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moises.barbera.ramos@cern.ch

LHC TI2/TI8 TL Stability Study during RUN II

Moises Barbera Ramos
CERN, CH-1211 Geneva, Switzerland

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Summary

This document presents a study of the stability of transfer lines (TL) TI2 and TI8 from the SPS to the LHC during RUN II. It shows the simulation process performed with MAD-X (Modelling Accelerator Dynamics software), to get familiar with TL optics and Model Independent Analysis (MIA). It carries out the analysis of real data from the LHC LoggingDB across the 4 year period of RUN II and the obtained results are then compared with the simulated ones aiming to find a source match with the element causing the trajectory oscillations. Evaluating results from RUN II (2015-2018) with those from RUN I (2008-2012), we observed an increased number of Eigen Modes above noise and hence suggesting the presence of more than one source. During 2017, a single month at each TL was identified with similar characteristics to the data from RUN I, making the MSE kicker a solid candidate for those periods. Further analysis is still needed to conclude on RUN II performance with respect to the last years of RUN I (after Power Converter Improvements).

Contents

1 Introduction

The injection process in the LHC is critical in terms of loss minimisation and preservation of the beam quality. During the last two runs, the injection phase was identified as one of the main limiting factors for a fast turnaround time.

Studies were performed for RUN I about the stability of the beam trajectories in the SPS-to-LHC TL (See ref. [1]). Despite the mitigations applied owards the end of Run I, the stability of the transfer lines seem to still have impacted the operation of the machine during RUN II. Analysing data from the LHC RUN II should provide a better insight on the stability status of the transfer lines.

Accordingly, this study requires getting familiar with the concept of trajectory variations as well as with the SPS extraction, beam transfer and LHC injection systems, Fig.1.

The focus of the study is analysing the trajectory of the particles which is recorded by the Beam Position Monitors (BPMs), placed at strategic position through the TL and recording the horizontal and vertical position of the beam.

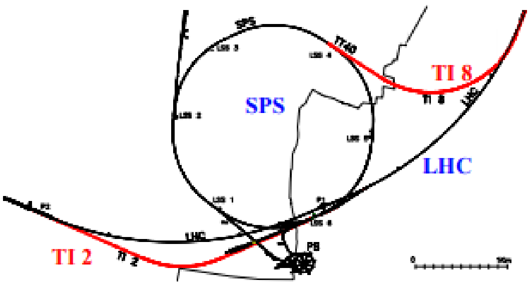


Figure 1: Layout of the SPS-to-LHC transfer lines TI2 and TI8 (highlighted in red)[4].

- **TI2**. Approximately 3 km long, transports the beam from the SPS Long Straight Section (LSS) 6 to the clockwise LHC ring.The extraction from the SPS is performed through the TT60 section (when referring to the TI2 on this document we are also including TT60 on the study). Features 59 BPMs.
- **TI8**. Approximately 3 km long, transports the beam from SPS LSS4 to the counter clockwise LHC ring. The extraction from the SPS is performed through the TT40 section (when referring to the TI8 on this document we are also including TT40 on the study). Features 51 BPMs.

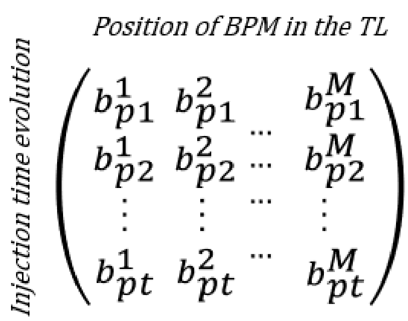
To analyse the trajectory variations of the beams, a series of simulations were performed with MAD-X to set up the environment for the MIA analysis of RUN II experimental data, implemented through a series of Python scripts and programs.

The results obtained from the simulated and experimental data are then presented in this document.

