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Study of the TI 8 optics and beam stability based on beam trajectories

J. Wenninger

Abstract

The optics and the stability of the SPS-LHC transfer line TI 8 was studied with beam trajectories during its commissioning in October 2004. Steering magnet response measurements were used to analyze the quality of the steering magnets and of the beam position monitors. A simultaneous fit of the quadrupole strengths was used to search for setting or calibration errors. A large setting error of a quadrupole was identified with this technique, as well as a 1% phase advance error in the vertical plane. Residual coupling between the planes was evaluated using high statistics samples of trajectories. The same high statistics sample were analysed using the Model Independent Analysis technique to understand possible sources of trajectory movements. The transfer line was found to be very stable and the dominant source of position jitter seems to be due to the ripple of the extraction septum.

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1. Introduction

TI 8, the first 2.7 km long transfer line between the Super Proton Synchrotron (SPS) and the LHC was commissioned in the autumn of 2004[1]. The beam tests were performed in two periods of 48 hours separated by two weeks. A large fraction of the beam time was devoted to studies of the line optics, aperture and stability.

This note presents the analysis of a large sample of trajectory data in order to study the transfer line optics and stability.

Studies of the TI 8 transfer line optics based on measurements of the trajectory response are presented in the first part of this note. Results on the transfer line stability using trajectory data during stability runs are discussed in the second part.

2. Trajectory Response Measurements

The observation of the trajectory response to controlled dipole corrector magnet deflections is a simple, yet powerful method to gain insight into the optics model of a ring or of a transfer line [2,3]. From a systematic measurement of the response for each corrector magnet, a significant amount of information on the optics model, beam position monitor quality and orbit corrector calibrations can be obtained from an adequate analysis of the data. For a transfer line it is not possible to obtain information on the actual betatron function since the response measurement is only sensitive to the effects of elements within the line, while the betatron functions depend on the initial conditions at the entrance of the transfer line.

The measurement and analysis of such a data set involves the following steps:

- The measurement is performed by recording two trajectories for different settings of selected orbit correctors. Typically one trajectory is recorded by applying a kick of 30-40 μrad with respect to the reference setting of the corrector, and a second trajectory is recorded for a kick with the opposite sign. The data analysis is always based on the trajectory difference for the two kicks in order to remove the effect of the 'static' trajectory.
- The data sample is processed and stored in a format suitable for a fit by the LOCO program [2,3] that was adapted to the CERN environment. LOCO is coupled to MADX in such a way that the optics model can be fitted by adjusting MADX strength parameters in an iterative procedure. More details on the fit procedures can be found in reference [3]. For a typical LOCO fit, all BPM and corrector calibrations as well as a selection of strength parameters are adjusted at the same time.

2.1. Measurement results

During the first TI 8 experiment a measurement involving all corrector magnets was performed in order to detect malfunctioning BPMs or correctors (polarity, calibrations…). The typical r.m.s. BPM noise for the measurements was 200 μm. A fit with LOCO was performed using as free parameters all BPM and corrector calibration factors and well as the strength of the main QF and QD quadrupole families.

The data analysis revealed a number of problems and features:

1. One vertical corrector did not affect the beam at all. It was later found to be disconnected.

2. A number of BPMs did not work correctly:
    - BPMIH.80404 was excessively noisy and erratic.
    - BPMIV.81504 showed almost no sensitivity. The fit tried to push the BPM gain factor above 3.
    - BPMIH.81804 (V plane signal) showed the same symptoms than BPMIV.81504.
    - BPMIV.85704 was afflicted by a sign error and frequently returned absurd readings..

3. Under the assumption that the average deflection of the orbit correctors is correct (i.e. the average field calibration is correct), the average BPM scale factor is 0.90 ± 0.01 for the horizontal plane and 0.88 ± 0.01 for the vertical plane, indicating that all the BPM readings are too large by ≈10%. The factors for the horizontal and vertical planes are almost consistent. A high statistics measurement performed with a limited number of correctors (see below) indicated that the spread of the BPM gain factors is not more than 1-1.5%.

4. An optics problem became quickly apparent at the end of the TT40 transfer line, see Figure 1. The trajectory response from the first horizontal corrector of TT40 indicated a large phase jump after the 4th BPM and did not match the model, even after fit. Within TI 8 no error was visible (Figure 3). No significant error was visible for vertical trajectories, indicating that the problem was most likely due to a horizontally focusing quadrupole. This fact was emphasized by a large error on the horizontal dispersion[4]. To localize the error source, the LOCO fits were performed again by using successively the strength of each quadrupole in the TT40 line as free parameter. Due to the limited number of BPM sampling points, it was not possible to fit all TT40 quadrupole strengths at the same time. Only a single fit using as free parameter the strength of quadrupole QTLF.4004 yielded physically meaningful results for both the corrector and BPM calibrations and for the quadrupole strength. The fit indicated that the strength of the quadrupole was too low by 20%. This result was later confirmed: it was due to a wrong database entry for the maximum current of the power converter. The fit result with the QTLF.4004 strength as free parameter is shown in Figure 2.

