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Performance Comparison of Streak Camera Recording Systems

Mark Derzon, Terry Barber

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Performance Comparison of Streak Camera Recording Systems

Mark Derzon,
Diagnostics and Target Experiment Department
Sandia National Laboratories
Albuquerque, NM 87185-1196
and
Terry Barber, K-tech Corporation
Albuquerque, NM 87185-1196

Abstract

Performance characteristics of various readout systems coupled to an EGG-AVO streak camera were analyzed and compared to scaling estimates. The purpose of the work was to determine the limits of the streak camera performance and the optimal fielding conditions for the Amador Valley Operations(AVO) streak camera systems. We measured streak camera limitations in spatial resolution and sensitivity. Streak camera limits on spatial resolution are greater than 18 lp/mm at 4% contrast. However, it will be difficult to make use of any resolution greater than this because of high spatial frequency variation in the photocathode sensitivity. We have measured a signal to noise of 3000 with 0.3 mW/cm² of 830 nm light at a 10 ns/mm sweep speed. We have compared lens coupling systems with and without micro-channel plate intensifiers and systems using film or charge coupled device (CCD) readout. There were no conditions where film was found to be an improvement over the CCD readout. Systems utilizing a CCD readout without an intensifier have comparable resolution, for these source sizes and at a nominal cost in signal to noise of 3, over those with an intensifier. Estimates of the signal-to-noise for different light coupling methods show how performance can be improved.

Outline

This document is organized so that an interested but not experienced reader gets necessary information in a sequential fashion and does not have to read the entire text. To assist in using this document as a reference work we are including a table of contents.

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Introduction

Streak camera based diagnostics are vital to the inertial confinement fusion program at Sandia National Laboratories.^{1,2,3} There is a companion paper to this which includes more information on the motivation and specific usage of these cameras at the Particle Beam Fusion Accelerator II.⁴ No tutorials have been found that simplify the coupling of the camera to a readout system or quantify and explain the tradeoffs for individual systems. In addition to this, each streak camera type has its own limitations with respect to sensitivity, photocathode length, resolution and dynamic range. Frequently film or CCDs are used as the recording media and are coupled to microchannel-plate intensifier (MCPI) tubes. The MCPI's are used to provide gain in order to view low magnitude signals. An MCPI affects the system spatial resolution and the dynamic range.⁵ In addition MCPIs are found to introduce shot to shot amplitude variations.⁶ This increases the uncertainty over systems without MCPIs when performing shot-to-shot comparisons. The intrinsic dynamic range of the streak camera systems is much greater than the dynamic range of an MCPI.⁷ For this reason we have compared sensitivity and resolution parameters for systems both with and without image intensifiers. We did not address amplitude jitter and dynamic range measurements in this work.

We compare systems using lens-coupled CCDs as a substitute for film coupled recording systems and have quantified the noise characteristics and spatial resolution of these systems. One obvious addition to this work would have been to include a readout system utilizing a fiber optic taper instead of a lens; unfortunately we did not have this hardware. The tapers could increase the S/N ratio by as much as a factor of 10.⁸ Typically, however, these devices are known to generate a moiré or aliasing type of problem due to the frequency overlap of the fiber spacing with the CCD pixel size and source input. The amplitude of the effect is very system- and source- dependent and should be amenable to software correction. The fiber optic tapers can also create geometric distortions in the image.

In addition to optimizing the readout system, one of the goals set for this work was to determine the performance characteristics of a streak-camera-

limited system with respect to spatial resolution and S/N. This is important when determining the optimal readout system so that the system is neither over specified or under specified. Spatial and temporal resolution in a streak-camera-limited system is determined by the photocathode characteristics and the internal electron optics. A streak-camera-limited system with regard to signal-to-noise would be limited by the ability to sense and count single photoelectrons.

For these measurements we used a EGG-Amador Valley Operations streak camera, type LA-CA-15.⁹ We have performed simple analytic scaling which predicts that streak camera limited operation, photoelectron limited in signal-to-noise and spatially limited by electron focusing, would be obtained by coupling a CCD directly to the streak camera output faceplate. The analytic estimates show that a CCD with pixels smaller than 20 μm coupled directly to the output of the streak camera would provide near streak-camera-limited performance in two primary figures of merit: spatial resolution, and S/N. Future work will include dynamic range, amplitude jitter, and reproducibility studies.

Experimental set-up

The experimental set-up is shown in Fig. 1. It consists of an optical comb generator, made by EGG, coupled to a 50 μm core fiber where the light out of the fiber is focused onto the streak camera photocathode. Initially the position of the fiber and lens was adjusted to provide a minimum in the magnitude of the FWHM and a maximum in the peak intensity of the measured spot at the streak camera output. The optical pulse generator provided a 2 μs long train of 500 ps FWHM impulses at 250 MHz and 820 nm. The generator internally splits the optical pulse into multiple outputs. One of these outputs was used to illuminate the photocathode and another was used to monitor system drift. The signal used to monitor the system drift was coupled to a photomultiplier tube (PMT). System drift, as determined by the time averaged peak in the comb output, was less than 10% over the course of these measurements. The connections to the PMT and the fiber incident on the photo cathode were not changed after the measurements were begun.

A typical time history of a comb output is shown in Fig. 2. Figure 2a shows a trace of the comb pulse train. The trace appears split vertically because the signal oscillates and the combined scope and film resolution is not adequate to view the pulse train. Figure 2b is a trace of the pulse train as recorded from the PMT output at a higher resolution; this trace shows a few of the individual comb pulses or impulses. The PMT and scope combination does not have adequate resolution to clearly define the shape of each impulse, but the peaks are clear and identifiable. This allows us to use the magnitude of the impulses as a relative calibration of variation in the comb intensity.