2 Model Independent Analysis (MIA)

To perform this analysis the data to analyse must be cleaned and organised to satisfy the following structure [3]:

1. Considering a sequence of M BPMs for P injections we can construct the Matrix B(P,M):



$$\begin{pmatrix} b_{p1}^{1} & b_{p1}^{2} & \cdots & b_{p1}^{M} \\ b_{p2}^{1} & b_{p2}^{2} & \cdots & b_{p2}^{M} \\ \vdots & \vdots & \cdots & \vdots \\ b_{pt}^{1} & b_{pt}^{2} & \cdots & b_{pt}^{M} \end{pmatrix}$$

   Where we have all the BPMs across the x axis of the matrix and the position of the beam at each BPM for each different injection across the y axis.

2. Then, the Singular Value Decomposition (SVD) is implemented to identify the temporal (U) and spatial (V^T) vectors as well as the eigenvalues (Λ).

3. The eigenvalues above noise show then the number of significant variables, providing a

corresponding spatial eigenvector for each dominant mode which shows the spatial trajectory followed by the beam trough the TL. The sources affecting the beam motion are then linear combinations of these eigenmodes.

3 MAD-X simulations

MAD-X (Modelling Accelerator Dynamics software) was used to generate 100 trajectories of beams, where a source of error (σ) of 50 μrad as the mean of a Gaussian distribution was applied at the start of the TL [5].

This simulated data-set is then used to set up the environment for the MIA analysis.

3.1 TEST eigenvalue analysis on Run II compared with Run I

Under these conditions, the MIA analysis described previously was used to obtain the Eigenvalue distribution of the simulated/test data, (see Figure 2), which was generated following TI2 characteristics.

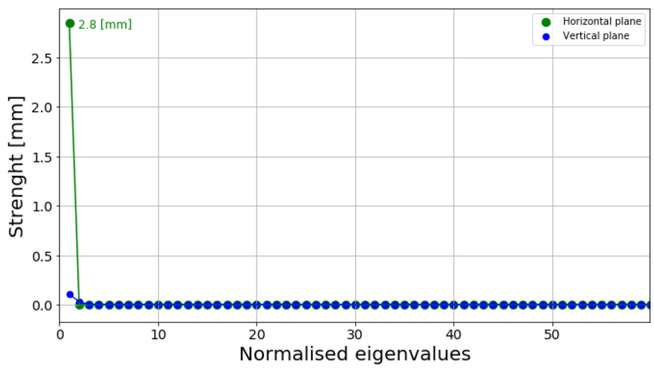


Figure 2: Eigenvalues from the MIA analysis performed on simulated data for TI2 TL RUN II, it presents one single dominant singular value of 2.8 mm on the horizontal plane as the source of error was applied only on this plane

In order to identify one single source causing the trajectory variations, it would be expected to find just one dominant eigenvalue while the rest of elements remain close to zero as noise background.

For the simulated set we can observe how RUN II and RUN I (see Figure 2) present an equivalent behaviour.

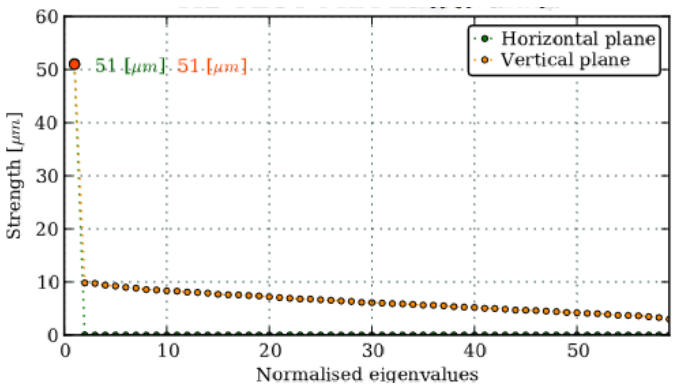


Figure 3: Eigenvalues from the MIA analysis performed on RUN I simulated data for TI2 TL, it presents one single dominant singular value of 51 μm on the horizontal plane[2].

