# LONGITUDINAL INSTABILITIES IN THE SPS AND BEAM DYNAMICS ISSUES WITH HIGH HARMONIC RF SYSTEMS

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*Abstract*

Even after the successful impedance reduction programme which eliminated the microwave instability, longitudinal instability in the SPS is still one of the main intensity limitations. It is observed during acceleration for both single bunch and multi-bunch beams at intensities below the nominal LHC intensity. The thresholds are increased in the new SPS optics with lower transition energy, under intensive study now, but even in this case the 4th harmonic RF system is required for stability of the nominal beams. The upgrade program for both RF systems has started in the SPS to cope with future higher intensity beams required for the High Luminosity LHC. The results of studies of the parameter space required for beam stability are presented and compared with operation modes of double RF systems in other accelerators.

## INTRODUCTION

Already by the end of 2010 LHC beams with both 50 ns and 75 ns spaced bunches became operational and were regularly taken by the LHC. In 2012 the SPS has been able to deliver at top energy (450 GeV) up to four batches of 36 bunches spaced at 50 ns with bunch intensity of $1.6 \times 10^{11}$ and nominal longitudinal (0.5 eVs) and smaller than nominal transverse (2.5 $\mu$m) emittances. The LHC beam at 25 ns bunch spacing with nominal intensity of $1.2 \times 10^{11}$ ppb was also obtained in the SPS a few years ago.

Various LHC upgrade scenarios which are presently under consideration are based on the SPS beam with bunches of $2.2\times10^{11}$ ppb spaced at 25 ns or of $3.6\times10^{11}$ ppb spaced at 50 ns [1]. In both cases the SPS must be able to reliably accelerate much higher beam intensities than achieved so far and therefore significant improvements to the machine performance should be found and implemented on the same time scale as the LHC upgrade. The upgrades foreseen in the SPS are related to the known intensity limitations: beam losses, longitudinal coupled-bunch instabilities, beam loading in the two RF systems as well as heating of different machine elements. The present machine seems to be well scrubbed and no signs of e-cloud instabilities are observed for intensities achieved so far.

## LONGITUDINAL INSTABILITIES

### *Observations*

The longitudinal multi-bunch instability observed during acceleration has the lowest intensity threshold: one batch of 36 bunches at 50 ns spacing with $2 \times 10^{10}$ ppb and nominal injected longitudinal emittances (0.35 eVs) is unstable with the RF feedback, feed-forward and longitudinal damper (low modes) in operation. Possible sources of this instability are the fundamental and HOMs of the main (200 MHz) and high harmonic (800 MHz) RF systems.

As expected from the calculated threshold for the coupled-bunch instability [2], the threshold clearly depends on energy and longitudinal emittance: more dense bunches become unstable earlier in the cycle. A comparison of LHC beams with different bunch spacing $T_b$ shows that the energy threshold scales roughly as $1/E_{th} \sim N_b/T_b$, or with total beam current. Indeed in our measurements the 50 ns beam with a bunch intensity of $N_b = 1.6 \times 10^{11}$ was unstable around 160 GeV/c and the 25 ns beam with $N_b = 1.2 \times 10^{11}$ at 110 GeV/c. Higher intensity 25 ns and 50 ns beams are also at the limit of stability on the 26 GeV/c flat bottom.

On the other hand the instability threshold doesn't depend on the number of batches in the ring, at least for the 50 ns spaced beam (with 250 ns batch gaps), see Fig. 1 (top). This short-range wake is compatible with the main impedances of the 200 MHz and 800 MHz RF systems which have, correspondingly, quality factors of 150 and 300.

One batch consisting of 6 bunches with $N_b = 1.6\times10^{11}$ spaced at 50 ns became unstable over a wide energy range (240-410) GeV/c. Note that these bunches are held by the phase loop and are usually slightly (5%) shorter.

