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Mitigation of intensity limitation in the CERN SPS using a double RF system

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The Super Proton Synchrotron (SPS) at CERN is the injector of the Large Hadron Collider (LHC). Multi-bunch instabilities limit the intensity of the beam that can be accelerated to 450 GeV in the SPS and transferred to the LHC. Without mitigation measures, the threshold of bunch intensity of the longitudinal instability is three times below the nominal bunch intensity of the LHC beam. The High Luminosity LHC project (HL-LHC), which requires a doubling of the nominal bunch intensity, relies on improvement of beam stability in the SPS. A fourth harmonic RF system allows, presently, to stabilize the beam up to nominal LHC intensity. It increases the synchrotron frequency spread inside the bunch, providing more efficient Landau damping of beam instability. However, nonlinearities of the synchrotron frequency distribution inside the bunch pose a limitation on bunch length. This paper explores possible intensity increase in the SPS by studying the effect on beam stability of the voltage ratio between two RF systems. The results are substantiated by beam measurements and particle-tracking simulations. An optimized voltage program of the second RF system during the cycle has been tested in operation and beam stability and the quality have been successfully improved.

Keywords: Double RF system; Landau damping; super proton synchrotron.

1. 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 LHC injector chain will be upgraded to enable the production of the 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 intensity target for the Super Proton Synchrotron (SPS), the LHC injector, is to extract

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to the LHC four batches of 72 bunches spaced by 25 ns with a bunch intensity of 2.3×10^{11} particles per bunch (ppb), each batch separated by 200–250 ns. During the acceleration cycle from 26 GeV/c to 450 GeV/c (transition energy $\gamma_{\mathrm{t}} = 18.0$), the multi-bunch longitudinal instabilities are a severe limitation for increasing bunch intensity.[3] Indeed, the maximum bunch length allowed for injection in the 400 MHz bucket of the LHC is fixed at 1.9 ns with an average value along the batch of 1.65 ns. It means that the longitudinal emittance of the bunch cannot be increased arbitrarily by uncontrolled longitudinal emittance blow-up, due to instability, or by controlled longitudinal emittance blow-up, which would increase the stability threshold. The limited RF power also restricts the maximum voltage available at flat top (450 GeV/c).

To reach the LIU target, major upgrades are necessary. The SPS RF system, operating at 200 MHz, will be upgraded with more cavities, more available power[4] and a better control of the beam loading through the low-level RF control loops (LLRF).[5] Moreover, the mitigation measures for impedances giving the lowest stability threshold have been identified[3] and are in the process of realization. Nevertheless, the baseline improvements may be insufficient to ensure beam stability at HL-LHC intensity. Further impedance reduction would be useful, but it is limited by technical and budget considerations. Therefore, different ways of enhancing beam stability have also been investigated, see, for example, Ref. 6. One of them is presented in this paper.

The multi-bunch instabilities in the SPS are coupled-bunch instabilities. They are cured, for nominal intensity (1.15×10^{11} ppb), by the second RF system, operating at 800 MHz. It provides more efficient Landau damping of beam instabilities[7] by increasing the synchrotron frequency spread within the bunch. Nevertheless, the intensity limit, in present operation, is below the HL-LHC intensity (2.3×10^{11} ppb).[3] The intensity threshold of coupled-bunch instability is proportional to the relative synchrotron frequency spread inside the bunch.[8] To reach higher intensity limits, a 800 MHz voltage larger than nominal would increase further the synchrotron frequency spread inside the bunch. However, the stability threshold can be drastically reduced for bunch lengths above some critical value, due to nonlinearities of the synchrotron frequency distribution inside the bunch, induced by the fourth harmonic or the intensity effects.

