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Recent Developments in Picosecond Streak Camera Systems

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Recent developments in picosecond streak camera systems

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A simple, compact, high performance streak camera system, using a new streak tube with a microchannel plate as an electron image intensifier, has been developed. The system consists of a streak camera and an automatic data acquisition system with a silicon intensified target vidicon camera and a video analyser employing a microcomputer.

First of all, the basic concept for designing the streak tube is discussed, comparing performances of the new tube with those of a streak tube followed by an image intensifier tube. The recent progress of the development of the tubes including ultraviolet, infrared and X-ray streak tubes is also presented.

Performance characteristics of the streak camera system, such as temporal resolution of better than 10 ps (f.w.h.m.) in a linear dynamic range of better than 100 at relatively small jitter of approximately ± 50 ps, are also presented.

1. Introduction

With the advent of picosecond light sources such as mode-locked laser pulses, synchrotron radiation, Čerenkov emissions from LINAC, etc., reliable and compact high-speed streak cameras are in demand for temporal and spatial resolved studies in beam diagnostics, high-speed phenomena ensuing from picosecond excitations and laser-induced plasmas.

A small, high-performance streak tube with a microchannel plate (m.c.p.) was developed (Kinoshita *et al.* 1976). This tube showed a temporal resolution of better than 10 ps for visible light input. Furthermore, a new tube having a temporal resolution of approximately 2 ps (Kinoshita *et al.* 1978), u.v., i.r. and X-ray tubes (Kuroda *et al.* 1978), have been developed. A simple, compact and high performance streak camera system (Tsuchiya *et al.* 1978), consisting of a streak camera (Tsuchiya *et al.* 1977) incorporating these tubes and an automatic data acquisition system with a silicon intensified target (s.i.t.) vidicon camera and a video analyser employing a microcomputer (Inuzuka *et al.* 1977, 1978), has been developed. In this paper, design and performance characteristics of the new tubes and the streak camera system are described.

2. Design theory

First of all, the basic concept for designing the streak tube is discussed, comparing performances of the new tube incorporating the m.c.p. with those of a streak tube followed by an image intensifier tube. The design and important parameters of the streak camera system are then described.

(*a*) *Consideration of a tube with the m.c.p.*

In the usual streak camera, a streak tube is combined with an image intensifier tube (i.i.) to improve the sensitivity and temporal resolution. These improvements can be achieved also by incorporating an m.c.p. into the tube for electron multiplication. To evaluate these two types, the noise figure, N, and spatial resolution of both types were calculated and compared with each other.

Calculation of N was carried out by assuming a Poisson distribution for the number of incident photons, the secondary emission process at the input of the m.c.p. and the scintillations at the phosphor screen, and a Furry distribution (Bell 1975) for the secondary electron multiplication process in the m.c.p. (see figure 1). The results are as follows:

$$N^2 = \frac{1}{\eta_1\beta_1\beta_2}\left\{1+\left(1+\frac{2}{\delta_1}\right)\Big/\alpha\eta_2\beta_3\gamma\right\} \tag{1}$$

for the coupling type, and

$$N^2 = \frac{1}{\eta_1\beta_1\beta_3}\left(1+\frac{2}{\delta_2}\right) \tag{2}$$

for the tube with m.c.p., where β_1, β_2 and β_3 are the mesh transmittance, the transmittance of an aluminum foil on the phosphor screen of the streak tube without the m.c.p. for electrons and the open area ratio (o.a.r.) of the m.c.p., respectively; η_1 and η_2 are the photocathode quantum efficiencies of the streak tube and i.i.; α is the optical coupling factor; γ is the conversion gain of the phosphor screen of the streak tube without the m.c.p.; and δ_1 is the average number of secondary electrons produced by the first collision in the m.c.p. for the coupling type, δ_2 for the tube with the m.c.p. Substituting values of $\beta_1 = 0.55$, $\beta_2 = 0.9$, $\beta_3 = 0.6$, $\eta_1 = \eta_2 = 0.1$, $\gamma = 400$, $\delta_1 = 1.5$, $\delta_2 = 1.3$, $\alpha = 0.02$ for the lens coupling type and $\alpha = 0.3$ for the fibre coupling type into (1) and (2), $N = 11$ for the lens coupling type, $N = 5.2$ for the fibre coupling type and $N = 8.8$ for the tube with the m.c.p. were obtained. If it were possible to increase the value of the o.a.r. of the m.c.p. and of δ_2, in future, this would result in the N of the tube with the m.c.p. becoming almost equal to that for the fibre coupling type. The f.w.h.m. of the line spread for both types are 44 μm for the coupling type and 34 μm for the tube with the m.c.p.

