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SIMULATIONS OF LONGITUDINAL BEAM STABILISATION IN THE CERN SPS WITH BLonD

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Abstract

The Super Proton Synchrotron (SPS) at CERN, the Large Hadron Collider (LHC) injector, will be pushed to its limits for the production of the High Luminosity LHC proton beam while beam quality and stability in the longitudinal plane are influenced by many effects. Particle simulation codes are an essential tool to study the beam instabilities. BLonD, developed at CERN, is a 2D particle-tracking simulation code, modelling the longitudinal phase space motion of single and multi-bunch beams in multi-harmonic RF systems. Computation of collective effects due to the machine impedance and space charge is done on a multi-turn basis. Various beam and cavity control loops of the RF system are implemented (phase, frequency and synchro-loops, and one-turn delay feedback) as well as RF phase noise injection used for controlled emittance blow-up. The longitudinal beam stability simulations during long SPS acceleration cycle (~20 s) include a variety of effects (beam loading, particle losses, controlled blow-up, double RF system operation, low-level RF control, injected bunch distribution, etc.). Simulations for the large number of bunches in the nominal LHC batch (288) use the longitudinal SPS impedance model containing broad and narrow-band resonances between 50 MHz and 4 GHz. This paper presents a study of beam stabilisation in the double harmonic RF system of the SPS system with results substantiated, where possible, by beam measurements.

INTRODUCTION

The High-Luminosity Large Hadron Collider (HL-LHC) project [1] is the next milestone at CERN for the LHC and its experiments. The linac and the three synchrotrons in the injector chain will be upgraded to enable the production of HL-LHC proton beam with a bunch intensity N_b twice that of the current setup, as specified by the LHC Injector Upgrade (LIU) project [2].

The LIU target for the SPS, the LHC injector, is to produce four batches of 72 bunches spaced by 25 ns with an intensity of 2.4×10^{11} particles per bunch (ppb), each batch separated by 225–250 ns. Large particle losses, increasing with intensity, are observed at the SPS flat bottom [3] and multi-bunch longitudinal instabilities limit the ability to increase the bunch intensity [4]. The maximum bunch length allowed for the extraction to the LHC injection is fixed at 1.9 ns with an average value along the batches of 1.65 ns.

To reach the LIU target, major upgrades are necessary. The SPS RF system will have more cavities, more power available and a better control of the beam loading through the low-level RF control loops (LLRF). Moreover, the longitudinal beam-coupling impedance of the machine will be reduced, but the baseline improvements may be insufficient to ensure beam stability at HL-LHC intensities [4]. Further impedance reduction would be useful but is limited by technical and budget considerations. Therefore, different ways of enhancing beam stability also have been investigated.

Currently, to provide a good quality beam to the LHC, a second RF system operating at 800 MHz supports the main 200 MHz RF system of the SPS. It increases the synchrotron frequency spread inside the bunch and provides more effective Landau damping of beam instabilities [5]. The longitudinal beam dynamics of the bunch train in the SPS is, in general, too complex to be treated with analytical estimations for instability growth rates in a single RF system. The double RF system and the large number of contributors to the impedance make particle tracking simulations a powerful tool in the analysis of instability mechanisms. Moreover, beam measurements in conditions close to those after LIU upgrade cannot be achieved since the present RF system is limited in power for LIU beam intensities. Predictions of future performance and longitudinal instability thresholds rely mainly on numerical simulations.

The particle tracking simulation code BLonD (Beam LONgitudinal Dynamics) [6] was used to study effects of the second RF system on beam stability and results are substantiated with beam measurements where available. In the first part of the paper we present the simulation code and the features of the SPS simulations. Then, the effects of the 800 MHz RF system on beam stability at flat top are investigated. Very promising results have been obtained in simulation at highest energy but they cannot be applied at flat bottom as explained in the third part of the publication. Finally, the goal was to find an optimum RF program for the 800 MHz RF system during the full acceleration cycle to enhance beam stability, and results are presented in the last part.