In this paper, the effect on beam stability, in the SPS, of different voltage ratios between the two RF systems is studied. The results of particle-tracking simulations, using the code BLonD (Beam LONgitudinal Dynamics),[9] with the detailed longitudinal impedance model[2,10–14] of the SPS, are presented, together with beam measurements. A possible way to improve the intensity threshold during the whole cycle is investigated. The paper is structured as follows. The synchrotron motion in a double RF system is presented in Sec. 1, where the effect of the second RF on the synchrotron frequency distribution inside the bunch is explained. In Sec. 2, the effect of the 800 MHz RF system on beam stability at flat top is examined (450 GeV/c), where promising results have been obtained, in simulations, for an increase of the intensity threshold. Section 3 explores the stability at flat bottom (26 GeV/c), where results obtained at flat top cannot be applied since the bunch length exceeds the critical value. Finally, an optimum RF program for the 800 MHz RF system to enhance beam stability during the full acceleration cycle is presented, before concluding.

1.1. *Double RF operation in the SPS*

The main RF system of the SPS consists of two four-section traveling wave (TW) structures and two five-section TW structures operating at 200 MHz,[10] where each section contains 11 cells. Together, they provide a total voltage with an amplitude V_{200} up to 7.0 MV for the nominal LHC beam. In addition, two three-section TW structures at 800 MHz, with 11 cells per section and four cells for the power couplers, deliver a total voltage with an amplitude V_{800} up to 2.0 MV for the nominal LHC beam. The double RF system generates a total voltage $V(\phi)$ at phase ϕ, measured in the RF radian units at 200 MHz,

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

where $r = V_{800}/V_{200}$ is the voltage ratio between the two RF systems, $n = h_{800}/h_{200}$ is the ratio of their harmonic numbers (equal to four in the SPS) and ϕ_{800} is the relative phase.

The synchrotron motion of an arbitrary particle is described, with respect to the synchronous particle, by the pair of coordinates $(\phi, \dot{\phi})$, where $\dot{\phi} = \frac{d\phi}{dt}$ is the conjugated momentum of ϕ.[15] The synchronous particle follows the reference trajectory along the accelerator structure. It circulates at an angular revolution frequency ω_0 and it crosses the accelerating gap of the cavity at the synchronous phase ϕ_s. The Hamiltonian of the synchrotron motion can be written as

$$H = \frac{\dot{\phi}^2}{2} + \omega_{s0}^2 U(\phi), \tag{2}$$

where $U(\phi)$ is the potential well defined by

$$U(\phi) = \frac{1}{V_{200}\cos\phi_{s0}} \int_0^{\phi} [V(\phi') - V(\phi_s)]d\phi', \tag{3}$$

and ω_{s0} is the linear angular synchrotron frequency in single RF,

$$\omega_{s0} = \omega_0 \sqrt{\frac{-eh_{200}\eta V_{200}\cos\phi_{s0}}{2\pi\beta^2 E_s}}, \tag{4}$$

with e being the elementary charge, β the velocity relative to the speed of light of the synchronous particle, E_s the synchronous energy and $\eta = 1/\gamma_{\mathrm{tr}}^2 - 1/\gamma^2$ the slip factor, where γ_{tr} is the transition energy and γ is the Lorentz factor.

The particle follows a trajectory in phase space of constant Hamiltonian. The region in longitudinal phase space, where the particle motion is bounded within the potential well, is call the RF bucket. If all changes are adiabatic, the Hamiltonian is quasi-static and the particle follows a trajectory of constant Hamiltonian. In this case, the action J is a constant of the motion and given by

$$J = \frac{\beta^2 E_s}{\omega_{RF}^2 \eta} \oint \dot{\phi} d\phi, \tag{5}$$

where the integration is taken along a trajectory of constant Hamiltonian. The area enclosed by the particle is called the longitudinal emittance ϵ, has dimensions eVs, and is related to the action by $\epsilon = 2\pi J$. The frequency of the synchrotron oscillations $\omega_s(J)$ is given by

$$\dot{\psi} = \frac{\partial H}{\partial J} = \omega_s(J). \tag{6}$$

In a double RF system, the angular synchrotron frequency in the bunch center, $\omega_s(0)$, is modified from the value in single RF, $\omega_{s0}(0)$, by the second harmonic as follows:

$$\omega_s^2(0) = \frac{\omega_{s0}^2(0)}{\cos\phi_{s0}}[\cos\phi_s + r\, n \cos(n\phi_s + \phi_{800})]. \tag{7}$$

