Characterizing Transverse Beam Dynamics at the APS Storage Ring Using a Dual-Sweep Streak Camera

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Abstract. We present a novel technique for characterizing transverse beam dynamics using a dual-sweep streak camera. The camera is used to record the front view of successive beam bunches and/or successive turns of the bunches. This extension of the dual-sweep technique makes it possible to display non-repeatable beam transverse motion in two fast and slow time scales of choice, and in a single shot. We present a study of a transverse multi-bunch instability in the APS storage ring. The positions, sizes, and shapes of 20 bunches (2.84 ns apart) in the train, in 3 to 14 successive turns (3.68 μs apart) are recorded in a single image, providing rich information about the unstable beam. These include the amplitude of the oscillation (~0 mm at the head of the train and ~2 mm towards the end of the train), the bunch-to-bunch phase difference, and the significant transverse size growth within the train. In the second example, the technique is used to characterize the injection kicker-induced beam motion, in support of the planned storage ring top-up operation. By adjusting the time scale of the dual sweep, it clearly shows the amplitude (±1.8 mm) and direction of the kick, and the subsequent decoherence (~500 turns) and damping (~20 ms) of the stored beam. Since the storage ring has an insertion device chamber with full vertical aperture of 5 mm, it is of special interest to track the vertical motion of the beam. An intensified gated camera was used for this purpose. The turn-by-turn *x-y* motion of a single-bunch beam was recorded and used as a diagnostic for coupling correction. Images taken with uncorrected coupling will be presented.

INTRODUCTION

The streak camera has been successfully used for accelerator diagnostics in the past two decades (1–7). Originally developed for the diagnostics of ultra-fast laser pulses, the camera's temporal resolution, from several ps down to less than 1 ps, is particularly suitable for measuring the length and longitudinal phase of particle bunches in modern accelerators. The addition of scanning capability in the second, horizontal axis enabled recording of successive images of the beam and study of its longitudinal dynamics (6,7). Many measurements also make use of one transverse dimension in the image (1–5), which amounts to taking the side or top view of the traveling particle bunch. This technique enabled the visual demonstration of dynamic effects such as intra-bunch wakefield interaction in the linac (1), strong head-to-tail instability in a high-energy storage ring (2,3), etc. When the horizontal beam size is dominated by the particle energy spread, found in high dispersion regions, the top view of the bunch was used to image the longitudinal phase-space distribution during longitudinal damping (5). In these measurements, the longitudinal beam dynamics were studied.

In this work, we present a streak camera technique that emphasizes recording the evolution of the front view of the particle beam, either from multiple particle bunches or from multiple turns of a single bunch in a circular accelerator. We will show that it is a powerful and flexible technique for studying transverse beam dynamics.

Basic Technique

The basic technique is illustrated in Figure 1. In a streak tube, photoelectrons generated by the instantaneous light pulse of the particle bunch on a photocathode are accelerated and focused on to a micro-channel plate (MCP), and the intensified electronic image is converted to light by the phosphor screen. When the vertical sweeping field ramps rapidly, the image scans down the screen, leaving a trace proportional to the length of the particle bunch. If, however, the sweeping field ramps slowly and the images from the head and tail of the bunch are almost overlapping, the resulting image is a good approximation of the front view of the particle bunch.

