TRANSIENT GENERATION OF SHORT PULSES IN THE APS STORAGE RING*

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Abstract

A method for obtaining very short pulses using modulation of the accelerating voltage gradient is described and simulation results are given. The idea is to operate the two rf stations with a phase separation adjusted so that the synchronous particle resides on the crest of one of the sources. Phase modulation of the on-crest system at twice the synchrotron frequency induces a longitudinal bunch shape oscillation with significantly reduced bunch length occurring twice each synchrotron period.

INTRODUCTION

There has been a renewed interest in hard x-ray sources with pulse duration significantly shorter than presently available at storage-ring-based synchrotron light sources, as evidenced by a number of recent workshops and meetings. While completely new types of sources such as energy-recycling linacs or free-electron lasers are being pursued to produce pulse durations below 1 ps, a number of methods to obtain shorter pulses with existing third-generation sources are under investigation [1,2]. The technique described here is relatively simple to implement, represents a real bunch compression requiring no special x-ray optics, and preserves the transverse beam emittance at full bunch charge.

BACKGROUND

The equilibrium bunch length in electron storage rings is limited by quantum excitation at low current and by wakefields and potential well distortion as the peak current is increased. Shown in Figure 1 is the typical bunch length plotted as a function of single-bunch current at the Advanced Photon Source (APS). The theoretical zero-current bunch length with 9.4 MV of rf voltage is 19.6 ps. Relevant parameters associated with the nominal APS longitudinal phase space are shown in Table 1.

The most common operating mode in use at the APS involves 102 mA distributed among 24 uniform bunches. With 4.25 mA per bunch, this indicates that the normal bunch length is 35 ps RMS, from Figure 1. A special operating mode optimized for pulsed x-ray experiments uses a single large bunch with 8 mA together with a large number of very small bunches located on the opposite side of the ring, to allow sufficient dead time for timing experiments, with acceptable lifetime. These types of experiments could benefit most from having a very short

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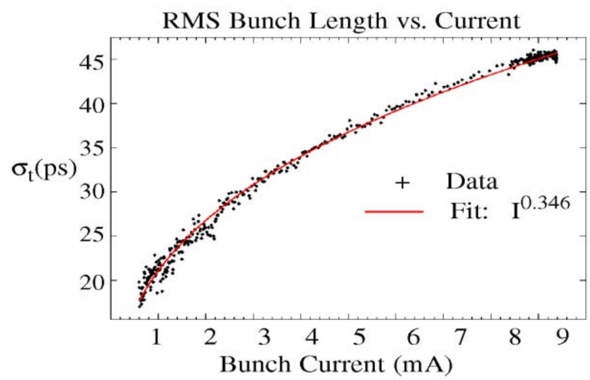

Figure 1: APS RMS bunch length vs single-bunch current, with 9.4-MV total rf voltage.

bunch length; however, here the bunch length is even longer, over 45 ps for the 8-mA bunch. Maximum charge with minimum bunch length are most desireable, but at the same time most difficult to achieve.

Table 1: APS Longitudinal Phase-Space Parameters

Energy	7 GeV
RF voltage	9.4 MV
Energy Loss / turn U_0	5.37 MeV
Synchrotron frequency f_S	2.16 kHz
Zero-Current Bunch length σ_{t0}	19.6 ps rms
Energy spread σ_E / E	.096 %
Energy acceptance	2.5 %
Damping time τ_E	4.75 ms
Momentum Compaction α_C	2.78e-4
Synchronous Phase ψ_S	145 degrees

SYNCHROTRON TUNE MODULATION

To understand the bunch compression technique, consider the following conserved quantity, associated with the synchrotron oscillation of an individual particle in longitudinal phase space, in the limit of small oscillation amplitude:

$$H = \alpha_C^2 \, \delta^2 + \Omega_s^2 \, \tau^2 . \tag{1}$$

Here α_C is the momentum compaction, Ω_s is 2π times the synchrotron frequency f_S, δ is the fractional energy

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offset relative to the synchronous particle, and τ is the time offset.

Shown in Figure 2 are sets of ellipses corresponding to Eq. (1) for two different values of synchrotron frequency. The two ellipses labeled Ω_S are intended to denote phase-space trajectories for two particles with different values of H but the same synchrotron tune, while the two ellipses labeled $\Omega_S + \Delta\Omega_S$ have a similar meaning, but for a slightly different synchrotron frequency. A particle initially at location A with synchrotron frequency Ω_S will normally proceed to location B after one-quarter of a synchrotron period, proceeding along the inner dashed ellipse as time progresses. Consider the effect of a sudden step change from Ω_S to $\Omega_S + \Delta\Omega_S$ at the moment the particle arrives at location A. The particle will instead follow the path indicated by the outer, solid ellipse, to the location labeled A'. Similarly, a particle initially located at B when the change occurs will proceed to location B' after one quarter of a synchrotron period. As can be seen from the figure, a distribution of particles initially occupying the inner, dashed ellipse, will occupy the tall, thin ellipse containing points A' and B' after a quarter period. The temporal extent of the bunch has been compressed at the expense of additional energy spread.

