THRESHOLDS OF LONGITUDINAL SINGLE BUNCH INSTABILITY IN SINGLE AND DOUBLE RF SYSTEMS IN THE CERN SPS

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Abstract

A fourth harmonic RF system is used in the SPS as a Landau cavity, in order to stabilize the high intensity LHC proton beam against the longitudinal instabilities. Numerous studies proved that operating the two RF systems, through the whole cycle, in bunch shortening mode is necessary to provide a good quality beam at extraction to the LHC. Furthermore, it was shown that the choice of RF parameters as voltage amplitude ratio and relative phase are critical for the beam stability. This paper presents the results of single bunch measurements performed in single and double RF systems with various RF settings and compares them with the results of macroparticle simulations for the SPS impedance model.

INTRODUCTION

A higher harmonic RF system is used in many accelerators either to change a bunch shape or to increase the synchrotron frequency spread inside the bunch, providing more effective Landau damping of beam instabilities. In the SPS, operation of the fourth harmonic RF system is required through the whole cycle, together with the main 200 MHz RF system, to deliver a good quality beam for the LHC. Indeed in a single RF system the LHC beam is unstable with bunch intensity five times less than the nominal one.

In the double RF system the external voltage seen by the particles has the form

$$V = V_{200} \sin\phi + V_{800} \sin(4\phi + \phi_{800}), \qquad (1)$$

where V_{200} and V_{800} are the voltage amplitudes of the 200 MHz and 800 MHz RF components and ϕ_{800} is the relative phase. Studies have shown that for the longitudinal stability, bunch shortening mode (BSM) is the best operating mode for the two RF systems [1, 2] (with $\phi_{800} = 180^\circ$ above transition). However, ϕ_{800} is defined up to some unknown phase offset (ϕ_0), which can be found from a beam based calibration. This calibration is performed at the beginning of each operational run by measuring the symmetry of the longitudinal profile of a single low intensity bunch ($\sim 1 \times 10^{10}$ p) [3]. Finally, for high intensity operation the relative phase is selected by scanning around the BSM and finding the value that provides the most stable beam on the SPS flat top.

The importance of the double RF system operation for the beam stability in the SPS and the effect which the relative phase has on it, initiated different studies both for multi and single bunch beams [4, 5]. This paper presents the results of beam stability measurements performed with a single bunch in a single RF system as well as in a double RF system with a voltage ratio V_r of 0.25 between the two RF components at injection energy. Scanning ϕ_{800} for this voltage ratio, different stability regions were obtained as compared to the BSM phase that is being used in operation (with $V_r \simeq 0.1$). Numerical simulations, performed using the code ESME [6] for the impedance model of the SPS are compared with this, measured behavior.

MEASUREMENTS

Single bunch instability was studied in the SPS in order to understand better the use of a double RF system [3, 5]. Instability thresholds and growth rates were measured for different values of ϕ_{800} and V_r by varying the intensity of the bunch. In this paper we investigate the effect of phase shift between the two RF systems (ϕ_{800}) on the bunch stability. In order to enhance the effect of the 800 MHz component, we selected rather a large value of $V_r = 0.25$. The results presented here were obtained during one machine development (MD) session for constant bunch intensity and longitudinal emittance with conditions that are described below.

The single bunch intensity in the SPS was around 1×10^{11}, close to the nominal values of the LHC beam with a 25 ns bunch spacing. The voltage amplitude of the 200 MHz was set to $V_{200} = 1$ MV. This value is close to the match voltage for the bunch coming from the PS, and is much lower than the one used for the LHC beams, where capture losses impose higher values (2 MV at injection increased after 50 ms to 3 MV). Note that the results obtained in matched situation would be easier to compare with analytical calculations, where a steady state distribution is assumed. The longitudinal emittance ϵ_l of the injected bunches was around 0.25 eVs, again lower than nominal. The scanning of ϕ_{800} was performed around the BSM phase (ϕ_{800}^{BSM}). The feed-back, feed-forward and longitudinal dampers were switched off, whereas the phase loop was still acting on the bunch. The chromaticity was set high enough for the beam to be stable in the transverse plane. Longitudinal bunch profiles were acquired along the 3.7 s of the 26 GeV flat bottom (FB).

The stability analysis is based on the evolution of the 4σ bunch length τ along the FB, obtained after applying to each acquired profile a Gaussian fit (without corrections for pick-up and cable transfer functions [7] which can be neglected in our case). An increase of τ at the end of the acquisition time (3.7 s) together with large bunch length amplitude oscillations (ΔT) indicates an unstable situation.

