PRODUCTION OF SHORT ELECTRON BUNCHES BY SLOW AND FAST EXCITATIONS OF LONGITUDINAL BUNCH-SHAPE OSCILLATIONS

S. Sakanaka, T. Mitsuhashi, T. Obina, and K. Umemori, High Energy Accelerator Research Organization (KEK), 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan

Abstract

In the Brookhaven AGS, an adiabatic excitation of longitudinal bunch-shape oscillations was successfully used for producing short proton bunches. We applied this method to electron bunches in the Photon Factory (PF) storage ring at KEK. As a result, the electron bunches could be shortened by a factor of about two by applying an rf voltage modulation. It was also found that another fast excitation of oscillations could be used to produce a little shorter bunches than the original slow excitation method. Both experimental and simulation studies are presented.

INTRODUCTION

In the Alternating Gradient Synchrotron (AGS) at the Brookhaven National Laboratory, short proton bunches were successfully produced by an adiabatic excitation of longitudinal bunch-shape oscillations [1]. These oscillations were induced by modulating an amplitude of rf voltage at near twice the synchrotron frequency. We applied this method to the 2.5-GeV Photon Factory storage ring [2] and investigated how short electron bunches can be produced. When applying this method to the electron storage ring, one must consider the effects of radiation damping and excitation, which eventually makes the bunches long. Then, the following conditions would be required: (i) to avoid reaching a stationary distribution of particles under rf modulation, a rise time of the oscillation must be shorter than the radiation damping time and (ii) to excite the oscillations "adiabatically", the rise time must be sufficiently longer than the synchrotron period. We show later that the above second condition is not necessary, and furthermore, an alternative fast excitation of oscillations can yield a little shorter bunches.

SLOW EXCITATION EXPERIMENT

The PF storage ring is a 2.5-GeV synchrotron light source. Each of four rf cavities in the ring is driven by an independent klystron [3]. A setup for the experiment is shown in Fig. 1. We modulated amplitudes in two of the four rf sources at a frequency of about twice the synchrotron frequency, which provided a modulation in the cavity voltage. With an amplitude modulation of roughly ±100% for these sources, an estimated modulation in the total voltage was about ±20% due to a bandwidth of the cavities. The modulation was gradually increased and decreased with the same rise/fall times of approximately 1.2 ms. This duration was shorter than the longitudinal damping time of 3.9 ms while much longer than the synchrotron period of 42 μs. Excited bunch-shape oscillations were then observed using a dual-sweep streak camera. The experiment was carried out with a single-bunch beam under such parameters as the beam energy of 2.5 GeV, an rf frequency of 500.1057 MHz, a total rf voltage of 1.7 MV, a radiation loss of about 400 keV/turn, and the synchrotron frequency of 24 kHz. A modulation frequency optimized for obtaining shortest bunches was approximately 45.5 kHz.

Figure 2(a) shows an example of the excited bunch oscillations at a low bunch current of 1.1 mA. The bunch

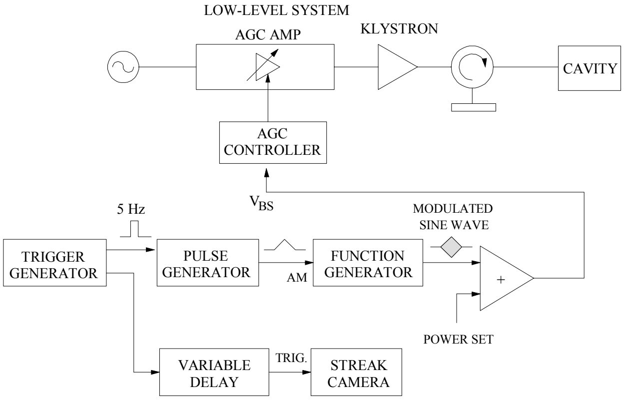


Figure 1: Setup for the rf voltage modulation.

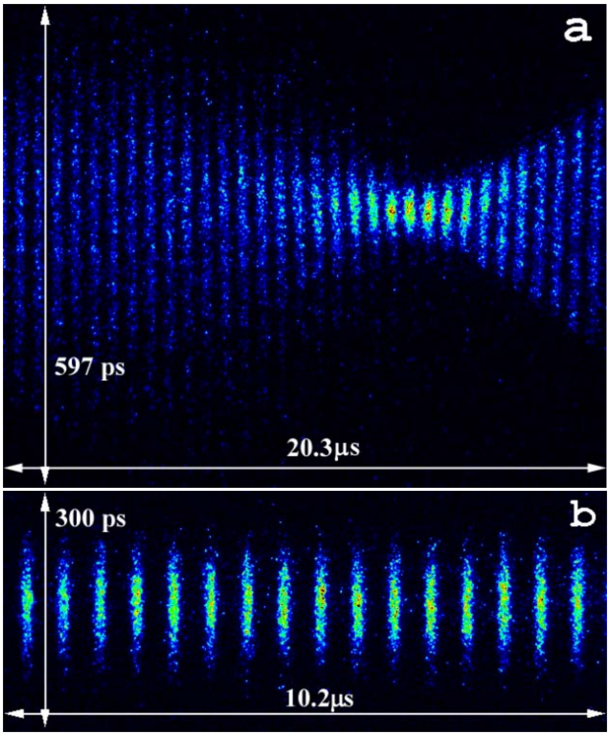


Figure 2: Longitudinal bunch profiles observed with a streak camera. (a) Under rf voltage modulation and (b) without any modulation.

