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MEASUREMENTS OF LONGITUDINAL LOSS OF LANDAU DAMPING IN THE CERN PROTON SYNCHROTRON

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Abstract

Landau damping represents the most efficient stabilization mechanism in hadron synchrotron accelerators to mitigate coherent beam instabilities. Recent studies allowed expanding the novel analytical criteria of loss of Landau damping (LLD) to the double harmonic RF system case above transition energy, providing an analytical estimate of the longitudinal stability. The threshold has a strong dependence on the voltage ratio between the harmonic and the main RF systems. Based on that, measurements of single bunch oscillations after a rigid-dipole perturbation have been performed in the CERN Proton Synchrotron (PS). Several configurations have been tested thanks to the multi-harmonic RF systems available in the PS. Higher-harmonic RF systems at 20 MHz and 40 MHz, both in phase (bunch shortening mode) and in counter-phase (bunch lengthening mode) with respect to the principal one at 10 MHz, have been measured.

INTRODUCTION

Landau damping [1] represents the most effective way to maintain the beam stable from uncontrolled coherent oscillations in hadron synchrotrons. In the longitudinal plane, the spread of synchrotron frequencies of individual particles caused by the non-linear voltage of the RF system establishes this stabilization mechanism, which was studied for many years [2–11]. Hence, employing a double harmonic RF system is a common way to modify the synchrotron frequency spread (Fig. 1) and to improve beam stability [12]. An analytic expression for the loss of Landau damping (LLD) threshold in the single harmonic RF case has been derived [13] using the Lebedev equation [2], which was confirmed by numerical calculations with the code MELODY [14] and macroparticle simulation with BLonD [15]. The predictions were also consistent with available beam measurements. The beam response to a rigid-dipole perturbation was also analyzed and shown to be strongly affected by Landau damping. Recently these studies were extended to a specific configuration of the double harmonic RF system and a new analytic expression was proposed [16].

The Proton Synchrotron (PS) is the second largest injector synchrotron at CERN, accelerating proton beams up to 26 GeV. The large number of RF systems employed in the PS (i.e., 2.8 – 10 MHz, 20 MHz, 40 MHz, 80 MHz and 200 MHz) makes it an ideal accelerator for the LLD study. The results of an extensive campaign of beam measurements with a double-harmonic RF system performed in the PS is presented in this contribution.

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RF CONFIGURATIONS AND MAIN DEFINITIONS

Two main configurations can be distinguished in accelerators with double harmonic RF systems, such as the PS. Bunch shortening mode (BSM) occurs when both RF systems are in phase at the bunch position; on the contrary, when the RF systems are in counter-phase, the bunch stretches, which reduces the peak longitudinal line density leading to the so-called bunch lengthening mode (BLM). Therefore, depending on the configuration, the flexibility of PS RF systems allows a variety of longitudinal beam manipulations [17], such as merging, splitting, and changing the spacing between bunches.

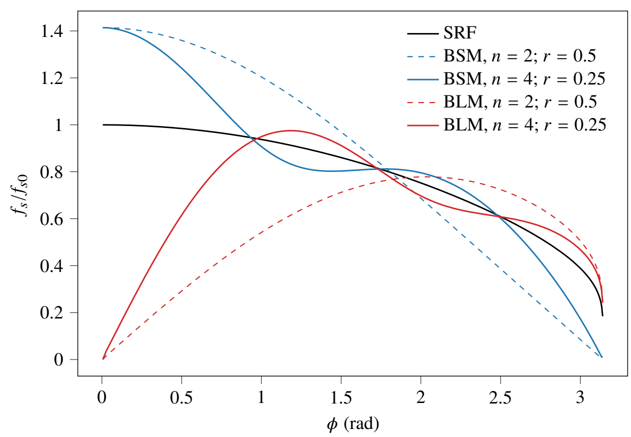

Figure 1: Synchrotron frequency distribution, normalized to small-amplitude synchrotron frequency f_{s0} in a single-harmonic RF system (SRF), as a function of the maximum phase deviation of the particle (black). The cases of BSM (blue) and BLM (red) are shown for two harmonic number ratios n, assuming a voltage ratio $r = 1/n$ at zero intensity.

