A KILOHERTZ PICOSECOND X-RAY PULSE GENERATION SCHEME

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Abstract

The duration of the x-ray pulse generated at a synchrotron light source is typically tens of picoseconds. Shorter pulses are highly desired by the users. In electron storage rings, the vertical beam size is usually orders of magnitude less than the bunch length due to radiation damping; therefore, a shorter pulse can be obtained by slitting the vertically tilted bunch. Zholents proposed tilting the bunch using rf deflection. We found that tilted bunches can also be generated by a dipole magnet kick. A vertical tilt is developed after the kick in the presence of nonzero chromaticity. The tilt was successfully observed and a 4.2-ps pulse was obtained from a 27-ps electron bunch at the Advanced Photon Source. Based on this principle we propose a short-pulse generation scheme that produces picosecond x-ray pulses at a repetition rate of 1∼2 kHz, which can be used for pump-probe experiments.

INTRODUCTION

Shorter x-ray pulse generation has been pursued recently at many synchrotron light sources. Short x-ray pulses can be used to study dynamical processes such as chemical reaction or phase transition. The minimum required pulse length for these time-resolved experiments is on the order of 100 femtosecond; however, the pulse length of synchrotron radiation is typically 100 picosecond. An adjustable pulse length in this gap could be advantageous for some experiments. In order to carry out these experiments on a synchrotron, the pulse length has to be compressed by two to three orders of magnitude, preferably continuous.

Many methods have been proposed to shorten the x-ray pulse radiated from a synchrotron. They can be divided into three categories. The first category includes those approaches that either vary or modulate the longitudinal phase space parameters, such as increasing the rf voltage, installing a higher harmonic rf system, lowering the momentum compaction factor [1], or modulating the rf phase or voltage [2]. Methods of the second category make use of the short duration of a laser pulse. Thomson scattering [3] and femtosecond laser slicing [4] fall into this group. The third group of methods take advantage of the smaller vertical beam size in a storage ring. Rf deflecting cavity method [5] and vertical kick method [6] belong to this category. In this paper we will focus on the vertical kick method.

In a storage ring accelerator the transverse and longitudinal motion is usually coupled due to chromaticity. If a bunch is kicked vertically by a pulsed kicker, even though each longitudinal slice has the same oscillation amplitude and phase in the beginning, because of synchrobetatron coupling they will have different betatron oscillation phases around $n + 1/2, n = 1, 2, 3...$ synchrotron period; therefore a tilt can be formed. This is similar to the tilt observed in the head-tail instability [7] but in a controlled fashion. In the case of linear motion the vertical beam size along the tilt equals the original value. Therefore the effect is equivalent to rf deflection, except that it is not continuous. In reality the beam size grows due to diffusion and nonlinearity, which limits the minimum achievable pulse length. However, the tilt angle is two to three orders of magnitude greater than the deflection method, which counteracts the vertical size growth. In a typical third generation synchrotron light source it is possible to generate picosecond or even subpicosecond pulses through this method. In the following text we will discuss the synchrobetatron beam dynamics and present the experimental results that were obtained at the Advanced Photon Source.

BUNCH TILT THROUGH SYNCHROBETATRON COUPLING

The particle motion in the longitudinal phase space can be described by

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

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 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 conditions.

At $\theta = 0$ if we give the bunch a vertical kick, the particles would oscillate according to

$$\begin{aligned} y &= A(s)\sin[\int_0^\theta \nu_y d\theta + \psi_{s,0}] \\ &+ \sqrt{2\beta_y(s)J_y}\cos[\int_0^\theta \nu_y d\theta + \psi_{s,0} + \psi_0], \quad (2) \end{aligned}$$

where the first term is due to the kick and second term is the thermal motion. Here $A(s) = \sqrt{\beta_y(s)\beta_y(s_0)}\Theta$ is the oscillation amplitude, β_y is the beta function, $\psi_{s,0}$ is the betatron phase advance from s_0 to s in one turn, $\nu_y = \nu_{y,0} + C_y\delta$ is the vertical tune, C_y is the vertical chromaticity, and J_y and ψ_0 represent the initial action and angle due to the vertical emittance.

