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LONGITUDINAL LOSS OF LANDAU DAMPING IN THE CERN SUPER PROTON SYNCHROTRON AT 200 GeV

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Abstract

Landau damping plays a crucial role in preserving single-bunch stability. In view of delivering the beam to the High-luminosity LHC (HL-LHC), the Super Proton Synchrotron (SPS) must double the intensity per bunch. In this intensity range, the loss of Landau damping (LLD) in the longitudinal plane can pose an important performance limitation. Observation of the beam response to a rigid-bunch dipole perturbation is a common technique in studying the LLD. This contribution presents measurements for a single bunch at 200 GeV in a double-harmonic RF system with a higher harmonic voltage at four times the fundamental RF frequency, showing the impact on Landau damping. Beyond the analytical estimates, the observations are moreover compared to the results from novel stability criteria implemented in the semi-analytical code MELODY, as well as with macroparticle simulation in BLonD.

INTRODUCTION

The stability of particle beams in hadron synchrotrons is a critical issue for achieving high-intensity and quality beams. One of the most effective mechanisms for maintaining beam stability is Landau damping [1]. In the longitudinal plane, the synchrotron frequency spread of individual particles, caused by the non-linear voltage of the RF system, establishes this damping mechanism, which was studied for many years [2–11]. To enhance beam stability, a common technique is to employ a higher harmonic RF system, which can modify the synchrotron frequency spread. For example, the Super Proton Synchrotron (SPS) at CERN is equipped with 200 MHz and 800 MHz RF systems, operating in phase at the bunch position, resulting in the so-called bunch shortening mode (BSM) to suppress longitudinal instabilities [12].

Analytical expressions for the loss of Landau damping (LLD) threshold in the single harmonic RF case have been derived [13] using the Lebedev equation [2] they are confirmed by numerical calculations with the code MELODY [14] and macroparticle simulations with BLonD [15]. The predictions are consistent with available beam measurements, and it has also been observed that the beam response to a rigid-dipole perturbation is strongly influenced by Landau damping. Recently, studies have been extended to a specific configuration of the double harmonic RF system, and a new analytic expression has been proposed [16].

This contribution presents beam-based measurements performed in the SPS to estimate the LLD threshold. The findings are compared with calculations using the MELODY code and macroparticle tracking using BLonD.

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LOSS OF LANDAU DAMPING

The LLD occurs when the coherent synchrotron frequency of a bunch moves out from the incoherent frequency band. An analytical expression for the LLD threshold has been proposed in BSM, based on refined estimates of the synchrotron frequency distribution [16]. This expression is designed explicitly for particle distributions that are modeled by a binomial family, denoted as:

$$\lambda(\phi) \propto \left(1 - \frac{U_{\mathrm{tot}}(\phi)}{U_{\mathrm{tot}}(\phi_{\mathrm{max}})}\right)^{\mu+1/2}, \qquad (1)$$

where $U_{\mathrm{tot}}(\phi)$ is the total RF potential well including intensity effects, and ϕ_{max} is the maximum phase deviation in the bunch. Equation 1 is applicable to a wide range of realistic bunch distributions in proton synchrotrons, depending on μ. Assuming the SPS configuration, the LLD threshold can be expressed as:

$$N_{\mathrm{th}} \propto \frac{1+64r}{\mu(\mu+1)(1+4r)^{1/2}} \frac{\phi_{\mathrm{max}}^4}{\mathrm{Im}Z_{\mathrm{eff}} f_c}, \qquad (2)$$

where r and $\mathrm{Im}Z_{\mathrm{eff}}$ represent the voltage ratio and the effective impedance model with cutoff frequency f_c. Similar to the single RF (SRF) case [13], the LLD threshold in the double-harmonic RF system is highly sensitive to the fourth power of the bunch length, depending on the voltage ratios.

The subsequent section outlines the experimental evaluation of the LLD threshold prediction made by a self-consistent semi-analytical calculation using MELODY. The code implements the latest beam coupling impedance model of the SPS [17] along with the one-turn delay feedback model [18, 19]. However, as is shown in Eq. (2), the accuracy of the threshold prediction is directly correlated with the precision of the impedance model and its cutoff frequency, f_c.