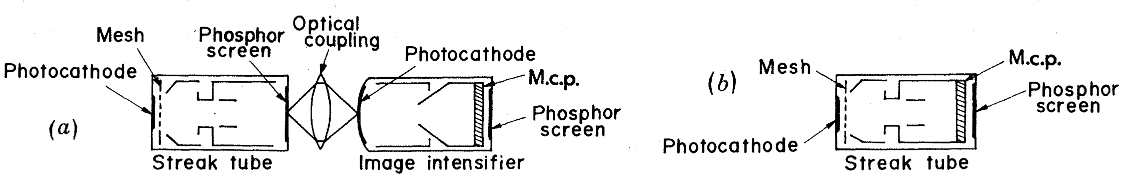

FIGURE 1. Schematic diagrams of (*a*) coupling type and (*b*) incorporating type.

The results of this comparison of N and the spatial resolution, when combined with the production of a simple and compact streak camera, indicate that the tube with the m.c.p. has a distinct advantage.

(*b*) *System design*

In the past, the streak image was usually recorded on a photographic film and analysed by a microdensitometer. This method had disadvantages, such as a long processing time and nonlinearity in the intensity scale of the film.

Recently, a demand for real-time processing of the data from a streak camera has arisen from the application of streak cameras to laser beam diagnostics and measurements of high-speed phenomena. An automatic data acquisition system to read out the streak image and analyse the streak data has been developed to meet to these situations.

In the usual method of operation, input signals received by the system, consisting of a streak camera and a direct readout system, are short light pulses. An immediate graphical representation of the intensity profile on a television monitor, or its analogue, or digital signals for a chart recorder or a host computer are required.

Important characteristics of such systems are the temporal resolution, the dynamic range, the linearity of the time scale, the triggering jitter and the detectability or the signal: noise ratio ($S:N$). These characteristics should be defined for the whole system. It is very important to understand that the $S:N$ of the system will be basically ruled by the shot noise produced at the section where the signal is the smallest. Accordingly, the difference of performance between lens and fibre coupling of the streak camera and the s.i.t. camera is no problem, since the photon signal is sufficiently large at the output of the streak tube with the m.c.p.

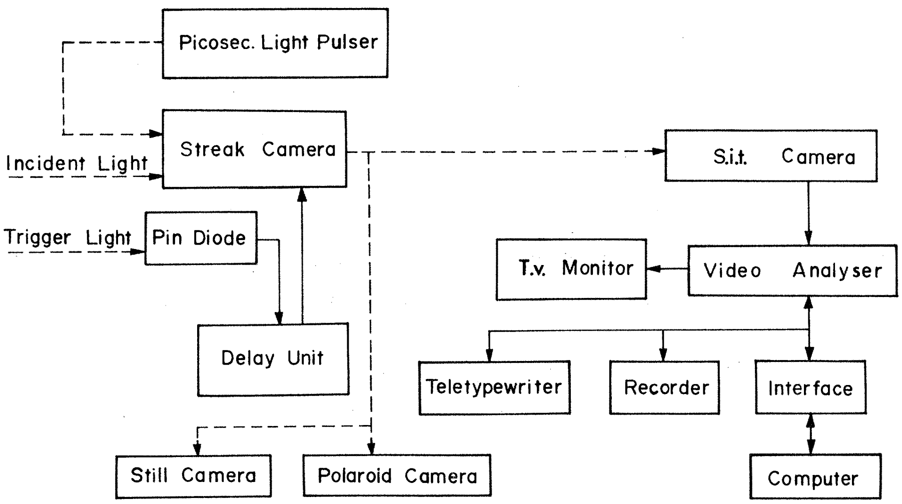

FIGURE 2. Block diagram of the streak camera system.

3. CONSTRUCTION OF THE SYSTEM

The construction of the streak camera system is shown in figure 2. Mainly it consists of a streak camera with the m.c.p., an s.i.t. camera and a video analyser. Peripheral equipment such as a PIN diode for the optical triggering, a delay unit for the adjustment of the delay time and analogue or digital data transferring system are also shown.