Prior to the phase scan in a double RF system, measurements in a single RF were performed showing that the bunch was stable under these conditions. On the other hand, in the case of double RF system operating in BSM and for $V_r = 0.25$ the situation was very unstable, see Fig. 1. This observation doesn't in fact contradict with the statement that 800 MHz is necessary for beam stability in the SPS, since in operation a ratio of $V_r \simeq 0.1$ is used. Decreasing V_r to this value confirmed this result. Stability was also improving for $V_r = 0.25$ by shifting ϕ_{800} in both directions from the BSM phase, leading after some point to a stable situation. Figure 1 shows the bunch length variation for the BSM phase (blue trace) and for $\phi_{800} = \phi_{800}^{BSM} - 64°$ (green trace).

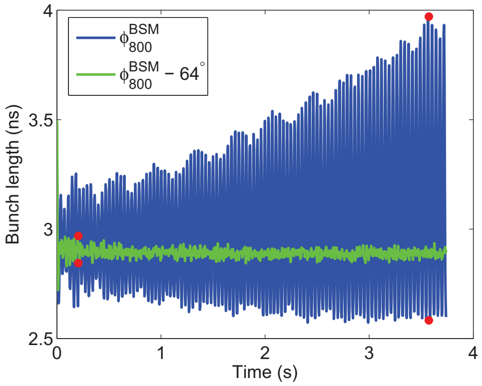

Figure 1: Bunch length evolution along the FB for $\phi_{800} = \phi_{800}^{BSM}$ and $\phi_{800} = \phi_{800}^{BSM} - 64°$. $V_{200} = 1$ MV and $V_{800} = 0.25$ MV.

As can be seen from Fig. 1 bunch is very unstable in the BSM since we observe a continuous increase both in τ and oscillation amplitude ΔT, the maximum of which is presented in the plot with the two red points. On the other hand, in the case of $\phi_{800} = \phi_{800}^{BSM} - 64°$ we can see that after damping of the initial oscillations (~ 100 ms) caused by the injection mismatch, the bunch remains stable for the rest of the cycle. Further, a phase shift towards the bunch lengthening mode (BLM, $\phi_{800} = 0$ above transition) was again leading to an unstable beam.

A summary plot of all the measurements with different values of ϕ_{800} (average of three acquisitions per value of ϕ_{800}), for $V_r = 0.25$ is presented in Figs. 2 and 3 (blue trace). Figure 2 displays the ratio of final to initial bunch lengths τ_{fin}/τ_{in} (averages for 100 ms), while Fig. 3 shows the ratio of final to initial bunch length oscillation amplitudes $\Delta T_{fin}/\Delta T_{in}$, multiplied by its maximum value ΔT_{max} (to take into account the cases where the maximum was reached not at the end of the acquisition). Therefore, in both figures higher values correspond to more unstable situations.

As follows from both plots stable regions appear between 50° and 100°, relatively far from the BSM phase in both directions and that a phase shift of around ±70° gives the best stability. Moreover, we can see that moving the phase towards BLM the beam starts to degrade again.

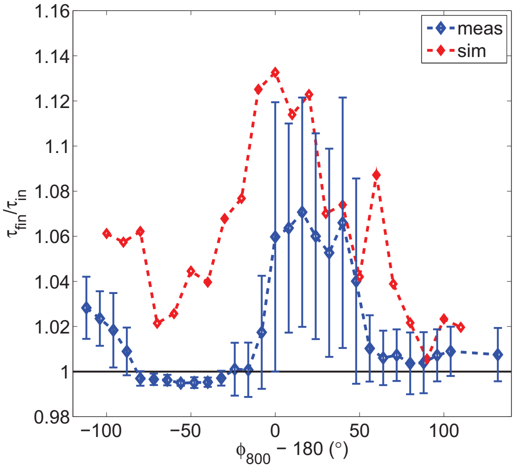

Figure 2: Ratio of final to initial bunch length obtained from measurements and simulations in the SPS double RF system for different values of ϕ_{800} and for $V_r = 0.25$. Bunch intensity $\sim 1 \times 10^{11}$ with $\epsilon_l \simeq 0.25$ eVs.

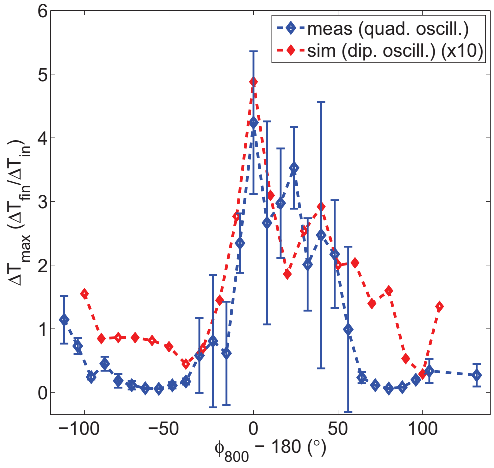

Figure 3: Ratio of final to initial quadrupole (measurements) and dipole (simulations) oscillation amplitude multiplied by its maximum value (ΔT_{max}) as a function of ϕ_{800} in the SPS double RF system with $V_r = 0.25$. Bunch intensity $\sim 1 \times 10^{11}$ with $\epsilon_l \simeq 0.25$ eVs.

