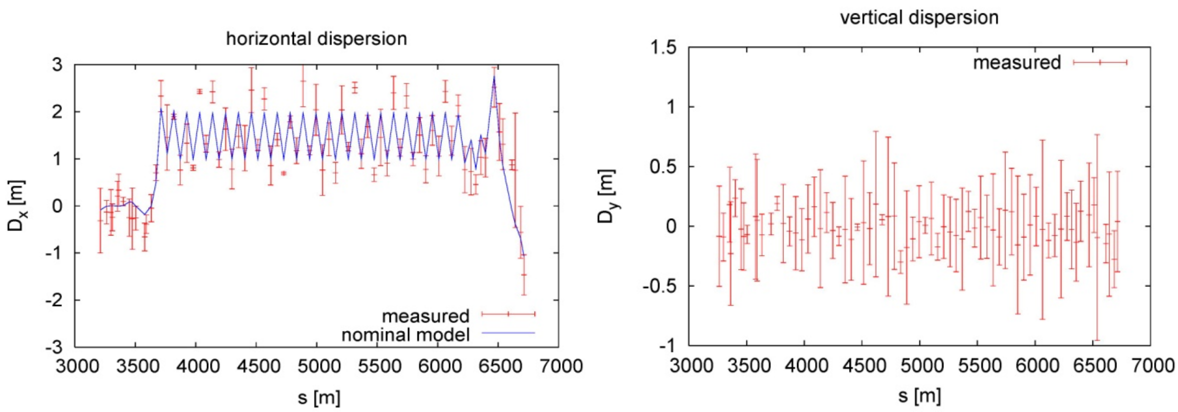

Figure 10: Horizontal and vertical dispersion in Sector 23 measured on 24 August 2008, compared with the design.

2.7 Kick-Response Measurements

Next to the dispersion diagnostics, the kick-response measurement turned out to be one of the most valuable sources of information during these early days of LHC beam commissioning, especially without circulating beam. From a systematic measurement of the response for each corrector magnet, information can be obtained on the optics model, beam position monitor quality and orbit corrector calibrations with an appropriate data analysis. At the SPS, response measurements and optics verifications have been performed successfully for the ring [1], the TT 10, the TI 8 [2], the TT 41 [3] and the TI 2 [4] transfer lines.

During the synchronization test on 9 and 10 August also part of the beam time was devoted to the measurement of such response data. 56 correctors (out of a total of 83 available in this region) were excited systematically by $\pm 40 \mu rad$ for these measurements. The following analysis is based only on a subset of these measurements (38 correctors) which was taken on 9 August. Although the aims of these measurements were both sorting out erroneous monitors and orbit correctors, and checking the optics of the sector in a systematic way, we do not treat any BPM and corrector issues, but discuss only the optics errors in this note. For this purpose readings from erroneous monitors were simply excluded from the data and therefore do not appear in the following graphs.

2.8 Kick-Response Analysis Principle

The principle used for analysing the response data is the same as that used by the LOCO software [5] and is described in detail, for example, in [1]. In order to render the analysis-procedure more comfortable and flexible the algorithm was rewritten in java, including a simple gui (ALOHA) and a slim madx-api for java to gain more flexibility in accessing model data and varying model parameters. In order to estimate the quality of a fit we introduce the rms of the elements of the relative difference-matrix which we define by

$$\Delta_{\mathrm{rms}} = \sqrt{\frac{1}{N_v - 1} \sum_{i,j} \frac{R_{ij}^{\mathrm{meas}} - R_{ij}^{\mathrm{model}}}{\frac{\sigma_i}{\delta_j}}}.$$

Where σ_i denotes the noise for monitor i, δ_j is the kick of corrector j, N_v is the number of all valid elements of the response-matrix and the sum must contain only valid elements. So the value of Δ_{rms} usually is greater than one and it equals one for a model error of the same magnitude as the noise. This latter case is being referred to as a “perfect fit”.

2.9 Hints for Optics Errors in the Kick Response

When searching for optics errors in response data it turned out to be useful to look at the model residual. The rms of the differences between the nominal model and the measured positions calculated over all measured trajectories is shown for all monitors in Figure 11. This figure illustrates that the errors increased in the horizontal plane from the very beginning of the sector, whereas in the vertical plane the errors stayed approximately at a constant level with a regularly alternating pattern through most of the sector and then steeply increased near the point 11L3 (BPM no 115).

