

Simulations of non-linear effects in the LHC

– Summer students report –

Saskia Mönig
Supervisor: Rogelio Tomás

Jul.-Sep. 2015

Abstract

Simulations of accelerators allow the investigation of complex dynamics arising from non-linear components. Furthermore, simulations can be used as a tool for the analysis of new concepts. In the context of my summer student project, I did simulations of some non-linear effects in the LHC for comparison with recent measurements at maximal beam energy. I used the LHC model to analyse the dynamic aperture of the LHC with AC dipole, meaning with forced beam oscillations. This gives a deeper understanding of the beam dynamics with AC dipole. As result of these studies, the operation of the AC dipole can be improved. Moreover, I had the opportunity to participate in measurements on the LHC during MD.

Contents

1	Introduction	1
2	The non-linear model for simulations at 6.5 TeV and $\beta^*=40$ cm	1
3	Testing of the model using some non-linear effects	2
3.1	Non-linear chromaticity	2
3.1.1	Analysis of the measured data	2
3.1.2	Simulation with PTC	3
3.2	Amplitude detuning with AC dipole	3
4	Dynamic apperture with AC dipole	6
4.1	AC dipole excitation with usual AC dipole tunes	7
4.2	Simulation using different AC dipole tunes	8
5	Conclusion	8

1 Introduction

The LHC contains a multitude of non-linear components, having a strong influence on the beam properties. Since a significant part of these non-linearities are due to unknown magnet errors, their effect has often to be determined from measurements on the beam. They can then be taken into account to optimize operation of the LHC.

An important diagnostic tool for non-linear components is the AC dipole. An AC dipole excites the beam coherently over many turns, with a driving frequency chosen to be sufficiently different from the natural tune, in order to avoid a resonance. Since all particles in a bunch are then oscillating with the same phase, a displacement of the center of gravity can then be measured with the beam position monitors (BPM) installed in the LHC. Non-linearities can then be seen through additional lines in the spectrum obtained from the Fourier transformation of the BPM signal. A more detailed description of AC dipoles can be found in [1]. In contrary to a single kick excitation of the beam, with following free oscillations at high amplitude, the AC dipole is a non destructive method. The oscillation amplitudes are adiabatically ramped up towards their maximum and ramped down again in the end. Adiabatic in this context means, that the emittance of the beam is unaffected once the AC dipole is turned off [2].

Since measurements on the LHC are difficult and very restricted in time, it is important to have a model which describes the effects in the machine as accurately as possible in order to be able to investigate certain effects via simulations. For this project, simulations of measured non-linear effects have been done. This allows a better understanding of the non-linear components in the LHC. The possibility of using the AC dipole to determine the dynamic aperture of the LHC at maximal beam energy has been investigated using simulations.

2 The non-linear model for simulations at 6.5 TeV and $\beta^*=40$ cm

For the simulations, a MADX [3] model of the LHC with a beam energy of 6.5 TeV and a β -function at the ATLAS and CMS interaction points of 40 cm has been used. Initial values for tune and chromaticity have been set according to the settings during the measurements from the 22.07.2015 in MD block I [4] on the LHC with the AC dipole:

$$\begin{aligned}Q_x &= 64.309 \\Q_y &= 59.320 \\Q'_x &= 2.00 \\Q'_y &= 2.00\end{aligned}$$

where $Q'_{x/y}$ is the first order chromaticity. The model includes non-linear magnet errors of the triplets and the magnet errors in the arcs, as well as corrections on the arcs as used during the MD. Misalignments have not been considered; the crossing angles and separation bumps have been turned off, as in the corresponding measurements.

In simulations with AC dipole, the AC dipole ramps have been set to 2000 turns according to the results in [8]. The flat top of the excitation is set to 6000 turns, which is about the length in measurements with the AC dipole in the LHC. The excitation amplitudes A_x and A_y of the AC dipole at locations with $\beta = 180$ m are set via the AC dipole voltage in MADX, given by:

$$V_{x/y} = 0.042 \cdot p_{\text{beam}} \cdot \frac{|Q_{x/y}^{AC} - Q_{x/y}|}{\sqrt{180.0 \cdot \beta_{x/y}^{AC}}} \cdot A_{x/y} \quad (1)$$

3 Testing of the model using some non-linear effects

3.1 Non-linear chromaticity

The tune varies as a function of the momentum deviation with respect to the nominal momentum $\frac{\delta p}{p}$:

$$Q_{x/y} \left(\frac{\delta p}{p} \right) \approx Q_{0,x/y} + Q'_{x/y} \cdot \left(\frac{\delta p}{p} \right) + \frac{1}{2} Q''_{x/y} \cdot \left(\frac{\delta p}{p} \right)^2 + \frac{1}{6} Q'''_{x/y} \cdot \left(\frac{\delta p}{p} \right)^3 + \dots \quad (2)$$

where $Q_{0,x/y}$ is the tune in x - and y -plane and $Q'_{x/y}$ the first order chromaticity which is usually called “chromaticity”. In a real accelerator with non-linear errors, higher order chromaticity terms become important. In this analysis, they have been considered up to the third order, as in eq. (2).

