FERMILAB-CONF-16-243-APC

ANALYSIS OF THE SPS LONG TERM ORBIT DRIFTS

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Abstract

The Super Proton Synchrotron (SPS) is the last accelerator in the Large Hadron Collider (LHC) injector chain, and has to deliver the two high-intensity 450 GeV proton beams to the LHC. The transport from SPS to LHC is done through the two Transfer Lines (TL), TI2 and TI8, for Beam 1 (B1) and Beam 2 (B2) respectively. During the first LHC operation period Run 1, a long term drift of the SPS orbit was observed, causing changes in the LHC injection due to the resulting changes in the TL trajectories. This translated into longer LHC turnaround because of the necessity to periodically correct the TL trajectories in order to preserve the beam quality at injection into the LHC. Different sources for the SPS orbit drifts have been investigated: each of them can account only partially for the total orbit drift observed. In this paper, the possible sources of such drift are described, together with the simulated and measured effect they cause. Possible solutions and countermeasures are also discussed.

INTRODUCTION

The SPS and LHC are connected through two ≈3 km long TLs which allow the injection of both Beam 1 (B1) and B2 at 450 GeV. The two TLs, namely TI2 for B1 and TI8 for B2, are equipped with a series of collimators to protect the LHC aperture from ultra fast failures. Such collimators are made of 1.2 m of Graphite and three of them are installed with $60° + n180°$ phase-advance to each other for each plane (horizontal and vertical).

Due to the protection that they have to guarantee, their half-gap has to be maximum $5\,\sigma_{\mathrm{lhc}}$, where $\sigma_{lhc} = \sqrt{\beta_{x,y}(s)\epsilon_N/(\beta\gamma)}$ and $\epsilon_N = 3.5$ mm mrad. The TL collimators are set up with a beam-based alignment procedure and their gap opening validated during the commissioning phase of the LHC. Such procedures rely on the established LHC closed-orbit and the TL trajectories. Variation of the TL trajectories can be clearly noticed during LHC operations as higher losses at the TCDIs (sometimes preventing injection) and large amplitude injection oscillations. Re-steering of lines, in case of trajectory variations, is then necessary and results in longer LHC turnaround.

During the LHC Run 1, variations of TL trajectories were observed, both fast, i.e. shot-to-shot variations, and slow, i.e. drift of the nominal trajectory. The fast variations were investigated and the source isolated to be the extraction septa (MSE) [1]. During the yearly technical stop between 2011 and 2012, a campaign to improve the current stability of the extraction septa was pursued. Measurements done during the commissioning of LHC Run 2, confirmed the expected improvement of the shot-to-shot stability. The long term drifts were extensively investigated [2] and the main source was identified as the SPS orbit [3, 4]. At the end of the LHC Run 1, a set of orbits was collected and analysed [3]. Different possible sources were investigated, but none of them found to be responsible for the drift observed.

During LHC Run 2 commissioning, a campaign of measurements was put in place to investigate possible sources, such as wrong transverse tune, large amplitude chromaticity trims, single dipole error, etc. The measurements carried out during commissioning of LHC Run 2 and during Run 2 itself are presented. The analysis performed and possible source candidates are also discussed.

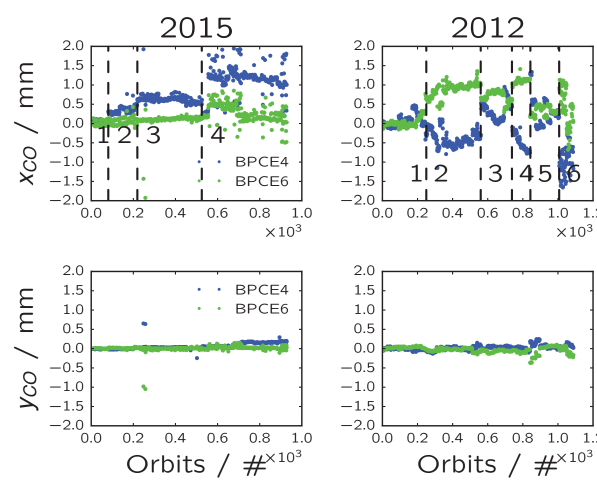

Figure 1: Fitted SPS orbit at the location of the extraction BPMs, BPCE4 and BPCE6, for the available orbit sets recorded during Run 1 (2012) and Run 2 (2015). The different periods in which the data have been divided are also indicated with black dashed lines.

ESTIMATION OF CLOSED ORBIT AT EXTRACTION

The SPS delivers B1 and B2 to the LHC using the Long Straight Section (LSS) 6 and LSS4 extraction channels, respectively. In the extraction regions, the Beam Position Monitors (BPM) need enlarged apertures to accommodate both circulating and extracted beam. This leads to very inaccurate readings from these monitors, which are called BPCEs, hence it is common practice to evaluate the beam centroid position at such locations using fitting techniques.

* operated by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the United States Department of Energy.

