Pre-Compression of Bunch Length in the SLC Damping Rings*

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Abstract

After extraction, the damping ring (DR) bunch length is compressed in the RTL (Ring-To-Linac) transport line to achieve the desired linac bunch length. For this, an energy spread is induced proportional to the DR bunch length, producing large, aperture filling, horizontal beam sizes in the dispersive regions of the RTL. There, non-linear magnetic fields and wakefields cause higher order dispersion at the beginning of the linac, which increases the effective beam emittance. More important, in the presence of DR extraction jitter this causes linac launch jitter which makes linac operation unstable at high currents. A pre-compression of the DR bunch length would reduce the horizontal beam size in the RTL and thus relieve the problems mentioned above. It can be achieved by a modulation of the damping ring RF amplitude with a so-called 'bunch muncher' shortly before extraction. A principle limitation is the inevitable increase in energy spread of the extracted bunch which sets the lower limit for the achievable bunch length in the linac. For SLC parameters the possible reduction in DR bunch length is about 35%. The routinely operation of the 'bunch muncher' consists of two 'munches', cancelling the effect of the beam loading and keeping the extraction phase unchanged.

1 Introduction

Longitudinal wakefields in the DR are excited at any vacuum chamber irregularities, like tube diameter changes, form changes, bellows, beam position monitors, cavities, etc. They cause a bunch lengthening (e.g. from 5 to 10 mm at $3 \cdot 10^{10}$ particles/bunch) due to the potential well distortion. Additionally, they can lead to an oscillatory microwave instability, recently observed in the SLC damping rings [1]. Besides a smoother vacuum pipe with a lower impedance, which will be hopefully implemented this fall, several approaches have been tried over the years. Beam losses in the RTL beam line (due to the bunch lengthening) were reduced by an aperture increase, which induced an emittance blow-up (30 %) from the non-linear magnetic fields and wakefields further away from the axis. This was reduced (≈ 10 %) by introducing two octupoles, correcting even a third order dispersion [2].

With the current set up of the DR-rf, which increases the bunch length even further, to avoid microwave instability oscillations [1], beam losses of 20 % were observed at very high currents ($4.7 \cdot 10^{10}$). Additionally, magnetic 12-pole components and/or wakefields at the RTL-bellows [3] give some with 3rd order uncorrectable emittance blow-up. Therefore an old idea, called bunch muncher [4] got interesting again. We discuss here this pre-compression scheme of the bunch length which takes place already in the DR. It decreases the beam losses, jitter and emittance. The principles and limitations of the bunch muncher which provides a bunch rotation in longitudinal phase space are presented. Then measurements about length reduction and beam improvements are given.

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2 Bunch Length Compression

The compression of the bunch length can be described as a bunch elongation and then a rotation of the longitudinal emittance ellipse in phase space. When the length projection is smallest, the beam is extracted.

2.1 Pre-Compression Scheme

Principle. In the case of the pre-compression in the DR, the rf-voltage is quickly lowered (e.g. to 50 %). Then the initially matched bunch in longitudinal phase space is not matched anymore. This can be described as an upright ellipse in this new normalized phase space. Afterwards the ellipse performs a rotation around a new synchronous phase $\theta_0 + \Delta\theta$:

$$\theta_b = \theta_0 + \Delta\theta(1 - \cos 2\pi\nu_{sn}t),$$

with θ_b is the bunch phase and ν_{sn} is the new synchrotron frequency at the lower voltage. An alternative point of view is that there is no change to a new normalized coordinate system, then the particles at the lower DR-voltage will follow an ellipse (see Fig. 1).

Simulations. A simulation program [5] has been used to study the bunch munching process. Fig. 2 shows the result for a bunch represented by 200 particles. The simulation starts with a bunch in equilibrium. Then the rf voltage is switched off and the bunch center moves on a parabola in longitudinal phase space while the bunch elongates. After the rf is switched back on, the bunch performs synchrotron oscillations. The response time of the cavity to field changes is included in the simulation, therefore the path of the bunch is a smooth curve. A limit for the achievable amount of the bunch reduction with one munch is the amplitude of the synchrotron oscillation. If is is too large, the bunch sees the nonlinearities of the rf and smears out in phase space.

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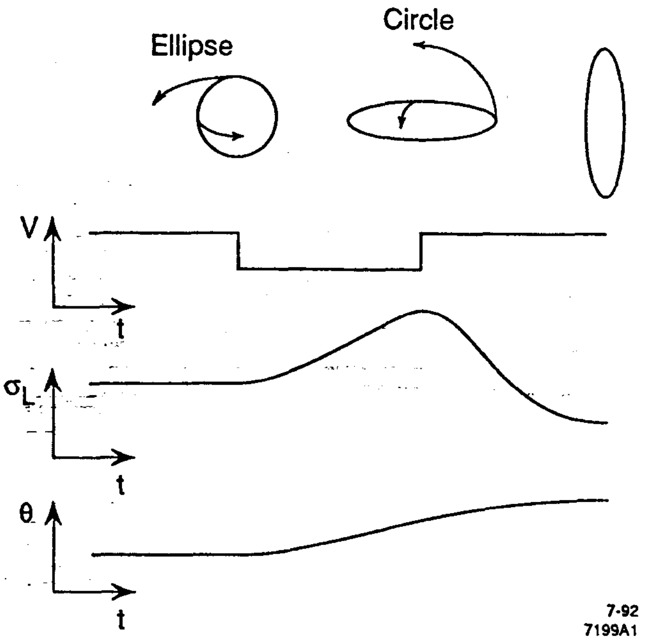

Figure 1: Principle of pre-compression in the DR.

