USING SYNCHROBETATRON RESONANCES TO GENERATE A CRABBED BEAM AT THE ALS

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Abstract

Several years ago experiments at the APS [1] demonstrated the possibility of creating crabbed beam through vertically kicking the beam and letting it oscillate for a half of a synchrotron period. Such a crabbed beam would allow the possibility of creating xrays with duration of a few picoseconds. At the ALS we have repeated these experiments. In this paper we will present the results obtained, compare them to theoretical predictions and discuss next steps.

INTRODUCTION

The Advanced Light Source (ALS) at Lawrence Berkeley National Laboratory is a third generation light source that delivers ~60ps FWHM long pulses of photons with high brightness, repetition rate, and with energy tunable from few tens of eV to several keV. For certain applications it is of great interest to compress the pulse length to the picoseconds timescale. One example is looking at the dynamics of bit flipping in magnetic materials which occurs on the picosecond time frame. For other applications even smaller pulse durations are needed. Following the movement of atoms and molecules during chemical reaction and phase transition requires pulse length that match the period of atom vibration which is ~100fs. Furthermore, tracking electrons in atoms, demands pulse length in the order of attoseconds.

The photon pulses generated from synchrotrons such as ALS can be compressed by various methods. These methods involve, as the first category, either varying or modulating longitudinal phase space parameters by manipulating RF system somehow, for example, by installing a higher harmonic RF system or modulating RF phase or voltage [3]. In another category, pulse compression is achieved by inducing electro- magnetic interaction of stored electron bunches with much shorter laser pulses , so as to truncate the bunch. Femtosecond laser slicing[4] (which is currently being used at the ALS), and Thomson scattering [5] belongs to this category. Another scheme involves tilting the beam so that the smaller vertical beam size is utilized for x-ray pulses generation. The beam tilt can be achieved by applying RF deflecting cavity or vertical kick method. RF deflecting cavity method involves developing a new device. The vertical kick method was proposed and successfully experimented at the Advanced Photon Source (APS)[1]. Currently, ALS is considering the same method for generating short pulses. In this paper, we describe a set of experiments performed at the ALS and we compare the results with the theoretical predictions. Plans for the future are also briefly discussed.

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WORKING MECHANISM AND PREDICTIONS

Synchrobetatron Coupling

Particles in the storage ring accelerators execute oscillations, namely, synchrotron oscillations, and

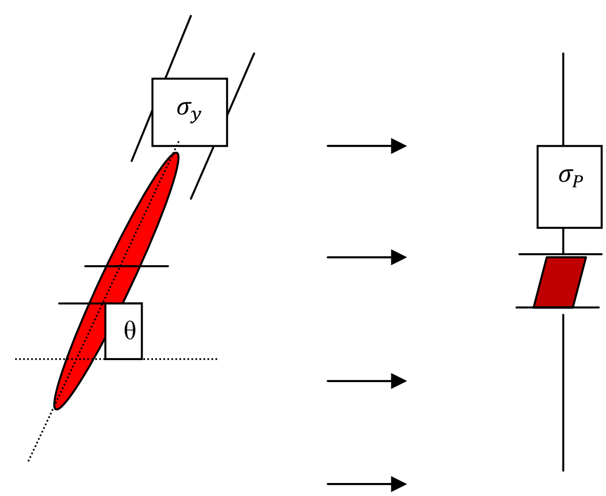

Figure 1: Shorter Pulse Generation from a Tilted Beam

betatron oscillations, during their orbit along the ring. The synchrotron oscillation is the longitudinal oscillation particles perform within the bunch, and the betatron oscillation is the transverse oscillation of the particles, in both the horizontal and vertical plains, about the ideal orbit. In the presence of non-zero chromaticity, both type of oscillations are coupled. In this situation, applying a vertical kick results in a bunch tilt because of the synchro-betatron coupling.

It can be shown that if a bunch is kicked vertically, particles going through longitudinal oscillations will exhibit different betatron oscillation frequencies and phases and that a tilt can be fully developed in a half synchrotron period[1]. Based on a particle motion in the longitudinal phase space, and using the beta function and betatron tunes, the development of the tilt is formulated as follows[1]:

$$\theta_{y-z}(\Delta\phi) = \frac{d\langle y\rangle(\Delta\phi)}{d\frac{c}{w}\Delta\phi}$$

$$= -\frac{\omega}{c}A(s)\frac{C_y}{h\alpha_c}\left(1 - cos\nu_s\theta\right)\ e^{-\xi^2}cos\Upsilon \qquad (1)$$

$$\left[\begin{array}{c} where\ A(s) = \sqrt{\beta_y(s)\beta_y(s_0)}\Theta \\ and\ \Upsilon = \nu_{y,0}\,\theta + \psi_{s,0} - \frac{C_y}{h\alpha_c}(1 - cos\ \nu_s\theta)\Delta\phi \end{array}\right]$$

ω is the angular frequency of the RF system, ν_s, the longitudinal tune, C_y the vertical chromaticity, α_c the momentum compaction factor, θ the orbital angle, (θ advances 2π every turn) , $\nu_{y,0}$,vertical betatron tune, $\beta_y(s, s_0)$, beta function at s (to observation point), s_0 (the kicker position) along the longitudinal direction, Θ kick strength in mrad, and $\psi_{s,0}$ is the betatron phase advance from s_0 to s in one turn. Note that A(s) is simply the oscillation amplitude at the observation point.

