Streak-Camera Measurements of the PEP-II High-Energy Ring*

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Abstract. The third commissioning run of the PEP-II High-Energy Ring (HER, the 9 GeV electron ring), in January 1998, included extensive measurements of single-bunch and multibunch fills using LBNL's dual-axis streak camera combined with Argonne's 119.0 MHz synchroscan plug-in. For single bunches, the dependence of bunch length on charge and rf voltage was studied from 0.5 to 2.5 mA and from 9.5 to 15 MV; the measured values ranged from 38 to 49 ps rms. The multibunch work focused on longitudinal instabilities as the current in the ring was raised to 500 mA, and the length of the bunch train was varied from 100 bunches (with 4.2 ns spacing) to a full ring. Large oscillations of up to 180 ps peak to peak were observed for bunches half a ring turn away from the start of the train, especially at higher currents and for trains filling roughly half the ring. These observations led to a new fill pattern with more gaps that allowed us to raise the current to 750 mA by the end of the run.

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INTRODUCTION

During the January 1998 commissioning run of the PEP-II *B* Factory at the Stanford Linear Accelerator Center (SLAC), the longitudinal characteristics of the electron beam in the High-Energy Ring (HER) were measured with synchrotron light and a dual-axis synchroscan streak camera, following techniques originally applied on LEP at CERN (1), on APS at Argonne (2), and more recently on ALS at LBNL (3). This paper describes measurements of both single-bunch and multibunch beams in PEP-II.

PEP-II and its diagnostics are discussed in another paper at this workshop (4). In particular, that paper describes the HER synchrotron-light monitor and the optical path added in December 1997 to transport some of this light to the streak camera, located in an optics room 11 meters above the tunnel.

STREAK-CAMERA EXPERIMENTAL CONSIDERATIONS

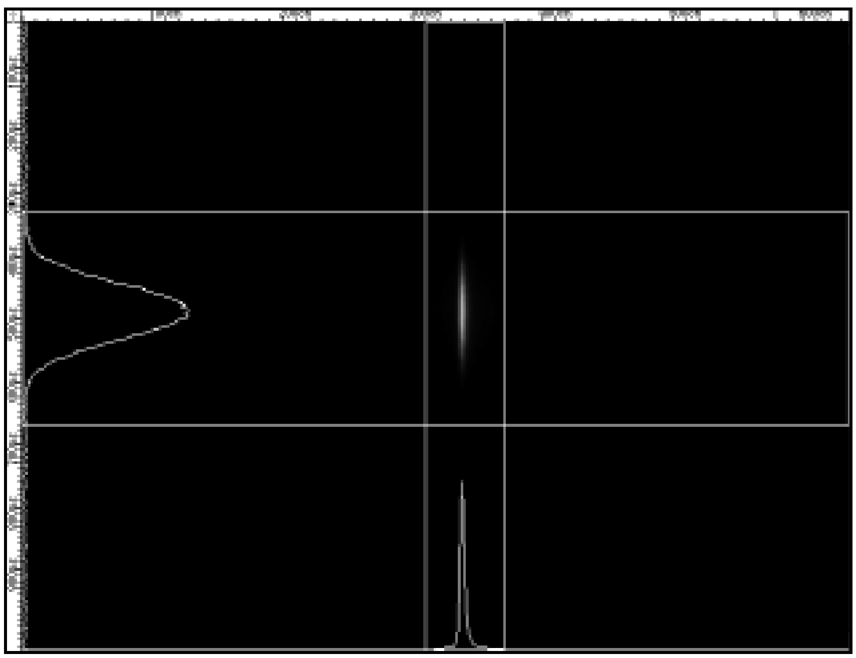

FIGURE 1. Typical single-axis streak image for bunch-length measurements, accumulated over many turns. Vertical: 1 ns full scale. Horizontal: position (channel number) along slit. The projections onto the axes, in the regions bounded by cursors, are shown along the sides.