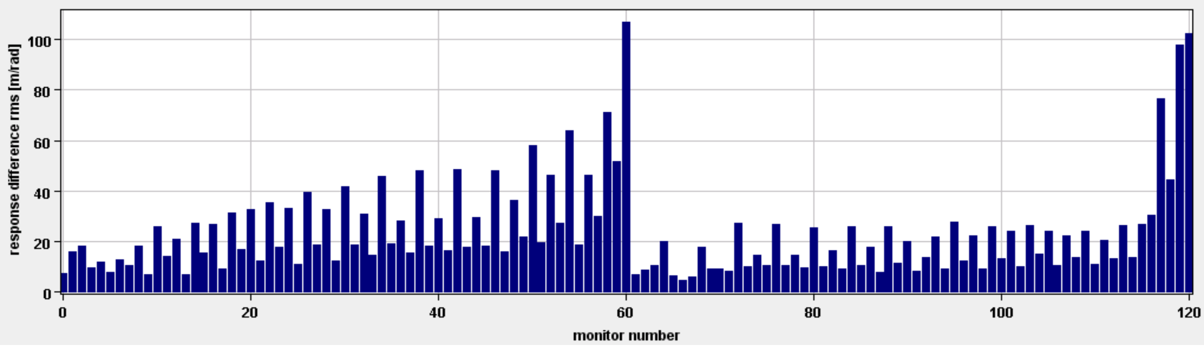

Figure 11: Rms difference between the nominal model and the measured kick-response data for each BPM in Sector 23. Indexes 0 to 60 represent horizontal monitors and 61 to 120 vertical ones.

An example horizontal trajectory for the sector under investigation is displayed in Figure 12. Also this plot reveals that the horizontal phase error increased from the very beginning (starting no later than BPM.13R2, no 11).

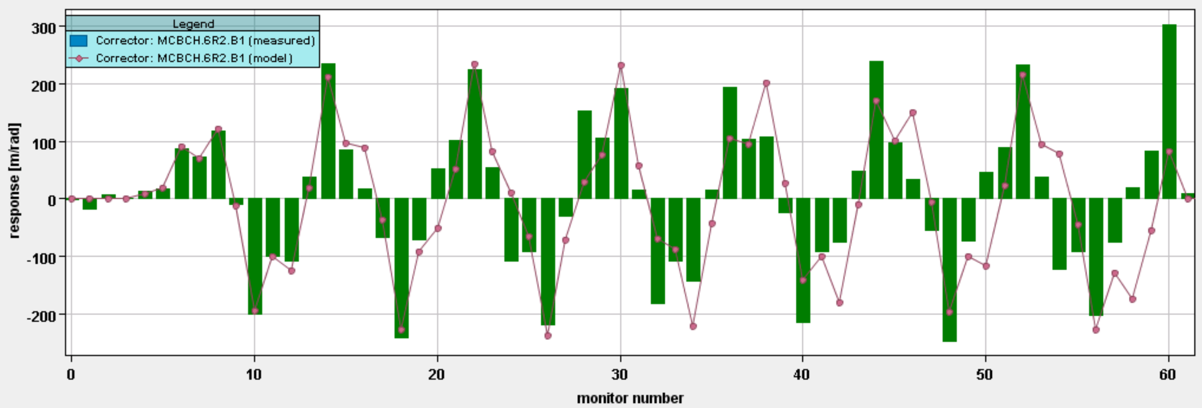

Figure 12: Comparison of measurement and model for an example response to a single corrector excitation (MCBH.6R2.B1). This chart shows only horizontal BPMs (no 0 to 60). The green bars represent the measured data and the red dots the model.

2.10 Fits to Kick-Response Data

From the above starting point various fits were performed, attempting to match the model to the measured data. In order to sort out more localized errors it is useful to first of all deal with the overall phase. To this end the main quadrupole strengths (kqf, kqd) were chosen as free parameters for the fit. In order to keep all the remaining errors visible in the residual, the monitor gains were not varied in this attempt, while the corrector gains were. After 3 fit-iterations we obtained $\Delta_{\mathrm{rms}} = 4.79$. The resulting residual for each monitor is shown in Figure 13.