5. The results of the fit strengths for the main QF and QD quadrupole revealed a 1% error on the QD strengths as shown in Table 1. The difference in the phase advance (nominally 90 degrees) is clearly visible when comparing Figure 3 (horizontal plane) and Figure 4 (vertical plane): for the vertical plane there is a clearly visible phase slip from one BPM to the next. This phase error appears consistently in all response measurements performed during the two TI 8 experiments.

During the second TI 8 experiment the response measurements were repeated for a subset of the corrector magnets to verify that all faulty elements had been repaired. The only remaining problem consisted of a gain factor of 2 that had to be applied to BPMIV.557.

Table 1 : Fit results for the main quadrupole strengths. The errors correspond to the full variation observed for different fits and data samples.

Quadrupole	Strength (10^{-2} m^{-2})	
	Nominal	Fit
KQF	+3.386	+3.384 ± 0.002
KQD	-3.388	-3.410 ± 0.002

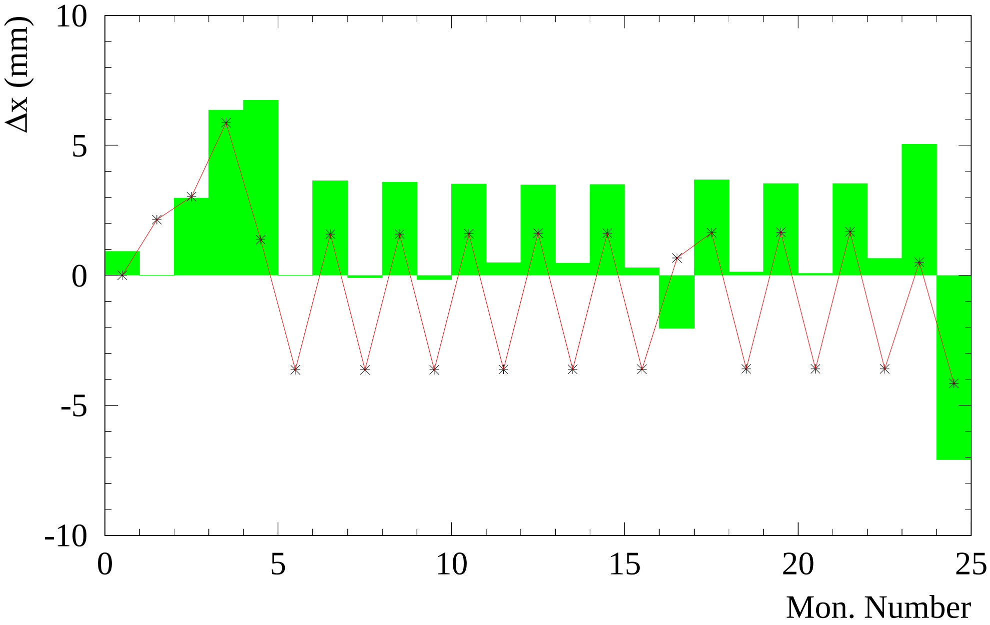

Figure 1 : Trajectory response data for the first horizontal orbit corrector in TT40 (histogram = data, points = model). A large phase shift is apparent between the data and the model, starting after the 4th BPM.

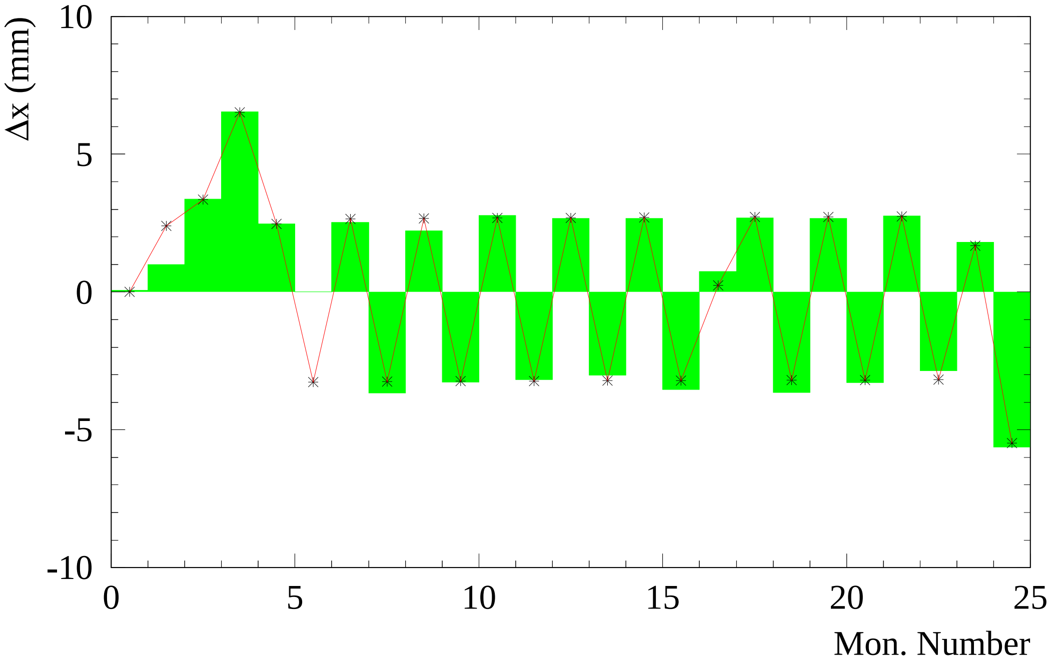

Figure 2 : Trajectory response data for the first horizontal orbit corrector in TT40 (histogram = data, points = model) after the strength of quadrupole QTLF4004 was restored to its nominal value. This model has to be compared to the previous figure before correction of the QTLF4004 strength.