FEATURES OF PARTICLE TRACKING SIMULATIONS IN THE SPS WITH BLOND

Developed at CERN, BLonD is a 2D particle tracking simulation code, modelling the longitudinal phase space motion of single and multi-bunch beams in multi-harmonic RF systems [6]. The particle motion is tracked through a sequence of longitudinal energy kicks and drifts. The equations of longitudinal motion are discretised in time on a turn-by-turn basis with a time step equal to the revolution

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period T_{rev} which is 23.1 µs in the SPS. Collective effects are taken into account by computing the induced voltage for a given impedance source, possibly on a multi-turn basis, added to the RF voltage. Various beam control loops of the LLRF system are tailor-made for each of the CERN synchrotrons; for example, the phase, frequency and synchro-loops, the one-turn delay feedback and the RF phase noise injection used for controlled emittance blow-up. The code is initially written in Python but the computationally intensive parts are optimized in C++ [7]. It has been benchmarked against measurements in different CERN accelerators [3,8,9] and also against other simulations codes like PyOrbit [10], Headtail [11] and ESME [12]. The code has been proven to be reliable and is now used to study performance of rings at CERN and even outside the laboratory.

Applied to the SPS, BLonD is an efficient tool in investigating instability mechanisms. There are many features which can be added in BLonD simulations, these include: the beam-coupling longitudinal impedance model, the large number of bunches in the beam, the bunch distribution defined by the injector, the double RF operation, the LLRF controls. During a nominal SPS cycle, four batches are injected every 3.6 s from the Proton Synchrotron (PS) with a synchronous momentum p_s of 25.92 GeV/c during the flat bottom which lasts 11.1 s. Then the beam is accelerated in 8.3 s to 451.15 GeV/c and is extracted to the LHC after half a second. Usually, only 72 bunches (or less) can be simulated because batches are weakly coupled by the SPS impedance sources [13], this keeps the computational time reasonable. At flat bottom, the bunch distribution defined by bunch rotation in the PS [14] leads to a full bucket and particle loss during direct bunch-to-bucket transfer [3]. The space-charge effect is not negligible at the injection energy [15] and is always included to the full SPS impedance model in the simulations. Other effects which impact beam stability during the cycle are the beam loading in the 200 MHz RF Travelling Wave Cavities (TWC), the particle loss, the controlled emittance blow-up applied during acceleration and the action of low-level RF controls.

SPS Longitudinal Impedance Model

The longitudinal SPS impedance model contains broad and narrow-band resonant modes between 50 MHz and 4 GHz [2, 16, 17], see Fig. 1.

The major contributors to the impedance model are the 200 MHz TWC. Both the accelerating and High Order Mode (HOM) bands contribute significantly. The fundamental pass-band impedance is reduced by the one-turn delay feedback and the feedforward whereas the HOM band at 630 MHz is damped by means of RF couplers. The two cavities at 800 MHz used for beam stability are of travelling-wave type and are included in the impedance model. The model also contains the kicker magnets with broad-band impedance, vacuum flanges and other vacuum equipment acting mainly at high frequencies (above 1 GHz). Many smaller contributions from beam instrumentation devices, resistive wall impedance, and space-charge are also included. The

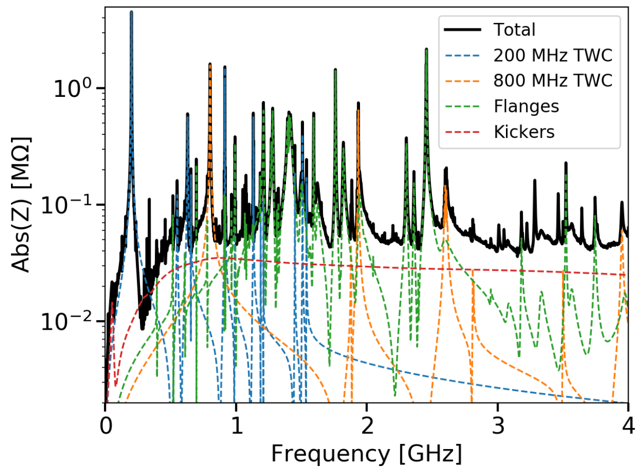

Figure 1: Longitudinal impedance model for the present configuration of the SPS. The contributions from the RF cavities, the vacuum flanges and the kicker magnets are also shown separatly [2, 16, 17].

impedance of all these devices has been stimulated and/or measured over many years.