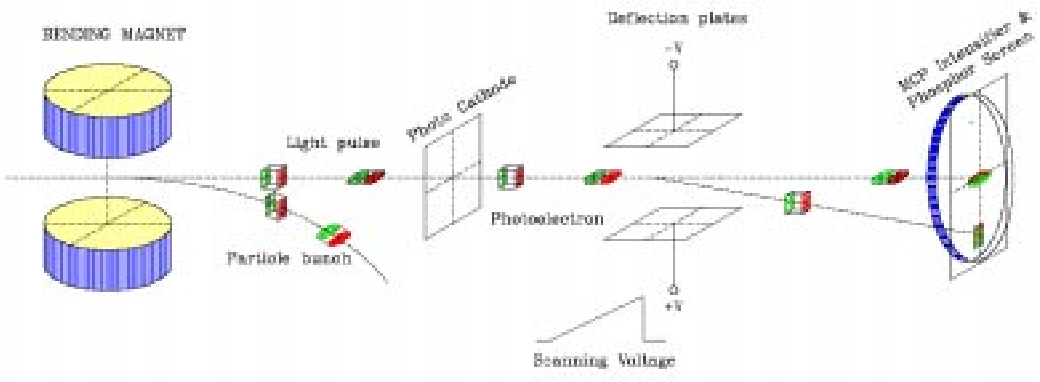


FIGURE 1. Schematic for recording the front view of the bunch with streak cameras. The accelerating and focusing electro-optics, as well as the horizontal deflection plates, are not shown for simplicity.

When the next event, the next bunch, or the next turn of the same bunch comes after a time period much longer than the bunch length, its image will be placed on a different location of the phosphor screen, preferably not overlapping with the previous one. In this manner a “fast sweep”—normally in the vertical direction and triggered by a timing pulse—records a chain of successive events. In a dual-sweep streak camera, when the horizontal sweep is also enabled, a second vertical sweep, triggered after a chosen time period, records a second series of images that are shifted from the first ones horizontally. In this manner, a matrix of beam images can be recorded. As we will illustrate below with examples, these images reveal rich information about beam dynamics. A few points are important for the application of this technique:

- The photocathode entrance slits need to be wide open for a good field of view.
- The imaging optics need to be carefully configured to maintain a balance between good spatial resolution and an adequate field of view.
- Because the bunch length is used to determine the exposure time of each image, the interbunch time (or turn period) needs to be much longer than the bunch length, a requirement often satisfied on many accelerators.
- The vertical time scale needs to be chosen to record an adequate number of events.
- The structure of the vertical timing pulse train and the horizontal scan time needs to be adjusted to suit the time scale of the dynamic phenomenon studied.

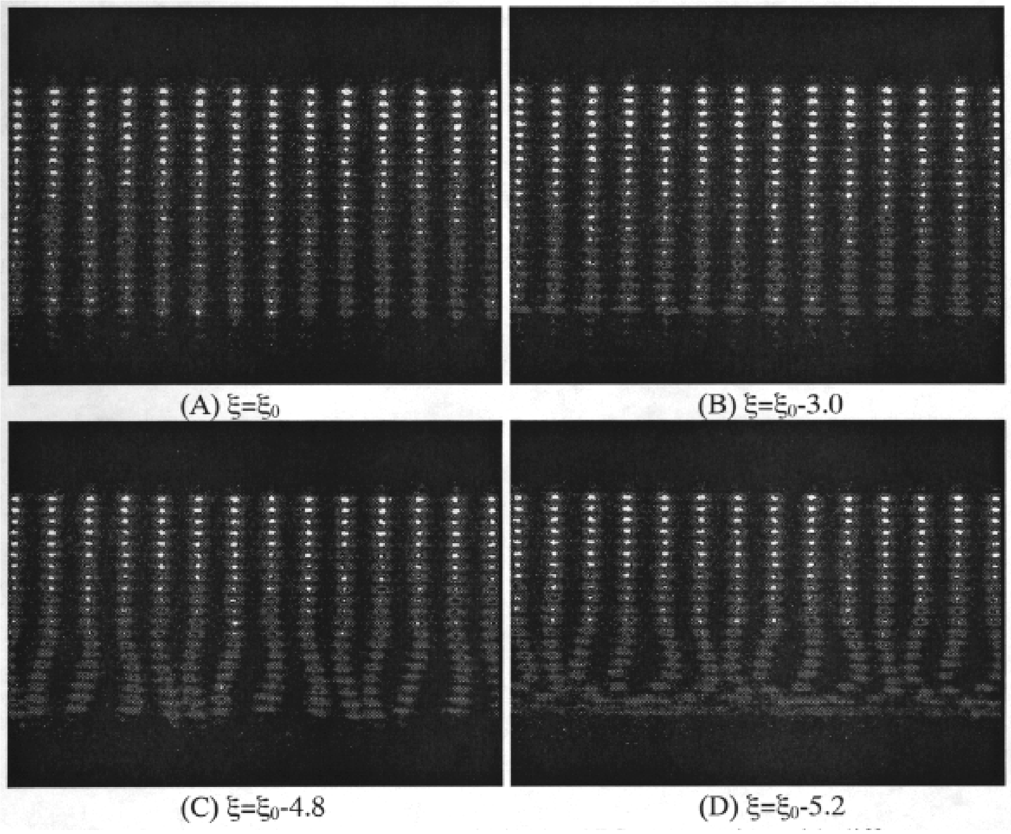
Multi-turn Images of a Bunch Train in the APS Storage Ring

