

# SINGLE BUNCH LONGITUDINAL INSTABILITY IN THE CERN SPS

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## Abstract

The longitudinal single bunch instability observed in the SPS leads to uncontrolled emittance blow-up and limits the quality of high intensity beams required for the High Luminosity LHC and AWAKE projects at CERN. The present SPS impedance model developed from a thorough survey of machine elements was used in macro-particle simulations (with the code BLoND) of the bunch behavior through the acceleration cycle. Comparison of simulations with measurements of the synchrotron frequency shift, performed on the SPS flat bottom to probe the impedance, show a reasonable agreement. During extensive experimental studies various beam and machine parameters (bunch intensity, longitudinal emittance, RF voltage, with single and double RF systems) were scanned in order to further benchmark the SPS impedance model with measurements and to better understand the mechanism behind the instability. It was found that the dependence of instability threshold on longitudinal emittance and beam energy has an unexpected non-monotonic behavior, leading to islands of (in)stability. The results of this study are presented and can be used to define possible parameter settings for the future CERN projects.

## INTRODUCTION

Longitudinal instabilities in the SPS are a major issue for many future projects at CERN. In order to study this limitation, an impedance model was developed from RF measurements and simulations [1–3], and the simulation code BLoND was adapted for these studies [4, 5]. The SPS longitudinal impedance is very complex and the model includes the contributions of various sources like the RF cavities and their HOMs (narrow-band), the kickers (broad-band) and the vacuum flanges (frequencies above 1 GHz), all of them leading to different instabilities depending on the beam and RF parameters. The study of a single bunch instability is an important step to gain trust in the model and assess the a potential of SPS impedance reduction for the High Luminosity-LHC project [6], as well as for the AWAKE experiment (requiring high intensity short bunches) [7].

## Measurement and Simulation Setup

Measurement data for single bunch instabilities was taken during the ramp (momentum from 26 to 450 GeV/c), to be compared with particle simulations using BLoND and the SPS impedance model. In simulations, the momentum and RF programs during the ramp, as well as the beam parameters at injection (bunch profile and intensity) were similar to those in measurements.

Two RF systems are used in operation in the SPS, one at 200 MHz to accelerate the beam, and at 800 MHz to increase beam stability. The RF voltage seen by a particle is:

$$V_{\text{tot}} = V_{200} \sin\phi + V_{800} \sin(4\phi + \phi_{800} + \phi_{\text{err}}), \quad (1)$$

where  $V_{200}$  and  $V_{800}$  are the voltage amplitudes of the two RF systems, the stable bunch position above transition in non accelerating bucket is  $\phi_s = \pi$ . Two different programs for the main RF system at 200 MHz were used in measurements. First,  $V_{200}$  was adjusted to keep a Constant Bucket Area (CBA, with a minimum voltage of 2 MV), while the other keeps a High constant Voltage through the main part of the ramp (HV,  $V_{200} = 7.2$  MV). Below,  $V_{800}$  is either set to zero (1RF) or to  $0.1 V_1$  (2RF) in bunch shortening mode during the ramp ( $\phi_{800} = \pi - 4\phi_s$ );  $\phi_{\text{err}}$  is the phase calibration error.

The bunch length was measured through the ramp (computed from Full-Width-Half-Maximum, rescaled to  $\tau = 4\sigma$  with  $\sigma$  assuming a Gaussian profile). To determine whether the bunch is stable, the peak-to-peak amplitude  $\Delta\tau$  and the average  $\tau_{\text{av}}$  of the bunch length oscillations were analyzed, and the bunch is considered unstable if  $\Delta\tau/\tau_{\text{av}} > 0.1$ . An example is shown in Fig. 1. The bunch intensity was scanned while keeping a constant longitudinal emittance  $\varepsilon_{2\sigma} \approx 0.25$  eVs [8]. Each single point of data in Figs. 2 and 3 corresponds to one measurement/simulation analyzed in the way shown in Fig. 1.

