SPS BEAM STEERING FOR LHC EXTRACTION

E. Gianfelice-Wendt, Fermilab*, Batavia, H. Bartosik, K. Cornelis,
L. Norderhaug Drøsdal, B. Goddard, V. Kain, M. Meddahi,
Y. Papaphilippou, J. Wenninger, CERN, Geneva

Abstract

Beside producing beams for fixed target operation, the CERN Super Proton Synchrotron (SPS) accelerates beams for injection into the Large Hadron Collider (LHC). During the 2012-2013 run drifts of the extracted beam horizontal trajectories have been observed and lengthy optimizations in the transfer lines were performed to reduce particle losses. The observed trajectory drifts are consistent with the measured SPS orbit drifts at extraction. The feasibility of an automatic beam steering towards a "golden" orbit at the extraction septa, has been therefore investigated. The challenges and constraints related to the implementation of such a correction in the SPS are described. Simulation results are presented and a possible operational steering strategy is proposed. As the observed drift is mainly horizontal, the horizontal plane only will be considered.

INTRODUCTION

The SPS is a 6.9 km long machine currently used as final injector for the LHC. The particles are accelerated from 26 to 450 GeV and extracted at straight sections LSS6 and LSS4 to be transferred to LHC through the 3 km long lines TI2 and TI8 respectively.

For avoiding damages due to failure of orbit correctors, the orbit at extraction is corrected by using only the interlocked correctors located at the extraction points ("bumpers"). There are 4 horizontal and 4 vertical bumpers per extraction point. The high energy overall orbit is optimized for target operation by displacing machine quadrupoles at start-up after shutdowns.

During the 2012-2013 run orbit drifts have been observed which may produce the beam trajectory changes observed along the transfer lines [1]. While the LHC transverse feedback minimizes emittance dilution due to injection errors, losses occurring in the transport lines and in the LHC call for time consuming corrections. The situation will be even more challenging when operating with the beam intensity expected by the LHC Injectors Upgrade.

While efforts are ongoing for understanding and possibly suppressing the sources of the SPS orbit drifts at extraction, the feasibility of an automatic steering of the beam to a "golden" orbit at the extraction septa by means of the interlocked correctors has been studied.

The SPS is equipped with 116 Beam Position Monitors (BPMs) measuring the orbit in the horizontal plane. Owing to the large aperture of the vacuum chamber, the precision of the six BPMs in the extraction regions, the so-called BPCEs, is poor even in a "orbit difference" mode and such a steering must rely on the measurement of the orbit in the rest of the ring.

Several algorithms for extrapolating beam position and angle at the extraction septa have been compared. On the basis of the observed orbit variations the magnitude of the correction kicks is evaluated.

SIMULATION SET UP

A set of 1001 SPS extraction orbit measurements acquired over the October-November 2012 period has been selected [1]. As we are aiming to correct orbit changes rather than the absolute orbit, the first of such orbits is arbitrarily defined as "golden" reference orbit and the differences wrt this reference are analyzed. For each of the 1000 orbit differences, values for the radial shift of all 216 SPS quadrupoles reproducing the measured orbit difference are computed after having subtracted a possible momentum offset contribution. In addition to the BPCEs, other BPMs with doubtful readings have been excluded.

These quadrupole offsets are inserted into the unperturbed MADX description of the SPS for setting up realistic models of the actual machine which are used for simulating the correction procedure. The values of the orbits at all BPMs other than BPCEs computed by MADX in presence of such quadrupole offsets are analyzed through 3 different algorithms

- "Fake" correction
- Fourier analysis
- Amplitude, phase and $\Delta p/p$ fit

which will be described in the next section. Each of these algorithms gives a closed expression of the orbit allowing to evaluate the change of beam position and angle everywhere around the machine circumference and in particular at the septa. The bumpers are then used for creating *closed orbit bumps* which restore the golden position and angle at the septa. Assuming no errors in the bumper setting, the goodness of the correction depends upon the goodness of the fit and may be quantified by the resulting oscillation amplitude A

$$A^2 = \gamma_s \Delta x_s^2 + 2\alpha_s \Delta x_s \Delta x_s' + \beta_s \Delta x_s'^2$$

where β_s, α_s and γ_s are the horizontal Twiss functions and Δx_s and $\Delta x_s'$ are the residual horizontal position and angle errors at the septum.

The values of position and angle error at the middle of the LSS6 extraction septum as "measured" by MADX and as computed by each of the three algorithms are quoted in Table 1 for one particular set of errors.

