STREAK CAMERA STUDIES OF VERTICAL SYNCHRO-BETATRON-COUPLED BEAM MOTION IN THE APS STORAGE RING*

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Abstract

We present experimental studies of synchro-betatron-coupled electron beam motion in the Advanced Photon Source (APS) storage ring. We used a vertical kicker to start the beam motion. When the vertical chromaticity is nonzero, electrons with different initial synchrotron phases have slightly different betatron frequencies from the synchronous particle, resulting in a dramatic progression of bunch-shape distortion. Depending on the chromaticity and the time following the kick, images ranging from a simple tilt in the bunch to more complicated twists and bends are seen with a visible light streak camera. We found that most of the experimental observations can be described by the synchro-betatron-coupled equations of motion. Also note that the fast apparent increase in vertical beam size after the kick is dominated by the internal synchro-betatron-coupled motion of the electron bunch. Experimentally this increase could be easily confused with decoherence of vertical motion if the bunch is only imaged head-on.

INTRODUCTION

It is a common technique to study beam dynamics by kicking a stored beam in a circular accelerator and observing its subsequent motion. In the APS, we have used it to measure damping behavior for some time [1]. During these measurements, we often found it difficult to explain the bunch's behavior immediately after the kick.

Recently, Guo et al. [2] proposed to use synchro-betatron coupling to obtain vertically tilted bunch dynamically by kicking the beam. His proposal can be qualitatively illustrated (Figure 1). A vertical kick initially displaces all electrons in the bunch equally. The electron ahead of the synchronous particle started with a higher rf voltage, and its energy is higher in the first half synchrotron period after the kick until it reaches the tail end of the bunch. If the vertical chromaticity (C_y) of the accelerator is positive ($C_y > 0$), as in the APS storage ring, the electron would accumulate betatron phase faster than the synchronous particle in this time interval. Conversely, an electron starting from behind the synchronous particle would accumulate less betatron phase as it moves towards the head of the bunch. As a result, different parts of the bunch will have different betatron phases and different vertical coordinates, resulting in a tilt and distortion of the bunch.

In this simple theory, the betatron oscillation amplitude of each electron does not change during a time interval well below the damping time (~ 20 ms). Let us envision a cylinder in *y-y'-z* 3D space, with its symmetry axis along the *z*-direction. We choose a scale of *y* and *y'* so that an electron in betatron oscillation moves in a circular orbit in the *y-y'* space. The thin ribbon beam in the storage ring, once displaced, will be a small patch, moving and diffusing on the cylindrical surface. Its projection in the *y-z* space can be captured by a streak camera taking the side view.

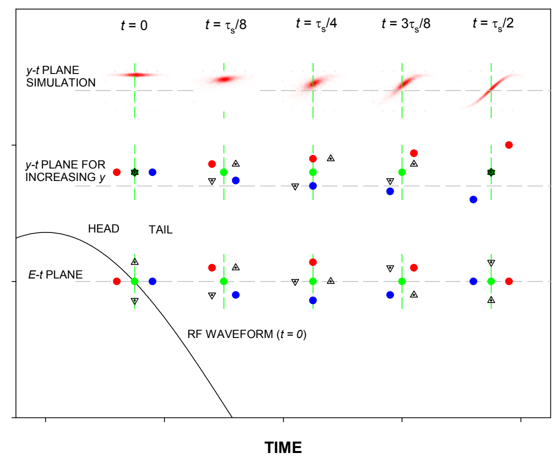

Figure 1: Illustration of an electron beam's synchro-betatron motion in a ring with positive chromaticity: (bottom row) longitudinal phase space motion of four electrons initially at the extreme ends of energy / time scale; (middle) motion of the four particles in *y-z* plane; and (top) collection of 10^4 electrons in *y-z* plane.