3.1.1 Analysis of the measured data

The measured data (from 22.07.2015, MD bock 1, $\beta^*=40$ cm) consists of tune measurements for different RF frequencies, which are related to the relative momentum deviation via

$$\frac{\delta p}{p} = \left(\frac{1}{\frac{1}{\gamma^2} - \alpha_c} \right) \cdot \frac{\delta \nu_{RF}}{\nu_{RF}} \quad (3)$$

where $\gamma = \frac{E}{m} = 6927.4$ is the Lorentz factor and $\alpha_c = 0.0003225$ is the momentum compaction factor. The “true” tune has to be separated from measured noise lines, using the fact that the tune changes with the RF frequency, while noise lines vary randomly or not at all, as can be seen in figure 1.

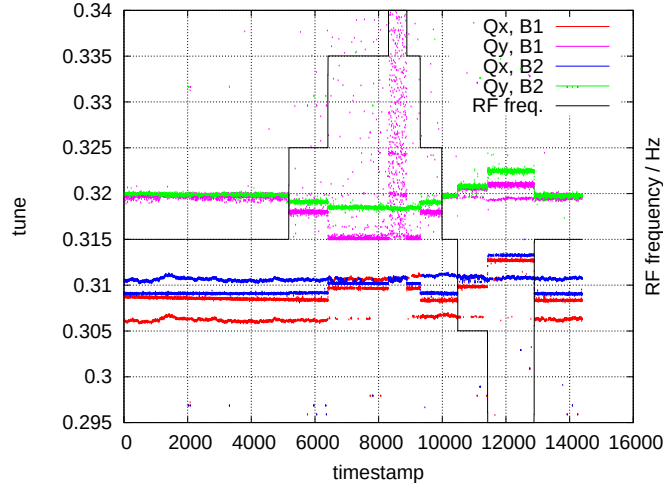


Figure 1: Tune measurement for different RF frequencies; the real tune line has to be separated from the noise measurements.

Once this separation has been done, a third order polynomial fit to the data allows the determination of the chromaticity values of different orders, as can be seen in figure 2. The resulting chromaticity values are:

$x - \text{plane}$	$y - \text{plane}$
$Q_0 = 0.30846 \pm 0.00003$	$Q_0 = 0.31978 \pm 0.00001$
$Q' = 2.3 \pm 0.1$	$Q' = 4.04 \pm 0.06$
$Q'' = (14.5 \pm 0.3) \cdot 10^3$	$Q'' = (-8.7 \pm 0.1) \cdot 10^3$
$Q''' = (1.9 \pm 2.4) \cdot 10^6$	$Q''' = (11 \pm 1) \cdot 10^6$

3.1.2 Simulation with PTC

The simulation of the non-linear chromaticity has been done using the model described in section 3, matching the tune and the first order chromaticity to the values obtained from the fit, namely $Q_{0,x} = 0.308459$, $Q'_x = 2.34$, $Q_{0,y} = 0.319780$ and $Q'_y = 4.04$. The errors on these values have not been taken into account, since the effect of slight deviation of these values was shown to be negligible. The higher order chromaticities have been calculated with the MADX [3] module PTCnormal. The result of the simulations are shown in figure 2 for 60 different magnet error seeds, in comparison to the measurements. Since the tune and the first order chromaticity have been matched during the simulations, their values agree exactly with the measurement. The higher order chromaticity terms show that the LHC model seems to contain more non-linearities than the actual machine. The seeds seem to have a relatively small impact on the results, compared to the deviation from the measurement.

It has been observed in previous simulations, that discrepancies between model and measurements can originate in wrong settings of the KCD values, since non-linear chromaticity terms are determined by high dispersion regions. Therefore, simulations have been done with the current model changing the KCD values by a common factor of 1.5, $\frac{1}{1.5}$ and 0. The influence on the non-linear chromaticity turned out to be negligible for this high beam energy.

3.2 Amplitude detuning with AC dipole

Another non-linear effect in the accelerator is the tune variation with changing action. The action is defined as $2J_{x/y} = \epsilon_{x/y}$, where ϵ is the emittance.

$$Q_{x/y}(\epsilon_x, \epsilon_y) = Q_{0,x/y} + \frac{\partial Q_{x/y}}{\partial \epsilon_x} \cdot \epsilon_x + \frac{\partial Q_{x/y}}{\partial \epsilon_y} \cdot \epsilon_y + \frac{1}{2} \left(\frac{\partial^2 Q_{x/y}}{\partial \epsilon_x^2} \cdot \epsilon_x^2 + 2 \frac{\partial^2 Q_{x/y}}{\partial \epsilon_x \partial \epsilon_y} \cdot \epsilon_x \epsilon_y + \frac{\partial^2 Q_{x/y}}{\partial \epsilon_y^2} \cdot \epsilon_y^2 \right) + \dots \quad (4)$$

Since an excitation with the AC dipole corresponds to an effective change of the action, the natural tune on the flattop of the AC dipole excitation changes according to the excitation amplitude. However, the amplitude detuning coefficients for forced oscillations differ from those of free betatron motion [10]. In the simulations the excitation amplitudes have been varied between 0.5 mm and 2.0 mm only in one plane at once, while the amplitude in the other plane has been kept constant at 0.5 mm. The dependencies of the tunes in x - and y -plane as a function of the actions in both planes have been considered separately, giving the terms $\frac{\partial Q_{x/y}}{\partial \epsilon_x}$ and $\frac{\partial Q_{x/y}}{\partial \epsilon_y}$.