The single bunch instability threshold on the flat top is around $1.1 \times 10^{11}$ and on the flat bottom it is close to $1.3 \times 10^{11}$ in the operational voltage of 2 MV. Injected bunches continue to oscillate during the whole 11 s long flat bottom. The threshold for the loss of Landau damping during the operational cycle [2] calculated using Sacherer' criterion [3] suggests that single bunches should be much more stable on the flat bottom than observed. Measurements on the flat bottom with phase loop on show that this instability threshold strongly depends on the capture voltage. Bunches with this intensity are much more stable in the lower capture voltage of 1 MV, impossible to use in operation with the LHC beam due to beam loading leading to beam losses. Another possible explanation for the low threshold is related to the particular bunch distribution coming from the PS after bunch rotation, see [4], which creates high frequency modulation of the bunch profile.

The LHC beam in the present operation is stabilised by increased synchrotron frequency spread using a 4th harmonic RF system in bunch-shortening (BS) mode (see below) and controlled emittance blow-up, see Fig. 1 (center).



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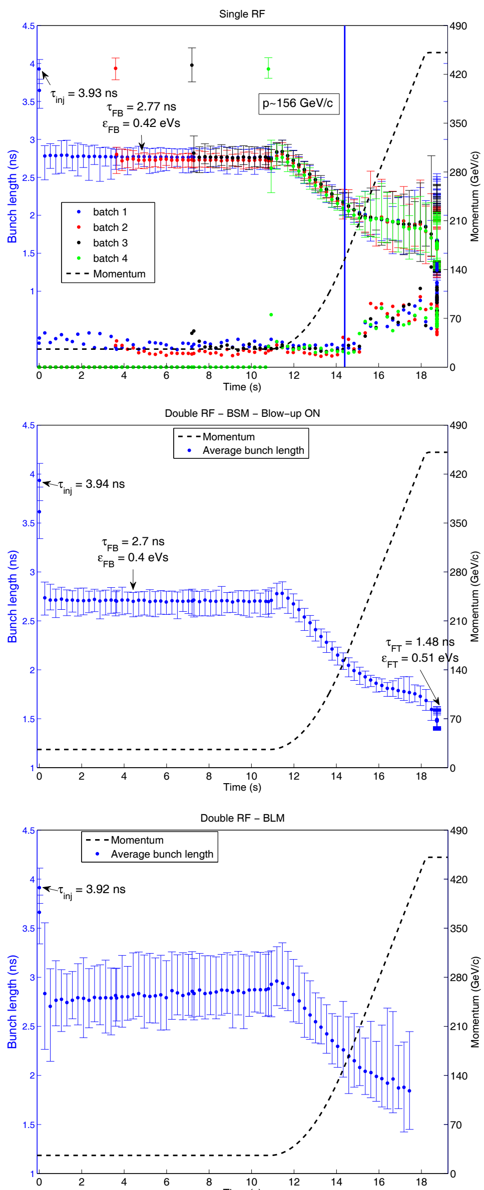


Figure 1: Average bunch length through the acceleration cycle for a 50 ns spaced beam. Injected average $N_b = 5.7 \times 10^{11}$. Top figure: single 200 MHz RF system, 4 batches of 36 bunches, no controlled emittance blow-up. The points on the bottom show the rms bunch length spread inside the batch. Center figure: one batch in a double RF system with $V_2/V_1 = 0.1$ in BS mode with controlled emittance blow-up. Bottom figure: as center figure but in BL mode and no controlled blow-up.

### *Cures*

The 800 MHz voltage during the cycle usually follows the 200 MHz voltage program at 1/10 level. In addition to the use of the 800 MHz RF system in bunch-shortening mode throughout the cycle, controlled emittance blow-up is performed with band-limited noise which increases the emittance to 0.5 eVs. The emittance blow-up in a double RF system has its own limitations due to the presence of beam loading [5]. Another possibility that has been studied is to inject larger emittance bunches, which in fact also improves beam stability in the PS, but may lead to increase of particle loss at the PS-SPS transfer. Promising results for optimisation of this transfer are presented in [4].