3.2 TEST trajectory analysis on Run II

As only one dominant eigenmode was obtained, the spatial eigenvector corresponding to that one mode represents then the trajectory of the beam across the TL, see upper Figure 4). This trajectory on the horizontal plane can be normalised by the square root of beta function, this normalisation process is used to identify the oscillation of the beam which, after plotting a sine function on top of the calculated trajectory, confirms a betatron oscillation across the totality of the TL, see lower Figure 4.

Having one dominant eigenmode implies the presence of one single source causing the trajectory variations. Generating a simulated kick on the MSE septa and plotting it on top of the normalised data, allowed to identify this MSE as the source causing the variations on this dataset with a kick of 0.009 mrad, see Figure 5.

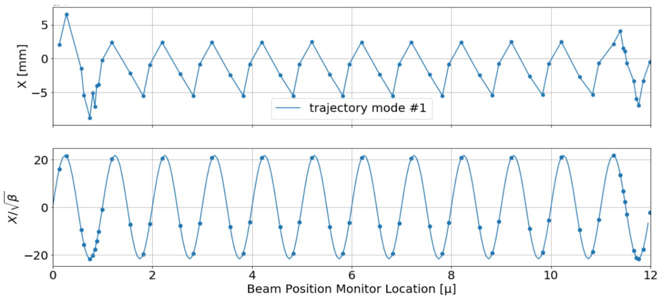


Figure 4: Upper plot: shows the trajectory corresponding to first spatial eigenvector (V^T), of the beam across the TL. Lower plot: presents the same trajectory normalised by $\sqrt{\beta}$ satisfying a betatron oscillation. Both plots present the totality of the transfer line in terms of the μ parameter for TI2.

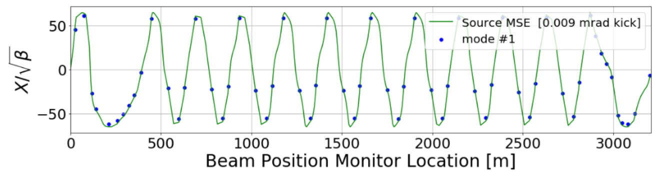


Figure 5: Image showing the normalised trajectory of the simulated/test data of TI2 matching the source trajectory, identified as the MSE applying a 0.009 mrad kick.

4 Data analysis

Across the 4 year period of RUN II, from 2015 to 2018, the months analysed for this study are those performing proton physics and scrubbing runs.

To perform the MIA analysis in this experimental data, the Python program developed for the simulated data was upgraded to automatically access LHC's database and select all the injections performed across any selected period. The program shows the filtering and cleaning steps to only use significant data on the study before performing the MIA analysis and subsequent visualizations.

This incorporated script helped to identify which injections across the selected month had an eigenvalue distribution where the rate of distance between first and second dominant eigenvalues was significant enough.

As it is not easy to identify significant changes by visualising all the fills for RUN II together, an approach to visualise the eigenvalue distribution for each month was followed instead, see Figure 6 and Figure 9.

4.1 TI2

The eigenvalue analysis for TI2 across RUN II shows how, for every month, there are more than one dominant singular value overall, see Figure 6.

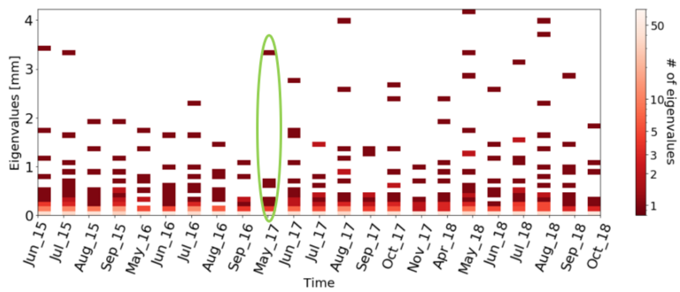


Figure 6: Image showing the amplitude change across RUN II divided in months, the month of May 2017 has been highlighted as the only month presenting a significant distance rate between first and second dominant eigen mode.

As a general trend, several eigenvalues above noise are found over RUN II. Only in one case, May 2017, we can observe a significant distance rate between the dominant eigenvalue and the rest of eigenvalues above noise.

