GENERATING PICOSECOND X-RAY PULSES WITH BEAM MANIPULATION IN SYNCHROTRON LIGHT SOURCES *

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Abstract

We show that X-ray pulses one order of magnitude shorter than the electron bunch length can be obtained through synchrobetatron coupling. A 6-ps rms visible light pulse from a 30-ps rms electron bunch was observed using a streak camera. Theory, simulation, and experimental results are presented.

INTRODUCTION

The X-ray pulse generated by synchrotron light sources has been widely used to explore the material structure on the atomic scale. The duration of the pulse is in the order of 100 ps. Shorter pulses are always desired for better resolution and fast dynamic process exploration.

The pulse length of the Advanced Photon Source (APS) is 20 - 40 ps rms. There is interest in compressing the pulse by two to three orders of magnitude. One possible scheme per A. Zholents [1] is to tilt the flat-lying electron bunch vertically using rf deflecting cavities. The generated X-ray beam therefore has y-t correlation; after reflection by an asymetrically cut crystal, the photons from different longitudinal slices can be synchronized. Hence the pulse length is determined by the vertical beam size, which is three orders of magnitude less than the bunch length.

In this paper we show that a vertically tilted electron bunch can be obtained with beam manipulation. A tilt is developed after a vertical kick due to non-zero chromaticity, and a transient shorter pulse can therefore be produced. This method can be applied to any synchrotron light source.

VERTICAL TILT BY SYNCHROBETATRON COUPLING

The particle motion in longitudinal phase space can be described by

$$\left\{ \begin{array}{rcl} \delta & = & \delta_0 \sin \nu_s(\theta + \theta_0) \\ \Delta\phi & = & -\frac{h\alpha_c}{\nu_s}\delta_0 \cos \nu_s(\theta+\theta_0) \end{array} \right. , \qquad (1)$$

where $\delta = (p - p_0)/p_0$ is the fractional momentum deviation, $\Delta\phi = \phi - \phi_s$ is the rf phase difference from the synchronous particle, h is the rf harmonic number, α_c is the momentum compaction factor, ν_s is the longitudinal tune, θ is the orbital angle, each turn θ gains 2π, and δ_0 and θ_0 are the initial amplitude and phase of the particle, respectively.

Radiation damping and quantum excitation affect the longitudinal motion. To simplify the model, we'll assume linear longitudinal motion given by Eq. (1) in this paper.

In the vertical phase space, if there is a kick Θ at s_0, the motion of the particle will be

$$\begin{aligned} y &= A(s)\sin(\nu_y\theta + \Delta\psi_\delta + \Delta\psi_\beta) \\ &+ \sqrt{2\beta_y(s)J_y}\cos(\nu_y\theta + \Delta\psi_\delta + \Delta\psi_\beta + \psi_0), \end{aligned} \qquad (2)$$

where the first term is due to the kick and the second term is the thermal motion. Here $\Delta\psi_\delta = \int_0^\theta C_y \delta d\theta$ is the phase advance caused by chromacity, $\Delta\psi_\beta = \psi(s) - \psi(s_0)$ is the betatron phase advance, $A(s) = \sqrt{\beta_y(s)\beta_y(s_0)}\Theta$ is the centroid oscillation amplitude, β_y is the beta function, ν_y is the vertical tune, C_y is the vertical chromaticity, and J_y and ψ_0 represent the initial amplitude and phase due to the vertical emittance, respectively.

From Eqs. (1) and (2), we find the phase advance due to chromaticity to be

$$\Delta\psi_\delta = \frac{C_y}{h\alpha_c}(1 - \cos\nu_s\theta)\Delta\phi(\theta) + \frac{C_y}{\nu_s}\sin\nu_s\theta\delta(\theta). \qquad (3)$$