Figure 1. Schematic drawing of the basic experimental setup for the streak camera performance measurements.

There are two CCD cameras used for these measurements. One was provided by Photometrics and it contains a 1024x1024 front-illuminated CCD made by Thompson that has square 20 μm pixels. The other camera is made by Princeton Instruments, it uses a back-illuminated 1024x1024 CCD made by Tektronics. The CCD in the Photometrics camera is roughly 3-times less sensitive than the Princeton camera by virtue of front versus back-illumination and the Photometrics camera has a 12 bit digitizer. This results in the PI camera having roughly 12x better sensitivity than the Photometrics camera. Aside from the quantum efficiency, the pixel size difference (20%) is the major difference between these cameras with respect to the work reported here.

Measurement of comb intensity and spot size

We determined the absolute measurement of the power and energy incident on the photocathode by replacing the streak camera with a calibrated Photodyne model #150 photodiode. To insure that photodiode saturation was not an issue, measurements were made at and away from best focus. This allowed us to ensure that we operated the photodiode in the linear regime and that all of the light was being collected. The Photodyne power meter reads continuous time-averaged light incident. It does not have the

sensitivity to accurately measure either the energy in a single pulse train or the average power during a pulse train. Each pulse train is a comb pulse and it is made up of individual impulses.

We varied the optical power flowing through the fiber by changing the frequency of the comb output. The slope of the power versus frequency plot then provided the time averaged power per pulse. The method for determining the average power is illustrated in figure 3, where the measured power detected versus frequency is plotted. The slope of the linear fit in units ($\mu\text{W}/\text{Hz}$) gives the average power due to a single pulse train. This is also the energy per pulse train, $0.20 \pm 0.01 \mu\text{J}$. From Fig. 2, each comb pulse train is $1.9 \pm 0.2 \mu\text{s}$ wide with 4 ns between impulses.

Figure 2. 2a) PMT trace of a typical comb output pulse. 2b) Higher resolution view showing comb turn-on.

Figure 3. Power at photodiode versus comb frequency.

From this measurement we can determine other important information about the light incident upon the photocathode. Equations 1-4 show how the calculations for the mean energy per comb pulse train, the mean power per impulse, the uncertainty in the estimate of mean energy per pulse train and the uncertainty in the mean power per impulse are performed.

$$\bar{E} = \frac{\text{Energy per pulse train}}{(\# \text{ impulses/pulse train})} = \frac{2.0 \times 10^{-4} \mu\text{W/Hz}}{(1900 \text{ ns} * 1 \text{ impulse}/4 \text{ ns})} = 4.29 \times 10^{-1} \text{ pJ} \quad (1)$$

$$\bar{P} = \frac{\bar{E}}{\sqrt{2\pi} \sigma^2} = \frac{4.29 \times 10^{-1} \text{ pJ}}{\sqrt{2\pi} (0.646 \text{ ns})^2} = 0.265 \text{ mW} \quad (2)$$

$$\Delta \bar{E} = \left\{ \left(\frac{d\bar{E}}{dE_c} \right)^2 \Delta E_c^2 + \left(\frac{d\bar{E}}{dt_c} \right)^2 \Delta t_c^2 \right\}^{\frac{1}{2}} = 3.0 \times 10^{-2} \text{ pJ} \quad (3)$$

$$\Delta \bar{P} = \left\{ \left(\frac{\delta \bar{P}}{\delta \sigma} \right)^2 \Delta \sigma^2 + \left(\frac{\delta \bar{P}}{\delta \bar{E}} \right)^2 \Delta \bar{E}^2 \right\}^{\frac{1}{2}} = 0.023 \text{ mW} \quad (4)$$

where $\bar{E}$ = mean energy per impulse

$\bar{P}$ = average peak power of an impulse

σ = standard deviation (in ns) of the impulse at the readout

E_c = energy per comb pulse train

t_c = width of comb pulse,

$\Delta \bar{E}$ and $\Delta \bar{P}$ are the uncertainties in $\bar{E}$ and $\bar{P}$ respectively.

The spatial footprint of a comb pulse was measured by placing a Photometrics CC200 CCD camera with a 1024x1024 Tektronix CCD (20 μm pixels) at the best focus of the fiber and lens. This provides an estimate of the point spread function (PSF) of the light on the streak camera photocathode. The footprint is shown in figure 4a and both vertical and horizontal lineouts are shown in figure 4b. The lineouts show that the central feature of the illumination has a width of roughly 34 μm , based on a least squares fit to the vertical lineout. This is important to consider when explaining the features measured in the spatial dependence of the photocathode sensitivity.

Figure 4. 4a) Point spread function of focused light at the plane of best focus. 4b) Vertical and horizontal lineouts through best focus with superposition of Gaussian least squares fit to the vertical lineout.

Characterization of photocathode uniformity

The streak camera manufacturer's data implies that the photocathode sensitivity was uniform and that the photocathode was 300 μm wide. Measurements of the sensitivity at two heights along the photocathode are significantly different and show large amplitude small-spatial-scale variations across the photocathode. These effects are illustrated in Fig. 5 where the peak intensity of the fourth impulse from a comb pulse is plotted as the lens is moved along the photocathode using a micrometer stage. The

fourth impulse is used to allow the comb generator intensity to stabilize. The second trace was obtained by moving the lens and the fiber vertically one mm, refocusing and then scanning again across the photocathode. For these measurements readout system #3, in Table 1, was used. The traces show that the photocathode width is between 150 and 200 μm . Features of roughly 25 μm can be observed in the response. This is approximately the measured source size. Since these features are the convolution of the photocathode sensitivity with the source size, it implies that there are even smaller features in the photocathode sensitivity.

