PAUL SCHERRER INSTITUT PSI	Project **SLS 2.0**
Title **Options for bunch length reduction in the SLS booster**	Document identification **SLS2-KJ81-005-1**
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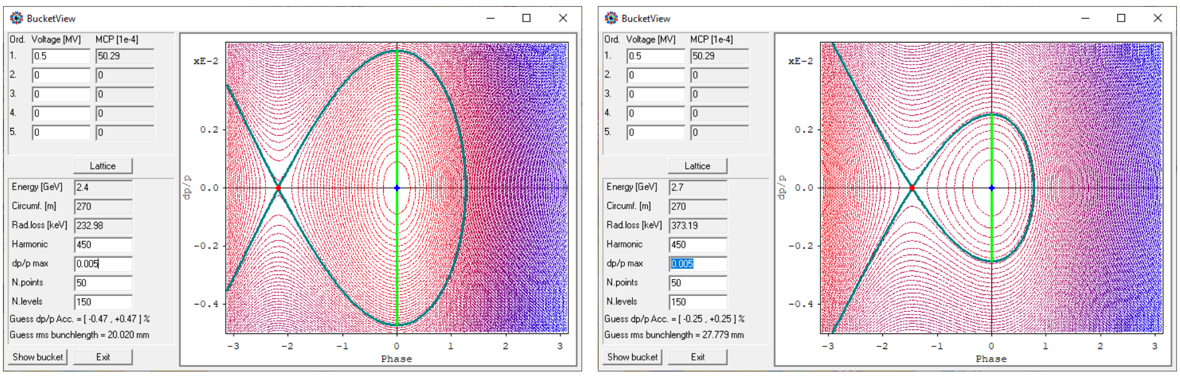
1 Introduction

The length of the bunch coming from the SLS booster is relatively long compared to the SLS 2.0 storage ring bucket, and in particular with respect to the stable 'golf-club' region of longitudinal phase space which may be utilized for longitudinal injection in the future.

The nominal RF voltage of the SLS booster is 500 kV, which at 2.4 GeV leads to an energy acceptance of approximately 5×10^{-3}. At 2.7 GeV the energy acceptance shrinks to only 2.5×10^{-3} as shown in Fig. 1. The RMS equilibrium bunch length at 2.7 GeV is 27.3 mm = 91 ps as calculated analytically using Accelerator Toolbox.

The very low energy acceptance at 2.7 GeV is small for particles affected by radiation damping and quantum excitation, which are then in risk of escaping the bucket when radiation is emitted. When including radiative effects in tracking simulations, there is a spillage of particles out of the bucket. More than 600 kV is needed to completely avoid losses. The booster cavity is an "Elettra-type" cavity which can, in principle, be operated up to 650 kV [1, 2]. At this voltage, the equilibrium bunch length becomes 21.6 mm (72 ps). Due to the simulation issues at 500 kV we will conduct all our tracking simulations in this document using a total RF voltage of 650 kV unless stated otherwise. It is noted that booster operation at 650 kV has not recently been tested in the SLS booster.



(a) 2.4 GeV (b) 2.7 GeV

Figure 1: RF buckets in the SLS booster with 500 kV voltage for 2.4 GeV and 2.7 GeV found using OPA.

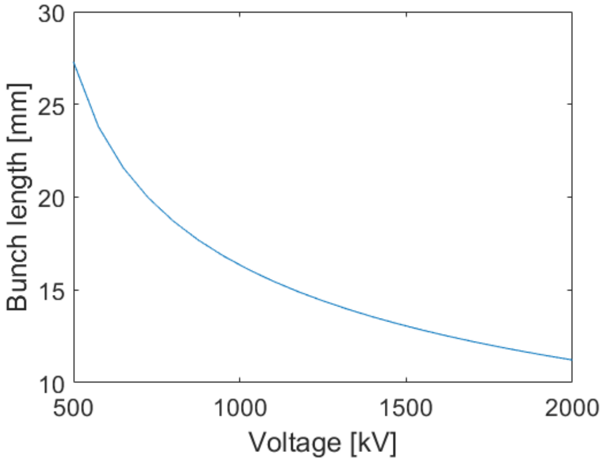


Figure 2: Variation of equilibrium bunch length in the SLS booster at 2.7 GeV as a function of total main RF voltage. Current operation voltage is 500 kV.

