Intensity dependent time-resolution and dynamic range of Photochron picosecond streak-cameras

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The dynamic range of operation of Photochron I and Photochron II picosecond streak cameras is shown to depend upon the time-resolution employed. For events ~2 ps a useful dynamic range of 30 is obtainable, and this increases to a value of 180 for 30-ps events. No accumulative saturation effects occur at a time resolution as short as 2 ps.

I. INTRODUCTION

The Photochron type of image-tube streak-camera, in which photoelectron time-dispersion spread is reduced by a high-potential planar mesh electrode close to the tube photocathode, has been developed to the stage where a camera instrumental resolution of less than 1 ps can be obtained. This high-field photocathode extraction electrode principle has since been almost universally adopted for picosecond streak cameras. When the time-resolution limit was reduced to <10 ps for the first time with a Photochron design of streak tube, it was noted that when the camera slit illumination was increased, time resolution deteriorated while spatial resolution was maintained. Earlier it had been demonstrated that picosecond exposure of a two-dimensional test pattern could be obtained without image distortion and with good spatial resolution, employing a gated four-stage cascade image-intensifier tube. It was postulated that the loss of time resolution in the streak-tube arose from an intensity-dependent transit-time spread, probably arising from space-charge near the photocathode. Recently reported measurements of the magnitude of this effect in streak-tubes have shown a dramatic loss of dynamic range in Photochron streak-tubes. If this performance were characteristic of these tubes then it would not have been possible to have obtained the theoretically predicted time resolution and good signal-to-noise ratio over a wide range of wavelengths in the uv, visible, and ir spectral regions, and with sources varying in duration from nanoseconds to less than 1 ps. Streak-cameras are being increasingly employed in chemistry, biology, and condensed matter physics where quantitative measurements of transient phenomena, with picosecond time resolution or better, are required. It was important therefore to carry out accurate measurements of the variation of temporal-resolution with input intensity, over as wide a range of time-resolution and operating wavelength as possible, to resolve the discrepancy between the results reported and our earlier publications. As a result of measurements with two types of streak-camera systems we can now define the conditions under which streak cameras can be reliably employed for quantitative measurements of luminous phenomena. The dynamic range performance has been determined to be a factor of 10 better than that indicated by the results of Ref. 10.

II. EXPERIMENTAL ARRANGEMENTS

A. Photochron I camera with S1 photocathode

The two camera systems tested are shown schematically in Fig. 1. The Photochron I system, with optical coupling to a four-stage magnetically focused image-intensifier (EMI type 9694), has been extensively described in earlier publications. The dynamic range was investigated with the arrangement of Fig. 2. A mode-locked Nd:phosphate-glass laser oscillator, operating in several transverse modes, was used to generate the test pulses. About five pulses were selected by a Pockels cell switch from the middle of the pulse train. In this manner signal-induced background, arising from the many pulses of the laser train, was reduced and the delay in the Krytron high-voltage ramp generator could be conveniently accommodated. Each of the selected-out pulses was injected into an air-gap Fabry-

