

Optics Studies of the LHC Beam Transfer Line TI 8

J. Wenninger, G. Arduini, B. Goddard, D. Jacquet,
V. Kain, M. Lamont, V. Mertens, J. Uythoven, CERN, Geneva, Switzerland,
Y.-C. Chao, Jefferson Lab, Newport News, USA

Abstract

The optics of the newly commissioned LHC beam transfer line TI 8 was studied with beam trajectories, dispersion and profile measurements. 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. Residual coupling between the planes was evaluated using high statistics samples of trajectories. Initial conditions for the optics at the entrance of the transfer line were reconstructed from beam profile measurements with Optical Transition Radiation monitors. The paper presents the various analysis methods and their errors. The expected emittance growth arising from optical mismatch into the LHC is evaluated.

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 paper presents the studies of the TI 8 transfer line optics based on measurements of the trajectory response, the dispersion function and beam profile measurements.

BEAM MOMENTUM MATCHING

The momentum of the line was set to 449.2 GeV to match the SPS extraction energy that was measured precisely using Lead ions [2]. Trajectory measurements indicate that the momentum of the extracted SPS beam and the transfer line settings were matched within a few 10^{-4} of relative momentum difference, the measurement accuracy being limited by the relatively low sampling of the trajectory by Beam Position Monitors (BPMs).

TRAJECTORY RESPONSE

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 [3]. The response for a set of correctors is obtained from two trajectory measurements. 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 based on the trajectory difference to remove the effect of the static trajectory. The data is processed with the LOCO program [3] that was coupled to MADX to allow fits of optics strength parameters through an iterative procedure. For a typical LOCO fit, all BPM and corrector calibrations as well as a selection of strength parameters are adjusted at the same time. An example is shown in Figure 1.

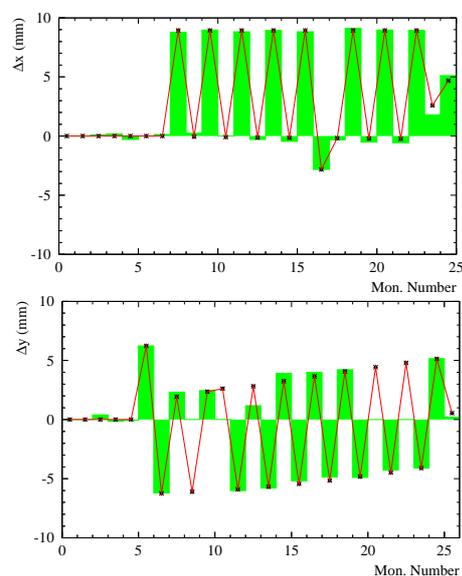


Figure 1: Examples for horizontal (top) and vertical (bottom) trajectory responses. The green histograms represent the data, the red points the fit model.

During the first test period a response measurement involving all corrector magnets was performed to detect malfunctioning BPMs or correctors. The data sample was fitted with LOCO using as free parameters all BPM and corrector calibration factors and well as the strength of the main QF and QD quadrupole magnet families. The data analysis revealed that one vertical corrector was not functioning and that about 10% of the BPMs suffered from polarity or calibration errors. The average calibration of the correctly functioning BPMs was $11 \pm 1\%$ higher than expected. All faulty elements were repaired for the second beam test. A response measurement during the second period confirmed that the problems had been fixed and showed that the spread of the BPM calibrations was in the range of 1-1.5%, but the 11% scale error of the BPMs remained and is not yet understood.

A significant optics mismatch was discovered from dispersion and trajectory response measurements during the first test. The problem was observed as a large phase jump of the trajectories in the first part of the transfer line. The error was mainly visible on the horizontal trajectory, indicating that the problem was due to a horizontally focusing quadrupole. To localize the source of the optics error, the LOCO fits were repeated using successively the strength of each quadrupole in the first part of the line as free parameter. The error could be tracked down to a quadrupole with a predicted strength error of 20%. This error was later confirmed to be due to a database problem that was fixed for the second beam commissioning period. The same problem affected a second quadrupole which could not be detected because it was installed close to the beginning of the line.

The results of the fit strengths for the main QF and QD quadrupole strings revealed a 1% error on the QD strength. The difference in the phase advance (nominally 90 degrees) is visible in Figure 1: for the vertical plane there is a phase slip in comparison to the horizontal plane.