In order to compare with the measurements, the same settings for the tune and for the AC dipole frequency have been chosen in MADX than during the measurement, being $Q_x = 0.309$, $Q_y = 0.32$, $Q_x^{AC} = Q_x - 0.012$ and $Q_y^{AC} = Q_y + 0.012$. The natural tune has been extracted from GetLLM [5], which takes the spectrum calculated by Drive [6] and [7] as input. The spectrum is calculated as the FFT of the single particle tracking data at the BPMs. The results of the simulation in comparison with the measured data are shown in figure 3.

The tendencies in the measurements are described by the simulation, even though the reasons for the discrepancies have to be further investigated. The model seems to fit the measurement better for beam 1 than for beam 2. In order to have a better comparison of the slopes, the simulated tune has in some cases been shifted. The tune at zero amplitude has a negligible effect on the amplitude detuning. For high actions, in the simulation a second peak appeared next to the natural tune line in the spectrum, with comparable amplitude, which might be caused by some resonant effect. Points with these high actions have therefore not been considered, since an accurate determination of the natural tune by GetLLM was not possible anymore.

A comparison of the results for different seeds has been done for a single point and for a reduced number of seeds, because of the too large size of the output files; again no difference has been seen between the different seeds.

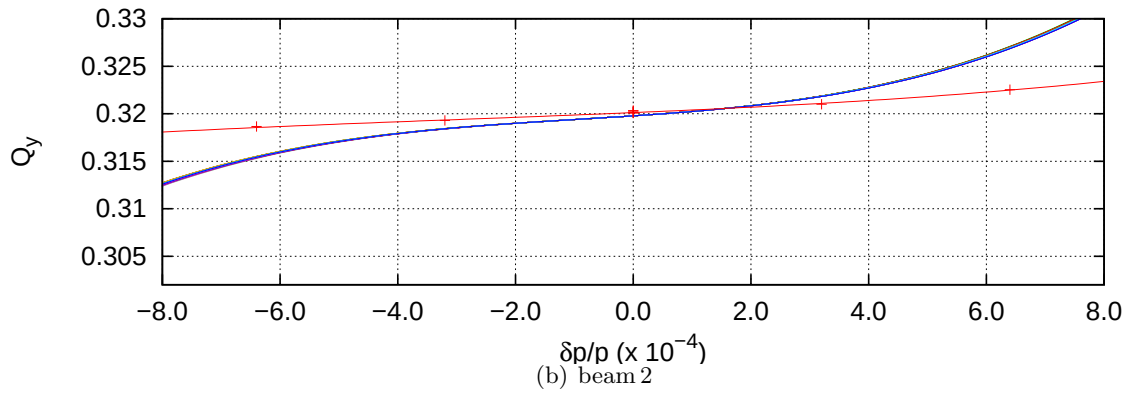
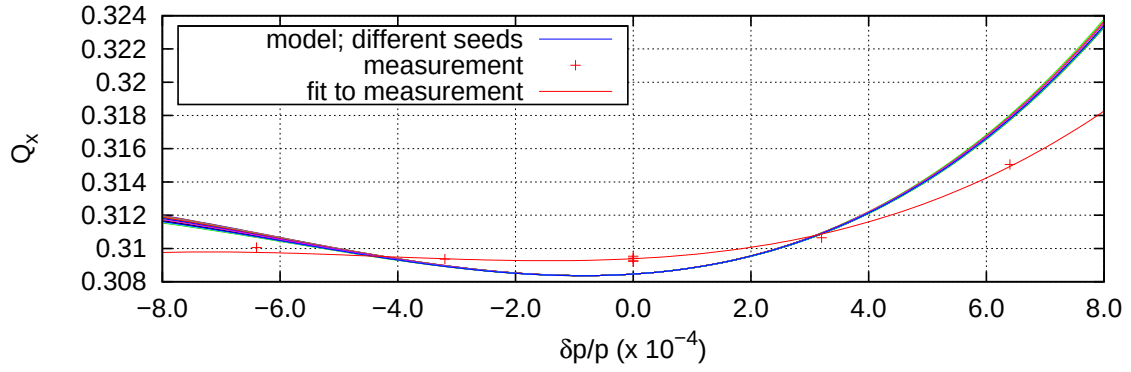
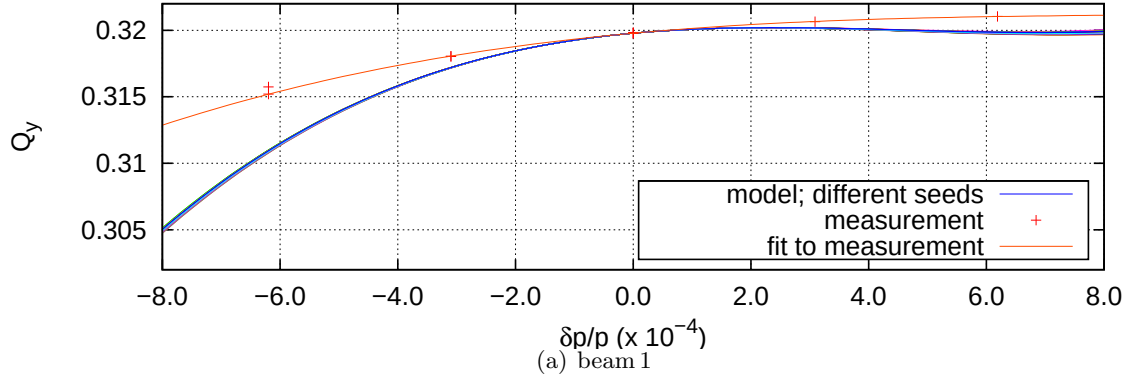
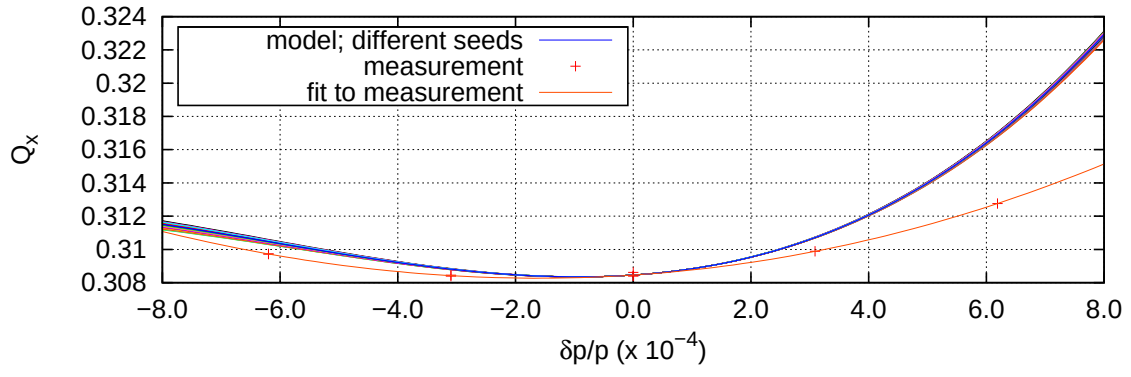
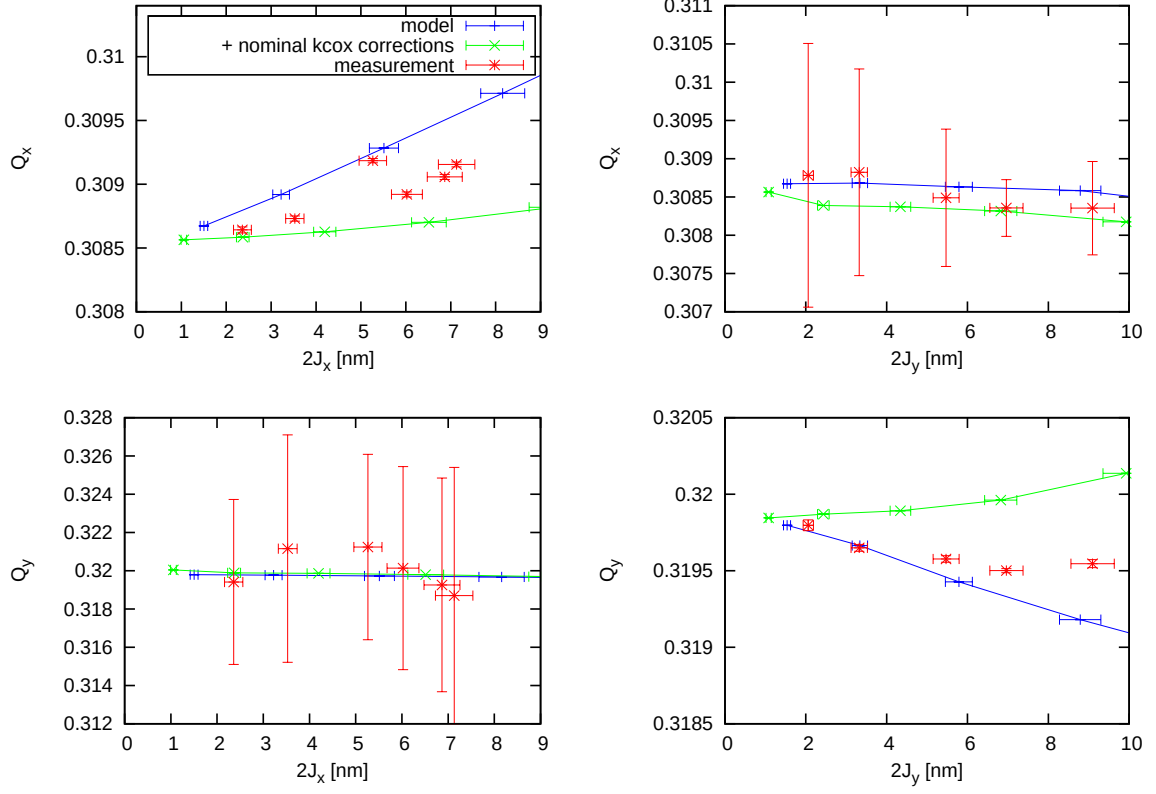
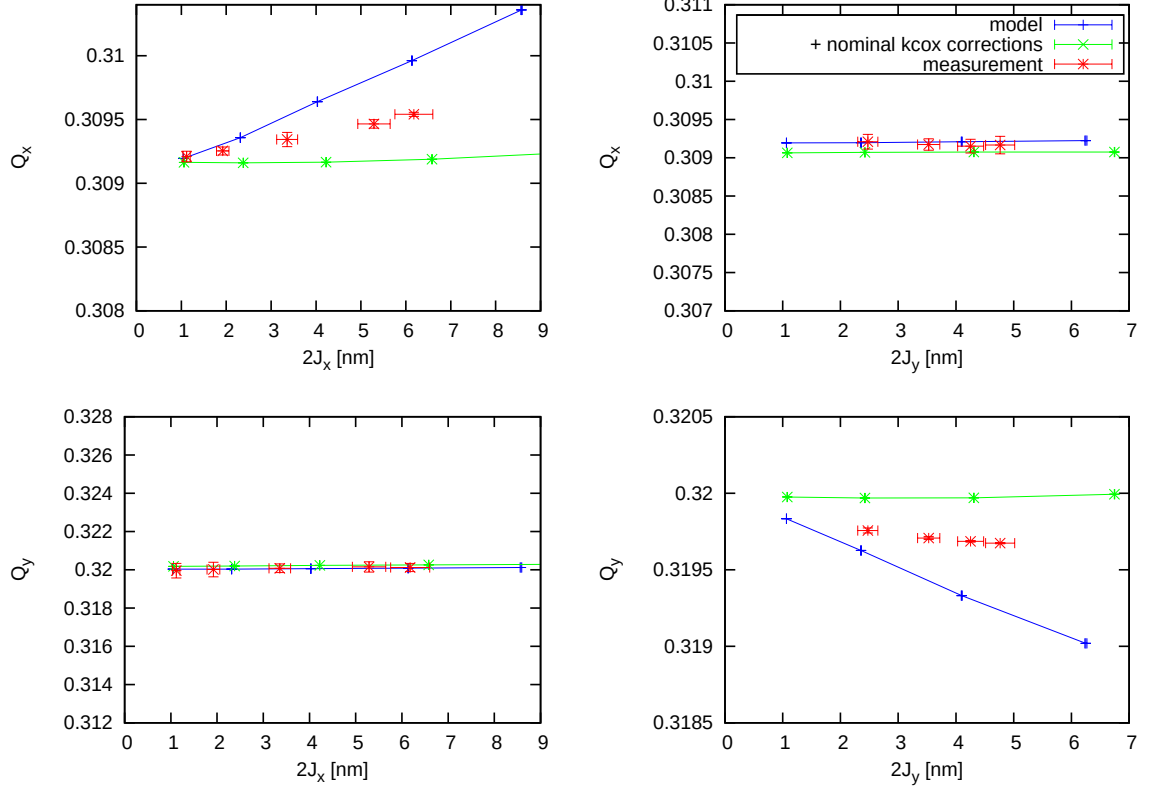


