HEAD-ON AND LONG RANGE BEAM-BEAM INTERACTIONS IN THE LHC: EFFECTIVE TUNE SPREAD AND BEAM STABILITY DUE TO LANDAU DAMPING

X. Buffat, EPFL, Lausanne, Switzerland and CERN, Geneva, Switzerland
W. Herr, E. Métral, N. Mounet, T. Pieloni, CERN, Geneva, Switzerland

Abstract

We discuss the Landau damping of coherent instabilities in the presence of betatron tune spread. This tune spread can originate from dedicated non-linear magnets such as octupoles, or through the beam-beam interaction. In the latter case we have to distinguish the contribution from head-on and parasitic beam-beam interactions and the collision pattern of different bunches plays an important role. The interplay of these sources of tune spread and the resulting stability is discussed for the case of the LHC.

INTRODUCTION

The effect of Landau damping originating from lattice non-linearities is usually evaluated by the means of stability diagrams [1]. In the presence of linear detuning, e.g. from octupolar magnetic component, and considering a Gaussian transverse beam distribution, the stability diagram can be computed analytically. This is no longer possible when considering detuning originating from beam-beam interactions in configurations as complex as those encountered in the LHC. The computation of stability diagram can however be addressed numerically [2, 3].

NUMERICAL EVALUATION OF STABILITY DIAGRAM

Considering a case without coupling, the stability diagram of each plane is obtained by solving the following dispersion relation for a given detuning $q(J_x, J_y)$ and distribution function $\psi(J_x, J_y)$ where J_x and J_y are the unperturbed action in each plane,

$$\frac{-1}{\Delta Q_i} = \iint\limits_0^\infty \frac{J_i \frac{d\psi}{dJ_i}}{Q - q_i(J_x, J_y)} dJ_x dJ_y,\ Q \in \mathbb{R},\ i = x, y.$$

The ΔQ_i found for different values of Q are the complex tune shifts at the limit of stability, therefore, they define an area in which the coherent modes are stable. The dispersion integral can then be evaluated by standard numerical techniques, in our case by adding a vanishing complex part to the denominator. A code was developed to solve such integrals, taking as input amplitude detuning numerically evaluated by tracking simulation, with MAD-X [4], in arbitrarily complex configuration, including beam-beam interactions and lattice non-linearities. As opposed to an analytical computation, it it also possible to use any type of distribution function. Applications to real LHC configurations are presented.

LONG-RANGE INTERACTION

In the LHC, the effect of Long-Range (LR) interactions becomes a significant component of the beams dynamics during the squeeze. The effect on the tune footprint and consequently on the stability diagram is shown on Fig. 1. Before the squeeze, the non-linearities are dominated by octupolar magnets, which can be powered with two polarities. The impedance induced tune shifts expected in the LHC have negative real parts, therefore the negative polarity is preferable in the configuration before the squeeze, when LR interactions are negligible [5]. With this polarity, however, the effect of LR is detrimental, leading to a reduction of the stability during the squeeze. The opposite is true for the other polarity. The choice of the polarity of the octupole results in a compromise between stability before and after the squeeze. The observation of instabilities at the end of the squeeze during the 2012 run of the LHC motivated the use of the positive polarity [6]. The instability at the end of the squeeze was, however, still visible after this change of configuration, indicating that the LR contribution to the stability diagram is not a satisfactory explanation for these instabilities.

HEAD-ON INTERACTION

The tune spread due to Head-On (HO) collision is usually larger than the one due to octupoles or LR. Moreover, the detuning is more important on the core of the beam rather than the tails, which significantly enhances its contribution to the stability diagram, as shown by Fig. 2. This indicates that bunches colliding HO should be stable, without requiring other stabilizing techniques, such as non-linear magnets or transverse feedback. In 2012, the LHC configuration included few bunches without HO collision, enforcing the usage of octupoles and the transverse feedback during luminosity production [7]. As these techniques may have detrimental effects on the luminosity lifetime, there is an interest in reducing their needs, by ensuring one HO collision for every bunch.

Also, the stabilizing effect of HO collision may be used to stabilize the beams earlier in the operational cycle, in particular before the end of the squeeze, as discussed in [8].

INTERMEDIATE SEPARATIONS

There are configurations during which the beams collide with intermediate separations, of a few σ (RMS beam

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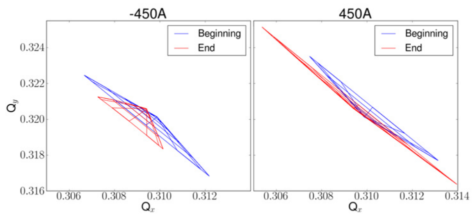
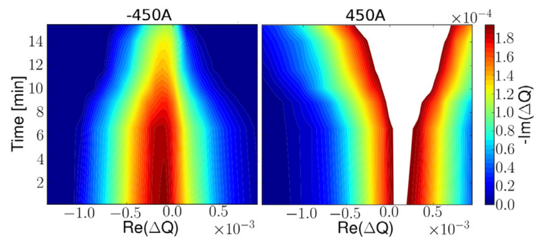


(a) Tune footprints before and after the squeeze.