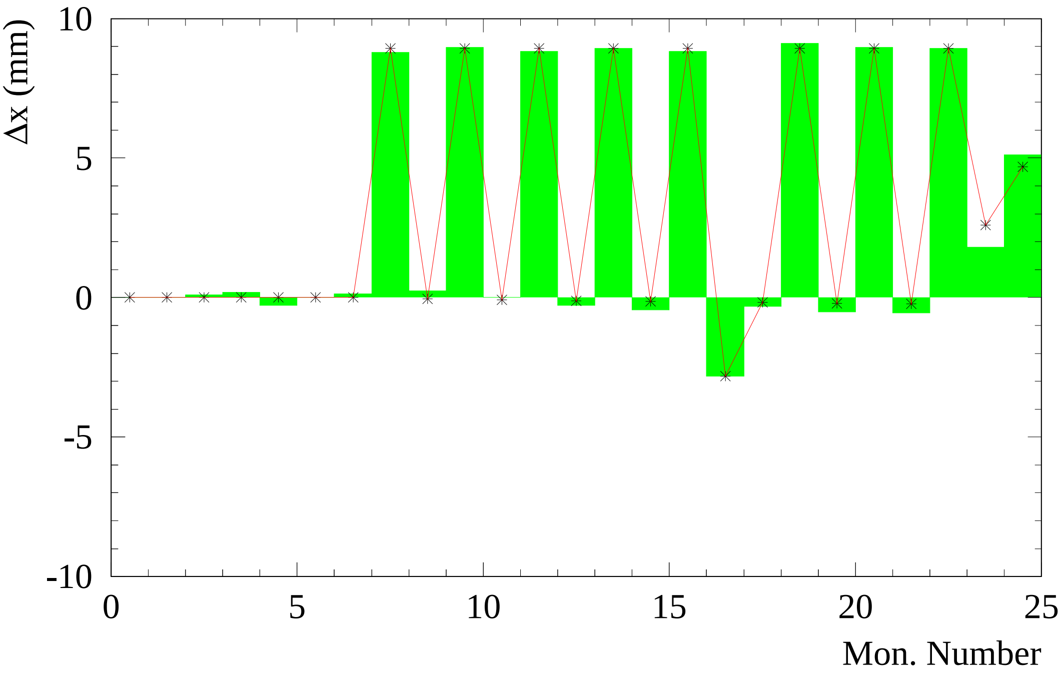

Figure 3 : Trajectory response data for the first horizontal orbit corrector in TI8 (histogram = data, points = model).

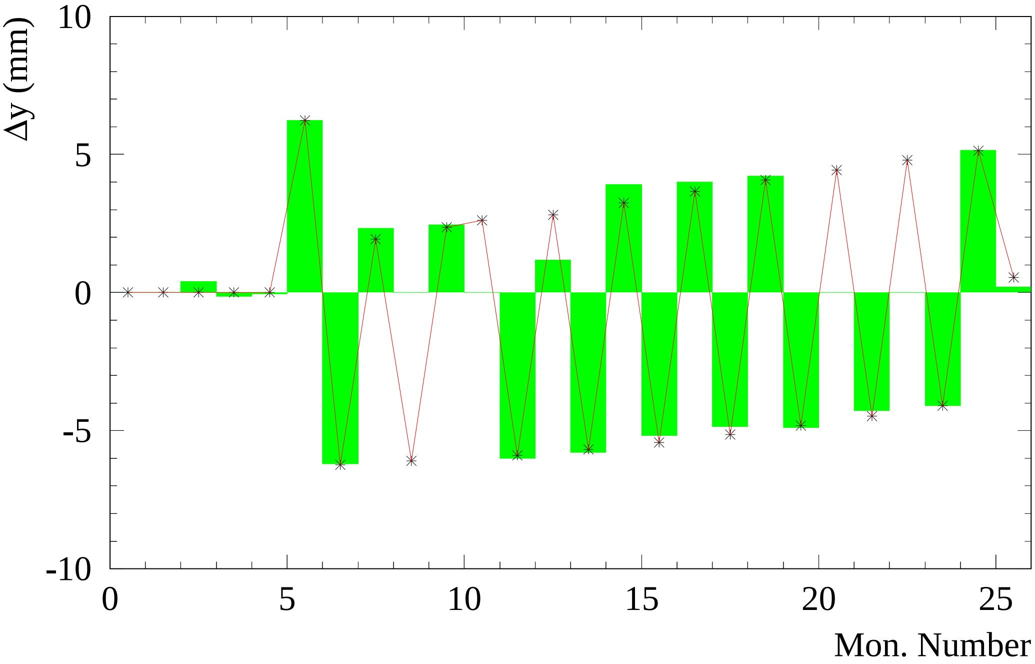

Figure 4 : Trajectory response data for the first vertical orbit corrector in TI8 (histogram = data, points = model). One notes that the phase advance between BPMs is not an integer multiple of 90 degrees, as compared to the horizontal plane shown in the previous figure. Some BPMs (no. 10, 20, 22) are missing in the data.