The present work will examine the two relevant cases of harmonic number ratios of $n = 2$ and $n = 4$. The fundamental RF frequency being about 10 MHz, the higher-harmonic RF systems at 20 MHz and at 40 MHz were operated in both BSM and BLM. For reference also measurements with a single harmonic RF (SRF) have been taken.

Loss of Landau Damping

The LLD occurs when the coherent synchrotron frequency of the bunch moves outside the incoherent frequency band. Recently, refined analytical estimates of the synchrotron frequency distribution allowed an extension of the analytical expression for the LLD threshold, specifically for particle distributions belonging to the binomial family in BSM [16].

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This threshold can be expressed as follows:

$$N_{\mathrm{th}} \propto \frac{1+rn^3}{(1+rn)^{1/2}}\tau_{\mathrm{full}}^4, \tag{1}$$

where r represents the voltage ratio. Similarly to the SRF case, the threshold is highly sensitive to the fourth power of the bunch length τ_{full}, but also strongly depends on the harmonic number and the voltage ratios. In the upcoming section, we will illustrate how Eq. (1) can be employed to evaluate the relative change of the LLD threshold moving from an SRF to a double-harmonic RF system for the case of the BSM.

BEAM-BASED MEASUREMENTS

Based on the machine parameters outlined in Table 1, this section will present the principal outcomes acquired from PS beam-based measurements.

Table 1: Main PS Parameters for LHC-type Beams [18] at Flat-Top

Parameter	Unit	Value
Circumference	m	628.32
Beam energy	GeV	26
Main harmonic number		21
Main RF frequency	MHz	10
RF voltage at fundamental harmonic	kV	200
RF voltage at 2nd harmonic (20 MHz)	kV	40
RF voltage at 4th harmonic (40 MHz)	kV	200

Following the injection of a single bunch from the PS Booster at a kinetic energy of 2 GeV, the beam was accelerated to the maximum energy of 26 GeV. The flat-top was chosen to minimize any contribution of space charge. Few milliseconds after reaching the flat-top energy, the second RF system (20 MHz or 40 MHz) was activated. The bunch was then excited by a dipole kick (phase jump), and it is thereafter allowed to oscillate in a rigid bucket. The beam phase and radial loops were disabled during the entire process. Therefore, the evolution of the bunch profile with respect to a beam synchronous trigger is obtained by so-called mountain range measurements, starting just before the excitation. The bunch position evolution can be extracted by computing the centroid of the acquired profiles, as shown in Fig. 2. When the beam intensity remains below the LLD threshold, the initial rapid decoherence of bunch oscillations is followed by subsequent slow decoherence. However, residual phase oscillations persist above this threshold, and their amplitudes are directly proportional to the bunch intensity. This observable relationship between residual oscillation amplitude and intensity is attributed to crossing the threshold of LLD. Below this intensity threshold damping is dominant.

Bunch Shortening Mode

Employing the 20 MHz as a second harmonic RF system in BSM ($n = 2$), the measurements started acquiring

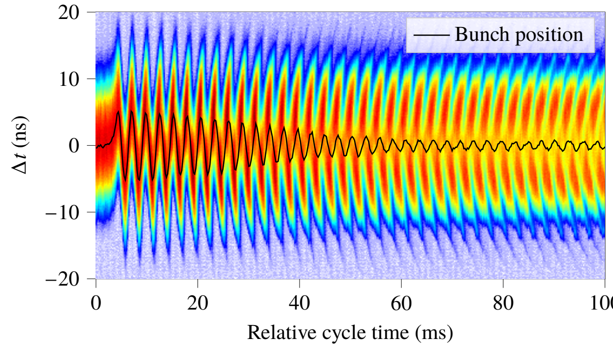

Figure 2: Line density waterfall obtained from multi-trigger acquisition in the PS for the SRF configuration at an intensity of $N_p = 0.35\times10^{12}$. The solid black line indicates the bunch position evolution.

different bunch intensities spanning from 0.27×10^{12} to 1.0×10^{12} in intensity steps of $\sim 0.1\times10^{12}$. According to Eq. (1), the threshold varies significantly with the bunch length and special care was therefore taken to keep it independent of intensity. Figure 3 illustrates the reproducibility of the bunch length for both, SRF and BSM, configurations with different voltage ratios.

