Beam Stability of the LHC Beam Transfer Line TI 8

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Abstract

Injection of beam into the LHC at 450 GeV/c proceeds over two 2.7 km long transfer lines from the SPS. The small aperture of the LHC at injection imposes tight constraints on the stability of the beam transfer. The first transfer line TI 8 was commissioned in the fall of 2004 with low intensity beam. Since the beam position monitor signal fluctuations were dominated by noise with low intensity beam, the beam stability could not be obtained from a simple comparison of consecutive trajectories. Instead model independent analysis (MIA) techniques as well as scraping on collimators were used to estimate the intrinsic stability of the transfer line. This paper presents the analysis methods and the resulting stability estimates.

INTRODUCTION

TI 8 ,the first 2.7 km long transfer line between the Super Proton Synchrotron (SPS) and the LHC was commissioned in the fall of 2004 [1]. Besides the studies of optics and aperture, the stability of the line was investigated. Both short- and long-term stability are critical for injection into the LHC, since they affect emittance growth, beam loss in the LHC injection regions and setup time of the lines. Stability studies were limited by the beam intensity that could be used during this commissioning phase, which had to be kept low in order to limit activation of the beam dump installed on the downstream end of the line which is close to the LHC tunnel.

This paper presents the two methods that were used to evaluate the stability despite the limitations imposed during the tests. The first method, based on so-called Model Independent Approach, is used to search for a coherent signal inside the beam position data, while the second is based on transmission measurements with a collimator.

TRAJECTORY MEASUREMENTS

During the TI 8 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, resulting in a total of 145 acquired trajectories. Due to the limitations on the total intensity that could be dumped on the TI 8 dump, the stability measurement had to be performed with bunches of 5×10^9 protons for which the single shot resolution of the beam position monitors (BPM) is 200 μm.

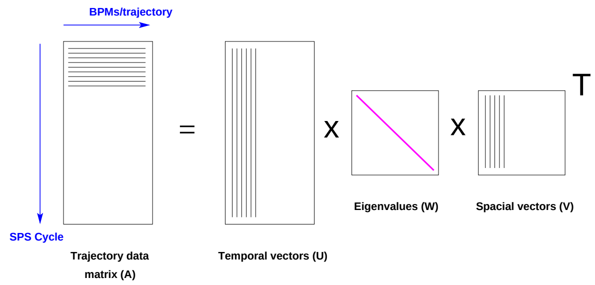

Figure 1: Schematic principle of the MIA singular value decomposition.

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 below the BPM resolution of 200 μm, which corresponds to $< \sigma_{beam}/4$ with σ_{beam} the r.m.s. beam size. A more in depth analysis of the trajectory sample collected during this measurement period was performed using the Model Independent Analysis (MIA) approach [2, 3]. The idea behind this technique is to analyze large data samples to unveil correlations between measurements, for example trajectory jitter. The basic technique in MIA is a spatial-temporal mode analysis via a Singular Value Decomposition (SVD) of the data matrix holding the data histories. The SVD analysis decomposes the spacial 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 $\mathbf{A}$ 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 (N $\times$ M) where N is the number of BPMs and M the number of trajectories in the sample. The SVD algorithm decomposes a matrix $\mathbf{A}$ of dimension N $\times$ M into

$$\mathbf{A} = \mathbf{U}\mathbf{W}\mathbf{V}^T \quad (1)$$

where W is a M $\times$ M diagonal eigenvalue matrix with non-negative elements,

$$\mathbf{W} = \begin{pmatrix} w_1 & 0 & \dots & 0 \\ 0 & w_2 & & \\ \dots & & \dots & 0 \\ 0 & \dots & 0 & w_M \end{pmatrix} . \quad (2)$$

$\mathbf{V}$ is a M $\times$ M orthogonal matrix and $\mathbf{U}$ a N $\times$ M column-orthogonal matrix. This decomposition is represented schematically in Figure 1. Matrix $\mathbf{V}$ contains the orbit pattern associated to each eigenvalue of $\mathbf{W}$ while the column vectors of matrix $\mathbf{U}$ describe the time evolution of the corresponding orbit pattern. Applying this technique to the trajectory sample reveals the eigenvalue spectrum $(w_1, ..w_i, ..w_M)$ shown in Figure 2. For the analysis 5 BPMs in each plane have been removed consistently from all trajectories because they regularly returned absurd readings. While the spectrum for the vertical plane is rather flat and consistent with noise, the horizontal spectrum contains one large eigenvalue that stands out above the background noise by a factor of two. The associated spacial vector (resp. trajectory) is shown in Figure 3.

