NON-LINEAR COUPLING STUDIES IN THE LHC

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Abstract

The amplitude detuning has been observed to decrease significantly as the horizontal and vertical tunes approach each other. This effect is potentially harmful since it could cause a loss of Landau damping, hence giving rise to instabilities. The measured tune split ($Q_x - Q_y$) versus amplitude is several times bigger than what can be explained with linear coupling. In this paper we present studies performed to identify the dominant sources of the non-linear coupling observed in the Large Hadron Collider (LHC).

INTRODUCTION

Linear transverse coupling has been studied thoroughly in a large number of accelerators. In light sources it plays an important role for the equilibrium emittance and it has been demonstrated to enhance other resonances [1, 2]. In the Large Hadron Collider (LHC) the control of the coupling is also of importance for a reliable tune feedback. The approach to correct the coupling in the LHC has been to first correct the strong local sources during commissioning [3] and then use two orthogonal knobs to correct the observed drifts of the global coupling [4]. The two knobs are designed to correct the real and the imaginary part of the C^- respectively. The absolute value of the $|C^-|$ is, in the linear theory, equal to the $\Delta Q_{\rm min}$ which is the closest approach of the transverse tunes [5]. A lot of progress in the control of the linear coupling was made during Run I of the LHC. The improvements included a better understanding of the resonance driving terms relation to the $|C^-|$, as well as improved data filtering and a tool to measure and correct the coupling based on the injection oscillations [6, 7].

The off-momentum dependence of the coupling, also known as the chromatic coupling was studied and a successful correction was demonstrated in [8]. These efforts have resulted in a good understanding and control of the linear and the off-momentum coupling in the LHC. In this article we discuss studies to identify sources of an observed amplitude dependence of the transverse coupling.

EXPERIMENTAL OBSERVATIONS

Particles with different amplitude will be focused differently in sextupoles but since the focusing is also dependent on the phase the effect almost cancels out. Octupoles magnets on the other hand introduce a bigger amplitude dependence of the tunes. This is of importance to reduce collective effect instabilities in the LHC. The behavior of this detuning is dependent on the powering of the octupoles but is also influenced by other resonances in the tune diagram.

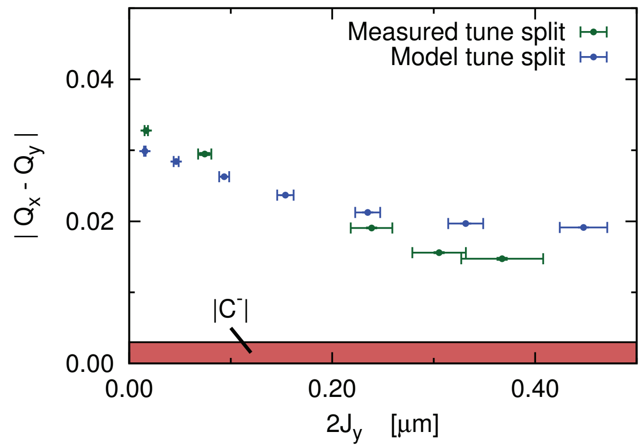

Figure 1: The tune split as a function of the action from the measured data as well as from the simulation based on the nonlinear model of the LHC. The linear $|C^-|$ was measured during the study and is indicated by the red area.

The naive expectation is that in a situation with coupling the detuning would be similar to the situation without coupling far away from the $|C^-|$ and only close to the stopband change the behaviour. During Non-linear dynamics studies in 2012 it was observed that this was not the case [9]. When large vertical kicks were applied to the beam the tunes did not approach each other as much as one would expect from the amplitude detuning. Instead the tune split seemed to saturate at a distance 4 times larger than the linear $|C^-|$. During the measurement the action was also measured and the large increase of the horizontal action for vertical kicks could not be explained by means of linear coupling. These observations gave rise to the interpretation of an amplitude dependent $|C^-|$. This feature was also well reproduced in the non-linear model of the LHC as seen in Fig. 1. The non-linear model of the LHC contains the best available knowledge about the errors in magnets as well as misalignment. The simulation was performed using tracking and the linear coupling was matched to the measured values. The magnitude of the kicks were also reproduced in the simulation.