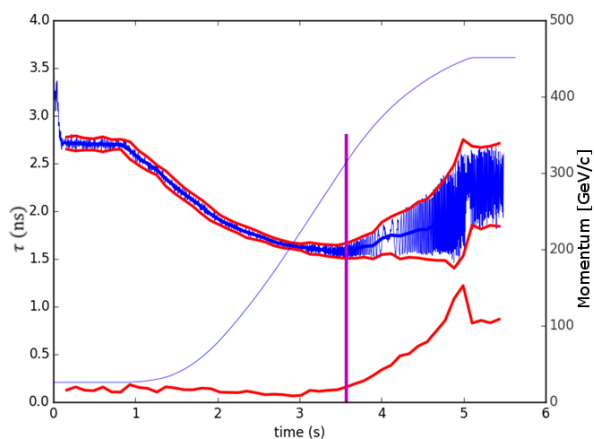


Figure 1: Example of a measured bunch length  $\tau$  (bold blue) through the ramp, plotted with the momentum program (thin blue), for the 1RF-CBA voltage program. The red lines show the peak-to-peak amplitude  $\Delta\tau$  of the bunch length oscillations, while the vertical line indicates the start of the instability according to our criterion.

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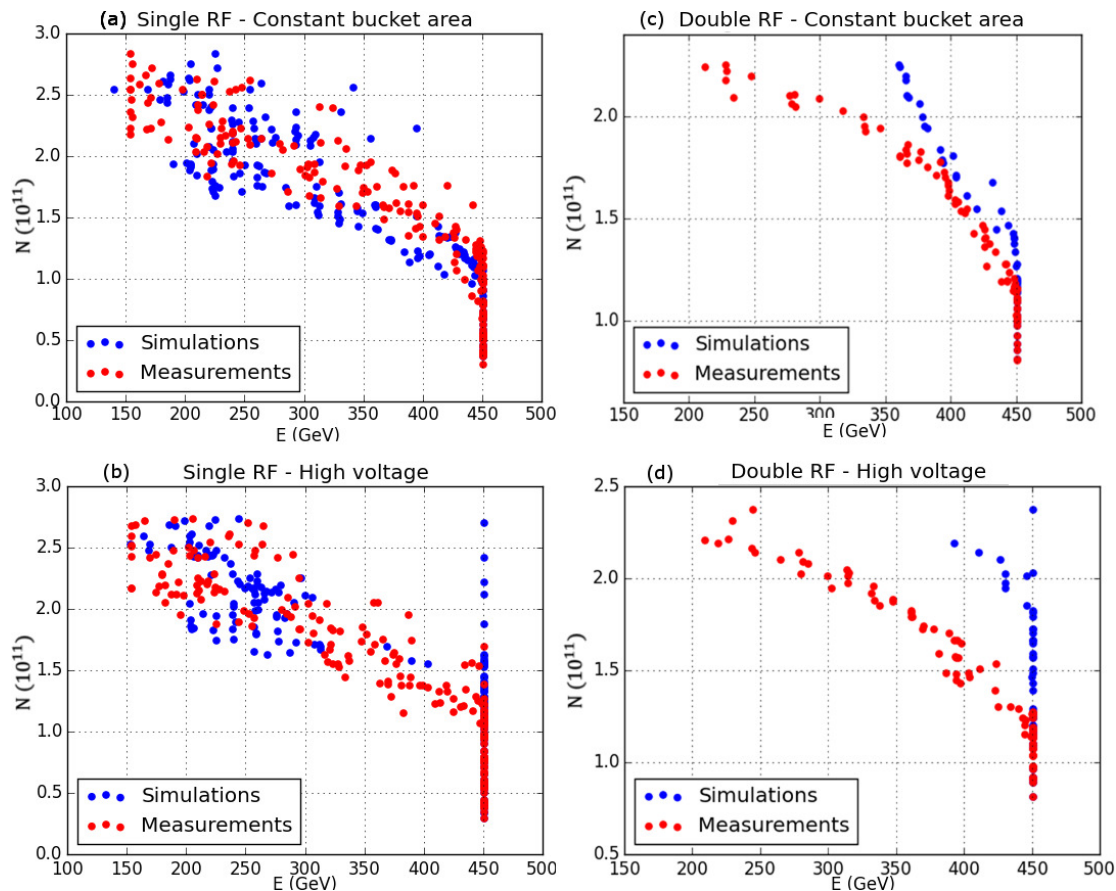