SINGLE RF

Based on the machine parameters outlined in Table 1, this section will present the principal outcomes acquired from beam-based measurements in the SPS. After injecting a single bunch from the Proton Synchrotron (PS) at a total energy of 26 GeV, the beam is accelerated to an energy of 200 GeV, minimizing space charge contributions. Within a few milliseconds of reaching the flat-top energy, the bunch is excited by a dipole kick, allowing it to oscillate in a rigid bucket. Throughout the process, the beam phase loop [20] was disabled. The evolution of the bunch offset was obtained by measuring the phase difference between the beam pickup

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Table 1: Accelerator Parameters of the SPS at Flat-Top

Parameter	**Unit**	**Value**
Circumference, $2\pi R$	m	6911.55
Beam energy, E	GeV	200
Main harmonic number, h		4620
Main RF frequency, f_{RF}	MHz	200.39
RF voltage at main harmonic, V_{RF}	MV	4.5

signal and the sum of the cavity voltages (i.e., phase-loop error [21]), as shown in Fig. 1. When the beam intensity is

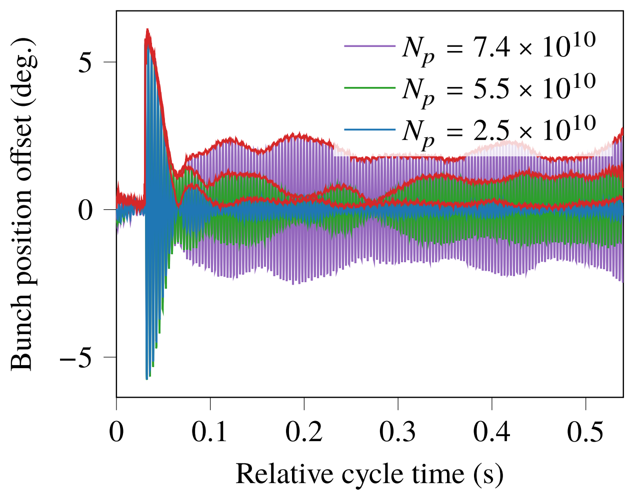
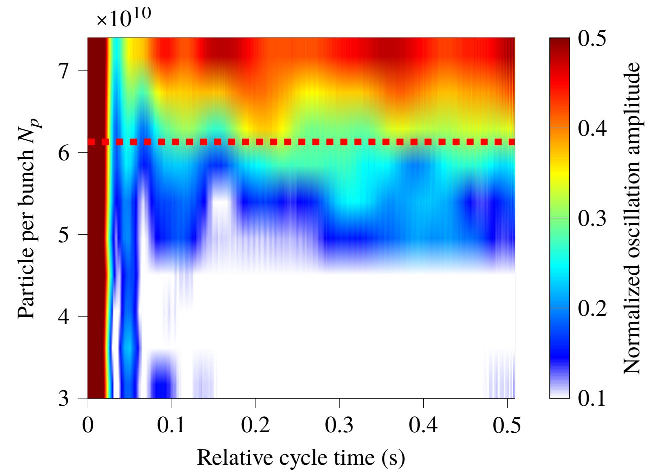


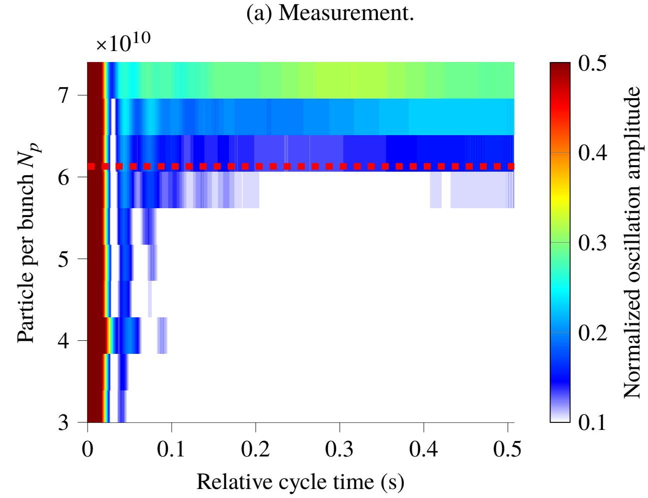
Figure 1: Bunch phase offset evolution with different intensities obtained measuring the phase-loop error in SRF. The red lines represent the envelopes of the traces computed using a Hilbert transform.

below the LLD threshold (e.g., blue line), the bunch oscillations rapidly lose their coherence, followed by subsequent slow decoherence. However, phase oscillations persist above the LLD threshold (e.g., purple line), and their amplitudes depend on the bunch intensity. This relationship between residual oscillation amplitude and intensity is attributed to crossing the LLD threshold. Below this intensity threshold, damping is dominant.