The rf-voltage (V) is lowered and the bunch starts to rotate on ellipses in longitudinal phase space. When the beam is a flat ellipse in phase space about after a quarter of a synchrotron oscillation, the rf is raised back to the regular value. The desired effect is a smaller bunch length (σ_L) at extraction. An undesired effect is a phase change (θ), which can be compensated by a second munch (rf off - on) cancelling the phase effect and adding to the length effect.

2.2 Stability of Phase and Energy

The stability issue has been one of the biggest concerns. Besides the phase and energy stability of the DR-rf and the compressor, the bunch muncher can introduce extraction phase jitter due to current dependent beam loading.

History. About five years ago, after the initial idea [4], a bunch muncher system with up to seven munches was successfully tested, but it had only a fixed local control for the munch duration (time where the rf is low). The final implementation about half a year later had a variable duration, but now the number of possible munches was reduced to one. This was probably done since one munch could reduce the bunch length up to 40 %, while four munches increased this only to 50 %. With this set up a lot of jitter, "up to 3 mm in the RTL" was reported.

Extraction Phase. One explanation for the above mentioned different successes might be the following scenario: Besides the desired bunch length compression, one munch produces a phase change θ, which is sensitive to current jitter, a second bunch might have compensated it. The sensitivity to current jitter can be estimated in the following way: Due to synchrotron radiation the energy loss is about $\Delta E_{syn} = 80\,\text{keV/turn}$ and let us assume

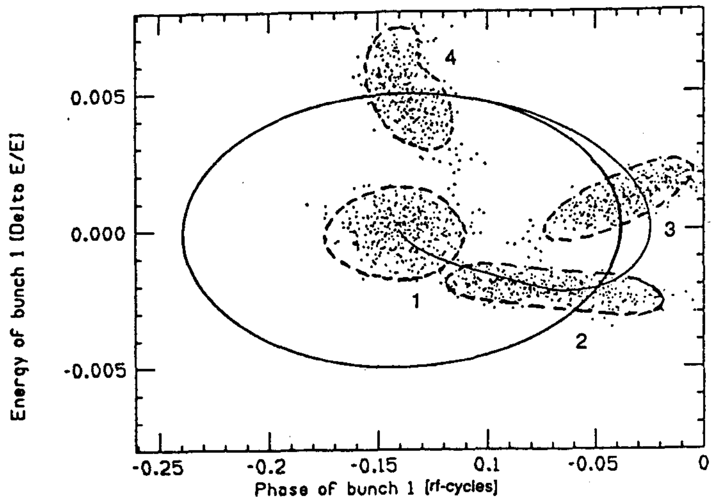

Figure 2: Pre-compression simulation.

A sample of 200 particles is tracked in the presence of the changing rf-voltage. The rf is switched off first and the particles follow a parabola curve, after switching on a synchrotron oscillation is performed (circle). The bunch distribution in phase space is shown for four different times. The bunch would be extracted at position 4 with a 30 % reduction in length.

that the higher order mode losses are of the some order ($\Delta E_{HOM} = 80\,\text{keV}$) at $5 \cdot 10^{10}$ particles in each of two bunches. For a DR voltage of $V_{rf} = 800\,\text{kV}$ the bunch will sit at about $\phi = 11.5°$

$$\phi = \arcsin\left(\frac{\Delta E_{syn} + \Delta E_{HOM}}{eV_{rf}}\right).$$

Lowering the voltage to 400 (200) kV will shift the synchronous phase by 12.1° to 23.6° (53.1°). A 10 % current jitter will only influence the higher order mode losses, so the loss per turn will change by 5 %, or the phase angle from (e.g.) 10.9° to 22.3° (49.5°). So if the initial phase is adjusted to the phase of the linac (S-band phase feedback), a 10 % lower current will cause a 12.1° − 11.4° = 0.7° (41.6° − 38.6° = 3.0°) which will be visible as an offset in the RTL ($\eta = 0.9\,\text{m}$) of 1.2 (5) mm. This result can be compared with the earlier observed jitter of 3 mm at a current of $3.2 \cdot 10^{10}$ particles per bunch.

