STABILITY OF THE LHC TRANSFER LINES

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Abstract

The LHC is filled from the SPS through two 3 km transfer lines. The injected beam parameters need to be well under control for luminosity performance, machine protection and operational efficiency. Small fractions of beam loss on the transfer line collimation system create showers which can trigger the sensitive LHC beam loss monitor system nearby and cause a beam abort during filling. The stability of the transfer line trajectory through the collimators is particularly critical in this respect. This paper will report on the transfer line trajectory stability during the proton run in 2011, correlations with injection losses, correction frequency and the most likely sources for the observed oscillations.

INTRODUCTION

The LHC is filled through the 3 km transfer lines, TI 2 (for injection of beam 1) and TI 8 (for injection of beam 2). The trajectories in the transfer lines have to be reasonably stable to keep injection oscillations within the good damping region of the LHC transverse damper and losses during injection low. The good damping region of the LHC transverse dampers is 2 mm [1].

2 MJ beams are transferred from the SPS to the LHC within 8 μs. Transfer line collimators are located at the end of the line at a setting of 4.5 σ from the reference trajectory to prevent damage of the LHC in case of failures during the transfer process. Even small losses on these collimators are picked up by the LHC Beam Loss Monitor (BLM) system on the nearby LHC super conducting magnets. Frequently the LHC BLMs trigger the beam dump at injection due to losses above threshold [2, 3].

The current LHC run conditions relevant for this paper are summarised in Table 1.

Table 1: LHC Run Configuration Since End of June 2011

Total number bunches for fill	1380
Max number bunches injected	144
Bunch spacing [ns]	50
Intensity/bunch	1.1 –1.4 $\times 10^{11}$
Emittance [μm]	1.8- 2.2
Intermediate intensity [bunches]	12
Number of injections per fill and beam	12 (+1 pilot)

Automatic Injection Quality Checks

At each injection the LHC injection quality check (IQC) process is triggered [4]. It analyses data of the transfer line and ring Beam Position Monitors (BPMs), the transfer line and injection region BLMs, the longitudinal Beam Quality Monitor (BQM) [5] and the injection kickers. Depending on the result of this analysis the next injection is inhibited via the LHC Software Interlock System. If the IQC latches on injection oscillations above limit, the interlock system blocks extractions from the SPS above intermediate intensity.

All the IQC raw data is stored on the LHC Post Mortem server [6] and can be re-analysed offline. Most data used for the analysis in this paper is IQC data.

OBSERVATIONS

The LHC transfer lines are drifting and have to be corrected back to the reference on average once a week. The correction algorithms tend to frequently propose the same correctors. In the case of TI 2, corrections of the horizontal trajectory are mainly carried out with corrector RCIBH.20804. Figure 1 shows the applied corrections during the 50 ns run period. The offsets are slowly drifting back and forth.

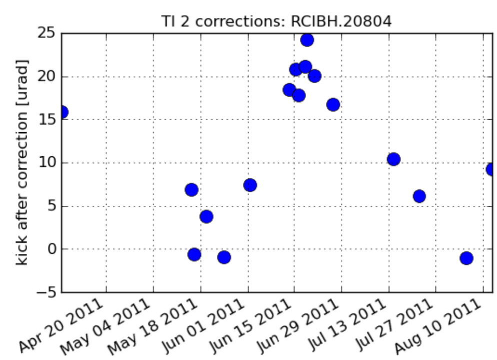

Figure 1: Evolution of settings of TI 2 corrector RCIBH.20804 during the 50 ns run, 2011.

The interlock limit for injection oscillations is set to 1.5 mm and rarely triggers (6 injection interlocks within 4 fills between middle of July and middle of August). In most cases corrections are triggered by high losses on the transfer line collimators. Even though the origin of the losses is frequently rather due to bad beam quality or inadequate scraping in the injectors, the trajectories have to be well centred in the collimators to reduce the sensitivity to quality issues. Figure 2 shows the correlation with the trajectory maximum excursion and the total losses on the transfer line collimators during a correction campaign (fill 1984).

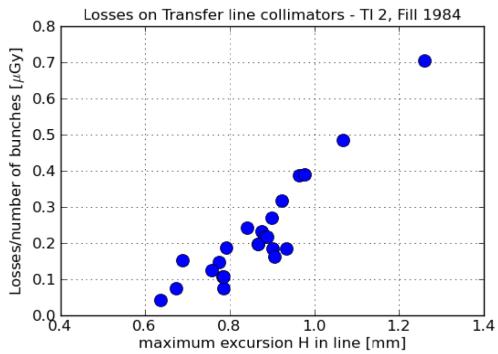

Figure 2: Correlation between maximum excursion in TI 2, horizontal, and total losses on transfer line collimators normalised to number of bunches.

