COUPLING AND VERTICAL DISPERSION CORRECTION IN THE SPS

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Abstract

Consolidation of the coupling correction scheme in the LHC is challenged by a missing skew quadrupole family in Sector 3-4 at the start-up in 2009-2010. Simultaneous coupling and vertical dispersion correction using vertical orbit bumps at the sextupoles, was studied by analyzing turn-by-turn data. This scheme was tested in the CERN SPS where the optical structure of arc cells is quite similar to the LHC. In the SPS, horizontal and vertical beam positions are measured separately with single plane BPMs, thus a technique to construct "pseudo double plane BPM" is also discussed.

INTRODUCTION

After the unfortunate accident in 2008, the SPS is used to test an alternative coupling correction scheme for the LHC. The correction knobs are vertical orbit bumps at sextupoles, that result in skew quadrupole component through feed-down. It is possible to correct the coupling and vertical dispersion simultaneously in this scheme. Because there are as many individual correctors as sextupoles. Typically only the amplitude of the coupling difference resonance has been measured in the SPS since it is not equipped with double plane BPMs [1]. A method to construct a "pseudo double plane BPM" is developed here in order to measure amplitude and phase of the difference and sum coupling resonances. Experiments have been carried out in the SPS to test this technique. In normal conditions SPS has equal integer transverse tunes, which implies that $\phi_x \approx \phi_y$ all around the ring, considerably simplifying the coupling correction. In order to get closer to LHC working point, the SPS integer tunes have been split by 1 to $26.13, 27.18$. Results of the experiment in the SPS, that have similar arc cell structure to the LHC, is discussed in this paper.

THEORY

The vertical turn-by-turn motion in the presence of strong betatron coupling is written as [2]:

$$h_{y,-}(s,N) = \cosh(2P)\zeta_y^- \\ -2i\sinh(2P)\left[\frac{f_{1001}}{P}\zeta_x^+ + \frac{f_{1010}}{P}\zeta_x^-\right] \quad (1)$$

A similar expression can be written for the horizontal plane. With $P = \frac{1}{2}\sqrt{-|2f_{1001}|^2 + |2f_{1010}|^2}$ and $\zeta_x^-, \zeta_y^-, \zeta_y^+$ being the eigenvectors,$\zeta_z^\pm = \sqrt{2I_z}e^{\mp i\psi_z}$. With $\psi_z = (2\pi Q_z N + \psi_{z,0})$, $\psi_{z,0})$ being the initial phase and z being either the horizontal plane, x or the vertical plane, y. The resonance driving terms can also be written in terms of amplitudes and phases $f_{jklm} = |f_{jklm}|e^{iq_{jklm}}$. The amplitude and phase of the secondary line is written as $B_{jklm}e^{i\phi_{jklm}}$. For the sum and difference resonance the amplitudes and phases can then be written as:

$$B_{1001} = \frac{2\sinh(2P)}{P}|f_{1001}|\sqrt{2I_x} \quad (2)$$

$$\phi_{1001} = \psi_x - q_{1001} - \frac{\pi}{2} \quad (3)$$

$$B_{1010} = \frac{2\sinh(2P)}{P}|f_{1010}|\sqrt{2I_x} \quad (4)$$

$$\phi_{1010} = -\psi_x + q_{1010} - \frac{\pi}{2} \quad (5)$$

From these equations it is possible to comput f_{1001} and f_{1010} as explained in Ref [3].

PSEUDO DOUBLE PLANE BPMS

In order to determine both amplitude and phase double plane BPMs are needed. The SPS is only equipped with single plane BPMs. Double plane BPMs are numerically constructed by "shifting" a vertical plane monitor towards the location of the horizontal one nearby. This is approximately realized by shifting the phase of the real spectrum lines in accordance with the model vertical phase advance between the horizontal and vertical monitors. Since the lines in the complex spectrum correspond to the sum and difference resonance. The assumption is made that the observable $\psi_x - \psi_y = q_{1001}$ and $\psi_x + \psi_y = q_{1010}$ remains constant along sections free of non-linear sources. The difference and sum resonances have opposite frequencies. Using the assumption and the equations above the corresponding vertical motion in the real BPM signal (y) at the location of a horizontal monitor $s = s_h$ is:

$$B_{1001}\cos(2\pi Q_x N + \psi_y(s_h) - \pi/2) + \\ B_{1010}\cos(-2\pi Q_x N - \psi_y(s_h) - \pi/2) \\ = \sqrt{B_{1001}^2 + B_{1010}^2 - 2B_{1001}B_{1010}\cos(2\psi_y(s_h))} \times \\ \sin(2\pi Q_x N + \alpha_h), \quad (6)$$

$$\tan\alpha_h = \frac{B_{1001} + B_{1010}}{B_{1001} - B_{1010}}\tan\psi_y(s_h) \quad (7)$$