A decrease in transition gamma $\gamma_t$ from 22.8 to 18 was achieved by lowering the present tunes (26.13 and 26.18) by 6 units, see [6]. For a low transition energy the expected increase in TMC and longitudinal coupled bunch instability threshold is proportional to the slip factor $\eta = \gamma^{-2} - \gamma_t^{-2}$. However for the same longitudinal parameters the required voltage also scales as $|\eta|$. Already the maximum voltage (7.5 MV) is used for beam transfer to LHC, but the controlled emittance blow-up can also be reduced for the same intensity. Indeed the threshold for the loss of Landau damping $N_{th} \sim \varepsilon^2 \eta \tau$. Thus one needs a smaller emittance $\varepsilon \sim \eta^{-1/2}$ for stability, which gives the same bunch length $\tau$ in the new optics as with the present one. This scaling is in fact confirmed by many measurements performed in 2011 and 2012 [6]. Significant improvement in beam stability was obtained on the flat bottom. However on the flat top the high harmonic RF system is still insufficient for stability of ultimate bunch intensities and one needs in addition the controlled emittance blow-up, which however can be smaller than in nominal optics.

## HIGH HARMONIC RF SYSTEM

In many accelerators a high harmonic RF system is installed in addition to the main RF system for different applications:

(1) To increase synchrotron frequency spread

(2) To reduce peak line density

(3) To increase available bucket area

(4) For RF manipulations (bunch splitting, bunch rotation, controlled emittance blow-up, beam transfer ...)

The first two are mainly aimed at increasing beam stability. In the first case the high harmonic RF system is often called a "Landau cavity" to indicate an expected increase of beam stability through Landau damping. So-called passive high harmonic RF systems in electron storage rings use (by correct choice of cavity de-tuning) the voltage generated by the beam itself.

The total external voltage seen by the particle in a double RF system is

$$V_{ext}(\phi) = V_1 \sin\phi + V_2 \sin(n\phi + \Phi_2), \qquad (1)$$

where above transition (the case considered below) and for a non-accelerating bucket, $\Phi_2 = \pi$ in bunch-shortening (BS) mode and $\Phi_2 = 0$ in bunch-lengthening (BL); $n = h_2/h_1$. The latter is used much more often since it is more attractive for many reasons. For the same voltage and harmonic ratios the BL mode gives larger synchrotron frequency spread. In addition it provides larger bucket area

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as well as reduced peak line density and therefore reduced space charge effects and machine elements heating.

In the SPS the 800 MHz RF system was installed in the ring as a Landau cavity in 1979, but is in operation since a few years only. Now it is used for the LHC beams from injection through the cycle in addition to the main 200 MHz RF system. There are two 800 MHz travelling wave cavities in the SPS [7]. Only one is connected to the RF power, the second is idle. It was used in many beam studies over the last 10 years to prepare the SPS as an LHC injector. From the very beginning it was discovered that, unlike many other accelerators, only bunch-shortening mode works for beam stabilisation [2], see also Fig. 1 (bottom). Many studies were conducted in order to understand this fact [8, 9]. Two main restrictions with BL mode were identified: (1) the very tight requirements on the accuracy of $\Phi_2$; (2) the region with a local maximum in the synchrotron frequency distribution inside the bunch (essential for long bunches) reducing the instability threshold. These two issues are discussed below.

### *Phase Control Between the two RF Systems*

Much tighter control of the relative phase $\Phi_2$ between the two RF systems is required in BL mode which is very difficult to achieve due to strong beam loading in both the main and high harmonic RF systems [8]. Residual beam loading in the main 200 MHz RF system (with one-turn feedback and feedforward systems in operation) produces a steady state shift of bunch positions $\Delta\phi_s$ (at 200 MHz) leading to the fact that bunches at both batch edges see an 800 MHz phase different from that programmed. In the absence of acceleration this phase shift $\Delta\Phi_2$ is connected to the measured displacement of bunch position $\Delta\phi_s^{meas}$ as [5]

$$\Delta\Phi_2 = n\phi_s^{meas}(1 + nV_2/V_1). \quad (2)$$

For typical values $\Delta\phi_s^{meas} \simeq \pi/25$ at batch edges we have $\Delta\Phi_2 \simeq \pi/5$ for $V_2/V_1 = 0.1$ (value used in operation). This shift creates problems even in BS mode where the region of allowed phase shift $\Delta\Phi_2$ is much wider than in BL mode as can be seen in Fig.2 (top). This shift also leads to non-uniform controlled emittance blow-up when applying band-limited phase noise in a double RF system. Indeed due to the phase shift (2) the synchrotron frequency distribution also varies along the batch leading unexpectedly to longer bunches at the batch edges [5].