The relative phase between the two RF systems, ϕ_{800}, can significantly modify the synchrotron frequency in the bunch center, and can be determined to maximize the synchrotron frequency spread within the bunch. This spread is close to maximum when $\omega_s(0)$ is maximum or minimum. The synchronous phase in double RF, ϕ_s, in (7) also depends on the relative phase ϕ_{800}. At a given time in the cycle, the synchronous phase in a single RF system ϕ_{s0} is linked to the energy provided to the synchronous particle in one revolution, δE_s, by

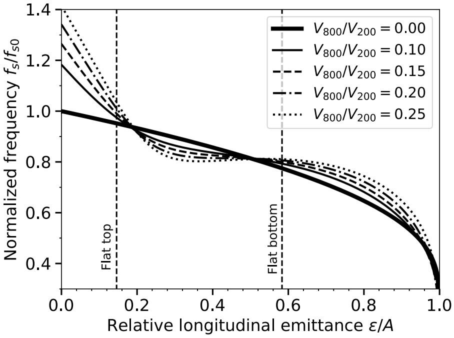
$$\delta E_s = \mathrm{eV}_{200} \sin\phi_{s0}. \tag{8}$$

The energy gain per turn is defined by the momentum program of the acceleration cycle and has the same value in single and double RF systems. Therefore, the synchronous phase ϕ_s in the double RF system is related to ϕ_{s0} by

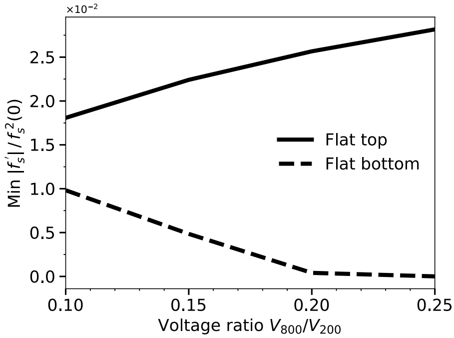
$$\sin\phi_{s0} = \sin\phi_s + r\sin(n\phi_s + \phi_{800}). \tag{9}$$

The synchronous phase in the double RF system and the value of ϕ_{800} maximizing the synchrotron frequency in the bunch center $\omega_s(0)$ can be determined from Eqs. (7) and (9). Without acceleration, two possible values of ϕ_{800}, 0 and π, maximize the value of $\omega_s(0)$. Above transition (as for the LHC beam in the SPS), 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 stem from the effect these two modes have on the bunch length for $n = 2$. In the SPS, the 800 MHz RF system operates in the BSM, since only this mode provides beam stability for the whole cycle.[7] In operation, during the ramp, the relative phase of the 800 MHz RF system is programmed in the BSM using

$$\phi_{800} = \pi - 4\phi_{s0}. \tag{10}$$



(a) Synchrotron frequency distribution



(b) Minimum of $\omega_s'(\epsilon \leq 0.35$ eVs)