To simulate the collective effects arising from the current impedance model, careful convergence study has been performed and the best available results are presented. A large number of macroparticles (usually 10^6 per bunch) are needed with a sufficient number of points in the wakefield calculation in frequency domain [9].

Double RF Operation in the SPS

The second SPS RF system operates at 800 MHz as a Landau system and is necessary to ensure stability of the LHC beam from intensity three times lower than nominal (1.15×10^{11} ppb). If the amplitudes of the 200 MHz and 800 MHz voltage are respectively V_{200} and V_{800}, the total voltage provided to a particle at phase ϕ is

$$V(\phi) = V_{200}\,[\sin\phi + r\sin(n\phi + \phi_{800})]\,, \quad (1)$$

where $r = V_{800}/V_{200}$ and $n = h_{800}/h_{200} = 4$ is the ratio of the harmonic numbers. The relative phase ϕ_{800} has a big impact on the synchrotron frequency distribution and can be determined to maximise the synchrotron frequency spread in the bunch center. At a given time in the cycle, the synchronous phase in a single RF system ϕ_{s0} is linked to the energy gain of the synchronous particle δE_s by

$$\delta E_s = V_{200}\sin\phi_{s0}. \quad (2)$$

For the same energy gain δE_s, the synchronous phase ϕ_s in double RF is related to ϕ_{s0} by

$$\sin\phi_{s0} = \sin\phi_s + r\sin(n\phi_s + \phi_{800}). \quad (3)$$

The synchrotron frequency in the bunch center $f_s(0) = \omega_s(0)/2\pi$ is modified by the second RF as follow

$$\omega_s^2(0) = \frac{\omega_{s0}^2(0)}{\cos\phi_{s0}}[\cos\phi_s + r\,n\cos(n\phi_s + \phi_{800})], \quad (4)$$

where $\omega_{s0}(0)$ is the synchrotron angular frequency in single RF. The value of ϕ_{800} maximising the synchrotron frequency

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spread is determined by Eq. (4) and the new synchronous phase is found from Eq. (3). At flat bottom or flat top in the SPS (above transition energy), $\phi_{s0} = \phi_s = \pi$. Two possible value of ϕ_{800}, 0 and π, maximise the synchrotron frequency spread. The first one ($\phi_{800} = 0$) is called the Bunch Lengthening Mode (BLM) and the second ($\phi_{800} = \pi$) is called the Bunch Shortening Mode (BSM). The names come from the effect these two modes have on the bunch length for $n = 2$.

The synchrotron frequency distribution can be written as a function of the single particle emittance (action variable). This emittance corresponds to the area enclosed by the particle trajectory in phase space and is measured usually in eVs. For $n = 4$, depending on the voltage ratio and the phase between both RF systems, the derivative of the synchrotron frequency distribution goes to zero and a plateau appears in the distribution, see Fig. 2. Particles in this region develop a large coherent response [18]. The Landau damping is lost and instabilities can be triggered by any perturbation.

In the nominal operation of the SPS, the BSM is used because only this configuration provides beam stability during ramp. The nominal bunch emittance is small enough to stay away from the plateau of the synchrotron frequency distribution for operational values of the voltage ratio ($r = 0.1$). This is not true in BLM where the flat portion appears for emittances smaller than nominal. The situation is also different at flat bottom where bunches are longer compared to flat top. During the cycle, the relative phase of the 800 MHz RF system is approximated in BSM by $\phi_{800} = \pi - 4\phi_{s0}$ [5].

EFFECT OF 800 MHz RF SYSTEM ON BEAM STABILITY AT SPS FLAT TOP

At high intensity, coupled-bunch instabilities are observed during the ramp. The mitigation measures for impedances giving the lowest stability threshold have been identified [4], but other possible cure also have been investigated, see, for example, [19]. The optimisation of the 800 MHz operation is one of them.