What makes correcting the LHC transfer lines difficult are large shot-by-shot variations in the horizontal plane.

SHOT-BY-SHOT VARIATIONS

60 fills (fill 1959 - 2020) from middle of July 2011 to middle of August 2011 were analysed. Only injections with at least 12 bunches were taken into account and pickups with doubtful readings were ignored. The maximum excursion for each injection was recorded. The minimum and the maximum of these excursions per fill (12 injections) in the vertical and horizontal plane for both lines are plotted in Fig. 3 – 6.

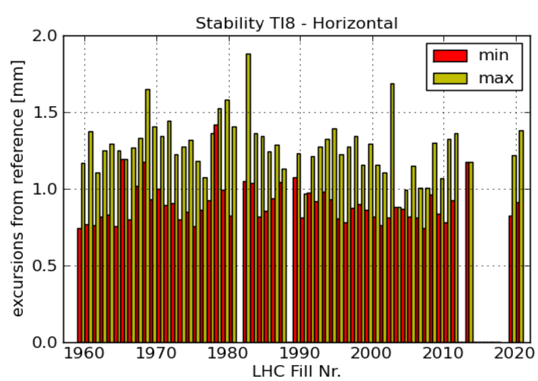

Figure 3: TI 8 Horizontal: Minimum and maximum excursion from reference during fill.

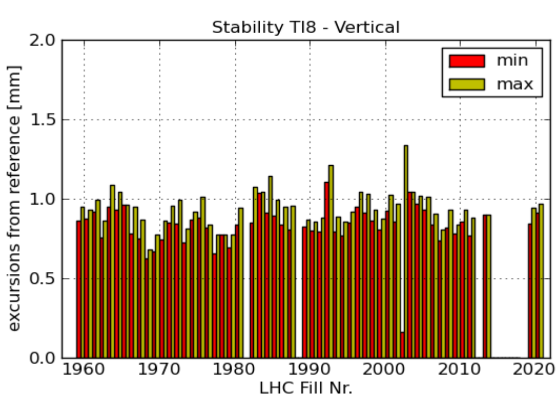

Figure 4: TI 8 Vertical: Minimum and maximum excursion from reference during fill.

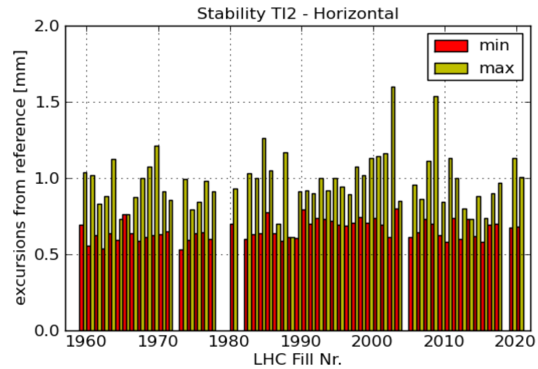

Figure 5: TI 2 Horizontal: Minimum and maximum excursion from reference during fill.

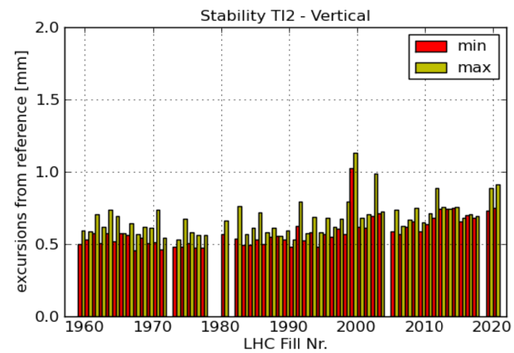

Figure 6: TI 2 Vertical: Minimum and maximum excursion from reference during fill.

Both lines show the same behaviour. In the vertical plane the maximum difference between the injections is about 100 μm. In the horizontal plane it is about 350 μm and frequently more than 500 μm. Table 2 summarises the results. As a consequence, transfer line corrections are only calculated on the average of several extractions.

SOURCES FOR HORIZONTAL SHOT-BY-SHOT VARIATIONS

The sudden oscillations in the horizontal plane affect the whole line and must therefore come from the SPS or the start of the line. The most likely candidates are the SPS extraction septa.

For TI 2 the typical excursions seen on one of the BPMs correlate with the current ripple of the extraction septum MSE observed during 80 test extractions performed on 19th of June, 2011, see Fig. 7 and Fig. 8. The fact that TI 8 is as unstable as TI 2 is new and the same measurements and analysis have not been performed yet for TI 8. The extraction septum current and power converter for TI 8 are however similar to the one for TI 2. Also, the corrector RCIBH.20804 of Fig. 1 is in phase with the TI 2 extraction septum. The slower line drifts as well as the shot-by-shot variations might come from the same source.