With Q_x being the horizontal betatron tune. The corre-

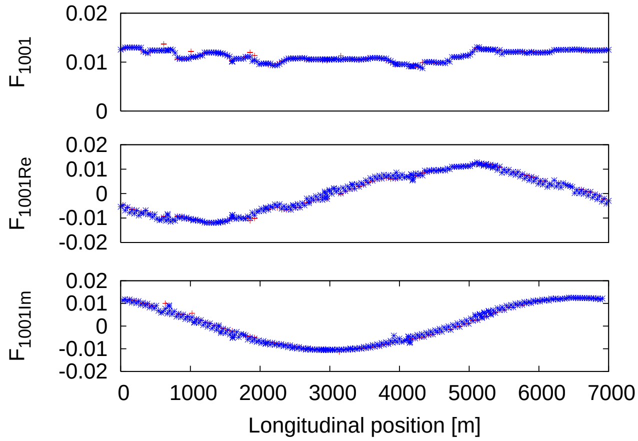

Figure 1: Simulation for coupling measurement with "pseudo double plane BPM", difference resonance is shown. No measurement error is assumed to estimate the systematic measurement error. Red is the measured value and blue the model

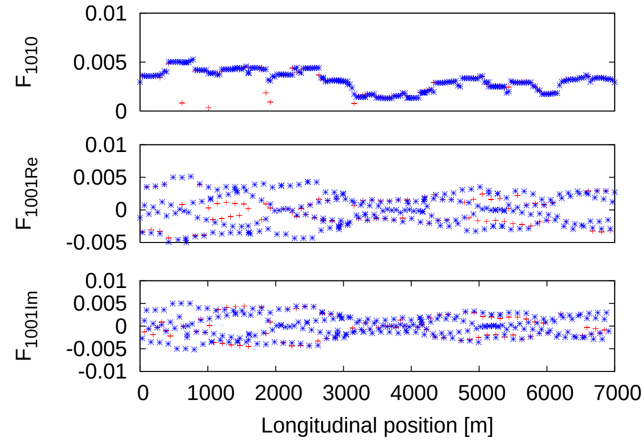

Figure 2: Simulation for coupling measurement with "pseudo double plane BPM", sum resonance is shown. No measurement error is assumed to estimate the systematic measurement error. Red is the measured value and blue the model

sponding BPM signal at the nearby vertical monitor is then:

$$
\begin{aligned}
& B_{1001}\cos(2\pi Q_x N + \psi_y(s_v) - \pi/2) + \\
& B_{1010}\cos(-2\pi Q_x N - \psi_y(s_v) - \pi/2) \\
&= \sqrt{B_{1001}^2 + B_{1010}^2 - 2B_{1001}B_{1010}\cos(2\psi_y(s_v))} \times \\
& \sin(2\pi Q_x N + \alpha_v), \qquad (8)
\end{aligned}
$$

$$
\begin{aligned}
tan\alpha_v &= \frac{B_{1001} + B_{1010}}{B_{1001} - B_{1010}}\tan\psi_y(s_v) \\
&= \frac{B_{1001} + B_{1010}}{B_{1001} - B_{1010}}\tan\left(\psi_y(s_h) + \Delta\psi_y\right) \qquad (9)
\end{aligned}
$$

$\Delta\psi_y$ is the phase advance between the monitors. Since we do not know the B_{1001} and B_{1010} at this stage, the amplitude and phase of the spectrum cannot be exactly transferred to the location of horizontal monitor. However, it is good approximation to keep the measured amplitude and shift the phase of real spectrum by $\Delta\psi$ when $B_{1001} >> B_{1010}$ or $B_{1001} << B_{1010}$, and the $\Delta\psi$ is about 45 degree for the SPS monitors while 90 degree would be the worst case for the approximation. Knowing this limitation, a simulation of coupling measurement was performed to confirm the entire analysis procedure. As shown in Fig. 1 and 2, the coupling parameters can be measured with reasonably small systematic error as far as one of the coupling resonances is dominant in the spectrum.

EXPERIMENT

The super proton synchrotron (SPS) has a circumference of 6918.5 m and accelerates particles to an energy of 450 GeV. The horizontal (Q_x) and vertical tune (Q_y) are 26.13 and 26.17 respectively.

The SPS has normal FODO arc cell structure where the cell phase advance is almost 90 degree. Sextupoles to compensate lattice chromaticity and orbit correctors are installed in every cell. However, the beam position monitors are single-plane system, i.e. the beam position of only horizontal or vertical plane is measured with a single BPM, and therefore "pseudo-double plane BPM" is numerically constructed in the analysis as discussed earlier. In normal conditions SPS has equal integer transverse tunes, what implies that $\phi_x \approx \phi_y$ all around the ring, considerably simplifying the coupling correction. In order to get closer to LHC the SPS integer tunes have been split by 1 to 26,13 and 27,17.

Measurement

Turn-by-turn beam position data was acquired by applying a single kick. An interpolated FT (SUSSIX, Ref [4]) was used to calculate the complex spectrum at every BPM. The two relevant spectral lines for the experiment are the main betatron tune line and the coupled tune line. The amplitude and phase of the two lines is used to construct the resonance driving terms for the difference and sum resonance.

The vertical dispersion is measured using the standard method, changing the reference momentum and measuring the difference orbits. The vertical dispersion in the SPS is around 20cm for the SPS.

