INSTABILITY LATENCY IN THE LHC

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Abstract

The Large Hadron Collider (LHC) has experienced multiple instabilities that occur between minutes and hours after the last modification of the machine settings. The existence of instabilities with high latency has been reproduced also in simulations. Dedicated experiments, injecting a controlled noise into the beam, have now been performed to discover the dependence of this latency on key parameters. The results seem compatible with a mechanism linked to a steady and slow modification of the transverse beam distribution leading to a loss of Landau damping.

INTRODUCTION

The beams in circular colliders become more prone to destabilising effects as the beam brightness increases [1]. A substantial amount of work has been done in recent decades, which has increased the understanding of instabilities in the LHC [2]. This work has led to configuration-dependent predictions of how much Landau damping is required to keep the beams stable. There are still differences between the predictions and the measurements that remain to be understood. First of all, the Landau octupole current in operation is still about a factor 2 larger than the predicted threshold. However, it was reduced slowly towards the end of Run 2, without reaching the stability threshold. The discrepancy is larger and non-constant for a chromaticity close to 0 [3, 4].

An instability mechanism that is not accounted for in those predictions, is the possibility for a bunch to go unstable a considerable time after a given machine configuration is set. The delay is referred to as the latency of the instability. This has been measured in regular operation of the LHC and in simulations [5, 6]. The current hypothesis is that this loss of Landau damping is caused by an amplitude dependent diffusion, driven by an external noise acting equally on all particles in a bunch [7], combined with the effects of strong wakefields. An experiment dedicated to this latency of instabilities has now been performed in the LHC [8]. The goals were first to confirm the hypothesis that external noise can lead to loss of Landau damping, and next to measure the dependence of the latency on a few key machine parameters and the external noise amplitude. In the following, we will present the main outcomes on both aspects.

EXPERIMENTAL PROCEDURE

This experiment was conducted over three fills in the LHC, at two different dates. Up to 13 proton bunches per beam

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Table 1: Important Parameters During the Experiment [8].

Parameter	unit	Fill 1	Fills 2 and 3
Energy per proton	[TeV]	6.5	6.5
Trans. norm. emitt.	[μm]	1.33	1.42
Intensity	$[10^{11}$ p/b]	0.91	1.10
Bunch length, $4\sigma_s$	[ns]	1.12	1.07
Trans. tunes, (Q_x, Q_y)	[mod 1]	(0.275,0.295)	(0.275,0.295)
RMS trans. detuning [1]	[1]	5.0×10^{-5}	5.3×10^{-5}
Synchrotron tune, Q_s	[1]	0.002	0.002
Revolution frequency	[kHz]	11.245	11.245
Total RF Voltage	[MV]	12	12

[1] Due to octupoles at $I_{oct} = 400$ A, for bunches with the listed average transverse normalised emittance and energy. Equal in both transverse planes.

were injected into the machine, with separations of 5.25 μs or more [8], and accelerated to flat top under nominal conditions in all three fills. Due to the large separations, we could avoid all beam-beam interactions. A few key parameters are listed in Table 1.

The LHC transverse feedback system was used as a feedback and to act on the bunches as an external source of white noise up to 40 MHz, which was Gaussian in the time domain. For a given machine configuration, a group of 4 bunches was acted on with noise of different amplitudes. Then we waited for these bunches to go unstable. An example of this process is presented in Fig. 1. Different machine configurations were tested systematically. In fill 1, the octupole current, I_{oct}, was varied; in fill 2, the chromaticity, Q', was varied; in fill 3, the transverse feedback gain, g, was varied, corresponding to a damping time, $\tau_g = 2/g$, in number of turns. In fill 1 the noise only acted horizontally, while in fills 2 and 3 the noise
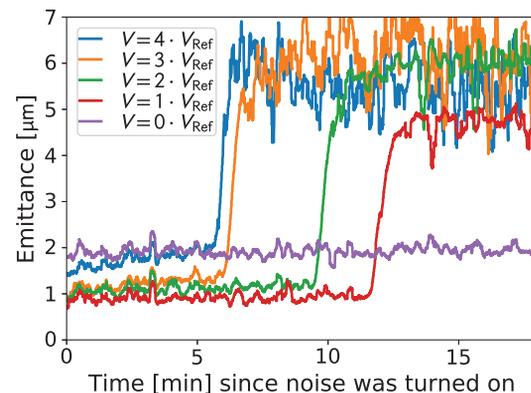