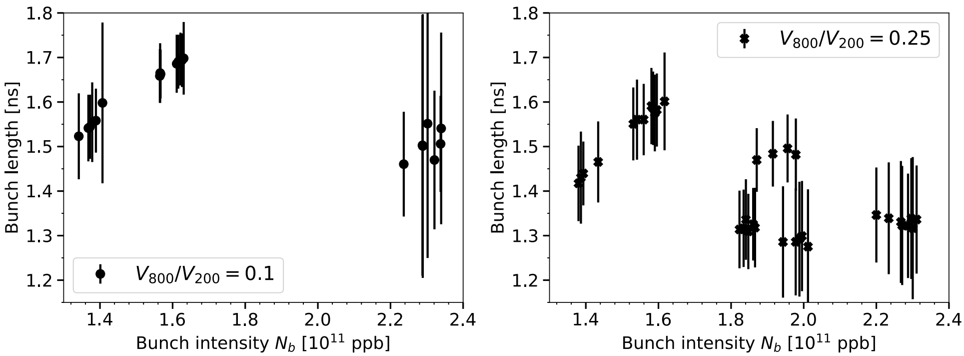
Fig. 1. Normalized synchrotron frequency in BSM as a function of the relative longitudinal emittance (a). The emittance is normalized to the bucket area A. The single RF case and the two RF system with different voltage ratios are shown. The dashed vertical lines present the relative longitudinal emittance at flat top (left line) and flat bottom (right line). The SPS 200 MHz voltage at flat bottom is $V_{200} = 4.5$ MV and at flat top $V_{200} = 7.0$ MV. The minimum of the derivative of the synchrotron frequency normalized, inside bunches with nominal longitudinal emittance, is also shown at flat top and flat bottom (b).

At flat bottom or flat top $\phi_s = \pi$ and, in nominal operation, $r = 0.1$ during the whole cycle.

For $n = 4$, as in the SPS, depending on the voltage ratio and the phase between the two RF systems, a plateau can appear in the synchrotron frequency distribution, where the derivative of the synchrotron frequency, is close to zero. Particles in the region with zero derivative may develop a large coherent response.[17] In this case, the Landau damping is lost and instabilities can be triggered by any perturbation. The normalized synchrotron frequency distribution as a function of the relative longitudinal emittance (normalized to the bucket area A) is shown in Fig. 1(a) for different voltage ratios. Increasing r increases the synchrotron frequency spread, but only for short bunches. Indeed, at flat top, bunches with nominal longitudinal emittance are far from the plateau in the synchrotron frequency distribution. At flat bottom, however, the bunch contains a region where the synchrotron frequency distribution becomes flatter with increasing voltage ratios. The Landau damping is lost when the derivative of the synchrotron frequency distribution goes to zero. In the case of small nonzero values of the derivative, the stability threshold is also reduced. The minimum of the synchrotron frequency derivative for different voltage ratios is shown in Fig. 1(b) for longitudinal emittances $\epsilon \leq 0.35$ eVs. At flat top, the voltage ratio can be safely increased from the nominal value but at flat bottom, the derivative is decreasing with V_{800}/V_{200} and approaches zero for ratios $V_{800}/V_{200} > 0.20$.

2. Effect of 800 MHz RF System on Beam Stability at SPS Flat Top

The effect of voltage ratio on beam stability was studied in the SPS. In measurements, a batch of 12 bunches was used to enable the acceleration of high intensity



(a) $V_{800}/V_{200} = 0.1$ (b) $V_{800}/V_{200} = 0.25$

Fig. 2. Average bunch length at flat top measured for one batch of 12 bunches with nominal longitudinal 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 the whole cycle, are presented. The 200 MHz voltage at flat top is 7 MV and feedback and feedforward were activated during the whole cycle.

beam, since, for nominal 72 bunches, the beam loading in 200 MHz RF system is too high due to lack of power. In this experiment, the nominal longitudinal emittance of 0.35 eVs was used. Figure 2 shows the average bunch length at flat top with error bars representing the maximum and minimum bunch length along the batch as a function of the bunch intensity. The two cases $r = 0.1$ (a) and $r = 0.25$ (b), kept during the whole cycle, are presented. The bunch length is computed from the Full Width at Half Maximum (FWHM) of the bunch profile, rescaled to 4σ assuming Gaussian distribution. In the case of a nominal voltage ratio (0.1), large oscillations are observed at high bunch intensity ($N_b > 1.8 \times 10^{11}$) which are suppressed when the voltage ratio is increased to $r = 0.25$. The instability, appearing at this intensity, can be cured at flat top with an increased voltage ratio. Operation also confirms the increase of beam stability with 72 bunches at larger voltage ratio on flat top. Since the measured stability threshold at flat top is well reproduced in simulations with 12 bunches (see Ref. 18), simulations are then used to study the effect of the 800 MHz RF system on beam stability with a nominal batch containing 72 bunches.