Correction

Coupling and vertical dispersion correction is performed with the general matrix inversion approach using the singular value decomposition (SVD) technique where the response matrix contains the coupling parameters and vertical dispersion at every pseudo-double plane BPM.

As the fractional part of the tunes are close to each other the influence of the difference resonance will be dominating. The weight for the correction was only placed on the difference resonance and vertical dispersion, the sum resonance was ignored. Only vertical orbit bumps at the sextupoles (using the feeddown effect) are used in the correction scheme.

Result

Figure 3 and 4 shows f_{1001} and D_y measured before and after the correction respectively. Both the difference resonance and vertical dispersion have been corrected by a factor of two. The RMS for D_y is reduced from 0.18451 to 0.09541 . Figure 5 shows a plot of the sum resonance before and after correction. Even though the weight was set to zero for the sum resonance, it was still corrected.

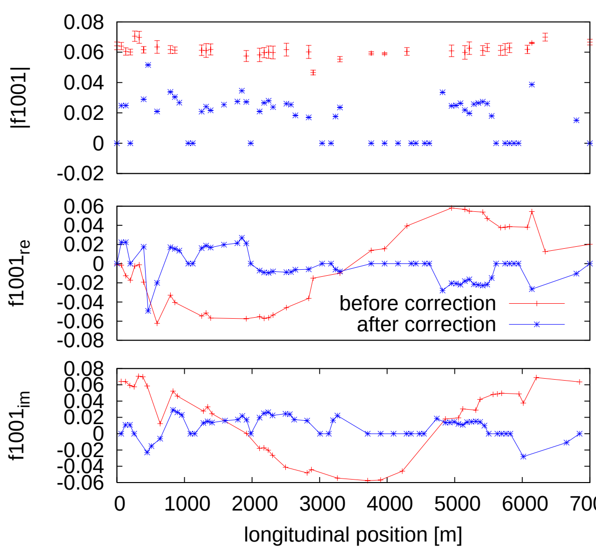

Figure 3: Difference resonance before (red) and after correction (blue). The plots are showing the amplitude, real and imaginary part. The difference resonance has been corrected with a factor of two.

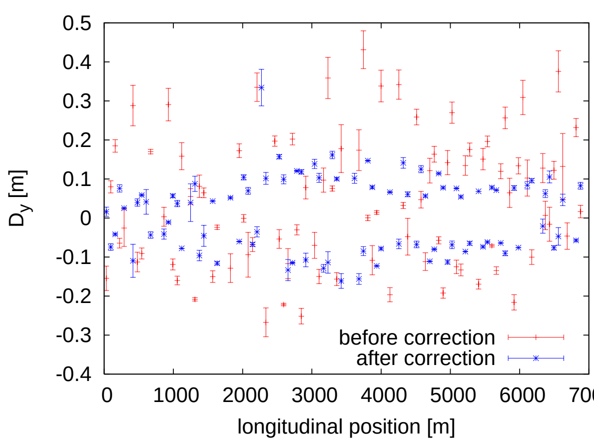

Figure 4: Vertical dispersion before (red) and after (blue) correction. The vertical dispersion has been corrected by a factor two. The RMS is reduced from 0.18451 to 0.09541.

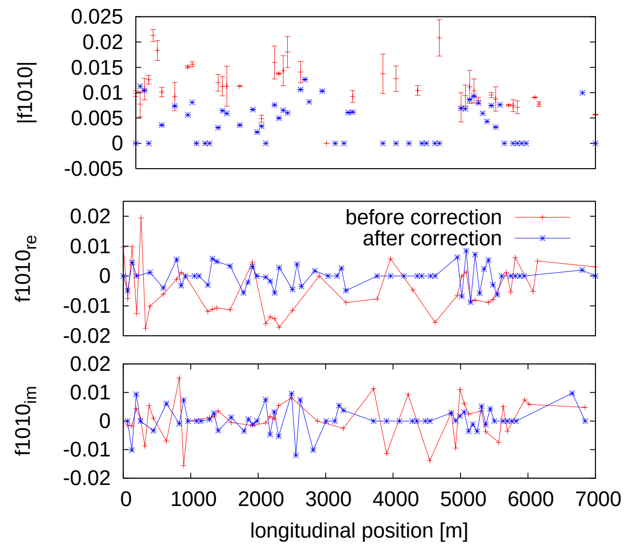

Figure 5: Sum resonance before (red) and after correction (blue). The plots are showing the amplitude, real and imaginary part. Even though for this correction the weight was not on the sum resonance it was still corrected.

DISCUSSION AND SUMMARY

The coupling and dispersion have been corrected by about a factor 2 in the SPS using the new approach of "Pseudo double plane BPMs". Although the correction was focused on the difference resonance and dispersion, the sum resonance was also corrected. This may imply that the sextupole misalignment and/or the vertical orbit error is one of main sources for coupling. This correction scheme can be applied together with the original coupling correction with skew quadrupole magnets, and would then be flexible enough to apply to the LHC where a skew quadrupole family is missing. However, one should be careful the height of the orbit bumps since the LHC aperture constraint is tight. In summary, the simultaneous coupling and vertical dispersion correction based on TBT optics measurement have been successfully tested in the SPS.

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