Figure 1: Evolution of normalised horizontal emittance for 5 bunches in beam 2, with linearly spaced external noise amplitudes. $I_{oct} = 452$ A, $Q' \approx 15$, and $\tau_g \sim 200$ turns.

acted on both transverse planes. The external background noise in the machine was assumed to be negligible compared to the applied noise. This was later supported by analysing the emittance growth rates.

If the latencies for a given configuration were too high, the current in the Landau octupoles was reduced stepwise, to measure how much the stability threshold had changed in a given time. The difference between the octupole current when the bunches went unstable, $I_{\text{oct,thr}}^{\text{emp}}$, and the predicted octupole stability threshold, $I_{\text{oct,thr}}^{\text{the}}$, is named $\Delta I_{\text{oct,thr}} = I_{\text{oct,thr}}^{\text{emp}} - I_{\text{oct,thr}}^{\text{the}}$. The predictions have been calculated with DELPHI [9], assuming a Gaussian distribution with the measured intensity, emittances and bunch length at the time the noise was turned on. The rate of change of the stability threshold will be presented as $\Delta I_{\text{oct,thr}}/\tau_{\text{noise}}$, where τ_{noise} is the time during which a given bunch was affected by the external noise before it went unstable.

RESULTS

The main hypothesis that was tested in this experiment, was if external noise could cause a bunch to go unstable at a higher octupole current than the predicted stability threshold current. In a configuration with $I_{\text{oct}} = 452$ A and a maximum noise voltage $4V_{\text{Ref}}$ corresponding to about $6 \times 10^{-4}\,\sigma_{x'}$, the emittances of a group of bunches in beam 2 evolved as in Fig. 1. The maximum noise amplitude was found from the measured emittance growth rates, and it is within the

uncertainty of the available kicker voltage measurement. The bunches became unstable in order of decreasing noise, while the bunch not affected by the external noise did not go unstable. A similar trend has been seen in simulations. The predicted stability thresholds, for the four bunches that did go unstable, were $I_{\text{oct,thr}}^{\text{the}} = [193\,\text{A}, 234\,\text{A}, 235\,\text{A}, 257\,\text{A}]$, in order of decreasing noise. The thresholds depend on the intensities, emittances and lengths of the bunches.

Different octupole currents were tested with two groups in beam 2, for $Q' \approx 15$ and $\tau_g \sim 200$ turns. The latency is presented in Fig. 2a, it was higher for a higher octupole current, as it also was found to be in simulations [6]. The rate of change of the stability threshold is presented in Fig. 2b, being higher for a lower octupole current.

Different chromaticities were tested with three groups in both beams. The chromaticities were set to be $Q' \in \{0, 5, 15\}$, but were spread around these values by $2 - 4$ units in both planes of both beams, according to measurements at the end of the fill. The rate of change of the stability thresholds for both beams are presented in Fig. 3. Here we found a non-monotonic trend in both beams, the rate was high for $Q' \approx 0$, low for $Q' \approx 15$ and negligible for $Q' \approx 5$.