The experiment to study the effect of chromaticity on bunch stability was performed at the APS UV/visible diagnostics beamline (8) with a Hamamatsu C5680 streak camera. The results are shown in Figure 2. We started with a high chromaticity setting. The 12 mA stored beam, in the train of 20 bunches filling successive buckets, is stable and the matrix of images are evenly spaced (Figure 2A). Each spot is the front view of a passing positron bunch. The vertical spacing between two adjacent spots is determined by the interbunch spacing of 2.8 ns, with the head of the train placed at the top of the image. The vertical scan is triggered every turn (3.7 μs). The horizontal scale is chosen to fit 14 columns of images on the screen without overlap.

As the horizontal chromaticity of the lattice was lowered, the last trailing bunch became unstable and its size grew horizontally (Figure 2B). Gradually, the latter half of the train began to execute a coherent oscillation, likely induced by interbunch coupling (Figure 2C). Eventually the horizontal size and oscillation amplitude of the trailing bunches got so large (Figure 2D) that they started to lose charge quickly.

From these beam images, one can obtain the center coordinates, horizontal and vertical size of each bunch in the train, and their turn-by-turn progression. This amount of information can put strong constraints on the theoretical model used to explain the instability. Without going into details, we can make some general observations: (1) The shape of the bunch train almost repeats itself every five turns, corresponding well with the fractional horizontal betatron tune of ~0.2 at the time of experiment. Hence, we conclude that the instability is transverse in nature and exciting betatron oscillations. (2) The amplitude of the oscillation increases quickly from the head of the train (~0 mm) to its tail (~2 mm), suggesting that (near-neighbor) interbunch coupling is feeding the oscillations through a wakefield. (3) The “wavelength” of the train shape in the coherent oscillation (Figure 2C) is determined by the phase of such couplings. It may provide clues about which wakefield component is responsible for the instability and what its bandwidth is.

Figure 3 shows two images taken with a test orbit after the recent installation of an insertion device chamber with 5 mm vertical aperture. Horizontal instability was observed on the left panel as a small-amplitude, coherent bunch-train oscillation in the horizontal direction. After we changed the current of sextupole magnets, the horizontal chromaticity was increased and the oscillation stopped. The vertical chromaticity, however, was simultaneously reduced and a vertical instability set in, as shown by the increased size of the last three bunches in the train on the right panel. Since these instabilities do not cause significant movement of the charge center of the six-bunch train, it is difficult for an electronic pickup device to detect. This example shows that the time-resolved transverse imaging technique may be used to quickly diagnose and visualize subtle instabilities and aid the search for a stable operating parameter space.


(A) $\xi=\xi_0$

(B) $\xi=\xi_0-3.0$

(C) $\xi=\xi_0-4.8$

(D) $\xi=\xi_0-5.2$

FIGURE 2. Image of a long bunch train in the APS storage ring with different chromaticity settings (in arbitrary units). The vertical scale is 100 ns and the horizontal scale is 50 μs.