Figure 5. Relative variation in photo cathode sensitivity with height and width. Relative uncertainties shown are 5 μm in position and 5% in relative amplitude.

The consequence of these spatial variations in photocathode sensitivity is that extreme care is required to obtain a reproducible intensity calibration. This is because there is difficulty ensuring that the alignment has not changed between the time of calibration and the acquisition of data. We have found it easy to maintain absolute alignment to within 40 μm but variations in alignment of within 10 μm occurred routinely.

The uncertainty in absolute sensitivity of the different readout systems that we use is as high as $1\sigma=20\%$. This number is based on our inability to ensure that the light focus stayed on the peak of the sensitivity curve, see Fig. 5, and $\sigma=20\%$ is used for most of the amplitude uncertainty estimates. Where we were certain that the focus was on the peak of the sensitivity plot, the uncertainty used is the quadrature addition of the relative error in the PMT amplitude gain and the relative error in the estimate of the power per impulse, 10% is typical under these conditions. We feel that best focus could be maintained for 4-hours, and when the data was acquired within the 4 hour limit the smaller intensity uncertainty is used.

Spatial resolution of our optical system - lens/CCD combination

To obtain the streak camera resolution we first measured the resolution of highest sample rate optical system. This system consisted of a Photometrics CC200 camera controller and a Tektronix 1024 x 1024, 20 μm square pixel CCD. This camera was chosen over our Princeton Instruments device because the pixels are 20% smaller in linear dimension. The highest resolution lens we used is a Nikon 1:1, f/1 lens quoted at 200 line pairs per mm (lp/mm) limiting visual resolution. Using a standard Air Force test pattern we obtained a 6% contrast at 18 lp/mm with this system. The image of the test pattern is shown in Fig. 7 and illustrates the appearance and blur observed for this figure of merit. Using the Princeton Instruments system we obtained 6% contrast at 14 lp/mm using the same lens.

Figure 7. Test pattern image at 18 lp/mm.

Because this measurement includes contributions from the source size and the CCD/lens combination the contribution of each part cannot be determined separately. The image discussed in Fig. 4 shows that a FWHM of ~ 1.5 pixels or $30\text{ }\mu\text{m}$ and a full width at tenth maximum of ~ 4 pixels is obtainable for the system. We can not accurately determine how much of that is due to the source or to the CCD/lens system.

Optical system resolution is normally quoted in line pairs per mm, typically at 4% contrast because with film-based imaging systems this is easy to measure; it is roughly the eye's ability to see contrast. For many optical systems this single figure of merit (lp/mm at 4% contrast) is acceptable. For solid state recording devices and many scientific grade instruments it is more precise to use Gaussian impulse responses and better-quantified figures of merit. In addition, given the resolution and reproducibility of the CCDs it is worthwhile to make the PSF measurements extend well below the peak signal (unlike the eye) to look at low level contributions to the response. Therefore, we feel that a single figure of merit more relevant to solid state devices is the FWHM assuming a Gaussian point spread function (PSF) rather than the often quoted lp/mm.

For a Gaussian impulse response in spatial units, alternatively called a Gaussian point spread function, the real part of the fourier transform of the PSF, called the modulation transform function (MTF), is Gaussian. This makes unfolding input data mathematically simple. In addition, for a Gaussian response the unfold is complete.

Confusion results because MTFs are generally assumed to be the system response to infinite sinusoidal wave functions. Thus, quoting resolution in terms of lp/mm makes a lot of sense if we are considering the power of a sine wave that will be passed or filtered at the lp/mm spatial frequency. 4% contrast is quoted because it is an easy single figure of merit not because it is a complete system specification.

Optical systems frequently have non-Gaussian responses and the shape of the MTF can be important in optimizing an optical coupling system¹⁰ and

the 4% figure of merit is frequently not adequate. If the assumption of a Gaussian shape is applicable then use of the FWHM is a more complete specification of the system and it reduces the number of assumptions that may be associated with a simple lp/mm specification.

We have developed a simple model to relate the two methods. For summed Gaussian pulses of standard deviation, σ_f , at a spatial frequency of L [lp/mm], there is a contrast between them of

$$\text{Contrast } (\sigma_f) = \frac{F_{\text{max}} - F_{\text{center}}}{F_{\text{max}} + F_{\text{center}}} \quad (5),$$

the contrast function is plotted in Fig. 8.

$$\text{Where } F(x) = \exp\left(-\frac{(x)^2}{2\sigma_f^2}\right) + \exp\left(-\frac{(x-1)^2}{2\sigma_f^2}\right) \quad (6),$$

is the formula for the two summed Gaussians and x is the variable denoting position along the summed Gaussians.

x/σ_f represents the ratio of the spatial frequency being sampled to the resolution of the system.

F_{max} is the maximum value of the function and F_{center} is the value between the two peaks. The FWHM can then be related to the contrast function by Equation 7 below. This provides a simple way of estimating the figure of merit between the two methods discussed. As a function of the contrast then the FWHM resolution can be determined with regard to a known limiting resolution and contrast. For example 6% at 18 lp/mm is roughly equivalent to a 50 μm FWHM Gaussian PSF.

$$\text{FWHM} = 2.35 \frac{\sigma_f}{(\text{limiting resolution at stated contrast})} \quad (7)$$

Fig. 8. Contrast function determined from two summed Gaussians.