The intensity threshold, for constant emittance, increases with the relative synchrotron frequency spread [18], which is increased by a larger ratio r. For higher voltage ratios up to 0.3, bunches with nominal emittance (0.6 eVs after controlled emittance blow-up) are not affected by the flat portion of the synchrotron frequency distribution, see Fig. 2, and beam stability is improved when the voltage ratio increases. This effect has been seen in simulations and then tested in measurements. A batch of 12 bunches was used in measurements to be able to accelerate high intensity bunches since for 72 bunches the beam loading is too high for the RF power available. In this experiment, the nominal emittance of 0.35 eVs was used without controlled emittance blow-up during ramp. Figure 3 shows the average bunch length at flat top with error bars representing the maximum and minimum bunch length measured along the batch as a function of the bunch intensity in the case $r = 0.1$ (a) and $r = 0.25$ (b), kept during whole cycle. In the first case, large oscillations

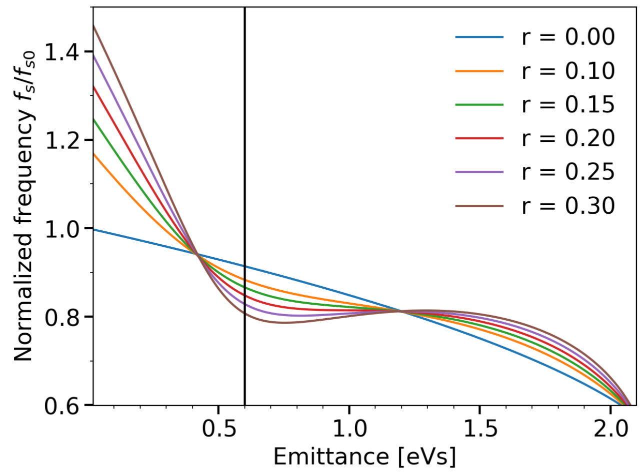
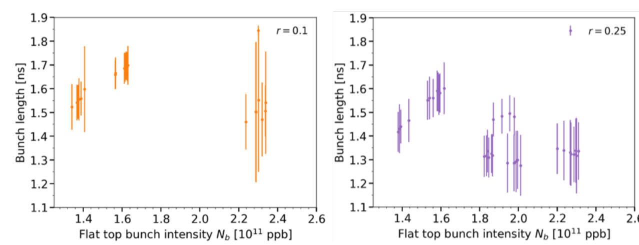


Figure 2: Synchrotron frequency distribution for the double RF system ($n = 4$) in BSM at SPS flat top as a function of the single particle emittance. For different values of the voltage ratio r, the frequencies are normalized by the synchrotron frequency in the bunch center computed for $r = 0$. The 200 MHz voltage is $V_{200} = 7$ MV. The vertical black line indicates the nominal bunch emittance at flat top (0.6 eVs).



(a) $r = 0.1$ (b) $r = 0.25$

Figure 3: Average bunch length at flat top measured for batches of 12 bunches with nominal emittance (0.35 eVs). The error bars represent the maximum and minimum bunch length measured along the batch. The cases $r = 0.1$ (a) and $r = 0.25$ (b), kept during whole cycle, are presented. The 200 MHz voltage at flat top is 7 MV and feedback and feedforward were activated during whole cycle.

are observed for higher bunch intensity ($N_b > 2.2 \times 10^{11}$) which are suppressed when $r = 0.25$. The bunch length is computed from the Full Width at Half Maximum (FWHM) of the bunch profile, rescaled to 4σ assuming a Gaussian bunch. Since the measured stability threshold is reproduced at flat top in simulations of 12 bunches (see [20]), simulations are then used to study the effect of the 800 MHz RF system on beam stability with a nominal batch containing 72 bunches. Operation also confirms the increase of beam stability with a larger voltage ratio r only on flat top.

Simulated Intensity Threshold for 72 Bunches

The instability threshold is at a minimum value at flat top. The simulations were done at a constant momentum of 451.15 GeV/c. Bunches which do not become unstable during acceleration can be considered as matched to the RF bucket with intensity effects at flat top. Then, 72 bunches

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spaced by 25 ns were generated with a bunch distributions matched to the RF bucket including intensity effects and parameters in agreement with measurements. The bunch distribution has the form of the binomial function

$$F(J) = F_0 \left(1 - \frac{J}{J_0}\right)^{\mu}, \qquad J \in [0, J_0], \tag{5}$$

where $J = 2\pi\epsilon$ is the action with ϵ being the bunch emittance. The emittance is computed in simulation by integrating the unperturbed potential well over the 4σ Gaussian bunch length obtained from the FWHM of the bunch profile; $J_0/2\pi$ is the initial bunch emittance and $\mu = 1.5$ was chosen, in agreement with measurements. Bunch emittance and intensity values were scanned to obtain the stability map.

