The streak camera development program at LLE

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ABSTRACT

The Diagnostic Development Group at the Laboratory for Laser Energetics has endeavored to build a stand-alone, remotely operated streak camera with comprehensive autofocus and self-calibration capability. Designated as the Rochester Optical Streak System (ROSS), it is a generic streak camera platform, capable of accepting a variety of streak tubes. The system performance is limited by the installed tube's electron optics, not by any camera subsystem. Moreover, the ROSS camera can be photometrically calibrated.

Key words: Streak camera, ultrafast detector

1. INTRODUCTION

The Laboratory for Laser Energetics operates the OMEGA laser system to conduct implosion and basic physics experiments in support of the National Inertial Confinement Fusion (ICF) Program. OMEGA's 60 laser beams focus 30 kJ of energy onto a millimeter-diameter target in approximately a nanosecond. To further our understanding of the laser–matter interaction, many of the laser and target diagnostics incorporate streak cameras, making use of their high bandwidth and the multiple channels of information that can be dispersed along the input slit.

As recently as 20 years ago, a streak camera–based diagnostic at LLE required a dedicated, full-time person to oversee its operation, data acquisition, and calibration. Since then, a significant streak camera–development program at LLE has built comprehensive, stand-alone systems that require minimal intervention by people. The performance requirements of the streak cameras have also been enhanced commensurate with the 60-beam OMEGA laser upgrade. The experiments conducted at LLE now demand quantitative, high-precision (peak SNR >100), large-dynamic-range (>1000) measurements. Three key innovations have been implemented into our cameras that now allow us to achieve our goal: (1) a recording system consisting of a large-format, scientific-grade CCD camera without an image intensifier; (2) remotely programmable, high-stability, closed-loop voltage control for all electrodes; and (3) slow ramps and internal light sources for calibrations. The increasing quality and reliability of solid-state electronics have made it possible to build our cameras with long-term stability.

Six optical streak cameras have been operated for the past five years as part of LLE's UV power balance diagnostic.[1] In addition, two other cameras have diagnosed the laser system's driver lines. All of these cameras use a P510 streak tube with either an S-20 or S-1 photocathode. The total number of target shots during this period exceeds 6000, plus each of the cameras has accumulated over 60,000 streaks for system calibration in support of the data analysis. The reliability of these cameras exceeds 99.9%. By monitoring voltages and looking for anomalous changes in the calibration data sets, we can generally spot a faulty or suspect component and replace it before total failure. The camera's modular design allows maintenance to be completed between laser shots (typically every 45 min). The most common reasons for missing data can be attributed to the OMEGA laser system, e.g., a mistimed trigger from the hardware timing system or the control system not arming the cameras prior to a shot.

These eight streak cameras have provided a remarkably successful test bed for our concept of a complete camera system. Over 500,000 streak records have been acquired to prove the technology and to demonstrate its reliability. The quality of the data has enabled the OMEGA system to realize high precision laser pulse shaping and to achieve 60-beam power balance at the $\sigma_{\text{rms}} < 2\%$ level. As our understanding of what it takes to make SNR >100 measurements grew, so did our list of system upgrades. The range of streak camera measurements that scientists at LLE wished to make also grew during this time, specifically improving time-resolution capability to 1 ps. This is not achievable with a P510 streak tube. About two years ago we embarked on a project to build a generic streak camera that could accept other streak tubes and where we would implement our list of subsystem upgrades. Our success with streak cameras had generated significant interest from other ICF laboratories; therefore, the redesign and packaging were also directed toward commercialization. Recently a technology transfer license was negotiated with Sydor Instruments[2] of Rochester.

2. ROCHESTER OPTICAL STREAK SYSTEM

The Rochester Optical Streak System (ROSS) is our new camera, designed and built at LLE with some mechanical and optical engineering support from LLNL. One of our design goals was to build a camera whose performance was limited by the streak tube's electron optics. The camera also had to accept a variety of streak tubes and is currently set up for the P510, P820, and PJX tubes, all from Photonis.[3] The design is general enough that any tube with an outer diameter <5 in. can be packaged into the camera. We also anticipated that the camera may be located in relatively inaccessible places and therefore should be fully operational from a remote site. The autofocus and self-calibration features ensure optimized system performance in advance of the shot.