Figure 2: Measured and simulated beam energy during the cycle at which the instability starts with respect to the bunch intensity, for different RF programs: (a) 1RF-CBA, (b) 1RF-HV, (c) 2RF-CBA, (d) 2RF-HV.

### STABILITY STUDY

The results for 1RF are shown in Figs. 2(a),(b). First, for a given intensity, we can observe a spread in the energy at which the instability starts. As the instability is a slowly rising one, it makes the determination of the instability starting point difficult. For CBA, a good agreement between measurements and simulations is found, both for the intensity threshold ( $N_b \approx 1.0 \times 10^{11}$  ppb) and at which energy the bunch gets unstable. For HV, a good agreement is obtained at high intensities ( $N_b > 1.5 \times 10^{11}$  ppb). Close to the intensity threshold, the bunch appears more stable in simulations than in measurements (small amplitude of oscillations). In this case, the instability manifests as quadrupole oscillations. Phase loop is not included in the simulations, as it mainly damps dipole oscillations. Its impact on the instability was neglected but could also explain some discrepancies.

In simulations, some bunches at high intensities ( $N_b > 1.9 \times 10^{11}$  ppb) are stable and can reach the flat top (blue points at  $p = 450$  GeV/c) for 1RF-HV in Fig. 2(b). The effect of the vacuum flanges impedance, as studied in simulations at flat top [9], leads to a non-monotonic behavior of the instability threshold and would even lead to islands of stability at low emittances due to modification of the synchrotron frequency distribution. More measurements are foreseen to prove the existence of these islands.

The results for 2RF are shown in Figs. 2(c),(d) where less spread in the measurement data is observed with respect to 1RF, due to the fact that the instability is much faster and more violent, making the threshold well defined. The fast nature of this instability suggests that it could be a microwave instability driven by high frequency impedances (vacuum flanges). The intensity threshold is similar in 1RF and 2RF for low voltages (CBA, around  $N_b \approx 1.0 - 1.2 \times 10^{11}$  ppb), while for the 2RF-HV case in simulations the intensity threshold is higher ( $N_b \approx 2.0 \times 10^{11}$  ppb).

As follows from Fig. 2 for 2RF, measurements and simulations don't agree especially for the HV case so further investigations were performed.

### DOUBLE RF SYSTEM CALIBRATION

A possible explanation of discrepancy in results for 2RF is knowledge of the voltage ratio  $V_{800}/V_{200}$  and phase error  $\phi_{err}$  in Eq. (1). To have an estimation of the real RF settings in the machine, the tilt  $\Delta t$  of the bunch profile as a function of the relative phase between the two RF systems was measured. The tilt is calculated from the difference in the center position of the top part of the profile (90%) with respect to the bottom part (25%), for the full range of  $\phi_{err}$  from  $-180^\circ$  to  $180^\circ$  [10].

Measurements were compared with simulations to assess what would have been the expected tilt depending on the