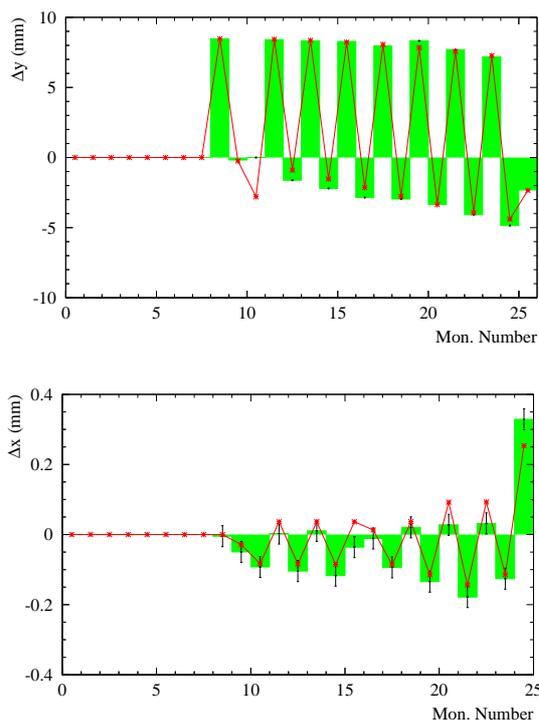


Figure 2: High statistics trajectory response for a vertical corrector. The top plot show the response for the in-plane data, the bottom plot for the cross-plane data.

High statistics response data was recorded for two horizontal and two vertical steering magnets located at the beginning of TI 8. For each plane the correctors were selected to be nominally 90 degrees apart in betatron phase. For each corrector setting trajectories recorded over a one hour period were filtered for bad BPM readings and averaged. Since measurable coupling was observed in the data, data sets were fitted with LOCO including coupling between the

planes. Because it is not possible to fit the roll angle of all quadrupoles at the same time due to insufficient sampling, the cross-plane trajectories were first analyzed using the MICADO algorithm to localize sources of kicks and narrow down the number of candidate sources for the coupling. The in- and cross-plane trajectories were then fitted simultaneously. The fit was iterated and at each step, the smallest coupling (near zero) sources were removed. After a few iterations the 5 most significant candidates were retained. An example of in-plane and cross-plane data is shown in Figure 2 together with the fit. The fit quality is good, but not perfect. In terms of trajectory amplitudes the coupling amounts to $\approx 2\text{-}3\%$ which does not represent a problem at this stage. The alignment of the most prominent source of coupling, a horizontally focussing quadrupole, was verified but no alignment error was detected. The coupling measurement will be repeated with more steering magnets in 2006.

DISPERSION

The dispersion in the transfer line was obtained by measuring trajectories in TI 8 for different RF frequency settings in the SPS at extraction. The momentum offsets ranged between -0.3 and $+0.3\%$.

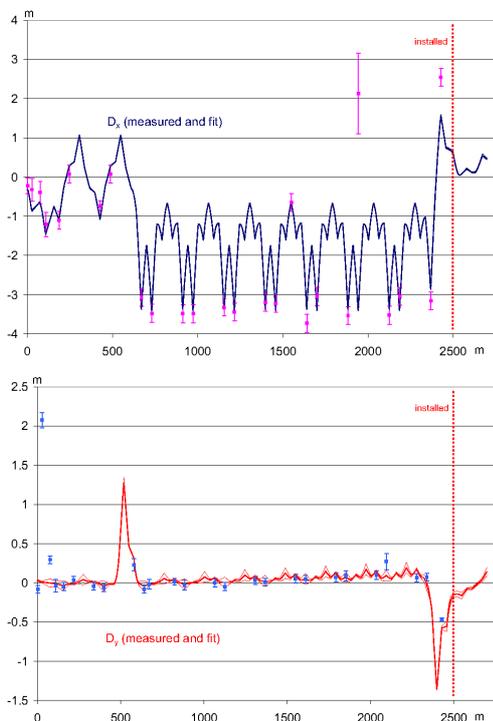


Figure 3: Horizontal (top) and vertical (bottom) dispersion function measured for TI 8. The points represent the measurements, the lines are the fitted dispersion functions.

The initial dispersion and dispersion derivative were obtained by fitting the measured dispersion to Cosine and

Sine-like trajectories using the design optics within the transfer line.

During the first measurement period large deviations of the horizontal dispersion from the design model were observed. Those deviations were due to the focusing strength error described in the previous section, and the problem was cured for the second period. Examples for data and fit results are shown in Figure 3 for the second test period. The overall fit quality is good, even though some degradation appears towards the end of the line. The deviation of the initial dispersion from the expected values are smaller than 3 cm for both planes and almost consistent with the design within the measurement errors of 1.5-2 cm. Only the horizontal dispersion derivative differs from the model by -0.012 .