A brief explanation of the dual-axis synchroscan streak camera (Hamamatsu model C5680) used for the PEP-II measurements is helpful for understanding the data. First, we consider a standard streak camera, with a single axis and a triggered sweep. The incoming light is imaged onto a slit that is narrow in the vertical direction, and is re-imaged onto a photocathode. While an axial voltage accelerates the photoelectrons toward a microchannel plate (MCP), a high-speed, high-voltage ramp is applied to a top-bottom pair of electrostatic plates to deflect the electrons as a function of arrival time across the MCP, converting the temporal distribution into a spatial one, in exchange for the loss of vertical spatial information. The MCP preserves the distribution while amplifying it. Another voltage accelerates exiting electrons onto a phosphor screen imaged by a video camera. The resulting image displays the temporal structure of the light pulse vertically, and its spatial distribution across the input slit horizontally. The time resolution can be as fast as 200 fs in the newest model.

Various effects limit these ideal characteristics, broadening the measured pulse duration. Chromatic dispersion in the lens between the slit and photocathode contributes an effect of typically a few percent for pulses of 40 ps rms. For broadband light, this problem is usually avoided by including an optical bandpass filter (≤10%) before the slit. A selection of filters allows measurement of the dispersion. For example, we found a 12 ps shift in the pulse centroid when changing the filter's center wavelength from 450 to 600 nm; if no filter were present, a measurement of a very narrow pulse extending over visible wavelengths would appear to be at least 12 ps wide.

If the input light is too bright, space charge between the photocathode and the MCP can spread the distribution. Consequently, the camera needs to be operated at a low light level, where shot noise is prominent. With repetitive signals (such as those from a stable storage ring), the statistics can be improved by summing several pulses, but any jitter in the trigger electronics for the ramp broadens the sum. Also, the retrigger rate is at best several kilohertz, preventing triggers on every ring turn.

FIGURE 2. The light from a single bunch captured on consecutive turns. Full scale: 1 ns vertical, 500 µs horizontal. The projections on the left show a single bunch and the sum of the 20 bunches (determined by the two sets of cursors).

One common idea is to use a trigger derived from the light itself, picked up by a fast photodetector, in order to reduce jitter in the electronics external to the camera. However, some of the jitter is in the internal trigger circuit. In addition, the streak camera's long internal delay (50 to 100 ns) necessitates a substantial optical delay line after the trigger pick-off, and this delay varies with the time scale selected on the camera.

If the light is tightly locked to a stable rf signal (e.g., light from a mode-locked laser or from a storage ring without large synchrotron oscillations), the trigger jitter can be avoided by replacing the fast ramp with the sinusoidal output of a tuned rf circuit. This "synchroscan" option, available on some models (usually not the highest-speed units, especially in combination with dual sweep), provides acquisition at every zero crossing (that is, at twice the drive frequency), while the peaks of the sine wave are off scale. This approach allowed us to accumulate the low-noise sum of Figure 1 for measuring the length of a single HER bunch. The summing continues over a full 30 Hz (for the RS-170 American format) video frame interval. Our measurements at PEP demonstrated the value of this technique, and also one of the pitfalls: the camera displayed previously unknown, intermittent, 100 ps jumps, lasting for several milliseconds, in the 119 MHz reference output of the standard PEP timing module. We obtained an alternate source while the Controls Department investigates what appears to be a common malfunction (although few triggered devices are as sensitive to this jitter as a streak camera).

For accurate measurements, it is important to verify the factory calibration of the time axis, especially, as in our case, when the plug-in used was not the one that accompanied the camera from the factory. By putting an etalon—an flat optical plate with partly reflecting faces and with a known thickness and refractive index—in the light path, the camera sees the main pulse and a diminishing series of echoes, spaced by the round trip time inside the etalon. Since 1 mm of glass adds 10 ps to the round trip, a convenient thickness separates the pulse from its first echo for calibration of the time base.

For storage rings, a valuable option is the addition of a second time axis, by slowly (nanoseconds to milliseconds) deflecting the photoelectrons horizontally with a second pair of plates. A sweep rate corresponding to several ring turns lets us compare the same single bunch on consecutive turns (Figure 2). When both synchroscan and the slower horizontal axis sweeping are combined, synchrotron oscillations show up plainly as oscillations in bunch arrival time. With a multibunch fill, we were able to examine longitudinal oscillations along the bunch train.