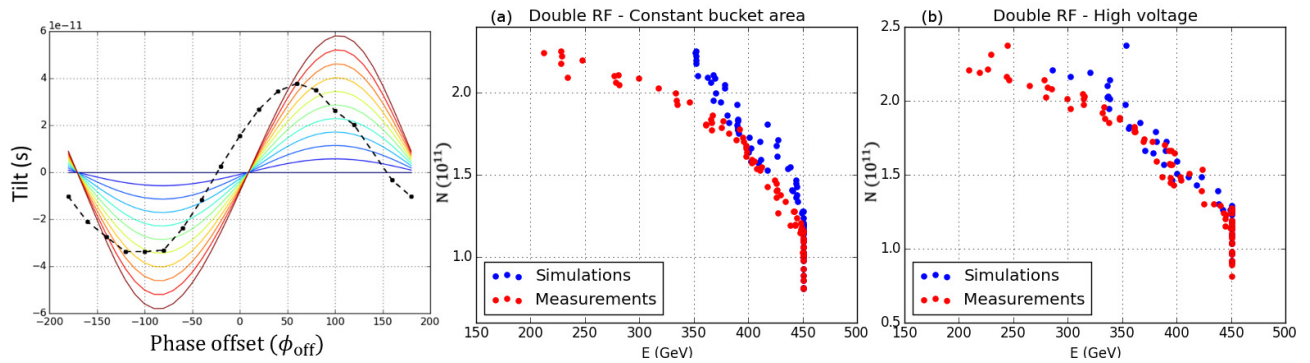


Figure 3: (a) Measured (black) and simulated (varying from  $V_{800}/V_{200} = 0$  (blue) to  $V_{800}/V_{200} = 0.1$  (red)) bunch tilt as a function of the phase calibration error  $\phi_{\text{err}}$ . Simulations including the corrections for the voltage  $V_{800}$  and phase  $\phi_{\text{err}}$  are shown for (b) 2RF-CBA, (c) 2RF-HV.

phase offset and voltage of the 800 MHz cavity. To do so, a bunch with an emittance as in measurements was generated matched to the bucket, including induced voltage. The tilt was then determined by scanning the phase offset but also the voltage. Results are shown in Fig. 3(a). First, the phase error  $\phi_{\text{err}}$  is determined by comparing the phase at which the tilt is  $\Delta t = 0$  in measurements and simulations. The phase error was  $\phi_{\text{err}} \approx 31^\circ$  at flat bottom and  $\phi_{\text{err}} \approx 42^\circ$  at flat top. Moreover, the 800 MHz voltage seems to be lower in measurements than what was assumed. Simulations show that the voltage ratio  $V_{800}/V_{200}$  was 0.06 instead of 0.1, both for flat bottom and flat top.

Making the simulations with the corrected RF values leads to the results shown in Fig. 3(b),(c). In the 2RF-HV case, the agreement is better, while in the 2RF-CBA case, the results didn't change significantly. The assumptions on the 800 MHz phase and voltage allows to predict the instability threshold more accurately, but the remaining discrepancies suggest that there still may be some impedance missing.

## SYNCHROTRON FREQUENCY SHIFT

The SPS impedance can be also probed by other beam measurements. An example is the synchrotron frequency shift for different bunch lengths, giving information on the reactive impedance of the machine. The method consists in measuring bunch length oscillations at injection to the SPS. The frequency  $f_{2s}$  of these quadrupole oscillations depends on the intensity, bunch length and the reactive part of the impedance  $\text{Im}Z/n$  and can be written as (for more details see [11]):

$$f_{2s}(\tau, N_b) = a(\tau) + b(\tau) N_b. \quad (2)$$

Measurements are compared with results of simulations using the SPS impedance model (including longitudinal space charge impedance of  $\text{Im}Z/n \approx -1 \Omega$ ) in Fig. 4.

The measured shift  $b$  is bigger than in simulations, probably due to some missing inductive impedance, or the bunch length for short bunches is larger than in reality. The transfer function of the measurement system can lengthen the bunch profile up to  $\approx 100$  ps. An agreement can be improved by

adding a constant impedance  $\text{Im}Z/n \approx 1 \Omega$ , or by multiplying the kickers impedance (biggest inductive component) by a factor 1.5.