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

Table 1: "Actual" and extrapolated Δx and $\Delta x'$ at MSE.61852 for one particular set of errors

	Δx (mm)	$\Delta x'$ (mrad)
MAD-X	0.935	-0.020
"fake" corr.	1.002	-0.021
Fourier	0.682	-0.016
Fit	0.825	-0.013

ORBIT ANALYSIS METHODS

"Fake" Correction

The largest meaningful number of machine elements is used as "corrector" in order to correct the global orbit as measured at the BPMs. The orbit and its slope due to the correctors alone is thus computed at the septa location and the bumpers are used for actually setting the changes through closed bumps. In practice this analysis may be carried out inside a MADX job by using the SVD orbit correction option. We used as correctors only the actually existing 121 horizontal correctors. When used in practice, a prior fit of $\Delta p/p$ is needed.

Fourier Analysis

The closed orbit may be written in terms of its Fourier components as

$$x(s) = \sqrt{\beta_x}\, \Sigma_{q=1}^{N} \left[u_q \cos q\phi_x + v_q \sin q\phi_x\right]$$

with

$$\left\{ \begin{array}{c} u_q \\ v_q \end{array} \right\} = \frac{2}{M} \Sigma_{i=1}^{M} \frac{x_i}{\sqrt{\beta_{x,i}}} \left\{ \begin{array}{c} \cos q\phi_{x,i} \\ \sin q\phi_{x,i} \end{array} \right\}$$

where M is the number of BPMs and $\phi_x(s) \equiv \int_0^s ds/(Q_x\beta_x)$, Q_x being the horizontal tune. The maximum number of harmonics which can be extracted from M BPMs readings is notoriously $M/2$ (Nyquist theorem). The component q=0 which represents a constant offset due for instance to a momentum offset, has been neglected as correcting a momentum error by orbit variations is not our purpose. Fig. 1 shows the spectrum of an actually measured difference orbit. As expected the largest component is at q=20, 20.13 being the Q20 SPS optics horizontal tune [2].

Amplitude, Phase and $\Delta p/p$ fit

The orbit oscillation in the region of interest is described by a *free* oscillation

$$x(s) = A\sqrt{\beta_x} \sin(Q_x\phi_x + \delta) + D_x \frac{\Delta p}{p}$$

D_x being the horizontal dispersion. The values of A, δ and $\Delta p/p$ are computed by a best fit to the orbit measured at the BPMs in the region of interest. The use of only few BPMs around the region of interest requires they work properly in particular if the correction procedure is automatized. Extending the region of interest, and thus the number of BPMs involved, may improve the fit quality, but increases the probability of invalidating the assumption of a free oscillation. The goodness of the fit depends upon the (unknown) location of the orbit drift source(s).

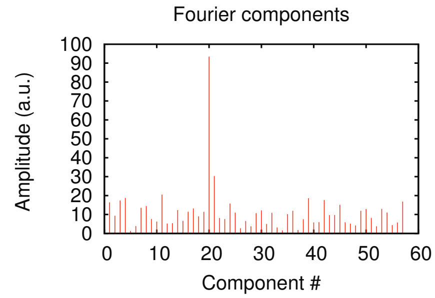

Figure 1: Difference Orbit Fourier spectrum.

SIMULATION RESULTS

Tables 2 and 3 show the results averaged over the 1000 orbit differences for the three orbit analysis methods described for LSS6 and LSS4 respectively.

Table 2: A^2 for LSS6, average over 1000 orbits

	A^2 (μm)
uncorrected	0.447e-2 ± 0.419e-2
"fake" correction	0.588e-6 ± 0.274e-5
Fourier Analysis (20±2)	0.120e-3 ± 0.884e-4
Fit (all BPMs)	0.965e-3 ± 0.722e-3
Fit (4 BPMs)	0.767e-5± 0.246e-4

Table 3: A^2 for LSS4, average 1000 orbits

	A^2 (μm)
uncorrected	0.111e-1 ± 0.912e-2
"fake" correction	0.318e-6 ± 0.528e-6
Fourier Analysis (20±2)	0.158e-3 ± 0.110e-3
Fit (all BPMs)	0.138e-2 ± 0.104e-2
Fit (4 BPMs)	0.333e-4± 0.606e-4

The correcting kick occurrences for the LSS6 bumpers MPSH.61402, MPLH.61655, MPLH.61996 and MPSH.62199 are shown in Fig. 2 for the "fake" correction method. Their nominal kicks for extraction are 0, 0.512, 0.094 and 0.398 mrad respectively.