EXPERIMENTAL SETUP

Figure 2 shows the experimental setup for the studies. The timing signals were obtained from the APS timing base. A 2 Hz timing pulse is used to trigger a vertical kicker magnet and, after a programmable delay, to trigger a Hamamatsu C5680 streak camera. The storage ring rf source (352 MHz) was divided down to generate 117 MHz rf signal to drive the streak camera's vertical scan unit. The visible bend magnet radiation was transported out of the radiation enclosure using a spherical imaging mirror. Secondary optics are used to produce an image at the streak camera photo cathode.

A dove prism was used in this experiment to rotate the image by 90° so the beam *y*-axis is parallel with the photo-cathode and side-view images of the bunch are produced when streaking is enabled. We first calibrated the streak camera by moving the source point by 200 μm in the horizontal direction. A calibrated x-ray pinhole camera was used to monitor the actual displacement of the source. Resolution of the imaging system was obtained by comparing the measured beam sizes using the streak

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camera focus mode and those using the pinhole camera (Table 1).

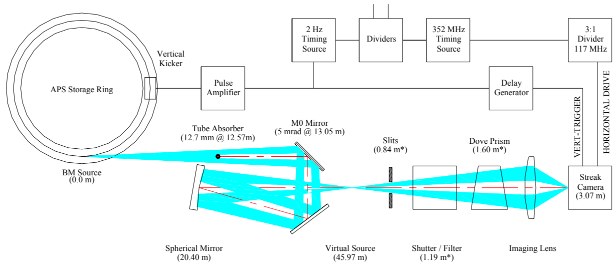

Figure 2: Streak camera studies setup.

Table 1: Streak Camera Calibration and Resolution

	Transverse (*x*,*y*)	Longitudinal (*z*,*t*)
Pixel size	0.037 mm	0.36 mm / 1.21 ps
Full scale	18.8 mm	175 mm / 583 ps
rms resolution	0.13, 0.10 mm	0.67 mm / 2.24 ps

OBSERVED IMAGES

We performed two experiments, using a single bunch of 1.3 mA in the first and a train of 10 equal bunches totaling 2 mA in the second. Figure 3 shows dual sweep streak images from the first experiment. Note that we have oriented the images so they resemble the actual side views of the traveling bunch. The longitudinal axis of the bunch is horizontal in the figure. The vertical time scale is 20 µs to contain five consecutive turns of the electron bunch. When multiple bunches are used, their spacing is well below the revolution time so that their images overlap one another.

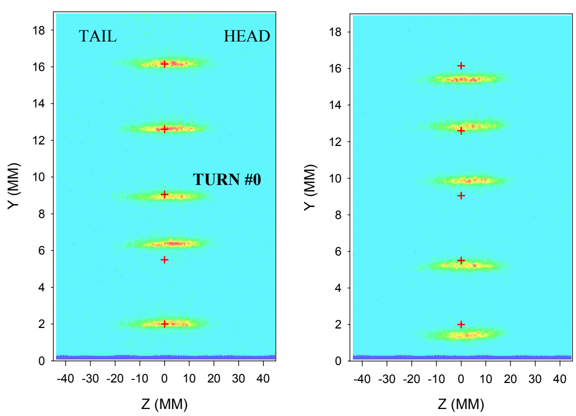

Figure 3: Side-view streak images of the stored beam probed by a vertical kicker. The turn indices are (left) No. -2 (top) to +2, and (right) No. 3 to 7.

Data from a 1.3 mA (5 nC) Bunch

A streak image taken with undisturbed beam was used to define the centers of the beam images in five consecutive turns, marked by crosses in Figure 3. The first turn after the kicker pulse was found by adjusting the streak trigger delay until a bunch disturbance is observed. After receiving the vertical kick, the bunch is seen to go into vertical betatron oscillation as a whole with a tune ~ 0.25. After 25 turns (about 1/8 into the first synchrotron period), the bunch grows significantly in height (Fig. 4). It also starts to show a distinct triangular shape in half of the projections. The height of the bunch continues to grow to reach its first peak around the 55th turn. If the beam is imaged only in the front view, the rms height of the beam would be oscillating strongly turn-by-turn, making it very puzzling to characterize.