Comparing the eigenvalue analysis for this month in RUN II, see Figure 7, with other eigenvalue analysis performed in RUN I, see Figure 8, we can observe how both distance rates between eigenvalues are equivalent between each other.

The source creating the trajectory oscillations for RUN I for the analysed period was identified to be an MSE septa. The MSE was investigated as a reasonable candidate to be again generating the trajectory variations for RUN II May 2017.

Superposing a simulated trajectory from an MSE with different kick strengths with the normalised trajectory of the beam on the studied

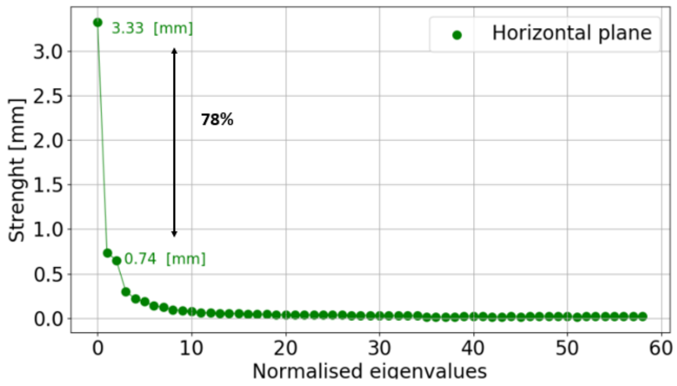


Figure 7: Image showing the amplitude change for May 2017 TI2, the difference rate is 78%.

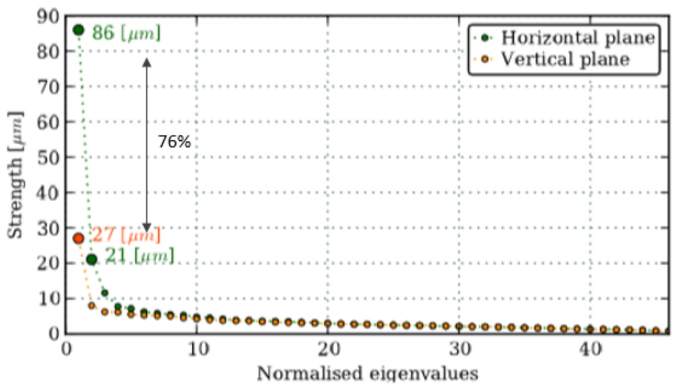


Figure 8: Image showing the amplitude change in TI2 for a given period in RUN I, it presents a difference rate between first and second dominant eigenmodes of 76% [2]

months, shows how for most months, the simulated MSE trajectory is close to that from the beam, see Figure 12 in appendix. Unfortunately, this source trajectory does not match the experimental data across the totality of the transfer line. This confirms that the MSE cannot be identified as the only source and, as there are several eigenvalues above noise background across the whole year, several sources should be expected.

4.2 TI8

Similar to TI2, the eigenvalue analysis for TI8 across RUN II shows how, for every month, there are more than one dominant singular value overall, see Figure 9.

Following the general trend specified on the

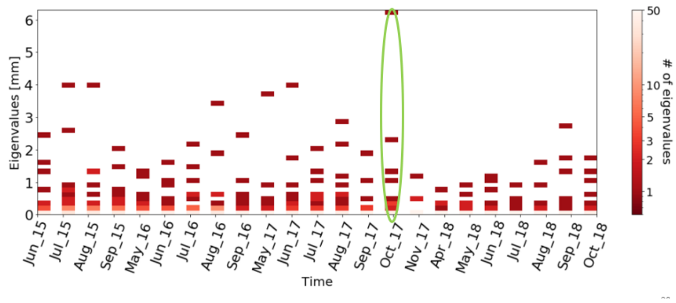


Figure 9: Image showing the amplitude change across RUN II divided in months, the month of October 2017 has been highlighted as the only month presenting a significant distance rate between first and second dominant eigen mode.

section above, several eigenvalues above noise are found over RUN II TI8 as well, and only in one case, May 2017, we can observe a significant distance rate between the dominant eigenvalue and the rest of eigenvalues above noise.

