# ANALYSIS OF LHC TRANSFER LINE TRAJECTORY DRIFTS

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*Abstract*

The LHC is filled from the SPS via two 3 km long transfer lines: TI2 for beam 1 and TI8 for beam 2. In the first years of LHC operation large trajectory variations were discovered. The sources of bunch-by-bunch and shot-by-shot trajectory variations had been identified and improved by the 2012 LHC run. The origins of the longer term drifts were however still unclear and significant time was spent correcting the trajectories. In the last part of the 2012 run the optics in the SPS was changed to lower transition energy. Trajectory stability and correction frequency will be compared between before and after the optics change in the SPS. The sources of the variations have now been identified and will be discussed in this paper. Remedies for operation after the long shutdown will be proposed.

## INTRODUCTION

After the first two years of LHC operation the machine had proven to be working remarkably well, but there were still issues to be addressed. One of the concerns was the long turnaround time, especially influenced by the time spent at injection [1]. The time spent at injection was higher partly due to unstable trajectories in the SPS-to-LHC transfer lines, TI 2 and TI 8, which required correction to avoid high beam loss at injection [2].

By the start of 2012 sources of bunch-by-bunch trajectory variations and short term trajectory variations had been identified and mitigated. The main source of trajectory variations was found to be the SPS extraction septa (MSE). After efforts of the power converter team the MSE current ripple could be reduced and the trajectory variations went down by a factor 2 [3].

## TRAJECTORY CORRECTIONS

During the 2012 run the LHC was operating with 50 ns bunch spacing. The filling scheme consisted of a low intensity pilot bunch injection and an intermediate injection of 6 bunches, then 11 high intensity injections (72 or 144 bunches). For safe operation, transfer line corrections need to be followed by test injections of lower intensity (6 or 12 bunches) and time is lost as the beam must be dumped to refill with the correct filling pattern afterwards. On average a steering campaign requires 30 minutes.

For most of the 2012 run transfer line corrections were required 1-2 times per week to keep injection oscillations and injection losses within predefined limits. Towards the end of the run, after LHC Technical Stop 3 (17 - 21 September 2012), the frequency increased to once a day, see Fig. 1. During this technical stop the optics in the SPS had been changed to the lower transition energy optics Q20 [4]. It was suspected that there was a relation to the increased correction frequency.

* Operated by Fermi Research Alliance, LLC under DE-AC02-07CH11359 with the U.S. DOE.

## ANALYSIS OF TRAJECTORY DRIFTS

To investigate trajectory variations in the transfer line a large number of trajectories were analysed. In order to find the true variations, the effect of corrections was calculated and subtracted from the measured trajectories. From these trajectories the difference trajectories with respect to the average of the set were calculated and analysed. The eigenmodes of these difference trajectories were obtained by Model Independent Analysis (MIA) [5]. Through singular value decomposition, MIA finds the eigenmodes corresponding to independent sources of oscillation and gives the spatial and temporal eigenvectors.

Two periods were used to examine if there was degradation due to the change in SPS optics: July-September with Q26 optics and October-November with the new Q20 optics after the technical stop.

### *TI 2 Results*

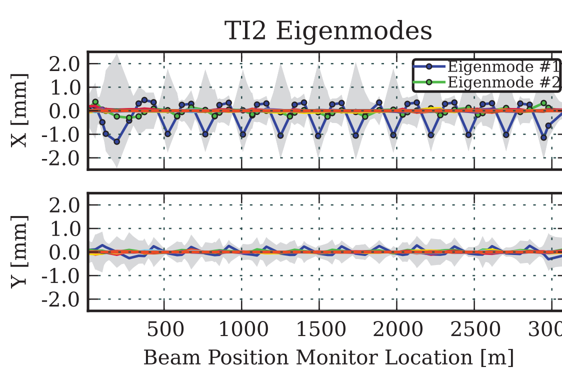


Figure 2: The observed variations for a period before the last technical stop is shown in grey. The variations are around 3 mm peak-to-peak in the horizontal plane. The MIA eigenmodes are given in the plot scaled by their eigenvalues. Only the two largest ones give a significant contribution indicating that there are two sources of variation. In the vertical plane the variations are small.