If we assume δ satisfies the Gaussian distribution, then the centroid of any longitudinal slice is

$$\langle y\rangle(\Delta\phi) = e^{-\xi^2}A(s)\sin\Upsilon, \qquad (4)$$

where $\xi^2 = \frac{1}{2}(\frac{C_y\sigma_\delta}{\nu_s}\sin\nu_s\theta)^2$ and $\Upsilon = \nu_y\theta + \psi(s) - \psi(s_0) + \frac{C_y}{h\alpha_c}(1 - \cos\nu_s\theta)\Delta\phi$. If we let $\nu_s\theta = \pi$ and $\nu_y\theta + \psi(s) - \psi(s_0) = 0$, then

$$\langle y\rangle(\Delta\phi) = A(s)\sin(\frac{2C_y}{h\alpha_c}\Delta\phi) \sim A(s)\frac{2C_y}{h\alpha_c}\Delta\phi \qquad (5)$$

if $\frac{2C_y}{h\alpha_c}\Delta\phi$ is small. Equation (5) means the vertical offset is correlated to the longitudinal position. Figure 1 shows the simulation result [2]. The chromaticity was intentionally set to a large value to show a sine function shape of the distribution. One can lower the chromaticity to get a linear tilt.

Averaging further over $\Delta\phi$, one obtains

$$\langle y\rangle = e^{-2(\frac{C_y\sigma_\delta}{\nu_s})^2\sin^2\nu_s\theta/2}A(s)\sin(\nu_y\theta + \Delta\psi_\beta). \qquad (6)$$

Here we have used the relation $\frac{\sigma_\delta}{\nu_s} = \frac{\sigma_{\Delta\phi}}{h\alpha_c}$. Equation (6) means the betatron oscillation after a kick is modulated by the longitudinal tune. Figure 2 is the simulation of the bunch centroid motion. In the simulation, quantum excitation and damping were turned off. One turn map was used for the vertical motion, but the tune of each particle was set

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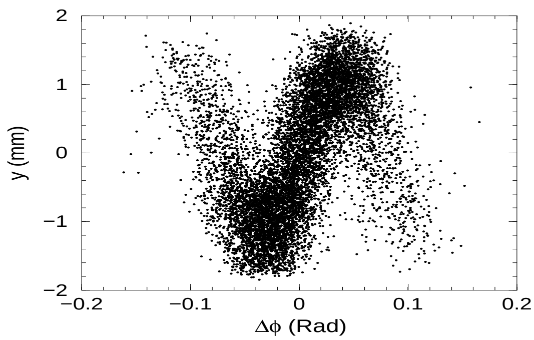

Figure 1: The particle distribution in the $(y, \Delta\phi)$ plane half synchrotron period after a vertical kick. The parameters are $C_y = 8$, $\frac{2C_y}{h\alpha_c} = 44.6$, and $\sigma_{\Delta\phi} = 2.5°$.

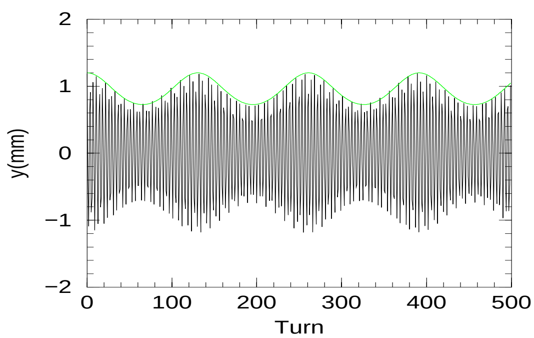

Figure 2: The bunch centroid motion after a vertical kick. The envelope is given by the exponential factor in Eq. (6). The parameters are $C_y = 4, \sigma_\delta = 0.001$, and $1/\nu_s = 130$ turns.

to $\nu_y = \nu_{y0} + C_y\delta$ to introduce synchrobetatron coupling. The modulation is clearly seen in the plot.