2 Static voltage increase

2.1 500 MHz

The first, and most straightforward, way of reducing the bunch length is by increasing the total main RF voltage in the booster. The equilibrium bunch length is given by [3]:

$$\sigma_z = \frac{\sqrt{2\pi}c}{\omega_0}\sqrt{\frac{\alpha_c E_0}{heV_{\rm rf}\cos\phi_s}}\frac{\sigma_E}{E_0} = \frac{\sqrt{2\pi}c}{\omega_0}\sqrt{\frac{\alpha_c E_0}{he}}\left(V_{\rm rf}^2 - U_0^2\right)^{-\frac{1}{4}}\frac{\sigma_E}{E_0}, \tag{1}$$

where the most interesting quantities are the momentum compaction factor, α_c, the total main RF voltage, $V_{\rm rf}$, the energy loss per turn, U_0, and the energy spread, σ_E. From this equation it is clear that increasing the RF voltage will lead to a reduction of the bunch length. Fig. 2 shows the effect of increasing the RF voltage on the bunch length in the SLS booster. Currently, the SLS booster operates at 500 kV, which will provide an equilibrium bunch length of 27 mm at 2.7 GeV. Increasing the total voltage to 1 MV would lead to a 16.3 mm bunch. This can potentially be achieved using one of the old Elettra-type cavities leftover from the SLS. A higher-voltage option would be to install one or two five-cell PETRA cavity[4], which could provide a voltage in the range 1-2 MV, thereby lowering the bunch length to 11.2 mm (36.4 ps) at 2 MV. These cavities are found in other boosters, e.g., the Elettra and Diamond (and Diamond-II) boosters [5, 6, 7]. However, such an installation would require significant work and investment on, e.g., new amplifiers and more [8].

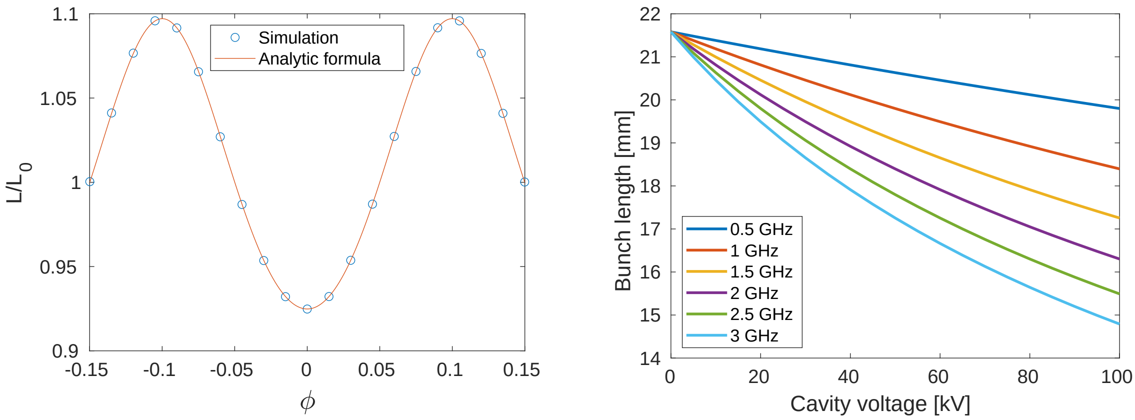
2.2 Higher harmonic

Instead of increasing the voltage of the main-harmonic 500 MHz system one can instead introduce a higher-harmonic RF system. This is well-known from storage rings where higher-harmonic cavities are used so lengthen bunches. We intend to do the opposite by shortening the bunch. Eq. (1) describes the equilibrium bunch length of an effective single-cavity system. The bunch shortening effect comes from the derivative of the RF voltage around the bunch arrival time. For a cavity which is adjusted to the synchronous phase, the voltage gradient is $V_{\rm rf}\cos(\phi_s)$. To see how higher-harmonic cavities can be helpful, we generalize Eq. (1) to an arbitrary number of cavities and phases:

$$\sigma_z = \frac{\sqrt{2\pi}c}{\omega_0}\sqrt{\frac{\alpha_c E_0}{he}}\frac{\sigma_E}{E_0}\sum_{i=1}^{M}\left(n_i V_{\text{rf, }i}\cos(n\phi_i)\right)^{-1/2}, \tag{2}$$

where M is the number of cavities and n_i is the harmonic number of the ith cavity. Note how ϕ_i is now generalized; the maximum gradient of a sine-wave is at the zero crossing ($\phi = 0$), but this will not be stable for an accelerating bucket (i.e., the case where the beam experiences synchrotron radiation). In practice, one cavity in a multi-cavity system should de tuned to provide the necessary bucket height while the remaining cavities may be set to the zero-crossing for maximum gradient. Note also that the bunch length scales with $\sqrt{n}$, indicating that a higher-harmonic cavity will be more effective at bunch lengthening for a constant cavity voltage.