Figure 2: Simulated and measured non linear chromaticity at 6.5 TeV, 40 cm.



(a) beam 1



(b) beam 2

Figure 3: Simulated and measured detuning with AC dipole at 6.5 TeV, 40 cm.

In general, the two interaction regions ATLAS (IP1) and CMS (IP5) are expected to have an important influence on the amplitude detuning, since they are the regions with the highest β -function. Therefore, further simulations have been done to investigate if wrongly estimated octupolar errors in these regions can be the reason for the discrepancy between model and measurements. Instead of changing the octupolar errors, for simplicity, octupolar corrections have been set. Both, setting the octupolar correctors at IP5 to $k_{\text{cox3.l5}}=1.344386861$ and $k_{\text{cox.r5}}=-1.245788321$ or setting the octupolar correctors at IP1 to $k_{\text{cox3.l1}}=0.827430657$ and $k_{\text{cox3.r1}}=-1.077167883$, leads to a very good agreement between the model and the measurement. Setting both corrections together, leads to an overcorrection by roughly a factor two, as shown in figure 3 (in green). The settings correspond to the nominal settings, calculated from the model in order to correct for the octupolar errors in the model. They are therefore compensating the octupolar errors. This suggests that both interaction points contribute similarly to the amplitude detuning, and that the octupolar errors in these regions have to be reconsidered. It has further been verified that these corrections do not affect the non-linear chromaticity.

4 Dynamic aperture with AC dipole

The dynamic aperture represents the phase space region in which the beam is stable. In this case, it means, that the particle is not lost within the AC dipole cycle, which corresponds to a short term dynamic aperture. One method to measure the dynamic aperture of the LHC consists in applying single kicks to the beam in both transverse planes [9]. Beam losses are then measured as a function of the kick amplitudes. The usage of the AC dipole instead of single kicks allows controlled and coherent excitations of the beam over many turns, with a ramp down of the excitation. The adiabaticity of the process [2], quantified by the oscillation amplitude after the ramp down, gives further information on the stability of the beam for given amplitudes. For single kicks, the beam growth is difficult to quantify and has therefore not been considered.

In general, the dynamic aperture is limited by resonances. With the AC dipole, new resonances show up, which might lead to a smaller dynamic aperture. Like for a one-dimensional driven motion with AC dipole [11], the two-dimensional resonance condition in presence of the hamiltonian term h_{jklm} is given by:

$$(k_1 - j_1) \cdot Q_x + (k_2 - k_3 + j_2 - j_3) \cdot Q_x^{AC} + (m_1 - l_1) \cdot Q_y + (m_2 - m_3 + l_2 - l_3) \cdot Q_y^{AC} = p$$

$$p \in \mathbb{Z}, j_i, k_i, l_i, m_i \in \mathbb{N}^0$$

$$\begin{aligned} j_1 + j_2 + j_3 &= j \\ k_1 + k_2 + k_3 &= k \\ l_1 + l_2 + l_3 &= l \\ m_1 + m_2 + m_3 &= m, \quad j_1 > 0 \text{ or } l_1 > 0 \end{aligned} \tag{5}$$

How these resonances are approached is determined by detuning with amplitude. Since forced oscillations with AC dipole feature larger amplitude detuning [10], particles might be brought into resonances at smaller amplitudes than with free oscillations. Hence, the dynamic aperture would be reduced, which has not been considered in previous work like [8] or [12].