The transient beam loading in the main 200 MHz RF system saturates quickly after injection and in the stationary regime, the impedance of the 200 MHz harmonic is reduced by the one-turn-delay feedback and feedforward by 20 dB, in agreement with measurements [3]. The present SPS impedance model has been used. The maximum voltage at 200 MHz was 7 MV for all intensities. Due to beam loading, the available voltage is intensity dependent and 7 MV can be obtained only at intensities comparable to nominal. However, the goal was to observe the effect of the fourth harmonic RF system; the power limitation will be raised in future. The simulated time at flat top was two seconds (compared to the 500 ms in the SPS operation) to observe slowly growing instabilities. However, in relevant intensity range, up to 2.5×10^{11} ppb, the multi-bunch instabilities are violent and appear before half a second. The ratio r was varied between 0.1 and 0.3. Larger values were not considered due to hardware limitations. A maximum ratio of 0.1 will be achievable for HL-LHC intensity after RF upgrades since the 200 MHz voltage at flat top will be increased to 10 MV. Figure 4 shows a good agreement of simulations with the reference measurements for the nominal case ($r = 0.1$) [4] and demonstrates that the SPS is already pushed to its limits for a batch of 72 bunches. Increasing the voltage ratio on flat top up to $r = 0.3$ improves the stability threshold. For the largest value, the intensity limit is increased by 150%. Simulations for situations after LIU upgrade also show that an increase of the voltage ratio can improve the stability threshold even beyond the scope of the HL-LHC project. However, other limitations will start to play a role—beam loading in the 200 MHz RF system for example.

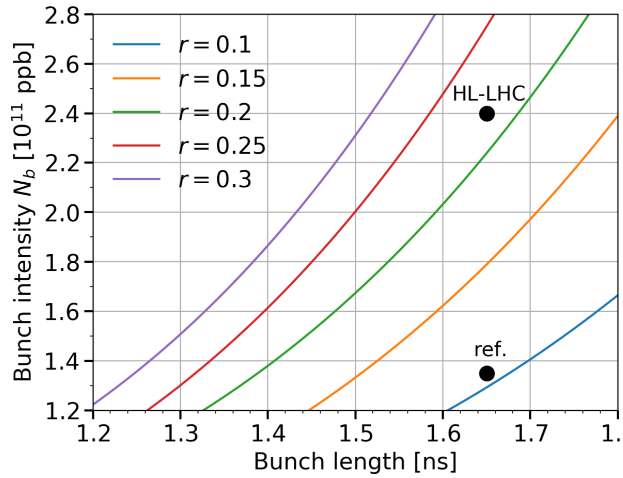

Figure 4: Simulated stability threshold at flat top as a function of the bunch length for 72 bunches spaced by 25 ns. The longitudinal impedance model (Fig. 1) is used. $V_{200} = 7$ MV and $V_{800} = r\,V_{200}$. A reference measurement for four batches with 72 bunches spaced by 25 ns is included [4], as well as the LIU intensity target. The maximum amplitude of the bunch length oscillations during cycle (normalised by the average) was used as a criterion to separate stable from unstable beams.

EFFECT OF 800 MHz RF SYSTEM ON BEAM STABILITY AT FLAT BOTTOM

The significant improvement of beam stability with a larger voltage ratio r cannot be obtained at flat bottom. In this case, some particles within the nominal injected emittance have a region in synchrotron frequency where the derivative goes to zero. With $V_{200} = 4.5$ MV, a flat portion in synchrotron frequency distribution appears for the voltage ratio above $r = 0.15$, see Fig. 5. Measurements also show larger bunch length oscillations at flat bottom when the voltage ratio r is increasing, see Fig. 6. For a ratio $r = 0.25$, the