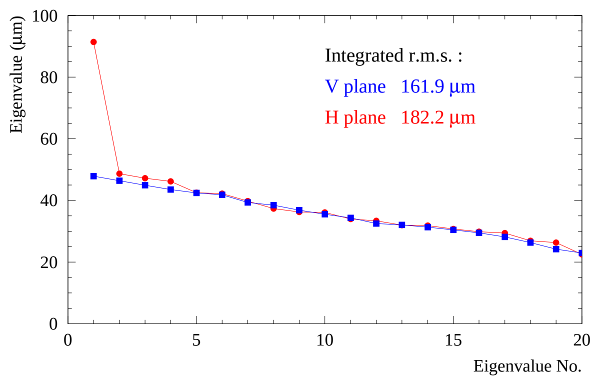

Figure 2: Spectrum of MIA eigenvalues for the horizontal and vertical planes ordered from the largest to the smallest. The quadratic sum of all eigenvalues yields the r.m.s. stability of the trajectories.

When the trajectory associated to the largest eigenvalue is analyzed to localize the source of the variation, a very good agreement is obtained assuming that the unique source is the SPS extraction septum magnet (MSE) at the

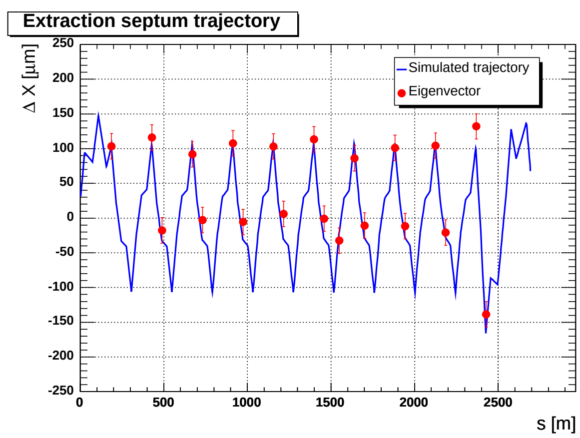

Figure 3: The spacial vector (trajectory) associated to the largest eigenvalue of the horizontal plane is compared to the simulated response due to a kick at the SPS extraction septum. The amplitude corresponds to the r.m.s. beam jitter due to this eigenvector.

start of the line, see Figure 3. From the amplitude of the eigenvalue it is possible to obtain the associated r.m.s. variation of the trajectory (beam jitter) and the corresponding ripple of the MSE power converter. The maximum kicks due to the MSE correspond to ± 4.5 μrad and to a current ripple of $\pm 3.8 \times 10^{-4}$. The r.m.s. kick is 1.4μrad amd the r.m.s. ripple 1.2×10^{-4}. The oscillation amplitude or beam jitter (at β = 100 m) associated to the r.m.s. kick is 100μm which corresponds to $\sigma_{beam}/8$. For all other eigenvalues, the spacial vectors are 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 10^{-4} in the line.

BEAM STABILITY MEASUREMENT WITH COLLIMATOR SCRAPING

During the TI 8 commissioning with beam an alignment method with beam of transfer line collimators was tested [4]. The proposed method is very sensitive to shot-to-shot beam jitter. The results of the test therefore also served as beam jitter measurement at the collimator location.

The alignment method is based on a transmission measurement of surviving protons when closing one of the two jaws of the transfer line collimators to the beam axis. Instead of beam loss monitors as commonly used for collimator set-up, the jaws are aligned with beam current transformers (BCTs) far downstream from the collimator location.

The measurement had to be calibrated with three different BCTs. The collimator was installed at the beginning of TI 8, in TT40, close to the first beam stopper in the line; two BCTs in the line, one in TT40 and one at the end of TI 8 before the second beam stopper, were used. The intensity measurement of these BCTs was normalized with the intensity measurement of the BCT in the SPS before extraction. Figure 4 shows the development of the intensity during the MD. The blue curve is the intensity at the BCT at the end of TI 8, the red curve is the transmission, defined as the intensity ratio between the end of TI 8 and the SPS. The nominal intensity during the test was some $3 \cdot 10^{10}$ protons per extraction in one bunch. The intensity minima marked by circles number 2 and 3 of Figure 4 correspond to collimator positions where one jaw was fully closed with different angular misalignment.

Calibration of Measurement

The BCT measurement errors were defined during the time period marked with number 1 in Figure 4. Both collimator jaws were out of the beam and beam jitter did not influence the intensity measurement.