Once the tilt is achieved, pulses with shorter duration could be generated by collimating the light as illustrated in Fig.1. The pulse length is related to the slice beam size and the tilt angle by the simple relation $\sigma_p = \frac{\sigma_y}{\theta}$.

Limitations due to Decoherence

There are several factors limiting the minimum achievable pulse length. These factors include quantum excitation, wakefields, linear x-y coupling, and higher order chromaticity, among other things. Some of these effects will cause the centroid and tilt oscillations, generated after the kick, to disappear over several hundred turns. The decoherence effect can be introduced in the theory obtaining the centroid oscillation [2].

It can be also showed that at low current, the decoherence is dominated by longitudinal diffusion, and that the minimum pulse length achievable is ultimately limited by the compression ratio [2],

$$R \approx \sqrt{2/\left[1 - \exp\left(-\frac{\pi\alpha_E}{\nu_s}\right)\right]} \qquad (4)$$

such that $\sigma_p(final) = R\,\sigma_p(initial)$. For the ALS operating at 1.9 GeV this low current limit corresponds to bunch length reduction of ~10 which would be of particular interest to several experiments.

MEASUREMENTS AND RESULTS

In the experiment a dual-sweep streak camera was used to take beam images, turn by turn, at the diagnostic beam line (BL3.1). A pinger magnet capable of delivering a single-turn kick to the beam was used for generating a maximum displacement up to ~ 7 mmad the observation point (BL3.1). The experiment was done at 1.9 GeV and with the ALS storage ring parameters of h=328, $\alpha_c = 1.37 \times 10^{-3}$, ν_s = 10.2kHz.

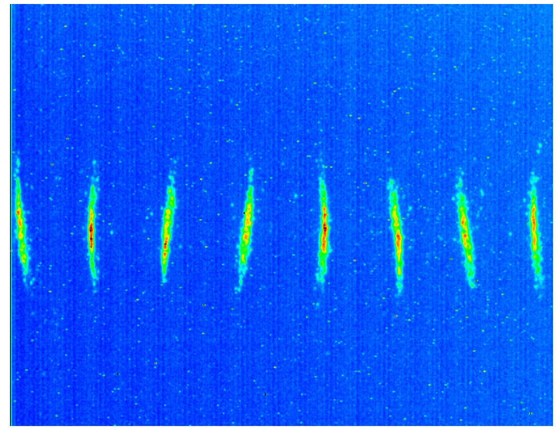

Figure 2: Example of streak camera image

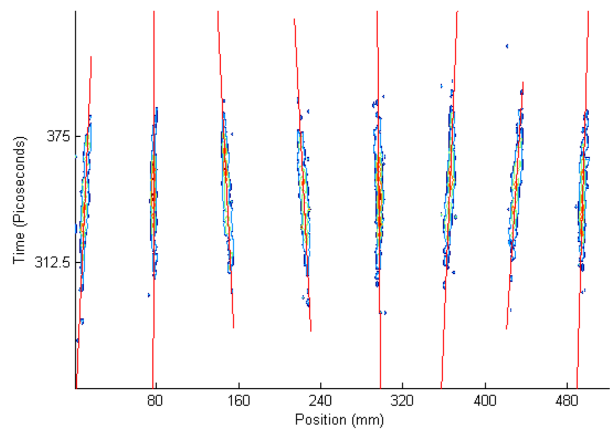

Figure 3: Example of a processed streak camera image.

Figure 2 shows an example of streak camera image. The vertical axis is the time (longitudinal) dimension, while the horizontal axis shows the vertical beam dimension (a dove prism was used to rotate the transverse plane of 90 deg). The figure shows images of a single bunch from turn 76 to 83, after a vertical kick that correspond to a maximum oscillation amplitude of 5.46mm. 75 turns correspond to half a synchrotron period. Figure 3 shows the same image after processing. (Note that the top and bottom are reversed). In the processed image, noise is first eliminated, and the tilt and centroid position are then extracted by fitting each of the images. The horizontal axis and vertical axis are calibrated using the pinger and streak camera calibrations. The straight lines in red are drawn using the calculated tilt angle and centroid.

