IMPACT OF INCOHERENT EFFECTS ON THE LANDAU STABILITY DIAGRAM AT THE LHC *

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Abstract

Instability thresholds are explored at the Large Hadron Collider (LHC) by means of the computation of the Landau Stability Diagrams (SD). In the presence of diffusive mechanisms, caused by resonance excitations or noise, the SD can be reduced due to the modification of the particle distribution inside the beam. This effect can lead to a possible lack of Landau damping of the coherent modes previously damped by lying within the unperturbed SD area. The limitations deriving from coherent instabilities in the LHC is crucial in view of future projects that aim to increase the performance of the LHC such as the High-Luminosity upgrade (HL-LHC). Simulation tools for the computation of the SD have been extended in order to take into account the incoherent effects from long tracking through the detailed model of the accelerator machine. The model include among others beam-beam interactions and octupoles and the interplay between both is addressed. Finally the simulation results are compared to the Beam Transfer Function (BTF) measurements in the LHC.

INTRODUCTION

In the LHC the stability thresholds are predicted by mean of the computation of the SD, analytically evaluated by solving the dispersion integral for a given detuning $\omega_{x,y}(J_x, J_y)$ and particle distribution $\psi(J_x, J_y)$ as a function of the transverse actions J_x and J_y in each plane [1]:

$$SD^{-1} = \frac{-1}{\Delta Q_{x,y}} = \int_0^\infty \int_0^\infty \frac{J_{x,y}}{\Omega - \omega_{x,y}(J_x, J_y)} \frac{d\psi}{dJ_{x,y}} dJ_x dJ_y \tag{1}$$

where $\Delta Q_{x,y}$ are the complex tune shifts at the stability limits for each frequency Ω. The term $\omega_{x,y}(J_x, J_y)$ is the detuning with amplitude in the beams, given by machine non-linearities such as octupoles magnets [2] and beam-beam interactions [3]. The contribution of the particle distribution enters in the dispersion integral in Eq. 1 with its derivative $\mathrm{d}\psi/\mathrm{dJ}_{x,y}$ therefore it may significantly modify the expectations w.r.t. a Gaussian distribution causing a possible lack of Landau damping. In order to take into account the incoherent effects on the Landau stability area, simulations tools have been extended to include the particle distribution from long term tracking by using the SixTrack code [4]. The detuning with amplitude $\omega_{x,y}(J_x, J_y)$ in Eq. 1 is given by the tracking module of MAD-X [5,6] including the machine non-linearities and the beam-beam interactions. The effects of the particle distribution are investigated in the presence of strong machine non-linearities at injection and in the presence of beam-beam long range interactions at the end of squeeze for different separations of the beam-beam long range encounters.

INCOHERENT EFFECTS ON STABILITY DIAGRAMS

The derivative $\mathrm{d}\psi/\mathrm{dJ}_{x,y}$ of the particle distribution in Eq. 1 may have a strong impact on the computed SD when in the presence of diffusive mechanisms. In order to take into account these effects, the PySSD code [3], meant to numerically solve the dispersion integral for different amplitude detuning and machine configurations, has been extended to include the tracked particle distribution in the integral evaluation. At the first turn, a uniform distribution is generated at a certain position in the accelerator machine according to the geometry of that position. In order to have enough statistics, especially when in the presence of significant beam losses during the tracking, usually 10^6 particles are generated at the first turn and tracked for 10^6 turns. The initial generated distribution is uniform between 0 to 6 σ in both planes, corresponding to 0-18 $J_{x,y}$ in terms of action variables and it is weighted with a bi-dimensional exponential function before the integration.

