KICK RESPONSE MEASUREMENTS DURING LHC INJECTION TESTS AND EARLY LHC BEAM COMMISSIONING

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Abstract

The transfer lines from the SPS to the LHC, TI 2 and TI 8, with a total length of almost 6 km are the longest ones in the world. For that reason even small systematic optics errors are not negligible because they add up and result in an injection mismatch in the LHC. Next to other lattice measurement methods Kick-response measurements were the most important sources of information during the early phases of beam commissioning of these transfer lines and the LHC ring. This measurement technique was used to verify orbit-corrector and BPM gains as well as to sort out optics errors. Furthermore fits to off-momentum kick response turned out to be an appropriate method to establish a model for systematic errors of the transfer line magnets. This paper shortly describes the tools and methods developed for the analysis of the taken data and presents the most important results of the analysis.

ANALYSIS PRINCIPLE

While in a circular machine several fast and reliable methods are available, optics measurements in a transfer line are a little bit more delicate, because only single pass acquisitions are possible. One method which can be used for such purposes is that of kick response measurements.

From kick response measurements it is not possible to directly deduce optics properties. Instead a fit is necessary, which varies certain parameters of a machine model to reproduce the measured data as close as possible. The optics properties in question can then be read off from the fitted model. This is often quoted as the *LOCO* principle [1]. The software used for the analysis was a software package called *Aloha* [2] which is a generalization of the *LOCO* principle for arbitrary *MADX* models.

Fitting Procedure

A fit in *Aloha* varies a set of N_f parameters c_l, $1 \leq l \leq N_f$, of the model such that the differences between the measured and calculated observables are minimized. The differences of certain observables between measurement and model are collected in a difference vector $\vec{V}$. The dependence of this difference vector on the set of parameters is described by the sensity matrix S. The fit minimizes the quadratic norm of $\vec{V}$. To approach the minimal solution the problem is linearized. As a first step the system of linear equations

$$S\Delta\vec{c} = \vec{V} \tag{1}$$

is solved in a least square sense to obtain a vector $\Delta\vec{c}$ representing the parameter changes. This is achieved with least square algorithms like SVD or MICADO. Then a new set of parameter-values can be calculated,

$$c_l{}' = c_l + \Delta c_l. \tag{2}$$

The values $c_l{}'$ are then applied to the model and the procedure is iterated until the parameters are stable.

For kick response measurements the observables are the elements of the response matrix R, whose elements are defined by

$$R_{ij} = \frac{u_i}{\delta_j}, \tag{3}$$

where u_i is the position (x or y) at the i^{th} monitor and δ_j is the kick of the j^{th} corrector. The elements of the difference vector $\vec{V}$ are defined by

$$V_k = R_{ij}^{\text{diff}} := \frac{R_{ij}^{\text{meas}} - R_{ij}^{\text{model}}}{\sigma i}. \tag{4}$$

R^{model} is the response matrix calculated from the model and R^{meas} is the measured one. σ_i denotes the rms noise of the i^{th} BPM. The elements of the sensity matrix S for standard (on momentum) kick response data are defined by

$$S_{kl} = -\frac{\partial V_k}{\partial c_l} = \frac{1}{\sigma_i}\frac{\partial R_{ij}^{\text{model}}}{\partial c_l}. \tag{5}$$

These sensity-matrix elements are (for arbitrary parameters) numerically approximated by the local fit gradient,

$$S_{kl} = \frac{R^{\text{model}}(c_l + \delta c_l) - R^{\text{model}}(c_l)}{\delta c_l\,\sigma_i} = \frac{\Delta R_{ij}^{\text{model}}(c_l)}{\sigma_i}. \tag{6}$$

The parameter increment δc_l has to be chosen carefully for each parameter.

Combination of Measurements

To gain constraints (e.g. for the b_3, see Eq. (7)) it is sometimes necessary to combine different kick response measurements which were taken at different machine conditions (e.g. different values of $\frac{\Delta p}{p}$). These measurements can then be fitted all together. Therefore the sensitivity matrices from the different measurements are combined into one big sensitivity matrix. Care has to be taken that different models (e.g. with the corresponding $\frac{\Delta p}{p}$ values) have to be used for creating the sensitivity sub matrices and the parameters of the models have to be varied in a consistent way.

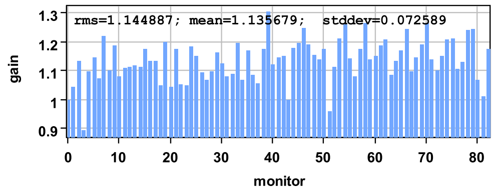


Figure 1: Monitor gains g_i for TI 8 monitors indicating a systematic error ($\langle g \rangle = 1.14$).