Assembling the hardware for the PEP measurements required a three-laboratory collaboration. The Advanced Light Source at Lawrence Berkeley National Laboratory provided the dual-axis streak camera. Each synchroscan plug-in is tuned at the factory for narrow-band operation at a single frequency between 75 to 165 MHz; the ALS plug-in uses 1/4 of their 500 MHz ring rf frequency. This is too far from the corresponding PEP subharmonic, 119 MHz. Instead, a 119 MHz plug-in from the Advanced Photon Source at Argonne National Laboratory was brought to SLAC for the final week of the January run.

BUNCH-LENGTH MEASUREMENTS

We measured the length of a single bunch in the HER, and the dependence of length on the synchrotron tune (that is, the rf voltage) and the charge in the bunch. To reduce the noise, we used the summing procedure discussed above, which gave a clean Gaussian profiles like those of Figure 1.

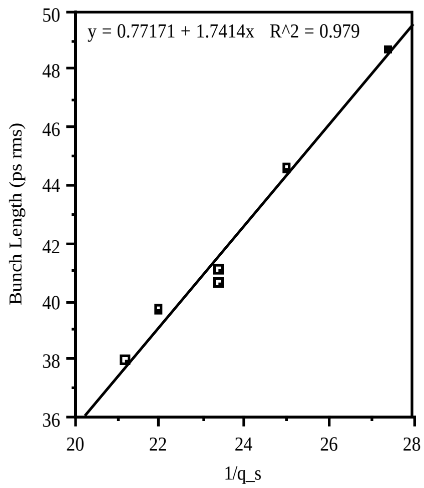

FIGURE 3. Variation of bunch length with the inverse of the synchrotron tune, for a single bunch at 1 mA.

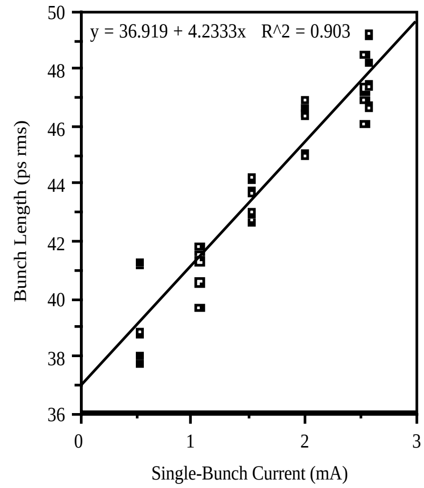

FIGURE 4. Variation of bunch length with single-bunch current, at 14 MV of rf; 1 mA corresponds to 4.6×10^{10} electrons in the bunch.

Bunch length was measured with a current of 1 mA for rf voltages between 9.5 and 15 MV, corresponding to synchrotron tunes q_s from 0.0365 to 0.0472 and frequencies f_s from 5.0 to 6.4 kHz. The bunch length σ_t should be related to the synchrotron frequency, energy spread σ_E / E, and momentum-compaction a by

$$\sigma_t = \frac{\alpha}{2\pi f_s}\frac{\sigma_E}{E} \quad . \tag{1}$$

The plot of Figure 3 shows this inverse variation with synchrotron tune. Using $\alpha = 0.00241$ for the HER, the measured bunch lengths at 1 mA correspond to an energy spread of $(6.31\pm0.08)\times10^{-4}$, in reasonable agreement with the design value of 6.14×10^{-4} and an independent measurement using the quantum lifetime.

Other scans studied bunch length versus single-bunch current in the ring, from 0.5 to 2.58 mA, with the rf held at 14 MV. We were restricted to this maximum to avoid peak-signal damage to the longitudinal-feedback system. The length appears to grow linearly (see Figure 4) over the range studied, consistent with potential-well distortion (5). There appears to be no sign of a knee due to the onset of the microwave instability; the calculated threshold lies between 1.8 and 6.4 mA (6).

In PEP's nominal parameter list, the standard HER fill—0.99 A in 1658 bunches (0.60 mA/bunch), with 14.0 MV of rf and a tune q_s of 0.0449—has a calculated bunch length of 38.4 ps, compared to 39.5 ps from the linear fits of these two plots.