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**FIG. 1.** The two types of streak cameras tested. In (a) the Photochron I streak tube had an S1 photocathode with absolute sensitivities of 0.36 mA/W at 1088 nm and 1.2 mA/W at 524 nm, respectively. In (b) the Photochron II tube had an S20 photocathode, of sensitivity 95 µA/lm.
Perot etalon of mirror reflectivities 50% and 100% [Fig. 2(b)]. Thus a train of pulses of monotonically decreasing intensities, and separated by the double-transit time of the etalon, was generated from each incoming laser pulse. It was then necessary to record only such a sub-train of pulses in a single streak photograph, to obtain a direct measurement of the useful dynamic range of the camera. The time resolution of the camera was adjusted to match the duration of the pulse employed. A typical streak photograph and the corresponding calibrated microdensitometer trace is shown in Fig. 3. Before entering the Fabry–Perot etalon each of the laser pulses had an energy of \( \sim 1 \, \text{mJ} \) and the typical duration was 10 ps. The streak camera was set\(^{18} \) to give a time resolution of 2.5 ps at a writing speed of \( 10^{10} \, \text{cm s}^{-1} \) at the streak-tube phosphor and the intensifier was operated at a gain of \( 10^6 \). The streak traces were photographed with Ilford HP5 film, developed to produce an ASA rating of \( \sim 3000 \) and a usable range of 1000 in exposed intensity. The film characteristic was determined for each series of exposures by employing a calibrated neutral density wedge. From records such as Fig. 3 it was possible to demonstrate that no significant broadening of the pulses with increasing intensity occurred at intensities less than 50 times the developed film fog level. The useful dynamic range of a streak camera can be defined as the range of intensity above fog level within which the measured pulse duration \( \tau_p' \) (FWHM), after allowing for the low-intensity camera instrumental response, does not exceed the actual pulse duration \( \tau_p \) by more than 20%. A convenient way of illustrating the intensity-dependent effects is to plot the ratio \( \tau_p'/\tau_p \) as a function of the pulse intensity. (The camera instrumental width is deconvolved from the records.) The variations of the ratio \( \tau_p'/\tau_p \) are shown in Fig. 4 for pulses of durations 10 and 35 ps. The longer duration pulses were produced by introducing into the laser resonator a bandwidth-limiting Fabry–Perot etalon of \( \sim 60 \, \mu \text{m} \) gap, and with mirrors of 70% reflectivity. For these longer pulses it was necessary to readjust the separation of the calibration etalon (of Fig. 2) to produce test pulses separated by 100 ps. The
camera writing-speed was reduced to $4 \times 10^3$ cm s$^{-1}$ to allow all of the sequence of attenuated pulses to be displayed on the streak-tube phosphor-screen. The points on the graphs, which represent the most probable value for $\tau_r / \tau_s$ at a given intensity, were obtained from 20–25 separate streak records. The error bars indicate the maximum variations in the values derived from the microdensitometer traces. From Fig. 4 it can be seen that for the 10 ps pulses the incident intensity can be increased to $\sim 55 \times$ above the fog level before the ratio $\tau_r / \tau_s$ reaches the value 1.2. This corresponds to a variation of $\pm 10\%$ in the measured pulse duration for pulses falling within this range of intensity, i.e., a useful dynamic range of $\sim 55$. The authors of Ref. 10 reported a value of only 5 for the useful dynamic range, employing the same criterion, of an Imacon 675 camera (Hudson Photonics Ltd.) tested with 10 ps pulses at 1053 nm. This camera has a channel plate intensifier, with fiber-optic coupling between the streak tube and intensifier as well as between the intensifier and the film plane [as in Fig. 1(b)]. For an Imacon 600 camera with lens coupling and a three-stage magnetically focused intensifier, the same authors determined a dynamic range of $\sim 15$ for 30 ps pulses. From our measurements (Fig. 4) the dynamic range for a similar camera system is $\sim 180$, for 35-ps pulses, again ten times better performance.

As an independent check of our measurements, the camera response was also investigated with a Michelson interferometer arrangement. With this device two subpulses were produced from each incident laser pulse. By inserting calibrated neutral-density filters into the interferometer optical arms, a series of values of the $\tau_r / \tau_s$ ratio were determined over a range of pulse intensities, employing many separate laser firings. The dynamic range values for 10-ps pulses agreed to within 10% with the results of Fig. 4.

The dynamic range of the S1 photocathode camera was also measured at the second-harmonic wavelength ($\lambda = 526$ nm) of the Nd:phosphate-glass laser, by placing a 15-mm-long, 10-mm-aperture ADP crystal after the pulse selector. An etalon with the appropriate reflectivity mirrors at the visible wavelength generated the test signal. The camera resolution was reduced to $\sim 4$ ps by the increase in the spread of the photoelectron initial velocities from a S1 photocathode at this wavelength. The second-harmonic frequency pulses were found to have durations of $\sim 7$ ps, but the dynamic range (Fig. 5) of $\sim 60$ was slightly better than that obtained with the 10-ps pulses at the laser fundamental frequency.