A picture of the ROSS camera without the optics module is shown in Fig. 1. The streak tube is in the upper half, with the electronics in a drawer in the bottom half. All fiber-optic input signals and electronic services are through the back panel of the ROSS. The camera dimensions are 7 in. wide × 21 in. long × 12 in. high. The optics module will increase the width to 10 in. and the length to 26 in. The streak tube is potted into a closed-end, cylindrical, mu-metal shell for EMI shielding. The CCD recording system is also enclosed in the mu-metal shield. Small apertures are available in the front end-cap for signal input, in the middle of the cylinder for streak tube wiring, and in the rear end-cap for CCD controls.

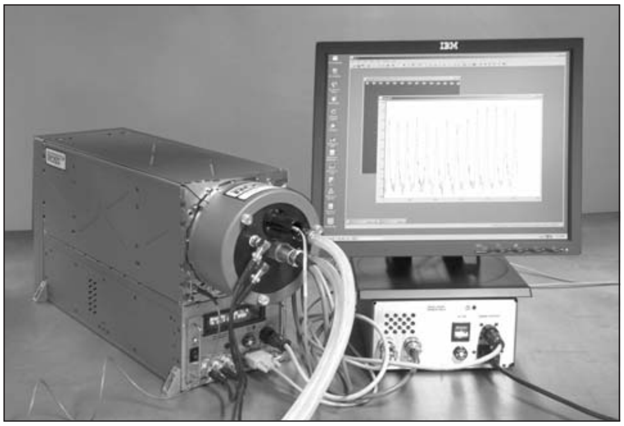
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Fig. 1. A view of the ROSS camera without its optical/calibration module. All fiber-optic input signals and electronic services are through the back panel. The camera dimensions are 7 in. wide × 21 in. long × 12 in. high.

The input optics remain an achromatic Offner triplet mirror system as presented in Fig. 2. The spherical Al-coated mirrors are readily available, and the system runs at *f*/2.5. A field-flattening lens is added for use with streak tubes that have a curved photocathode plane. This can also serve as the substrate for an antireflection coating for the streak tube window. There are two object planes in our design. An air path for coupling in signals from external sources can be selected with a flip-in mirror, or one can use the homogenizer arrays (Fig. 3) for fiber-optic signals and the

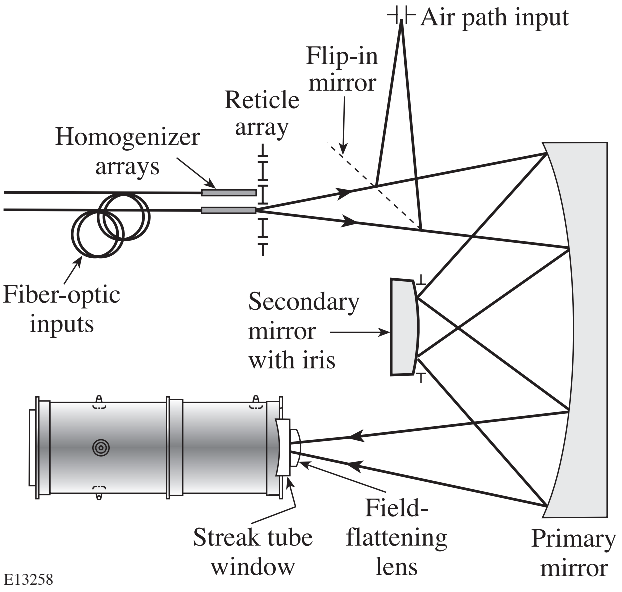

Fig. 2. The input optics is an achromatic Offner triplet system that uses spherical Al-coated mirrors and operates at *f*/2.5. An air path for coupling in signals from external sources can be selected with a flip-in mirror, or one can use the homogenizer arrays for fiber-optic signals and the internal calibration sources. Autofocus functionality is obtained with motorized stages for translation and rotation of the relevant components.

