AUTOMATIC CORRECTION OF BETATRON COUPLING IN THE LHC USING INJECTION OSCILLATIONS

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Abstract

The control of the betatron coupling at injection and during the energy ramp is critical for the safe operation of the tune feedback and for the dynamic aperture. In the LHC every fill is preceded by the injection of a pilot bunch with low intensity. Using the injection oscillations from the pilot bunch we are able to measure the coupling at each individual BPM. The measurement is used to calculate a global coupling correction. The correction is based on the use of two orthogonal knobs which correct the real and imaginary part of the difference resonance term f_{1001}, respectively. This method to correct the betatron coupling has been proven successful during the normal operation of the LHC. This paper presents the method used to calculate the corrections and its performance.

INTRODUCTION

Transverse coupling is normally generated in accelerators by either solenoids or skew quadrupolar fields. In the presence of coupling the horizontal and vertical planes are no longer the eigenplanes of the particles oscillations. A consequence of this is that the horizontal and vertical tunes are no longer independent. This may affect the tune feedback, which is of importance for safe operation. The coupling can also reduce the available dynamic aperture [1]. One of the future scenarios for the LHC includes operation with flat beams. This would put even tighter requirements of the control of the coupling. In order to prepare for such a scenario it is important to demonstrate good control of the coupling.

The resonance driving terms f_{1001} and f_{1010} are proportional to the Hamiltonian terms and can be written as [2]

$$f(s)_{\substack{1001\\1010}} = -\frac{\sum_v k_v \sqrt{\beta_x^v \beta_y^v}\; e^{i(\Delta\psi_x^{sv} \mp \Delta\psi_y^{sv})}}{4(1 - e^{2\pi i(Q_x \mp Q_y)})} \quad (1)$$

where k_v is the vth integrated skew quadrupole strength, $\beta_{x,y}^v$ are the twiss functions at the location of the vth skew quadrupole, $\Delta\psi_{x,y}^{sv}$ are the phase advances between the observation point, noted s, and the vth skew quadrupole, and $Q_{x,y}$ are the horizontal and vertical tunes, respectively.

The fractional tunes in LHC are at injection $Q_x = 0.28$ and $Q_y = 0.31$ and the collision tunes are $Q_x = 0.31$ and $Q_y = 0.32$. Equation (1) implies that the $f_{1001} >> f_{1010}$ with these fractional tunes and we will in this article therefore only focus on the correction of the f_{1001}. The relation of the f_{1001} to the ΔQ_{min} and $|C^-|$ is described in the following equation:

$$\Delta Q_{min} = |C^-| \approx 4\Delta Q\overline{f_{1001}} \quad (2)$$

where ΔQ_{min} is the closest the tunes can approach each other.

The correction of the global coupling in the LHC is done with two control knobs. Each knob consists of a set of skew quadrupoles. They are designed to be as orthogonal as possible in the complex space of the f_{1001} while keeping the powering of the skew quadrupoles as low as possible [3]. The global knobs are traditionally used by the operator in an iterative manner to correct the coupling. The best setting is found by testing different settings of the global knobs while observing the $|C^-|$ in the Tune Viewer. The measurement is based on the residual betatron oscillations detected with a dedicated high precision pickup, referred to as the BBQ (diode-based base-band-tune) [4]. This can be a time consuming operation. In particular, when the measurement is noisy it is hard to find the optimum setting. The fact that this optimization process relies on a single pickup at a single location is also a limiting factor, as minimizing the coupling at a single location is not guaranteed to be the same as minimize the coupling globally.

In order for any approach with global coupling knobs to be effective it is crucial that the strong local sources are first corrected. The corrections of the strong local sources were done during the commissioning in the beginning of 2012. An explanation of how the local corrections are calculated can be found in [5]. The local corrections have remained very stable throughout the year. Although the strong sources are corrected, a drift of the global coupling is observed. In this article we will describe a method based on the measurements of the injection oscillations to control the global coupling. We will describe the method, implementation and present correction done using this approach.

METHOD

The method is based on the turn-by-turn data for the first ∼1000 turns after an injection, after which the beam has damped to the closed orbit. The noise of the BPMs is reduced by performing a SVD cut of the least significant eigenvalues. Using this algorithm the noise can be reduced significantly, which is of big importance since the injection oscillations are relatively small yielding a low signal to noise ratio.