2.2. High Statistics Response Data

During the last night of the first TI 8 experiment high statistics response data was recorded for two horizontal and two vertical steering magnets at the beginning of TI 8. For each plane the correctors were selected to be nominally 90 degrees apart in betatron phase: MCIAH.816 and MCIAH.818 for the horizontal, MCIAV.815 and MCIAV.817 in the vertical plane. For each corrector setting the recorded trajectories were filtered (bad BPM readings, absence of beam) and averaged. The resulting average response sets (2 per plane) were fitted using LOCO.

In a first step only the in-plane trajectories (i.e. horizontal readings for horizontal kicks, and similarly for the vertical plane) were fitted to the model. The free parameters were the BPM and corrector calibration factors as well as the strengths of the main QF and QD quadrupole strings. This is similar to what has been described in the previous section. The data and the fit results are presented in Figure 5 (horizontal plane) and in Figure 6 (vertical plane). The agreement between data and model is good, the typical r.m.s. deviation between fit and data is or the order of 250 μm for peak excursions of around 10 mm. The r.m.s. deviation is therefore roughly 10 times larger than the statistical error of ≈ 30 μm. One can however observe isolated deviations data-fit of up to around 0.7 mm, mostly at places were the trajectory excursions are *small*.

In second step the LOCO fit was expanded to also include the cross-plane data since significant coupling is observed in the data. Because it is not possible to fit the roll angle of all TI 8 quadrupoles at the same time due to insufficient sampling, the cross-plane trajectories were first analyzed using the MICADO algorithm to narrow down the possible coupling sources. The in- and cross-plane trajectory data was then fitted simultaneously using a set of 12 candidate sources of coupling. The fit was iterated and at each step, the smallest coupling (near zero) source was removed from the fit. After a few iterations the 5 most significant candidates were retained. The results are shown in Figure 7 and Table 2. The fit quality is rather good, but not perfect. In terms of trajectory amplitudes, the coupling amounts to 0.25 mm/10 mm ≈ 2-3% which does not represent a significant issue. From Table 2 it is evident that QIF.824 is the prime candidate as source of coupling. Unfortunately a verification of its alignment did not reveal any apparent error. The coupling measurement will have to be repeated and confirmed (with more steering magnets) in 2006.

Table 2 : Fit results for quadrupole roll angles and integrated skew strengths K_sL.

Quadrupole	Int. skew strength K_sL (10^{-4} m^{-1})	Roll angle ϕ (mrad)
QID.819	-1.24	1.2
QIF.822	2.46	2.6
QIF.824	4.71	5.0
QID.855	1.27	-1.2
QID.859	1.11	-1.1

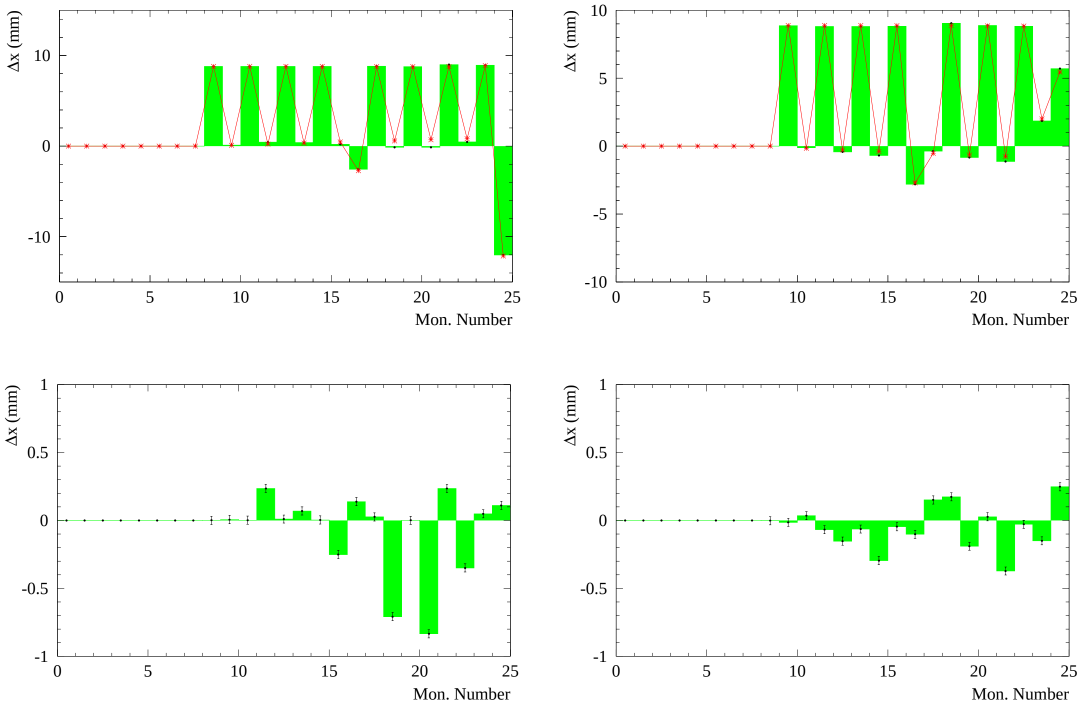

Figure 5 : Trajectory response for the high statistics sample for the horizontal plane. The top plots show the trajectory response for the 2 correctors (histogram = data, points = fit model), the bottom plots the difference between data and fit model.