Comparing this month's results for RUN II, see Figure 10, with the eigenvalue results for a given period in RUN I, see Figure 11, show how this significant distance rate is equivalent for both runs. As for one normalised eigenvalue we find the MSE septa to be the one causing the trajectory variations in RUN I, this septa was again investigated as a candidate for this month in RUN II.

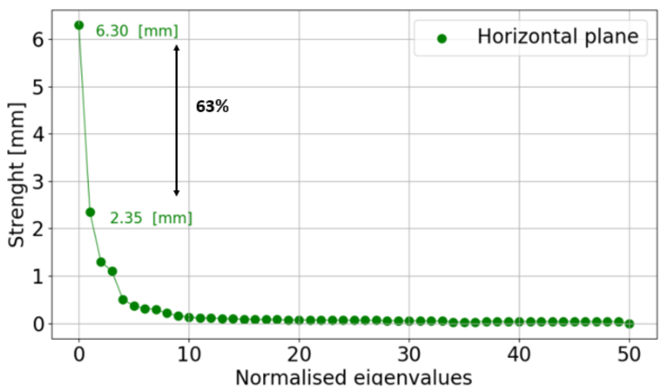


Figure 10: Image showing the amplitude change for October 2017 TI8, the difference rate is 63%.

Despite the equivalent results, RUN II presents more eigenvalues above background noise, making this assumption for the MSE less strong.

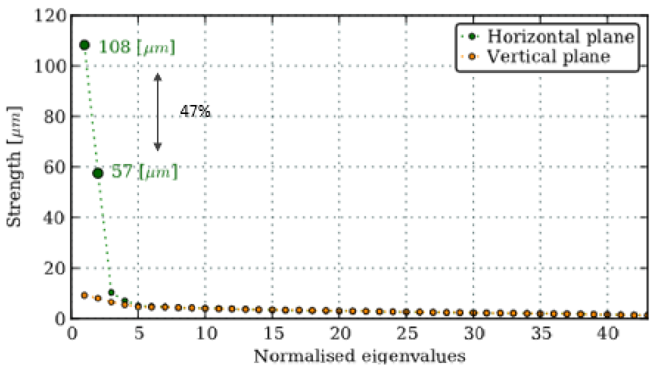


Figure 11: Image showing the amplitude change in TI8 for a given period in RUN I, it presents a difference rate between first and second dominant eigen modes of 47% [2].

Superposing the MSE simulated data to the experimental beam trajectories would produce a similar outcome to that describe in the subsection TI2, where despite the MSE trajectories seem to follow part of the trajectory of the beam, this source matching is not fully completed across the transfer line TI8, see Figure 13 in the appendix. More sources causing trajectory variations should then be expected.

5 Conclusions

- Simulations with MADX allowed to set up the environment for the MIA analysis RUN II experimental data.
- The analysis was performed binning monthly data during proton physics fills and scrubbing runs.
- From this analysis we observe that during Run II in general there is no singular dominant Eigen mode (single source).
- In only one case per line, a single source could be identified and seems to be due to the MSE as observed in Run I.
- Further analysis is needed to conclude on Run II performance with respect to the last years of Run I (after MSE PC improvements).

References

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[5] Laurent Deniau; Hans Grote; Ghislain Roy; Frank Schmidt; Iselin F.C.; Herr W. and many other contributers. MADX. `http://mad.web.cern.ch/mad/`.