IDENTIFICATION OF SOURCES

The non-linear model of the LHC contains many sources of non-linear errors and misalignment. In order to determine which type of sources were needed to cause an am-

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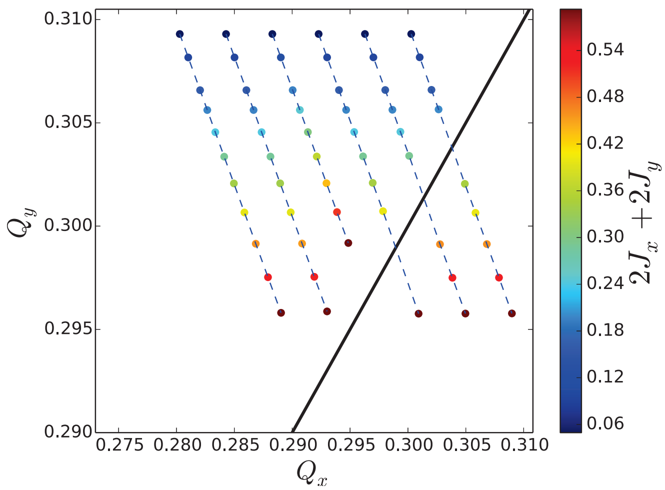

Figure 2: Simulated kicks for different tunes and amplitudes of the vertical kicks. The black diagonal line indicates the resonance $Q_x = Q_y$.

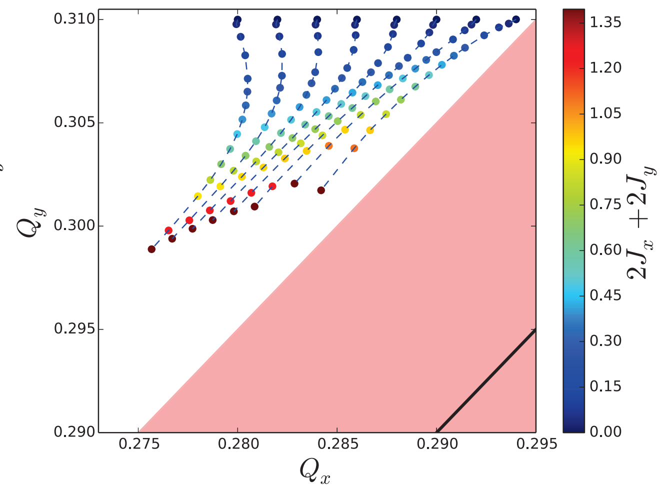

Figure 3: Simulated kicks for different tunes and amplitudes. The vertical kicks ranged from 0.5 mm to 4.5 mm while the horizontal were kept at 0.5 mm. The light red area indicates the linear $|C^-|$ stopband which was kept at 0.015. The octupoles were kept at nominal powering.

plitude dependent $|C^-|$ a large number of simulations were launched using Polymorphic Tracking Code (PTC) [10]. It used the nominal model of the LHC for Beam 2 and the particles were tracked for 1050 turns. The optics used was injection optics and the octupoles were at nominal settings of the first part of 2012 (-3m^{-4}, the powering was 6A). The horizontal tune was matched to values ranging from 64.28 to 64.30 and for each of these settings different transverse kicks were applied. The size of the kicks were between 0.1 mm to 4.5 mm at a location with $\beta_x = 44$ m and $\beta_y = 350$ m. The action was reconstructed using the amplitude and the beta functions for each BPM, as described in [9].

Using the nominal model without any skew quadrupolar components the detuning behaves almost linearly, as seen in Fig. 2. We, however, observe that none of the points are on the diagonal which could indicate a small $|C^-|$. This possible stopband is very small in comparison to the observation, as seen in Fig. 1.

In order to have a more realistic situation, linear coupling was introduced using the skew quadrupoles. Running this simulation for different initial fractional tune splits showed that there is a mechanism pushing the tunes away from each other already far away from the linear $|C^-|$ which in this case was set to 0.015. The light red area shows the stopband for the linear $|C^-|$. This is shown in Fig. 3. In particular it is interesting to observe how the particles starting close to the $|C^-|$ are pushed away from the stopband.

The same procedure was repeated for kicks in the horizontal plane and shown in Fig. 4. The horizontal tunes were changed but the linear coupling and vertical tune was kept the same and the magnitude of the horizontal kicks were increased. It is a remarkable observation that for some of the kicks, starting close to the $|C^-|$, the particles penetrate the stopband. This means that the tunes can approach each other closer than what is possible in linear coupling theory. This shows that the $|C^-|$ is only a true stopband in the linear approximation of coupling.

A set of simulation for different linear $|C^-|$ was also performed. The result showed that the smaller linear coupling the smaller was the effect on the amplitude detuning. However, the effect that particles with larger amplitude have a relative larger tune split remained.