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The calculation of the f_{1001} uses the relative amplitude between the tune peak and the coupling peak, in the frequency spectrum, as well as the phase advance of the two peaks to the neighboring BPM. In this way the f_{1001} is calculated for all BPMs. A full description of the algorithm can be found in [6]. The data used is from the undamped oscillations from the pilot bunches that precede every fill in the LHC. From the $\overrightarrow{f}_{1001}$, representing the f_{1001} measured at all the BPMs, the optimum setting of the coupling knobs is calculated. The correction algorithm is based on matrix inversion. The response matrix $\mathbf{R}$ is created using the ideal model. The matrix relates the f_{1001} at the BPMs with setting of the two knobs.

$$\mathbf{R}\Delta\overrightarrow{K}_{knobs} = (Re\{\overrightarrow{f}_{1001}\}, Im\{\overrightarrow{f}_{1001}\}) \quad (3)$$

The measured coupling is then multiplied with the generalized inverted matrix: $\mathbf{R}^{-1}$ to calculate the optimum setting of the coupling knobs. To make the algorithm more robust the worst 5% BPMs are removed before the correction is calculated.

$$\Delta\overrightarrow{K}_{knobs} = \mathbf{R}^{-1}(Re\{\overrightarrow{f}_{1001}\}, Im\{\Delta\overrightarrow{f}_{1001}\}) \quad (4)$$

In order for this method to be useful it is not sufficient to be able to measure and correct the coupling. It is also essential that the coupling is stable on timescales of $\sim$1h. If this is not the case, the coupling will again have drifted before the beam is injected for physics. In such a case it would be necessary to either find the sources of the drifts and stabilize them, or find a different and faster way to measure and correct the coupling. Figure 1 shows data for 40 injections that were done over $\sim$6h. The blue stars show the settings of the coupling knobs that best reproduce the measurement in the model. Before three injections, marked with red circles in the figure, the settings of the coupling knobs were changed. The circles indicate the values we expect to measure based on our model. The agreement between the predictions and measurements is good. We observe a small discrepancy, more pronounced for larger changes of the coupling knobs, between the measured f_{1001} (as characterised in the plot by the equivalent LHC coupling knob settings - blue stars) and the applied knob settings (red circles). The effect however is small, and is not an obstacle in the use of these observables and knobs for correction. We can also conclude that the coupling remains stable on time scales of hours.

IMPLEMENTATION

The turn-by-turn data is read from a file that is stored every time there is an injection of a pilot bunch into the LHC. Using this data the correction is calculated as described in the method section. The calculation takes less then 30s and the results from the calculations are published to a software which is available to the operator in the control room. The software presents the suggested adjustment of the coupling knobs, the f_{1001} present in the machine and the expected

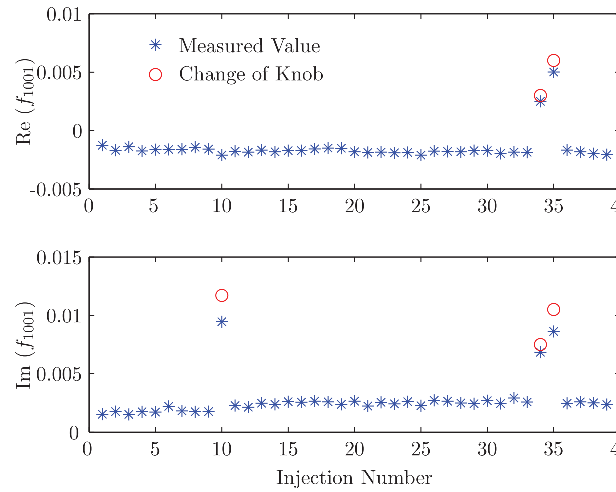

Figure 1: Measured f_{1001} for the different injections. The blue crosses show the setting, in the model, of the coupling knobs which best reproduce the coupling measurement. The red circles show the strength of the manual changes of the coupling knobs that were applied. The changes were applied before three different injections.

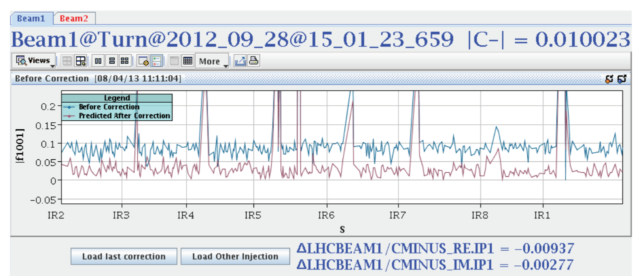

Figure 2: A screen shot of the software when it was used in normal operation of the LHC. It was after a technical stop, in September 2012, when the coupling had increased, which was corrected using the software.

reduced f_{1001} after correction. This enables the operator to predict the performance of the correction. The software also provides the functionality to look at coupling measurements from injections that took place earlier in time. A screen shot from the software is shown in Fig. 2.

