TRANSFER LINES - STABILITY AND OPTIMIZATION

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Abstract

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 different effects will be quantified and an estimate for downtime caused by them in 2011 will be given. The sources of the instabilities, solutions for 2012 and achievable improvements will be discussed. Possible future upgrades will also be mentioned.

INTRODUCTION

Beam is injected from the SPS into the LHC from 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].

Many mitigation measures had been put in place between 2010 and 2011. The strategy for setting up the TCDIs and establishing reference trajectories had also been greatly improved. Nevertheless transfer lines were still a concern. As it turned out throughout the course of the year the main problem is trajectory variations. Several partly independent issues have been identified: trajectory drifts, shot-by-shot variations of the trajectory and even bunch-by-bunch variations. In this paper studies to identify sources of variations in the transfer line trajectories will be presented. Impact on operations and mitigations will also be discussed.

DRIFTS

The transfer lines are drifting and need to be steered regularly. Frequently the same correctors are proposed. For TI 2 it is mainly RCIBH.20804 which is in phase with the MST and MSE (SPS extraction septa). The kick strength seems to be drifting back and forth, see Fig. 1. The cause of the drifts is still unclear and not further treated in this paper.

SHOT-BY-SHOT VARIATIONS

Large shot-by-shot variations have been observed in the horizontal plane for both transfer lines [2]. The transfer line stability (maximum variations at BPMs) was investigated using IQC (Injection quality check [3]) data from

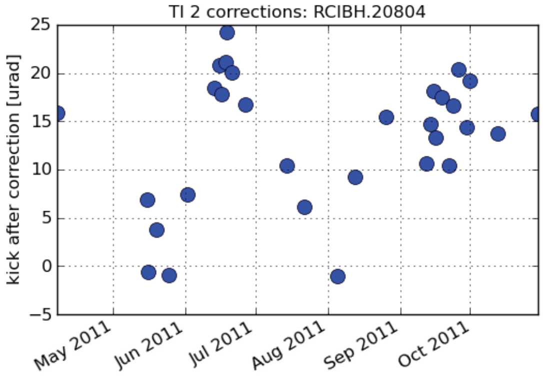

Figure 1: Applied corrections for the TI 2 corrector RCIBH.20804 during the 2011 proton run. This corrector was frequently proposed for correcting the line. It is in phase with the MST and MSE (SPS extraction septa).

144 bunch injections during the summer 2011. The variations were around 0.6 mm in the horizontal plane for TI 2 and about 0.4 mm for TI 8. In the vertical plane they were about 0.1 mm for both lines.

To investigate the sources of the variations dedicated stability studies were performed. For sufficient statistics repeated extractions on to the downstream TED were recorded for a period of 1.5 hours.

Form this data the difference trajectories from the average were calculated. The data was then analysed using model independent analysis (MIA) to find the eigenmodes of oscillation [4], [5]. MIA uses singular value decomposition to separate the spatial and temporal eigenvectors of a series of trajectories. From the result the trajectories corresponding to the strongest sources of oscillation can be obtained.

TI 2

For TI 2 a dedicated stability study was done in June 2011. 82 shots were recorded and analysed using MIA. For the horizontal plane the variations from the average trajectory was up to 760 μm, see Fig. 2. In the vertical plane the variations are smaller, up to 260 μm.

From this data set the MIA analysis gives one strong eigenmode of oscillation in the horizontal plane, see Fig. 3. All other eigenvalues are at an acceptable level and are not considered further.

The corresponding spatial eigenvector is a betatron os-

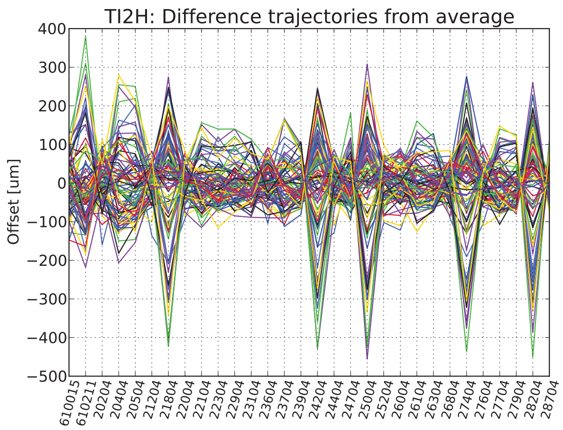

Figure 2: Difference trajectories from average per BPM for TI 2 in the horizontal plane during a dedicated stability study in June 2011. The variations go up to 760 μm.

cillation beginning at the start of the line meaning that the source is a single kick before the start of the transfer line, see Fig. 4 . To investigate possible sources MAD-X simulations of various errors were used. For the MSE the simulation matches the result of the MIA analysis. See Fig. 5 for a comparison of the trajectories.