Another possible confusion is that the Nyquist sampling criterion implies the system resolution is limited to twice the sampling length size or $40 \mu\text{m}$ (25 lp/mm) for the Photometrics camera. This criterion truly applies only to infinite sinusoidal inputs and effects smaller than this criterion may be observable for non-periodic inputs. Also, near the Nyquist limit aliasing may be an issue for periodic input signals, having the effect of artificially enhancing the apparent resolution. This aliasing problem does occur with the Photometrics system with the 1:1 lens and a sinusoidal 18 lp/mm input signal. It is important when designing a system to avoid signal inputs modulated near the Nyquist frequency.

The phenomenon is observed in Fig. 7 and is not presently accounted for when estimating the optical systems' contribution to measured resolution; however, the effect has no effect on the conclusions drawn. The important point is that sampling rate or length scale, when converted to equivalent source size, may be the limiting factor in estimating the system performance at a given spatial frequency.

Estimation of streak camera resolution

To estimate the streak camera resolution we focused this lens/CCD system on the streak camera output plane without an image intensifier. Figure 9

shows an image of the early-time comb impulses. To obtain the value for the impulse width we did a least squares fit to the lineouts. The 400 ns sweep speed was chosen because the comb data shows fairly round impulse dots, and it was the sweep speed used during many of our experiments. Changing the sweep speed will affect the S/N, the dynamic range and the resolution.

Figure 9. Early-time image of streak camera response to comb input. Time increases along the direction of the dots. The dots are on a slight angle because the CCD was rotated slightly with respect to the direction of the time domain. The data is shown in its raw uncorrected form.

We estimated the resolution of the streak camera system by subtracting the resolution of the various system components from the measured impulse width in quadrature as shown in Equation 8. This works well if one component dominates the system response and if the components are near-Gaussian in their response. Using this method we estimate the streak camera FWHM to be nominally 28 μm (~ 30 lp/mm). This value is determined using the 50 μm FWHM estimated for the lens/CCD combination and 34 μm for the source. The inferred streak camera response may be high because effects of the CCD and sampling errors are counted twice. The camera may approach the resolution stated by

EGG/AVO as the static resolution of 40 lp/mm at 4% contrast. We specify such a large uncertainty because we know that the various system responses that we have measured deviate significantly from Gaussian. However, we do believe that the camera is capable of reproducing source spatial features of 25-50 μm in size and in order to understand the response better we require a better-characterized input and a higher-resolution optical system.

If these responses were Gaussian in shape then a 44 μm FWHM (the quadrature addition of 28 and 34 μm) could be obtainable with an ideal recording system. To be truly streak camera limited, using the 28 μm impulse response (where the streak camera resolution accounts for more than 90 % of the measured width of a point source), the sample rate would need to be about 7 μm at the streak camera output.

$$\begin{aligned} \text{FWHM}_{\text{Strk Camera}} &= \sqrt{\text{FWHM}_{\text{comb @ CCD}}^2 + \text{FWHM}_{\text{Lens/CCD}}^2 + \text{FWHM}_{\text{Source}}^2} \\ &= \sqrt{67^2 - 50^2 - 34^2} \\ &\sim 28 \mu\text{m} \end{aligned} \quad (8)$$

After the experiments were completed and the data analyzed, we learned that the resolution of the camera is slightly dependent on the location of the light source on the photocathode¹¹. In addition, the Photometrics system data was taken before we understood that the light source was moving slightly between measurements; this motion is responsible for the large uncertainties in gain and resolution that we quote later in the paper. The data taken with the Princeton Instruments CCD was taken after we started testing for drift.

Making use of the resolution greater than 20 lp/mm will be very difficult because of this drift and small spatial-scale variations in sensitivity. This kind of effect, the assumed Gaussian addition of resolution, and source size spatial variations in the PSF of the lens, all imply that analysis of features < 50 μm in size will be very difficult even if an adequate recording system is used. As a practical matter it is our opinion that 20 lp/mm for the streak

camera is a more reasonable figure-of-merit to use than 40 lp/mm when determining how to best couple these cameras when designing a diagnostic system.

One could spend a lot of money getting an imaging system to make use of any photocathode resolution greater than 20 lp/mm. There are few sources that require this resolution; and designing a mount to hold the light source to the necessary nominal 10 μm positioning (see fig. 5) will be difficult. It seems more reasonable to match the source to the available streak camera and readout systems than building the system to always be streak camera limited in resolution whenever possible.

MCPI characterization and discussion of film as readout medium

Before discussing the comparison of the various readout systems, we would like to describe the performance of the MCPI as a component. For small input signals the use of MCPIs can greatly improve the S/N ratio. We needed to determine their effect as a component on our system performance. There is a wealth of information about the performance of MCP's. A few of the relevant papers are included in the references (4-8). In general, each component of a system has its own limitations; specifically for the MCPI we are concerned with effects on system resolution and noise. Effects on dynamic range, shot-to-shot reproducibility and uniformity will not be discussed in this work.