SIMULATIONS

The results obtained in the measurements were compared with simulations performed using the code ESME (version es2009_4) [6], a longitudinal beam dynamics simulation program, after introducing the SPS impedance model. This model includes the fundamental modes of the 200 MHz (long and short types) and 800 MHz travelling wave RF systems, one higher order mode (HOM) of the

200 MHz RF system and the impedance of 16 kickers, the latter approximated by a broad-band resonator with Q=1. The parameters of main impedance sources used in simulations are presented in Table 1.

Table 1: SPS Impedance Model

	f_r (MHz)	R_s (MΩ)	Q
TWC200-F (long)	200.2	2.86	150
TWC200-F (short)	200.2	1.84	120
TWC200-H	629.0	0.388	500
TWC800-F	800.8	1.94	150
Kickers	800	0.06	1

The initial phase-space particle distribution of the bunch was obtained by reconstructing a typical tomography measurement in the PS and simulating it through the complicated RF manipulations till extraction to the SPS [8]. The results are summarized in Figs. 2 and 3 (red trace). A very good agreement between measurements and simulations for bunch length evolution in the SPS double RF system is shown in Fig. 2. Since simulations were performed in absence of beam phase loop the dipole oscillations are also present there and their amplitude is shown in Fig. 3 as a function of the phase shift ϕ_{800} together with the measured quadrupole oscillation amplitude. The threshold of the loss of Landau damping is usually lower for the $m = 1$ (dipole) mode and this is in fact what we observe from simulations.

This observation implies that the loss of Landau damping could be a possible explanation of the unstable cases appearing for certain phase shifts between the two RF systems, when any resistive wake would drive instability for the modes that are not anymore damped. This argument is supported by the synchrotron frequency distributions shown for a single RF and for different values of ϕ_{800} and V_r in a double RF system (no intensity effects) in Fig. 4. Indeed in the BSM with $V_r = 0.25$, particles in the tails of bunches used in our measurements (their emittance is shown with a vertical line) may lose Landau damping, since the derivative of the synchrotron frequency distribution as a function of action (bunch emittance) $\omega_s^{'}(J)$ is zero at this point [1]. However this dependence is monotonic for the other cases shown in the plot (including the operational BSM with $V_r = 0.1$), also stable in our measurements and simulations.

Analytical calculation of the loss of Landau damping threshold following the approach from [9] is not yet conclusive; this work is in progress.

CONCLUSIONS

Thresholds of longitudinal single bunch instability versus the relative phase between the two RF systems were measured in the SPS for a voltage ratio of 0.25 and constant intensity of $\sim 1 \times 10^{11}$. They show that a phase shift between 50° and 100° (at 800 MHz) in both directions (relative to the BSM phase) stabilizes the otherwise unstable bunch. Particle simulations using the SPS impedance model show a good agreement with these measurements. This dependence on phase shift, in addition to the sensitivity on the voltage ratio V_r (also observed in measurements), indicates that the loss of Landau damping in the flat region of the synchrotron frequency distribution inside the bunch can be a possible explanation for the observed undamped oscillations. This gives both a justification and the limitation to the 800 MHz voltage amplitude used in operation for the LHC beams in the SPS. Measurements for other bunch and RF parameters, with and without phase loop, are planned for this year.

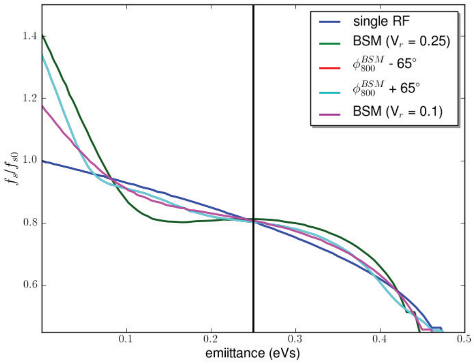

Figure 4: Synchrotron frequency distribution (no intensity effects) as a function of longitudinal emittance for different RF parameters. The bunch size in our measurements is shown with a vertical line.

ACKNOWLEDGMENTS

We would like to thank A. Burov for many helpful discussions and H. Bartosik, Y. Papaphilippou, G. Rumolo, B. Salvant and the OP shifts for their help during MDs. The work of C. Bhat is supported by Fermi Research Alliance under Contract No. DE-AC02-07CH11359 with the US DOE and US LARP.

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