The AC dipole excitation amplitudes have been set via eq. (1), and it has been verified that the amplitudes measured at the BPMs with $\beta = 180\text{m}$ correspond relatively well to the ones set with eq. (1) for both planes. They further agree with the amplitudes obtained with single kicks. The amplitude of the the oscillations after the ramp down is computed from the simulated turn by turn data at BPM.22L1.B1, at which $\beta_x = 180\text{m}$, using the 500 turns following the ramp down.

4.1 AC dipole excitation with usual AC dipole tunes

The AC dipole tunes have been set to the usual values during LHC operation, which are:

$$\begin{aligned} Q_x^{AC} &= Q_x - \Delta Q \\ Q_y^{AC} &= Q_y + \Delta Q \\ \text{with } \Delta Q &= 0.012 \end{aligned}$$

The results are shown in figure 4.

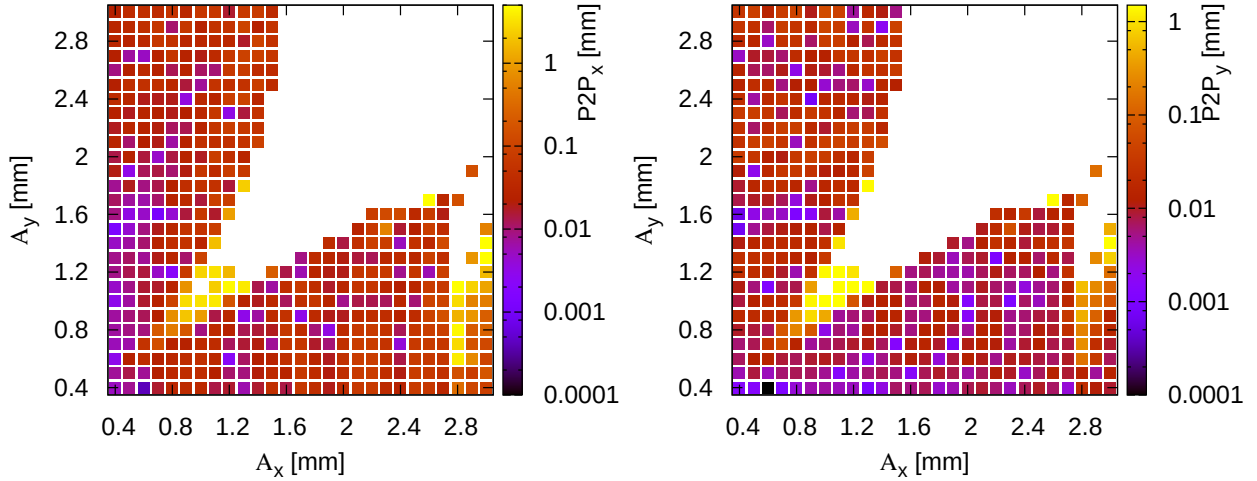


Figure 4: Peak-to-peak (P2P) oscillation amplitude of the simulated particle after ramp down of the AC dipole for $Q_x^{AC} = Q_x - 0.012$ and $Q_y^{AC} = Q_y + 0.012$ as a function of the excitation amplitude. The short term dynamic aperture corresponds to the colored points. In the region without points, the particle has been lost before the end of the flat top.

As expected, the particle becomes more and more unstable for large amplitudes, which can be seen in the growing oscillation amplitude after ramp down. For these AC dipole tune settings, an additional region of instability in both planes along the diagonal affects the beam dramatically. The particle gets lost after a few turns of tracking already for small amplitudes. This effect can be explained by a resonance, as the following condition turns out to be fulfilled:

$$\begin{aligned} Q_x^{AC} + Q_y^{AC} - Q_y &\approx Q_x \\ Q_x^{AC} + Q_y^{AC} - Q_x &\approx Q_y \end{aligned} \tag{6}$$

where $Q_{x/y}$ and $Q_{x/y}^{AC}$ are the fractional tunes. This resonance can be driven, according to equation 5, by the two octupolar terms in the Hamiltonian h_{2020} and h_{1111} . As shown in figure 5, the coupling line approaches the natural tunes towards diagonal excitation, since these are changing with the amplitude of the AC dipole excitation. For very small amplitudes on the diagonal, this effect can not be seen, even though equation 6 is fulfilled; probably the amplitude of the coupling line is negligible there compared to the amplitude of the natural tune. Since the resonance frequency line is determined by the sum of the AC dipole tunes, it will occur for every AC dipole tunes with equal ΔQ in both planes.

This resonance explains the significant beam losses observed in measurements with the AC dipole in

the LHC, limiting the excitation amplitudes to approximately 1 mm. For further use in the LHC, the AC dipole tune should therefore be changed, using different values for ΔQ in both planes.