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From Eq.(1), the integral

$$\int_0^\theta \nu_y d\theta = \nu_{y,0}\theta - \frac{C_y}{h\alpha_c}(1-\cos\nu_s\theta)\Delta\phi(\theta) + \frac{C_y}{\nu_s}\delta(\theta)\sin\nu_s\theta \quad (3)$$

The momentum spread in one longitudinal slice satisfies Gaussian distribution. Averaging $\delta(\theta)$, J_y, and ψ_0 in Eq. (2), one gets the vertical displacement of a longitudinal slice

$$\langle y\rangle(\Delta\phi) = A(s)\exp(-\xi^2)\sin\Upsilon, \quad (4)$$

where

$$\xi^2 = \frac{1}{2}(\frac{C_y\sigma_\delta}{\nu_s})^2(1-\cos^2\nu_s\theta), \quad (5)$$

and

$$\Upsilon = \nu_{y,0}\theta + \psi_{s,0} - \frac{C_y}{h\alpha_c}(1-\cos\nu_s\theta)\Delta\phi. \quad (6)$$

Therefore, the vertical displacement $\langle y\rangle(\Delta\phi)$ is related to the longitudinal position $\Delta\phi$, and a tilt can be formed.

The tilt angle is given by

$$\theta_{y-z}(\Delta\phi) = \frac{d\langle y\rangle(\Delta\phi)}{d\frac{c}{\omega}\Delta\phi} = -\frac{\omega}{c}A(s)\frac{C_y}{h\alpha_c} \times (1-\cos\nu_s\theta)e^{-\xi^2}\cos\Upsilon, \quad (7)$$

Note at $\nu_s\theta = \pi$ the tilt reaches maximum, and the betatron tune $\nu_{y,0}$ and chromaticity C_y can be adjusted such that the particles stay in the linear region of the sine function, hence the tilt is linear.

In an electron storage ring there are various effects that deteriorate this correlation, like radiation damping and quantum fluctuation, amplitude tune dependence, and second order chromaticity. The tilt disappears quickly after a couple synchrotron periods. For a complete treatment of these effects, interested readers can refer to [6].

If the kick angle $\Theta \sim 1$ mr, one finds that the tilt angle is typically 100 mr, which is much bigger than the tilt that can be produced by rf deflecting, which is typically about 100 μr. However, the beam size also grows due to the deteriorating effects mentioned above. As a result of both effects, the slitted pulse length is also in the range of picosecond for a typical third generation synchrotron light source.

IMAGING THE TILTED BUNCH AND SLITTING FOR SHORTER PULSE

In order to observe the tilted bunches, we conducted imaging experiments at the APS diagnostic beamline [8]. A dual-sweep streak camera was set up to take bunch profiles in the (y, z) plane turn by turn. A vertical kicker kicks the beam at 2 Hz with a maximum strength of 0.15 mr. The vertical chromaticity was lowered from 6 to 3.5 to make the bunch tilt as linear as possible. The horizontal chromaticity was kept at 6.6 because it does not affect the bunch tilt. With the lowered chromaticity, we were able to store 1.3-mA current in a single bunch when the kicker was on. A profile sweep was performed from turn 0 to 200 after the kick. The sine-shaped bunch was immediately observed. Figure 1 shows the side-views of a bunch at several successive turns.

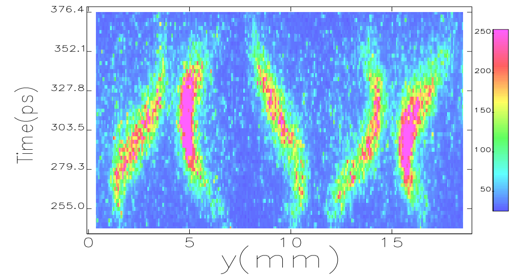

Figure 1: The side views of a bunch at turn 63 to 67 after a vertical kick.

At half the modulation period, the tilt reaches maximum and the slice emittance reaches a minimum; therefore, it is the best time to slice for short pulse. We changed the above experiment setup to observe the shortest possible pulse. To avoid the collective effects, we injected ten 0.03-mA bunches into every third bucket. The longitudinal scan of the streak camera was synchronized to one third of the rf frequency. A x-ray filter of 10×550 nm was used to reduce the diffraction effect in the optics. A slit of 75 ± 15-μm effective width was used to clip the image right before the streak camera.

Figure 2 shows the pulse length with and without the slit. The profiles are overlapped for 300 shots. The one without the slit gives the original bunch length, which is 27.4 ps. As a comparison, the zero current bunch length is about 20 ps. The one with the slit gives 8.2 ps. Even though each individual pulse is much shorter, the tune jitter changes the arrival time of the slitted pulse and results in a longer overlapped profile. One can calculate the corresponding tune jitter to be $\Delta\nu_y = 1.6 \times 10^{-4}$, which agrees with the tune jitter measurement result. From the plot, one can calculate the slitted photon flux to be about 10% of the pulse.