The results of a scan of phase for a 3th harmonic cavity (1.5 GHz) with 30 kV voltage is shown in Fig. 3a. The analytic formula agrees very well with calculated equilibrium parameters. Setting the harmonic cavity to the zero crossing provides the best bunch shortening. In Fig. 3b we have scanned the voltage for different cavity harmonics with the phase set to zero crossing. An evaluation of the technical feasibility of having a higher-harmonic cavity in the booster has not yet been performed; it is therefore unclear what kind of voltage can be achieved in practice.



(a) (b)

Figure 3: a) ratio of equilibrium bunch length with a 3th harmonic secondary cavity with 30 kV as a function of phase relative to the bunch length without the secondary cavity. b) Absolute bunch length as a function of cavity voltage and RF frequency of secondary cavity at zero crossing.

3 Resonant voltage modulation

3.1 $2f_s$ modulation using 500 MHz-system

Studies at the Photon Factory at KEK have shown that bunch compression is possible by modulating the RF voltage at twice the synchrotron tune [9]. The same simulation is done for the SLS booster. The RF voltage is modulated as:

$$V_{\mathrm{rf}}(t) = V_0 + V_{\mathrm{mod}} \sin(2\pi(2f_{\mathrm{s}})t), \tag{3}$$

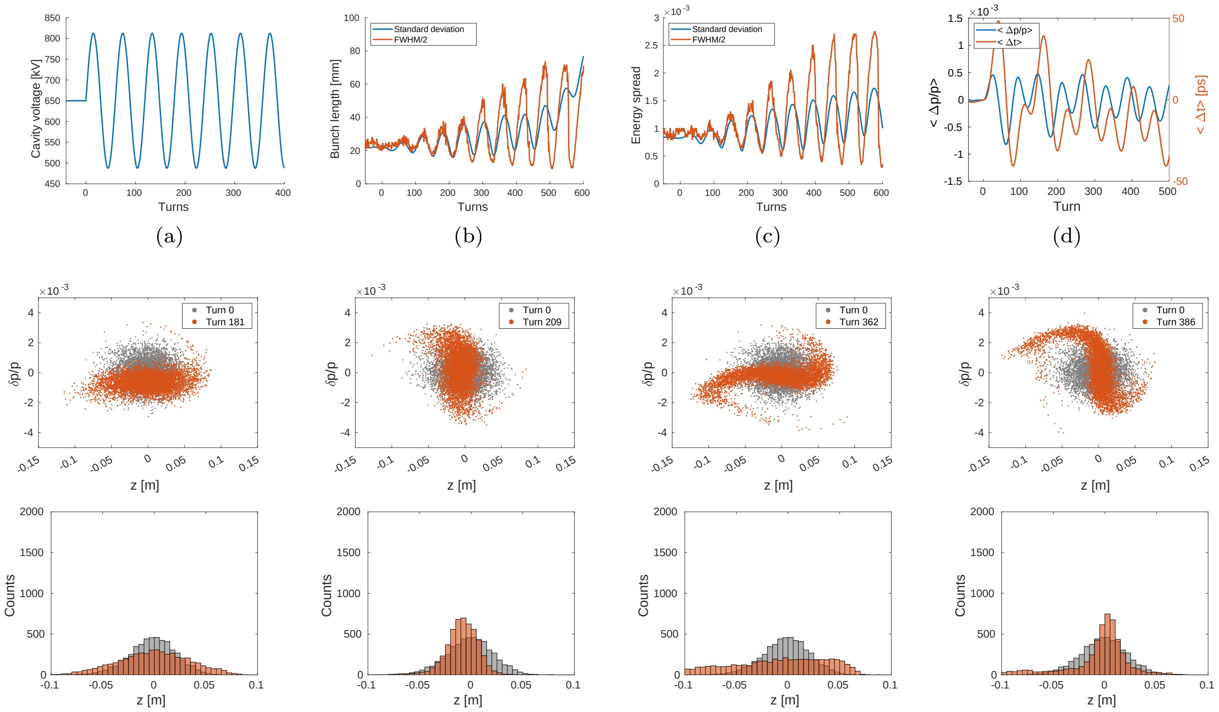
where V_0 and V_{mod} are the nominal and modulation voltage, respectively, while f_{s} is the modulation frequency set to the synchrotron frequency.