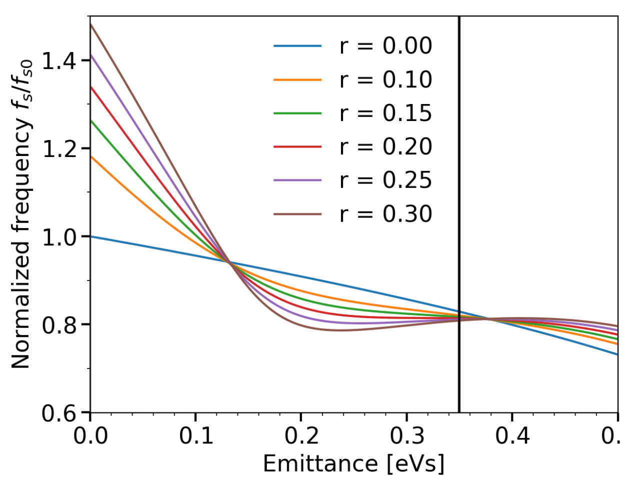

Figure 5: Normalised synchrotron frequency distribution for the double RF system in BSM at SPS flat bottom, as a function of the emittance for different value of the voltage ratio r. The 200 MHz voltage is $V_{200} = 4.5$ MV. The vertical black line indicates the nominal bunch emittance of 0.35 eVs.

bunch length oscillations increase compared to the lower value $r = 0.1$. Larger losses also appear at the start of acceleration.

When the feedback and feedforward were deactivated during whole cycle, a beam instability has been observed at flat bottom for different bunch train at lower intensity, comparable to nominal. The instability is likely caused by the impedance of the 200 MHz main harmonic which will be further reduced after planned RF upgrades. However, if another impedance source contributes to the instabilities, the 800 MHz RF system will lack efficiency to mitigate it, since

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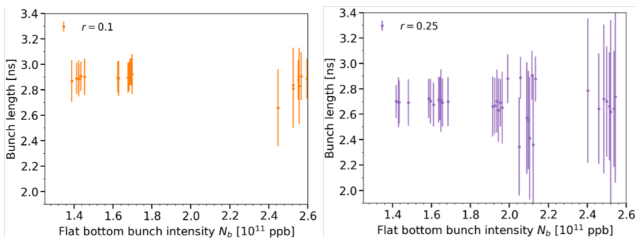

(a) $r = 0.1$ (b) $r = 0.25$

Figure 6: Average bunch length at flat bottom measured for batches of 12 bunches with nominal emittance (0.35 eVs). The error bars represent the maximum and minimum bunch length measured along the batch. The cases $r = 0.1$ (a) and $r = 0.25$ (b), kept during whole cycle, are presented. The 200 MHz voltage at flat bottom was 4.5 MV, feedback and feedforward were activated during whole cycle.

the bucket is full. With the one-turn delay feedback and feedforward activated at flat bottom, it has been observed that a voltage ratio of 0.1 provides better stability for trains of 48 bunches with intensities above nominal. To remove the plateau in the synchrotron frequency distribution, it is also possible to shift the relative phase ϕ_{800} away from the BSM. Improvements of the stability threshold with a phase shift have been shown in simulations [21]. However, the longitudinal acceptance, already full, is reduced.

The intensity thresholds measured for batches of 12 bunches without feedback and feedforward are presented in Fig. 7. First, simulations have been carried out with bunches matched to the RF bucket (with intensity effects). The maximum amplitude of the bunch length oscillations during cycle (normalised by the average) was used as a criterion to separate stable beam from the unstable one and similarly in measurements. As one can see in this case, the stability limit is far above the measured one. The simulations done with realistic bunches gave much better results. This indicates that the bunch distribution defined by the injector has a large effect on the instability occurring during the 10 s flat bottom cycle. The realistic distribution is defined by the bunch rotation in the PS and has an S-shape [3]. Particles completely fill the RF bucket after filamentation and resulting bunch profile has larger components interacting with the high frequency part of the machine longitudinal impedance.

The bunch distribution after rotation was generated by simulations in the PS without intensity effects. Bunches were matched at PS flat top with the distribution from Eq. (5) using a large number of macroparticles (3.6×10^7). The nominal RF program for bunch rotation in the PS is used. Then, each of the 12 bunches in the SPS are generated as a subset of one million macroparticles randomly selected. Simulations are compared with measurements done in single RF in Fig. 8. The measured stability threshold is reproduced if the rotated bunch distribution is used in simulation. The double RF operation with a voltage ratio $r = 0.1$ does not improve the beam stability.

