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TRANSVERSE COUPLING MEASUREMENTS WITH HIGH INTENSITY BEAMS USING DRIVEN OSCILLATIONS

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Abstract

Transverse linear coupling has been linked to instabilities and reduction in dynamic aperture and it is hence a crucial parameter to control in the LHC. In this article we describe the development to use driven oscillations to measure the transverse coupling with high intensity beams. The method relies on the use of the transverse damper to drive an oscillation in a similar way as with an AC-dipole. The calculation of the linear coupling is based on the turn-by-turn data from all available BPMs gated for the excited bunch.

INTRODUCTION

The LHC is operating with small fractional tune split. During the squeeze of the optics the tune split is 10^{-2} and at collision it goes down to 4×10^{-3}. At these tunes, even small values of transverse coupling ($|C^-|$) have large impact on the motion. It has been shown that transverse coupling reduces dynamic aperture and has been linked to beam instabilities [1–4]. Furthermore, in the presence of linear coupling the horizontal and vertical tunes cannot be adjusted separately and this can cause problems for the tune feedback. It has also been shown that octupoles in conjunction with coupling can cause an Amplitude Dependent Closest Tune Approach (ADeCTA) that might change the Landau damping [5–8]. All this makes transverse coupling a very important property to control in the LHC.

There are two main techniques to measure transverse coupling in hadron machines. The first one consists of approaching the tunes as close as possible together and from the difference between the horizontal and vertical tune conclude on the value of $|C^-|$ [9]. The second technique consists of using turn-by-turn data and to extract a spectrum from the time series. If the coupling is large enough a peak at the frequency of the vertical tune will be visible also in the horizontal spectrum. The C^- can be calculated from the ratio between the amplitude of the main tune peak and the coupling peak, together with fractional tune split.

The procedure to control the coupling in the LHC has been to correct firstly the local sources and then go through the entire cycle and find the best setting of the two global coupling knobs, namely $\Re(C^-)$ and $\Im(C^-)$. These knobs are designed to distribute the coupling correction on the arc skew quadrupoles avoiding the generation of a too strong local coupling. These corrections have been based on measurements performed with the AC-dipole [10]. Drifts of the coupling value over the year were often corrected observing the coupling provided by the Base-Band-Tune (BBQ) [11] while applying different knob settings. This process was time consuming and not fully reliable due to measurement noise and, moreover, it was measuring a combination of C^- and C^+ (sum resonance) [12, 13]. An alternative method consisted of using the injection oscillations similarly to a free kick [12, 14]. However, this method was, due to its nature, only available at injection.

The method to correct the coupling based on the measurement from the AC dipole is both reliable and can reach very low levels of coupling [15]. The AC dipole is, however, only able to excite all bunches in the machine and, due to machine protection considerations, it cannot be used when several high-intensity bunches are present. Instead, a special mode of the ADT (Accelerator Damper Transverse) has been developed [16]. It allows the excitation of a single bunch in a similar way as the AC-dipole. The benefit of an AC-dipole like excitation is that it does not increase the transverse emittance [17]. In this article we describe the recently-developed tool, based on excitation from the ADT, to measure and correct automatically the linear coupling in the LHC. The tool was preceded with several tests during machine development periods [18, 19].

IMPLEMENTATION

The application is composed of different parts, shown in Fig. 1. The first part is the user interface, which is meant to start the measurement. The user can chose the amplitude and the desired driven tunes. The excitation is then triggered and the ADT excites the beam at the selected frequency for a total of 10600 turns, where 2000 turns are for the ramp up of amplitude and 2000 turns are for the ramp down. The part with constant amplitude is recorded by all the available Beam Position Monitors (BPMs). The user interface is not directly driving the ADT, but it is instead communicating with it through a server. This prevents several excitations to be triggered at the same time and enables the same result to be displayed on all screens where the application is running. The server receives the turn-by-turn data and propagates them to the analysis part. This part performs firstly a noise filtering using Singular Value Decomposition (SVD) followed by a Fourier Transform of the signal. The filtering plays a fundamental role since the excitation is in the range of 0.1 mm-0.2 mm peak-to-peak and this is in the same range as the LHC BPM resolution. From the filtered data f_{1001} is calculated as described in [12, 20]. It is

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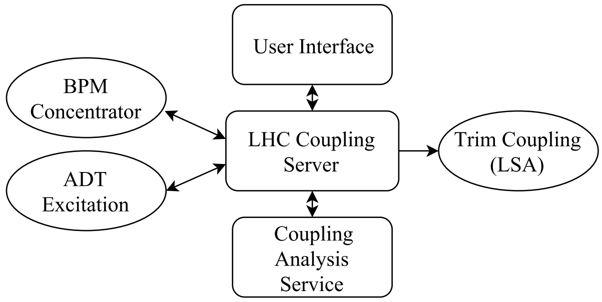

Figure 1: Flowchart of the measurement and analysis processes.