length of approximately 18 ps (rms) was obtained at a moment when the bunch length became the shortest. For a reference, the longitudinal bunch profiles without any modulation is shown in Fig. 2(b). Natural bunch length in Fig. 2(b) was approximately 33 ps. Note that the vertical scales in both Figs. 2(a) and 2(b) are the same. Several waveforms under this experiment are shown in Fig. 3.

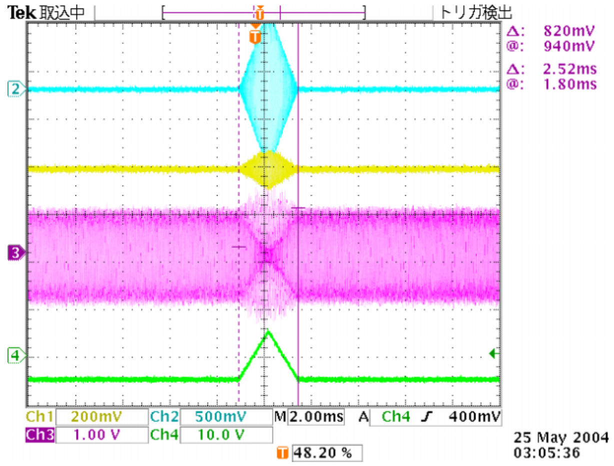


Figure 3: Waveforms under the rf voltage modulation. Upper to lower: a modulation signal, a set voltage for the AGC controller, an output rf from the klystron, and an output from the pulse generator. Horizontal scale: 2 ms/division.

SIMULATIONS

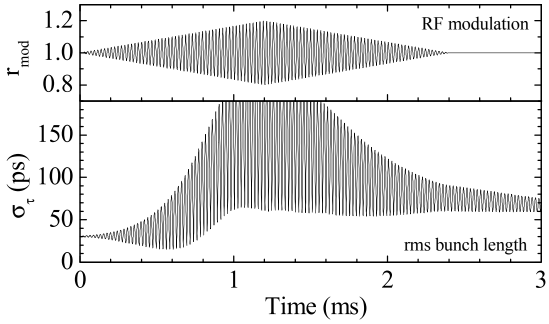
To understand the physics in the above experiment, we carried out some simulations. First, a multiparticle tracking simulation was carried out using similar parameters to those in the experiment. The longitudinal motions of 1000 particles under the rf modulation were tracked including both the damping and the excitation effects due to radiation while neglecting a beam-loading effect. The lower graph of Fig. 4(a) shows thus calculated variation of the bunch length due to an assumed rf modulation (in the upper graph). The figure predicted that a minimum bunch length of 15.4 ps would be obtained at a time of 0.54 ms after starting the modulation. It reproduced our experimental result well.

Next, we investigated the cases where the rf modulations were applied suddenly. Figure 4(b) shows a result of the simulation where the voltage modulation of ±20% was applied for a duration of 0.5 ms. In this case, it predicted a minimum bunch length of 12.3 ps at a time of 165 μs after starting the modulation. This suggested that the slow rise in the voltage modulation is not essential for producing the short bunches and that another sudden excitation of oscillations might be more effective.

Figure 4(a) also shows that after the modulation is finished the bunch length becomes longer than the initial one. This was observed in the experiment as well. These observations indicated that the bunch-shape oscillations cannot be induced reversibly even when the modulation is applied gradually. This issue was examined further with some single-particle simulations. It was shown that (i) even when the radiation damping and excitation are excluded, the excitations of longitudinal oscillations are not reversible with rise/fall times ranging 1-20 ms and (ii) when the radiation loss (U_0) per turn is assumed to be zero, the oscillation can be induced reversibly.

When there are some radiation losses, the rf-amplitude modulation yields both a parametric oscillation term (a gradient modulation) and a forced oscillation term in the equation of motion. The latter term can be responsible for the non-reversibility of the oscillations.

(a) slow excitation



(b) fast excitation

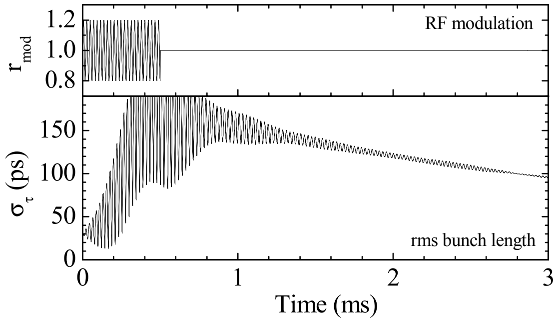


Figure 4: Calculated variations in the rms bunch length as a function of time. The modulation in the rf voltage was changed slowly in the case (a) while it applied suddenly in the case (b).