The phase calibration between the two RF systems is done in the SPS using the asymmetry of the RF potential well (and therefore of the bunch) as a function of the phase $\phi_2$. In Fig. 2 measurements of the bunch tilt (bottom figure) are shown together with expected asymmetry (shift of synchronous phase) for different voltage ratios of the two RF systems (top). Intersections of this curve with the line corresponding to the tilt of a low intensity bunch in a single RF system line give correct phases for BS and BL modes.

In the SPS operation (above transition) the phase $\phi_2$ is programmed during acceleration cycle as

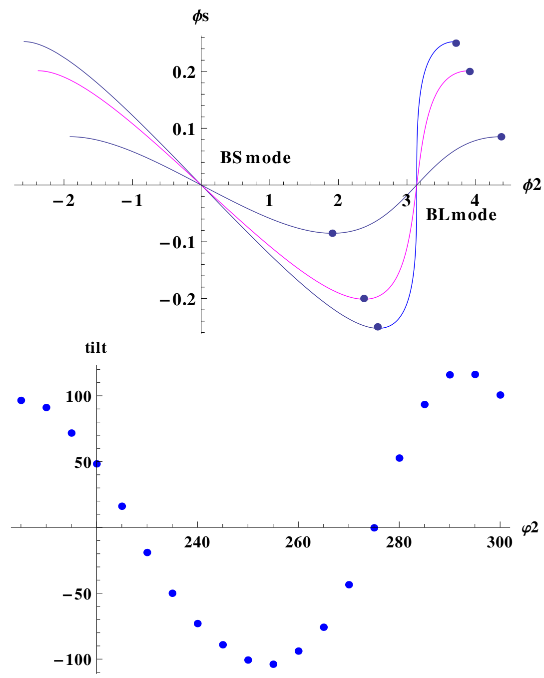


Figure 2: Calibration of phase $\Phi_2$ in the SPS. Top: calculated shift of the synchronous phase versus phase $\Phi_2$ for $V_2/V_1 = 0.25$ (maximum amplitude), 0.2 and 0.1. Region of BL mode is decreasing with voltage ratio increase. Bottom: measured bunch tilt (a.u.) versus relative phase (in deg at 200 MHz, unknown offset), 26 GeV/c, $V_2/V_1 = 0.2$.

$$\Delta\Phi_2 = -4\phi_{s0} + \pi, \quad (3)$$

where $\phi_{s0}$ is the synchronous phase in a single RF system. However in reality for high intensity beam the phase $\Phi_2$ is strongly affected by beam loading in the 800 MHz RF system itself.

Beam induced voltage in the TW RF system can be written in the form [7]

$$V_b = -I_2 r_c \left[ \left( \frac{\sin\theta/2}{\theta/2} \right)^2 - j\,2\,\frac{\theta - \sin\theta}{\theta^2} \right], \quad (4)$$

where for the SPS 800 MHz RF system $r_c = 0.968$ MΩ, $\theta = L/v_g(\omega - \omega_r)$ and cavity filling time $L/v_g = 0.33\ \mu$s. The phase slip between bunches and travelling wave $\theta$ is zero at transition energy and $\pi/6$ at flat top (450 GeV/c). During the cycle the beam current component at 800 MHz $I_2$ grows by approximately a factor 10 due to decreasing bunch length and on the flat top the induced voltage in the two cavities for the 50 ns spaced LHC beam with a bunch intensity of $1.6 \times 10^{11}$ is very close to the maximum operational voltage of $V_2 = 650$ kV. With one 800 MHz cavity in operation the phase $\Phi_2$ for total voltages in two RF systems is defined by

$$\sin\Phi_2 = \frac{V_b\cos\phi_3}{(V_b^2 + V_2^2 + 2V_2V_b\sin\phi_3)^{1/2}}, \quad (5)$$