Effects of Machine Non-Linearities

In the presence of strong machine non-linearities, the beam particles may be subject to diffusion mechanisms under the effects of excited resonances. SixTrack simulations have been performed for different octupole currents at the LHC injection energy (450 GeV) at collision tunes ($Q_x \sim 64.31$, $Q_y \sim 59.32$) for a normalized beam emittance of $\epsilon = 2.0\,\mu\mathrm{m}$ in both planes. In the presence of octupole magnets as the only source of tune spread in the beams, the detuning with amplitude is linear in the transverse actions [2]. The corresponding linear detuning coefficients for an octupole current of 6.5 A, 26 A, and 35 A have been considered for the evaluation of the detuning with amplitude $\omega_{x,y}(J_x, J_y)$. Figure 1 shows the tracked particle distribution for the highest octupole current used $I_{oct} = 35$ A (Fig. 1a) together with the corresponding SD (Fig. 1b). The solid black line corresponds to the computed SD for a Gaussian distribution. The blue and red lines represent the computed SD from the tracked distribution in the horizontal plane and in the vertical plane respectively. Increasing the octupole current, the stability area increases due to the larger spread in the beams. For the case of 6.5 A, the particle distribution is almost uniform and any important changes in the computed

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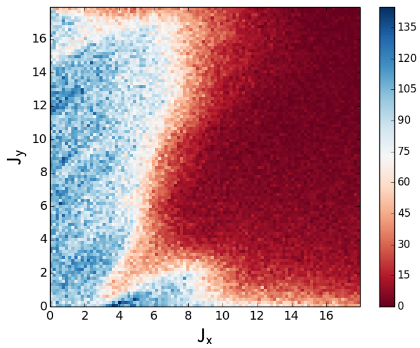
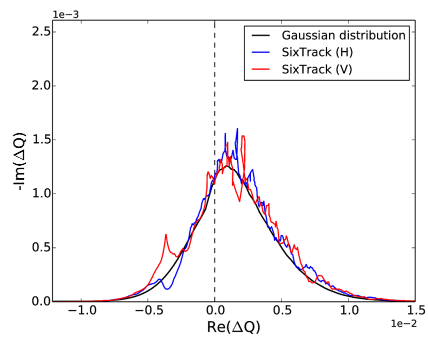
ISBN 978-3-95450-182-3



(a) Tracked distribution with an octupole current of 35 A.



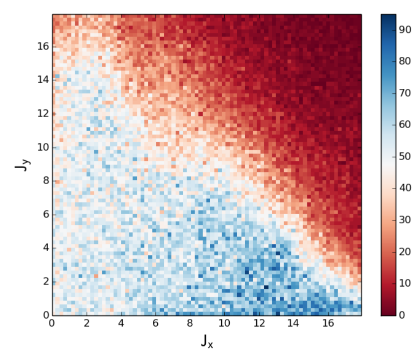
(b) Computed SD with an octupole current of 35 A.

Figure 1: Particle distribution from SixTrack tracking at injection energy for an octupole current of 35 A together with the corresponding SD. The solid black line corresponds to the computed SD for a Gaussian distribution. The blue and red lines are the computed SD from the tracked particle distribution in the horizontal plane and in the vertical plane respectively. The color bar in the distribution plot represents the number of particles per bin.

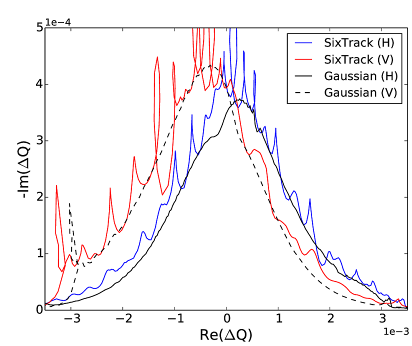
SD are visible w.r.t. to the Gaussian distribution case. Particle losses become more important while increasing the octupole current, and for 35 A, the particle distribution is affected by losses of ≈ 57% and a cut in the horizontal SD becomes visible on the side corresponding to the negative coherent tune shifts (Fig. 1b). Increasing the tune spread in the beams is beneficial for the Landau damping properties of the beams as long as any diffusive mechanism is not present. In this case the particle distribution modification can deteriorate the stability diagram.