The instability threshold is at a minimum value at the SPS flat top.[8] The simulations are done at a constant momentum of 451.15 GeV/c. Bunches which did not become unstable during acceleration are assumed to be matched, at flat top, to the RF bucket with intensity effects. A batch of 72 bunches spaced by 25 ns was generated with particle distribution described by the binomial function

$$F(J) = F_0 \left(1 - \frac{J}{J_0}\right)^{\mu}, \quad J \in [0, J_0], \tag{11}$$

where $2\pi J_0$ is the initial longitudinal emittance. In agreement with measurements, the parameter μ was fixed to the value 1.5. The bunch length was computed in simulations, like in measurements, through the FWHM of the bunch profile, rescaled to 4σ assuming a Gaussian distribution. Then, the bunch emittance and intensity were varied to obtain the stability map.

The full SPS longitudinal impedance model was used in simulations. The transient beam loading in the main 200 MHz RF system saturates quickly after injection and, in the stationary regime, the 200 MHz impedance is reduced by the one-turn-delay feedback and feedforward by -20 dB.[5] Presently, the maximum voltage at 200 MHz is fixed to 7 MV. Due to beam loading, the available voltage is intensity dependent and 7 MV can be obtained only at nominal intensities.

The goal of studies was to observe the effect of the fourth harmonic RF system for future intensities; this power limitation will be raised in the future. The simulated time at flat top is 2 s (compared to the 500 ms in the SPS operation) to observe slowly growing instabilities. In the relevant intensity range, up to 2.5×10^{11} ppb, the multi-bunch instabilities are usually violent and appear before 500 ms. The voltage ratio between the two RF systems was varied between 0.1 and 0.25 since its maximum value is fixed by the ratio of the harmonic numbers.[7] A maximum ratio of 0.16 will be achievable for HL-LHC intensity after RF upgrade since the 200 MHz voltage at flat top will be increased to 10 MV. The stability thresholds for the different cases are shown in Fig. 3. A beam measurement of reference for the nominal LHC beam[3] is also included and agrees well with simulations. For HL-LHC, the SPS will be pushed to its limits. Increasing the voltage ratio at flat top up to $r = 0.25$ increases the stability threshold. With the largest value, the intensity limit is doubled for the nominal bunch length of 1.65 ns. Simulations for the situation after LIU upgrades also show that an increase of the voltage ratio can improve the stability even beyond the scope of the HL-LHC project. However, other limitations should be taken into account, one of them is beam loading in the 200 MHz RF system.

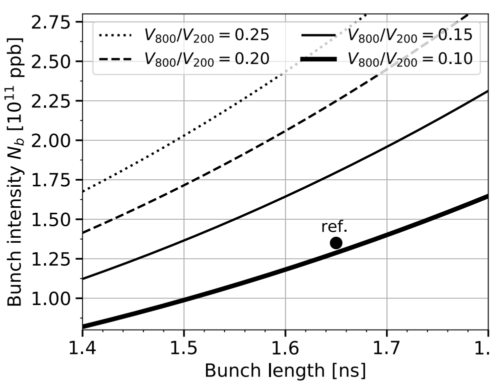


Fig. 3. Stability threshold simulated at flat top as a function of the bunch length for 72 bunches spaced by 25 ns. The full SPS longitudinal impedance model is used, $V_{200} = 7$ MV and $V_{800} = r \times V_{200}$. The beam measurement of reference with four batches of 72 bunches spaced by 25 ns is also shown by Ref. 3. The maximum amplitude of the bunch length oscillations during the cycle (normalized to the average) was used as a criterion to separate stable beams from unstable.