The situation is simulated in the SLS booster following the “fast excitation” procedure from [9]. As described in Section 1, the RF voltage is assumed to be 650 kV, and a 25% modulation, corresponding to 162.5 kV, is applied. The synchrotron tune is 0.0084, meaning that the synchrotron frequency and period is 9.4 kHz and 119 turns, respectively. The “fast excitation” is characterized by an abrupt start of the modulation rather than a modulation of slowly increasing amplitude. A bunch of 5000 particles is tracked in the booster lattice with synchrotron radiation and quantum excitation effects enabled.

The resulting bunch length and energy spread are shown in Fig. 4 together with a few examples of the longitudinal phase space. The bunch length and energy spread is both computed as standard deviation and full-width half-maximum (FWHM): As the bunch undergoes several synchrotron oscillation periods the bunch stops being

Gaussian and the width is therefore not well-described by the standard deviation any more. This is particularly clear when looking the longitudinal phase space at turn 362, where the histogram of the particle distribution is clearly narrower than for turn 209, but the long tails make the standard deviation of the bunch large. A drawback of this method is that it introduces oscillation of the average energy and bunch arrival time as shown in Fig. 4d. The oscillation arises as a consequence of the non-zero synchronous phase of the booster cavity. To visualize the problem we have plotted the RF voltage with nominal, maximum and minimum voltage according to Eq. (3) with respect to the bunch arrival time in Fig. 5 without and with synchronous phase. The dots highlight the voltage seen by the beam. When the synchronous phase is zero (Fig. 5a), the bunch sees no centroid voltage difference for the three voltage curves, but rather only a gradient error, i.e., the voltage modulation introduces a quadrupolar oscillation. However, when the synchronous phase is the nominal value of 0.6 rad, the bunch will see variations of the voltage, leading to both a dipolar and quadrupolar oscillations longitudinally. To ensure that no dipolar oscillations occur, it is neccessary to also introduce a phase modulation, which depends on the synchronous phase, as described in Appendix A.

Obviously, bunch compression using this type of method is transient, meaning that the bunch does not reach a lower equilibrium bunch length. Evidently, the bunch must be extracted at the time when the bunch length is minimized.



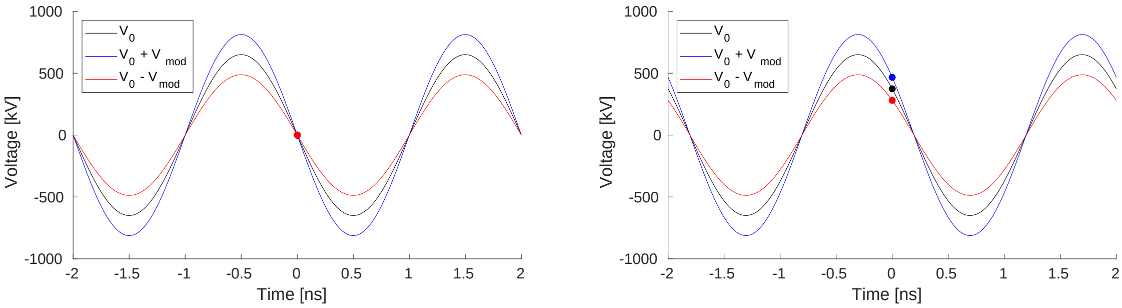
(a) (b) (c) (d)

(e) Turn 181 (f) Turn 209 (g) Turn 362 (h) Turn 386

Figure 4: Bunch lengths, energy spreads and longitudinal phase spaces before and during a 25% RF voltage modulation at a frequency of twice the synchrotron tune.

3.2 Higher-harmonic

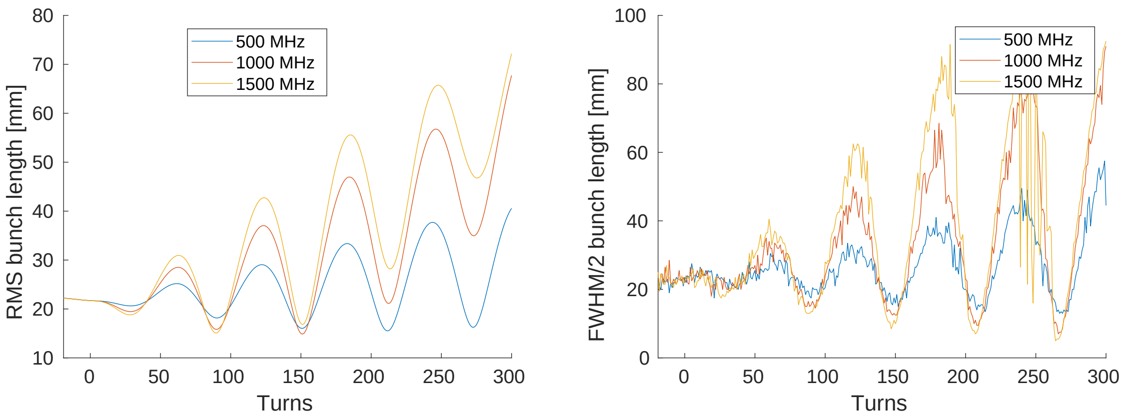
A configuration using higher-harmonic cavities can be envisioned as providing the oscillating voltage rather than the main cavity. The benefit in using a higher-harmonic cavity is the larger gradient around the zero-crossing, leading to a stronger excitation of the quadrupolar oscillations. In the following, we perform the same calculation as above, but using three different frequencies: 0.5 GHz, 1.0 GHz and 1.5 GHz corresponding to the main, second and third harmonic. A voltage of 100 kV is used for each case. Results are shown in Fig. 6. The higher frequencies seem to be beneficial at compressing the beam due to the higher gradient. However, as more oscillations are performed, the effect of the non-linearities from the shorter wavelengths makes the phase space more diffuse, which leads to longer RMS bunch lengths.