FAST EXCITATION EXPERIMENT

In the second experiment, we imposed a sudden amplitude modulation for a duration of 0.5 ms, as shown in Fig. 5. With an amplitude modulation by ±55% in two of the klystron outputs, an estimated cavity-voltage modulation of ±12% was applied. By scanning the trigger timing for the streak camera, we observed that the bunch became shortest approximately 156 μs after starting the modulation; the bunch length was then 16 ps at a beam current of 2.1 mA. A typical bunch-shape oscillation is shown in Fig. 6. Machine parameters under this experiment were the rf voltage of 1.6 MV, the rf frequency of 500.1120 MHz, the synchrotron frequency of 23.7 kHz, and the modulation frequency of 45.0 kHz. The natural bunch length without any modulation was 36 ps at the same current. Figure 7 shows a comparison of the longitudinal bunch profiles with and without the modulation.

This experiment demonstrated the effectiveness of the fast excitation of oscillations, as expected from the simulations.

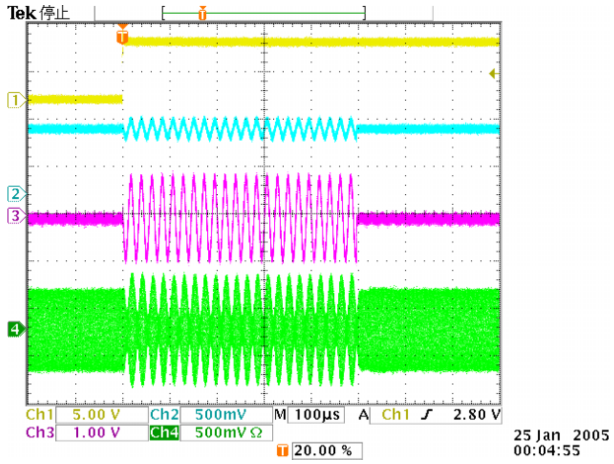


Figure 5: Waveforms under the second experiment. Upper to lower: a trigger pulse, a set voltage to the AGC controller, a modulation signal, and an output rf from the klystron. Horizontal scale: 100 µs/division.

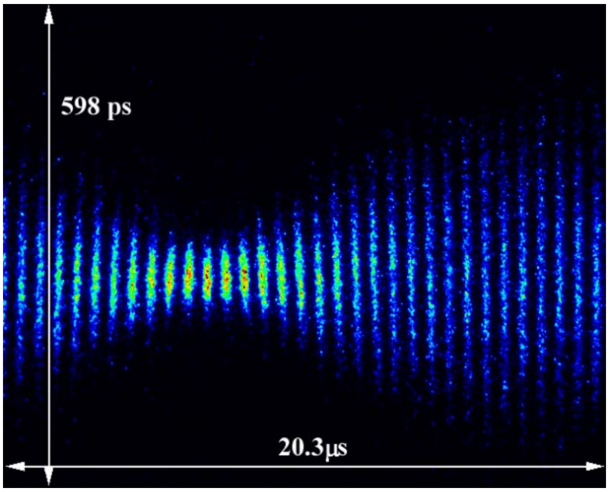


Figure 6: Longitudinal bunch-shape oscillation under the sudden rf voltage modulation. Approximately 156 µs after starting the modulation.

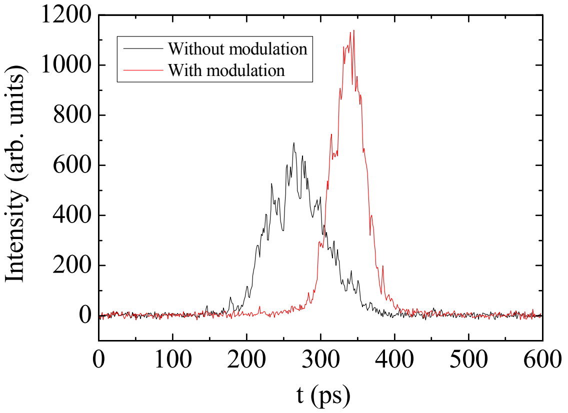


Figure 7: Longitudinal bunch profiles with (red line) and without (black line) rf voltage modulation.

CONCLUSIONS

The experiments at the PF storage ring showed that (1) the bunch length could be shortened by both the slow and the fast excitations of longitudinal bunch-shape oscillations, (2) the fast excitation yielded a little shorter bunch of 16 ps, which was about 44% of the natural bunch length at a low beam current, and (3) the bunch-shape oscillations could not be excited reversibly even when the voltage modulation was increased slowly. These results were reproduced well in the simulations.

The achieved bunch length of 16 ps is not sufficient for the usage of very short synchrotron light. However, this method will be useful in other storage rings for such applications as a controlled production [4] of coherent synchrotron radiation (CSR) where an intense CSR can be produced at the timings synchronized with an applied modulation signal.

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