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MODES ON A SHORT SPEAR BUNCH AS OBSERVED WITH A STREAK CAMERA[*]

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Introduction

We have studied the longitudinal structure of electron bunches in the storage ring SPEAR on a single pass with time resolution ≈ 10 ps. The measuring instrument we used is an image-converter streak camera, a specialized device heretofore used mostly by laser workers.

Unexpectedly, we find that under some conditions the charge in a single RF bucket breaks up into two short sub-bunches which we believe rotate about a common center in energy-phase space. We see no evidence for other, higher-frequency structure on the bunches.

The Streak Camera (SC)

The direct ancestor of the image-converter SC is the optical SC, in which the image of an entrance slit is swept across the film at a high speed by mechanically rotating mirrors. In the modern version the optical information is spatially and temporally modulated onto electrons, whose trajectory is swept by rapidly changing electric fields.

Figure 1 shows a complete SC measurement setup. The incoming light I is focused onto slit S by lens L1. Lens L2 focuses the slit onto the surface of the streak tube's (T) transparent photocathode K. The extractor grid G is at a high + potential (2.5 kV in our camera) with respect to K, and accelerates the electrons emitted from K through the electrostatic focussing system E. The electron image of the illuminated area of the photocathode is swept transversely across the phosphor face P of the streak tube by voltages applied to the deflection electrodes D.

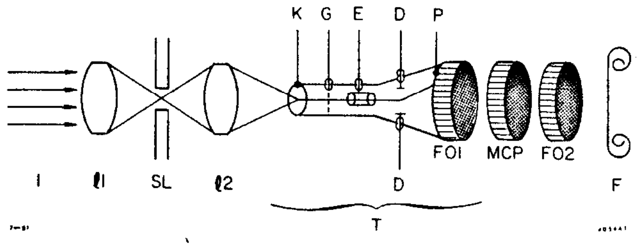

Fig. 1. Streak Camera measurement setup.

With the electron image swept across the tube face, the information at the output is two dimensional. The intensity distribution perpendicular to the sweep (time) axis can represent useful information, e.g., the SC can look at the output of a spectrograph and see a fast, time-resolved spectrum.

The time resolution of the SC is limited mostly by space charge effects at and near K, thus the emitted charge must be kept at a low level. A stage of image intensification follows the tube T to bring the light output of the tube phosphor up to a level sufficient to expose film or activate another detector.

In our camera (LLL Compact SC) the phosphor is coupled directly to a fiberoptic faceplate FO1, then to the photocathode input of a multichannel plate intensifier MCP. The output phosphor of the MCP is again directly coupled to a fiberoptic faceplate FO2, then to the film F at output. The input light intensity variation in time becomes intensity variation in space at the streak tube output, and on the film.

Modern SCs use television cameras or CCD-scanned diode arrays to record the output in a form which can be immediately stored, displayed, and manipulated by data-processing equipment. The two-dimensional high resolution and dynamic range of film are difficult to match, but the difficulties of nonlinearity and delayed data analysis weigh in favor of modern methods.

Gating and Synchronization

An important technical problem in the SC is developing and synchronizing the sweeping voltage applied to the deflecting electrodes. In general, the trigger jitter time > resolution of the SC, thus successive shots cannot be directly superimposed nor can absolute timing information be extracted from SC data.

The camera system cannot tolerate light striking the photocathode before or after the pulse of interest, for two reasons.

1) There is no control grid as such, and all front-end electrodes are left at operating voltages. Photoelectrons emitted by the cathode are swept away from the output screen by deflecting-plate fields, but they cause secondary emission within the streak tube, activating the output phosphor and fogging the film.
2) The streak tube will function during the slow (12 ns) retrace.

Since the SPEAR revolution frequency is 1.28 MHz, fast gating must be used with the camera. Our camera had its cathode bias lowered by 5 kV so that it was slightly + with respect to the extractor grid. A 5 kV pulse 150 ns long generated by a charging-line thyratron pulser drove the cathode negative to make the tube operative for a fraction of a SPEAR revolution period. The recharge time of the pulser is ≈ 1/10 s. In addition, a 1/60 s mechanical shutter built into the camera is actuated for each shot, and the MCP is also gated on for 100 μs only after the sweep (Fig. 2). An anti-bounce circuit triggered by the mechanical shutter holds all other triggers off for 1 sec after each actuation.