We first took data for different delays, between the kick and the streak camera acquisition, to measure the tilt amplitude at different turns. Figure 4 shows the results. It shows that the tilt amplitude is maximum around the 75th turn and minimum at turns 0 and 150. These results are consistent with the measured synchrotron tune and the ALS revolutions frequency of ~ 1.52 MHz.

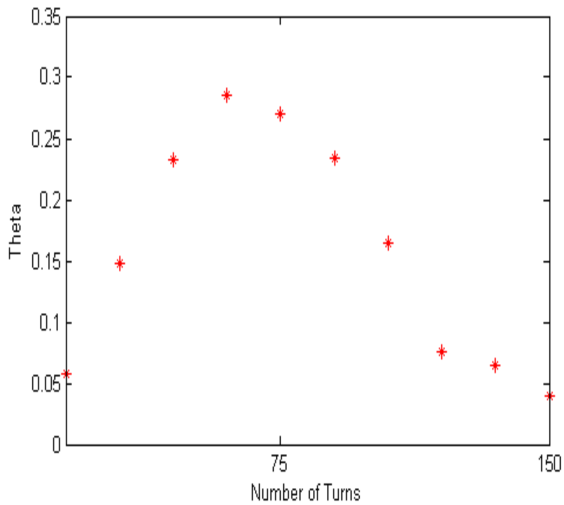

Figure 4: Tilt angle amplitude in rad vs. number of turns.

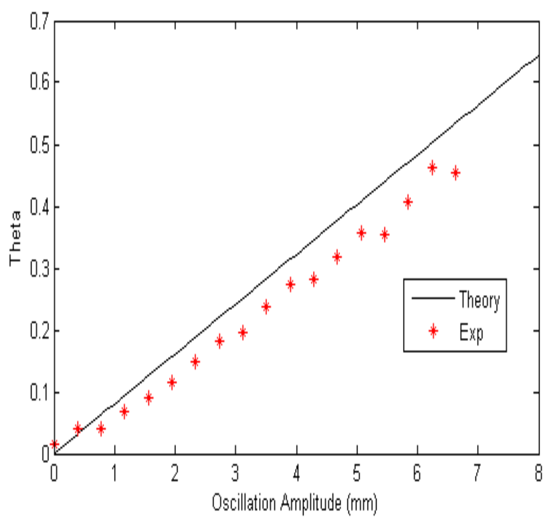

Figure 5: Tilt angle in rad vs. oscillation amplitude.

We also recorded beam images for oscillation amplitudes (kick strength) up to ~ 6.7 mm, with vertical chromaticity set to 1.6. All images were recorded after half a synchrotron period (~75turns). The theoretical tilt angles, calculated by Eqn.(1)] are plotted in Fig. 4 together with the experimental data. Considering the finite accuracy of the pinger calibration, the agreement between data and theory is quite satisfactory, showing a maximum discrepancy of about 16%.

Additional measurements were made while varying the vertical chromaticity from 0.1 to 2.6, keeping the kick amplitude fixed to ~2.7 mm. The results are plotted in Figure 6 together with the theoretical results. We observe that the tilt angle gets larger with the vertical chromaticity, as it should, according to Eqn. (1). However, the experimental tilt values are systematically smaller than the theoretical ones with a maximum difference of ~ 40%. We attribute such a discrepancy to inaccuracy in the chromaticity value (it was not directly measured but derived from a calibrated lattice model), and to non-linear chromatic effects that start to distort the bunch shape making the fit results less accurate.

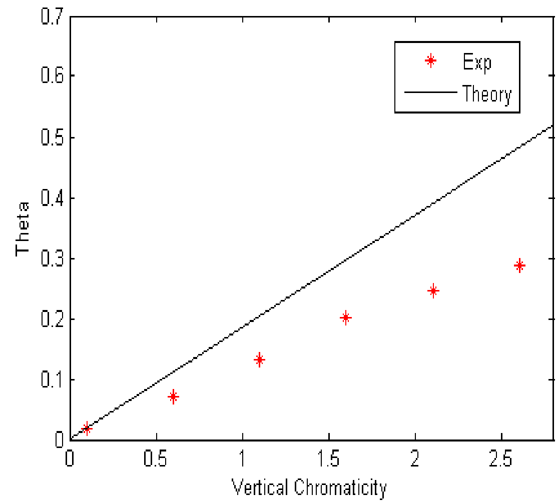

Figure 6: Tilt angle in rad vs. chromaticity

FUTURE PLANS

The next step will consist of measuring the vertical beam size. This is important because the final photon pulse duration after collimation is a function of the tilt angle, and the vertical beam size. Of course, the final validation of the technique will be obtained by collimating the light from the tilted beam and measuring the duration of the photon pulse at some of the ALS beamlines.

If successful, the far future plan would be to combine bunch tilting technique with the pseudo-single bunch operation [6] in order to allow user with short pulses during normal high current operation.

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