6 Appendix

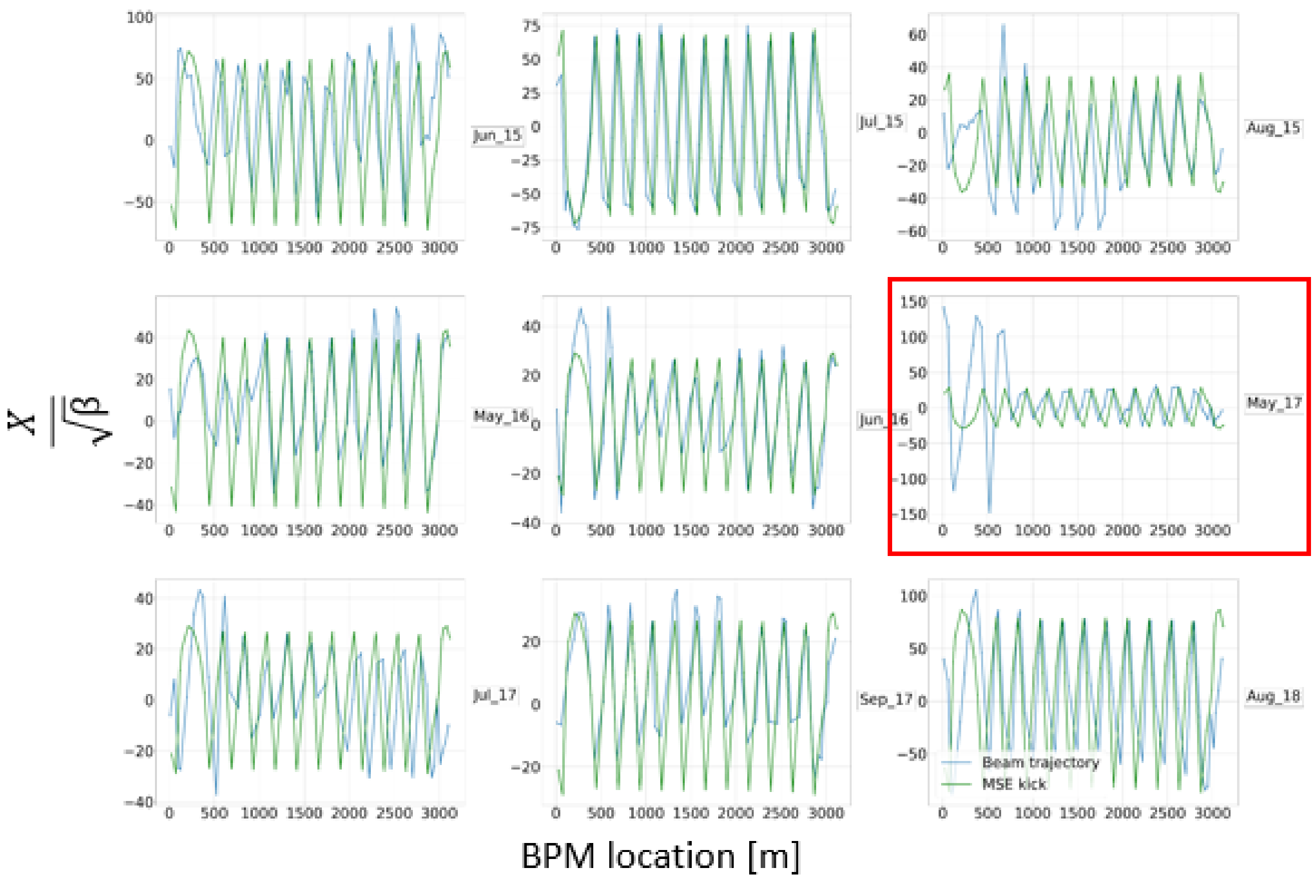

Figure 12: Image showing a matrix of plots with the best attempts of achieving a source matching for the different months analysed for TI2 during RUN II. Highlighted in red is May 2017, the studied month with a bigger chance of suffering trajectory variations due to the MSE after comparing results with those obtained from RUN I. Green line shows the simulated MSE trajectory while the blue line shows the trajectory of the beam.