(a) (b)

Figure 5: Voltage curves for the cavity as a function of arrival time of the bunch. a) with zero synchronous phase, b) with nominal synchronous phase of 0.6 rad

One benefit of using a second cavity to do the resonant modulation is that the cavity will not introduce dipolar oscillation in the longitudinal phase space, since the cavity is adjusted to the zero crossing, hence, the average voltage seen by the beam is always the same.



(a) (b)

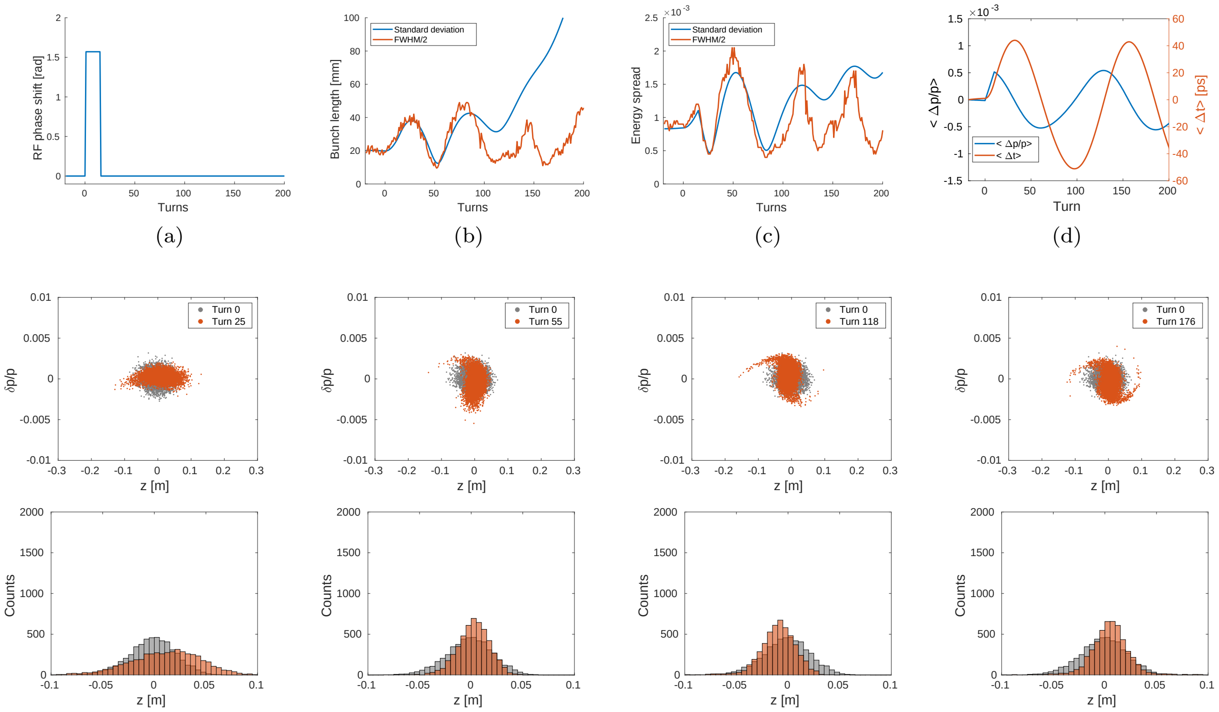
Figure 6: Bunch lengths during a 100 kV RF voltage modulation at a frequency of twice the synchrotron frequency for the main, second and third RF harmonic.