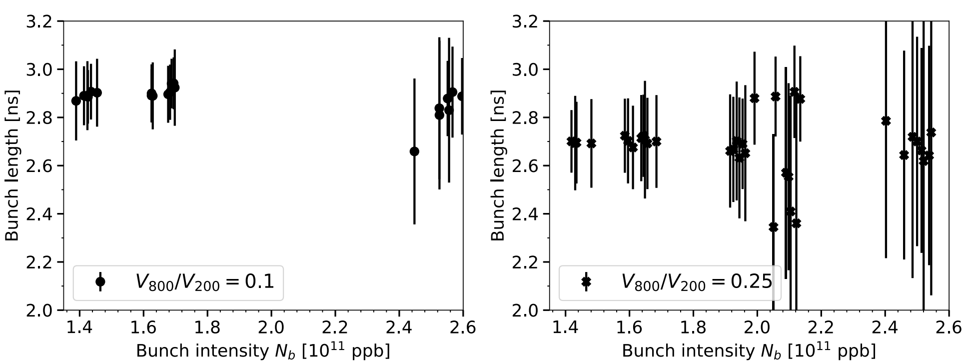
3. Effect of 800 MHz RF System on Beam Stability at Flat Bottom

Contrary to flat top, the significant improvement of beam stability with a larger voltage ratio cannot be obtained at flat bottom. Indeed, in this case some particles within the nominal injected longitudinal emittance are contained in a region where the derivative of synchrotron frequency is close to zero. Measurements also show larger bunch length oscillations at flat bottom when the voltage ratio r is increased from the nominal value of 0.1, see Fig. 4. Larger particle losses have also been measured at the start of the acceleration for increased r.

When the feedback and feedforward were deactivated, a beam instability has been observed at flat bottom, at nominal intensities. This instability is likely caused by the fundamental impedance of the 200 MHz RF system which will be further reduced after the planned RF upgrade. However, if another impedance source contributes to the instabilities, the 800 MHz RF system will lack efficiency to mitigate it, since after the beam capture, the RF bucket is full.[19] 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 than a larger value of the ratio for batches 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 with a phase shift have been demonstrated in the past in simulations.[20] However, the longitudinal acceptance is also reduced in this case, which may lead to additional losses.

The stability thresholds measured for batches of 12 bunches without feedback and feedforward are presented in Fig. 5. First simulations have been carried out with bunches matched to the RF bucket (with intensity effects). The maximum



(a) $V_{800}/V_{200} = 0.1$ (b) $V_{800}/V_{200} = 0.25$

Fig. 4. Average bunch length at flat bottom measured before acceleration (11 s), for batches of 12 bunches with nominal injected longitudinal emittance (0.35 eVs). The error bars represent the maximum and minimum bunch length along the batch. The cases $r = 0.1$ (a) and $r = 0.25$ (b) are presented. The 200 MHz voltage at flat bottom was 4.5 MV, feedback and feedforward were activated.

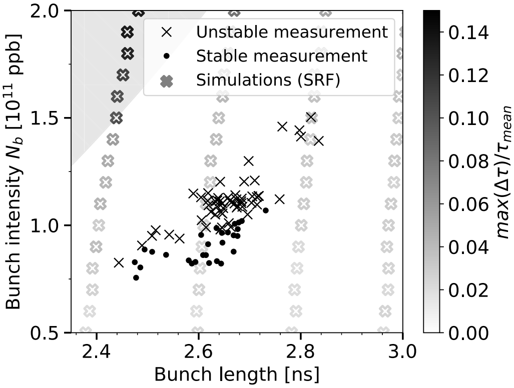


Fig. 5. Intensity threshold at flat bottom as a function of the bunch length after filamentation for a batch of 12 bunches matched to the RF bucket with intensity effects. The 200 MHz voltage is 4.5 MV, $r = 0$ (single RF), and feedback and feedforward are deactivated. The full SPS longitudinal impedance model is used. Corresponding beam measurements are included. For simulations, the grayscale of crosses corresponds to the maximum amplitude of the bunch length oscillations during the cycle, normalized by the average.