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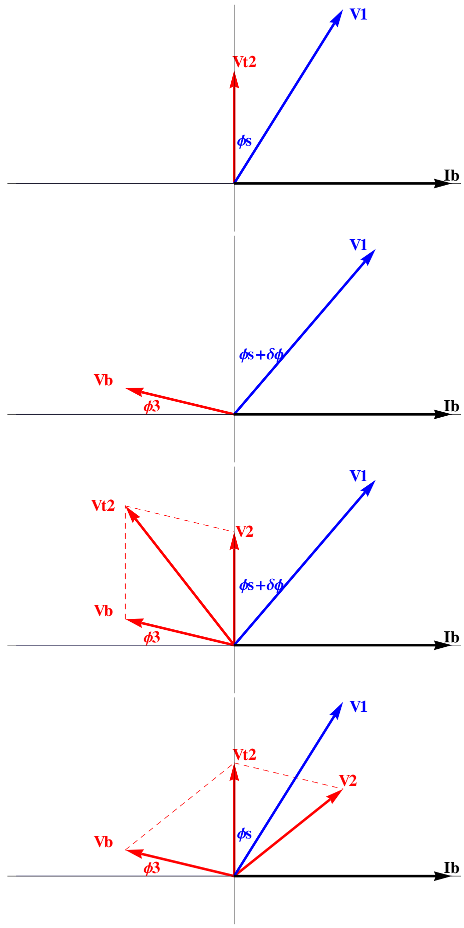


Figure 3: Schematic vector diagram showing the beam loading effect in the 800 MHz TW RF system in the SPS in steady state. From top to bottom: (1) no beam loading; (2) induced voltage in the 800 MHz RF system $V_b$ with the 800 MHz off $V_2 = 0$; (3) total voltage at 800 MHz $V_{t2}$ with the 800 MHz on and beam loading effect; (4) total voltage at 800 MHz when beam loading will be compensated by 1-turn feedback.

where $\phi_3 = \theta/3$. In this case on the flat top $\Phi_2 \simeq \pi/4$. The situation for beam stability is worse when the 800 MHz RF is switched off. In this case the phase of the high harmonic voltage is very far from BS mode: $\Phi_2 \simeq \pi/2 - \phi_3$. These cases are illustrated by the simplified vector diagrams (no transients and no beam loading in the 200 MHz RF system) in Fig. 3. This phase error is very difficult to take into account in the programmed phase shift during the cycle since it depends on beam intensity and bunch distribution. One should also remember that the first 6-7 bunches spaced by 50 ns see different induced voltage (and phase) due to transient beam loading in these cavities with a filling time of 330 ns. The only reliable solution to this problem is one-turn feedback and feedforward systems for the 800 MHz RF cavities, which will be implemented in 2014, and upgraded beam control of the 200 MHz RF system (2020).

### *Synchrotron Frequency Distribution*

The maximum change of the small amplitude synchrotron frequency, $\omega_s(0) = 0$, leading potentially to the maximum synchrotron frequency spread in the bunch can be achieved in BL mode, when $V_1/V_2 = n$, see Fig. 4. In this case for BS mode the increase of $\omega_s(0)$ is only $\sqrt{2}\omega_{s0}(0)$, where $\omega_{s0}$ is the synchrotron frequency in a single RF system.

The BL mode is characterised by the existence of regions where the derivative of the synchrotron frequency $\omega_s'(J) = 0$, where $J$ is the action. Note that this effect also appears in BS mode for sufficiently large voltage ratio, see Fig. 4. The second RF system with a high harmonic ratio $n = h_2/h_1$ provides larger synchrotron frequency spread for the same voltage ratio $V_2/V_1$, but as can be seen from Fig. 4, has more restricted parameter space (bunch length or voltage ratio for BS mode) for operation due to the fact that the regions where Landau damping is lost are in this case closer to the center of the bunch. From this point of view the second harmonic RF system has the largest useful parameter space.