We used the system as shown in Fig. 1, first with a Photometric CCD camera (Thomson 1024x1024 CCD) and a 2.5:1, f/0.58 relay lens, manufactured by Tinsley, viewing the streak camera output and then with film as the readout medium. The voltage across the MCPI was varied from 500 to 900 V. The FWHM along the spatial dimension of the fourth comb impulse in a comb pulse train and the peak amplitude for the pulse were obtained. Plotting these in Fig. 10, we show the resolution of the entire system and the gain as a function of voltage. The figure shows that for point sources at this amplitude input the FWHM is nominally 2.2 pixels (110 μm) and is independent of voltage. The errors shown are $\pm 10\%$ and this value is the standard deviation of the FWHM obtained from the fourth

to fourteenth impulses at 700 V. The value is representative at all the voltages. Unfortunately, this data was acquired with the 2.5x Tinsely lens which sample rate limits the FWHM and this measured FWHM does not reflect the performance of the intensifier with voltage. This simply implies that for these voltages and this system the resolution is always dominated by the sampling.

The peak intensity curve is fit well by a power law gain $\sim V^{9.6}$. The uncertainties shown are $\pm 20\%$ based on an estimated 2% shot-to-shot variation in voltage from the voltage source. The data shows that at these voltages and with these amplitudes neither the MCPI or the CCD are saturated.

Fig. 10. Comparison of resolution and gain as a function of voltage across MCPI.

After acquiring these data the lens and CCD were removed and images were obtained on TMAX film. The film was developed and the film response was unfolded using the techniques developed by Bailey.¹² Using this method a test film is exposed to a calibrated light source near the time when the data is taken on the streak camera and developed at the same time with the same chemicals and conditions as the streak data. The known intensity exposing the test wedge is used to generate a lookup table and

curve fit for doing the conversion of film density to intensity [ergs/cm²]. The film sensitivity curve for the data analyzed is shown in Fig. 11.

The highest density observed in the comb data at 900 V was 5.0 and the knee in the curve is at 5.11. By examination of the figure it seems clear that the data should be away from the knee and saturation should not be a problem. However, by varying the voltage from 700 to 900 V the CCD data shows that the intensifier output should increase by a factor of 10. Inspection of the film response at ND=4.6, the density obtained with the intensifier at 700 V, shows that the film should go hard into saturation when the intensifier is operated at 900 V. Saturation effects such as increased noise were not observed in the data we obtained at 900 V. Such non-obvious and non-linear saturation needs to be a concern for anyone operating near the knee of the film response. We quote results for film NDs at 4.6, although we have not shown that we do not have a problem at this lower density. However, At 700 V the highest density we consider is 4.6 and it is well away from the knee in the calibration curve; we assume that saturation is not an issue at this value.

Figure 11. Example of film calibration unfold from step wedge.

Comparison of the streak camera readout systems.

We have discussed each of the components of the streak camera and readouts systems we employ; the streak camera, the readout system, and the intensifier. The matrix given in Table 1 shows the various combinations of image intensifiers, lenses, film or CCDs we have used, including some comments regarding the advantages and disadvantages of each combination. The first column is an arbitrary reference number referring to a specific streak camera and readout systems configuration.

The CCD cameras used were either a Princeton Instruments camera (PI) with a back-illuminated Thompson 1024x1024 CCD (PI24) that has 24 μm square pixels, or a Photometrics CC200 with a front illuminated Tektronix 1024x1024 that has 20 μm square pixels (PM20). The Nikon lens used was a 1:1, f/1 lens with a quoted resolution of 200 lp/mm. The Tinsley lens is quoted at 20 lp/mm, 2.5:1 magnification and f/0.58.

The first three configurations of the table allow comparison of the CCDs and lens combinations. Comparison of configurations 4 & 5 allow comparison of the effect of the intensifier at two voltages and configurations 6 and 7 show the effect of the film with two different amplitude signals.

Table 1. Readout system configuration used in comparisons.

<u>#</u>	<u>Detector</u>	<u>Intensifier</u>	<u>Lens</u>	<u>Comments</u>
1	PI24	not used	Nikon	This system has a 24 mm square field of view at the streak output. A 1024x1024x24 μ m pixel back-illuminated CCD was used.
2	PM20	not used	Tinsley	This system has a roughly 50 mm square field of view. However distortions in the lens are obvious at a radius of 14 mm. A 1024x1024x20 μ m pixel front-illuminated CCD was used.
3	PM20	not used	Nikon	The reason for this data point is to allow comparison of the PI24 to the PM20 in terms of S/N and resolution.
4	PI24	Y-700 V	Nikon	Systems 4&5 allow comparison of the intensifiers affect on resolution and S/N at two voltages.
5	PI24	Y-900 V	Nikon	Comparison of this signal to the film based system determines the effect of voltage on system resolution.
6	film	Y-700V	not used	Systems 6&7 allow comparison of the intensifiers affect on resolution and S/N at two voltages. Scanned at 38 μ m spacing.
7	film	Y-900V	not used	Saturation effects are not obvious- ND below curve knee, however, intensity non-linear and FWHM changes with voltage.
8	film	N	not used	There was no signal observed on the film without the intensifier.

We start comparing the systems qualitatively by comparing the point spread functions (PSF). The effect of the different hardware components on the central portion of the PSFs is shown in Fig. 12. The broader the PSF the poorer the performance of the system.

Figure 12. Comparison of the normalized point spread functions of the different systems.

Signal-to-noise (S/N) limitations in the various systems show up as differences in the backgrounds of the normalized PSFs. Fig. 13 shows the PSF on both log-linear scales and linear-linear scale to clearly illustrate background differences. Some systems are not shown because they overlap those shown and add no additional understanding. Fig.13a, shows the intensity well away from the peaks as differing between 10^{-4} and 3×10^{-3} the peak intensity.