RESULTS

In Fig. 3 an example of a coupling correction for Beam 1 using the injections oscillations is presented. The example is taken after a technical stop, in September 2012, when it was observed that the coupling had increased significantly for Beam 1. In this example only the knob controlling the imaginary part was used for the first correction and for the second injection a full correction using both knobs was applied. The correction reduced the $|C^-|$ from 0.01 to 0.0021 for the full correction. The results were in good agree-

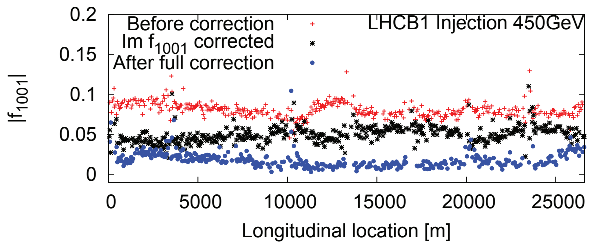

Figure 3: Coupling corrections of Beam 1 using turn-by-turn data from the pilot injections in the LHC. First a correction with the knob controlling the imaginary part of f_{1001} was performed and later a full correction of the f_{1001} was applied.

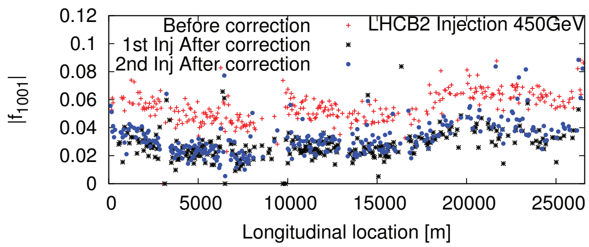

Figure 4: A correction of the coupling for Beam 2. The red crosses show before the correction, the black squares show the first injection after the correction and the blue dots show the second injection after a correction.

ment with the $|C^-|$ measured with the independent BBQ-system.

Figure 4 shows a coupling correction for Beam 2. The first injection was used to calculate the correction and the two consecutive were used to evaluate the correction. No new corrections were applied between those two injections. A significant improvement of the coupling is seen between before and after correction.

Figure 5 shows the f_{1001} measured with the BBQ-system for the same occasion as presented in Fig. 4. The vertical line indicates when the correction was applied. While the correction was still trimmed in the beam was dumped due to other reasons. However, we see that the coupling decreased when the correction was applied also for the two consecutive injections. We observe that the measurement of the coupling from the BBQ is in good agreement with the one from the injections oscillations.

CONCLUSION AND OUTLOOK

We have in this article presented the method used to calculate and correct the linear coupling based on automated measurements from the injection oscillations. We have demonstrated that the method works under normal LHC conditions.

The turn-by-turn data can also be used to calculate other optics parameters like the beta functions, chromaticity by

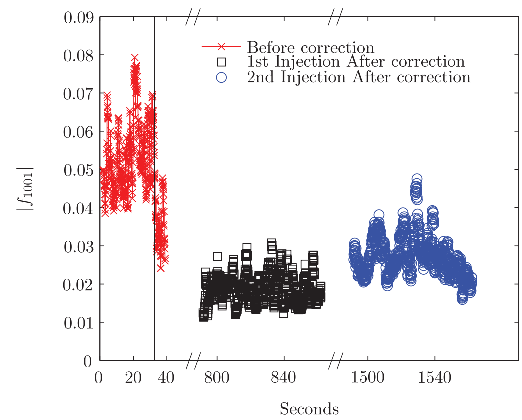

Figure 5: The measured coupling using the BBQ-system. The vertical line indicates when the correction was applied. The red crosses show before the correction, the black squares show the first injection after the correction and the blue dots show the second injection after a correction.

looking at the dechorence of the beam. Using this information it is possible to monitor the stability of the optics. Analysing all the data from the recorded injection oscillations will give insight into the evolution of the optics parameters over time in the machine.

A possible future step could be to include the measurement in the injection quality control and put some requirement on the coupling and β-beat before an injection of high intensity beams is allowed.

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