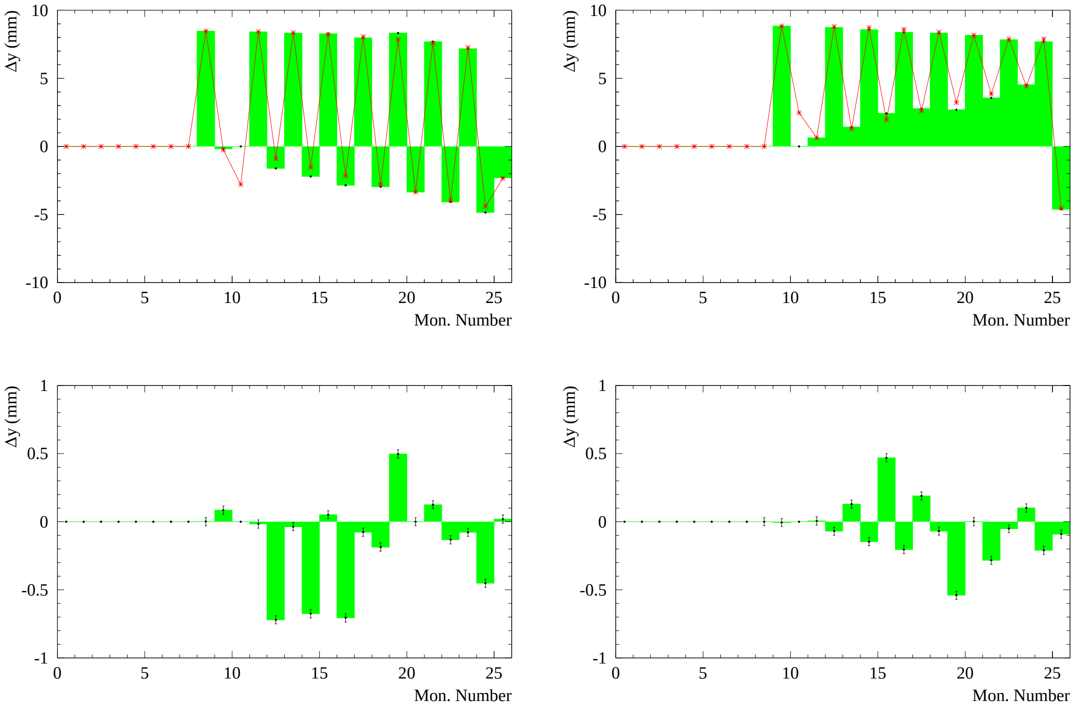

Figure 6 : Trajectory responsefor the high statistics sample for the vertical plane. The top plots show the trajectory response for the 2 correctors (histogram = data, points = fit model), the bottom plots the difference between data and fit model.