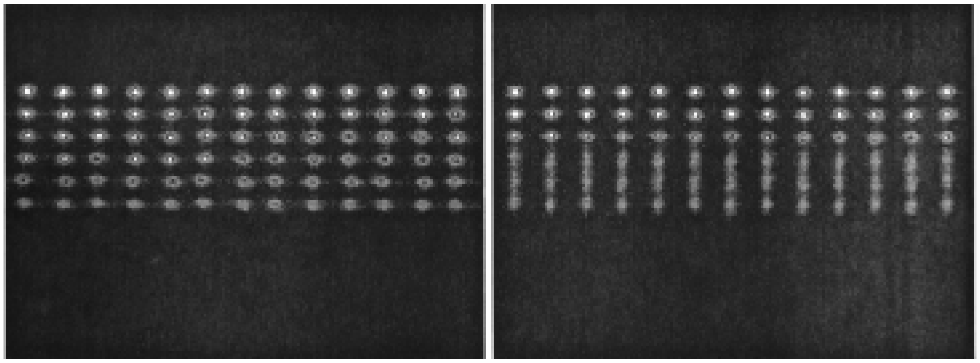


FIGURE 3. Images of a short bunch train in a test orbit in the APS storage ring after a 5 mm insertion device chamber was installed. The vertical scale is 50 ns and the horizontal scale is 50 μs. Current of a sextupole (S4) was increased by 4 amperes (< 3%) to produce the image on the right.

Multi-turn Images of a Single Bunch in the APS Storage Ring

To support the top-up mode of operation, one needs to understand the transient beam motion after injection. We combined the streak camera with a gated intensified camera (Stanford Computer Optics QUIK05) to record the transient beam motion. Since the ring is equipped with insertion device chambers with vertical apertures as small as 5 mm, we are particularly interested in the amplitude of the vertical motion.

The initial experiment was performed with single-bunch stored current (~4 mA) in an orbit with the vertical coupling uncorrected. The injection kicker was fired at a 2 Hz rate to simulate the injection event. Figure 4 shows the streak camera image of the front view of the bunch in successive turns. Before the injection kicker was fired, a regular array of beam images was obtained (left panel). After the kicker was fired, the beam started to move in the horizontal direction. The motion quickly (in a single turn) coupled to the vertical direction and the beam entered into a large amplitude betatron oscillation in both directions. The bunch quickly decohered and its size increased dramatically. A number of streak images were taken and appeared to be identical to Figure 4. This indicated that the kicker operated reliably and reproducibly. We switched to a gated intensified camera for its higher spatial resolution and larger field of view.

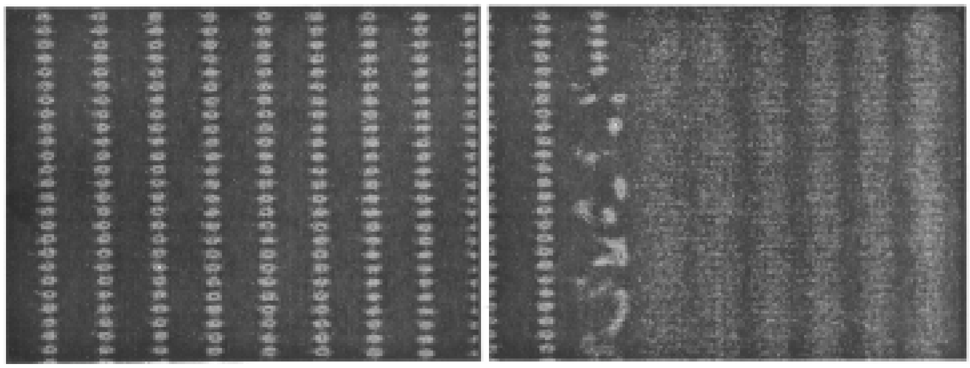


FIGURE 4. Effect of injection kicker on a single bunch in the APS storage ring. The full scale of the vertical sweep is 100 μs and the horizontal one is 5 ms. The vertical sweep was triggered every 6 ms. Before the injection kicker was fired (left panel), and after the kicker was fired (right panel).

Figure 5 shows the images taken with the gated camera. Calibration was done with a target located at the bending magnet source point, which has four 1 mm holes arranged in a 3 mm × 4 mm rectangle. The fifth hole shown is used to indicate the upper-outboard corner of the target. From this image, we infer that the total field of view is 6 mm × 6 mm and that the image is tilted by 4.5° by the transport optics. A sixth hole, 127 μm in diameter, located at the center of the pattern, was used to estimate the rms system resolution, which is 120 μm(H) × 90 μm(V).