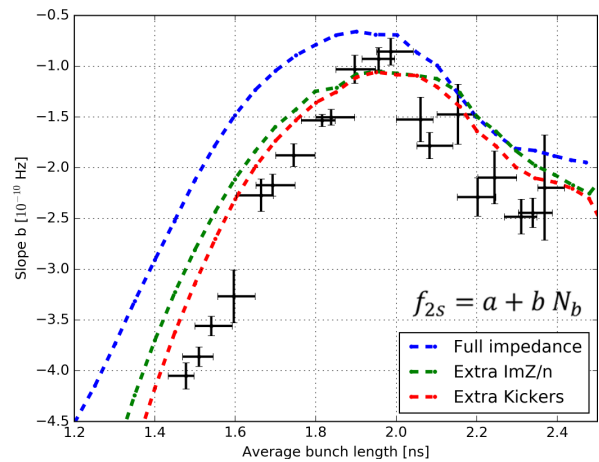


Figure 4: Measured synchrotron frequency shift  $b$  (crosses) compared to simulations using the SPS impedance model at flat bottom (blue). The effect of adding  $\text{Im}Z/n \approx 1 \Omega$  is shown in green, and in red multiplying the kickers impedance by 1.5.

## CONCLUSION

The presented simulation model is able to reproduce most of the observations for single bunch instabilities during the SPS ramp. In double RF, the agreement is conditioned by our knowledge of the voltage and phase of the fourth harmonic RF system. Some impedance sources may still be missing, further investigations are needed. This impedance model was also used for multibunch studies [12].

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## REFERENCES

- [1] J. Varela *et al.*, “An Extended SPS Longitudinal Impedance Model”, in *Proc. IPAC’15*, Richmond, VA, USA, May 2015, paper MOPJE035, pp. 360–362.
- [2] J. Varela *et al.*, “Longitudinal Impedance Characterization of the CERN SPS Vacuum Flanges”, in *Proc. IPAC’15*, Richmond, VA, USA, May 2015, paper MOPJE036, pp. 363–365.
- [3] B. Salvant, J. Varela, C. Zannini, SPS Impedance Model Update, Meetings of the LIU-SPS BD WG, CERN, <http://cern.ch/spsu/>
- [4] BLoND, Beam Longitudinal Dynamics code: <http://blond.web.cern.ch/>
- [5] H. Timko *et al.*, “Benchmarking the Beam Longitudinal Dynamics Code BLoND”, presented at the 7th Int. Particle Accelerator Conf. (IPAC’16), Busan, Korea, May 2016, paper WEPOY045, this conference.
- [6] E. Shaposhnikova *et al.*, “Removing known SPS intensity limitations for High Luminosity LHC goals”, presented at the 7th Int. Particle Accelerator Conf. (IPAC’16), Busan, Korea, May 2016, paper MOPOY058, this conference.
- [7] P. Muggli *et al.*, “AWAKE, the Advanced Proton Driven Plasma Acceleration Experiment”, presented at the 7th Int. Particle Accelerator Conf. (IPAC’16), Busan, Korea, May 2016, paper WEPMY019, this conference.
- [8] S. Hancock, “Improved longitudinal blow-up and shaving in the Booster”, CERN-ATS-Note-2013-040 MD (2013).
- [9] A. Lasheen, E. Radvilas “Simulations of single-bunch instability on flat top”, “Single-bunch instability during ramp” (06/08/2015), Meetings of the LIU-SPS BD WG, CERN, <http://cern.ch/spsu/>
- [10] T. Argyropoulos, “Longitudinal beam instabilities in a double RF system”, PhD Thesis, National Technical University of Athens (2015).
- [11] A. Lasheen *et al.*, “Synchrotron Frequency Shift as a Probe of the CERN SPS Reactive Impedance”, in *Proc. HB2014*, East-Lansing, MI, USA, November 2014, paper THO4LR02, pp. 409–413.
- [12] A. Lasheen *et al.*, “Effect of the Various Impedances on Longitudinal Beam Stability in the CERN SPS”, presented at the 7th Int. Particle Accelerator Conf. (IPAC’16), Busan, Korea, May 2016, paper TUPOR008, this conference.