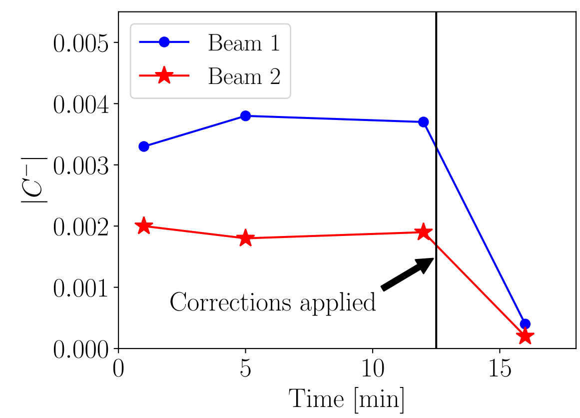

Figure 2: Measured $|C^-|$ at $\beta^* = 40$ cm before and after correction.

worth noting that f_{1001} depends on the tune split of the free tunes that is normally not measurable from the spectrum. The free tunes have instead to be obtained from the BBQ system [11]. A correction is then computed using the two pre-calculated coupling knobs and the values are propagated from the analysis to the server and then the user interface. From the user interface the operator can send the calculated values directly to LSA (LHC Software Architecture), which in turn triggers the change of the power supplies powering the skew quadrupoles.

RESULTS AND OBSERVATIONS

The application has been used for every fill since August 2017. In Fig. 2 the first correction of the coupling with squeezed optics is shown. We see that the coupling values for Beam 1 and Beam 2 were several 10^{-3} before the correction, but after the correction they both converged to below 10^{-3}. This is in line with the normal level of correction achieved in operation [21].

Measurements Uncertainties

The coupling measurement is dependent on a good knowledge of the natural machine tune. This is normally impossible to obtain directly from the measurement since the driven motion is the dominant one. So far, the tunes have been obtained from the BBQ, which relies on residual oscillations. To increase the resolution of the tune measurement, yet another special mode of the ADT has been developed [16].

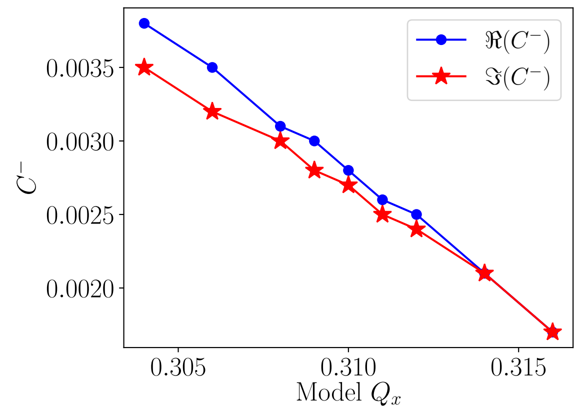

Figure 3: Computed correction of C^- as a function of the assumed Q_x. The correct value was in this case $Q_x = 0.31$.

The sensitivity of the measurement errors in the tune determination was investigated in numerical simulations. The correct fractional tunes were $Q_x = 0.31$, $Q_y = 0.32$ and the driven tunes were $Q_{x,driven} = 0.30$, $Q_{y,driven} = 0.33$. All these parameters are used to reconstruct the coupling. In the simulation, we analyzed the data using a Q_x that differs from the correct one and the result is shown in Fig. 3. We observe that if we assume a too low tune the correction increases in strength. This is in agreement with expectation, since for a given $|C^-|$, f_{1001} will be smaller if the tune split is larger. This is taken into account in the calculation and therefore, in this case, it overestimates the strength needed to correct the coupling. We also observe that there is a slight difference in the slope of the real and imaginary part of C^-. This corresponds to a different phase of the correction due to the error in the model tune. We observe that the phase error is relatively small so using an iterative approach would reduce the coupling, provided the tunes are known better than $\sim 8 \times 10^{-3}$ in this case. However, in cases with smaller tune split a better accuracy for the tunes is needed for the corrections to converge.

Signal-to-Noise Ratio

The signal-to-noise ratio in the turn-by-turn data is of course important for the coupling measurement. In particular, it has been noted that the phases for the BPMs close to the ADT are of high importance since they determine the required compensation to cancel the distortion coming from the driven motion [22, 23]. In order not to be too sensitive to this, more BPMs have been used for the compensation and this has reduced significantly the error of the phase of the C^-.