Two smaller munches can effectively cancel this jitter. Each munch makes a phase change of $\theta \pm \Delta\theta$ but with different signs, so there will be no phase change at all, which results in the fact that only a small, if any at all, overall adjustment of the DR phase to the linac is necessary. A fast rf-feedback has decreased the beam loading effect even further [6].

Other Jitter Sources. Since the synchrotron and quadrupole oscillation frequencies are slightly current dependent the above mentioned cancellation is not perfect. Another source which is quite annoying, is the fact that the bunch muncher phase is very sensitive to the initial rf-voltage, since a munch is a certain change of that voltage. Phase shifts were observed after changes in the cavity-tuners or adjustments of the DR-rf-ramp (a device which lowers the amplitude of the rf voltage during the store time and ramps it up again at the end to fight the microwave instability oscillations [1]).

Combination of Pre- and RTL Compression. A current measurement of the energy spread showed that the minimum bunch length after full RTL compression would be 0.65 mm at $3 \cdot 10^{10}$ in the linac, compared to 0.5 mm at zero current. A pre-compression of 20 % ($\Delta\sigma_L/\sigma_L$ see below) will have only a weak effect to the bunch length in the linac, since the bunch is not totally compressed in the RTL (compare Fig. 3).

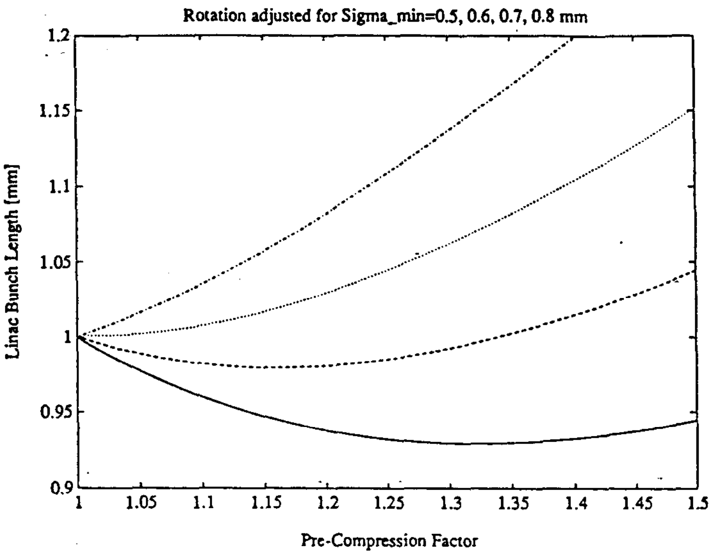

Figure 3: Influence to linac bunch length.

The RTL compressor is always adjusted to get a 1 mm bunch length in the linac independent of different energy spreads, which would result in a minimum bunch length of 0.5 to 0.8 mm (solid to dash dotted). Then the pre-compression in the DR is turned on. At $\sigma_{min} = 0.65$ *mm only a very weak disturbance on the linac bunch length is generated.*

3 Set Up and Measurements

The bunch muncher consists of two munches. The first munch of 2 μs is followed by a second one about 3 μs later. This time and the duration of the second munch have been slightly adjusted till the phases are compensated and the compressions are enhanced. The absolute scale of the length reduction is measured with a streak camera (Fig. 4), which has been calibrated first by an optical delay to less than 3 % absolute error. The RTL losses are reduced by a factor of five and the emittance by about 15 %.

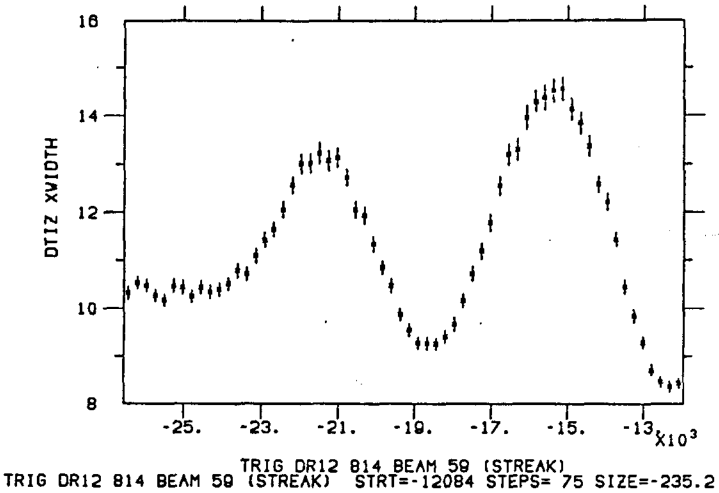

Figure 4: Bunch length measurement by a streak camera.

The measured (digitized) bunch length in mm is plotted against the last 15 μs before extraction. The pre-compression was set to 20 % =(10.5-8.4)/10.5.

4 Conclusion

The pre-compression of the DR bunch length is a stable (with two munches) and helpful rf set-up to lower the RTL beam losses, decrease the emittance blow-up and reduce the jitter due to asymmetric beam loss. It is now routinely running producing a 20 % shorter bunch at extraction.

Acknowledgement

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