Aside from giving a larger PSF, the film data shows increased amplitude away from the central feature; these film induced artifacts are present in all the film data we have analyzed. The strength of the artifact is intensity dependent and rarely symmetric, yet it appears consistently. We do not feel that these artifacts are part of the signal from the streak camera because they are never seen on the CCD based systems. At present we have no explanation for cause of the artifacts. We acknowledge their existence and otherwise ignore them.

The tails in all the systems extend to many times ($> \times 10$) the FWHM of the distribution and are definitely non-Gaussian in shape, see Fig. 13b, but whether the low level intensity is due to the lens/CCD system or the streak camera has yet to be determined. Other investigators have observed these tails and believe they are due to cross-talk between fibers in the output faceplate of the streak tube.¹³ A certain amount of the tail is due to the intensifier, but even without an intensifier the tail exists. Fig 13c shows the shapes of the CCD/lens PSFs and the difference in PSF observed when film is used as the readout.

The noise, when the Princeton Instrument camera is used without an intensifier, Fig. 13b, is dominated by the amplitude digitization of a single count in the camera. This means that the PI system is limited in sensitivity by either the A/D converter or the readout noise in the camera.

(13a)

(13b)

(13c)

Figure 13. Plots of the point spread functions for the most clearly different readout systems configuration given in table 1.

A quick comparison of each system's performance is given in Table 2, where the measured signal-to-noise and the FWHM of a single impulse are listed. Note that none of these systems is in the sample rate limited regime. For the film based systems, where the film could be scanned at higher resolutions, it is either or both the film limitations or the intensifier that limit performance. For the unintensified CCD results, it is the lens coupled to the pixel size which limits the measured width. For the best system we have the source and streak camera estimated spot size ($44\text{ }\mu\text{m}$) coupled to a $40\text{ }\mu\text{m}$ sampling limit the quadrature estimate for the measured width to $59\text{ }\mu\text{m}$. The measured $67 \pm 7\text{ }\mu\text{m}$ places us close, however, to be truly streak camera limited (where the streak camera resolution accounts for more than 90% of the measured width of a point source) the sample rate would need to be about $7\text{ }\mu\text{m}$ at the streak camera output. With this sample rate the equivalent FWHM would be $46\text{ }\mu\text{m}$ instead of $59\text{ }\mu\text{m}$.

In table 2, we have also listed the estimated FWHM after correcting for the $34\text{ }\mu\text{m}$ source size, FWHM_c . The signal-to-noise (S/N) was determined by taking the peak intensity divided by the standard deviation of the background far from the comb data. The uncertainties in the quoted S/N represent variations obtained by changing the region chosen for obtaining the standard deviation in background. The differences in FWHM between the CCD systems with and without the intensifier are probably insignificant. However below 10% of the impulse peak intensity there are appreciable differences in the tails of the PSFs.

Table 2. Summary of readout system performance. Shown are raw spot size FWHM, FWHM corrected for 34 μm source size, Nyquist limited spot size (2x pixel size), signal-to-noise ratio and comments.

#	FWHM [μm]	FWHM c [μm]	NYQ- LIMIT	S/N	Comments
1	91	84	50	200 ± 100	Measured with source at location of photocathode sensitivity peak. Noise dominated by digitizers least significant bit. CCD pixel size doesn't account for all of this resolution difference. Circular 24 mm field of view.
2	106	100	100	44 ± 10	System has a roughly 50 mm square field of view. Distortions due to the lens are obvious at a diameter of ~ 30 mm. Lens magnification is the biggest contributor to the resolution.
3	67	57	40	14 ± 6	Highest sampling-rate system. 12 bit digitizer results in poor sampling of low amplitude signal. Signal to noise is dominated by digitizers least significant bit.
4	90	83	50	1200 ± 300	Direct comparison of system 1 & 4 shows intensifier is not the dominant factor in system resolution. 10% error in FWHM measured means FWHM differences between configurations is insignificant. Different dots have different widths. It does increase the S/N over the same system without an intensifier.
5	88	81	50	3000 ± 300	Increase in voltage slightly increases S/N. There is an effect on wings of the PSF.
6	130	125	76	1200 ± 400	Systems 6&7 allow comparison of the effect that MCPI has on resolution and S/N at two voltages using film. Peak ND=4.6
7	200	200	76	750 ± 250	Peak ND=5.01. Broadening of impulse and saturation effects observed. Saturation not well studied and onset is difficult to determine.

The modulation transfer function represents the spatial frequency range for which the total system can pass information. These are shown for different system configurations in Fig. 14. The figure illustrates the differences in resolution between systems as a function of frequency. The higher the MTF the better the resolution. The figure also shows the estimated MTF of the source and CCD. The effect of the streak tube and readout system is approximated by the area between the source curve and the system curve.

Figure 14. MTF of system at streak camera output for various readout systems.

If an intensifier is used the systems with lens/CCD readouts clearly offer better performance than systems with film as recording media. Without an intensifier there is not enough signal for film to be a viable detector at these intensities. In the film-based systems, it is the characteristics of the film that degrade the resolution compared to the CCD-based systems and variations in the neutral density from grain to grain that generate the background noise. As long as there is adequate light the un-intensified CCD based systems have an advantage in resolving the tails of the PSF, see Fig. 13. With higher sampling rates larger differences in resolution between intensified and unintensified systems are expected.