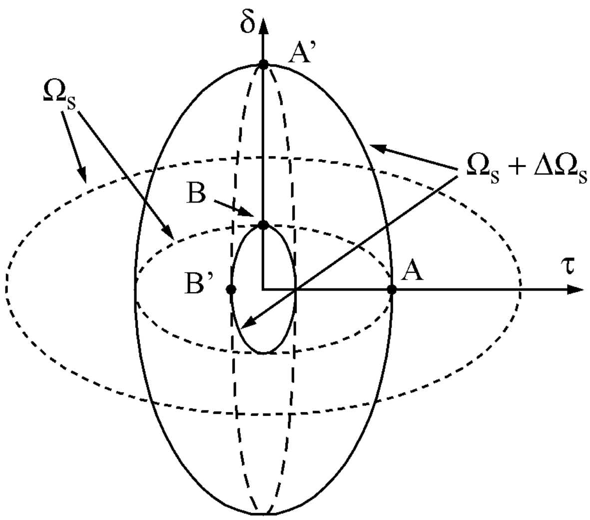

Figure 2. Phase space representation illustrating the bunch compression process.

The process can be continued by switching the frequency back to its original setting at the instant that particle A arrives at A'. After two quarter-synchrotron periods (they differ slightly), the bunch will be elongated temporally by a factor of $1+\Delta\Omega_S/\Omega_S$ and have its energy spread reduced by the same factor. As the process is replicated, compression proceeds exponentially, i.e., the phase-space dimensions change by the same factor each half period, with the bunch length alternating between ever smaller and larger values. The process is ultimately limited by bucket nonlinearity at large amplitude.

A simple calculation shows that the minimum bunch length associated with the width of the upright ellipse decreases according to

$$\sigma_\tau = \sigma_{\tau 0} e^{-\varepsilon t} , \qquad (2)$$

where the decay rate ε is simply $2\,\Delta f_S$. The maximum bunch length, which is delayed by one quarter of a synchrotron period, grows exponentially at the same rate.

In a proton machine, where the synchronous phase ψ_S is equal to π, a simple change in rf voltage can be used to effect the increment in synchrotron frequency, and bunch compression schemes similar to this are not uncommon [3]. For a light source, amplitude modulation will result in an undesirable centroid oscillation, since the synchronous phase depends on rf voltage.

For machines such as the APS, which have two independent rf systems, one can effectively modulate the *gradient* of the rf voltage with minimal amplitude modulation by first separating the phases of the two systems until the beam resides on the crest of one of them, and then applying phase modulation to the on-crest system. A handy formula relating the synchrotron frequency to the voltage gradient is

$$\Omega_s^2 = \frac{-\omega_{RF}\,\alpha_C\, e}{E\, T_0} \left.\frac{dV}{d\psi}\right|_{\psi=\psi_s} , \qquad (3)$$

where ω_{RF} is the angular rf frequency, α_C is the momentum compaction, e the electronic charge, E the beam energy, T_0 is the revolution period, and ψ is the rf phase $\omega_{RF}\, t$. Here V represents the total rf voltage obtained by summing contributions from the two systems.

Writing $\phi = \psi - \psi_S$, the total rf voltage becomes

$$V = V_1 \sin(\phi + \phi_1) + V_2 \cos(\phi + \Delta\phi_2) , \qquad (4)$$

and $$\left.\frac{dV}{d\phi}\right|_{\phi=0} = V_1 \cos\phi_1 - V_2 \sin\Delta\phi_2 . \qquad (5)$$

Note that V_2 represents the on-crest system and that small changes $\Delta\phi_2$ translate directly into changes in synchrotron frequency Δf_S. Combining Eqs. (3) and (5), and taking $\Delta\phi_2$ to be small, the bunch compression decay rate ε needed in Eq. (2) becomes

$$\varepsilon = 2\Delta f_s = \frac{f_{RF}\,\alpha_C\, eV_2}{\Omega_S\, E\, T_0} \Delta\phi_2 . \qquad (6)$$

The quantity $\Delta\phi_2$ should be strictly interpreted as the peak-to-peak amplitude for square-wave phase modulation, with modulation frequency equal to two times f_S. With 1 MW of available rf power, the factor V_2 in the numerator provides ample compression capability.