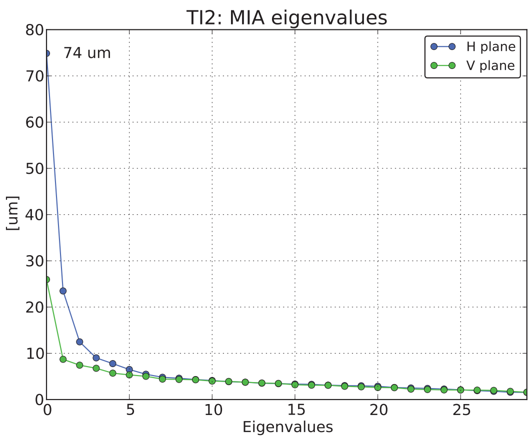

Figure 3: Eigenvalues found by MIA analysis of the TI 2 stability data. The analysis gives 1 strong eigenvalue in the horizontal plane pointing to one strong source of instability.

For the same period logged power converter currents of possible sources were investigated. The current variations were used as field errors in a simulation. The resulting excursions at a relevant BPM is given in Fig. 6. The MSE ripple correlates best with this BPM and its ripple is large enough to produce the variations observed. For the MST and other magnets investigated the observed current variations are not large enough.

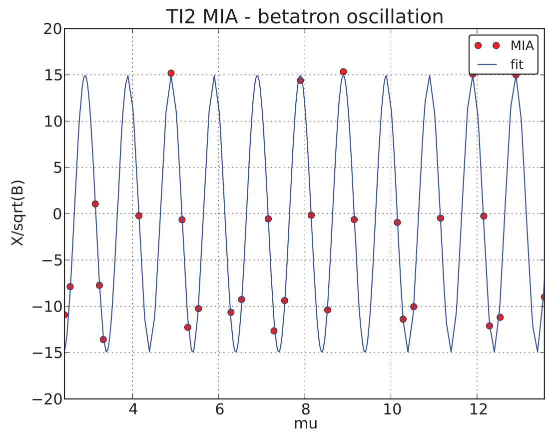

Figure 4: The spatial eigenvector found by MIA corresponds to a betatron oscillation beginning at the start of the line.

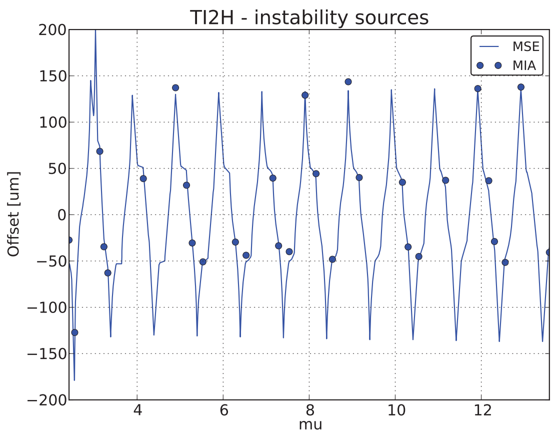

Figure 5: MAD-X simulations of an MSE error gives a good match to the trajectory found by MIA.

TI 8

In November the same study was done for TI 8, giving 117 shots used in MIA. The maximum variations from average in the set were 770 μm in the horizontal plane and 260 μm in the vertical plane. See Fig. 7 for the full set of trajectories with respect to the average for the horizontal plane.

Using this data set in MIA, two strong eigenvalues were found in the horizontal plane, see Fig. 8. The corresponding eigenvectors are also betatron oscillations starting at the beginning of the line pointing to errors from the SPS extraction system or upstream of the line.

Possible sources are found simulating field errors by MAD-X. For the two largest spatial eigenvectors a good match is found with the MSE and the MKE (SPS extraction kicker), see Fig. 9.

For the MSE this is confirmed by the logged current variations. The simulation shows that the observed cur-

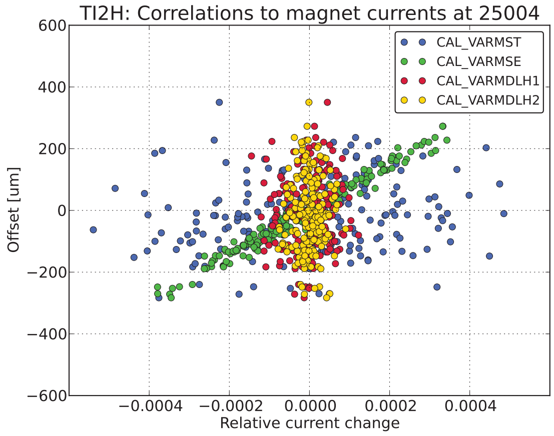

Figure 6: Simulations of magnet field errors using logged current variations gives a clear correlation to the MSE at BPMI.25004. The observed errors are large enough to produce variations of 760 μm.