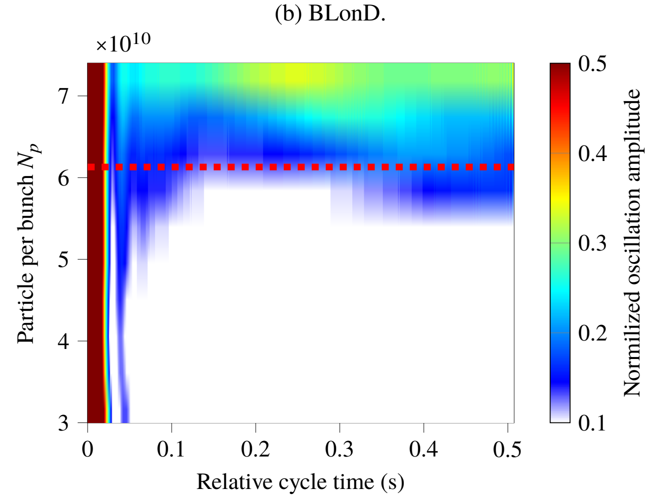
In the SRF configuration, measurements were conducted [similarly to [22]] to acquire various bunch intensities ranging from 3.0×10^{10} to 7.0×10^{10}, in increments of ~ 0.5×10^{10}. Figure 2 shows the time evolution of the bunch phase oscillation amplitude (color coding), following a dipole excitation, for different intensities. The oscillation amplitude from turn-by-turn bunch offset was extracted using a Hilbert transform [23]. The measured profiles were fitted with Eq. (1) and subsequently provided as input to simulations. In particular, Fig. 2c is obtained with a self-consistent semi-analytical approach (also used in [13, 24]) performed by means of MELODY, whereas, Fig. 2b is derived from a conventional macroparticle tracking simulation with BLonD. Both methods assume accelerator parameters according to Table 1, including the SPS impedance model.



(a) Measurement.



(b) BLonD.



(c) MELODY.

Figure 2: Time evolution of the normalized bunch phase oscillation amplitude (color coding) after a dipole excitation in the SRF. The measurement results (2a) are compared with outcome of BLonD (2b) and MELODY (2c) analysis for different intensities. The MELODY prediction of the LLD threshold at $N_{\mathrm{th}} \approx 6.1 \times 10^{10}$ is shown in a red dashed line.

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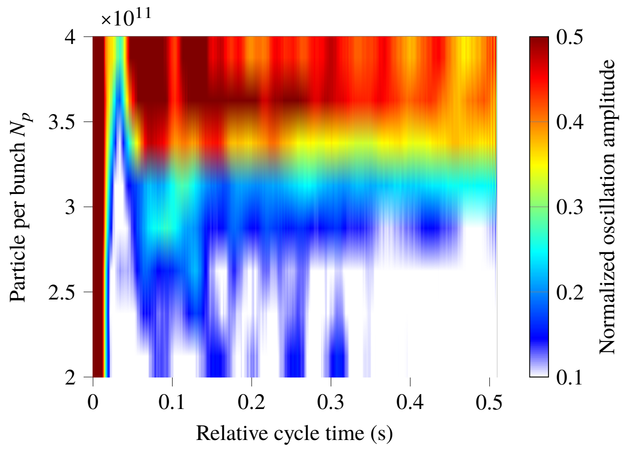

Figure 3: Measured time evolution of the bunch phase oscillation, normalized by the kick strength, in BSM for different intensities with voltage ratio $r = 0.1$.