This region created problems in the beam control of the

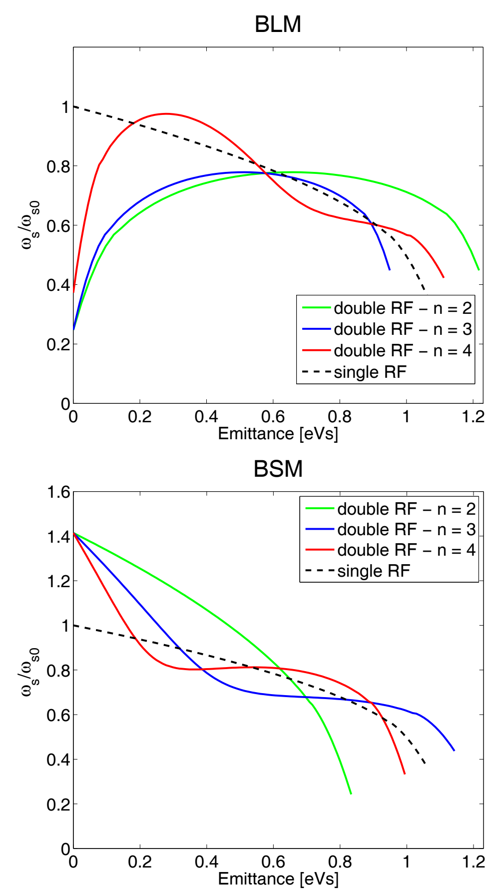


Figure 4: Synchrotron frequency distribution inside the bunch for different harmonic ratios $n = h_2/h_1$ and voltage ratio $V_1/V_2 = n$ for BL (top) and BS (bottom) modes. Example for The 100 MHz voltage $V_1 = 0.6$ MV, 26 GeV/c.

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CERN PSB due to the large coherent signal in a double harmonic RF system [10]. Large amplitude coherent response was also measured in BTF in BL mode at frequencies corresponding to $\omega_s'(J) = 0$ in the SPS [9]. Later the effect of non-monotonic behavior of synchrotron frequency on beam stability has been investigated both theoretically and by simulations. A much lower threshold for the loss of Landau damping has been found in a double RF system (BL mode) than in a single RF system for any bunch length due to space charge effect below transition in [11]. It has been shown in [12] with a resistive wake that the threshold for loss of Landau damping in BL mode is the highest for small emittances but for higher emittances drops first below the threshold in BS mode and then below the single RF case [12]. Recent calculations [13] using the same method as in [12] show similar behavior in an inductive impedance above transition [13]. However stability can be significantly improved by shifting the phase of the 2nd RF system and creating asymmetric bunches. These results, confirmed by numerical simulations, can explain observations during $p\bar{p}$ operation in the SPS at 26 GeV/c (above transition), when it was not possible to have stable flat bunches in a double RF system (100 MHz plus 200 MHz) above longitudinal emittance of 0.65 eVs [14] see Fig. 4 (top). In a similar way, by shifting phase $\Phi_2$, stability can be restored for long bunches in BS mode with $n = 4$ (as in the SPS) and voltage ratio of $1/4$. The measured dependence of the instability threshold on phase $\Phi_2$ between the two RF systems with single bunches was confirmed by simulations using the SPS impedance model [15]. This points out that non-monotonic behavior may also lead to problems in BS mode. This is why a low voltage ratio ($V_2/V_1 = 0.1$) is used through the cycle in operation in the SPS. It was observed that increase of voltage ratio in multi-bunch operation doesn't improve stability and could even degrade it on the flat bottom where bunches are the longest.

Note that for the accelerating regime the critical values of bunch length and voltage ratios can be smaller than in the storage regime.

Tilted bunches were also obtained in a double harmonic RF system in the CERN PS at 26 GeV/c (above transition) when BL mode was applied for otherwise successful stabilisation of relatively short bunches. This can be explained by the beam loading effect [16].

## SUMMARY

Active high harmonic RF systems are successfully used for beam stabilisation in many accelerators in the world, including the CERN SPS. The mode of operation of this system (bunch shortening or bunch lengthening) can be different depending on RF parameters (harmonic and voltage ratio), impedance of the ring (inductive or capacitive) and bunch length (usually short electron bunches or long proton bunches). Bunch lengthening mode of operation has many advantages but requires very tight phase control, difficult to achieve in the presence of strong beam loading, that may also affect operation in BS mode.

The second RF system with a high harmonic ratio provides larger synchrotron frequency spread for the same voltage ratio but has more restricted parameter space due to the fact that the regions where Landau damping is lost are in this case closer to the center of the bunch. From this point of view the second harmonic has the largest parameter space. All these considerations are much less important for short lepton bunches.

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