SOURCES AND SOLUTIONS FOR LHC TRANSFER LINE STABILITY ISSUES

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Abstract

The LHC is filled through two 3 km long transfer lines from the last pre-injector, the SPS. During the LHC proton run 2011 large drifts, shot-by-shot and even bunch-by-bunch trajectory variations were observed with the consequence of high losses at injection and frequent lengthy trajectory correction campaigns. The causes of these instabilities have been studied and will be presented in this paper. Based on the studies solutions have been proposed. The effect of the solutions will be shown and the remaining issues will be summarized.

INTRODUCTION

Beam is injected from the SPS into the LHC through two transfer lines: TI 2 for beam 1 and TI 8 for beam 2. The trajectory in the transfer line must be well controlled in order to limit losses at the transfer line collimators and to minimize injection oscillations for the available aperture in the LHC (<1.5 mm) [1]. The main source of losses are trajectory variations; during the 2011 run shot-by-shot variations, bunch-by-bunch variations and long time drifts were observed [2].

Frequent trajectory correction (steering) of the transfer lines was necessary in 2011 impacting LHC efficiency. Steering the lines was complicated due to the large shot-by-shot and bunch-by-bunch variations and had to be repeated several times per week taking 0.5 - 2 h per correction campaign [3]. The typical correction strength is about 10 μrad.

BUNCH-BY-BUNCH-VARIATIONS

The bunch-by-bunch analysis of the automatic LHC Injection Quality Check (IQC [4]) indicated large bunch-by-bunch differences of the injection oscillation amplitudes in the horizontal plane for beam 2 (TI 8) see Fig. 1. An insufficient flatness of the waveform of the SPS extraction kicker, MKE4 was suspected. A waveform scan indeed revealed a large ripple of 3.8% (specification: 1%), see Fig. 2.

Due to machine protection reasons trajectory correction is done with 12 bunches only. In 2011 the part of the waveform which was sampled with the first 12 bunches was unfortunately not representative for the full batch (144 bunches) as indicated also in Fig. 2. The first 12 bunches were following a very different trajectory from the rest of the bunches due to the large ripple at the beginning of the waveform. For the 2012 run the MKE delay was changed from 54 μs to 53.2 μs to only sample the region after the second overshoot. This should make steering with 12 bunches more straight forward. The waveform could however not be flattened in the short shutdown between the 2011 and 2012 run.

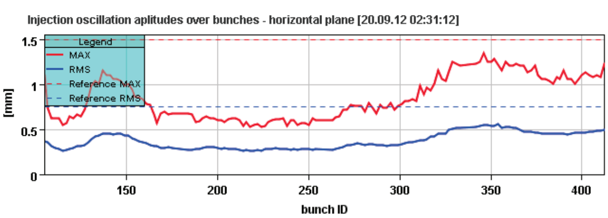

Figure 1: IQC plot of injection oscillation amplitudes as a function of bunch in the horizontal plane for a full 50 ns batch of 144 bunches, beam 2. Due to the large ripple of the SPS extraction kicker waveform, the bunch-by-bunch variations are large.

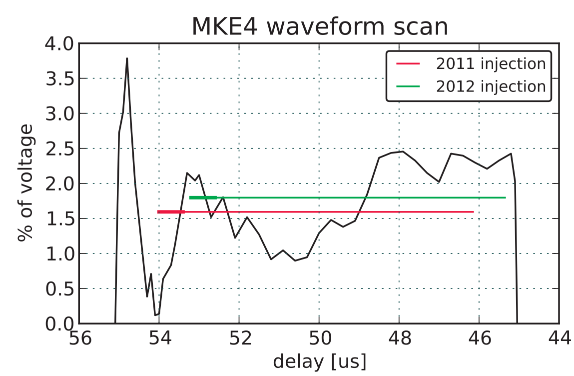

Figure 2: Scan of the SPS extraction kicker waveform for TI 8: The difference between minimum and maximum voltage along the waveform is 3.8%. In 2012 the kicker delay with respect to extracted beam was changed. The area of the waveform a full batch sampled in 2011 is indicated in red, for 2012 it is indicated in green.

SHOT-BY-SHOT VARIATIONS

Large trajectory variations were observed from one shot to the next. The analysis of the 2011 proton data recorded by the IQC show that the shot-by-shot variations are particularly large in the horizontal plane, around 0.6 mm for TI 2 and 0.4 mm for TI 8. The variations are around 0.1 mm in the vertical plane for both lines [3].

To understand the phenomenon dedicated stability studies were carried out extracting beam onto the beam stoppers

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(TEDs) at the line ends and recording about 90 trajectories. The difference trajectories were analysed using Model Independent Analysis (MIA [5]) to find the eigenvalues and eigenvectors of the trajectories over time. The spatial eigenvectors corresponding to the strongest eigenvalues are then compared with trajectories from error sources.