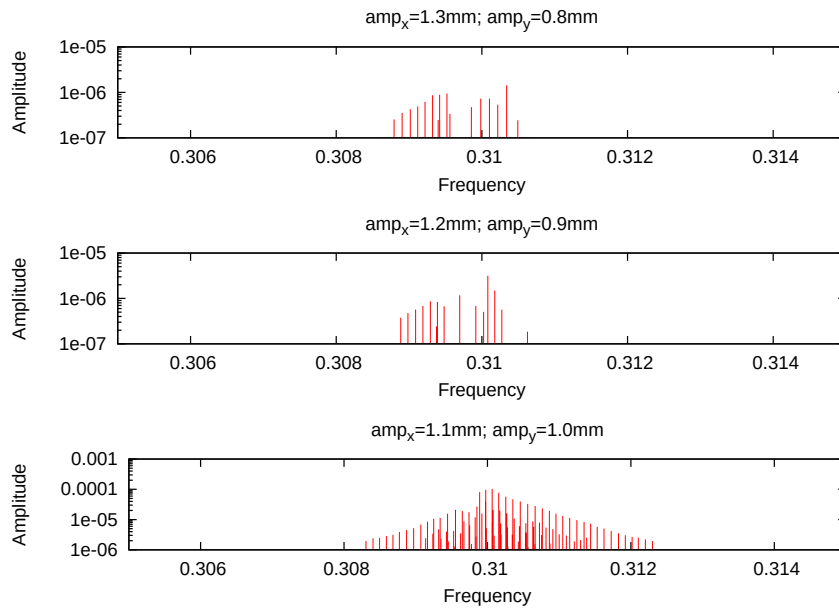


Figure 5: Spectrum in x-plane around the natural tune line for different excitation amplitudes. The tune line corresponding to $Q_x^{AC} + Q_y^{AC} - Q_y$ moves towards the natural tune when approaching the resonance.

4.2 Simulation using different AC dipole tunes

To avoid the resonance described above, different ΔQ for both planes have been chosen for the AC dipole tune in further simulations. Two different configurations have been tested, namely $\Delta Q_x = 0.010$ and $\Delta Q_y = 0.014$ in figure 6(a) and $\Delta Q_x = 0.012$ and $\Delta Q_y = 0.015$ in figure 6(b).

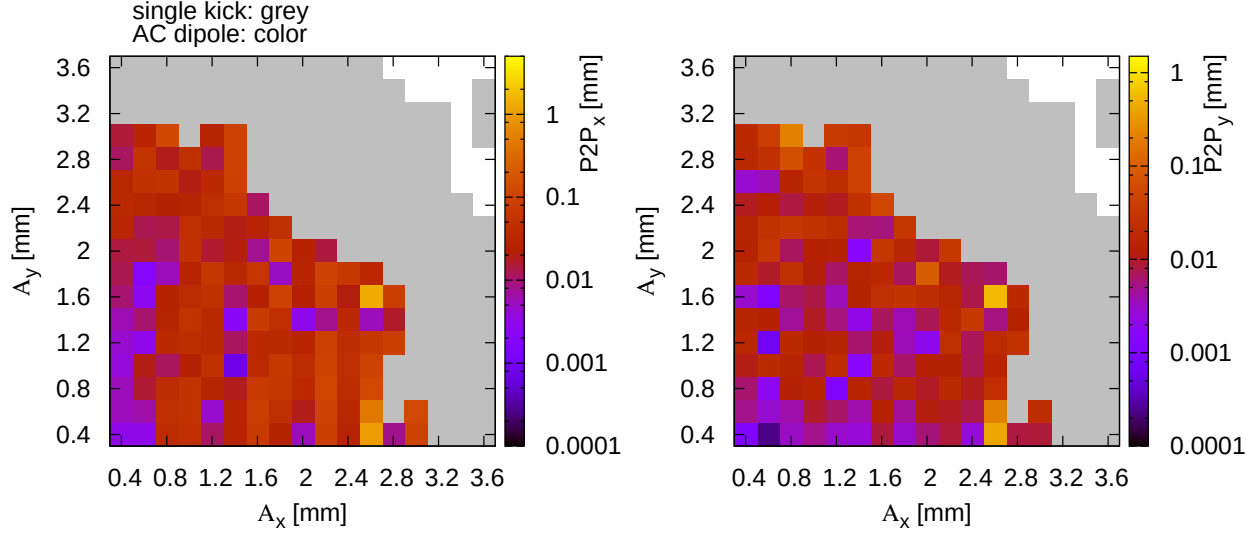
As expected, the resonance observed in figure 4 does not occur anymore. However, the stable region still seems to be limited by some resonances, showing up on each side of the diagonal with $A_x = A_y$ in figure 6(b), and leading to beam losses for high amplitude diagonal excitations in figure 6(a).

The figures additionally show a comparison of the dynamic aperture with AC dipole excitation and with single kick excitations. It can be clearly seen that with the AC dipole, beam loss appears already at smaller amplitudes than with single kicks. This is expected, as explained in section 1. An additional limitation of the excitation amplitudes with AC dipole may be the mutual approach of the natural tunes of both planes due to amplitude detuning.