4 Phase modulation

4.1 Slip and rotate

Phase modulation of the RF cavity can force the beam to stretch and rotate in the longitudinal phase space. The modulation can be done in several stages to shape the beam in different ways. A two-stage approach is investigated: first, the RF phase is changed by $+\pi/2$, which leads to a longitudinal stretching, i.e., a longer bunch. Then, the phase is reset back to its nominal value, which makes the beam rotate around the synchronous phase. After some time, the bunch has rotated such that the bunch length stretching has now translated into energy spread and visa-versa, thereby leading to a smaller bunch length after the procedure. A few different stages of the technique is visualized in Fig. 7. Note that the beam becomes non-Gaussian as it rotates in phase space, leading to a discrepancy in standard deviation and FWHM estimates of the bunch length. A drawback of this method is that the synchrotron radiation damping lead to a shift of the centroid energy of the bunch which must be dealt with.

The effectiveness of the bunch compression depends on the duration of the “stretching phase”; a longer duration leads to more stretching, but also increases the longitudinal tails when the RF phase is reset and the bunch starts to rotate.



(a) (b) (c) (d)

(e) Turn 25 (f) Turn 55 (g) Turn 118 (h) Turn 176

Figure 7: Bunch lengths, energy spreads and longitudinal phase spaces before, during and after a $\pi/2$ RF phase shift.

4.2 Resonant phase modulation

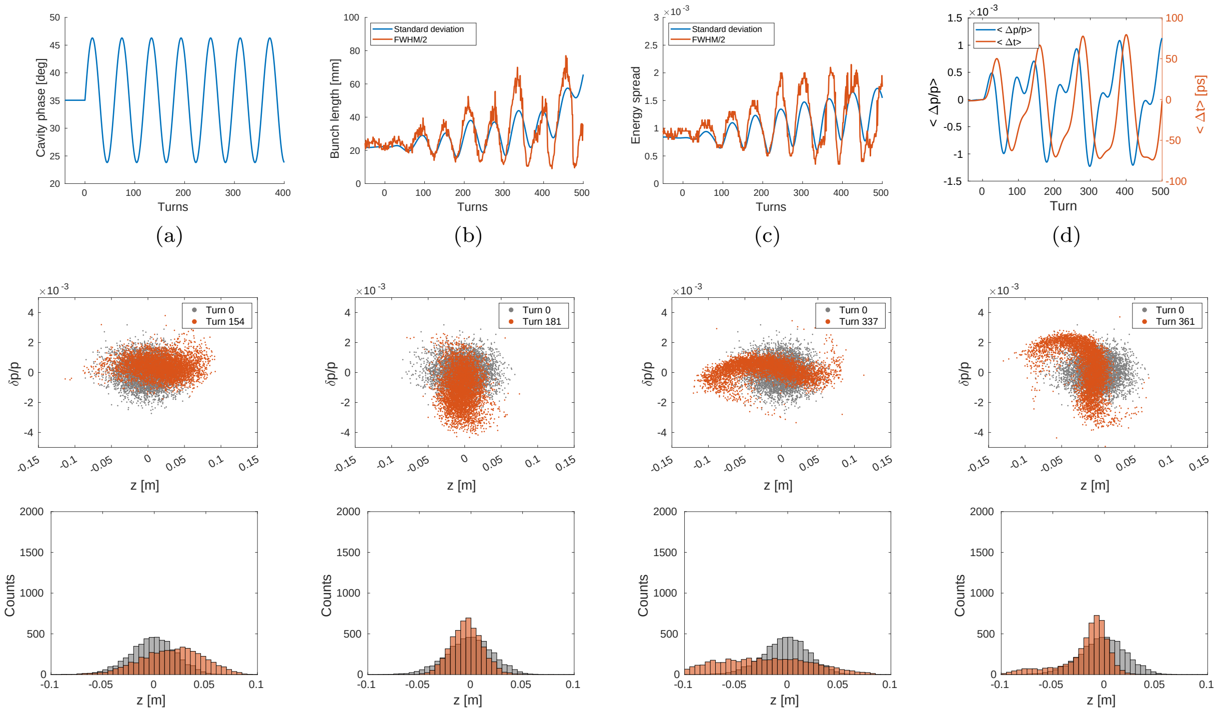
Similarly to the resonant voltage modulation in Section 3, it is possible to induce shape-oscillations by resonantly modulating the phase of the cavity. Studies conducted in the APS show that this is possible using a two-cavity system, where one of the cavities operate on-crest of the sine-wave and wobble the phase around the crest [10]. However, we will simulate a simpler single-cavity system.