MULTIBUNCH INSTABILITIES

Other measurements, made during the last two days of the January 1998 run, examined the onset of longitudinal instability in long bunch trains. For this work, we used horizontal sweep settings of 5 or 10 μs, close to the ring's 7.3 μs revolution time. Vertically, the fast axis was set to either 600 ps or 1 ns full scale, in order to resolve the lengths and especially the relative phases of the bunches.

The normal fill pattern puts charge in every second 476 MHz rf bucket of the ring, corresponding to a bunch spacing of 4.2 ns (238 MHz), except for a gap which we varied to study its effect on stability. The camera's synchroscan drive was at 119 MHz, half the bunch spacing; with a proper phase delay, consecutive bunches appeared in alternation on the rising and falling zero crossings of the sine-wave drive. Because the direction of the sinusoidal sweep (and hence the direction of the time axis) alternates, it is preferable to slightly offset the phase from the zero crossings, so that the image shows the even and odd bunches of the train slightly separated. The typical result (Figure 5) resembles a bunch train and its mirror image. Because this figure uses a 10 μs horizontal sweep, the gap in the train appears twice; the head of the train (Bunch 0) is just to the right of the first appearance of the gap, on the left; the tail is to the right. For our choice of phase delay, the time axis for the upper train points downward, while it points up for the lower train.

In the first multibunch observations, the ring was filled to currents between 400 and 525 mA, using a roughly uniform pattern with a gap of 5% of the ring's circumference. For these currents, the middle of the train exhibited significant phase instability, with 100 ps peak-to-peak oscillations, as Figure 5 shows for a 480 mA fill (and which were even more apparent in the rapid motion of the streak-camera video, captured on videotape). The head and tail of the train remained stable, with only a constant phase shift over the first 100 bunches due to the transient in loading of the rf cavities due to the gap. For part of that day, similar observations were made in tests of the longitudinal

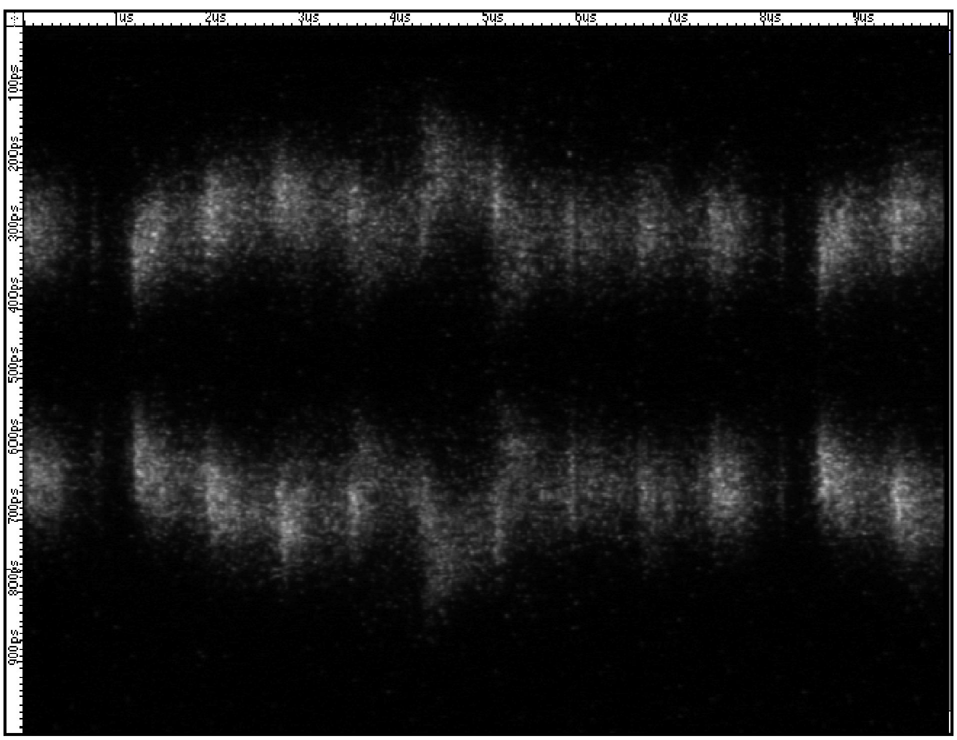

FIGURE 5. Longitudinal instability in the center of a 1658-bunch train with a 480 mA current. Filled in a 9-zone pattern with 4.2 ns spacing and a 5% gap. Full scale: 1 ns vertical, 10 μs horizontal.

feedback system (7), which provided turn-by-turn recordings of the phases of each bunch. (Because power amplifiers were out for repairs, the system could not be used to stabilize the train.)

