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SLOW VS FAST LANDAU DAMPING THRESHOLD MEASUREMENTS AT THE LHC AND IMPLICATIONS FOR THE HL-LHC

X. Buffat*, L. Giacomel and N. Mounet, CERN, Geneva, Switzerland

Abstract

The mechanism of Loss of Landau Damping by Diffusion (L2D2) was observed in dedicated experiments at the LHC using a controlled external source of noise. Nevertheless, the predictions of stability threshold by L2D2 models are plagued by the poor knowledge of the natural noise floor affecting the LHC beams. Experimental measurements of the stability threshold on slow and fast time scales are used to better constrain the model. The improved model is then used to quantify requirements in terms of Landau damping for the HL-LHC.

INTRODUCTION

At the LHC flat top, the Landau octupoles are usually powered with about twice the current predicted by the stability diagram theory [1] based on an unperturbed Gaussian distribution and complex tune shifts predicted by DELPHI [2] following on the LHC impedance model [3]. When performing dedicated experiments to assess the instability threshold by varying the octupole strength, it seemed that the agreement between experimental data and model was good when the octupole was varied on the time scale of minutes. While the (twice) higher threshold was seen when varying the octupoles on the scale of tens of minutes. This slow time scale is the relevant one for operation, since few tens of minutes are usually elapsed between the arrival at top energy and the establishment of collisions. Once in collision, the tune spread is dominated by the contributions of beam-beam interactions, providing large stability margins.

In this slow time scale, the diffusion induced by external sources of noise changes the particle distribution and thus affects Landau damping. The existence of coherent modes stabilised by Landau damping leads to local diffusion depleting the areas of phase space which are generating damping for the coherent modes. Eventually, the distorted distribution no longer provides Landau damping, thus leading to an instability through a Loss of Landau Damping by Diffusion (L2D2) [4,5]. We present here an experiment which directly compares the result of an instability threshold measurement using either a slow or fast octupole scan in identical conditions. The results and the caveat of this experiment are then discussed based on comparison with numerical simulations of L2D2 using the code PyRADISE [6]. Finally, the implications for HL-LHC and possible mitigation strategies are discussed.

MEASUREMENT

In two consecutive cycles, 3 bunches per beam were brought to top energy (6.8 TeV) and kept with a fixed optics ($\beta^* = 1.33$ m). The bunches were placed such that they never meet in common chambers, thus preventing beam-beam effects. They were spaced longitudinally with more than 10 μs, thus preventing electron cloud effects and limiting the effect of long-range wakefields to the minimum. After the instability threshold measurement, the chromaticity was measured to 11 ± 1 units using an energy modulation.

The octupoles [7] were ramped down in steps of 20 A every 15 minutes for the slow scan and every 1.5 minutes for the fast one, as shown in Fig. 1a. First instabilities during the slow scan are observed at 177 A. Three bunches became unstable in the next two steps (157 and 137 A). During the fast scans, all bunches became unstable at 79 A. The evolution of the beam parameters are shown in Figs. 1b, 1c and 1d. In this regime, the horizontal stability threshold is proportional to the bunch intensity and inversely proportional to the bunch length and the vertical emittance [8]. By scaling the obtained threshold with the relevant measured quantities of each bunch, we find that the ratio between the slow and fast threshold is 2.0 ± 0.2, which is compatible with the operational experience discussed in the introduction.

DISCUSSION

We use the code PyRADISE [6] to simulate the evolution of the transverse distribution and of the stability diagram under the impact of an external noise source and the resulting diffusion due to electromagnetic wakefields. We define the instability latency as the time elapsed between the start of the simulation with an unperturbed Gaussian distribution until the point when the stability diagram reaches the complex tune shift of one of the coherent modes.

The instability latency for different detuning and noise amplitude is shown in Fig. 2. The detuning is expressed in units of the detuning on the threshold with an unperturbed Gaussian distribution. We find that a noise amplitude of $(6 \pm 2) \cdot 10^{-4}\ \sigma_{x'}$ is compatible with a threshold measured at 2.0 ± 0.2 times the unperturbed detuning for a latency below 15 minutes. This noise amplitude is 5 to 10 times higher than the one inferred from emittance growth in collision [9]. While this measurement through the emittance growth also suffers from important uncertainties, it is likely that our present measurement overestimates the amplitude of the noise experienced by the beam. We discuss two possible causes for this overestimation.