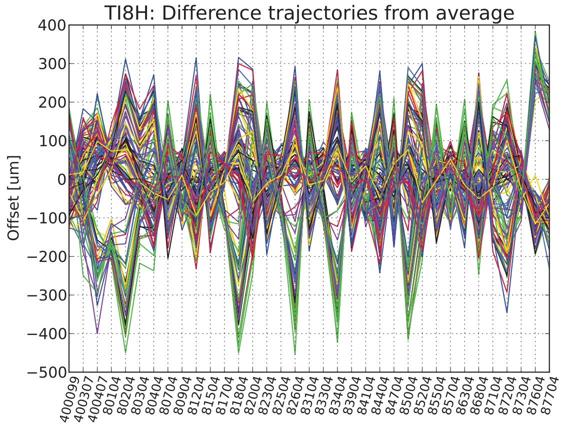

Figure 7: Variations from average trajectory in the horizontal plane of TI 8 during the stability study in November. The variations go up to 770 μm.

rent variations are large enough to produce the observed trajectory variations, see Fig. 10. A similar study is still necessary for the MKE.

Evolution of stability

The power converter team was informed about the MSE6 (TI 2) current variations and work was started to improve the stability. As a result the peak-to-peak ripple could be improved by a factor 2 by the end of the run. Variations measured using IQC data also seem to show a reduction, see Fig. 11. More statistics are necessary to confirm this. No further improvements have been done for TI 8.

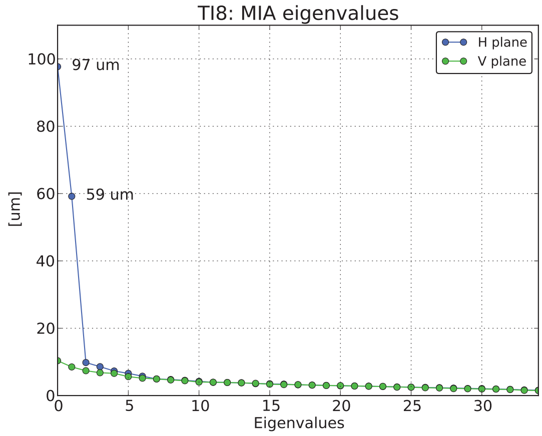

Figure 8: Eigenvalues found by MIA analysis of TI 8 stability data. Two strong eigenmodes give two sources of instability.

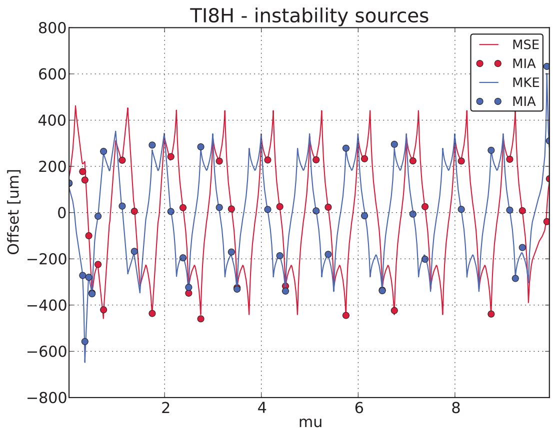

Figure 9: The two sources found in the MIA analysis match MAD-X simulations of errors on the MSE and the MKE.

BUNCH-BY-BUNCH VARIATIONS

In the horizontal plane for TI 8 the injection oscillations analysis in the IQC indicated large bunch-by-bunch variations in the injected batch indicating problems in the low inductance MSE or the waveform stability of the MKE, see Fig. 12. A waveform scan was performed to investigate a possible ripple on the waveform.

MKE waveform scans

For beam 2, two separate scans were performed extracting pilot beams on the upstream TED varying the kick delay. For the waveform scan a strong ripple up to 4% on the waveform was observed, see Fig. 13. From specifications this should be no larger than 1%. Reviewing a previous measurement, the ripple was already present in 2009. For 2012 the delay will be adjusted to avoid the worst part of the waveform ripple.

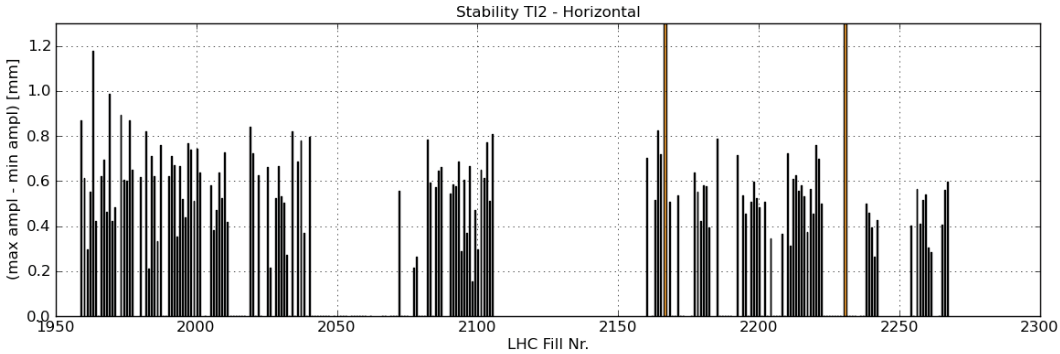

Figure 11: Stability of TI 2 for the 2011 proton run. Work was done to improve the MSE power convertors in two interventions marked by yellow lines. By the end of the run the stability seemed to have improved.