In Fig. 2 and 3 the difference trajectories in the two periods are shown. For both periods there are large variations in the horizontal plane. In the vertical plane the variations are

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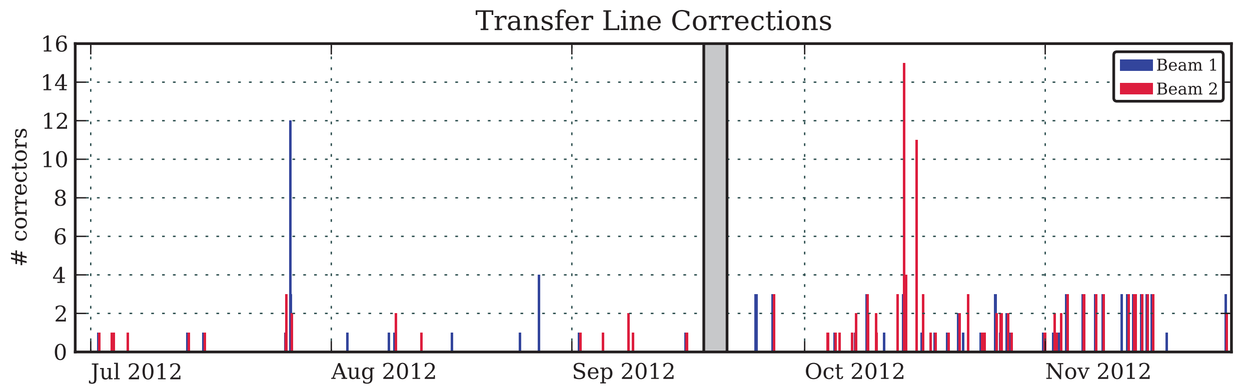


Figure 1: Frequency of transfer line corrections are shown for a period in summer with normal optics and for a period after the SPS optics change during the technical stop (shown in grey). The correction frequency dramatically increased from 1-2 times per week to almost daily in the second period.

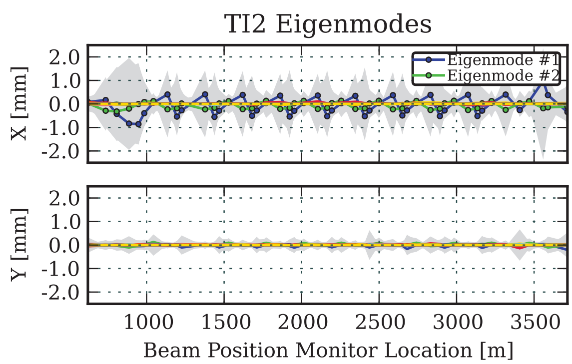


Figure 3: The plot shows trajectory variations after the SPS optics change. The variations have approximately the same size as before, but the pattern is different.

small and will not be considered further in this paper. Compared to the earlier period the Q20 optics does not seem to make the trajectory variations worse in amplitude, but the pattern has changed. The sources of variation can be found from the eigenmodes with the largest eigenvalues. For TI 2 there are two modes with significant eigenvalues corresponding to the same sources for both periods.

### *TI 8 Results*

For TI 8 the calculated variations are shown in Fig. 4 and 5. Also for TI 8 the variations are stronger in the horizontal plane. After the optics change the variations are similar, also here the pattern is slightly different. Nevertheless for both cases there are two strong eigenmodes indicating the same two sources.

### *Sources*

The sources of variation can be found as linear combinations of the significant eigenmodes. The eigenmodes were matched to simulations of possible sources, see Fig. 6 for TI 2. The data used are from the second period. As expected the MSE is still a source. Other elements were also

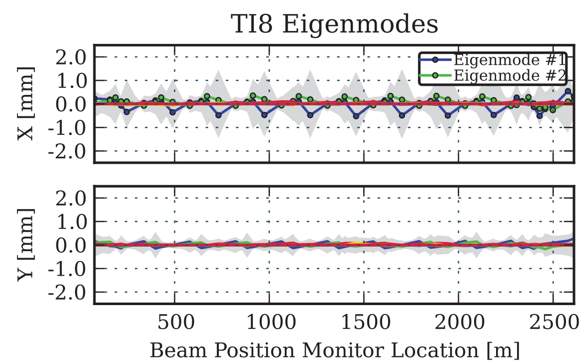


Figure 4: Trajectory variations for TI 8 before the technical stop are shown. In the horizontal plane there are large variations coming from two independent sources.

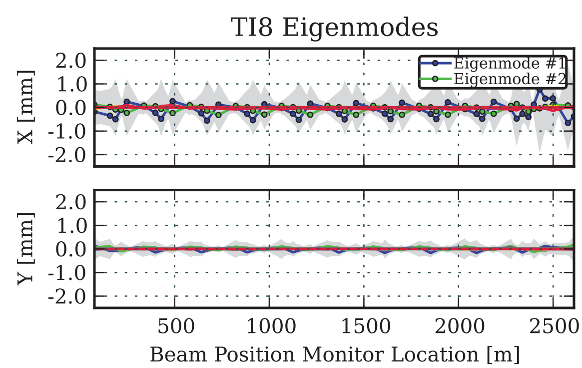


Figure 5: The plot shows the observed (grey) and calculated trajectory variations in TI 8 after the technical stop.

investigated, but are not strong enough to cause the variations observed in the transfer lines. The orbits in the SPS were monitored over a period of a few weeks and the resulting variations at the extraction point calculated. The orbit variations match the second source of trajectory variations in the transfer lines.