The unperturbed instability threshold obtained with the impedance model of the LHC is about 120 A, which is significantly higher than the observed threshold of 77 A in the fast scan. This difference cannot be attributed to the uncertainty on the impedance model itself, since other observables sug-

* xavier.buffat@cern.ch

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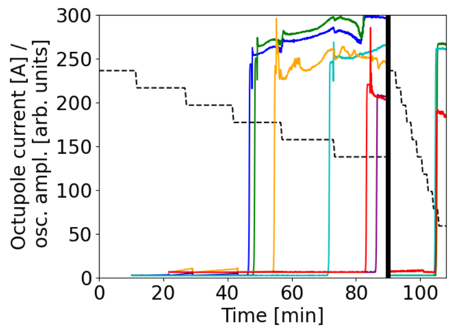

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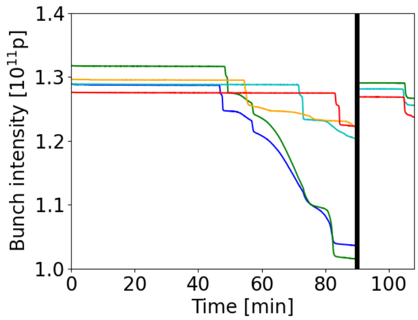

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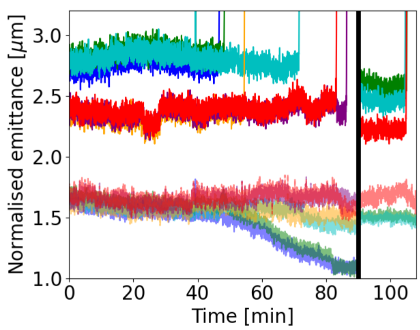

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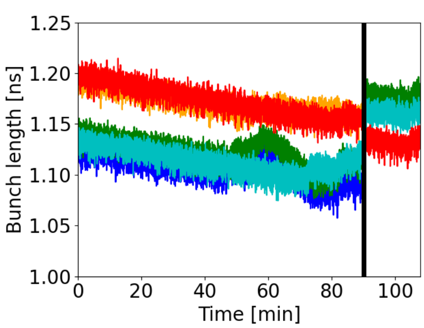

(d)

Figure 1: Measured beam parameters during the experiment. The curves corresponding to bunches in B1 are colored in blue, green and cyan, whereas curves corresponding to B2 are colored in red, orange and purple. To differentiate them from the horizontal emittances, vertical emittances in (c) are shown with shaded lines. On the top plot, the black dashed line shows the variation of the octupole current. The data corresponding to the slow and fast octupole scans are separated by a thick vertical line.

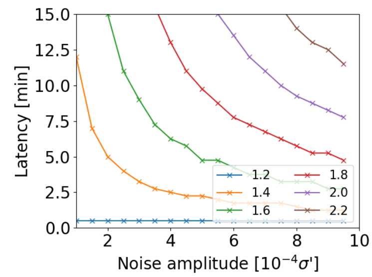

Figure 2: Instability latency obtained with PyRADISE as a function of the noise amplitude expressed in unit of the beam divergence at the location of the external source of noise. The curves are labelled with the amplitude detuning coefficient relative to the stabilising one obtained without noise.

gest that it underestimates the machine impedance by 30 to 50% [10]. This difference could however be attributed to missing components in the instability model, such as non-linear chromaticity, non-linear longitudinal focusing or the existence of a residual source of transverse detuning due to other lattice non-linearities. These aspects could impact the estimation of the machine noise and should be studied further. For example, if the presence of an external source of tune spread corresponding to the missing 43 A [11] were confirmed, the ratio between the slow and fast threshold would become 1.7 ± 0.1 and the corresponding machine noise $(3.5 \pm 1) \cdot 10^{-4}$. This remains nevertheless significantly higher than past estimations based on emittance growth.

Due to the long LHC cycle, it is not practical to measure the instability threshold with a fresh beam for each octupole settings. However the experiment presented here, with steps in octupoles, yet keeping the same circulating beam, suffers from an important caveat. In the slow scan, the beam distribution is affected at each step, thus affecting the stability at the following step. While the impact is minor when the detuning is sufficiently larger than the threshold, the second to last step is by construction close to the threshold and may therefore have an impact on the measured latency. We quantify this impact by performing PyRADISE simulations in two steps: The first one corresponds to the last stable configuration, thus featuring a high octupole strength and a fixed length of 15 minutes. The second step of the simulation corresponds to the final configuration at which the beam become unstable (i.e. featuring the lowest octupole strength). In Fig. 3, we report the latency observed in this final configuration for different relative changes of the octupole strength between the low and the high octupole configuration. Based on these simulations, we find that the relative octupole change should be larger than 15% in order to avoid a significant perturbation of the measured latency. In the experiment conducted, the second to last step ranges from +11 to +13% of the octupole current at the last step. In this regime, the measured latency may be 20% shorter than the one that would be observed without the perturbation of