Once the difference from a chosen reference orbit is taken, the closed orbit, at any position s in a ring, can be written as combination of harmonic functions, exploiting the Twiss formalism. Assuming prior knowledge of the machine optics, a fitting function can be written, e.g. for the horizontal plane, as:

$$x_{CO}(s) = \sqrt{\beta_x(s)}[A\cos(\mu_x(s))+B\sin(\mu_x(s))]+D_x(s)\delta_p \quad (1)$$

where β_x, μ_x and D_x are the beta-function, phase-advance and dispersion of the ring respectively. The parameters A and B are the fitting parameters together with δ_p, which represents the momentum offset of the beam.

Once the fitting parameters are known, the closed orbit at the BPCEs can be calculated. In Fig. 1 the orbit at the BPCEs in LSS4 and LSS6 is shown, for the two set of measurements, 2012 and 2015. The set from 2012 spans over two months and the one from 2015 three months. A clear variation of maximum 1.3 mm can be observed for both sets and only in the horizontal plane. The almost unchanged vertical orbit is an indication that the source of such drift is not a geological variation of the SPS tunnel floor, which would have affected the vertical orbit as well.

TUNE AND CHROMATICITY VARIATIONS

Due to the non ideal SPS orbit and the presence of the extraction bumps, the beam is non-centred in quadrupoles and sextupoles. Hence, variation of their strengths translates in a different closed orbit. To assess the expected effect of the tune variation onto the orbit at extraction, measurements have been done varying the nominal horizontal tune (20.13) and measuring the orbit. This was also done for two different settings of horizontal chromaticity, i.e. high chromaticity (HC) $Q'_x = 21.92$ and low chromaticity (LC) $Q'_x = 4.8$. The results of these measurements, are shown in Fig. 2. In order to reproduce the observed closed orbit variation as function of the horizontal tune, the nominal SPS orbit was reconstructed with MADX using the embedded correction algorithm SVD (Singular Value Decomposition). Also, the measured chromaticity was reproduced using the machine sextupoles. The simulation results are plotted in Fig. 2 as solid lines showing a very good agreement with the measurements (dots).

The amplitude of the tune variation needed to explain the observed orbit drift is beyond what has been observed during normal operation. In fact, the tune fluctuations, which will be then compensated, are in the range of ± 0.01 units, which would only mean few hundred microns of closed orbit variation at the BPCEs.

When the LHC is requesting beam the SPS RF frequency may change by ± 10 Hz. This can feed back into the orbit, depending on the non-zero dispersion in the extraction regions. In addition, in case of non-zero chromaticity, the tune could be varied and adjustment could be foreseen to bring it back to the nominal value. Measurements were done to evaluate the effect of such variation, but it was observed that the expected orbit change is more than an order of magnitude smaller than what is shown in Fig 1.

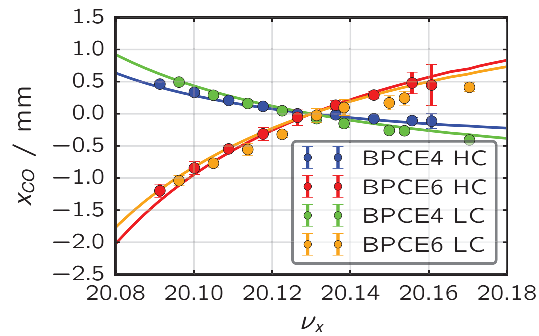

Figure 2: Fitted closed orbit at the BPCE4 and BPCE6 for different tune (±0.4) and chromaticity settings (HC and LC). In blue and red are shown the measurements results for HC settings as markers and MADX simulations as solid lines. In green and yellow the same but with LC settings.

EXTRACTION SEPTA STRAY FIELD

The SPS orbits recorded during Run 2 commissioning have shown a significant impact on the closed orbit of the stray field of the extraction septa if not properly taken into account. During normal operation with LHC beams, both extraction bumps, in LSS4 and LSS6, and both extraction septa are on at a fixed setting, and hence they cannot be considered as a source for the orbit drift over time. The contribution to the orbit can be up to 1 mm for both LSS4 and LSS6. Although both bumps and septa are active during LHC beam operations in the SPS, the stray field of the septa could act as an amplifier of other error sources.

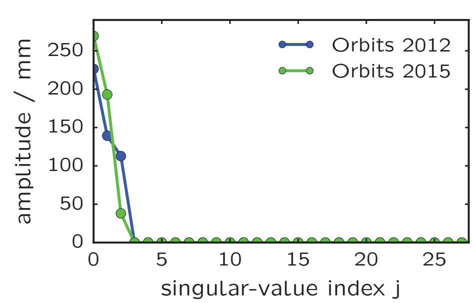

Figure 3: Singular-values plot for the two available orbit sets, 2012 and 2015.