Absolute sensitivity of the streak camera recording systems

The best recording system sensitivity possible is that which allows a single photoelectron to be observed. It is necessary to define a figure-of-merit that represents sensitivity with respect to the noise such that a single photoelectron can be observed. The gain necessary to obtain the ratio of the S/N to the number of photoelectrons at the photocathode (N_{pe}) is given by the ratio $[S/N]/N_{pe}$. When this ratio equals 1 the amplitude of a single photoelectron event is equal to the amplitude of the noise. At this intensity we have reached what we somewhat arbitrarily have defined as the streak-camera-limited sensitivity, because at this point a single electron event has a roughly 50% chance of being identified based on a single-pixel measurement. Smoothing techniques may be able to enhance the ability to observe single photoelectrons based on the size of the PSF (number of pixels involved). In this case the data could be processed and averaged to increase confidence in the identification of a single electron.

We know the absolute energy in our source signal and the resolution of the various systems that we have tested. We now develop this relationship between the amplitude of the incoming signal, the resolution and the signal-to-noise.

The number of photoelectrons generated in the streak tube for a given impulse is estimated by Eqn. 9.

$$N_{pe} = \frac{\bar{E}}{E_{\gamma}(\lambda)} * QE(\lambda) \quad (9)$$

where N_{pe} = number of photoelectrons for a given input energy

$E_{\gamma}(\lambda)$ = average incident photon energy

$QE(\lambda)$ = quantum efficiency for the photocathode at λ

$\bar{E}$ defined in Eqn. 1

For the comb source we are using there are roughly 1.2×10^4 photoelectrons per impulse. If the photons are distributed at the streak

camera output in a 2-D Gaussian distribution the areal density is as given in Eqn. 10,

$$\rho_{pe} = \frac{N_{pe}}{2\pi\sigma_s^2} \exp\left(-\frac{(x-x_0)^2}{2\sigma_s^2}\right) \exp\left(-\frac{(y-y_0)^2}{2\sigma_s^2}\right) \quad (10)$$

where ρ_{pe} = equivalent photoelectron density at the output
and $\sigma_{spatial} = \sigma_s$ is the standard deviation of the point spread
function at the streak camera output.

The peak photoelectron areal density for a 67 μm FWHM impulse is then 2.3 $\text{pe}/\mu\text{m}^2$. If the peak of an impulse was centered in a round pixel of radius r the signal in that pixel, or the equivalent number of photoelectrons in a single pixel, would correspond to

$$N_{eq} = N_{pe} [1 - e^{-r^2/2\sigma_s^2}] \quad (11)$$

This was obtained by integrating Eqn. 10. For a 13.5 μm radius pixel, roughly equivalent to a square pixel 24 μm on a side, this would be equivalent to having roughly 1200 photoelectrons in the peak pixel.

In Table 3, we compare the ratio, $[S/N]/N_{eq}$, to the values of S/N that have been obtained for three of the configurations fielded. The results for the three systems shown in Table 3 show that for the case where the MCPI is used the system gain should be adequate to resolve a single photoelectron if there were enough of them to be observed. In the case of systems without the intensifier 3 to 50 electrons are required to get a S/N of 1.

For the PI camera and the Nikon 1:1 lens, three times more sensitivity would be required to get a S/N of 1 in the peak pixel. The photometrics CCD showed a relatively poor sensitivity because the camera was purchased with a 12-bit digital to analog converter and the least significant bit is expected to be greater in amplitude than the equivalent in the PI camera. The PI camera is also back-illuminated and this expected to give a 2- to 4-times greater quantum efficiency. Together these account for the difference in S/N between the two CCD cameras.

The single-electron events may one day be observed in a frequency histogram of low amplitude events as is observed with photomultiplier tubes. Single photoelectrons are routinely used to determine the gain in

photomultiplier tube systems and to characterize dark current. We attempted to observe single electron events by generating a frequency histogram of the amplitudes in a streak. The integer amplitude features characteristic of multiple electron are not seen in the histogram of a single streak output shown in Fig. 15b. The lack of a single event history profile is not of great concern because in a single sweep there is not enough dark current or signal to generate a statistically significant number of single photoelectron events. By placing an adjustable attenuator in the fiber path and inducing a known number of single electron events we may be able to generate a near single-electron spectrum. We plan to attempt this in future calibration work.

A basic point is that if a single photoelectron is observable, then the only way to improve the sensitivity further is to increase the quantum efficiency. Further improvement in sensitivity might bring the signal farther out of the noise, but dynamic range may suffer as the amplitude per unit signal would be further increased.

Table 3. Comparison of the measured S/N ratio in the peak pixel to the number of photoelectrons estimated to be in that pixel. The numbers in the table represent the relative amplitude of a single photoelectron event compared to the system noise.

The equivalent fraction of a photoelectron in peak pixel, relative to the noise	Photometric CCD/Nikon w/o intensifier	Princeton Instruments CCD/Nikon w/o intensifier	Princeton Instruments CCD w/ intensifier @ 700v
$\frac{(S/N)}{N_{pe} \left[1 - e^{-r^2/2\sigma^2} \right]}$	$\frac{14}{878} = 0.02$	$\frac{200}{708} = 0.3$	$\frac{1200}{720} = 2$

Figure 15. a) Image of comb signal using PI camera with MCPI at 700 V. b) Frequency histogram of comb signal over area of 15a.