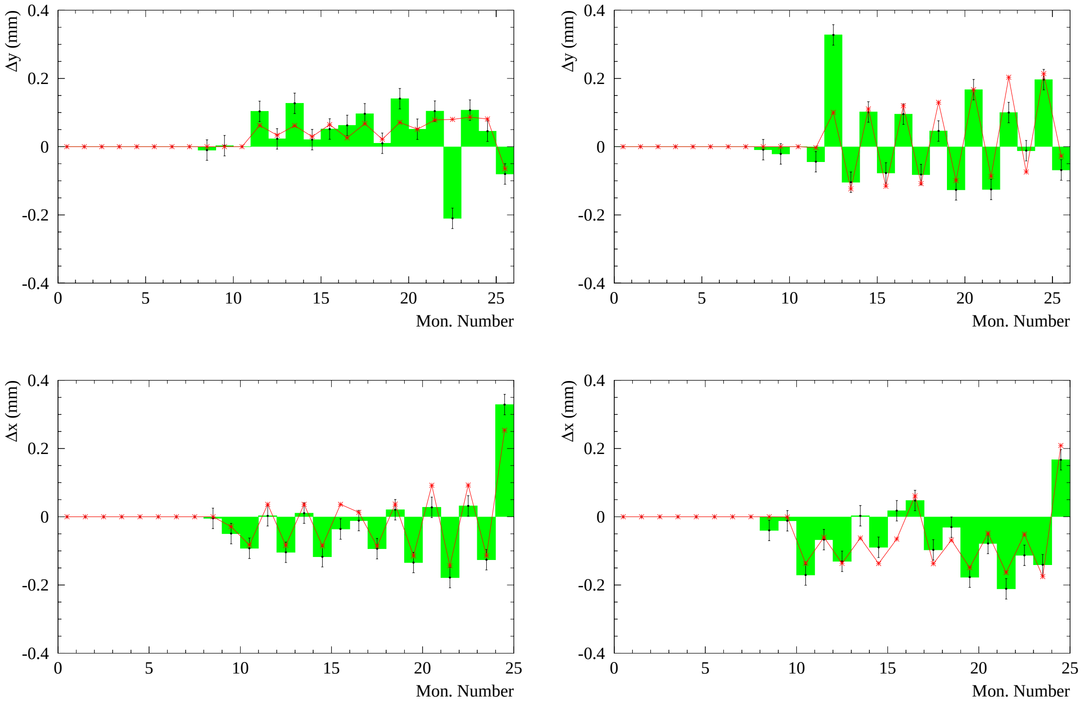

Figure 7 : Coupled trajectory response for the high statistics data sample. The top plots show the coupling H to V, the bottom plots the coupling V to H.

2.3. Transfer matrix

The high statistics trajectory measurements described above with two trajectories roughly 90 degrees apart can be used to determine the transfer matrix between selected regions of the transfer line. Two consecutive BPMs are used to define position and angle using the assumption that the local transfer matrix between them is accurate. With one BPM pair at the start of the line and another pair at the end of the line it is possible to reconstruct the transfer matrix.

For the horizontal plane the selected BPM pairs are BPMIH.826-BPMIH.828 and BPMIH.874-BPMIH.876. The pairs are used to reconstruct position and angle at BPMIH.826 and BPMIH.876. For the vertical plane, the BPM pairs are BPMIV.823-BPMIV.825 and BPMIV.871-BPMIV.873, and they are used to reconstruct position and angle at BPMIV.823 and BPMIV.873.

Using the strength values fitted with LOCO as given in Table 1, the nominal horizontal transfer matrix from BPMIH.826 to BPMIH.876 is

$$T_{826\to 876} = \begin{pmatrix} -0.114 & 54.192 \\ -0.015 & -1.534 \end{pmatrix}$$

while the trajectory data yields the matrix

$$T_{826\to 876} = \begin{pmatrix} 0.058 \pm 0.146 & 64.3 \pm 5.9 \\ -0.018 \pm 0.004 & -1.70 \pm 0.16 \end{pmatrix}$$

that is consistent with the expectations. The errors are estimated from the uncertainties on the BPM scale (1.5%) and from the r.m.s. deviation between data in model as seen in Figure 5. If the nominal QF/QD strengths are used instead of the values obtained from the LOCO fits, then the nominal response matrix becomes

$$T_{826\to 876} = \begin{pmatrix} -0.297 & 47.682 \\ -0.012 & -1.432 \end{pmatrix}$$

This matrix clearly shows larger disagreements with the measurements.

For the vertical plane, the transfer matrix from BPMIV.823 to BPMIV.873 is

$$T_{823\to 873} = \begin{pmatrix} 1.805 & 92.913 \\ -0.064 & -2.745 \end{pmatrix}$$

from the LOCO fit strengths, while the trajectory data yields the matrix

$$T_{823\to873} = \begin{pmatrix} 1.78 \pm 0.27 & 90.9 \pm 9.9 \\ -0.064 \pm 0.008 & -2.72 \pm 0.30 \end{pmatrix}$$

that is in good agreement with the model. Again the errors are estimated from the uncertainties on the BPM scale (1.5%) and from the r.m.s. deviation between data in model as seen in Figure 6. For the nominal QF/QD strengths the response matrix is

$$T_{823\to873} = \begin{pmatrix} 2.476 & 102.459 \\ -0.072 & -2.565 \end{pmatrix}$$

that is still reasonably consistent with the measurement, but in worse agreement than the matrix based on the fitted strengths of Table 1.

3. Beam Stability

During the tests a 6 hour period was devoted to the measurement of the transfer line stability from 00:00 to 06:10 on October 24th. To minimize the amount of beam send to the dump, beam was only send down the line for about 15 minutes every hour. 145 trajectories were acquired during that period. Due to the limitations on the total intensity that could be dumped on the TI8 TED, the stability measurement had to be performed with pilot bunches for which the resolution is limited to ≈ 200 μm. A simple visual inspection of the trajectory differences between the start and the end of this period reveals no significant signal, implying that over such a period the line drift is below the BPM resolution of 200 μm. When the trajectory sample taken during the first 15 minutes is averaged and compared to the similar average over the last 15 minutes period, the r.m.s. change over the line is 50 μm, and the pattern is consistent with noise. This indicates that slow drifts over a period of ~6 hours do not exceed 50 μm at places where β= 100 m.

A more in depth analysis of the trajectory sample collected during this measurement period was performed using the Model Independent Analysis (MIA) approach [5,6]. The idea behind this technique is to analyze large data samples to unveil correlations between measurements, for example some trajectory jitter. The basic technique in MIA is over a spatial-temporal mode analysis via a Singular Value Decomposition (SVD) of the data matrix holding the data histories. The SVD analysis decomposes the spatial and temporal variation of the beam into a superposition of orthogonal modes. Those modes are related to the underlying process that is driving the variations.