internal calibration sources. Autofocus capability has been added by building the components on motorized stages. Both the air path and homogenizer array inputs have two translational, as well as one rotational, degree of movement. The secondary mirror controls have three degrees of movement and the iris in front of it is also motorized. The air-path input has a remotely adjustable slit width. The fiber-optic input has an array of up to ten discrete masks or reticles that can be placed at the homogenizer output plane to be relayed to the photocathode. Finally, three independently timed shutters are available to control signal access to the photocathode. The optical performance of the Offner triplet must exceed that of the streak tube's electron optics. Modulation-transfer-function (MTF) calculations for our selection of streak tubes are presented in Table 1. This optical setup provides us the means to verify that the system is properly focused and to re-optimize for best spatial or temporal resolution at a specific photocathode position.

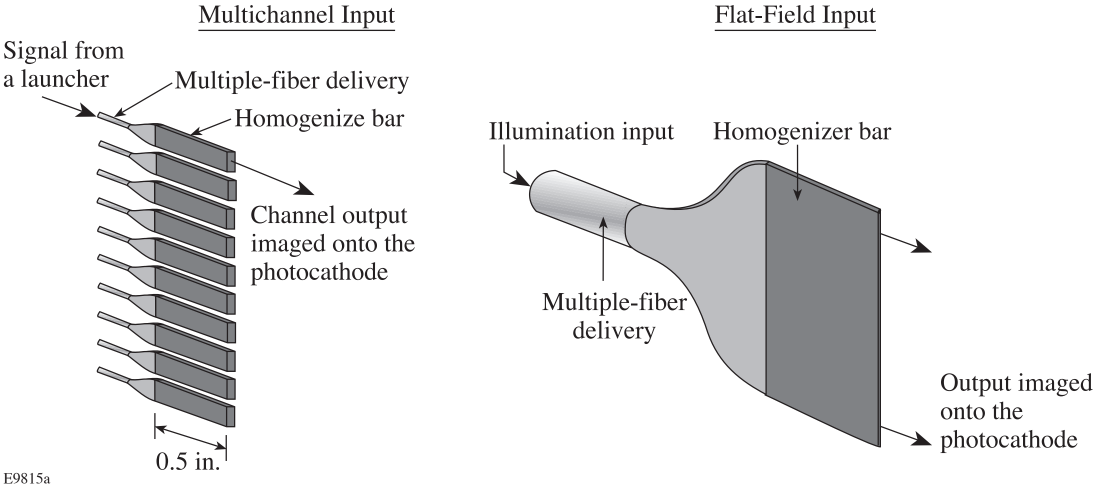

Fig. 3. Solid glass homogenizer bars (four-mirror kaleidoscopes) are used to form uniform illumination profiles that are relayed to the photocathode.

Table 1: Offner triplet modulation-transfer-function calculations.

Streak tube	**Photocathode**	**Primary**	**MTF @ *f*/2.5**	**MTF @ *f*/5.0**
P510	22.0 mm	R = 140 mm	79% @ 10 lp/mm 60% @ 15 lp/mm	91% @ 10 lp/mm 84% @ 15 lp/mm
P820	10.0 mm	R = 140 mm	77% @ 20 lp/mm 52% @ 40 lp/mm	91% @ 20 lp/mm 81% @ 40 lp/mm
PJX-std.	60.0 mm	R = 160 mm	63% @ 5 lp/mm 28% @ 8 lp/mm	91% @ 5 lp/mm 79% @ 8 lp/mm
PJX-inv.	6.0 mm	R = 160 mm	79% @ 40 lp/mm 69% @ 60 lp/mm	84% @ 40 lp/mm 75% @ 60 lp/mm