amplitude of the bunch length oscillations during the cycle (normalized by the average) was used as a criterion to separate stable beams from unstable, similarly to measurements. The stability limit was, however, far above the measured one. Much better agreement is obtained when the bunch rotation in the Proton Synchrotron (PS), injector of the SPS, is taken into account in simulations. This indicates that the realistic particle distribution, defined by the SPS injector, has a large effect on the instability occurring during the 10 s flat bottom. The particle distribution after the bunch rotation in the PS has a peculiar shape, called S-shape.[19] Particles completely fill the RF bucket after filamentation and the resulting bunch profile has larger components interacting with the high frequency part of the longitudinal machine impedance. The particle distribution after rotation was generated by simulations of the RF manipulation in the PS without intensity effects. Bunches were matched at PS flat top before rotation with the distribution from Eq. (11). The nominal PS RF program for bunch rotation was used. The 12 rotated bunches were then injected in SPS simulations and results were compared with measurements done in single RF in Fig. 6. The measured stability threshold is reproduced in simulations when the particle distribution produced by the bunch rotation is used.

The double RF system with a voltage ratio $r = 0.1$ was also applied in simulations. No improvement of beam stability has been observed in this case, even the intensity threshold is reduced.

Different values of μ have been used for the bunch generation in the PS. Figure 6 presents the results with $\mu = 1$ from Eq. (11) but similar stability limits are obtained for larger values of μ up to 2. Larger values of μ have also been studied and the intensity threshold decreases significantly. Assuming that the flat bottom instability can be cured by the one-turn delay feedback and feedforward systems, to improve

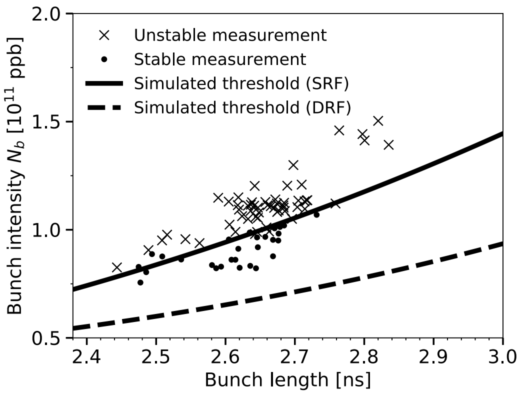


Fig. 6. Intensity thresholds at flat bottom as a function of the bunch length after filamentation for a batch of 12 bunches. The particle distribution is generated by simulations of the rotation in the PS. The simulated intensity threshold in single RF is compared with the beam measurements under the same conditions. The simulated threshold in double RF operation ($r = 0.1$) is also shown. The feedback and feedforward are off.

the beam stability during the whole cycle the voltage ratio should be kept at low value ($r \leq 0.15$) at flat bottom and increased during acceleration to reach the largest value at flat top.

4. Voltage Optimization During the Cycle

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

$$\epsilon_c = \min\{0 < \tilde{\epsilon} \leq A \text{ such that } \omega_s'(\tilde{\epsilon}) = 0\}, \tag{12}$$

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 $\epsilon_{\max}$. For larger longitudinal emittances, the Landau damping is lost. If ϵ_c does not exist, the maximum longitudinal emittance is chosen to be the acceptance. The synchrotron frequency and its derivative are computed numerically during the cycle without intensity effects. The evolution of $\epsilon_{\max}$ during the cycle is shown for different voltage ratios in Fig. 7. In the cases $r \leq 0.2$, the derivative of the synchrotron frequency distribution does not vanish during the cycle but it becomes very close to zero at flat bottom for $r = 0.2$. The intensity effects may modify the synchrotron frequency distribution and result in a loss of Landau damping. A voltage ratio $r = 0.1$ is more favorable for beam stability at flat bottom.