The dependence on the feedback gain was also scanned with multiple groups. At low gains, zero bunches went unstable while affected by the noise. The noise was therefore turned off, and the gain was increased to test a new group. Many of the bunches tested at low feedback gains became
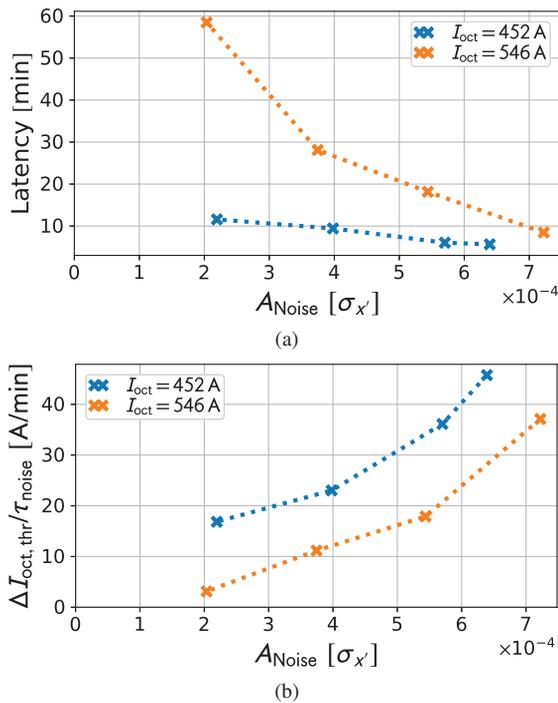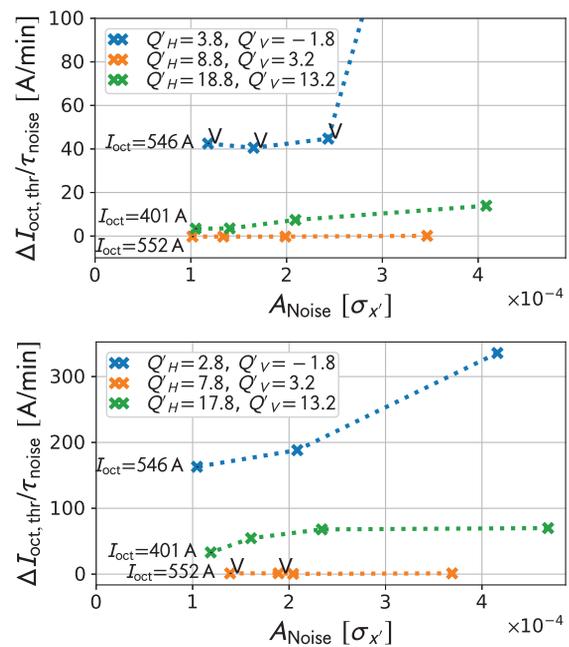

(a)

(b)

Figure 2: Scan of octupole current in beam 2, with a chromaticity $Q' \approx 15$ and damping time $\tau_g \sim 200$ turns in both transverse planes. The values for I_{oct} when the noise was turned on is given in the legends. (a) shows the latency. (b) shows the rate of change of the stability threshold.

Figure 3: Scan of chromaticity in both beams. Beam 1 is on top, where the last point is at $(4.7 \times 10^{-4}\,\sigma_{x'}, 404\,\text{A/min})$. Beam 2 is below. The points marked with a 'V' became unstable vertically. The values for I_{oct} when the noise was turned on are annotated next to the lines. The damping time was $\tau_g \sim 200$ turns.

unstable shortly after the gain was increased to the nominal, corresponding to $\tau_g \sim 200$ turns. However, no clear trend could be observed in the rate of change of the stability threshold [8]: at a low noise amplitude the rate was higher with a low gain, while at a high noise amplitude, the rate was higher with a high gain.

DISCUSSION

We did in this experiment manage to lose Landau damping by applying an external noise. One expects the emittance to grow in the presence of noise, which we did measure. Neglecting any modification of the particle distribution, the stability threshold octupole current should then have been reduced. Here it was increased significantly, currently believed to be due to a modification of the distribution through an amplitude dependent diffusion. As the change is driven by the noise, it was expected that the rate of change would be higher for a higher noise.