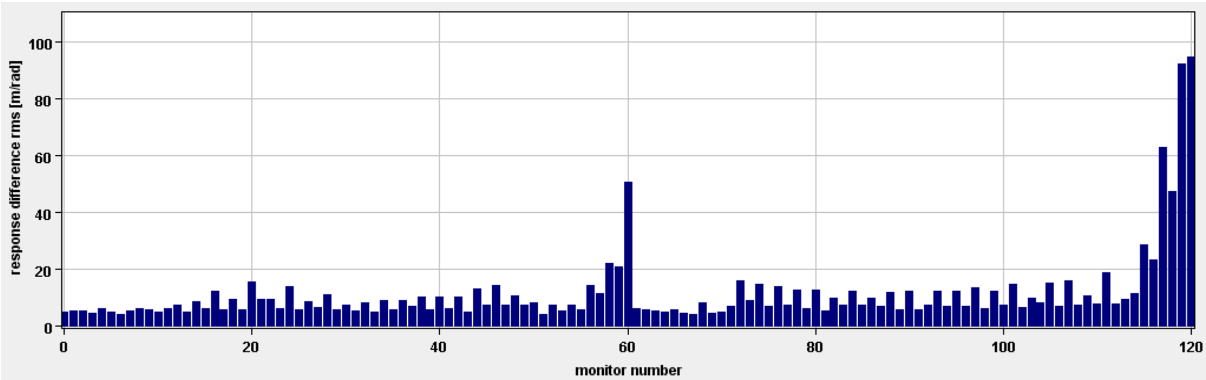

Figure 13: Residual for each BPM after a fit with the main quadrupole strengthes kqf and kqd. BPM numbers 0 to 60 correspond to horizontal BPMs and 61 to 120 to vertical BPMs. The residual error still increases at about BPM.10L11 (no 56) for the horizontal plane and at BPM.11L3 (no 115) for the vertical plane.

In order to localise the error sources, various combinations of quadrupole strengths were next tried as additional free parameters. Also the proposed inversions of MQTL.11R2 or MQTL11.L3 were investigated, partly for a separate measurement series taken on 11 August. Unfortunately no real evidence was found for one of these magnets to be the main source of the observed errors. As mentioned in the previous sections, the most promising hypothesis was then put forward by Stephane Fartoukh, namely that all odd numbered MQTLs, MQT.13R2 and MQT.13L3 in this sector might have had the wrong polarity. In order to verify this hypothesis we performed a fit with exactly these strengths (and again the main quadrupole strengths) as free parameters. This fit yielded $\Delta_{\mathrm{rms}} = 1.78$ after 4 iterations. It provided a strong evidence for the inversion of almost all the selected free parameters as shown in Figure 14.

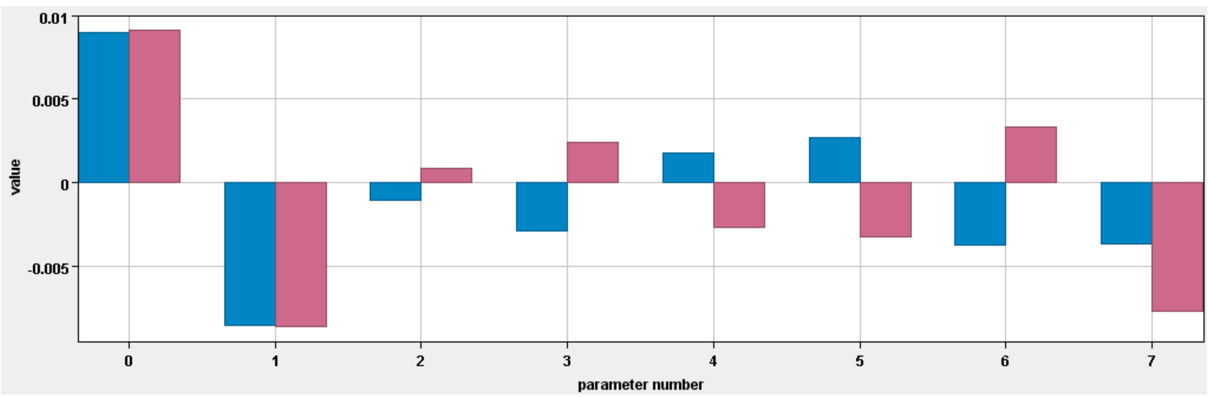

Figure 14: Free parameters before and after the fit. Blue bars indicate the levels before the fit and red ones the values after the fit. The numbers correspond to the following strength

parameters of the madx model: kqf (0), kqd (1), kqtl11.r2b1 (2), kqt13.r2b1 (3), kqt13.l3b1 (4), kqtl11.l3b1 (5), kqtl9.l3b1 (6), kqtl7.l3b1 (7).

The only parameter for which the fit did not result in a clear inversion was kqtl7.l3b1. This was due to the fact that it was constrained by one pickup only, namely BPM.6L3, which in addition turned out to be inverted in the vertical plane. To further verify the hypothesis we tentatively inverted the quadrupoles in question in the model. Then we again fitted with the main quadrupole strengths, but this time also using the monitor gains as free parameters so as to enable the fit to deal with the inversion of BPM.6L3. This fit resulted in $\Delta_{rms} = 1.69$ after three iterations and visibly reduced the residual for all BPMs (see Figure 15, note the different y-scale compared to Figure 11 e.g.).