One can also find the beam moment

$$\sigma_y^2(\Delta\phi) = \beta_y(s)\epsilon_y + A^2(s)\sinh\xi^2 e^{-\xi^2} \times(1 + e^{-2\xi^2}\cos 2\Upsilon), \quad (7)$$

and the tilted angle at any $\Delta\phi$

$$\theta_{y-z}(\Delta\phi) = \frac{d\langle y\rangle(\Delta\phi)}{d\frac{c}{\omega}\Delta\phi} = \frac{\omega}{c}A(s)\frac{C_y}{h\alpha_c}(1-\cos\nu_s\theta)e^{-\xi^2}\cos\Upsilon, \quad (8)$$

where c is the speed of light and ω is the angular frequency of the rf system. The tilt angle θ_{y-z} and the beam moment σ_y^2 are plotted in Fig. 3. The tilt angle reaches maximum at half a synchrotron period, and the σ_y^2 decreases to a minimum; therefore half a synchrotron period after the kick is the ideal time to get shorter X-ray pulses.

We note that $\langle y'\rangle$ also has z correlation, which has to be included into the model. Another point worth mentioning is that the chromaticity in the horizontal direction does not affect the tilt; therefore, it can be varied to keep the beam stable.

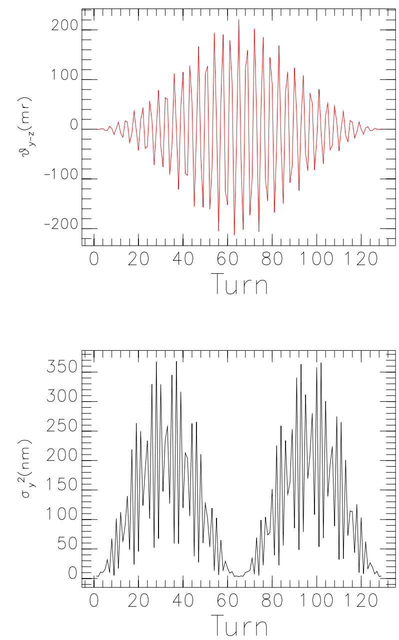

Figure 3: The tilt angle and the beam height after a kick. Both were calculated for the center slice. The synchrotron period is 130 turns, $\Theta = 0.12$ mr and $C_y = 4$.

THE SHORTER PULSE

If a bunch is tilted in the (y, z) plane at an angle of θ_{y-z}, the beam distribution can be written as

$$\rho(y,z) = \frac{1}{2\pi\sigma_z\sigma_y}e^{-\frac{(y - z\tan\theta_{y-z})^2}{2\sigma_y^2}}e^{-\frac{z^2}{2\sigma_z^2}}. \quad (9)$$

The bunch length at any $y = y_0$ is given by

$$\sigma_z^2(y_0) = \frac{\sigma_{y0}^2}{\tan^2\theta_{y-z} + (\sigma_{y0}/\sigma_z)^2}. \quad (10)$$

If a Gaussian slit with σ_s is put at y_0, the bunch length will still be given by Eq. (10) but with σ_{y_0} replaced by $\sigma_{y,eff}^2 = \sigma_{y0}^2 + \sigma_s^2$. Since the tilt angle $\theta_{y-z} \ll 1$, if we substitute Eqs. (7) and (8) into Eq. (10) and let $\nu_s\theta = \pi$ and $\cos\Upsilon = 1$, we get

$$\sigma_z^2(y_0) = \frac{\sigma_z^2}{\frac{4\beta(s_0)\Theta^2}{\epsilon_y}(\frac{C_y\sigma_\delta}{\nu_s})^2 + 1}. \quad (11)$$

Figure 4 shows the pulse length calculated from Eq. (10). According to the calculation, a 0.55-ps (rms) pulse can be obtained from an initially 20-ps (rms)-long bunch. We note that this conclusion is drawn from a simplified model; the decoherence and wakefield effects are not included. The vertical emittance will increase when decoherence occurs and the pulse length will be significantly longer.

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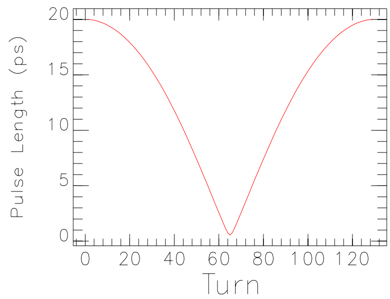

Figure 4: The minimum achievable pulse length by a vertical kick. The shortest pulse length is 0.55 ps at the 65th turn. The parameters used are: $\Theta = 0.12$ mr, $\beta(s_0) = 4.79$ m, $\epsilon_y = 0.025$ nm·rad, $\sigma_\delta = 0.001$, $C_y = 3.5$ and $1/\nu_s = 130$.