Possibilities for improvement

Spatial resolution

We were not able to determine the streak camera resolution limit to better than a factor of two because the source used was comparable in size to the best readout system resolution. An accurate determination of the streak camera's resolution will require at least a factor of two reduction in both the size of the source and the spatial sampling. However, the variations in photocathode sensitivity with position will make it difficult to quantitatively analyze data obtained where features of less than 50 μm FWHM need to be observed. In most cases this will not be practical since there are few sources this small. Readouts capable of high contrast, $\sim 50\%$ at better than 25 μm FWHM (40 lp/mm) and sample sizes, folded in with camera and lens resolution, of less than 12 μm will extract nearly all of the useful streak camera performance. To map 40 mm of source, corresponding to the sweet spot in the streak camera output, to 12 μm pixels would require a CCD of 3300 pixels square, this is near the limits of present technology.

However, both 1k x 1k CCDs and 2k x 2k CCDs will improve performance over what is routinely obtained with film and intensifiers at present.

Sensitivity and signal-to-noise

As a practical matter 2k x 2k pixel CCDs are becoming widely available with overall sizes of 2 cm to 5 cm. To compare different readout systems, we have prepared Table 4 which contains a few potential configurations and some estimated prices, as of fall 93. The costs do not include the cost of the streak camera itself. None of the options includes an image intensifier. High-throughput lenses or fiber optic coupling with near 1:1 magnifications would be attractive methods of coupling to the streak camera outputs with near-streak-camera-limited spatial resolution, high sensitivity and large fields of view. Equations 12 & 13 relate the system Nyquist limits, and the anticipated S/N to that of the PI/Nikon lens system (system 1 of Table 1).

$$\frac{S/N}{S/N_{PI/NK}} = \frac{(1 - e^{-\frac{r^2}{\omega_0^2}})}{(1 - e^{-\frac{r_k^2}{\omega_0^2}})} \frac{OT QE}{OT_{PI/NK} QE_{PI/NK}} \quad (12)$$

$$N_y = \frac{1}{(2 * \text{pixel size [mm]} * RED)} \quad (13)$$

Where OT is the overall transmission equal to the transmission through the lens times the collection efficiency, QE is the quantum efficiency of the CCD, N_y is the Nyquist frequency and RED is the reduction ratio of the lens.

Table 4 shows that streak camera limited systems can be assembled without image intensifiers. Note that the configuration numbers in Table 4 do not correspond to those of Table 1. Information from table 3 and Table 4 is plotted in Fig. 16. The configurations shown in the figure were chosen to provide a perspective comparing present capability with future possibilities. Configuration 2 is considered and displayed because we are purchasing a lens for this system. It has adequate resolution and sensitivity for our near-term purposes and if higher resolution is desired it can be used with CCDs that have smaller pixels and larger array sizes, this would correspond to configuration 3.

Note that in Fig. 16 the measured resolutions do not equal the Nyquist limit. The Nyquist limit represents the ability of the readout to sample the image and represents the limit of the recording system only. The measured FWHM includes pixel size, lens magnification and streak camera performance. The system resolutions, where we have data, do not equal the Nyquist limit after correction for source size. This is likely due to some combination of width due to the CCD/lens PSF and the source PSF.

Table 4. Design estimates of readout system configurations for future work.

#	pixel size/ QE	overall transmission/ magnification	Nyquist limit @streak camera [lp/mm] from eqn.7	Amplitude of a single photoelectron w/r/t noise. Scaled from PI camera w/Nikon lens. *=measured	Estimated cost - optic + CCD (k\$)
1*	24 μ m/0.8	0.049/1	21	0.3*	35+10, FOV=24mm
2	24 μ m/0.8	0.07/1.67	12	0.72	30+35
3	12 μ m/0.8	0.07/1.67	25	0.2	30+45
4*	20 μ m/0.2	0.048/2.5	10	0.02*	30+30
5	24 μ m/0.8	0.5/1-taper	21	5	120,if possible

* Data discussed earlier in paper.

Figure 16. Diagram of different configurations with respect to streak-camera-limited operation. Predicted performances from table for use the Nyquist limited FWHMs. Experimental points are displayed raw and corrected for 34 μm source size. The number between the measured and corrected points refers to the configuration as described in table 1.

In considering Fig. 16, none of the systems will be streak camera limited in performance, but a 1:1 taper coupled to a 2k x2k CCD comes very close. This system would provide a factor of nearly 2 improvement in spatial resolution over those now used and much improved performance in the tails of the PSF over the intensified systems and film based systems now in use.

Summary and conclusions

The film-based systems are clearly limited to lower dynamic ranges and poorer resolution than are obtainable with the CCD systems. The film also adds artifacts to the data and adds unfolding steps to the analysis procedure. Where possible solid state readouts should be employed. The added expense of the solid state recording need to be weighed against the advantages of immediate access to the data, simplified analysis (meaning time) and the improvement in diagnostic performance.

The intensified CCD systems are able to see near the photoelectron limited noise level and operate equally well at 700 V or 900 V. The intensifier had no notable effect on the FWHM resolution at nominally 10 lp/mm, however it did cause changes in the tails of the distribution.

For best dynamic range, we recommend operating the intensifiers at 700 V if an intensifier is used on a CCD recording system. In addition there is evidence that the intensifier both adversely affects the reproducibility of the signal amplitudes and at higher resolutions it will cause broadening of an impulse.

Near streak-camera-limited performance in resolution and sensitivity may be obtained using large-format CCDs and fiber-optic coupling. With our available hardware, however, light-level-limited instruments require MCPs to provide extra sensitivity.

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