4.2.1 $2f_s$ modulation using 500 MHz-system

Again, we try modulating the main 500 MHz RF system at twice the synchrotron frequency; this time, the modulation is done on the cavity phase. A modulation amplitude corresponding to 0.20 rad (11.25°) is applied using the formula

$$\phi_{\mathrm{rf}}(t) = \phi_0 + \phi_{\mathrm{mod}} \sin(2\pi(2f_{\mathrm{s}})t), \tag{4}$$

as visualized in Fig. 8a. The synchronous phase of the booster at 2.7 GeV and 650 kV is 35°. The tracking results are shown in Fig. 8. Again, it is possible to reduce the bunch length down to approximately 16 mm after 181 turns. The phase modulation also introduces a small oscillation of the average energy and arrival time of the beam as shown in Fig. 8d. An arrival time shift of ±75 ps could be problematic for the injection into the storage ring, since this is already on the timescale of the booster bunch length. However, if the time offset is static (i.e., reproducible between ramp cycles), then it could potentially be compensated for by the timing system.



(a) (b) (c) (d)

(e) Turn 154 (f) Turn 181 (g) Turn 337 (h) Turn 361

Figure 8: Bunch lengths, energy spreads and longitudinal phase spaces before and during cavity phase modulation at a frequency of twice the synchronous frequency.

5 Unavailable methods

It is important to also mention methods which can compress the bunch length but are either unavailable or unrealistic for the case of the SLS booster.

5.1 Lowering of momentum compaction

An alternative approach to decreasing the bunch length is the minimization of the momentum compaction factor, α_c, as can also be seen from Eq. (1). A reduction of α_c requires optics modifications which are restricted by the use of combined function bending magnets for the focusing in the arcs in the SLS booster. Only the three quadrupole families in the straight sections can be used. No mentionable improvement has been found so far.

6 A combined proposal

As described in Section 1, the energy acceptance of the booster at 2.7 GeV, and so it seems beneficial to increase the RF voltage above the nominal 500 kV to the maximum design value of 650 kV. An additional, similar cavity (either of the same ELETTRA type cavity or an EU HOM-damped cavity as used in the storage ring) could also be installed to increase the total RF voltage to about 1.3 MV. These two effets will reduce the equilibrium bunch length from 27 mm to around 16.5 mm. The slip and rotate technique (Section 4.1) or resonant phase or voltage modulation may also be employed to further decrease the bunch length.

A Appendix: Voltage and phase control to avoid longitudinal dipole oscillation

An issue in the resonant $2f_s$ excitation of either voltage or phase is the dipolar oscillations which are being induced because of the non-zero synchronous phase. This problem was illustrated in Fig. 5 for the voltage modulation case. To try to avoid this, we can attempt to modulate both voltage and phase simultaneously. To find the correct amplitude and phase, we must first consider the conditions we aim for:

First, let us introduce the voltage and its derivative:

$$V(t) = A\sin(2\pi ft - \phi_0 + \phi_c), \tag{5}$$

$$\frac{\partial V(t)}{\partial t} = V'(t) = A2\pi f\cos(2\pi ft - \phi_0 + \phi_c), \tag{6}$$

where $V(0)$ and $V'(0)$ is the voltage and its derivate that the beam will experience, A is the maximum voltage of the cavity ϕ_0 is the synchronous phase and ϕ_c is a modulation phase. A and ϕ_c are the variables that we can influence. Now, let us introduce our requirement. First, we wish that the beam always sees the same voltage on each turn

$$V_0(t=0) = V_1(t=0) \tag{7}$$

where subscript-0 indicates the nominal cavity settings while subscript-1 indicates modified cavity settings. Our goal is that the gradient of the voltage is modulated at $2f_s$ with some modulation amplitude k:

$$V_1'(t=0) = (1+k)V_0'(t=0). \tag{8}$$

Starting from our second requirement, we find

$$A_0\sin(\phi_0) = A_1\sin(-\phi_0 + \phi_c) \tag{9}$$

$$\Rightarrow (1+k)2\pi f\cos(-\phi_0) = A_1 2\pi f\cos(-\phi_0 + \phi_c) \tag{10}$$

$$\Rightarrow A_1 = (1+k)A_0\frac{\cos(-\phi_0)}{\cos(-\phi_0+\phi_c)} \tag{11}$$

