SHORT TERM DYNAMIC APERTURE WITH AC DIPOLES

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Abstract

The dynamic aperture of an accelerator is determined by its non-linear components and errors. Control of the dynamic aperture is important for a good understanding and operation of the accelerator. The AC dipole, installed in the LHC for the diagnostic of linear and non-linear optics, could serve as a tool for determination of the dynamic aperture. However, since the AC dipole itself modifies the non-linear dynamics, the dynamic aperture with and without AC dipole are expected to differ. This paper will report the results of studies of the effect of the AC dipole on the dynamic aperture.

INTRODUCTION

One method to measure dynamic aperture (DA) consists in applying single kicks to the beam in the transverse planes [1]. Beam losses are then measured as a function of kick amplitude. In this paper the possibility of using an AC-dipole as a tool to estimate DA is discussed, based on MAD-X [2] simulations. The AC-dipole allows controlled and coherent excitation of the beam over many turns, with a ramp up and down of the excitation. Figure 1 contrasts simulated turn-by-turn data for single kick (red) and AC-dipole excitation (green).

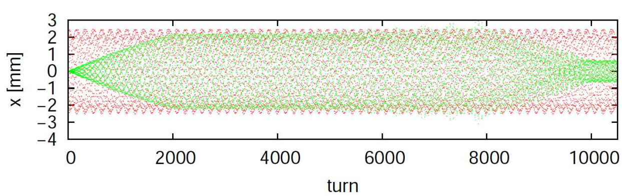

Figure 1: Tracking data for single kick (red) and AC-dipole excitation (green).

In this paper we refer to short-term dynamic aperture as the region of the AC-dipole excitation strength not leading to particle loss within the AC-dipole cycle. The adiabaticity of the process [3], quantified by the oscillation amplitude after AC-dipole ramp down (as seen in Fig. 1), gives further information on particle stability. For single kicks, only particle loss is considered.

Dynamic aperture is in general limited by resonances. With the AC-dipole new resonances appear, which may lead to a smaller DA. In a 2-D system resonance lines due to Hamiltonian term h_{jklm} (order $n = j + k + l + m$) are linear combinations of the natural and driven tunes in the horizontal and vertical planes. Analogously to the derivation in [4], it can be shown that the resonance condition in this case is given by:

$$(k_1 - j_1) \cdot Q_x + (k_2 - k_3 + j_2 - j_3) \cdot Q_x^{AC} + \\ +(m_1 - l_1) \cdot Q_y + (m_2 - m_3 + l_2 - l_3) \cdot Q_y^{AC} = p \quad (1)$$

$$\begin{aligned} p \in \mathbb{Z},\ j_i, k_i, l_i, m_i \in \mathbb{N}_0 \qquad & j_1 > 0 \text{ or } l_1 > 0 \\ j_1 + j_2 + j_3 = j \qquad & k_1 + k_2 + k_3 = k \\ l_1 + l_2 + l_3 = l \qquad & m_1 + m_2 + m_3 = m \end{aligned}$$

where j has been redefined compared to [4] as $(j - 1) \rightarrow j$. How these resonances are approached is determined by detuning with amplitude. Since forced oscillations with AC-dipole feature larger amplitude detuning [5] particles may be brought into resonances at smaller amplitudes than with free oscillations, and the dynamic aperture would be reduced. This effect has not been considered in previous work like [6] or [7].

MODEL AND ANALYSIS

Single particle tracking simulations were performed in a MAD-X model of the LHC at 6.5 TeV and $\beta^* = 0.4$ m at the ATLAS and CMS interaction points. Initial values for tune and chromaticity were set to $Q_x = 64.309$, $Q_y = 59.32$ and $Q'_{x,y} = 2$ (these being values measured during $\beta^* = 0.4$ m optics commissioning [8]). The model includes non-linear magnetic errors in the insertion regions and arcs, as well as corrections in the arcs as applied during commissioning. Alignment errors were not considered. Crossing angles and separation bumps were turned off, as is typical for optics measurements. All simulations were done for Beam 1. AC-dipole ramps were set to 2000 turns according to the results in [6]. The flattop of the excitation was set to 6000 turns - the length currently used in the LHC. Excitation amplitudes A_x and A_y of the AC dipole (located in the LHC at $\beta_{x/y}^{AC} = 180$ m) are set via the AC dipole voltage in MAD-X, given by:

$$V_{x/y} = 0.042 \cdot p_{\text{beam}} \cdot \frac{|Q_{x/y}^{AC} - Q_{x/y}|}{\sqrt{\beta_{\text{BPM}} \cdot \beta_{x/y}^{AC}}} \cdot A_{x/y} \quad (2)$$

which depends on the distance of the driven tune to the natural tune $|Q_{x/y}^{AC} - Q_{x/y}|$. It was verified that the simulated amplitude at the BPMs correspond well to those set with Eq. (2). The amplitude of the the oscillations after the ramp down of the AC dipole was computed from the simulated turn-by-turn data at BPM.22L1.B1, at which $\beta_{\text{BPM},x} = 180$ m, using 500 turns following ramp-down.

TYPICAL AC-DIPOLE EXCITATION

Simulations were performed with the usual values for the AC-dipole tunes in the LHC, specifically:

$$Q_x^{\mathrm{AC}} = Q_x - \Delta Q$$
$$Q_y^{\mathrm{AC}} = Q_y + \Delta Q$$
$$\Delta Q = 0.012$$

Figure 2 shows the short term dynamic aperture, together with the figure of merit given by the peak-to-peak amplitude of the residual oscillation after AC dipole ramp down in color code. The dynamic aperture corresponds to the colored region of AC dipole excitation amplitudes, where the particle is not lost within the simulated turns.

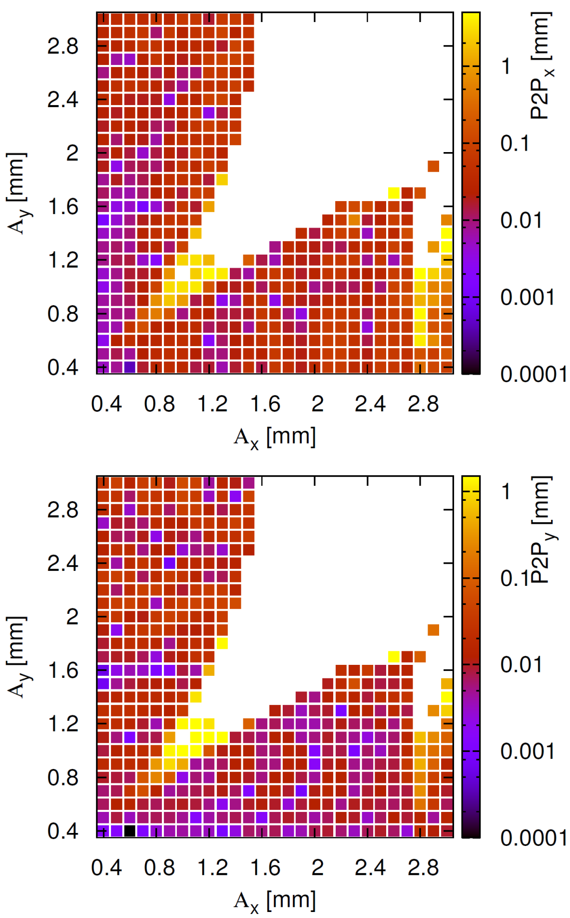

Figure 2: Simulated peak-to-peak amplitude after AC-dipole ramp down for $Q_x^{\mathrm{AC}} = Q_x - 0.012$ and $Q_y^{\mathrm{AC}} = Q_y + 0.012$. DA is given by the colored points, in white regions particles were lost before the end of the flattop.