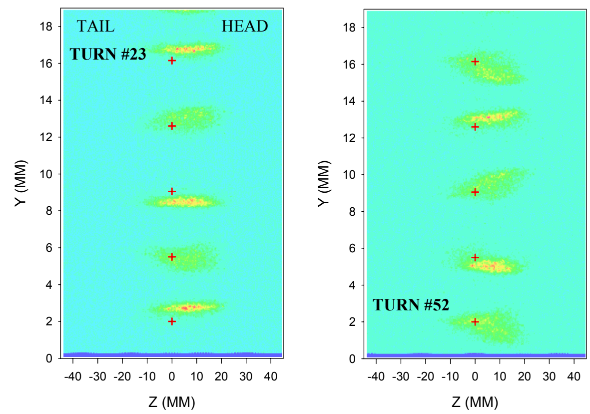

Figure 4: Side-view streak images of with turn indices (left) No. 23 to 27, and (right) No. 47 to 52.

After reaching the peak, the bunch height gradually decreases to finally reach a minimum around the 90th turn, where the bunch tilts up to ~3°. While a bunch moves and tilts every turn, an apparent "stationary" point can be found near the end of the bunch, where the electrons have very small betatron oscillation amplitude (Fig. 5). The minimum does not last long. In the next 15 turns, the bunch quickly broadens, and the triangular shape now develops into "lobster-claws." Since the betatron period is around four turns, Figure 5 is consistent with a claw-like distribution in *y-y'-z* 3D space, showing its projection sequentially on four coordinate planes: *yz*-plane, *y'z*-plane, *yz*-plane other side, and *y'z*-plane other side.

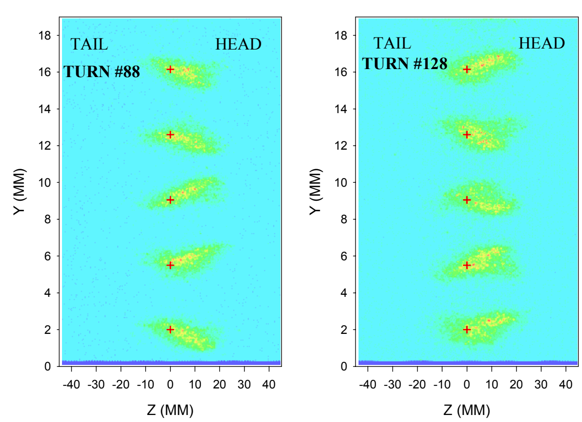

Figure 5: Side-view streak images of with turn indices (left) No. 88 to 92, and (right) No. 128 to 132.

By the end of the first synchrotron oscillation period, the transverse motion has significantly decohered (Fig. 6). The centroid motion is less than one-third of the initial betatron excitation. The transverse motion is nearly

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completely decohered by the end of the second period, with the centroid motion amplitude reduced further.

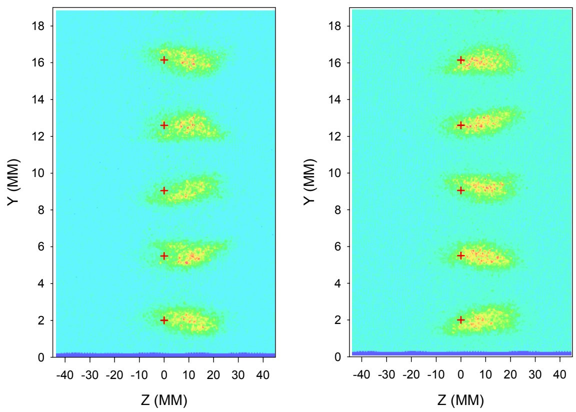

Figure 6: Side-view streak images of with turn indices (left) No. 178 to 182, and (right) No. 398 to 402.

Data from low-current run

Figure 7 shows images taken from the second, low-current run, where a higher kicker pulse can be applied. We can see that most observations described in the high-current run are also evident in these images. However, the low-current bunch appears to be narrower at the end of a half synchrotron period. This dependence on the bunch current indicates that the impedance of the ring plays a significant role in the decoherence process.