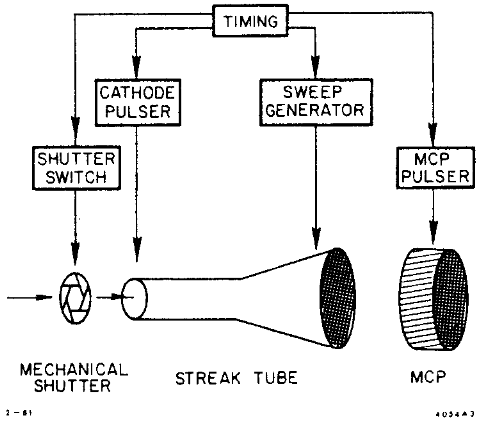

Fig. 2. Timing and gating of the streak camera for operation with the storage ring.

Synchrotron Light

Visible synchrotron light is taken out of the SPEAR optical diagnostics with a horizontal opening angle of 2×10^{-3} radian and brought into a laboratory outside the shielding wall. The distance from beam point to SC is 5 m. There are no focusing optics between the beam and

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the laboratory, and a telescope on the SC optical bench gives a clear, single image. Time dispersion of the synchrotron light pulse with respect to the electron bunch is 2 ps,[3] negligible compared to SC time resolution.

Data Analysis

The deflection of the electron beam in the streak tube is not linear with time, nor is the deflection time uniform from camera to camera. Detailed time calibration of the camera is required.

The standard method of time calibration used by laser workers is shown in Fig. 3. The short laser pulse is passed through a glass block (etalon) with highly reflecting coatings on both surfaces. The SC sees successive light pulses of decreasing intensity spaced apart by a time set by the optical thickness of the block. Figure 4 shows a calibration shot made with a 100 ps etalon and a singe YAG laser pulse at LLL.

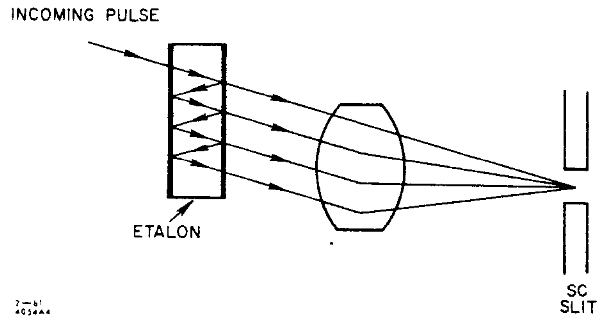

Fig. 3. Time calibration method for a streak camera using a fast pulse and an etalon.

A standard density wedge was exposed onto every data film prior to SC exposure. When the SC data films were analyzed, the density wedges were scanned for every shot (see below).

Results: Microwave Modulation

Earlier workers with an SC on SPEAR[4,5] reported evidence for very high-frequency, ≈ 50 GHz, longitudinal structure on short electron bunches. We see no evidence of this effect.

Figure 5 is a clear shot of a single bunch, or possible superposition of 2 sub-bunches. The modulation seen in the sensity tracing (Fig. 5b) is similar to that seen by Monahan et al.[4] The density tracing was made with a slit parallel to the space axis (Fig. 5a) moving parallel to the time axis. Tracings made along the space axis produced modulation of the density similar to the modulation along the time axis. The distribution along the space axis in our data is due only to the properties of synchrotron light and our optics, and is known to be very smooth on the scale corresponding to the observed modulation. Our observed modulation, 1.5 dB peak to peak (Fig. 5), is smaller than that observed by Monahan et al., this probably being due to our streaks being wider along the space axis[6] than theirs, thus averaging the graininess of the output MCP better. The widest possible streaks and two-dimensional Fourier analysis of the data need to be used to put the best lower bound on possible modulation.