The distribution changes due to the noise, in presence of only the transverse feedback and amplitude detuning from the octupoles. However, this effect seems to be too slow to explain the results of the experiment discussed here [7]. Based on simulations, it seems that the effect of the wakefields is critical in this mechanism. In particular, in a simulation including external noise and a model for the impedance in the LHC, the relative change of the distribution, shortly before a bunch went unstable, is visualised in Fig. 4 [6]. The diffusion is enhanced for particles resonant with the coherent modes, driven by wakefields, that are closest to their stability thresholds. A similar distribution change is known to dig a hole in the stability diagram [5]. Therefore, it appears that a key ingredient in this mechanism is the noise induced coherent motion, and the resulting amplitude dependent diffusion.

The experiment confirmed that with a higher I_{oct}, it takes longer to lose Landau damping. Moreover, with a lower I_{oct}, when the bunch is closer to its stability threshold, the rate of change of the stability threshold is higher. This supports the idea that the noise induced coherent motion, of the modes closest to their stability thresholds, participates strongly in this mechanism.

In this experiment it was found that the rate of change of the stability threshold was by far highest for $Q' \approx 0$. As referred to in the introduction, there is a larger mismatch between the empirical and predicted stability threshold for such chromaticities, which could be explained by this mechanism. However, the high rate can also be the result of an underestimation of $I_{oct,thr}^{the}$ [4]. Therefore, this behaviour has to be confirmed with another experiment with a larger octupole current in this configuration.

Finally, the latency seemed to be lower with a higher feedback gain in the experiment, at odds with simulations with an ideal feedback, where the latency was proportional to the feedback gain [6]. This apparent discrepancy might be explained by the additional noise introduced by the feedback itself, but requires further studies.

SUMMARY

In this experiment it was successfully shown that Landau damping can be lost due to external noise. This instability mechanism might explain why it is typically necessary to use an octupole current in the LHC about a factor 2 larger than what is predicted from a stability diagram approach.

The latency of the instabilities, which is the time from the external noise was turned on to the time when the bunches became unstable, have some dependencies on key machine parameters. A higher noise amplitude leads to a lower latency. A higher octupole current leads to a higher latency. The dependence on chromaticity was non-monotonic, the latency was highest with $Q' \approx 5$, intermediate with $Q' \approx 15$ and lowest with $Q' \approx 0$. A higher feedback gain seemed to lead to a lower latency in the experiments. The latter is not compatible with results obtained in simulations, but might be explained by the noise introduced by the feedback, and requires further studies.

Another measurement presented was the rate of change of the stability threshold octupole current from the predicted value, assuming a Gaussian bunch, to the value of I_{oct} when the bunch actually went unstable. These values are more straightforward to compare than the pure latencies, as they filter out dependencies on a few bunch-to-bunch and group-to-group variations. The rate of change was higher with a higher noise amplitude. It was lower with a higher octupole current, implying that the process is faster as the instability threshold is approached. The dependence on chromaticity was again non-monotonic, the rate of change was negligible for $Q' \approx 5$, larger for $Q' \approx 15$, and largest for $Q' \approx 0$. The dependence on the feedback gain could not be properly resolved experimentally. Note that no bunch went unstable while the LHC was operated with a gain lower than the nominal one, although they were acted upon by noise at such gains. This was not expected, and will require further analysis to be understood.
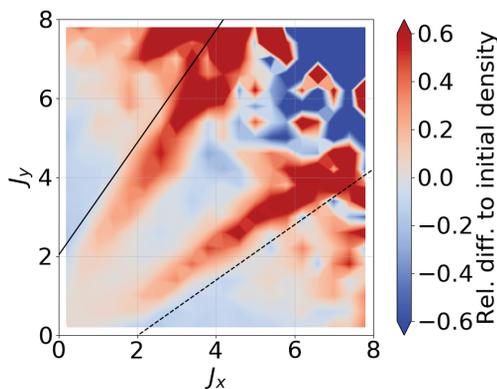

Figure 4: Relative change of the bunch distribution from an initially Gaussian bunch, in normalised transverse action space (J_x, J_y), in a simulation including external noise and impedance. The black solid (dashed) line shows the actions that correspond to the most unstable mode in the horizontal (vertical) plane. Courtesy of X. Buffat [6].

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