Table 2: Difference Between Maximum and Minimum Excursion in TI 2 and TI 8 for Fills 1959 to 2020

Line	plane	average [um]	max [um]
TI 2	H	335	986
TI 2	V	102	289
TI 8	H	395	877
TI 8	V	94	225

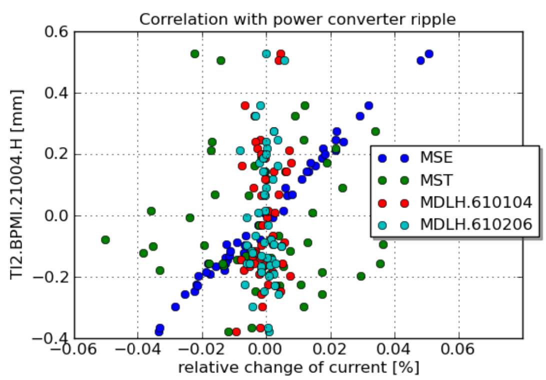

Figure 7: Simulation with MAD-X: excursion at TI 2 BPM versus measured power converter ripples of several dipole circuits at the beginning of TI 2. The MSE ripple correlates well with the BPM excursion.

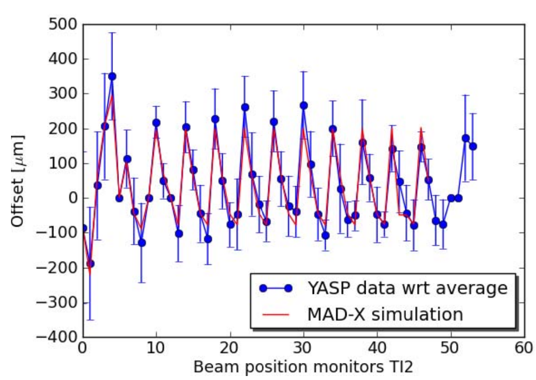

Figure 8: Measured trajectory in TI 2 with respect to average of extraction test period on 19th of June, 2011and MAD-X simulation of expected trajectory with current error of MSE at the moment of the measurement.

BUNCH-BY-BUNCH VARIATIONS

The LHC injection oscillations are measured bunch-by-bunch and at least 75 % of the injected bunches have to have amplitudes below the limit not to create an injection interlock. Only recently it was discovered that horizontal beam 2 injection oscillation amplitudes can vary up to more than 1 mm for different bunches along the injected batch, see Fig. 9. For the other beam and plane this variation is about 250 μm. The ripple of the waveform of the horizontal SPS extraction kicker for TI 8 is a very likely source for this, although it should be checked whether the low-inductance extraction septa could produce ripple with this high frequency. Investigations to understand and improve the situation are still ongoing.

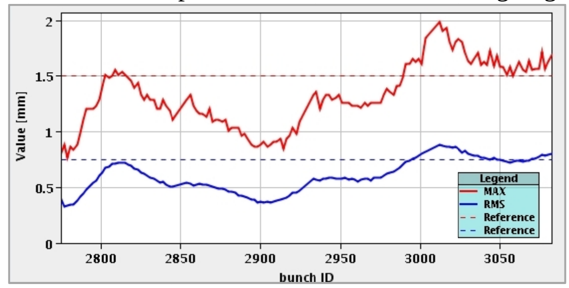

Figure 9: IQC plot of injection oscillation amplitudes and RMS for 144 bunches of a beam 2 injection. The difference between minimum and maximum amplitude is more than 1 mm.

CONCLUSION

The LHC transfer lines are long and the trajectories are observed to move with time. Corrections on average once a week are sufficient to keep these under control. However, also large shot-by-shot variations in the horizontal plane for both lines and large bunch-by-bunch variations in the horizontal plane for beam 2 are observed. Possible sources could be the extraction septa in the SPS and the extraction kicker for TI 8. Investigations are still ongoing. As soon as the origins of the trajectory instabilities have been indentified, effort will be put on solving the issues.

The LHC aperture at injection is large (about 12 σ) which leaves sufficient margin with the tight transfer line collimators for injection oscillations in the order of 1 – 2 mm. The limit had to be increased from 1.5 to 1.75 mm for beam 1 H, however, to cope with the instabilities of the line. With the beam scraping correctly set up in the SPS and the slow drifts regularly corrected for, enough margin is also available at the transfer line collimators. As however the beam quality in the injectors is not entirely reproducible, other measures should be pursued in view of larger emittance 25 ns beams and if the sources of these instabilities cannot be cured: re-locating the more sensitive collimators, increasing BLM thresholds in the injection region, increase reproducibility of SPS scraping.

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