The excitation becomes less and less adiabatic for large amplitudes, as seen in the growing oscillation amplitude of the particle after ramp down. For even higher excitation amplitudes the particle becomes unstable, leading to its loss during the AC dipole cycle. This limitation is not as relevant, since it concerns larger amplitudes than typical excitation with the AC dipole in the LHC of about 1 mm. For these settings however, an additional region of instability in both planes along the diagonal affects the beam dramatically. Particles are lost after a few turns of tracking already for small amplitudes. This effect can be explained by a resonance, as the following condition is fulfilled for the AC-dipole tunes normally used in the LHC:

$$Q_x^{\mathrm{AC}} + Q_y^{\mathrm{AC}} - Q_y \approx Q_x \qquad (3)$$
$$Q_x^{\mathrm{AC}} + Q_y^{\mathrm{AC}} - Q_x \approx Q_y$$

where $Q_{x/y}$ and $Q_{x/y}^{\mathrm{AC}}$ are the fractional tunes. This resonance can be driven, according to Eq. (1), by the two octupolar terms in the Hamiltonian h_{2020} and h_{1111}. As shown in Fig. 3, the coupling line and the natural tunes approach each other as AC-dipole excitation approaches the diagonal. The reason is the change of the natural tunes with the amplitude of AC-dipole excitation. For small amplitudes on the diagonal this effect cannot be seen, even though Eq. (3) 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 all AC-dipole tunes with equal ΔQ in both planes. For use in the LHC the AC-dipole tune should be changed, using different values for ΔQ in each plane.

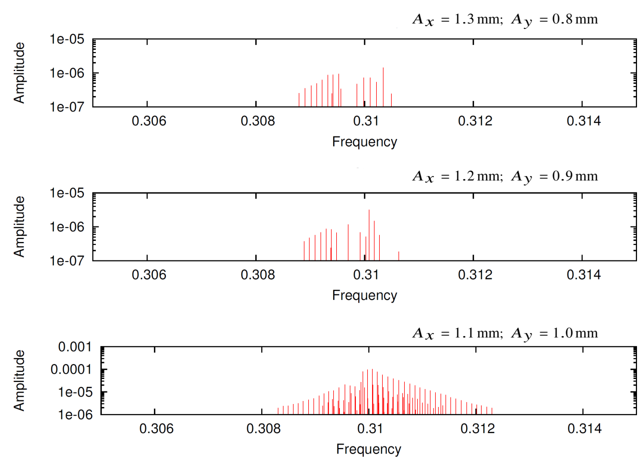

Figure 3: Spectrum in x-plane around the natural tune line for different AC dipole excitation amplitudes. The tune line corresponding to $Q_x^{\mathrm{AC}} + Q_y^{\mathrm{AC}} - Q_y$ moves towards the natural tune when approaching the resonance.

SHORT TERM DA WITH NEW Q^{AC}

To avoid the resonance described above, different ΔQ for the AC dipole tune in each plane were chosen for further simulations, namely $\Delta Q_x = 0.010$ and $\Delta Q_y = 0.014$ in Fig. 4 and $\Delta Q_x = 0.012$ and $\Delta Q_y = 0.015$ in Fig. 5.

As expected, the resonance observed in Fig. 2 does not occur anymore. However, the stable region still seems to be limited by some resonances, showing on each side of the diagonal with $A_x = A_y$ in Fig. 5, and leading to beam losses for high amplitude diagonal excitation in Fig. 4. The figures show a comparison of AC-dipole excitation with the single kick dynamic aperture. It can be clearly seen that with AC-dipole excitation beam-loss appears at smaller amplitudes

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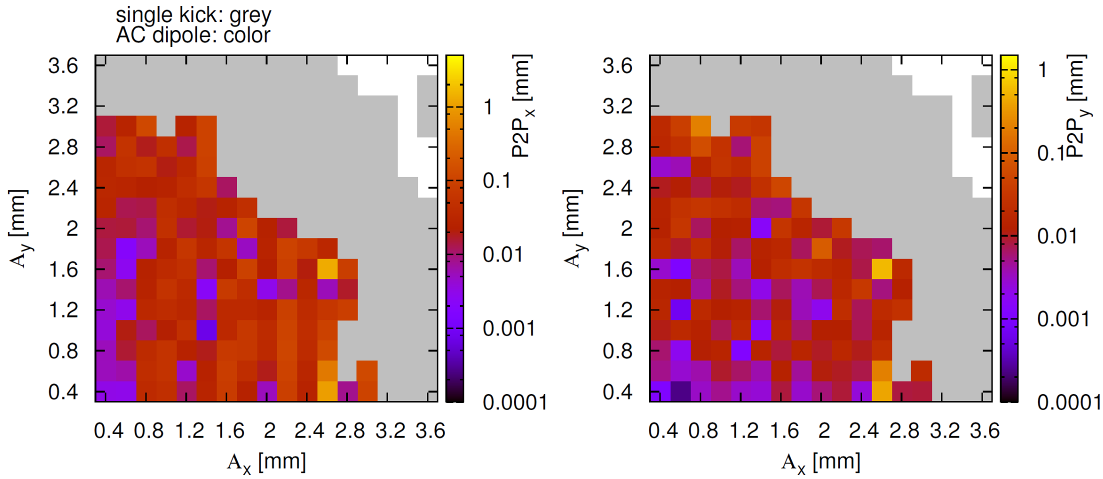