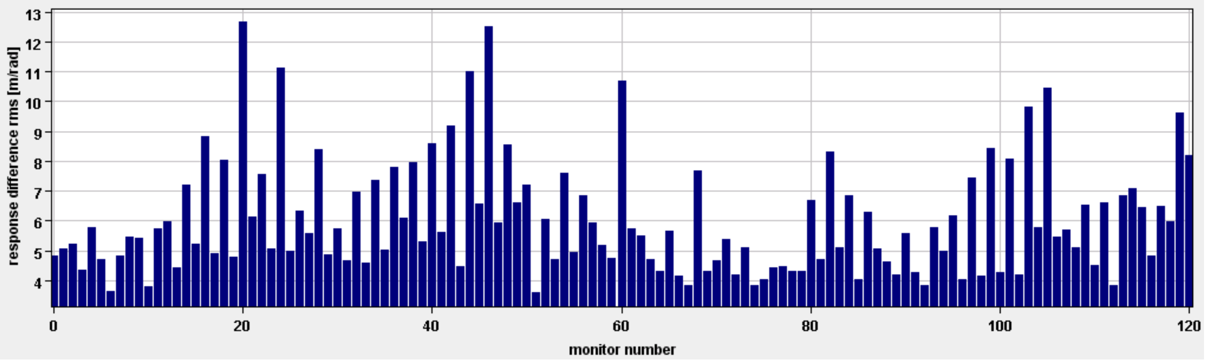

Figure 15: Rms difference between model and measurement for each pickup after a preliminary inversion of all odd kqt(l)s in the model and fitting with the main quadrupole strengths. The BPM numbers 0 to 60 correspond to horizontal BPMs and 61 to 120 to vertical ones. BPM.6L3 is no 60 (in H) and no 120 (in V).

The resulting fitted values for the main quadrupole strengths are summarised in Table 1. It is worth noting that this fit result indicated a non negligible strength error of about 1.4 % for the focusing plane. A resulting example (horizontal) trajectory for this final fit is shown in Figure 16.

Table 1: Results from fit to kick-response data from 10 August 2008 after tentatively inverting the odd numbered kqt(l)s.

	Nominal [m^{-2}]	Fit [m^{-2}]	relative change
kqf	0.00899	0.00911	0.01369
kqd	-0.00860	-0.00865	0.00560

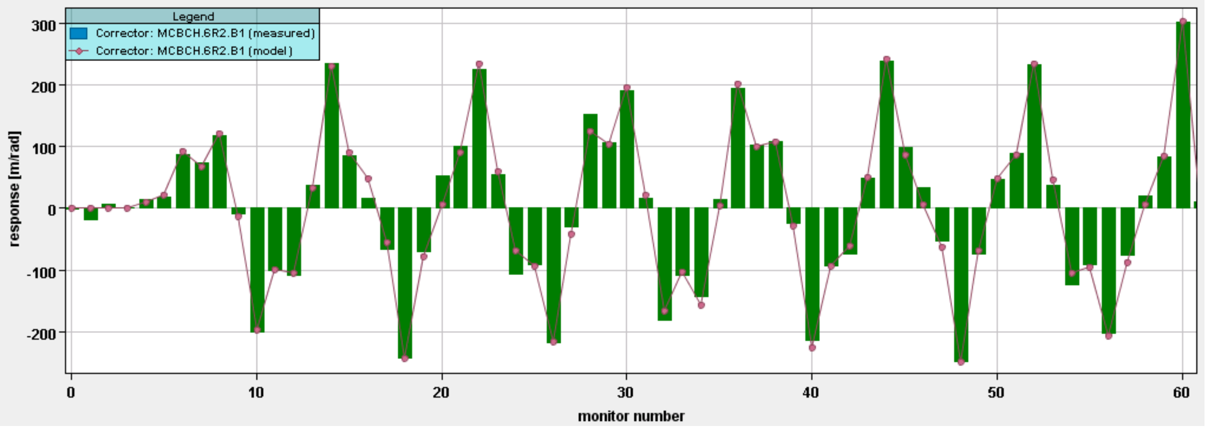

Figure 16: Comparison of model and measurement for an example trajectory, after the fit with main quadrupole strengths and a tentative inversion of all odd numbered kqt(l)s. The plot only shows the horizontal BPM readings (no 0 to 60). The green bars represent the measured data and the red dots represent the model.

3. Conclusions

During the first LHC injection test in Sector 23 the horizontal dispersion measurement indicated a large optics error on the left side of point 3. Independent checks revealed a polarity error for QTL11.R2. The subsequent hypothesis, supported by other evidence, that all odd numbered QTLs (as well as some sextupoles, octupoles, etc.) were inverted for beam 1 in Sector 23 was verified independently both with the measured dispersion and by analysing kick-response data. Beam measurements during the second injection test two weeks later confirmed that the optics error was indeed corrected by changing the sign of the excitation current for all these trim magnets.

References

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[3] J. Wenninger, Beam Stability and Optics Studies of the CNGS Transfer Line, AB-Note-2007-008 OP.

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[5] J. Safranek, Nucl. Instr. Meth. A388 (1997) 27.