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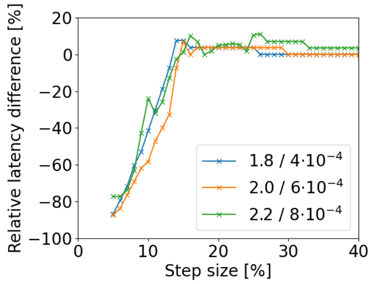


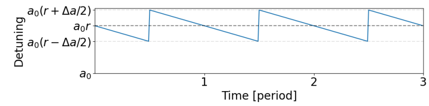
Figure 3: Impact of spending 15 minutes with a larger amplitude detuning on the measured instability latency at the next step in octupole strength. The step size corresponds to the amplitude detuning of the initial part relative to the final one. The measured latency is expressed relatively to the one obtained without the 15 minute step beforehand. The curves are labelled with the tune spread relative to the unperturbed instability threshold and the relative noise amplitude.

the second last step. If the hypothesis of an external source of spread is verified, the relative step size becomes less than 10%, and thus the measured latency would be severely affected by the previous step.

Based on this analysis, we conclude that the comparison of instability threshold measurements with slow and fast octupole scans was successful at demonstrating the importance of the instability latency to define the required strength of the Landau octupoles. However, the estimation of the relevant noise amplitude is plagued by an important uncertainty on the residual detuning of the lattice as well as the perturbation of the beam distribution during the last stable step in octupole strength. These two points could be addressed by direct measurements of the amplitude detuning and with an additional measurement of the instability latency close to the threshold with a fresh beam in a separate cycle.

IMPACT FOR HL-LHC

The current design of the HL-LHC is based on an instability margin of a factor two [8, 12], which is well justified by the experiment conducted here. Nevertheless it is assumed that such a margin should be maintained in dynamical phases of the cycle, even when the tune spread is strongly varying. This is the case, for example, during the collapse of the separation bumps which lasts only about one to two minutes and during which the tune spread drastically changes. At the start of the process, the detuning is mostly linear with the transverse actions. It is driven by lattice non-linearities, Landau octupoles and long-range beam-beam interactions. Once in collision the tune spread is dominated by the effect of the head-on beam-beam interactions. During this process, the tune spread and the corresponding stability diagrams vary in a non-trivial way [13]. While the simulation of the full process is beyond the scope of this paper, it is fair to assume that a significant local perturbation of the beam distribution will not have time to develop in such short and dynamical process. We may therefore reduce the strength of the octupoles during the process and thus improve the dynamic aperture when the collisions are established [14]. This improvement is relevant for operation, since it should help mitigating the loss spike observed when collisions are established, due to the sharp decrease of the dynamic aperture. However, given the complexity of this process, experimental validation at the LHC would be beneficial.



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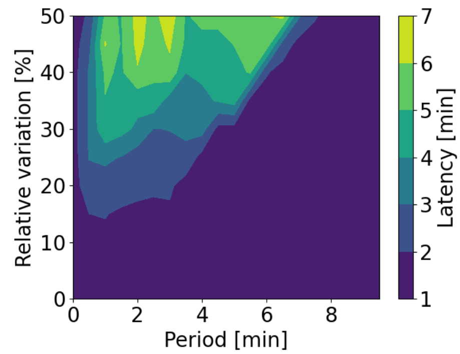

(b)

Figure 4: PyRADISE simulation of the impact of dynamical variations of the tune spread following a sawtooth function (top plot) on the instability latency. The initial detuning is 40% higher than the unperturbed instability threshold a_0 ($r = 1.4$). The peak-to-peak variation of the detuning Δa is expressed relative to the unperturbed detuning. The noise amplitude is $4 \cdot 10^{-4}$.

Mitigation with Dynamical Variations

Given that the additional tune spread required to maintain the beam stable on long time scale is due to a slowly developing local distortion of the particle distribution, it is tempting to use slow dynamical variations of the tune spread to smear the distortion and thus extend the latency. In order to evaluate the potential of such a mitigation, we implement a sawtooth variation of the spread (Fig. 4). The latency is quadrupled for relative variations in the order of 40% over a period comparable to the latency without dynamical variations (1.5 min). We note that the latency would be comparable if the detuning was instead kept constant at a detuning correpdonding to the peak of the modulation. In other words, it is possible to reduce the average strength of the octupoles for a given latency, but the peak spread remains comparable. Other dynamical variations were attempted, such as a sawtooth with a positive slope, but the sawtooth with a negative slope yields the largest extension of the latency.

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