The center coordinates of the bunch can be extracted from the turn-by-turn images by fitting their integrated profiles. The horizontal motion follows a simple sinusoidal curve, indicating a well-behaved free betatron oscillation after the initial kick (Figure 6, left panel). The vertical betatron oscillation started one turn later (Figure 6, right panel), and its amplitude does not remain constant, as expected from tracking simulations.

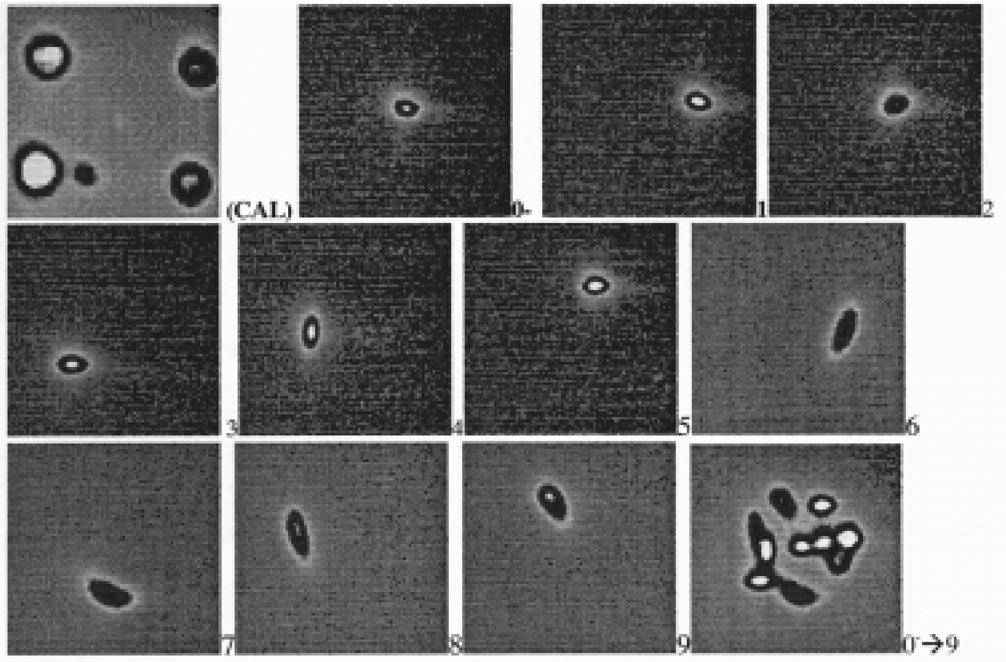


FIGURE 5. Image of a single bunch in the APS storage ring. Image (CAL) is the image of the calibration target. Images labeled 0 through 9 were taken on 0th through 9th turn after the kicker was fired. The last image is the integrated image from No. 0 through No. 9, taken with long exposure time.

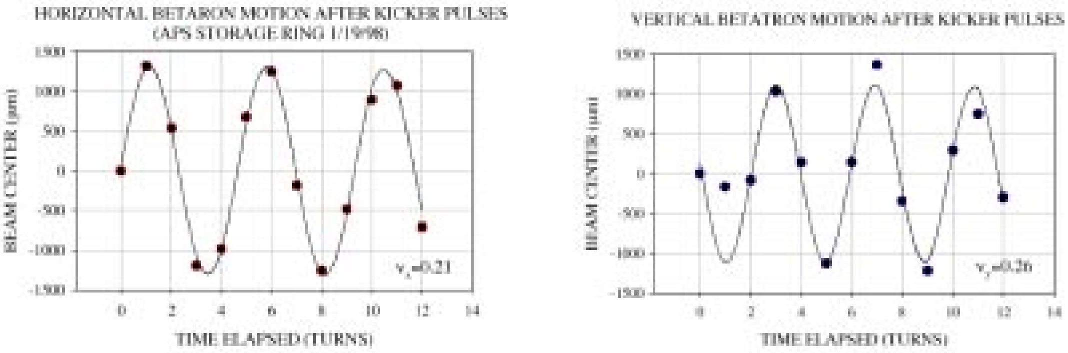


FIGURE 6. Coordinates of the electron bunch center as a function of time after the kicker was fired.