In practice the BPM trajectories are stored in a matrix A where the ith row contains the ith trajectory. The average trajectory is subtracted from the individual measurements. For convenience the matrix is normalized by a factor $\sqrt{(N\ M)}$ where N is the number of BPMs and M the number of trajectories in the sample. The SVD algorithm decomposes a matrix A of dimension N×M into

$$\mathrm{A} = \mathrm{U}\mathrm{W}\mathrm{V}^{\mathrm{T}}$$

W is a M×M diagonal matrix with non-negative elements,

$$\mathrm{W} = \begin{pmatrix} w_1 & 0 & \ldots & \ldots & 0 \\ 0 & w_2 & 0 & \ldots & \ldots \\ \ldots & 0 & \ldots & 0 & \ldots \\ \ldots & \ldots & 0 & \ldots & 0 \\ 0 & \ldots & .. & 0 & w_M \end{pmatrix}$$

V is a M×M orthogonal matrix and U a N×M column-orthogonal matrix

$$\mathrm{V}\mathrm{V}^{\mathrm{T}} = \mathrm{V}^{\mathrm{T}}\mathrm{V} = 1 \qquad \mathrm{U}^{\mathrm{T}}\mathrm{U} = 1$$

This decomposition is represented schematically in Figure 8. Matrix V contains the orbit pattern associated to each eigenvalue of W while the column vectors of matrix U describe the time evolution of the corresponding orbit pattern.

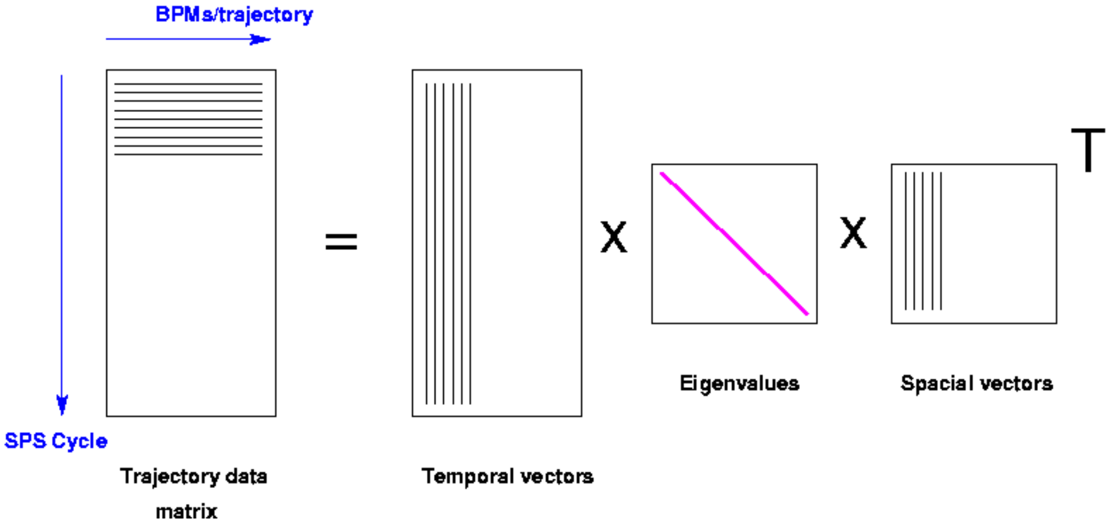

Figure 8 : Schematic principle of the MIA singular value decomposition.

Applying this technique to the trajectory sample reveals the eigenvalue spectrum shown in Figure 9. For the analysis 5 BPMs in each plane have been removed consistently for all measurements because they regularly returned absurd readings. While the spectrum for the vertical plane is rather flat, the horizontal spectrum contains one large eigenvalue that stands out roughly twice as large as the background noise. The associated spatial vector (respectively trajectory) is shown in Figure 10 (red data points).