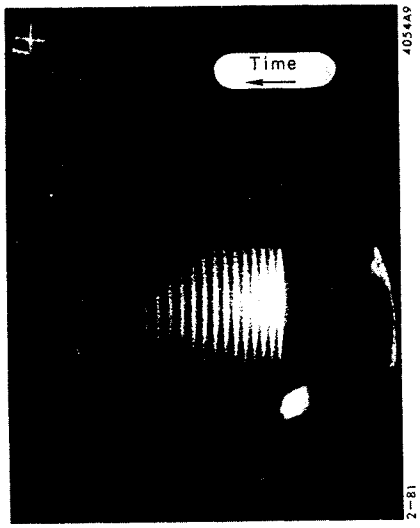

Fig. 4. Streak camera calibration shot. Time between pulses is 100 ps.

Results: Split-Bunch Mode

Another beam effect appears in our data. The electrons in single buckets appear to be broken up into two sub-bunches of approximately equal charge which move longitudinally with respect to each other in time.

Figure 6 is an example of a datum showing this clearly. The separation of the centers of the bunches

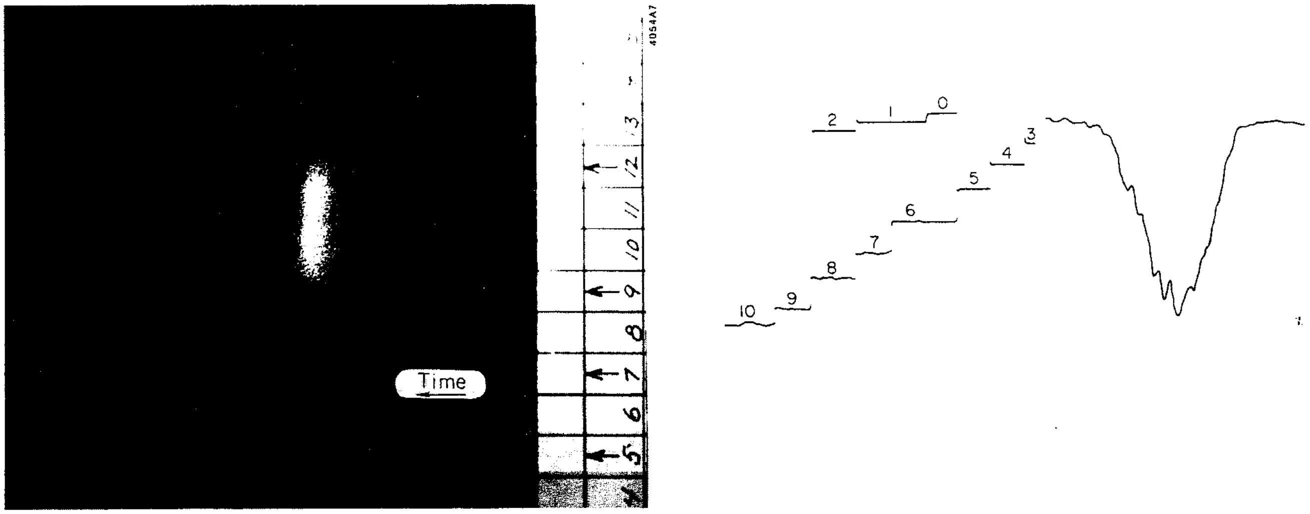

Fig. 5. (a) Direct streak camera data #5. (b) Densitometer scan of (a) taken with a scanning densitometer. (c) Density wedge calibration associated with (a).

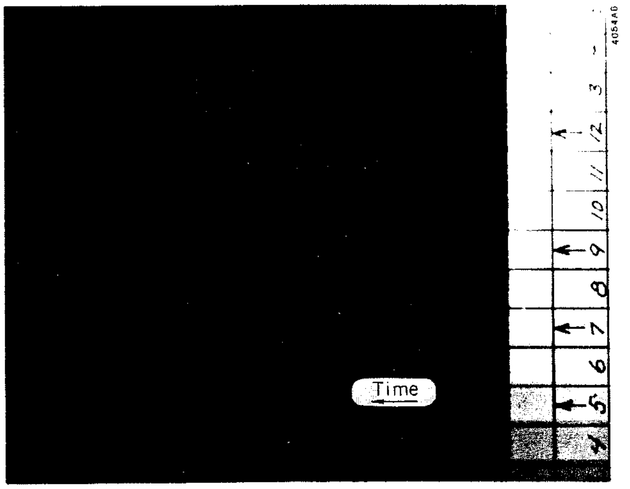

Fig. 6. Split bunch showing different bunch lengths for 2 sub-bunches, datum #6.