Effects of Beam-Beam Interactions

In the LHC the Landau octupoles are turned on during the operational cycle in order to provide beam stability through Landau damping mechanisms [2] . The spread provided by the Landau octupoles can be affected by other sources of machine non-linearities such as the beam-beam interactions. At the end of the betatron squeeze, due to the reduced β^* at the IPs, the beam-beam long range interactions are stronger and can modify the spread provided by the octupole magnets. In order to investigate the effects of the long range interactions on the particle distributions, and therefore on the computed SD, SixTrack simulations have been performed for nominal and reduced (full) crossing angles α_c in IP1 and IP5 ($\alpha_c = 370$ µrad, $\alpha_c = 270$ µrad and $\alpha_c = 210$ µrad) with positive octupole polarity ($I_{oct} = 470$ A) for the LHC 2016 machine configuration at the end of the betatron squeeze with $\beta^* = 40$ cm. Reducing the crossing angle, the separation of the beam-beam long range encounters reduces enhancing their effects. Simulations have been carried out for a normalized beam emittance $\epsilon = 1.8$ µm (corresponding to the experimental conditions during the Machine Development study described in [7]). In this configuration the long range separations are: 14.5 σ, 10.6 σ and 8.24 σ for the respective crossing angle used. Figure 2 shows the tracked distributions in action variables (J_x, J_y) for the smallest crossing angle used $\alpha_c = 210$ µrad (Fig. 2a) and the corresponding SD (Fig. 2b). By reducing the crossing angle the overall tune spread increases, giving as a result a larger stability diagram. This is because in the presence of positive octupole polarity the spread given by the machine non-linearities and the beam-beam long range interactions add up to each other. Evident modifications in the tracked particle distribution

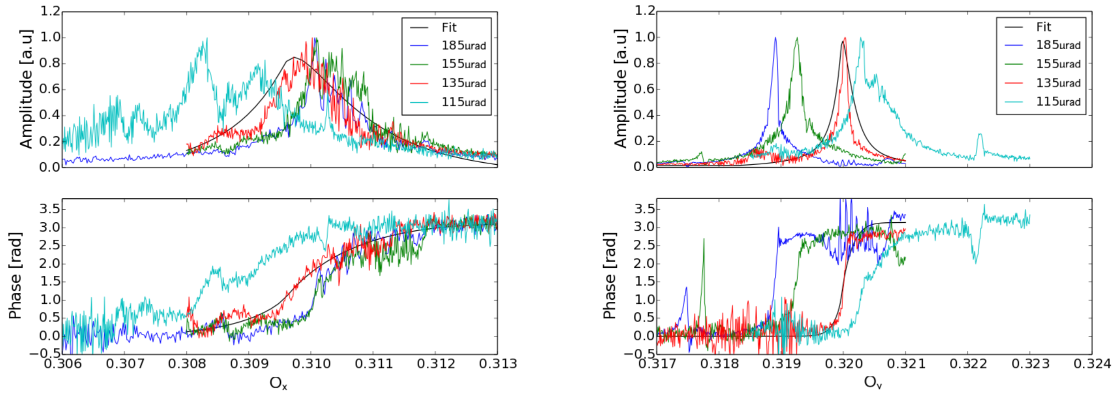


(a) Tracked particle distribution with $\alpha_c = 210$ µrad in IP1 and IP5.



(b) Computed SD from tracked distribution with α_c = 210 µrad in IP1 and IP5.

Figure 2: Particle distribution from SixTrack tracking and computed SD for a reduced (full) crossing angles in IP1 and IP5 ($\alpha_c = 210$ µrad) at the end of the betatron squeeze (LHC 2016 configuration). The solid and dashed black lines correspond to the computed SD for a Gaussian distribution in the horizontal and vertical plane respectively. The blue and red lines are the computed SD from the tracked particle distribution in the horizontal plane and in the vertical plane respectively. The color bar in the distribution plot represents the number of particles per bin.



(a) BTF response in the horizontal plane.

(b) BTF response in the vertical plane.

Figure 3: Measured BTF for Beam 1 for different crossing angles in IP1 and IP5. The given crossing angle values are half of the crossing angle at the IPs.

are clearly visible in Fig. 2a w.r.t. the initial uniform distribution. However only the large amplitude particle are lost ($J_x = J_y \approx 10 - 8\ \sigma$) without giving any remarkable deformation on the computed SD. Including multipolar errors in the model could result in a more important deterioration of the particle distribution.

