

# IMPACT OF LANDAU DAMPING FROM OCTUPOLES ON INSTABILITY GROWTH RATES MEASURED IN THE LHC\*

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## Abstract

Dedicated instability studies were performed in the LHC to quantify the impact of Landau octupoles on transverse beam stability. Controlled single-bunch instabilities were intentionally triggered at injection energy, and the corresponding growth rates were measured while systematically varying the Landau octupole knob. A clear correlation between the octupole current and the measured instability growth rate was observed. These measurements are compared with theoretical expectations to improve and benchmark the real part of the LHC impedance model, in particular its broadband component. The results not only provide valuable input for refining the impedance model, but also represent a direct quantitative observation of Landau damping in the LHC.

## INTRODUCTION

The beam coupling impedance, which characterizes the electromagnetic interaction between the beam and its surrounding environment, can lead to an exponential growth of coherent oscillations of the beam centroid, potentially resulting in beam degradation or loss [2]. Impedance-driven instabilities therefore represent a potential limitation on the achievable proton bunch intensity in both the Large Hadron Collider (LHC) and its high-luminosity upgrade (HL-LHC), making it essential to accurately estimate, monitor, and control the machine impedance over time.

The machine impedance can be experimentally probed through instability measurements. In particular, the growth rate of transverse instabilities is directly related to the real part of the transverse impedance [2]. The stability of the beam is ensured through a combination of Landau damping, chromaticity, and transverse feedback systems. Landau damping plays a central role in stabilizing the beam by introducing a spread in betatron frequencies, which suppresses the coherent motion. In the most critical phase for stability in the LHC, i.e. at flat top before collisions are established, the tune spread is primarily generated using Landau octupole magnets. By adjusting the octupole current, the strength of the nonlinear detuning, and therefore the amount of Landau damping, can be controlled.

In order to measure instability growth rates in a controlled and quantitative manner, it is necessary to operate in a regime where Landau damping is minimized. In previous measurements, the presence of strong Landau damping prevented the

observation of clear exponential growth, limiting the precision of the measurements [1]. Therefore, a dedicated experimental strategy was developed to reduce the stabilizing effect of octupoles while maintaining controlled beam conditions. Because of the operational constraints associated with performing such measurements at top energy, the experiments presented in this work are carried out at injection energy, where rapid cycling and improved reproducibility can be achieved. Although the impedance at injection is dominated by fixed-aperture elements rather than collimators, the latter can be tightened to partially reproduce a configuration closer to that at top energy [1]. This approach enables systematic and repeatable measurements while retaining sensitivity to the dominant impedance contributions, both at top energy (collimators) and at injection (fixed-aperture devices).

In this paper, we present a systematic study of instability growth rates measured under conditions of minimized Landau damping, ensuring controlled instabilities and characterizing them as a function of chromaticity, bunch length, and collimator settings. The results are compared with theoretical predictions, providing valuable input for benchmarking the LHC impedance model.

## STRATEGY FOR INSTABILITY MEASUREMENTS

The measurements presented in this study were performed on September 4<sup>th</sup>, 2025, at injection energy (450 GeV), allowing fast, reproducible instability excitation. Although impedance-driven instabilities are more critical at top energy, their characterization is significantly slower because of the long cycle time required for injection, ramp, and dump. Injection energy offers a practical compromise for controlled experiments.

At injection, the impedance is distributed among several machine components including devices such as beam screens and warm sections. To partially reproduce flat-top-like conditions, the collimator gaps were systematically reduced below their nominal values, allowing the collimators to become a dominant contribution to the transverse impedance even at injection energy. To investigate their impact, the measurements were repeated for different IR7 collimator configurations: nominal (operational) configuration (primaries at  $5.7\sigma$ , secondaries at  $6.7\sigma$ , and tertiaries at  $10\sigma$ ), a tighter configuration with reduced gaps (primaries at  $3.5\sigma$ , secondaries at  $4.5\sigma$ , and tertiaries at  $10\sigma$ ) to enhance the collimator impedance contribution, and a configuration with

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retracted collimators (primaries at  $10\sigma$ , secondaries at  $13\sigma$ , and tertiaries at  $17\sigma$ ) to minimize their impact.

This approach provides a controlled way to modify the relative weight of different impedance sources in the machine, enabling a direct assessment of how the measured instability growth rates depend on contributions from collimators as well as from other broadband (or resistive-wall) sources relevant at injection, such as beam screens and warm vacuum chambers. This is of particular importance in the context of benchmarking and improving the LHC impedance model.