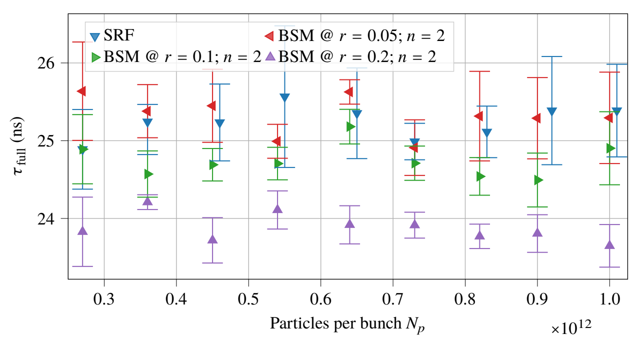

Figure 3: Mean values of the full bunch lengths taken across multiple measurements for LHC-type beams in the PS and their 95% confidence intervals. The experimental configuration includes SRF and BSM cases with different voltage ratios.

Figure 4 shows the time evolution of the bunch phase oscillation amplitude (colour coding) after a dipole excitation for different intensities. Passing from the SRF (Fig. 4a) to the BSM case (Figs. 4b - 4d), upon the initial rapid decoherence, it is observed that bunch oscillations become undamped at higher intensities for the larger voltage ratios. Assuming that the LLD threshold in SRF is $N_{\mathrm{th}} \approx 0.36\times10^{12}$ (black dashed line in Fig. 4a) we can employ the Eq. (1) to predict the threshold of the other configurations including the variation of the bunch length, namely: $N^{\mathrm{BSM}}_{\mathrm{th},r=0.05} = (0.48\pm0.06)\times10^{12}$ (Fig. 4b); $N^{\mathrm{BSM}}_{\mathrm{th},r=0.10} = (0.53\pm0.05)\times10^{12}$ (Fig. 4c); $N^{\mathrm{BSM}}_{\mathrm{th},r=0.20} = (0.63\pm0.08)\times10^{12}$ (Fig. 4d). Consequently, the predictions are consistent with the measurements.

As far as the fourth harmonic RF system ($n = 4$, higher harmonic RF frequency at 40 MHz) is concerned, the mea-

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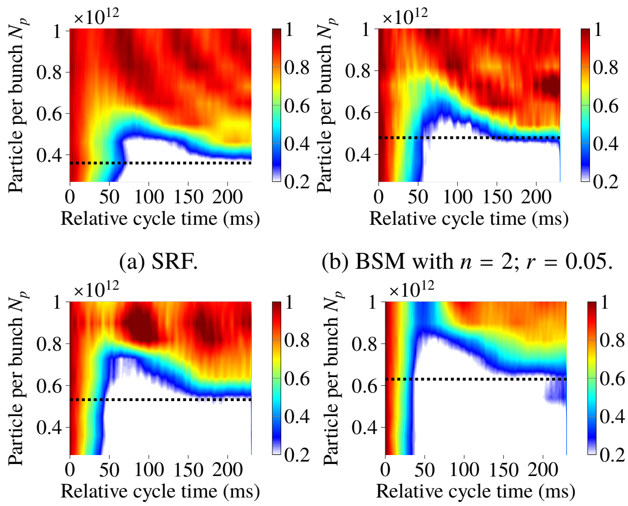

(a) SRF. (b) BSM with n = 2; r = 0.05.

(c) BSM with n = 2; r = 0.1. (d) BSM with n = 2; r = 0.2.

Figure 4: Time evolution of the normalized bunch phase oscillation amplitude (color coding) for different intensities after a dipole excitation.

surements have been performed at the same bunch length as with $n = 2$, again covering different voltage ratios. However, no LLD has been observed in the same range of intensities. This behaviour is expected since already for a voltage ratio of $r = 0.05$, using Eq. (1), an LLD threshold increase by a factor of almost 4 is predicted. It would therefore be well beyond the feasible intensity range for the given bunch length in the PS.