Figure 5 shows the dependence of the tune split on the powering of the octupoles. In this case both the focusing and defocusing octupoles were changed and the initial tunes for the zero kick case were matched to $Q_x = 64.289$, $Q_y = 59.31$. In case of small values for the octupoles the amplitude detuning decreases and we observe a merely linear amplitude detuning. When the powering of the octupoles is increased we can observe how the tune split first decrease and then stays constant and for the higher powering of the octupoles the tune split is again increasing for the higher kicks.

As a final test we investigated whether it was possible to create an amplitude dependent $|C^-|$ using only skew octupoles without any skew quadrupolar component. The normal octupoles in the LHC sequence were rotated with a few different angles and the particles were tracked. However, it was not possible to find a condition which caused the effect observed with skew quadrupoles and normal octupoles.

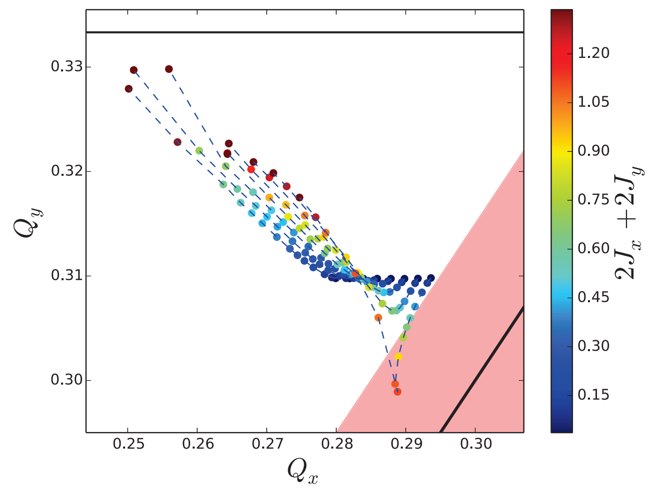

Figure 4: Simulated kicks for different tunes and amplitudes. The kicks in the horizontal plane ranged from 0.5 mm to 4.5 mm while the kicks in the vertical plane were kept at 0.5 mm. The light red area indicates the linear $|C^-|$ stopband which was kept at 0.015 for all cases. The octupoles were kept at nominal powering. The two black lines show the resonance $Q_x + Q_y$ and $3Q_y$ respectively.

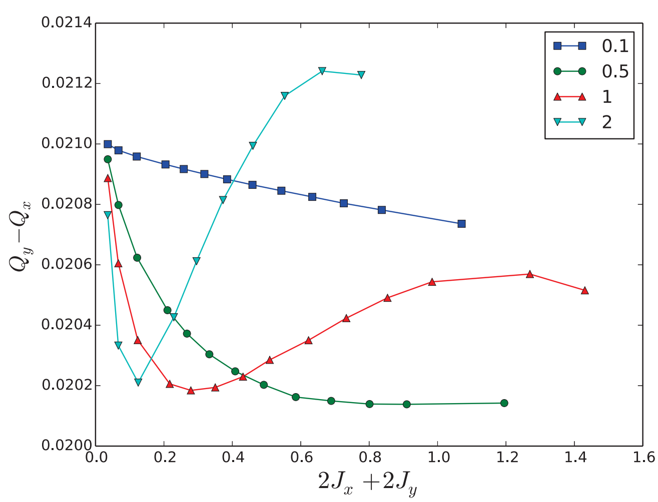

Figure 5: The tune split as a function of the action for different powering of the octupoles in relative units of the nominal powering (1 is equal to nominal powering) and $|C^-| = 0.015$

CONCLUSION

The observation of the amplitude dependent $|C^-|$ can be reproduced in the model using linear coupling in combination with octupoles. We have also shown that it is possible to enter the stopband $|C^-|$ given an appropriate size of the kick together with favorable settings of the octupoles. It has been observed that neither normal skew quadrupolar fields nor octupolar fields are sufficient alone to generate the amplitude dependent $|C^-|$ observed. Instead a combination of them are needed. These observations are of importance since this effect may reduce the landau damping which is important for beam stability. Since amplitude detuning is needed in the LHC, due to collective effects, it is not possible to reduce the strength of the octupoles and instead the way to reduce amplitude dependent coupling is to reduce the linear coupling. This observation strengthens the motivation for controlling the linear coupling and the foreseen coupling feedback for the LHC [7].

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