### Method for Triggering Instability

The machine configuration during the growth rate measurements is summarized in Table 1. This initial configuration was used to establish the appropriate conditions for subsequently performing the full set of measurements in a controlled and reproducible way.

Table 1: Machine parameters at injection during the initial part of the growth rate measurements.

Parameter	Value
Transverse feedback (ADT)	OFF
Tune H / V (fractional part)	0.275 / 0.293
Bunch intensity [ $10^9$ p/b]	8
Bunch length ( $4\sigma$ RMS) [ns]	1.1

It is worth mentioning that the LHC operates above transition energy. In this regime, the head-tail mode 0 is unstable for negative chromaticity. Therefore, a pilot bunch with intensity of  $8 \times 10^9$  p/b was injected with the transverse damper (ADT) active and a positive chromaticity ( $Q' \approx +10$ ), ensuring a stable initial state. After injection and once the beam and machine conditions had settled, the chromaticity was trimmed to the desired negative value and the transverse feedback was switched off. The settings were well tuned such that the coherent oscillations were triggered without the need of applying a controlled transverse kick. The subsequent evolution of the beam motion was recorded using turn-by-turn data from the ADT observation box. At the end of each cycle, the beam was dumped. From the raw turn-by-turn data, the oscillation amplitude as a function of time is extracted. This amplitude exhibits an exponential growth, which is then fitted; the exponent of this fit directly provides the instability growth rate, as illustrated in Fig. 1.

Once a configuration which enabled a reproducible excitation of transverse instabilities was established, the focus shifted to the optimization of the stabilizing mechanisms. In particular, the Landau octupole current was scanned to identify the regime of minimum Landau damping, as detailed in the following section.

### Quantitative Observation of Landau Damping and its Minimization

During instability measurements performed in 2024, a discrepancy was observed between measured and simulated instability growth rates, with the experimental values consistently lower than the predictions [1]. This behaviour was

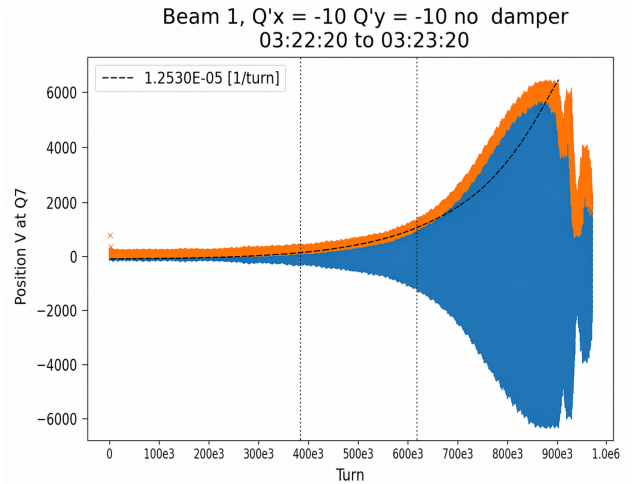


Figure 1: Transverse instability example with exponential growth of the oscillation amplitude, as recorded by the ADT.

attributed to sources of Landau damping not included in the simulations, such as residual amplitude detuning and non-linear chromaticity. To address this, efforts were made to correct optics non-linearities, in particular those related to amplitude detuning. However, these corrections were not sufficient to fully explain the observed discrepancy and to significantly reduce the effective Landau damping. This indicated that additional, not fully controlled sources of tune spread were still present in the machine.

For this reason, a different strategy was adopted in the 2025 measurements. Instead of attempting to compensate individual non-linear effects, the approach consisted in directly minimizing the overall Landau damping by scanning the Landau octupole current. Rather than simply setting the octupoles to zero current, the current was varied in the region close to zero to experimentally identify the operating point corresponding to the strongest instability, i.e. the largest exponential growth rate. The results obtained with this approach are summarized in Fig. 2, and exhibit a clear dependence of growth rates on the octupole current.

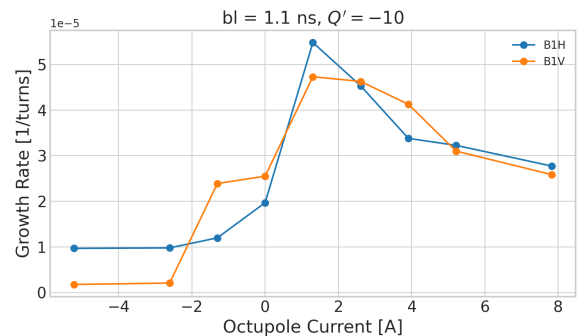


Figure 2: Instability growth rate for  $Q' = -10$  and a full bunch length of 1.1 ns, as a function of octupolar current.