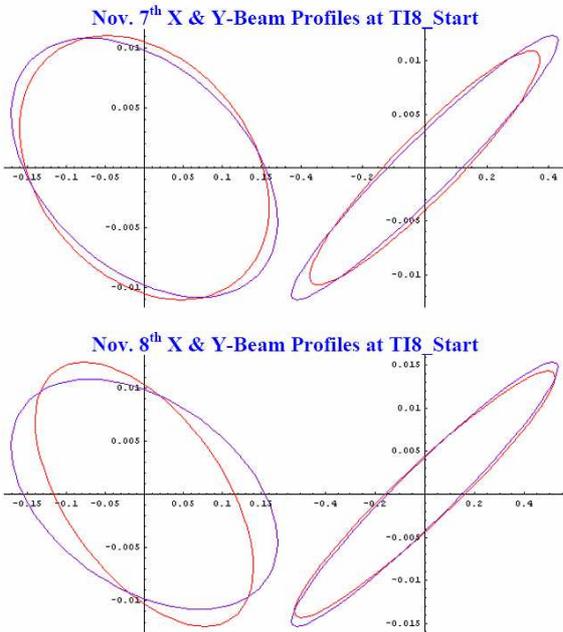


Figure 4: Comparison of design and measured beam profiles at the start of the line for the second beam test of 07/11 (top) and 08/11 (bottom). Horizontal profiles are shown on the left, vertical profiles on the right side. The units for the axes are mm (hor.) and mrad (vert.). Measurements are shown in red, design values in blue.

BEAM PROFILES

A total of 11 Optical Transition Radiation (OTR) screens are located in the path of beam in TI 8. OTR images are digitized pixel-wise and are translated into transverse 2-D distributions of the beam. The current analysis is based on the r.m.s. widths of the distributions projected onto the horizontal and vertical axes. The r.m.s. widths and errors, as well as design optics, are used to evaluate transverse beam phase space distribution, or emittance and Twiss parameters, at arbitrary given points with associated errors. The

TI 8 OTR screen configuration constitutes a parameter fitting system that yields robust numbers.

Parameter	7 th Nov.	8 th Nov.	Design
β_x (m)	17.4	15.2	13.6
α_x (m)	0.546	0.311	0.668
CS-invariant	1.09	1.24	1
β_y (m)	123.8	92.4	118.2
α_y (m)	-3.41	-2.53	-3.09
CS-invariant	1.16	1.09	1

Table 1: Initial parameters of the TI 8 transfer line for two measurements corresponding to the profiles of Figure 4.

Measurements on the second test period showed beam characteristics very close to their nominal values, although fluctuations between measurements were also observed. Fluctuations were assessed by analyzing OTR data accumulated over a six-hour period. The Courant-Snyder (CS) mismatch factors are represented in Figure 4 and Table 1 for two typical measurements, showing design and measured beam profiles in phase space at the start of TI 8. Deviation from design is found to be small, with CS mismatch factors staying within a few tenths of unity in both planes. The results on emittances and momentum spread are within 10% of those measured in the SPS before extraction.

The 2D OTR profile contains much more information than was exploited so far. No intrinsic X-Y correlation of the beam distribution was analyzed, although it can have bearing on the control of emittance. Likewise intrinsic momentum-betatron correlation was not analyzed other than taking them to be the same as the outcome of the dispersion measurement valid for beam centroids. A much more elaborate analysis, as it was performed for the injection line into the SPS [4] could be developed in the future.

CONCLUSION

Optics studies during the TI 8 commissioning period indicate that the actual transfer line optics is very close to the design model after initial settings errors were identified and corrected. Beam profile studies yield a Courant-Snyder mismatch factor in the range of 1 to 1.25, an excellent result for a such a long and new transfer line after only four days of beam operation.

REFERENCES

- [1] J. Uythoven et al., *Commissioning of the LHC Beam Transfer Line TI 8*, these proceedings.
- [2] J. Wenninger et al., *Energy Calibration of the SPS with Proton and Lead Ion Beams*, these proceedings.
- [3] J. Safranek, Nucl. Instr. Meth. A388 (1997) 27. J. Wenninger, *Orbit Response Measurements at the SPS*, CERN-AB-2004-009.
- [4] G. Arduini et al., *Analysis and Measurement of Coupling Effects in the Transfer Line from PS to SPS for the LHC Proton Beam*, proceedings of PAC 2001.