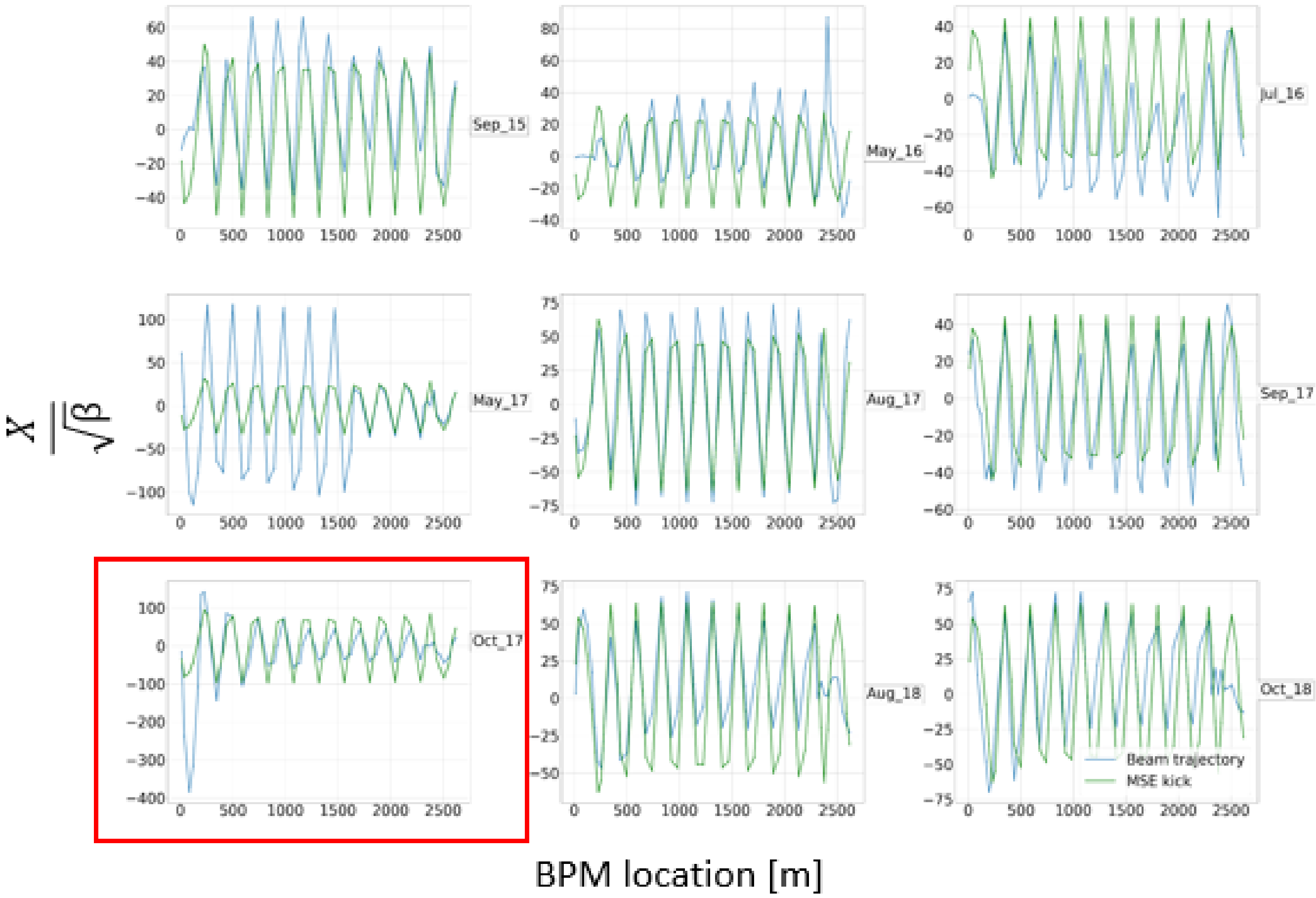

Figure 13: Image showing a matrix of plots with the best attempts of achieving a source matching for the different months analysed for TI8 during RUN II. Highlighted in red is October 2017, the studied month with a bigger chance of suffering trajectory variations due to the MSE after comparing results with those obtained from RUN I. Green line shows the simulated MSE trajectory while the blue line shows the trajectory of the beam.