4. THE STREAK TUBE

The S-20 streak tube with an m.c.p. having a temporal resolution of better than 10 ps was developed first, a streak tube with temporal resolution of better than 2 ps, and u.v., i.r. and X-ray streak tubes also with m.c.p., have been subsequently developed.

(a) *The original streak tube*

A cross-sectional view of the tube is shown in figure 3 and the mechanical dimensions and the operating voltages are listed in table 1 (Kinoshita *et al.* 1976). The photoelectrons accelerated by the strong electric field between the S-20 photocathode and the mesh electrode pass through the focusing and anode electrodes and come into the streaking field. After passing through the streaking field, these electrons are multiplied by the m.c.p. and then form a streak image on the phosphor screen.

At the applied voltage of 900 V to the m.c.p. and a voltage of 3 kV between the m.c.p. output electrode and the phosphor screen, the light amplification factor is larger than 10^4.

The temporal resolution is limited mainly by the following three phenomena: time dispersion caused by the initial velocity distribution of the photoelectrons, the spatial spread of the slit image on the phosphor screen, and the transit time dispersion occurring in the deflexion field region. These three are represented by Δt_1, Δt_2 and Δt_3, respectively, in table 2. The total time spread is calculated to be 11 ps and agrees with the experimental result of 9 ps.

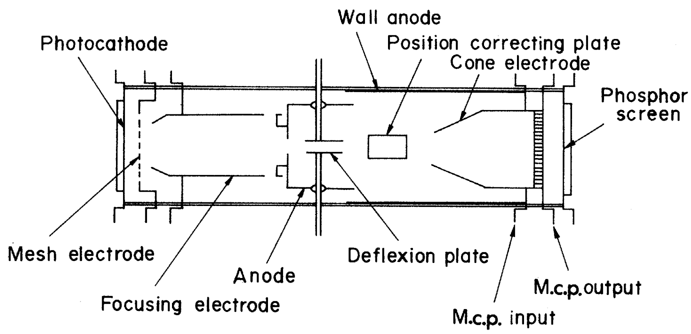

FIGURE 3. Cross-sectional view of the streak tube with m.c.p.

TABLE 1. DIMENSIONS AND OPERATING VOLTAGES OF THE STREAK TUBES

item	original tube	improved tube	X-ray tube
diameter/mm	52	52	52
overall length/mm	130	150	145
photocathode to mesh separation/mm	3	0.75	3
m.c.p. to screen separation/mm	1	0.5	1
photocathode/kV	−6.5	−10	−6.5
mesh electrode/kV	−5	−8.5	−5
focusing electrode/kV	−5.6	−8.7	−5.6
anode (m.c.p. in)/kV	0	0	0
m.c.p. out/kV	+0.5∼ +0.9	+0.5∼ +0.9	+1.0∼ +1.8
screen/kV	+3.9	+3.5∼ +3.9	+4∼ +4.8

(b) *Improvement of the temporal resolution*

To improve the temporal resolution, a new type of the streak tube has been developed by considering the following items (Kinoshita *et al.* 1978).

The transit time spread was decreased by increasing the electric field between the photocathode and the mesh electrode, and the accelerating voltage between the photocathode and the anode. The time spread caused by the spatial spread of the slit image on the phosphor screen was decreased by improving the spatial resolution of the tube itself, decreasing the magnification of the electron lens and increasing the streak speed. The distance between the m.c.p. and the phosphor screen affects strongly on the spatial resolution because of the proximity focusing method employed. Accordingly, the spacing was made as small as possible.

The mechanical dimensions, the operating voltages and the improved characteristics of this new tube are listed in table 1 and table 2. The theoretical temporal resolution of the tube is approximately 1.7 ps. Experiments with this tube have shown the temporal resolution to be better than 2 ps.

Table 2. Estimate of the temporal resolution of the streak tubes

item	original tube	improved tube	X-ray tube
$\Delta\epsilon$/eV	0.5	0.5	10
E/(V/m)	5×10^5	2×10^6	5×10^5
M	3.5	1.3	3.5
W/μm	110	50	350
V/(m/s)	1.5×10^7	5.7×10^7	1.5×10^7
Δt_1/ps	3.3	1.1	15
Δt_2/ps	9.5	0.9	23
Δt_3/ps	3.8	0.9	—
Δt/ps	11	1.7	28

Symbols: $\Delta\epsilon$, f.w.h.m. of the emitted photoelectron energy distribution; E, accelerating electric field near the photocathode; M, magnification; W, f.w.h.m. of the slit image on the screen; V, streak speed; Δt_1, transit time spread; Δt_2, the time spread caused by the spatial spread of the slit width; Δt_3, the time spread due to the deflexion electric field; Δt, temporal resolution $\Delta t = (\Delta t_1^2 + \Delta t_2^2 + \Delta t_3^2)^{\frac{1}{2}}$.