At high octupole strengths, the induced tune spread provides higher Landau damping, reducing the instability growth rate. As the current is reduced, the tune spread de-

creases and the damping weakens, leading to an increase of growth rate and therefore stronger instability. Moreover, an operating point corresponding to a minimum Landau damping can be identified with a non-zero, slightly positive value of the octupole current of 1.5 A. In this regime, the measured growth rates are expected to directly reflect the real part of the machine impedance, with minimal distortion from nonlinear detuning effects. Furthermore, the results in Fig. 2 provide a direct measurement and quantification of Landau damping in the LHC.

The selected operating point was then used as the reference condition for all subsequent measurement scenarios. In particular, scans were performed for different chromaticity settings in order to evaluate its impact on the measured growth rates, as well as for different collimator settings, as discussed above. The bunch length was also lowered to further characterize the instability growth rates, it was set as low as achievable by the injectors (0.6 ns). The corresponding results will be presented in the next section.

## INSTABILITY GROWTH RATE IN THE LHC: MEASUREMENTS AND MODEL

Using nominal collimator settings, the instability was measured as a function of chromaticity, going from -20 to -5, as depicted in Fig. 3. The expected reduction in growth rates was observed, in agreement with theoretical predictions obtained from macroparticle tracking simulations [3] using the LHC impedance model [4].

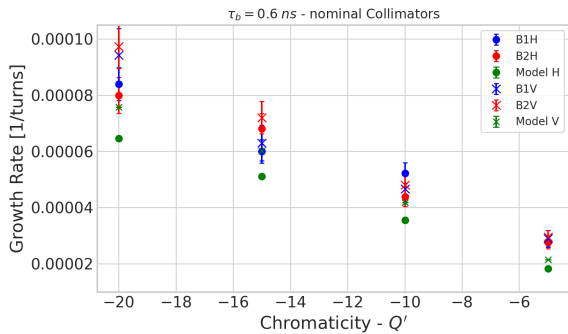


Figure 3: Instability growth rate vs chromaticity for the horizontal (dots) and vertical plane (crosses). Measurements are in blue for B1, red for B2, and simulations are in green.

After the chromaticity scan, for a fixed value of the latter, measurements were performed at different collimator gaps. They revealed variations in growth rate in good agreement with the expected impedance scaling, as shown in Fig. 4.

Overall, the measured growth rates show very good agreement with model predictions, both in absolute value and in their dependence on chromaticity and collimator settings.

In the worst case, corresponding to the coarse configuration where the collimators are significantly retracted, the maximum discrepancy between model and measurements reaches approximately 30%. This already represents a significant improvement with respect to previous measurements.

Moreover, this agreement improves as the collimator aperture reduces, indicating that part of the remaining discrepancy is mainly linked to the fixed aperture devices, such as beam screens. In fact, their impedance model is being refined and ongoing work is focused on improving the accuracy of the real part of the impedance of these devices. The comparison between measurements and simulations shows that, in selected cases where Landau damping is minimized, the intrinsic instability dynamics can be accurately captured, enabling a meaningful comparison with theoretical models.

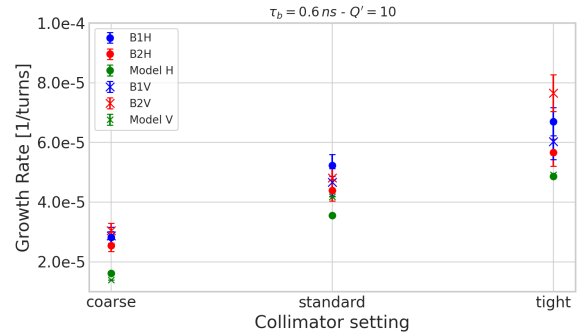


Figure 4: Instability growth rate for different collimator apertures, in the horizontal (dots) and vertical plane (crosses). Measurements are in blue for B1, red for B2, and simulations are in green.

## CONCLUSIONS

A dedicated experimental campaign was carried out in the LHC to measure instability growth rates under controlled conditions with minimized Landau damping. By systematically varying the octupole current, an operating point was identified where the stabilizing effect of nonlinear tune spread is close to zero, enabling precise measurements of instability growth rates.

Using this configuration, growth rate measurements were performed as a function of chromaticity, bunch length, and collimator settings. The results show excellent agreement with theoretical predictions and provide important input for refining the machine impedance model.

These measurements constitute a direct quantitative observation of Landau damping effects in the LHC and the methodology developed in this work opens the way for more precise characterization of collective effects and improved predictions for future high-intensity operation.

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