The ROSS goal of SNR >100 motivated the repeatability and stability specification for the streak camera electronics. The electronics are modular in design with the components packaged into mu-metal boxes. This enhances their EMI immunity from external sources and as an EMI source in proximity to the streak tube's electron optics. The camera operates from an external, well-filtered, and regulated +28-V dc supply. All streak tube electrode and ramp supply potentials are under closed-loop voltage control through a 24-bit ADC and a 16-bit DAC circuit that provides better-than-0.02% voltage stability. Long-term repeatability is ensured through high-precision, temperature-stabilized voltage references. All voltages are remotely monitored and programmable. Great care was taken with high-voltage isolation since a little static discharge at shot time could easily degrade the electron optic focus or void the system calibration. A number of 1-ms-resolution timer circuits are available for controlling shutters and CCD exposure timing. Shutter openings are monitored with miniature LED-photodiode pairs. Each of four remotely selectable sweep speeds has a retrace hold-off time of 30 ms to allow for closure of one of the input shutters. The basic sweep circuit is a MOSFET/avalanche transistor stack.[4] Presently, the fastest sweep duration is 1 ns. Thermocouples are used throughout the electronics enclosures to monitor the temperature; an anomalous change would be indicative of a potential component failure. System control is via a serial link to a PC.

The recording system consists of a Spectral Instruments[5] 800 Series camera incorporating a fiber-coupled E2V[6] 42-40 back-illuminated CCD. The CCD is mated to the streak tube's fiber-optic faceplate without any additional image intensifiers. The large-format CCD (2048 × 2048 pixels @ 13.5 μm square) allows us to use a 1:1 fiber stub and avoid the losses associated with a fiber taper. The CCD read noise at a 200-kHz readout rate is $\sigma_{\mathrm{rms}} < 5$ electrons. The dark current at our –40°C operating temperature is <0.025 electron/pixel/s. This allows us to take the 20-s exposures that are required to reduce the phosphorescence to acceptably low levels on very-large-dynamic-range streak images. CCD gain is measured with a standard variance-mean plot, and the camera linearity is verified to be better than 0.5% with a simple ratio test. The CCD camera is powered from the ROSS +28-V supply, but its control and data link is via fiber, independent of the rest of the camera controls.

A very important factor in the recording system is the choice of material for the fiber stub to which the CCD is bonded. Typically, the core-area ratio for fiber stubs is in the 60% to 75% range, and with an NA = 1.0 fiber, 25% to 40% of the light from the phosphor is not guided properly as part of the image relay. If the nonguided light is not absorbed before it reaches the CCD, the point and line spread functions (PSF and LSF) can be expected to sit on a low-level pedestal. Although this may be difficult to observe in the PSF, the magnitude of the pedestal may compromise the LSF below the 0.1% level. Certainly we have noted a significant wing on the edge spread function (ESF) of a poor fiber stub. The amplitude of the wing can be at about the 1% level and extend for many millimeters across the CCD. Our choice of material is Incom[7] BPLSE-6. The fiber stub is 50 mm in length to support the

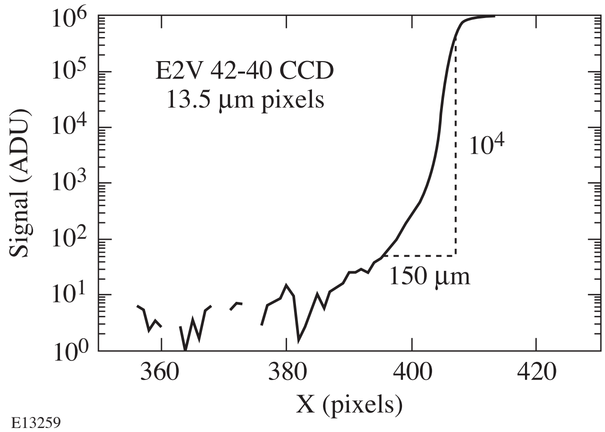

Fig. 4. A Spectral Instruments CCD camera with a 1:1 fiber stub (material is Incom BPLSE-6) produces a sharp ESF, dropping four decades in 150 μm.

temperature gradient. A plot of the CCD camera's ESF is shown in Fig. 4. The leading edge of the laser pulse recorded in our multichannel mode and the channel crosstalk are examples where having a sharp ESF is most important.