Bunch Lengthening Mode

It was shown in the past that Landau damping can be significantly affected by the presence of zero derivative of the synchrotron frequency distribution $df_s/d\phi$ [11]. Once the bunch length exceeds the point at which $df_s/d\phi = 0$, Landau damping is lost even at zero intensity. As shown in Fig. 5 for $n = 4$ (red), this inflection point ($df_s/d\phi$=0) of the synchrotron frequency distribution is well below the current bunch length ($\tau_{\text{full}} = 25$ ns), leading to the vanishing LLD threshold. This phenomenon was observed experimentally, when the bunch position oscillation was persistently undamped also for the lowest possible bunch intensity ($N_{\text{th}} = 0.27 \times 10^{12}$).

With $n = 2$ and $r = 0.05$, the synchrotron frequency distribution, shown in Fig. 5 (blue, dash-dotted), is similar to the SRF case without any significant enhancement in synchrotron frequency spread. This observation is consistent with the result presented in Fig. 6 in which the employment of a double harmonic RF system does not bring benefits for the LLD threshold with respect (Fig.4a).

CONCLUSION

The loss of Landau damping in synchrotrons is a critical condition that can lead to beam instabilities and particle loss. The LLD threshold can be raised, in principle, by reducing longitudinal impedance. However, increasing the synchrotron frequency by means of a double-harmonic RF system is often more efficient. This work applied a straightforward beam-based measurement technique to study LLD experimentally. In the PS, the findings have shown a good agreement with the analytical predictions, and a longitudinal stability gain for different double-harmonic RF configurations has been proven in BSM ($n = 2$). For BSM with a fourth harmonic RF system the intensity reach did not allow to observe LLD. For the BLM case ($n = 4$) the bunches were not damped, as their length exceeded the phase of the inflection point. Future studies are focused on the detailed bench-marking of the measurements with theory.

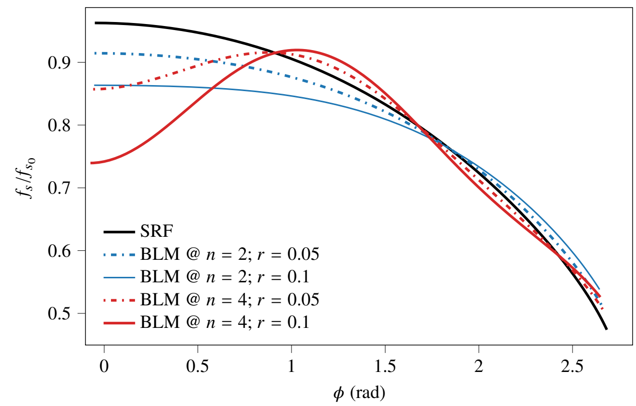

Figure 5: Synchrotron frequency distribution normalized to the small-amplitude synchrotron frequency f_{s0} as a function of the maximum phase deviation of the particle. The blue lines denote the BLM for $n = 2$ and the red lines for $n = 4$, when the intensity is $N_p = 0.25 \times 10^{12}$.

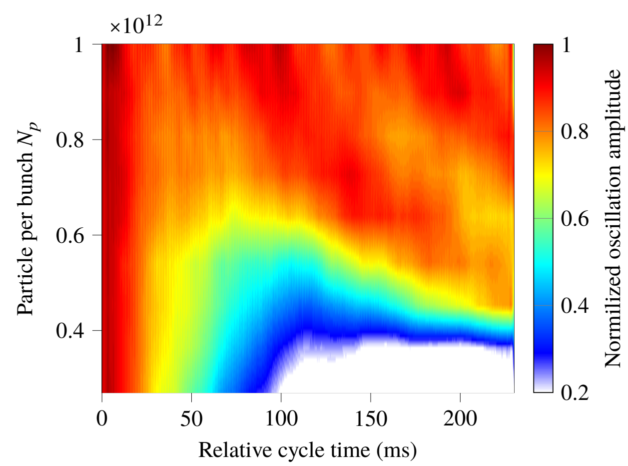

Figure 6: Time evolution of the normalized bunch offset amplitude (colour coding) in BLM for $n = 2$, $r = 0.05$ and $\tau_{\text{full}} = 35$ ns.

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