(b) Maximum imaginary part of the tune shift of a stable mode as a function of its real tune shift (i.e. stability diagram) and the time during the 2012 squeeze [9].

Figure 1: Analysis of the stability during the squeeze for both octupole polarity (±450 A). The β^*at $t = 0$ are 11 m in IP1&5 and 10 m in IP2&8, at the end 0.6 m and 3 m respectively. This analysis considers the most common bunch, with the largest number of LR interactions. The effect is similar but of lower amplitude for bunches with a lower number of LR.

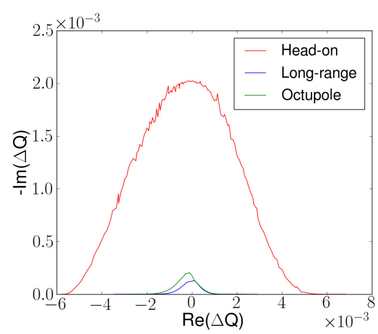


Figure 2: Comparison of stability diagrams from either octupoles powered with -450A, LR in IP1&5 or HO in IP1&5, with LHC 2012 parameters.

size), e.g. when bringing the beams into collision and while leveling luminosity with a transverse offset. As shown on Fig. 3, the tune spread, while reducing the separation, changes sign, which has a significant effect on the stability diagram (Fig. 4). In particular, there exists a minimum of stability for separations in the order of 1 to 2 σ. The exact separation, and the amplitude of this minimum depends on the configuration. Nevertheless, in the four configurations considered on Fig. 4, the stability is most critical between 1 and 2 σ transverse separation.

Bringing the beams into collision takes several seconds in the LHC, as the separation bumps are ensured by superconducting magnet. When going as fast as possible to

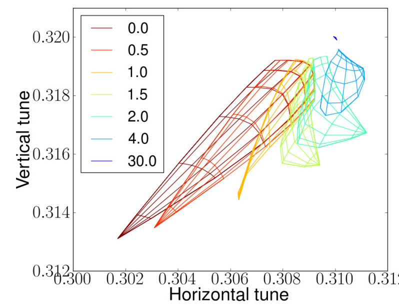
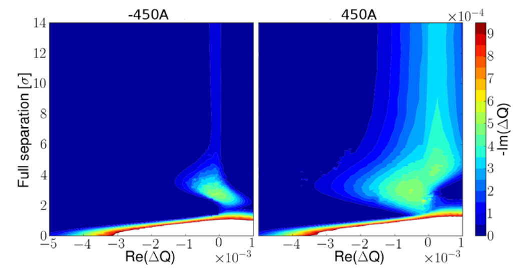
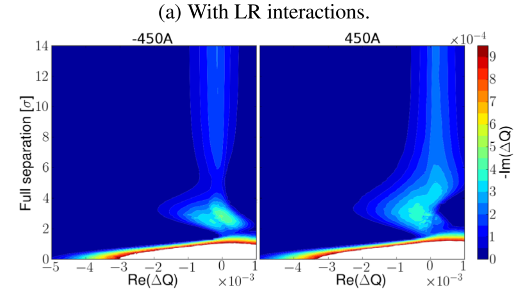


Figure 3: Example of tune footprint of a bunch colliding in IP1 with different (full) separations in the horizontal plane.



(a) With LR interactions.



(b) Without LR interactions.

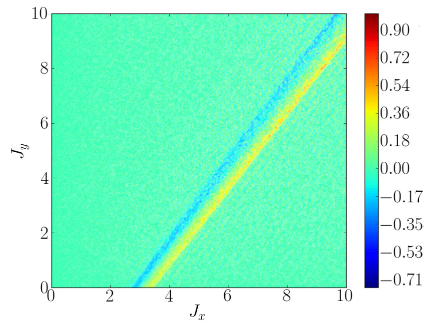
Figure 4: Stability diagram as a function of beam separation in IP1&5 for a bunch with either maximum number of LR interactions or none, and both polarity of the octupoles.

HO collision, the time spent at the minimum of stability is smaller than the rise time of expected instabilities. If this condition would not be met, instabilities could be observed while bringing the beams into collision, as presented in [6].