BPM AND COD CHECKS

Corrector Gains

In 2008, fits to data of LHC arc 23 using the corrector gains as free parameters revealed an obvious correlation between the magnet length and the kick strength of the magnets. The results of such a fit are summarized in Table 1. The explanation for this correlation was found soon afterwards by J. Wenninger and was simply due to the fact that the steering application sent its trims as kick angles δ the layer underneath was expecting dipole strengths k_0. Since those two are related by $\delta = k_0\, l_{\mathrm{mag}}$ (l_{mag} is the magnetic length), the final trim which was sent to the magnets was too large by the factor of the magnetic length of the magnet which is different for the families.

Table 1: Comparison between lengths of corrector magnets and the gain factors obtained by fitting corrector gains to kick-response data.

Corrector Type	l_{mag}	gain factor (aloha)
MCBX H/V	0.450	0.45 ... 0.61
MCBY H/V	0.899	1.02 ... 1.10
MCBC H/V	0.904	1.04 ... 1.21
MCB H/V	0.6470	0.68 ... 1.00

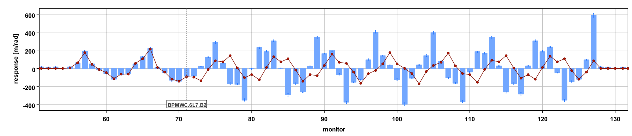
Monitor Gains

During the analysis of the transfer line optics the fitted monitor gains came out more than 10% too large. This is illustrated in Fig. 1. The plot shows the monitor gains obtained from fits to kick-response data with 25 correctors for TI 8. The corrector gains were assumed to be perfect and therefore not varied during this fit. The main quadrupole strengths of the line were used to compensate for the phase errors. The mean of the corrector gains g_i obtained from this fit is about $\langle g \rangle = 1.14$ i.e. systematically too high. Detailed investigations of this issues revealed that the observed errors were the result of calculation of the real positions in the BPM front ends implemented at that time which did not take into account nonlinear errors of the BPM electronics. A new version of the front end software which takes into account all the calibrations correctly was deployed short after the problem was understood.

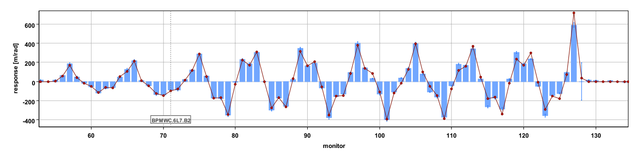
OPTICS MEASUREMENTS

Inversion of Q6.L7

When taking beam 2 the first time to LHC point 6 on 6 September, 2008, an optics problem around IR7 rapidly became evident. Fits to kick response data varying quadrupole strengthes in this region soon led to a clear inversion of Q6.L7 which is driven by a bipolar power supply. Figures 2 show measurement compared to the nominal model and to a model with Q6.L7 inverted. The good agreement with the inverted model is nicely visible.



(a) MCBH.14R7.B2, nominal model



(b) MCBH.14R7.B2, model with Q6.L7 inverted

Figure 2: Comparison between kick response measurement (blue bars) and model (red dots) in LHC sectors 67, 78.

b_2 and b_3 Flat top Dependence in MBIs

During the first injection tests a non-negligible optics mismatch was observed at the injection point between the transfer lines and the LHC. Following an idea by S. Fartoukh the possible origin of the errors in field errors of the main bends in the transfer lines (MBIs) was investigated. The results were already published in [3] and their incorporation into the new transfer line model is described in [4]. One of the remaining questions was the source of these higher order components.

Since one suspicion was that these field errors might come from eddy currents resulting from reaching the flat top of the cycle, off-momentum kick response measurements were performed for different settings for the delay time of the extraction kicker after reaching top energy in the SPS. Using the described method the *MADX* model was then fitted to the measured data using four degrees of freedom: $\frac{\Delta K}{K}$, b_2, b_3 and $\frac{\Delta p_0}{p}$.