We have measured the streak camera gain as the number of CCD electrons recorded per single-electron events hitting the streak tube phosphor.[8] We used superpixel histograms of sparse streak records to generate the pulse-height distribution for detecting single electrons (see Fig. 5). Measured gains are in the range of 108 to 150 CCD electrons per 15-kV streak tube electron, and the noise factor is only 1.17. These measurements validate that the ROSS camera recording system can detect single-electron events with an SNR of 2 to 3 and is superior to a system employing an MCP-based image intensifier that has a noise factor >2.0. The spatial resolution of our system is also better than a system that includes any type of image booster or intensifier.

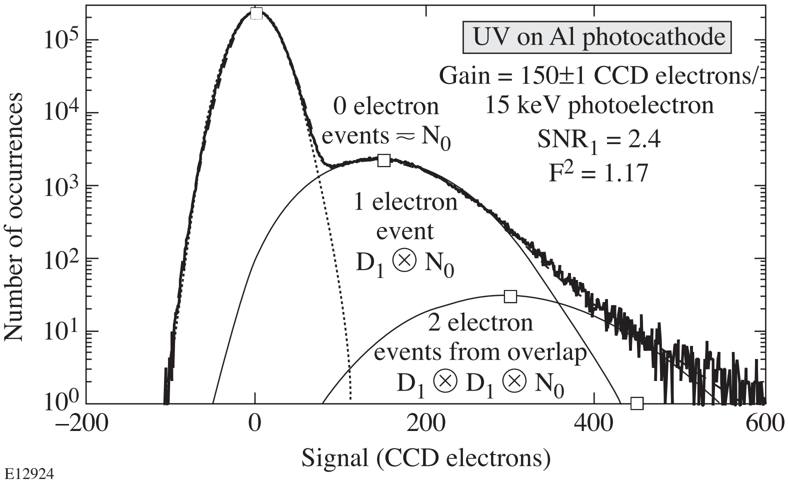

Fig. 5. The superpixel histogram of sparse streak records generated by UV light on an Al photocathode is fit by the sum of the pulse-height distribution for recording 0 to 3 electron events. N_0 is the Gaussian read noise. $D_1(S)$ is the single-electron distribution fit by $S \times \exp[-(S-\mu)^2/2\sigma^2]$, $\mu = 99$, and $\sigma = 76$. The small D_2 and D_3 components are from overlapping events. The symbol ⊗ denotes convolution.

3. CALIBRATIONS

Quantitative analysis of streak data beyond an SNR ≈ 10 requires an extensive set of camera calibrations. Foremost among these is flat-fielding the system response on a pixel-by-pixel basis. The SNR of the flatfield image should be at least ten times better than the SNR of the data set to be analyzed to avoid degrading the data. Since the SNR of a single flat-field image can be no better than the best data image if they are acquired with the same streak duration, hundreds of flat-field images must be collected and averaged to achieve the requisite SNR. There are two major problems with attempting flat-field calibrations with a nominal 10-ns streak duration. First, charge depletion at the photocathode would limit operation to photoelectron currents well below the tube's peak current capability. Second, it is immensely difficulty to produce a short-duration, high-brightness, and constant-amplitude light source.

Flat-field calibrations at LLE are done using slow sweep ramps[9] with typical durations of 1 to 10 s. A dc–dc converter driven with a variable time and amplitude step DAC is used to generate the slow ramps. The validity of the slow-ramp, flat-field technique is based on the fact that the system response (which includes the input optics, photocathode quantum efficiency, photoelectron throughput, phosphor conversion efficiency, fiber-optic transmission, and CCD quantum efficiency) is not dependent on the rate at which the image is acquired. We use simple LED's operating in cw mode, gated with mechanical shutters as our constant amplitude light source, and homogenizer bars to obtain spatial uniformity. Alternatively, a white-light source and an interference filter can be used to match the spectral region of interest. The uniformity of the source in space and time can be verified by comparing images taken under various conditions. Neither a shift of the homogenizer bar spatially nor a change in the initial bias voltage on the deflection plates should change the flat-field calibration. A photocathode current of 100 pA is sufficient to generate a signal approaching full well (FW) in each pixel of our 4M-pixel CCD in a 5-s-duration slow sweep. Thus the number of flat-field images that must be averaged is reduced to about 10, given that typical streaks have peak signals <10% FW. The streak tubes from Photonis for the ROSS camera have been customized to include an electron dump in front of the phosphor screen. This is a simple baffle to block photoelectrons from scattering off any internal structures to the phosphor when the beam is biased off-screen. This is especially important for the flat-field calibrations that do have large signals at the edges of the image.