It can be seen that the correction kicks are small and their average is non-vanishing. Recent laboratory measurements show a setting precision of nrad levels at 450 GeV [3]. Yet it must be proven that the bumpers are not "*troublemakers*". Therefore after the end of the current SPS shutdown it is planned to monitor these circuits during real operation to assess the reproducibility in the actual environment.

The robustness against random BPM calibration errors and missing monitors has been studied for the three orbit

ISBN 978-3-95450-132-8

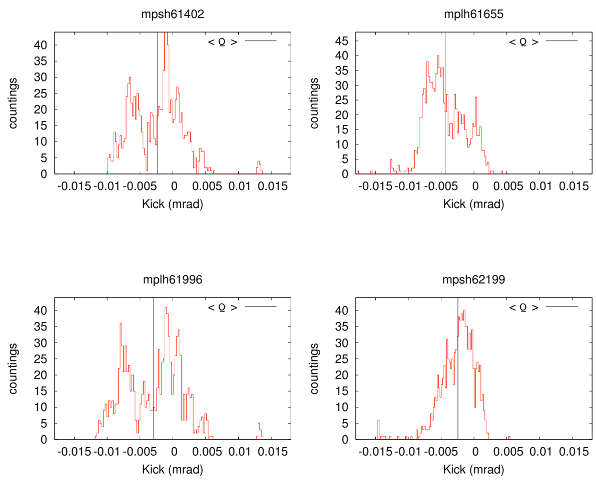

Figure 2: Correction kicks for LSS6, "fake" correction.

analysis methods. In Table 4 the results for LSS6 and 25% random calibration errors for one particular seed are summarized.

Table 4: LSS6, 25% Random Calibration Errors

	A^2 (μm)
uncorrected	0.447e-2 ± 0.419e-2
"fake" correction	0.422e-4 ± 0.584e-4
Fourier Analysis (20±2)	0.134e-3 ± 0.971e-4
Fit (all BPMs)	0.928e-3 ± 0.670e-3

Few simulations with different seeds showed the insensitivity of the orbit reconstruction to random calibration errors and missing BPMs. This insensitivity is explained by the fact that the difference orbit is uncorrected and therefore it has a single large Fourier component.

Finally measured calibration errors [4] have been assigned to the BPMs to assess what happens when single monitors affected by large calibration errors are "naively" included in the analysis, a situation which may occur in real operation. The concerned BPMs and their measured calibration errors are quoted in Table 5.

Table 5: Measured Gains

	x_{meas}/x_{true}
BPD.11906	1.24
BPH.13008	1.48
BPH.13608	0.16
BPA.21605	1.24
BPH.31808	1.35
BPH.41608	1.28
BPH.60408	1.20
BPH.61008	1.24
BPH.61408	0.08
BPH.62008	1.43

The results on the achieved correction are summarized in Table 6, again for LSS6.

Table 6: LSS6, with Measured Calibration Errors

	A^2 (μm)
uncorrected	0.447e-2 ± 0.419e-2
"fake" correction	0.291e-3 ± 0.474e-3
Fourier Analysis (20±2)	0.138e-3 ± 0.104e-3
Fit (all BPMs)	0.984e-3 ± 0.731e-3

While the Fourier analysis filtered out the effect of the individual large BPMs errors, the correction obtained with the "fake" correction analysis is much worse than in presence of random calibration errors.

CONCLUSION

It has been shown that SPS orbit changes may be well reconstructed on the basis of the BPMs readings and orbit variations at the extraction septa computed without resorting to the BPCEs. Three methods for analyzing the BPMs readings have been compared. They are already at hand in the SPS control system so that the use of any of them for stabilizing the beam position and angle at extraction may be envisaged.

The Fourier analysis has the advantage of being simple and robust and therefore suitable for an automatized correction application.

It has been shown that local steering at the extraction septa by the bumpers is feasible. The bumpers being interlocked an operational window must be determined for the permitted kick variations. The current window of ±10 μrad around the reference covers almost all simulated cases. The reference may be adjusted by machine protection experts if needed. Interlocking strategy does not need any upgrade.

Tests with beam are foreseen after the current long shutdown.

REFERENCES

[1] L. Norderhaug Drøsdal et al., "Investigations of SPS Orbit Drifts", IPAC'14, Dresden, Germany, June 2014, MOPRI100, These Proceedings.

[2] H. Bartosik et al., "Optics considerations for lowering transition energy in the SPS", IPAC'11, San Sebastián, Spain, September 2011, MOPS012.

[3] Gilles Le Godec, Private communication.

[4] H. Bartosik et al., "SPS kick response measurements", talk at MSWG, March 26, 2013, http://indico.cern.ch/event/242142