(c) *Extension to invisible spectral regions*

In order to extend experiments to the u.v., i.r. and X-ray spectral regions, streak tubes with m.c.p. have been developed. For the u.v. streak tube, the borosilicate glass window of the original tube was replaced by a u.v. glass window, to extend the spectral range to 200 nm.

For the i.r. streak tube, instead of the S-20 photocathode of the original tube, an S-1 photocathode has been studied. Its sensitivity at 1.06 μm has been higher than 300 μA/W. The mechanical dimensions, the operating voltages and the estimated temporal resolution of these tubes are the same as for the original tube.

For the X-ray streak tube, a 15 μm thick beryllium window is used instead of the glass window in the original tube. The photocathode is a gold film of thickness 10 nm. Two cascaded m.c.p.s are used to satisfy the gain requirement. The mechanical dimensions and the operating voltages are summarized in table 1. The temporal resolution of the tube was calculated to be 28 ps as shown in table 2 (Kuroda *et al.* 1978).

In experiments with the X-ray streak camera, X-ray pulses enter the slit in a configuration of 5° off axis of the tube to avoid direct exposure of the m.c.p. to X-ray pulses, since the m.c.p. is sensitive to X-rays. A streak image of the X-ray pulse from a brass target irradiated by a 30 ps f.w.h.m. light pulse from a glass laser showed the X-ray pulse to last for approximately 64 ps. By using this streak tube, the temporal behaviour of laser implosion processes was observed (Sasaki *et al.* 1978).

5. The streak camera system

The streak camera system, in which the streak camera was combined with an automatic data acquisition system consisting of an s.i.t. camera and a video analyser based on a microcomputer, can produce the graphical intensity profile data on a t.v. monitor or analogue and digital signals for the peripheral equipment. The performance of the total system must be considered.

(*a*) *Streak camera*

Figure 4 shows a block diagram of the streak camera. It consists of input optics to focus the slit image onto the photocathode of the streak tube, the streak tube itself with the m.c.p., output optics to focus the streak image developed at the phosphor screen onto an external focal plane, a sweep generator with avalanche transistors and a streak tube control circuit (Tsuchiya *et al.* 1977).

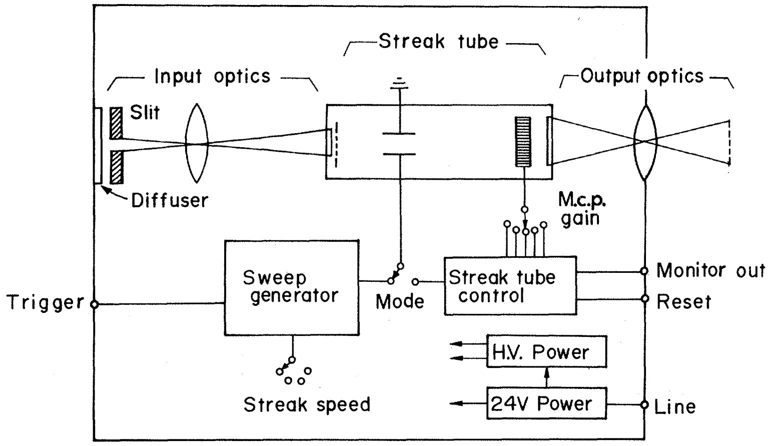

FIGURE 4. Block diagram of the streak camera.

(*b*) *Readout system*

The system consists of an s.i.t. camera, a video analyser and a t.v. monitor. The s.i.t. camera is used to pick up the streak image. At the same time, the video analyser integrates the video signal intensity along a prescribed portion of every horizontal video line. The output is in a format of 256 intensity levels times 256 time channels times 2 windows. This output is available as a graph of the intensity profile on the t.v. monitor and can be transferred to a chart recorder, to a teletype or to a host computer.

To read out the accumulated charges of the streak image on the target of the s.i.t. vidicon completely for each shot, integration is available up to 16 frames. To sum the data of several shots for averaging, integration of up to 256 events is available. The other essential features are the calibrations of the dark count and the sensitivity shading of the combined system.