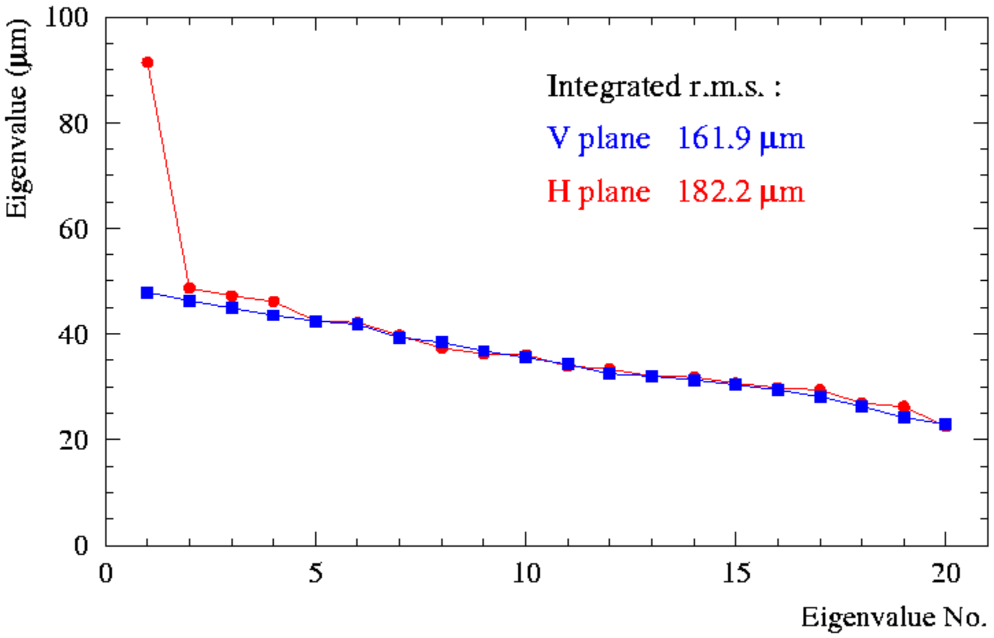

Figure 9 : Spectrum of MIA eigenvalues for the horizontal and vertical planes ordered from the largest to the smallest. The quadratic sum of all eigenvalues yields the r.m.s. stability of the trajectories.

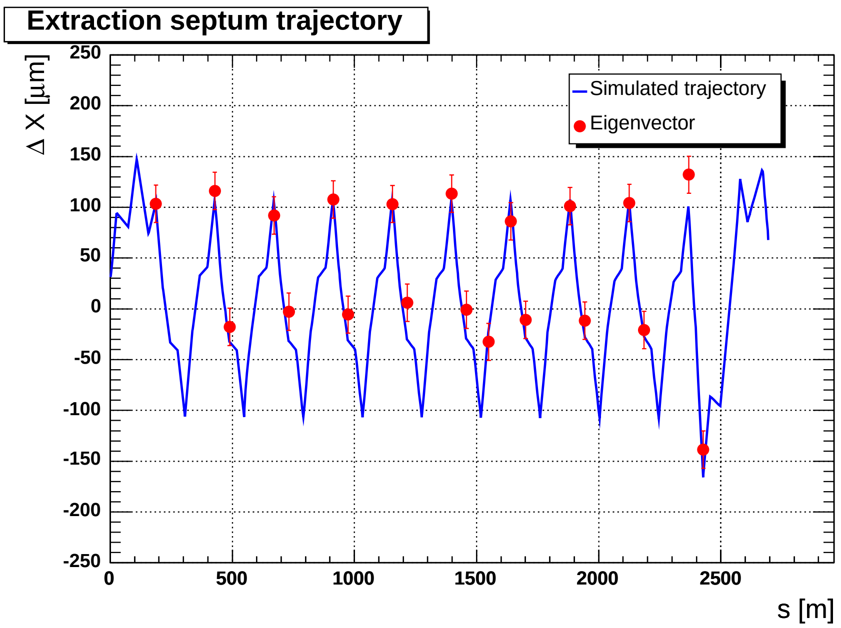

Figure 10 : The spatial vector associated to the largest eigenvalue of the horizontal plane corresponds to the red data points (measured at the BPMs). The horizontal axis corresponds to the longitudinal position along the line number while the vertical axis is the trajectory amplitude. The pattern is characteristic for a betatron oscillation. The solid blue line is the prediction of a trajectory excursion excited by the extraction septum MSE.418, with the amplitude adjusted to match the eigenvalue.

When the trajectory associated to the largest eigenvalue is analyzed using the MICADO algorithm to localize the possible sources of the variation, a very good agreement is obtained assuming that the unique source is the MSE.418 septum magnet at the start of the line, see Figure 10. From the amplitude of the eigenvalue it is possible to obtain the associated r.m.s. variation of the trajectory and the corresponding ripple of the MSE power converter. The maximum kicks due to the MSE correspond to ±4.5 μrad, or a current ripple of $\pm 3.8\times10^{-4}$. The r.m.s. kick is 1.4 μrad, the r.m.s. ripple 1.2×10^{-4}. The oscillation amplitude (at β = 100 m) corresponding to the r.m.s. kick is ≈100 μm which corresponds to $\sigma/8$ for the nominal LHC normalized emittance of 3.5 μm.

For all other eigenvalues the spatial vector is consistent with random noise.

The effect of the temperature of the cooling water and of the magnet coils on the trajectory was investigated by switching off the transfer line power converters for a period of 2 hours and by measuring the trajectory difference before switching off and just after switching back on. The trajectory difference is consistent with a momentum change of $\pm 1\times10^{-4}$ in the line.

4. Conclusions

Optics studies during the TI 8 commissioning period using the response matrix technique indicate that the actual transfer line optics is very close to the design model after initial settings errors were identified and corrected. The basic fit results for BPM and corrector calibration errors were available in the control within 30-60 minutes after data taking.

The stability of the TI 8 transfer line was found to be much more stable than anticipated, with practically no visible drifts over periods of many hours. The dominant source is trajectory instability was found to be consistent with a ripple of the MSE septum of few parts in ten thousand. More studies are necessary in the future to refine this information.

5. Acknowledgments

I thank all my friends and colleagues of the small TI 8 commissioning team for their support, patience, interest and whatever it takes to make a successful commissioning.

6. References

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