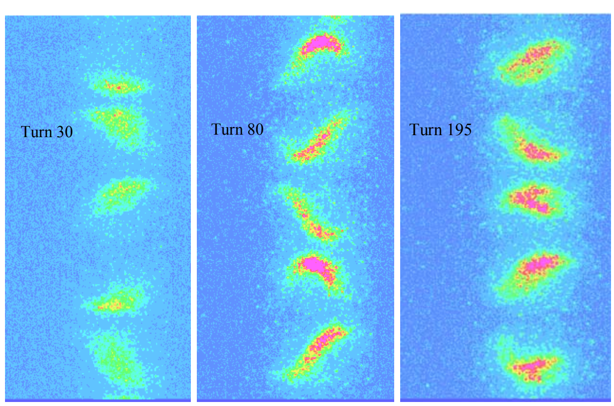

Figure 7: Side-view streak images of 0.2 mA bunches with turn indices (left) No. 29 to 33, (middle) No. 89 to 93, and (right) No. 194 to 198.

DISCUSSION

We have observed the main features of kicker-induced synchro-betatron coupled motion: The bunch tilt angle gradually increases in the first half synchrotron period and then gradually decreases in the second half; the bunch broadens in the first 1/4 synchrotron oscillation period and then narrows in the next 1/4 period. The maximum height difference between the bunch head and tail is also comparable to the amplitude of the initial kicker-induced bunch displacement.

However we have also seen features inconsistent with the simple theory of synchro-betatron coupled motion where only betatron oscillation amplitude is not changed over time. First, the theory predicts that the bunch tilt angle vanishes a complete synchrotron period after the kick. Our search found a minimum in bunch tilt near the 200^{th} turn, but the tilt angle never vanishes. This strongly suggests that the synchrotron motion of the electrons in the bunch is not completely coherent, which may be due to amplitude-dependent tunes, quantum excitation, or other causes for incoherent motion. At this storage ring, the electron energy loss per turn is comparable to the rms energy spread (0.1%). Our analysis indicates that quantum excitation comprises the dominant contribution to the decoherence process.

We notice that the tail of the bunch has smaller betatron oscillation amplitude than that of the head. The picture of motion in a single degree of freedom, a small patch on a cylinder in y-y'-z 3D space, could not explain this observation, no matter how we choose the directions of projection over four consecutive shots. This suggests that coupling into horizontal dimension (x) or with electrons may play a significant role even in this short time scale.

If the vertical motion is not coupled to other degrees of freedom, the phase decoherence of a displaced beam would generate a ring in the y-y' phase space, or a band in y-y'-z 3D space, with a radius comparable to the initial displacement. When projected in the y-z space, we expect to see two parallel bars at a distance twice the initial kick and an intensity transfer between the two bars when phase decoherence is partially complete. If we allow the two bars to tilt, they will form a "lobster-claw" (Figures 5 and 6). Since only one branch of the claw lights up (intensity jumping) at a time, we know that decoherence in y-phase space is not complete at the end of the first synchrotron period. Again, we note that the simple theory does not allow the tilt of the bars nor the "stationary point."

SUMMARY

We studied side-view images of the APS storage ring beam excited by a vertical kicker magnet. The images confirmed the synchro-betatron coupled motion to be the dominant feature for the kicker-induced motion in the first two synchrotron oscillation periods. Evidence suggests that coupling into horizontal dimension or interaction between electrons (impedance) plays significant role in the short period after the kicker pulse is applied. The decoherence of the transverse motion also appears to be strongly correlated with the longitudinal motion.

REFERENCES

[1] B. X. Yang et al., "Characterizing Transverse Beam Dynamics at the APS Storage Ring Using a Streak Camera," AIP Proc. 451, 229 (1998).

[2] W. Guo et al., "Generating Picosecond X-ray Pulses with Beam Manipulation in Synchrotron Light Sources," these proceedings.