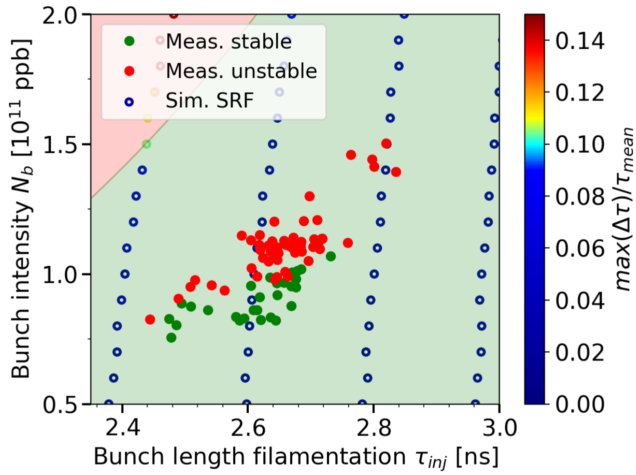

Figure 7: Stability threshold at flat bottom as a function of the bunch length after filamentation for 12 bunches matched to the RF bucket with intensity effects. The 200 MHz voltage is 4.5 MV and $r = 0$ (SRF), feedback and feedforward are deactivated. The longitudinal impedance model (Fig. 1) is used. Beam measurements in the same configuration are included. For simulations, colours of circles correspond to the maximum amplitude of the bunch length oscillations during cycle normalised by the average.

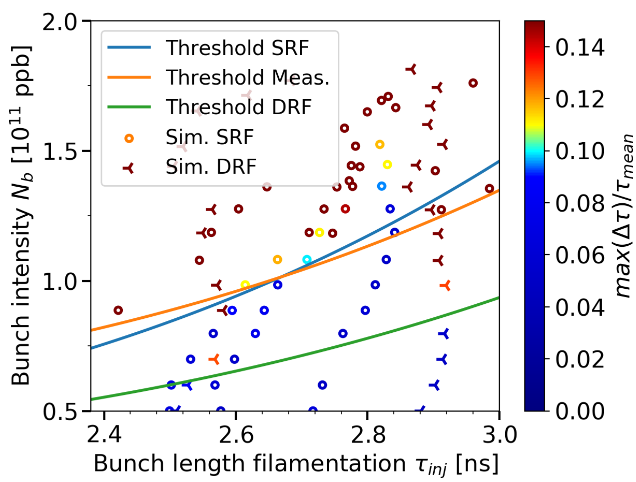

Figure 8: Intensity limit of 12 bunches as a function of the bunch length after filamentation at flat bottom. The bunch distribution is generated by simulations of the rotation in the PS. The single RF case (SRF) is compared with the intensity threshold measured under the same conditions. The results for double RF operation (DRF, $r = 0.1$) are also shown. The feedback and feedforward were deactivated. For simulations, colours of circles correspond to the maximum amplitude of the bunch length oscillations during cycle normalised by the average.

Different values of μ were used for the bunch generation in the PS. Figure 8 presents the results with $\mu = 1$ from Eq. (5) but similar stability limits are obtained for larger value of μ up to 2. Larger values of μ have been also studied and the intensity threshold decreases significantly. Assuming that the flat bottom instability can be cured by the one-turn delay

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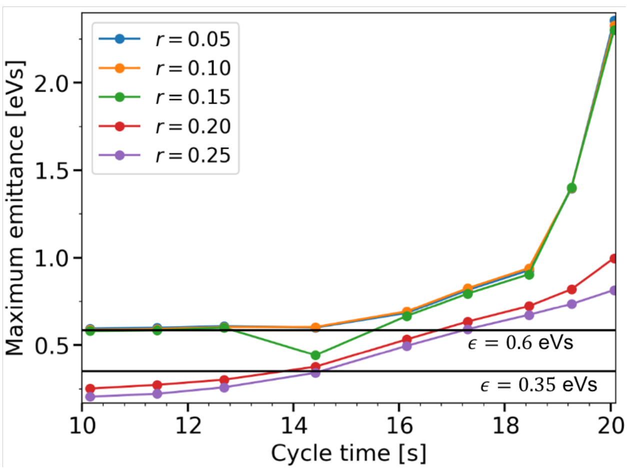

Figure 9: Maximum bunch emittance ϵ_{max} during cycle for different voltage ratios r, where ϵ_{max} is the critical emittance defined by Eq. (6) if it exists or the bucket area otherwise. The two horizontal lines show the nominal emittances at flat bottom (0.35 eVs) and at flat top (0.6 eVs).

feedback and feedforward systems, to improve the beam stability during all the cycle the voltage ratio should be kept at low value ($r \leq 0.1$) at flat bottom and increased during acceleration to reach the largest value at flat top.