During acceleration, the voltage ratio can be gradually increased to reach the value of 0.25 at flat top. The resulting voltage program is plotted in Fig. 8. These settings have been tested under 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) with a bunch intensity up to 2.3×10^{11} ppb. The evolution of the bunch length during the cycle with the nominal voltage ratio and the optimized

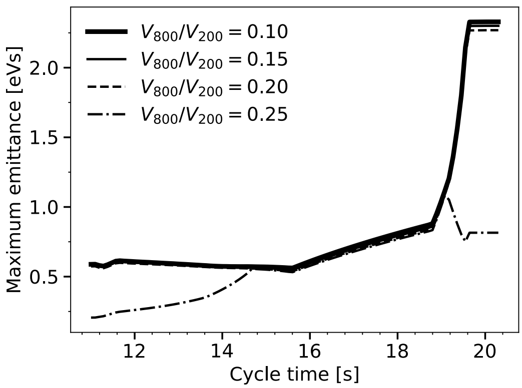


Fig. 7. Maximum longitudinal bunch emittance $\epsilon_{\max}$ during the cycle for different voltage ratios r, where $\epsilon_{\max}$ is the critical emittance defined by Eq. (12) if it exists or the bucket area A otherwise.

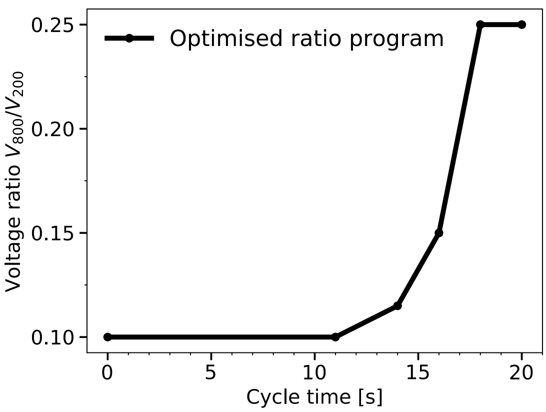


Fig. 8. Optimized voltage ratio r between the two SPS RF systems during the acceleration cycle for the LHC proton beam.

program is shown in Fig. 9 for the Q20 optics. The average bunch length of the third batch from four along the cycle is presented. In the case of the optimized program, bunches are less affected by the uncontrolled longitudinal emittance blow-up during acceleration and the final bunch length is smaller, which demonstrates the improvement of beam stability. 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 synchrotron frequency in the bunch center is reduced by 4% for the first bunch and by 11% for the 12th bunch. As a next step in the optimization, the collective effects could be taken into account in the design of the voltage program.

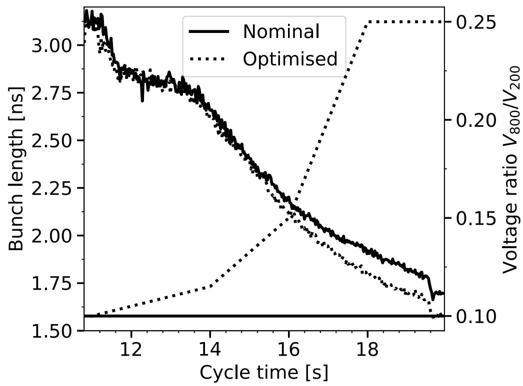


Fig. 9. Evolution of the bunch length, during the SPS cycle, for a bunch intensity $N_b = 2.3 \times 10^{11}$ ppb, in the Q20 optic. The nominal case (solid lines) is compared with the optimized voltage ratio program (dashed lines). The two voltage programs are also shown.

5. 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 improve (doubled) the stability threshold at flat top by increasing the voltage ratio between the main and the fourth harmonic RF systems. At flat bottom, larger bunch length oscillations are observed when the voltage ratio is increased. They are caused by the plateau in the synchrotron frequency distribution as a function of the particle phase oscillation amplitude. If the voltage ratio $r = 0.1$ is used at flat bottom and increased during the ramp to $r = 0.25$ at flat top, the stability is improved. The stability enhancement with these settings has been demonstrated in operation for four batches of 12 bunches with an injected intensity of $N_b = 2.3 \times 10^{11}$ ppb.

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