The two approaches exhibit similar behavior and agree well with the LLD threshold predicted by MELODY (red dashed line). However, the residual oscillation amplitude depicted by measurement in Fig.2a results in being larger than from the simulations. The resulting LLD threshold predictions of $N_{\mathrm{th}}^{\mathrm{SRF}} = 6.13 \times 10^{10}$ overestimates the measurements.

The SPS impedance model was developed for many years based on measurements and simulations of accelerator components [25, 26]. Nevertheless, obtaining accurate impedance behavior at high frequencies presents significant challenges. As illustrated by Eq. (2), the LLD threshold highly depends on the cutoff frequency f_c. Consequently, inaccuracies in the impedance model or in its cutoff frequency have a significant impact on the computed threshold.

BUNCH SHORTENING MODE

This section extends the studies to BSM configuration to evaluate the relative change of the LLD threshold when transitioning from an SRF to a double-harmonic RF system for the case of the fourth harmonic RF.

Figure 3 illustrates the measured time evolution of the normalized bunch phase oscillation amplitude, relative to the kick strength, in BSM for a voltage ratio of $r = 0.1$. A significant benefit can be observed when employing a double-harmonic RF system as compared to the SRF case shown in Fig. 2a. In particular, the usage of BSM results in an increase of approximately ~ 6 in terms of the LLD threshold. However, direct comparison is not straightforward since beam conditions at significantly higher intensities differ. In particular, Fig 4 shows the measured bunch profile with the corresponding binomial fit (1) in orange. Moving from the SRF scenario (top) to the BSM case (bottom), it is visible a reduction in bunch length and a noticeable change in bunch shape (lower μ). Moreover, the theoretically predicted LLD threshold in BSM is, similarly to the SRF case, overestimated $N_{\mathrm{th}}^{\mathrm{BSM}} \approx 77 \times 10^{10}$.

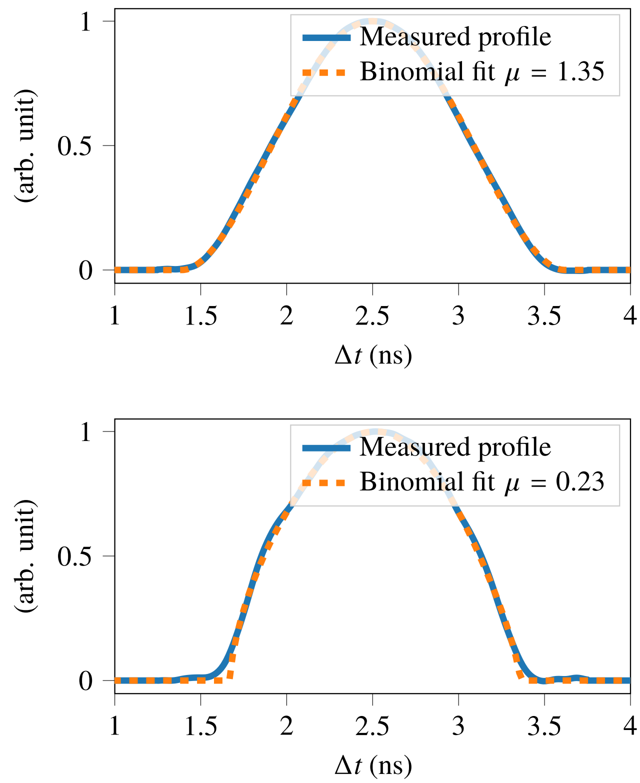

Figure 4: Comparison between measured line density in SRF (top) and BSM (bottom). The binomial fit [Eq. (1)] of the profile is depicted in orange.

CONCLUSION

Landau damping is one of the most effective methods for stabilizing coherent beam instabilities in hadron synchrotrons. Recent investigations have led to new analytical criteria for predicting the LLD threshold, which can be applied to double-harmonic RF systems operating above the transition energy. In this work, the kick-response technique was applied to experimentally study LLD threshold in the SPS. In particular, the threshold increase for double-harmonic RF configurations has been demonstrated. The findings were benchmarked with a self-consistent semi-analytical calculation using MELODY and macroparticle tracking simulation with BLonD. Both methods exhibit excellent agreement. However, discrepancies between the measurements and simulations may indicate imperfections in the SPS beam coupling impedance model. Further investigations will focus on refined measurements as well as theoretical benchmarks.

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