VOLTAGE OPTIMISATION DURING CYCLE

To determine an optimal voltage ratio during cycle, we define the critical emittance

$$\epsilon_c = \min\{0 < \epsilon' \leq A \text{ such that } \frac{\partial}{\partial \epsilon} f_s(\epsilon = \epsilon') = 0\}, \quad (6)$$

where A is the bucket acceptance. If ϵ_c exists, the synchrotron frequency distribution has a plateau and ϵ_c is the maximum allowed bunch emittance ϵ_{max}. If ϵ_c does not exist, the maximum emittance is the acceptance. The synchrotron frequency and its derivative are computed numerically during cycle without intensity effects. The evolution of ϵ_{max} is shown for different voltage ratios in Fig. 9.

A voltage ratio $r \geq 0.15$ at flat bottom creates a plateau in the synchrotron frequency distribution for the nominal emittance, so the voltage ratio was fixed to $r = 0.1$. During acceleration, after 16 s (before blow-up), r can be increased to 0.15 and after 18 s the ratio can be increased to 0.25. The resulting voltage program is plotted in Fig. 10. These settings have been tested in real conditions with up to four batches of 12 bunches and improvement of beam stability was demonstrated for two different SPS optics (Q20 and Q22).

However, one should also keep in mind that intensity effects modify the synchrotron frequency distribution. In simulations for high intensity (2.3×10^{11} ppb) the synchrotron frequency distribution is affected by the induced voltage differently for each bunch. The frequency at zero amplitude is reduced by 4% for the first bunch and by 11% for the twelfth bunch. As a next step in the optimisation of the voltage

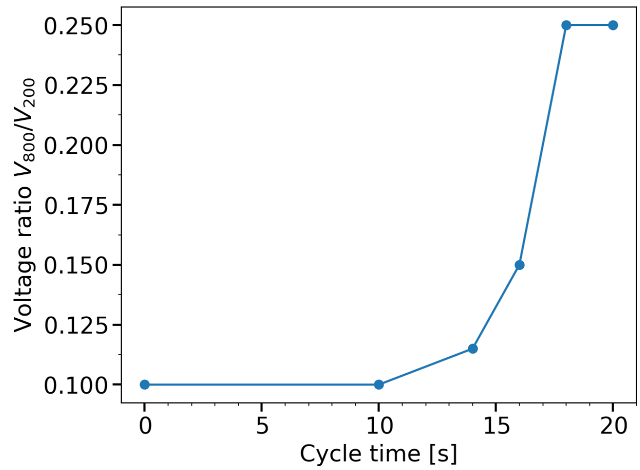

Figure 10: Optimised voltage ratio r between the two SPS RF systems during acceleration cycle for the LHC proton beam.

program, the collective effects could be taken into account in the design of the voltage program.

CONCLUSION

The fourth harmonic RF system is one of the main cures of beam instabilities in the SPS. Simulations have shown the possibility to significantly (by 150%) improve the stability threshold at flat top by increasing the voltage ratio between main and fourth harmonic RF systems. In the present operation, the voltage ratio of two RF systems is fixed at 0.1 during whole cycle. At flat bottom, larger bunch length oscillations are observed when the intensity increases up to 2.5×10^{11} ppb with voltage ratios larger than $r = 0.1$. They are caused by the plateau in the synchrotron frequency distribution. If the voltage ratio $r = 0.1$ is used at flat bottom and increased during ramp to reach $r = 0.25$ at flat top, the stability threshold is improved. The stability enhancement with these settings has been demonstrated in operation with four batches of 12 bunches for an injected intensity of $N_b = 2.3 \times 10^{11}$ ppb.

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