SINGLE DIPOLE ERROR

The MADX model, developed in the context of the aforementioned studies, has been used to investigate for possible single kick errors. As previously done in [3] for the set of orbits recored at the end of Run 1, the Model Independent Analysis (MIA) [5] has been used to evaluate if the single dipole error assumption is valid and, if so, to isolate

ISBN 978-3-95450-147-2

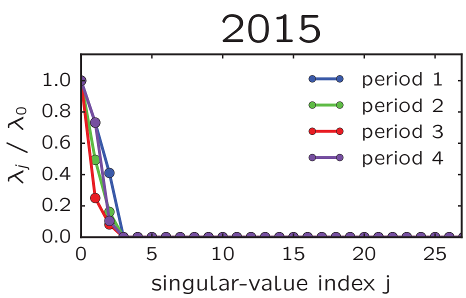

Figure 4: Singular-value plot for the orbits set from Run 2 divided in sub-periods as proposed in Fig.1.

a possible source. MIA consists in constructing a measurements matrix M, where the measured orbits are vertically stacked. Then, via SVD, the matrix M is decomposed as: $M = USV^T$, where U and V are the orthogonal matrices of the left and right eigenvectors, respectively, and S is the diagonal matrix of the singular-values λ_j. The left and the right eigenvectors represent the temporal and spatial modes respectively. The low order spatial modes, which correspond to the highest singular-values, can be used to identify the source of errors.

In Fig. 3 the amplitude of the singular-values, for the horizontal plane, for both set of orbits are shown. In both cases, more than one dominant singular-value is present, hence sub-periods can be considered in order to have only one main source of error. The 2015 set can be divided in five sub-sets, as marked in Fig. 1 with dashed lines, because the orbit at the extraction BPMs does not vary significantly in these periods. The SVD analysis is then repeated for each sub-set and the resulting singular-values are shown in Fig. 4. Only for *period 3*, which corresponds to 1-2 August 2015, there is one dominant singular-value, indicating only one main source. The MADX correction routine MICADO is used to identify such a source, which indicates the LSS6 half-cell 631-632. Every other element with phase-advance close to $\mu_x = n0.5 + 0.13 + m$, with m and n integers, can produce an equivalent betatron oscillation. In fact, the second best group of correctors belongs to the LSS1 half-cell 111-112, which has an equivalent phase-advance. The oscillation originating from such elements is plotted, together with the 0-mode, in Fig. 5. A very good agreement can be noticed when comparing the sub-period 3 0-mode and the orbit generated by the MBA.63170, or equivalent elements. The same oscillation is also compared with the 0-mode of the whole 2015 set (Fig.6), but in this case the missing contribution from another source is clear.

The set of orbits from Run 1 has been processed in the same manner with the intent of finding some analogies with more recent data. Also in this case, a division in sub-periods was necessary to obtain only one dominant mode. The 2012 set overlaps with the one analysed and discussed in [3], although it covers a bigger time span. The best correctors for the periods where only one source is clearly dominating belong to the half-cell in LSS6 634-635, which do not appear in the 2015 set.

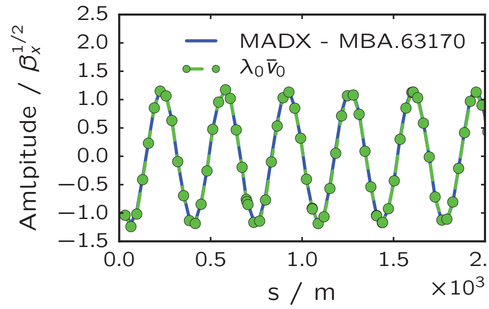

Figure 5: Dominant eigenmode from the 2015 set period 3. The dashed green line represents dominant eigenvector times the corresponding singular-value and the solid blue line is the betatron oscillation originated from the MBA.63170 with a kick of 110 µrad. Both are normalised to the square root of the local beta-function.

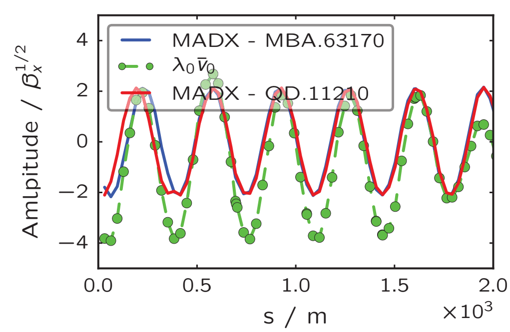

Figure 6: Dominant eigenmode from the 2015 set. The dashed green line represents dominant eigenvector times the corresponding singular-value. The solid blue and red lines are betatron oscillations originated from the MBA.63170, with a kick of 200 µrad, and the QD.11210, with an equivalent kick of 150 µrad. All of them are normalised to the square root of the local beta-function.

OUTLOOK AND CONCLUSIONS

The SPS orbit drifts observed during the LHC Run 1 are still present during Run 2 operation. Different sources were considered and measurements carried out to try to explain the observations. No source has been isolated yet as the sole cause of the orbit drifts. The possible tune variations could only partially account for the drift observed.

The possibility of a single dipole error was also investigated leading to two possible candidates. More orbits will be recorded in the upcoming LHC physics run to try to corroborate these results.

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ISBN 978-3-95450-147-2