### III. PHOTOCHRON II CAMERA WITH S20 PHOTOCATHODE

Dynamic range measurements were also carried out with the Photochron II camera system of Fig. 1(b). This second-generation streak-tube$^{11}$ had been constructed with an S20 photocathode on a sapphire substrate, a sapphire input window, and an output fiber-optic face plate, for the study$^{19}$ of the generation of third-harmonic (200 nm) pulses from a mode-locked dye laser. A Mullard type 50/40 channel-plate intensifier was fiber-optically coupled to both the streak tube and the recording photographic film. This electrostatically focused intensifier was operated at a gain of $10^6$ and was gated open for an exposure of 100 $\mu$s. A flash-lamp pumped Rhodamine 6G dye laser, mode locked by DODCI$^{20}$ and tuned to operate at 605 nm, produced test pulses of durations $\sim 5$ ps. At the laser wavelength the S20 photocathode had a sensitivity of 24 mA/W. The camera was operated at a streak speed of $6 \times 10^4$ cm s$^{-1}$ to give a time resolution of $\sim 2$ ps. A typical streak-photograph and the corresponding calibrated microdensitometer trace are shown in Fig. 6. Under these conditions the dynamic range was $\sim 55$. (Fig. 7). Pulses of duration 2 ps were generated$^{11}$ by employing DQOCI as a mode-locking dye in the laser. Increasing the camera streak writing speed to $10^5$ cm s$^{-1}$ provided an instrumental time-resolution limit of 1.4 ps.$^{12}$ From Fig. 7 it can be seen that even for pulses as short as 2 ps the useful dynamic range remains as high as 30.
An accumulative effect on the measured pulse intensities was also reported in Ref. 10. The intensity recorded for successive pulses was influenced and reduced by the preceding pulses when three 30-ps pulses of equal intensity, spaced 120-ps apart, were recorded on single streaks. The effect apparently increased with increasing intensity of the incident pulses. We have repeated this type of measurement with a quartet of equal intensity 2-ps pulses, each separated by 8 ps, using the Photochron II camera system. The streak photograph and microdensitometer trace of Fig. 8 show that the camera faithfully reproduces the pulse profiles and confirms that there are no accumulative photocathode saturation effects on this time scale.

IV. DISCUSSION

Our results, summarized in Table I, have confirmed the original observation that the time resolution of picosecond streak cameras deteriorates if the streak tube photocathode is illuminated with too high an intensity. However, we have found that the useful dynamic ranges measured by us are considerably
Table I. Summary of dynamic range measurements

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Photochron I (S1) camera</th>
<th>Photochron II (S20) camera</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test laser pulse duration</td>
<td>30 ps</td>
<td>7 ps</td>
</tr>
<tr>
<td>Wavelength</td>
<td>1.05 µm</td>
<td>0.53 µm</td>
</tr>
<tr>
<td>Photocathode sensitivity</td>
<td>0.3 mA/W</td>
<td>1.2 mA/W</td>
</tr>
<tr>
<td>Dynamic range measured</td>
<td>180</td>
<td>60</td>
</tr>
</tbody>
</table>

better than the values reported earlier, for similar camera systems.\textsuperscript{10} The dynamic range of a shortened version of an S1 Photochron I image tube (ITL) has also been measured.\textsuperscript{21} This system incorporates a four-stage magnetically focused intensifier in an arrangement similar to our S1/PHI camera. Based on a criterion of a broadening of 3 ps in their 50-ps test pulses (cf. 20% in this publication) these authors reported a dynamic range of 223 which is fairly consistent with our results of Table I.

The overall linearity of the streak camera is also substantiated by our results. The photographic film characteristic imposes the only nonlinearity in the responses of the systems. Work is now in progress to evaluate the performance of an optical multichannel array readout (PAR 1205D) as a replacement for film recording, with the aim of producing a completely linear response camera.

**ACKNOWLEDGMENT**

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\textsuperscript{5} D. J. Bradley and W. Sibbett, Appl. Phys. Lett. 27, 382 (1975).
\textsuperscript{6} See Ref. 2, pp. 32, 101, 107, 112, 118, 124, 130, and 136.
\textsuperscript{11} P. R. Bird, D. J. Bradley, and W. Sibbett, Ref. 2, p. 112.
\textsuperscript{15} H. B. Eisenenthal, Ref. 14, p. 275.
\textsuperscript{17} D. von der Linde, Ref. 14, p. 204.
\textsuperscript{20} D. J. Bradley, Opto-Electronics 6, 25 (1974).