In the LHC transverse BTF measurements have been acquired at the end of the betatron squeeze as a function of the crossing angle in IP1 and IP5. The BTFs provide a direct measurement of the SD since BTF $\propto$ SD^{-1}. The BTFs are sensitive to the detuning with amplitude as well as to the particle distribution changes. The beam amplitude and phase responses are shown in Fig. 3 as a function of the crossing angle in IP1 and IP5 simultaneously changed in the two IPs. An unexpected asymmetric response was observed between the horizontal (left plot) and the vertical plane (right plot). In particular the vertical plane seems to be less affected by the long range interactions in terms of tune spread w.r.t. the horizontal plane while decreasing the crossing angle. A larger tune shift is observed in the vertical plane for the first crossing angle changes. The black line corresponds to a fit function applied for the case with $\alpha_c = 270\,\mu$rad giving a factor 2.5 w.r.t. tune spread expected in the horizontal plane in this configuration and a factor 0.3 w.r.t. the tune spread expected in the vertical plane. The tracked particle distribution for different crossing angles can not explain such asymmetric response between the horizontal and the vertical plane. Other mechanisms need to be included in the models to explain the observed asymmetric behavior in the two planes at the end of the betatron squeeze. A possible mechanism could be the linear coupling [8]. Tune footprints are shown in Fig. 4 for different C^- values at the end of the betatron squeeze ($\epsilon = 1.8\,\mu$m) for the 2016 LHC machine configuration. The footprint gets distorted when the linear coupling increases. The particles towards the diagonal are pushed away from having $Qy \approx Qx$ and an asymmetry is visible between the horizontal and the vertical detuning.

CONCLUSION

The particle distribution may affect the SD shape when in the presence of diffusion mechanisms due to non-linearities such as beam-beam interactions or Landau octupoles. At injection energy with a large octupole current (35 A) an effect from the tracked particle distribution on the computed SD has been observed, producing a cut of the SD in the horizontal plane on the side of negative coherent tune shifts (Fig. 1b). Beam Transfer Function measurements at the end of the betatron squeeze in the 2016 have shown an asymmetric behavior in terms of tune spread and tune shifts between the horizontal and vertical plane. The beam-beam long range interactions only can not produce any evident deformation on the particle distribution, even when in the presence of a reduced beam-beam long range separation of 8.24 σ (Fig. 2b). This suggests that other mechanisms must to be included in the models to explain such an asymmetric response of the beams (linear coupling or multipolar errors). As shown in Fig. 4, the linear coupling may have an impact on the detuning with amplitude breaking the symmetry between the tune spread in the two planes. Further studies are needed in order to explore, by means of BTF measurements at the LHC, the behavior of the beams when in the presence of linear coupling and beam-beam long range interplay.

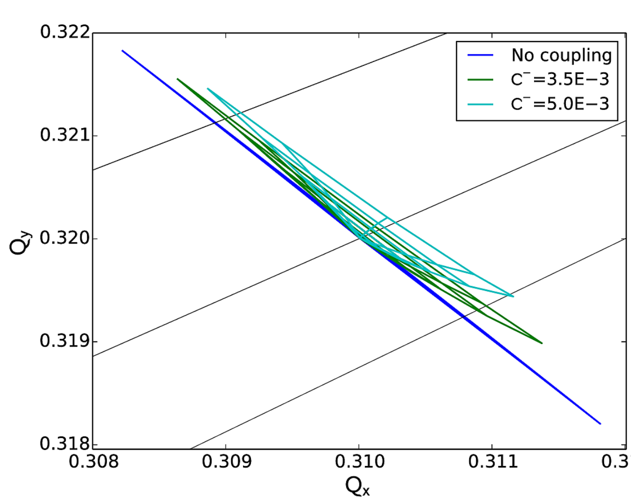


Figure 4: Tune diagram at the end of the betatron squeeze in the 2016 configuration without linear coupling (blue line) and for different C^- values.

ISBN 978-3-95450-182-3

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