The betatron period is about four to five turns, and the integrated image of the first 10 turns (in Figure 5) gives a good average of beam motion over all betatron phases. The vertical extent of the image is now routinely used as a direct visual aid when vertical coupling of the injection orbit is corrected.

Figure 7 show the same series of single-pass images extended further in time. The bunch decoherence before and damping after 500 turns can be seen clearly. The width of bunch profiles may be extracted from these images and give information about transverse damping (Figure 8). These data compare well to the theoretical damping time of 9.5 ms in either transverse plane.

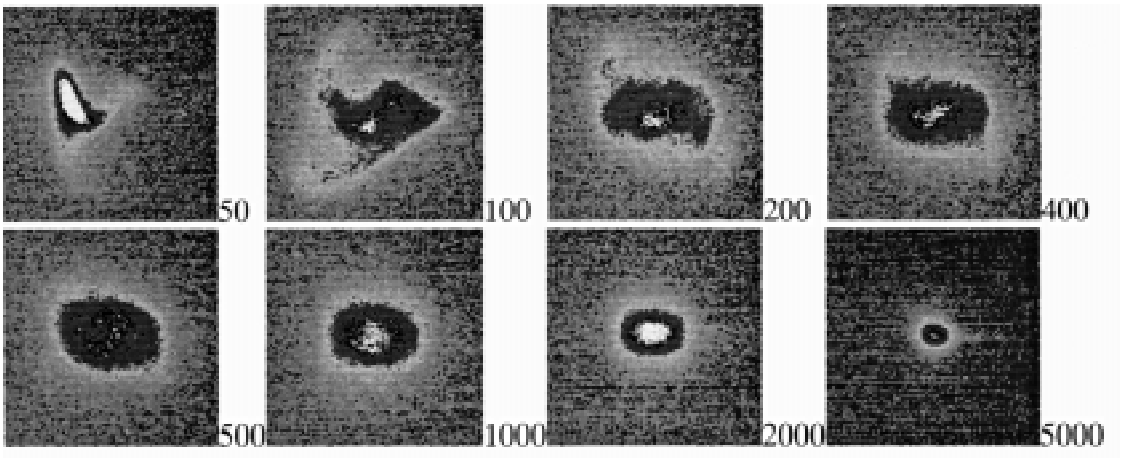


FIGURE 7. Image of a single bunch in the APS storage ring. Label for each panel shows the time of recording (in number of turns) after the kicker event.

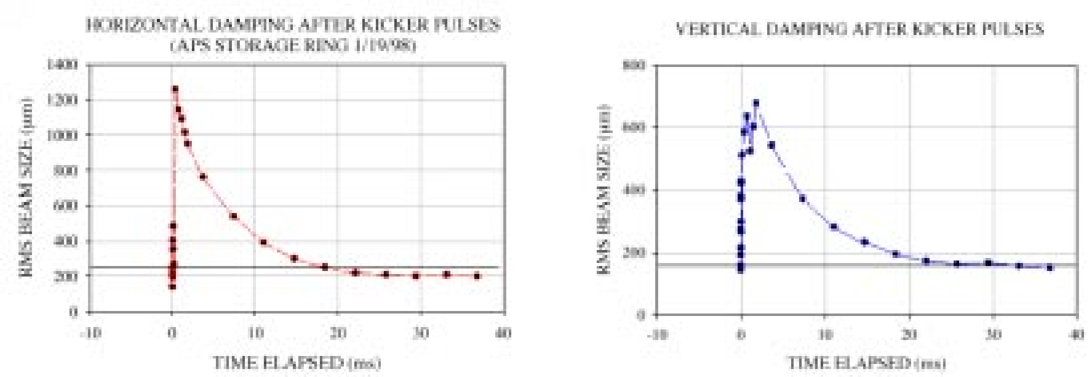


FIGURE 8. The rms bunch profile width as a function of time after the injection kicker is fired.

CONCLUSION

The timing structure of rf accelerated particle beams enables us to make a series of front-view images of the bunches in a train. This extension of the dual-sweep technique makes it possible to display non-repeatable beam transverse motion in two fast and slow time scales of choice, all in a single shot. It is a powerful and flexible technique for studying beam dynamics.

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