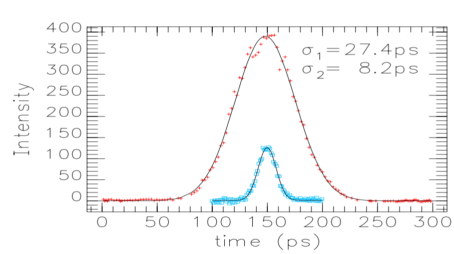

Figure 2: The length of the long-time-overlapped pulses. Red crosses, without the slit; blue squares, with the slit.

At very low current, the wake field effect becomes negligible, and the decoherence is dominated by the longitudinal diffusion. In that case the pulse compression ratio is

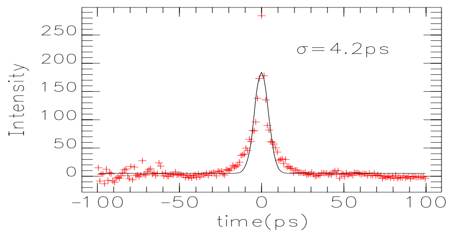

Figure 3: The average length of the slitted pulse when the time jitter is removed.

$R \approx \sqrt{2/[1-\exp(-\pi a_E/\nu_s)]}$. Fig. 3 shows the average slitted-pulse length when the time jitter is removed manually from the data. The value of 4.2 ps is very close to the predicted value of 4 ps. This pulse length is of interest because the time jitter can be overcome with available techniques [9]. The time jitter can even be utilized to scan the interested interval.

THE SHORT PULSE GENERATION SCHEME

Based on the above principle, we propose the short-pulse generation scheme illustrated in Fig. 4. N bunches are stored in the ring, a fast kicker kicks one bunch (the black one) at a time, and a second kicker gives a reverse kick after one synchrotron period. A timing source controls the kick and sends a delayed signal to the detector. The gate of the detector opens only at the time when the tilt reaches maximum. The tilted pulse (the black dotted lines) goes through the focusing mirrors and the wave-length-filtering monochromator like the normal pulse (the blue long dashed lines). Because of the tilt, the shorter pulse can be obtained by an offset slit; therefore shorter pulse experiments can be performed in parallel. It takes a few damping time periods for the beam size to damp down. Other bunches can be kicked during the interval; therefore, the repetition rate will be $\sim N/\tau_y$. In such a setup the vertical chromaticity does not have to be low as long as the kick amplitude is much bigger compared to the slit width. An additional advantage is that there is no need to change the x-ray optics.

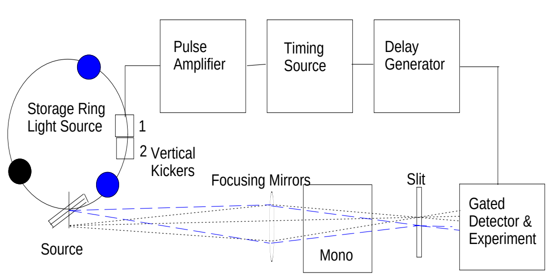

Figure 4: The short-pulse generation scheme.

Take the APS as an example. The tune jitter gives a 13% residue of centroid oscillation after the second kick. More reverse kicks controlled by a real-time feedback can be applied to eliminate the residue. Because of the decoherence, the beam size increases by 40% of the kick amplitude. ELEGANT [10] simulation shows that a repetition rate of 1.2 kHz can be realized with 24 bunches if the kick amplitude is less than 0.05 mr. The 1∼2-kHz frequency matches the laser frequency in pump-probe experiments. In order for the fast kickers to kick a single bunch, the pulse duration should be less than 0.3 μs. The flux of each pulse will be about 10% of a single bunch if an effective slit of 50 μm is used. The minimum pulse length will be about $3 \sim 4$ ps for a bunch with $1 \sim 2$-mA current. At higher current the pulse length is longer and the repetition rate has to be lower due to the wake field decoherence and bunch lengthening.

There are methods to increase the photon flux. One way is to store 24 bunch trains instead of singlets. This requires the kicker pulse to be flat-top; and the x-ray pulses might be lengthened due to the long-range wake field. A second method is to replace the slit with a compression optics similar to that proposed in Ref.[5]. We note the tune jitter results in about 6% tilt angle change, therefore degrades the compression.

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