Even larger SPS orbit changes than seen during regular


ISBN 978-3-95450-122-9

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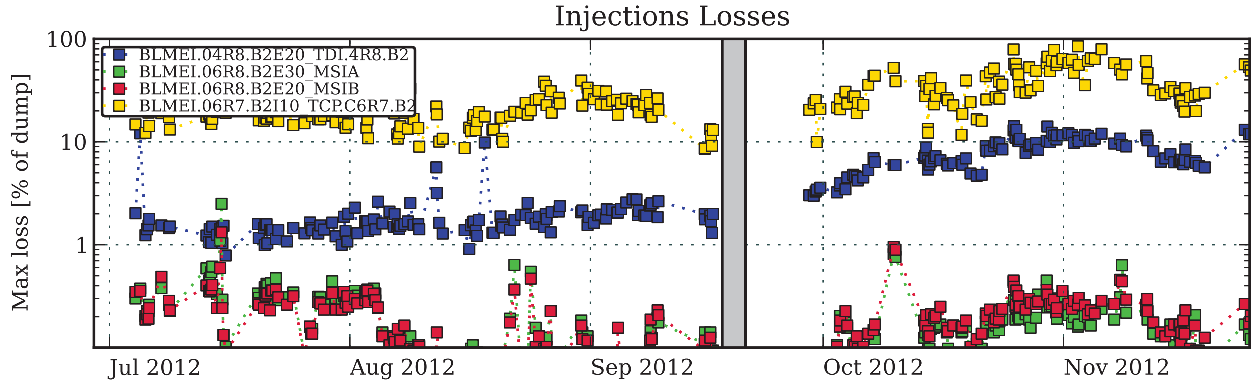


Figure 7: Maximum beam loss at injection per fill for selected beam loss monitors. After the last technical stop (shown in grey) an increase in the losses at the TDI and downstream at the TCP was observed. This loss signature indicates that the losses are longitudinal. Losses from the transverse plane (given by the BLMs at the MSI) remained low.

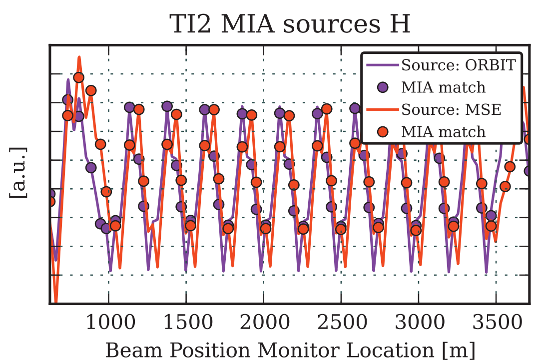


Figure 6: The sources are matched to simulations of an SPS orbit error and MSE current variations. Combining these sources can explain the variations observed.

operation can occur after technical stops. These are however not of concern for transfer line stability, as they require in general only one transfer line correction campaign.

The LHC has now entered its first long shutdown period (LS1) until the beginning of 2015. The MSE current ripple was already improved, but now further improvement require significant hardware modifications and are under investigation. The orbit variations in the SPS possibly come from dipole errors. Some improvement may be possible during LS1, but it is difficult to quantify [6].

## INJECTION LOSSES

Trajectory corrections are often initiated by beam losses in the injection region or at the primary collimators, which are above the reference thresholds. Increased losses after the techincal stop are seen at the BLMs at the TDI (injection protection element) and the TCP (downstream LHC collimators). Losses at the transfer line collimators (observed at MSI BLMs) did not increase, see Fig. 7. This signature indicates that the losses come from the longitudinal rather than the transverse plane. In this case transfer line corrections do not reduce the losses. The losses could possibly come from an increased satellite population (low intensity bunches between the nominal 50 ns spaced nominal bunches), but need to be investigated further. The losses at the TCP are very high and often above 50 % of the dump thresholds which could explain why the operators felt compelled to correct the transfer lines. The diagnostics will be improved to better guide the operators on when to steer the transfer lines.

## SUMMARY

In 2012, transfer line trajectories have been recorded over an extended period to analyse the trajectory stability over time. In the horizontal plane drifts of several millimeters were observed, in the vertical plane the variations were below 1 mm. Using Model Independent Analysis, the sources causing the variations in the horizontal plane were identified to be the SPS extraction septa (MSE) and orbit changes at the SPS extraction point for both transfer lines.

After the optics change in the SPS to the low transition optics Q20, the transfer line correction frequency increased significantly, but the analysis showed that this was not due to worse trajectory stability, but most probably due to misinterpreted increased longitudinal losses.

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