SIMULATION

The *elegant* tracking code [4] was configured to simulate a number of phase modulation scenarios, including both square and sine waves for the APS storage ring. To simplify the latter experiment, it is convenient to set both rf system voltages to match the 5.4-MV energy loss per turn. In this case, the on-crest condition corresponds to having the two rf systems in quadrature, with the total rf voltage dropping from 10.8 MV to 7.6 MV as a result of the 90-degree phase separation.

Shown in Figure 3 is the result of a simulation where eight cycles of sinusoidal phase modulation, with 10 degrees p-p, were applied to the on-crest system. The RMS bunch length (initially 23.5 ps, plotted on a log scale) oscillates at twice the synchrotron frequency, in this case $2\, f_S = 3.6$ kHz. A peak-finding algorithm was used, followed by a linear fit to the first four peaks and valleys, to arrive at the growth and decay rates shown on the plot.

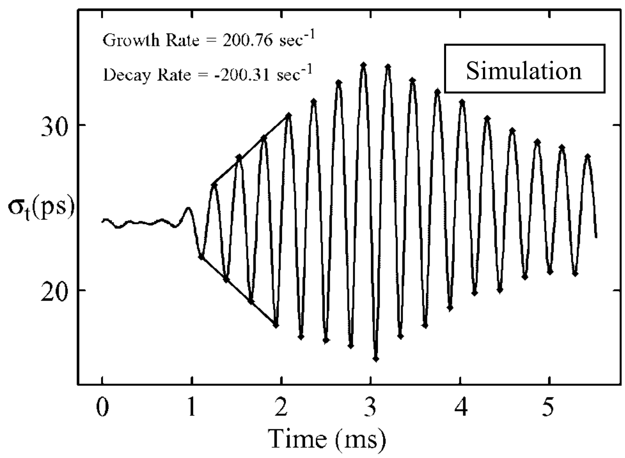

Figure 3: Log plot of bunch length vs. time.

Interestingly, if one "de-rates" Eq. (6) by a factor of $2/\pi$, i.e., the ratio of the areas of a sine- vs. square wave, one arrives at a decay rate ε of 200.38 sec^{-1}. Further, the growth rate from simulation is proportional to phase modulation amplitude as expected, while the decay rate rolls off to lower values as modulation is increased.

EXPERIMENT

A function generator (SRS DS345) was used in "burst" mode to introduce sinusoidal tone bursts inside of the phase regulation loop of one of the two APS RF systems with an analog summing junction. It was verified that the system responded to stimuli up to 8 kHz, and an independent fast phase detector was used to quantify the actual phase modulation amplitude. The function generator, the turn-by-turn beam position monitor history buffers, and a streak camera observing visible light were triggered at a 2-Hz rate.

Prior to applying the modulation, a single bunch of 5 mA (18.4 nC) was stored and the two rf system phases were separated nominally by 90 degrees, according to phase shifters interfaced to the control system. The calibration of these phase shifters was later determined to be nonlinear, perhaps in error by as much as 18 degrees. The klystron forward power was used as the best diagnostic to determine the sign of the necessary phase shift. The function generator frequency was set equal to twice the measured synchrotron frequency, and each of the two rf systems were adjusted to provide the desired 5.4 MV. Figure 4 shows a streak camera image collected using eight cycles of approximately 26 degrees p-p sinusoidal drive. The vertical axis is the fast time axis showing bunch length, while the horizontal axis indicates slow time. The initial bunch length is longer than indicated by Figure 1, commensurate with the lower effective gap voltage resulting from the phase separation.

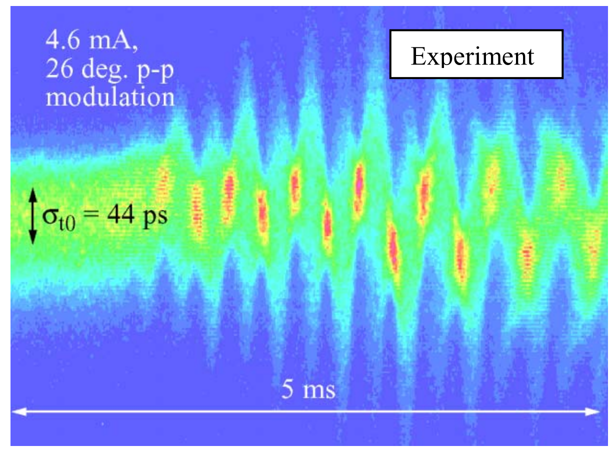

Figure 4: Streak image showing compression.

Analyses of images like Figure 4 indicate good agreement with simulation, with the overall best achieved compression to 60% of initial bunch length at 7 GeV, i.e., 22 ps at 2.8 mA. Lower energy operation holds the potential for production of very short bunches. Detailed results are being prepared for journal publication.

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