Figure 4: Simulated peak-to-peak amplitude after AC-dipole ramp down with $Q_x^{AC} = Q_x - 0.010$ and $Q_y^{AC} = Q_y + 0.014$.

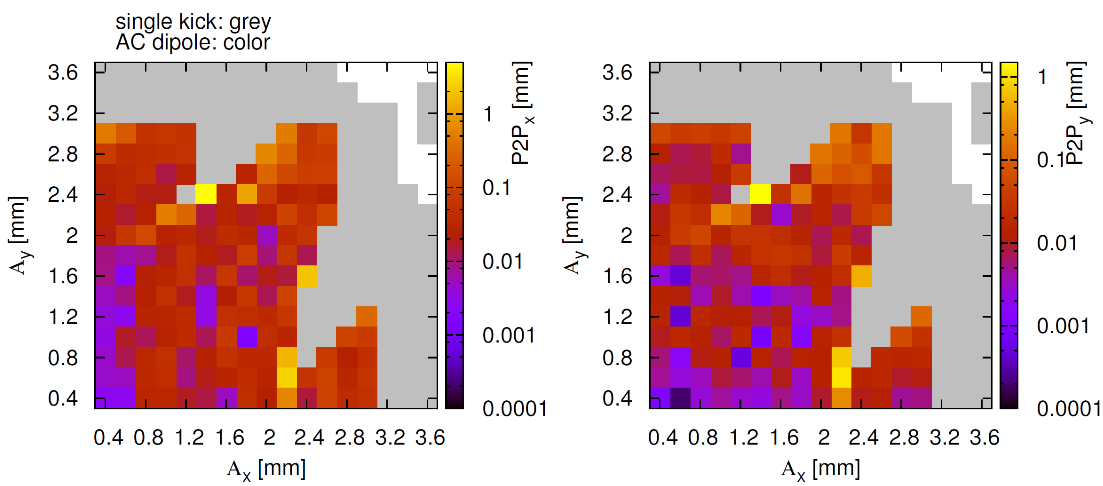

Figure 5: Simulated peak-to-peak amplitude after AC-dipole ramp down with $Q_x^{AC} = Q_x - 0.012$ and $Q_y^{AC} = Q_y + 0.015$.

than with single kicks. This is expected, as explained above. An additional limitation of the excitation amplitude may be the approach of the natural tunes of the two planes due to detuning with amplitude.

The tune configuration shown in Fig. 5 appears convenient for linear optics measurement in the LHC where diagonal kicks are used, while that of Fig. 4 may be more useful for amplitude detuning studies, since higher amplitudes can be reached in the H and V plane independently of the excitation amplitude in the other plane.

CONCLUSIONS

Simulation of short term 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 AC-dipole tunes should 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 show that $\Delta Q_x = -0.010$ and $\Delta Q_y = 0.014$ allow stable operation to high excitation amplitudes relative to current limits on LHC AC-dipole operation for many angles in A_x/A_y, while $\Delta Q_x = -0.012$ and $\Delta Q_y = 0.015$ allows for large diagonal kicks which are particularly useful for linear optics studies. As a result of these studies AC-dipole operation in 2015 and 2016 switched to these new configurations.

In general, it has been shown that with AC-dipole excitation the beam is lost for smaller amplitudes than for single kick excitation. This results from the effect of additional resonance conditions for an excited oscillation, together with 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 gain deeper understanding of resonance effects. More detail on these studies can be found in [9].

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