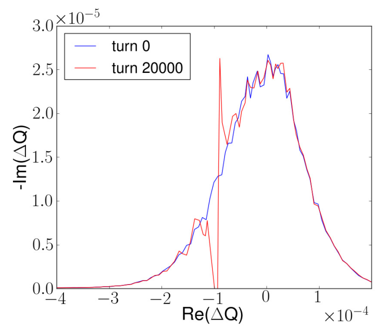
When leveling luminosity with a transverse offset, a significant time is spent at intermediate separations. In this case, the stability has to be ensured by other means, e.g. by colliding HO at another Interaction Point (IP), using lattice non-linearities and/or by the means of a transverse feedback.

PERTURBED DISTRIBUTIONS

The beam distribution function plays a crucial role in the computation of the stability diagram and is usually poorly known experimentally. A Gaussian distribution is usually assumed, whereas not always justified by measurement [10]. The effect of distribution with tails cut have been con-



(a) Relative difference to initial distribution in action space after $2 \cdot 10^4$ turns.



(b) (Un)perturbed stability diagrams.

Figure 5: Stability diagram derived from a distribution perturbed by external noise in the presence of amplitude detuning. The noise is a sinusoidal excitation with a correlation time of a 100 turns.

sidered in [11], here we consider the effect of a distribution perturbed by external noise. Figure 5 shows such a distribution obtained by tracking simulation with linear detuning and a sinusoidal excitation of finite coherence. As expected [12], the diffusion has been enhanced for resonant particles, creating under/over populated areas in the distribution. The stability diagram, being a function of the derivative of the distribution function is very sensitive to such modifications, resulting in a hole in the stability diagram (Fig. 5b).

While very simple, this model gives an insight in the difficulty to probe the beam stability experimentally, as modifications out of measurement reach can dramatically deteriorate the stability. In fact, non-measurable modifications of the distribution have often been invoked to explain discrepancies in stability measurement in the LHC [11, 13].

Different mechanisms can be envisaged to create such modification of the distribution, on going studies suggests that configurations where both a transverse feedback and amplitude detuning are required to ensure the beam stability can be critical in the presence of wideband noise [3].

CONCLUSION

Stability diagrams are derived numerically in arbitrarily complex configurations including beam-beam interactions and lattice non-linearities, allowing to treat real LHC configurations. In particular, it was found that the stability due to octupoles can be deteriorated or improved by the incoherent effect of LR interactions, depending on the polarity of the octupoles. Also, the stability of the beams was found to be critical for separations in the order of the beam size, having an impact on the strategies to ensure the stability of all bunches, in particular when leveling luminosity with a transverse offset.

HO collisions are shown to be more effective to provide Landau damping than other sources of detuning, to the point that other stabilizing techniques are no longer required for bunches experiencing at least one HO collision.

While a powerful tool, the concept of stability diagram rely on a good knowledge of the beam distribution function, which is usually poorly known. It was shown that non-measurable modifications of the distribution, caused by the external sources of noise, can compromise the stability.

REFERENCES

[1] J.S. Berg and F. Ruggiero, "Landau Damping with Two-Dimensional Betatron Tune Spread," CERN SL-AP-96-71 (AP) (1996).

[2] W. Herr, *et al.*, Tune Distributions and Effective Tune Spread from Beam-Beam Interactions and the Consequences for Landau Damping in the LHC, LHC Project Note 316 (2003).

[3] X. Buffat, *et al.*, "Stability Diagram of Colliding Beams," Proceedings of the ICFA Mini-Workshop on Beam-Beam effects in Hadron Colliders, Geneva, 2013.

[4] http://mad.web.cern.ch/mad

[5] J. Gareyte, *et al.*, "Landau Damping, Dynamic Aperture and Octupoles in LHC," 1997, CERN LHC Project Report 91 (revised)

[6] T. Pieloni, *et al.*, "Observations of Two-beam Instabilities during the 2012 LHC Physics Run," TUPFI034, these proceedings.

[7] W. Herr, *et al.*, "Observation of Instabilities in the LHC due to Missing Head-on Beam-beam Interactions in the LHC," TUPFI032, these proceedings.

[8] X. Buffat, *et al.*, "Colliding During the Squeeze and β^* Leveling in the LHC," TUPFI033, these proceedings.

[9] S. Redaelli, *et al.*, "Operation of the Betatron Squeeze at the LHC," TUPFI038, these proceedings.

[10] S. Redaelli, *et al.*, "Experience with High-intensity Beam Scraping and Tail Populations at the LHC," MOPWO039, these proceedings.

[11] E. Métral, *et al.*, "Stability Diagram for Landau Damping with a Beam Collimated at an Arbitrary Number of Sigmas," CERN-AB-2004-019-ABP.

[12] A. Bazzani, *et al.*, "Diffusion in Hamiltonian systems driven by harmonic noise," J. Phys. A: Math. Gen. 31 (1998).

[13] N. Mounet, *et al.*, "Single-beam measurements of LHC instability threshold in terms of octupole current," CERN-ATS-Note-2012-073 MD.

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