Geometric distortions in the streak image are very easily mapped with the slow-ramp feature of the ROSS camera. The spatial profile from the flat-field homogenizer can be modulated with a reticle, and the LED light source can be electrically modulated to produce a slow scan image with a grid pattern of about 30 × 30 distinct points. Our standard unwarpping algorithm includes fitting a 2-D polynomial to the centers of the grid points, followed by a coordinate transformation (that includes the Jacobian for the area correction).

Streak speed calibrations are also self-contained in the ROSS camera. We have included a comb generator—a few-microsecond-duration train of pulses from a laser diode. The four discrete comb frequencies are selectable in the range of 100 MHz to 10 GHz. Each frequency is stabilized to $1{:}10^5$. The comb can be directed to a combination of homogenizer channels through a sequence of fiber-optic splitters. It is important to calibrate the streak speed at all spatial locations in the image as it can easily vary by more than 1% due to the fringing fields at the edges of the deflection plates or more commonly by mechanical misalignment of the plates. The ROSS camera also includes a fiber-optic spigot to inject an external comb pulse.

Detailed quantitative data analysis must also include knowledge of the PSF, LSF, and ESF at all locations in the image. We have incorporated this capability into the ROSS camera. The necessary tools are an internal light source, a selection of reticles to produce the desired spatial profile, and programmable voltage control; all are built into the system. Further, one can verify or adjust the electron optic focus with the available controls. An example of optimizing the temporal resolution of the P510 tube in a specific region of interest (ROI) is presented in Fig. 6. The

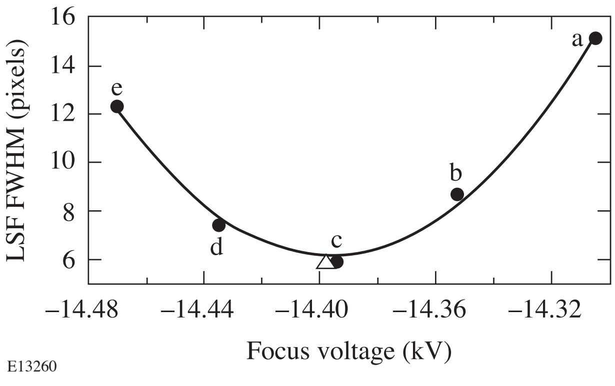

Fig. 6. The temporal resolution of the P510 tube can be optimized in a specific region of interest by collecting a sequence of LSF images while varying the focus voltage. The measured FWHM data points versus focus voltage are well fit by a parabola as expected from the field curvature aberration.

procedure is simply to collect a sequence of LSF images while varying the focus voltage. The FWHM in the ROI is calculated and plotted versus focus voltage. The data points are well fit by a parabola as expected from the field curvature aberration.

4. DISCUSSION

We have designed and built a comprehensive streak camera, ROSS, with full autofocus and self-calibration capability. All of the scientific and engineering concepts have been tested and validated on our eight prototype cameras over the last five years. The ROSS camera is mostly a re-packaging of proven technology with a few subsystem upgrades to complete full operation from remote sites. This alleviates all concerns regarding maintaining calibration to the 1% level as the camera is moved about the facility. An evaluation of the ROSS camera with a P510 tube was performed at LLNL with very favorable results.[10] We will continue our research into large-format, high-current-handling-capability streak tubes for the ICF Program, but, in the short term, we will focus on improving our time resolution to the subpicosecond regime.

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