THE STREAK CAMERA MEASUREMENTS

The vertical kicker in the APS storage ring can kick the beam with a maximum amplitude of 0.15 mr. The pulse-length measurements were conducted at the APS diagnostics beamline [3]. A dual-sweep streak camera, which has the capability of taking bunch profiles at every third bucket, was used to take images turn by turn. A dove prism was used to rotate the beam; therefore, the profile can be either in the (x, z) plane (top-view) or in the (y, z) plane (side-view).

In the experiment a profile sweep was first performed from turn 0 to turn 190 after the kick. The sine-shaped bunch was immediately observed. Figure 5 shows some typical side-view bunches. From the side-view pictures we determined the turn number at which to observe the slitted photon pulse.

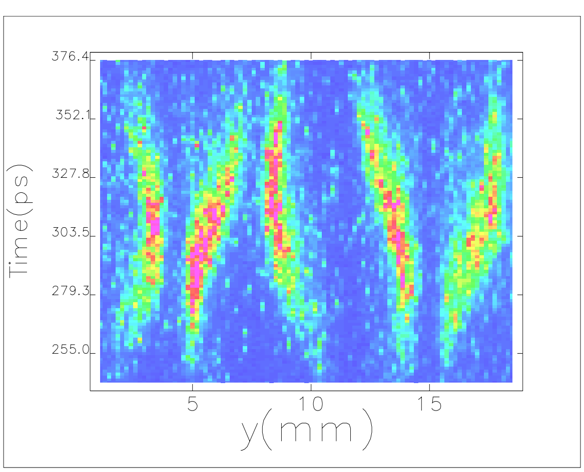

Figure 5: The side-view images of turns 83-87 after the kick. The bunch head is shown on the top.

Two pulse-length measurement experiments were carried out. In the first experiment a single bunch of current 1.3 mA was used. To obtain enough photons for a good Gaussian fit, we had to overlap the profiles from several shots. Even though each shot was taken at the same number of turns after the kick, the time duration of the sum profile is longer than that of a single shot because of tune jitter. Nonetheless, a 13.6-ps rms pulse was obtained from a 31-ps rms bunch. The effective slit's width was 100μm.

In the second expriment, a bunch train was injected into every third bucket. The current of each bunch was only 0.2 mA, the photons from five bunches were accumulated to get a profile fit. The shortest pulse observed was 5.7 ps rms. Figure 6 is a clip from the bunch-length measurement control interface when the shortest pulse was observed. The pulse is longer than we expected because 1) the decoherence makes the vertical slice emittance grow (note the kick amplitude is about $50\sigma_y$), and 2) the focusing resolution of the streak camera is about 2.2 ps, which also contributes to the measured pulse length [4].

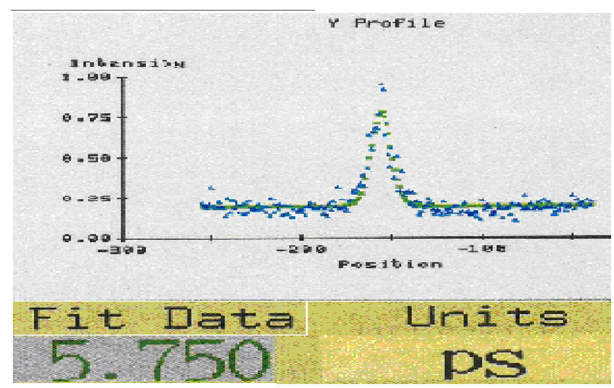

Figure 6: The shortest pulse observed from the control screen.

CONCLUSION

The bunch motion after a vertical kick was studied. Vertical and time $(y - t)$ correlation develops due to synchro-betatron coupling after the kick. This phenomenon can be used to obtain short X-ray pulses using vertical slits. Visible light pulses one order of magnitude shorter than the bunch length were observed. Detailed studies, including decoherence, are still ongoing.

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