The stability test of TI 2 was carried out in June 2011. MIA indicates one strong eigenvalue in the horizontal plane for the recorded data, see Fig. 3. The corresponding trajectory matches an error on the SPS extraction septum MSE, see Fig. 4. The MSE is a single loop, low inductance magnet with a big deflection of $\sim$ 12 mrad.

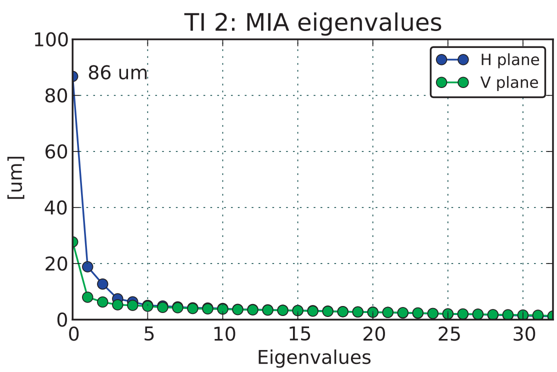

Figure 3: MIA eigenvalues for TI 2 June 2011 extraction test. One strong eigenvalue in the horizontal plane is found.

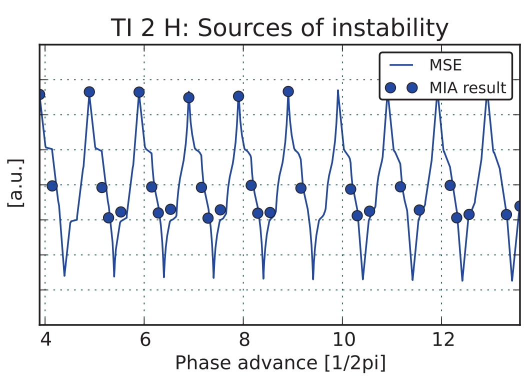

Figure 4: The spatial eigenvector corresponding to the strong eigenvalue in TI 2 fits with an error on the septum MSE in the SPS extraction region LSS6.

Most of the issues with injection losses were observed in TI 2 (also due to the topology of the transfer line collimators). After the first analysis results from IQC data on transfer line stability, efforts were made to improve the stability of the MSE power converter; The flat-top ripple was improved from 18 A to 9 A peak-to-peak. During the 2012 start-up a stability test in TI 2 was repeated showing indeed and improvement of the MSE eigenvalue in MIA by a factor 2, see Fig. 5. Investigations are still ongoing to even further improve the stability of the power converter. Another factor 2 would be desirable.

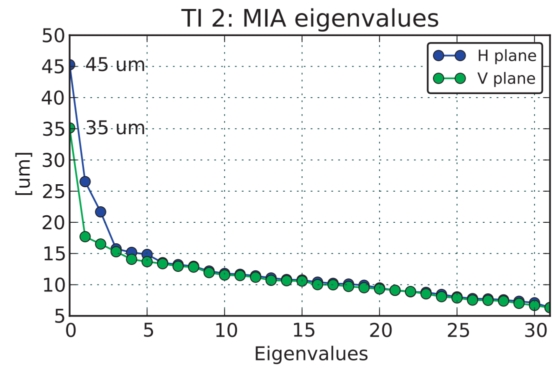

Figure 5: MIA eigenvalues for TI 2 March 2012 extraction test. The MSE is still a strong source, but the strength has been reduced by a factor 2.

The stability test for TI 8 was done only in October 2011. Two strong eigenvalues show up in the horizontal plane when analysing with MIA, see Fig. 6. The eigenvalues correspond to errors from the MSE and MKE in the SPS extraction region LSS4, see Fig. 7.

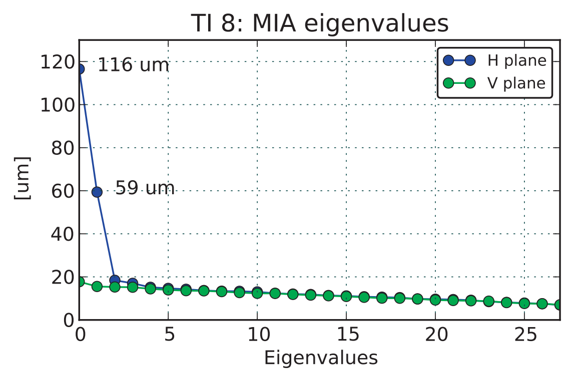

Figure 6: The first stability study of TI 8 in 2011 shows two strong sources of shot-by-shot variations in the horizontal plane.

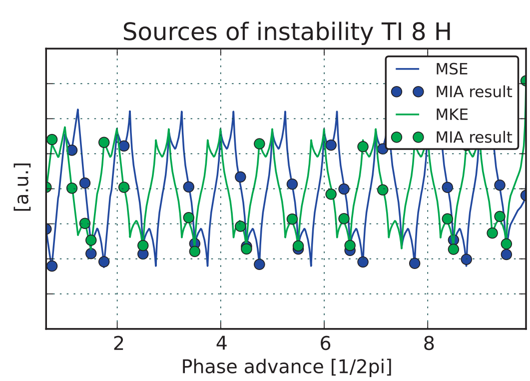

Figure 7: The eigenvalues correspond to errors on the septum MSE and the kicker MKE in the SPS extraction region.