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Long-Range Beam-Beam

Transverse coupling was regularly measured during the squeeze in 2017. The results proved to be reproducible and the corrections applied corresponded well to the predictions [24]. However, it was noted that, when the filling scheme was modified, this also changed the measured C^-. This could be due to different patterns for the long-range beam-beam (LRBB) encounters between the probed bunches. A special machine development session was dedicated to investigate this further. It was concluded that there was a shift directly linked to LRBB, but that there also was a shift in the measured tunes. Hence, the measurements performed during operation with bunches with LRBB were affected by both effects. The direct impact on coupling could come from a roll of the crossing angles at one or several of the IPs [25, 26].

COUPLING DECAY AT INJECTION

The coupling correction tool has proven to work in a wide range of configurations and hence minimized the harmful impact of linear coupling on operation. It was observed that the coupling was changing significantly more often at injection than at other configurations. The total strength of the correction, however, seemed to stay within a fixed range. In this context, it was decided to try to better understand the origin of this drift.

The automatic compensation for the b_3 component in the main dipoles was removed at injection during a special test. Such a correction is used to keep the chromaticity constant at injection in spite of the persistent current effects [27] and this is achieved by powering the spool pieces mounted next to the main dipoles [28]. In Fig. 4, $|C^-|$ is plotted as a function of time since the LHC magnets reached their injection settings. At time "1." a correction of the chromaticity was applied and at time "2." a correction of the orbit and chromaticity was applied. The correction of the chromaticity was done with the main lattice sextupoles. We observe a small change in the coupling, which is expected in case there is non zero orbit through the sextupoles. At time "3." the correction of the main sextupoles was removed and the equivalent correction was applied using the b_3 spool pieces. We observe that there is a large shift in the transverse coupling. This could be explained by a systematic vertical misalignment of the b_3 spool pieces, since the feed down to skew quadrupolar, k_{skew}, is

$$\Delta k_{skew} = -\Delta y \Delta k_{sextupole}, \quad (1)$$

where Δy is the vertical offset, and $k_{sextupole}$ is the integrated strength. From this it is possible to calculate the coupling as

$$|C^-| = |\frac{1}{2\pi} \int \sqrt{\beta_x(s)\beta_y(s)} k_s(s) e^{\phi(s)_x - \phi(s)_y} ds|, \quad (2)$$

where $\beta_{x,y}$ are the optical functions and $\phi_{x,y}$ are the phase advances.

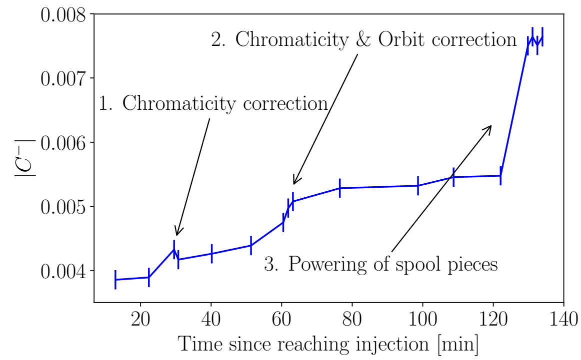

Figure 4: Change of the transverse coupling as a function of time after injection. The arrows indicates when a change to the machine was applied.

Assuming that all errors add up, then a 0.15 mm systematic offset would be sufficient to explain the observed coupling decay.

The preliminary results from a test where the strength of the spool pieces for the different sectors were changed individually indicate that they all had an impact on the transverse coupling. However, a careful analysis is needed to further quantify the effect.

CONCLUSION AND OUTLOOK

The new coupling correction tool has been proven to be capable of controlling the coupling to the level of 10^{-3}. Theses results have only been possible due to extensive machine development studies and the big efforts provided by several groups, all with different areas of expertise. The described tool together with careful attention to the coupling during the optics commissioning has lead to a good coupling control so that no major disturbance for operation was observed in 2017. There are still activities ongoing to increase the accuracy of the correction as well as its speed. The latter will be increased through parallelization of the software together with a faster method to compute the turn-by-turn spectrum [29]. Using the coupling correction tool an unexpected effect of LRBB on the linear coupling measurement has also been observed. This effect is important since it potentially means that different bunches experience different level of coupling and that the best correction is not necessarily that based on the bunch without LRBB.

The new mode of the ADT to measure the tune will certainly increase the resolution of the tune measurement, thus decreasing the uncertainty of the coupling measurement.

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