$\frac{\Delta K}{K}$ denotes a systematic error of the main quadrupole strengths with respect to the nominal settings. b_2 and b_3 denote the systematic relative quadrupolar and sextupolar field errors in units of 10^{-4} with respect to the main field of the bend. These were implemented directly in the *MADX* model of the transfer line by the use of

$$k_{n-1} = \frac{b_n}{R_{\mathrm{ref}}^{n-1}} \frac{\alpha}{l} 10^{-4} (n-1)!, \qquad (7)$$

where k_n denote the multi pole strengths applied to the main bends in *MADX*, α is the bending angle of the magnet, l its length and R_{ref} is a reference radius which is defined for the main bends in the transfer line as $R_{\mathrm{ref}} = 0.025$ m. The "true" momentum mismatch $\frac{\Delta p}{p}$ is given by

$$\frac{\Delta p}{p} = \frac{\delta p}{p} + \frac{\Delta p_0}{p}, \tag{8}$$

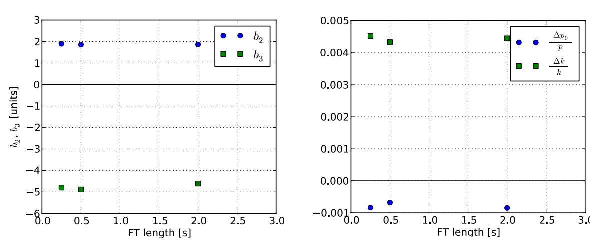
where $\frac{\delta p}{p}$ denotes the trimmed momentum offset and $\frac{\Delta p_0}{p}$ an a priori unknown initial momentum error.

For each of the three measurements two correctors per plane were used for which the response was measured at five different values of $\frac{\delta p}{p}$ (-2.2, -1.1, 0.0, +1.1 and +2.2 permille).

Table 2: Results of off-momentum kick-response fits for different flat top lengths

FT-length [s]	b_2	b_3	$\frac{\Delta K}{K}$	$\frac{\Delta p_0}{p}$
0.25	1.896	-4.798	0.00452	-8.35e-4
0.5	1.856	-4.883	0.00433	-6.78e-4
2.0	1.866	-4.610	0.00445	-8.46e-4
mean	1.873	-4.764	0.00443	-7.86e-4
stddev	0.017	0.114	0.00008	0.77e-04

The results of these fits are collected in Table 2 and plotted in Figs. 3. No significant dependence on the length of the flat top can be deducted from these measurements. From this it was clear that a different source had to be responsible for the systematic b_2 and b_3 errors.



(a) b_2, b_3 (b) $\frac{\Delta p_0}{p}$, $\frac{\Delta K}{K}$

Figure 3: Dependence of fit results on flat top length.

Finally the sextupole component b_3 of about -4.5 units of 10^{-4} at a radius of 25 mm was confirmed by 2D simulations of the dipole magnet and the quadrupole component is believed to originate from a feed-down from this sextupole component due to the large sagitta of the magnets [4].

b_2 Component of LHC Main Bends

As a test of the methods used for the transfer lines, LHC data was analyzed in a similar way. At that time no b_2 correction was in place in the LHC. No off-momentum kick response measurements were done, so only a fit for b_2 was possible and not for b_3. Since the b_2 in the LHC have different signs for the different apertures the fit was done with one b_2 parameter per sector. Example results for such a fit on beam 1 data are shown in Table 3.

Table 3: Comparison of fitted and model b_2 in LHC main bends. (Model data courtesy of M. Alabau)

	b_2 model	b_2 fitted	diff	rel diff
Sector 12	-1.49	-1.68	-0.20	13.23%
Sector 23	1.46	1.40	-0.06	-4.08%
Sector 34	1.35	1.67	0.32	23.46%
Sector 45	1.31	1.44	0.13	10.12%
Sector 56	-1.05	-1.75	-0.70	66.57%
Sector 67	-1.23	-1.57	-0.33	27.16%
Sector 78	-1.06	-1.20	-0.15	13.71%
Sector 81	1.30	1.30	0.00	-0.01%

The model data quoted in the table is field error data as produced by the WISE simulation tool which uses a combination of measured magnet data and statistical simulations as replacement for missing information [5].

The fit was done with the parameters listed in the table, plus a systematic detuning of the quadrupoles as parameter which resulted in $\frac{\Delta K}{K} = 2.31 \cdot 10^{-4}$. The sign and the order of magnitude of the b_2 is nicely reproduced by the fit, although some big deviations from the model are visible (e.g. sector 56, almost 67 %).

SUMMARY

Model fits to kick response data proved to be a very useful diagnostics tool during the early phase of LHC beam commissioning. Several problems were identified during polarity checks of BPMs and CODs in the main ring as well as in the transfer lines. Furthermore, since this method allows optics measurement without the need of the full ring it was heavily used during the injection tests and allowed to deduce potential systematic quadrupolar and sextupolar field errors of the main bends in the transfer lines. It was shown that these field errors are independent of the flat top length of the magnet ramp and thus not originating from eddy currents. Finally, the method was crosschecked with (partly) measured magnet data in the LHC ring.

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