With the assumption that both BTCs in the transfer line

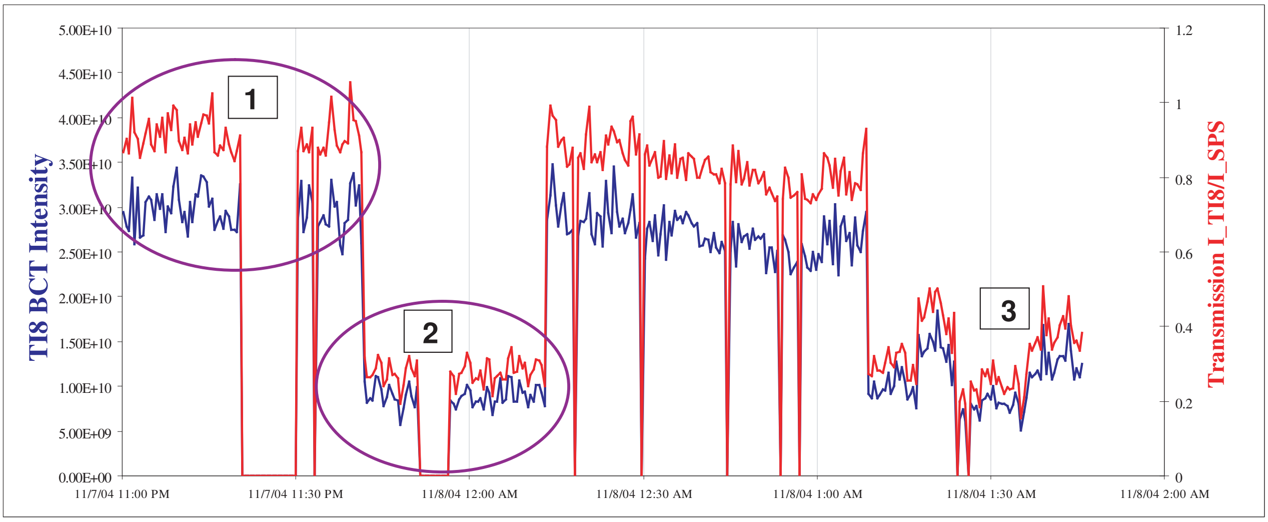

Figure 4: Measured BCT intensity at the end of TI 8 (in protons) in blue and transmission as ratio of intensity at the end of TI 8 over SPS intensity in red. During period number 1 both collimator jaws were open; during period number 2 one of the jaws was closed; during period number 3 one of the jaws was closed and the angular misalignment was varied.

have the same accuracy and that apart from calibration errors the ratio of the intensities I_{TI8}/I_{TT40} should be 1, the relative error of the BCT measurement at the end of TI 8 is estimated to 5%.

For the same period, number 1 in Figure 4, the measurement error of the SPS BCT was defined, where again the average of all measurements should be 1 for I_{TI8}/I_{SPS} using a scaling factor for the right calibration. Using the relative TI 8 BCT error, the relative error on the SPS BCT measurement is 0.5%, in agreement with the expected resolution of 10^8 charges.

Scraping and beam stability

For period 2 in Figure 4 one of the jaws was closed and left at the same position for about half an hour. The variation of the intensity at the BCT at the end of the line now depends on the variation of the intensity in the SPS and the variation of the beam position at the collimator jaw.

The average transmission during this time was $I_{TI8}/I_{SPS} = 0.305$. At this reduced intensity the BCT resolution determined above increases to 8%. This value is obtained from the 5% relative error determined above by comparison with measurements performed for intensities of 5×10^9 protons. The resulting intrinsic measurement error on I_{TI8}/I_{SPS} due to instrument resolution is therefore 0.024. The measured error on I_{TI8}/I_{SPS} is 0.034, with a contribution from the beam jitter of $\sigma_{jitter} = \sqrt{0.034^2 - 0.024^2} = 0.024$.

The collimator was a horizontal collimator at a location with a horizontal beam size of $\sigma_{beam} = 0.3$ mm ($\beta_x \approx 50$ m, $\varepsilon = 1.8 \times 10^{-9}$m). The average beam axis was hence 0.153 mm inside the collimator jaw (a Gaussian particle distribution was assumed). The r.m.s. error on the transmission measurement generated by the beam jitter translates into a beam stability at this location of

$$\sigma_{RMS} = 0.02\,\mathrm{mm} \tag{3}$$

which corresponds to $0.07 \times \sigma_{beam}$. The result obtained with the limited data sample gives confidence that the r.m.s. beam stability is well below 100 μm at this location.

The stability obtained from the transmission analysis is clearly consistent with the stability estimated from the MIA analysis.

CONCLUSION

The TI 8 transfer line was found to be very stable, with practically no visible drifts over a period of 48 hours. Two measurement methods have been presented. The dominant source for trajectory instability was found from MIA analysis to be consistent with a ripple of the SPS extraction septum of a few parts in ten thousand. The stability measurement with a collimator gave a beam jitter of well below 100 μm at the collimator location, consistent with the trajectory analysis. Both method consistently indicate that the r.m.s. beam jitter is of the order of $\sigma_{beam}/10$. More studies are necessary in the future to refine this information.

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