In March 2012 the TI 8 stability check was repeated. The

MKE eigenvalue was suppressed, the MSE one stayed at a similar level as in 2011, see Fig. 8. The MKE result is still not understood. Later on in the 2012 run, the MKE instability seemed to become stronger again. Further investigations are still ongoing. Another stability test is scheduled after the start-up period.

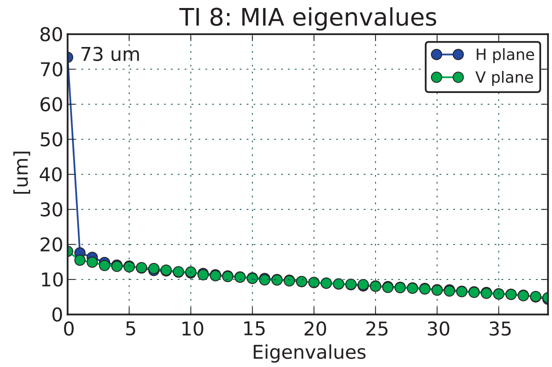

Figure 8: At the beginning of 2012 the stability study for TI 8 was repeated. An MKE error source was not present.

DRIFTS

In addition to the shot-by-shot changes the 3 km long transfer line trajectories are also drifting. After a period of 2 to 5 days a correction with 1 or 2 correctors of less than 10 μrad is needed to stay close to the reference trajectory. Drifts are stronger in the horizontal plane than in the vertical plane. The trajectories of all physics injections from 3^{rd} to 21^{st} of April were used for MIA analysis. The effect of the applied corrections in the period of reference had been removed from the trajectory data. The MIA results are shown in Fig. 9 and Fig. 10. The transfer line drifts seem to have many origins as shown by the several strong eigenvalues found for both beams. Also, the vertical eigenvalues are large. The extraction septa are among the sources for both lines. The other sources still have to be determined.

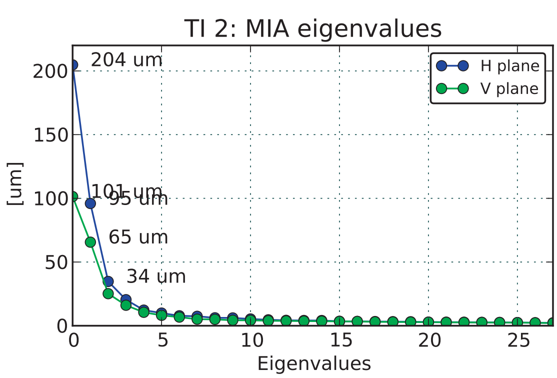

Figure 9: Eigenvalues found by MIA analysis of TI 2 over a period of 3 weeks in the beginning of 2012. Several sources are found in both planes.

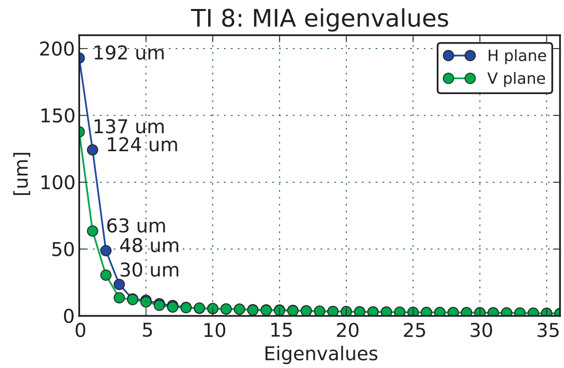

Figure 10: Eigenvalues found by MIA analysis of TI 8 using data taken over 3 weeks in the beginning of 2012. The result show several sources in both planes.

SUMMARY

The LHC transfer lines suffer from large shot-by-shot trajectory variations in the horizontal plane (~ 500 μm). In addition there are bunch-by-bunch variations of up to 1 mm in the horizontal plane for beam 2 due to a large ripple on the SPS extraction kicker waveform.

Sources of trajectory variations in the transfer line have been analyzed using Model Independent Analysis (MIA). For TI 2 the source of shot-by-shot variations was identified as the SPS extraction septum. Due to improvements on the MSE power converter the trajectory variations could be reduced by a factor 2 by the end of 2011. Studies are ongoing to improve the stability even further. For TI 8, two sources of trajectory variations have been identified: the extraction septum MSE and the extraction kicker MKE. In the vertical plane the shot-by-shot stability is acceptable.

Long term drifts are due to several independent sources and will therefore be more difficult to get under control. Even though the drifts are stronger in the horizontal plane, the vertical plane also shows large variations with time for both beams. The investigations concerning long term drifts have only started.

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