Subsequently, we filled the ring with bunch trains of varying lengths, with the same charge per bunch and 4.2 ns spacing. The instabilities began after filling about one third of the ring. Figure 6 shows a 700-bunch train (about half of the ring, shown this time on a 5 μs scale) with 228 mA. The last 250 bunches oscillate even more than before, with up to 180 ps peak-to-peak motion, while the head remains still.

Later, we again filled the ring consecutively but at a lower current, so that it reached 330 mA when filled with the normal 5% gap. As before, the tail of the train was unstable for train lengths filling 1/3 to 2/3 of the ring, but once the train got longer it stabilized. The instability threshold depends on the length of the gap and the current.

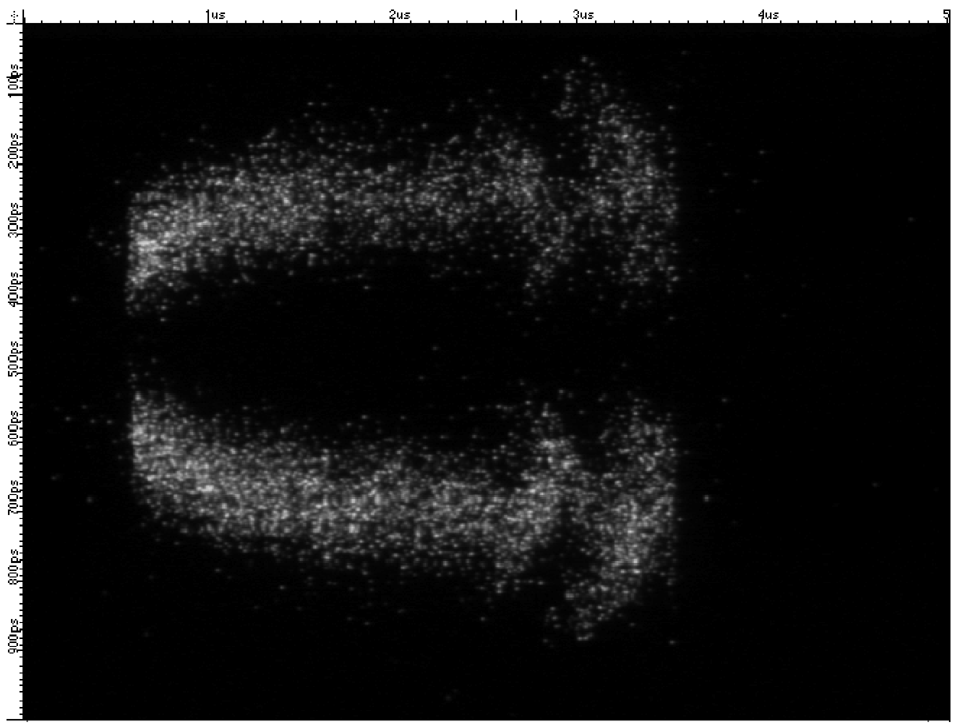

FIGURE 6. Large longitudinal oscillations at the end of a 700-bunch train with a 228 mA current and 4.2 ns spacing. Full scale: 1 ns vertical, 5 μs horizontal.

The instability often led to rapid current loss. On several occasions, within a single video frame of the streak camera, most of the bunches in the ring were lost, with only those at the head of the train remaining. The fact that these instabilities were strongest half way around the ring from the gap eventually suggested that we could achieve a higher total current with more gaps than the nominal fill. In the final hour of the run, a new current record for the HER—750 mA—was set using six 5% gaps evenly spaced around the ring. These efforts will continue later this year, with the goal of reaching the intended operating current of 1 A. However, 750 mA is sufficient to achieve the design luminosity.

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