To test the readout system combined with the streak camera, we first measured the linear dynamic range of the system in the focus (non-streaking) mode for the streak camera. It was found that the γ factor is unity within 1% error over an input light range of better than 200:1 for a single video frame. By integration of 256 frames, the linear dynamic range is extended to greater than 1000:1 (Inuzuka *et al.* 1977, 1978).

(*c*) *Performance of the system*

The temporal performance of the combined system was tested by using a train of picosecond laser pulses separated by a constant time interval, and having an exponential decaying envelope in the intensity time profile. This calibrating pulse train is produced by passing a single 6 ps f.w.h.m., 530 nm second harmonic of a mode-locked Nd:glass laser through a pair of partially transmitting mirrors (transmittance T) separated by an etalon air spacing corresponding to 30 ps.

In figure 5, the peak intensity is plotted against the number of observed peaks to demonstrate a single exponential decay. The reduction ratio from peak to peak is determined to be 0.75, which is in good agreement with the measured value of T for each mirror. The input intensity range covered in figure 5 is over 100. The average deviation of the observed 17 peaks is constant within 10%. Therefore the linear dynamic range in the streak mode at 15 mm/ns is better than 100.

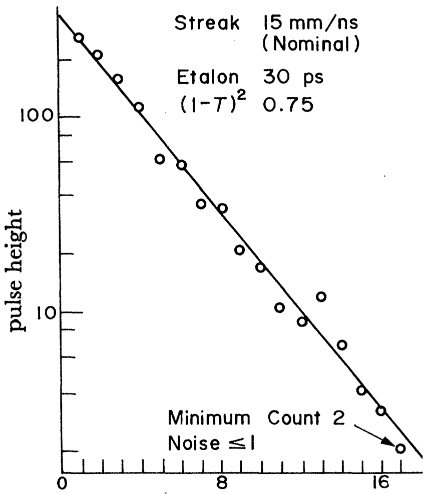

FIGURE 5. The peak intensity is plotted against the number of observed peaks to demonstrate a single exponential decay and a dynamic range of the streak camera better than 100:1.

As for the streak speed, the average channel numbers Δx for 30 ps is 12.1 ± 0.7 channels, where 0.7 is the standard deviation of the distribution of the 16 observed Δx values. Hence, the streak speed linearity is well within 6% of the average streak speed.

The average f.w.h.m. of the recorded 17 pulses is 4.5 channels and this corresponds to a 11 ps f.w.h.m. On the other hand, the input pulse is 6 ps. Therefore, assuming a Gaussian profile, the f.w.h.m. of the spread function of the streak camera system is $\surd(11^2-6^2) = 9$ ps.

The time jitter of the streak camera was studied in both optical and electrical triggering mode. In the optical triggering mode the 30 ps f.w.h.m. light pulse from an Nd:YAG mode-locked laser has been used. By deconvolution with the average f.w.h.m. of a single streak and the f.w.h.m. of 100 streaks integrated on the video analyser, a 50 ps time jitter was observed. In the electrical triggering mode, the 40 ps f.w.h.m. single light pulse from a GaAlAs laser diode has been used and a 20 ps time jitter was observed (Tsuchiya *et al.* 1978).

To study the detectivity of the streak camera system, the 530 nm laser pulse irradiated the streak camera and the streak was recorded on a tri-X film. The minimum detectability in term of numbers of photoelectrons per unit photocathode area was 4×10^4 photoelectrons/mm^2. Since the sensitivity of the s.i.t. camera was measured to be at least 100 times higher than tri-X film, it can be concluded that the minimum detectability of the streak camera system is 4×10^2 photoelectrons/mm^2 at the photocathode.

6. Conclusion

We have developed small, high-performance new streak tubes with the m.c.p. We have discussed the design and the performance of the new tubes, having temporal resolutions of 9 and 2 ps, u.v., i.r. and X-ray streak tubes. It has been clarified that the new tubes with the m.c.p. are the key component to realize compact and high performance streak cameras allowing easy operation.

Real-time operation of the streak camera system has also been realized by developing the automatic data acquisition system, which can produce a graphical output immediately after the arrival of the input signal. The automatic data acquisition system consists of an s.i.t. camera to pick up the streak image, and a video analyser based on a microcomputer to analyse the streak image. The total system, in which the streak camera was combined with the automatic data acquisition system, showed a temporal resolution of 10 ps (f.w.h.m.) with a linear dynamic range of better than 100 at a relatively small jitter of about ± 50 ps.

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