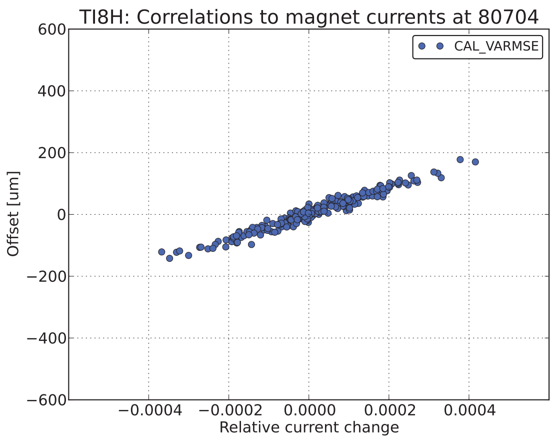

Figure 10: Simulations of logged current variations of the MSE gives high excursions at BPMI.80704.

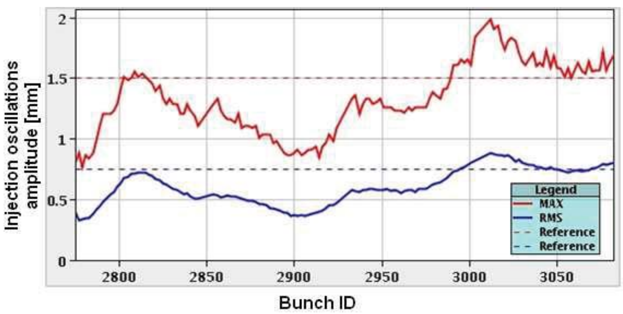

Figure 12: IQC plot showing large variations for the bunch-by-bunch injection oscillations amplitudes of the injected batch in the horizontal plane for beam 2.

For beam 1 this issue does not exist. A waveform scan (albeit fewer points) confirms this.

IMPACT ON OPERATIONS

Due to drifts of the transfer lines frequent correction has been necessary. For the 2011 proton run steering was re-

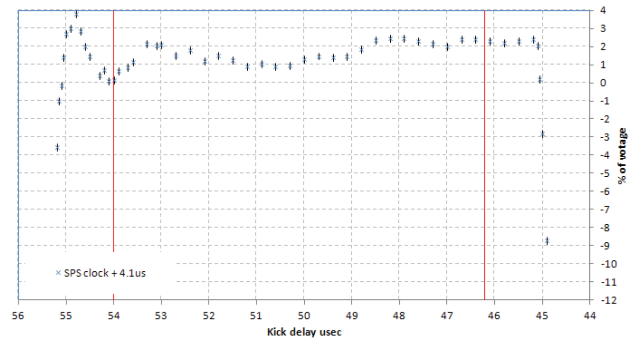

Figure 13: Scan of the SPS extraction kicker waveform in TI 8 - MKE4. The scan was done extracting a pilot bunch and varying the kicker delay. The waveform has a large ripple going up to 4 %.

quired several times a week (by the end of the run every second day). Because of shot-by-shot instabilities and bunch-by-bunch variations steering was complicated and time-consuming. Also the transfer line trajectory and LHC orbit eventually had drifted apart making it difficult to optimize for both LHC injection oscillations and losses due to the trajectory at the transfer line collimators. The typical time spent for steering of the transfer lines was 0.5-2 hours. Roughly approximating the expected time spent on steering in 2012: 1h x 0.5/days x 120 days = 60h.

SUMMARY

The main issues were tracked down to trajectory instabilities, especially in the horizontal plane. Much time was spent on steering the transfer lines in 2011. Steering was complicated due to trajectory drifts, shot-by-shot variations and bunch-by-bunch variations. Studies have been done to investigate the sources of trajectory variations.

Shot-by-shot instabilities in the horizontal plane for TI 2 seem to be caused by variations in the current of the MSE6. Work has started to improve the stability of the power converter.

For TI 8 both shot-by-shot instabilities and bunch-by-bunch variations were observed in the horizontal plane. Two sources of shot-by-shot variations were found: MSE4 and possibly the MKE4. Variations of the MKE4 still need to be investigated. The bunch-by-bunch variations are caused by a large ripple of the MKE4 waveform.

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