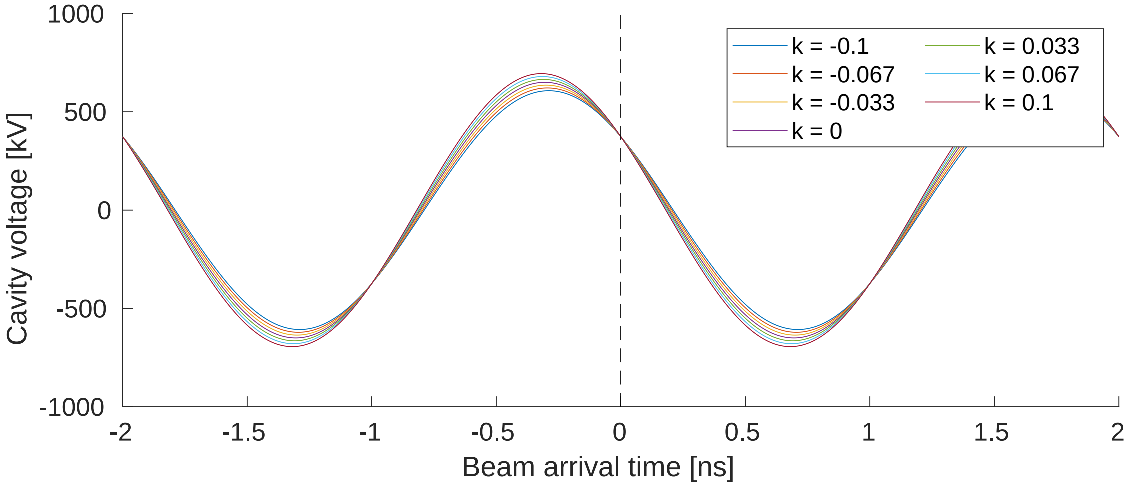
Inserting this result in our first requirement leads to

$$A_0\sin(-\phi_0) = (1+k)A_0\frac{\cos(-\phi_0)}{\cos(-\phi_0+\phi_c)}\sin(-\phi_0+\phi_c) \tag{12}$$

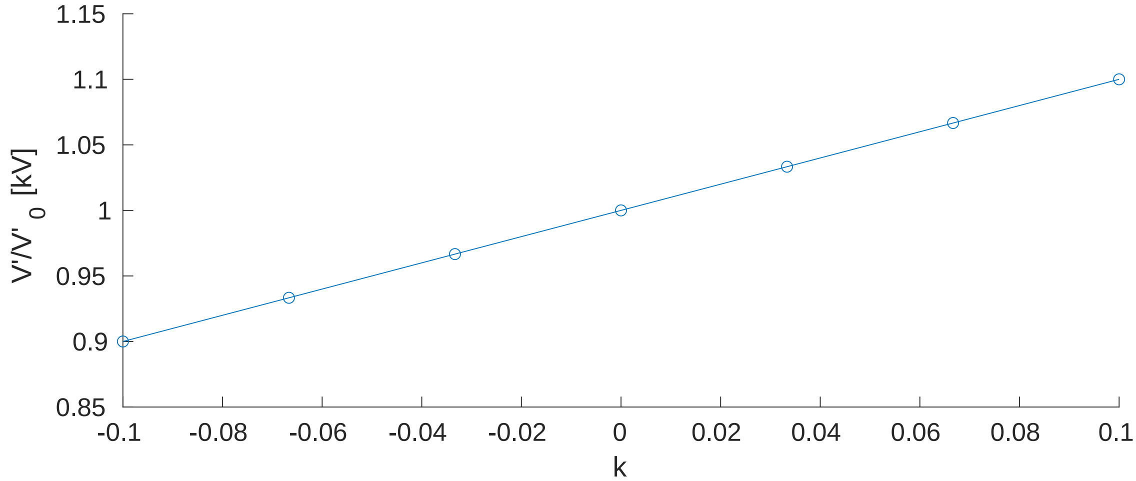
$$\Rightarrow A_0\tan(-\phi_0) = (1+k)A_0\tan(-\phi_0+\phi_c) \tag{13}$$

$$\Rightarrow \phi_c = \arctan(\frac{1}{1+k}\tan(-\phi_0)) + \phi_0. \tag{14}$$

With these equations, it is easy to formulate how the cavity phase and voltage should vary in order to fulfil our requirements. The result of the voltage curves with $k = 0.1$ is shown in Fig. 9, while the derivative taken around the stored beam arrival time ($t = 0$) is shown in Fig. 9b. As can be seen, the beam will see the same voltage for each turn (i.e., no dipolar motion), while the gradient is change by $\pm 10\%$ which then leads to a quadrupolar motion when excited at $2f_s$.



(a)



(b)

Figure 9: Cavity voltage and derivative as a function of beam arrival time after compensation of phase. The voltage derivative is increased by $\pm 10\%$ without introducing any dipolar longitudinal motion.

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