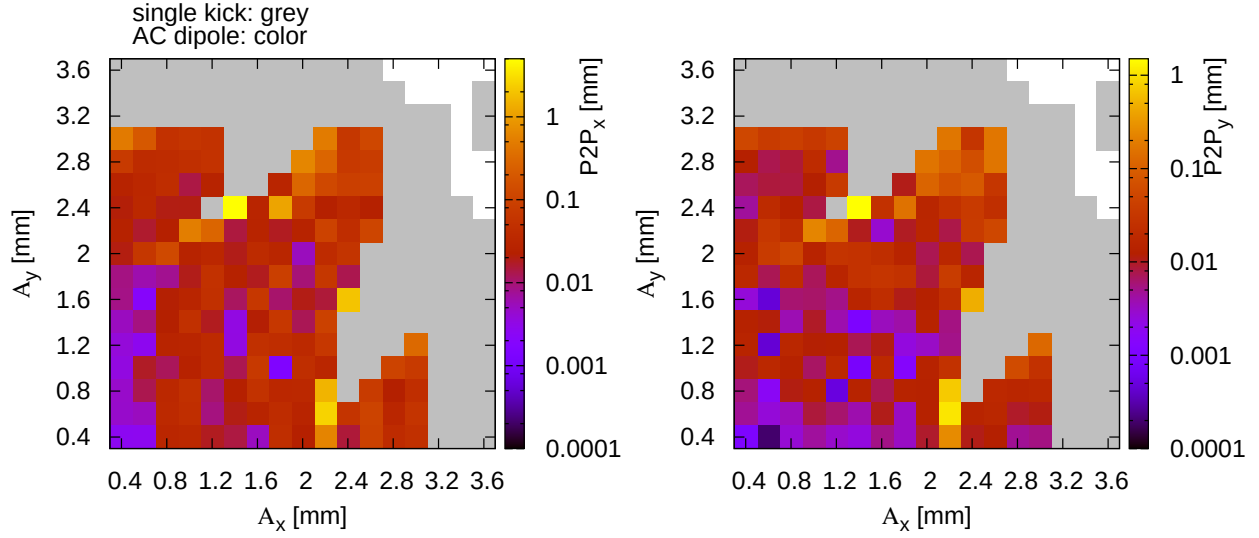
However, the tune configuration shown in figure 6(a) seems to be quite convenient for the operation of the AC dipole in the LHC, since relatively high amplitudes can be reached in both planes, independently of the excitation amplitude in the other plane.

5 Conclusion

With non-linear simulations, the measured tendencies of amplitude detuning and non-linear chromaticity at the LHC can be reproduced. Nevertheless, quantitatively, there are still differences to the measured ones, showing that the model has still to be improved. A good candidate for improvement are the octupolar errors in the interaction regions of CMS and ATLAS, which turned out to be overestimated by roughly a factor two.



(a) $Q_x^{AC} = Q_x - 0.010$ and $Q_y^{AC} = Q_y + 0.014$



(b) $Q_x^{AC} = Q_x - 0.012$ and $Q_y^{AC} = Q_y + 0.015$

Figure 6: Peak-to-peak (P2P) oscillation amplitude of the simulated particle after ramp down of the AC dipole as a function of the excitation amplitude, compared to the short term dynamic aperture with single kick excitation.

A first look at the dynamic aperture with driven oscillations showed that the standard operation of the LHC AC dipole sits on an octupolar resonance driven by h_{2020} or h_{1111} . This explains the beam losses observed already for relatively small excitation amplitudes. To avoid this resonance, the AC dipole tunes should, for future operation, be chosen to be $Q_x^{AC} = Q_x - \Delta Q_x$ and $Q_y^{AC} = Q_y + \Delta Q_y$ with $\Delta Q_x \neq \Delta Q_y$. Simulations have shown that the combination $\Delta Q_x = 0.010$ and $\Delta Q_y = 0.014$ allows a stable operation up to relatively high excitation amplitudes. This configuration should therefore be used for the AC dipole in the LHC rather than the present settings.

In general, with AC dipole excitation, the beam gets lost for smaller amplitudes than for single kick excitations. This results from the effect of additional resonance conditions for an excited oscillation, together with the stronger amplitude detuning with AC dipole. However, a lower bound for the free dynamic aperture can be measured with this method. It can further serve as tool to get a deeper understanding of the resonance effects.

References

- [1] Ryoichi Miyamoto, Diagnostics of the Fermilab Tevatron Using an AC Dipole, Dissertation, Aug. 2008
- [2] R. Tomás, “Adiabaticity of the ramping process of an AC dipole”, Phys. Rev. ST Accel. Beams, Vol. 8, Feb. 2005
- [3] CERN - BE/ABP Accelerator Beam Physics Group, MAD - Methodical Accelerator Design
- [4] A. Langner *et al*, “LHC optics commissioning at $\beta^* = 40$ cm and 60 cm”, MD note, Sep. 2015 (To be published)
- [5] <http://beta-beating.web.cern.ch/Beta-beating/doc/bbeat/getllm/index.html> (Last visit: 17.09.2015)
- [6] T. Bach and R. Tomás, “Improvements for Optics Measurement and Corrections software”, CERN-ACC-NOTE-2013-0010, Aug. 2013
- [7] <http://beta-beating.web.cern.ch/Beta-beating/doc/bbeat/drive/index.html> (Last visit: 17.09.2015)
- [8] R. Tomás, S. Fartoukh and J. Serrano, “Reliable operation of the AC dipole in the LHC”, WEPP026, Proceeding of EPAC’08, Genoa, Italy
- [9] E.H. Maclean, R. Tomás, F. Schmidt and T.H.B. Persson, “Measurement of nonlinear observables in the Large Hadron Collider using kicked beams”, Phys. Rev. ST Accel. Beams, Vol. 17, Aug. 2014
- [10] S. White, E.H. Maclean and R. Tomás, “Direct amplitude detuning measurement with ac dipole”, Phys. Rev. ST Accel. Beams, Vol. 16, Jul. 2013
- [11] R. Tomás, “Normal form of particle motion under the influence of an AC dipole”, Phys. Rev. ST Accel. Beams, Vol. 5, May 2002
- [12] R. Tomás, R. Miyamoto, M. Cattin, J. Serrano, “Signal quality of the LHC AC dipole and its impact on beam dynamics”, THPE083, Proceedings of IPAC’10, Kyoto, Japan