is ≈ 600 ps. Figure 6 also shows the two sub-bunches with different lengths, leading to the tentative conclusion that the sub-bunches are also executing individual quadrupole-mode oscillations.

The absolute time of the SC shots is not stable. We cannot be certain of the phase and amplitude relations of the bunches in energy-time space. A simple hypothesis is that the two bunches revolve about equilibrium phase so that their center of charge is stationary.

Simultaneous with the streak camera data taking, an RF spectrum analyzer looking at a beam pickup electrode is observed. In all cases, strong signals close to 2x the calculated synchrotron frequency are observed. If each sub-bunch oscillates at ω_s, then the two oscillating out of phase give signals similar to that received from a quadrupole mode oscillation at $2\omega_s$.

Table I summarizes the conditions under which we observed this mode. Our data is sparse due to the limited time in which we had access to the SC, thus we cannot give thresholds and amplitudes as functions of current and energy. The Table gives all the conditions under which we took data, and we saw the mode at all but one of them. The maximum separation observed was 1.24 ns at 600 MeV. The observed separation is always within the stable area of the RF bucket.

Table 1. The split-bunch mode was seen at these operating conditions except the last.

E(GeV)	i(mA)	ν_s	V_{RF}(kV)
1.835	7.0	.0267*	850*
1.50	4.0	.0335*	910*
1.0	.9	.039**	820*
.6	.7	.0503**	827*
.8	.7	.064**	1800*

* Observed ** Calculated

This result is difficult to believe: Quadrupole-mode oscillations in which the bunch lengthens and shortens at 2x the synchrotron frequency are well known,[7] distortions of the bunch shape exhibiting a distinct second peak have been predicted[8] and observed, but a longitudinally split bunch seems to be a new phenomenon for e⁻ accelerators. If the streak camera represents bunch conditions accurately, this mode may be having serious effects on SPEAR operation, and affect short-bunch operation on other rings.

Monahan et al.[4] did not observe the split-bunch mode. Since the strengths of other longitudinal instabilities in SPEAR are strongly influenced by the exact settings of RF cavity tuners, it seems likely that differences in longitudinal impedance between the two observations account for the different results.

Is the camera double-firing and showing the same bunch twice with the separation caused by jitter? Four events must coincide for a streak image to be formed (Fig. 1): 1) Mechanical shutter open (1/60s), 2) sweep circuit fires (12 μs retrace), 3) cathode pulser fires (150 ns), 4) MCP gated on 100 μs). The cathode pulser has a recharge time ≈ 50 ms, and thus cannot fire again until well after the mechanical shutter closes. 2) and 4) could fire spuriously, but the delays in the other events make a complete spurious coincidence impossible.

Is there a multiple reflection in the optical system which introduces a delay in one path? Multiple images have never been seen in the optical diagnostics, and a reflection which introduces 500 ps delay in a path 5 m long would have a minimum offset angle of 14°; that is, it would never emerge from the vacuum chamber. In-line reflections would have many successive pulses of decreasing intensity, as in the calibration pictures (Fig. 4) and the interpulse separation could not change from shot to shot, as it does in the data.

We conclude that the simplest explanation of the results is that the double-bunch mode actually exists.

Conclusions

The streak camera has proven itself a useful storage ring diagnostic tool in finding a heretofore unsuspected beam phenomenon. This split-bunch mode is of special interest to workers who intend to use synchrotron radiation from storage rings for fast timing studies in physics, chemistry and biology.

The mode needs to be studied and suppressed, most probably by longitudinal feedback, as has been done with the quadrupole mode at SPEAR.[9]

Acknowledgement

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