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FAST IMAGING APPLICATIONS IN THE NUCLEAR TEST PROGRAM

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FAST IMAGING APPLICATIONS IN THE NUCLEAR TEST PROGRAM

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Abstract

Applications of fast imaging employ both streak cameras and fast framing techniques. Image intensifier tubes are gated to provide fast two-dimensional shutters of 2-3 ns duration with shutter ratios of greater than 10^6 and resolution greater than 10^4 pixels. Shutters of less than 1 ns have been achieved with experimental tubes. Characterization data demonstrate the importance of tube and pulser design.

Streak cameras are used to simultaneously record temporal and intensity information from up to 200 spatial points. Streak cameras are combined with remote readout for downhole uses and are coupled to fiber optic cables for uphole uses. Optical wavelength multiplexing is being studied as a means of compressing additional image data onto optical fibers. Performance data demonstrate trade-offs between image resolution and system sensitivity.

Introduction

Imaging is used in underground nuclear testing to study implosion symmetry and burn efficiency of fission or fusion devices. The imaging system is actually a very large pinhole camera, as shown in Fig. 1. The size, shape, and symmetries of a radiation-emitting volume are measured by imaging the radiation through a 20-in.-long steel "pinhole" and onto a plastic fluoro. The pinhole design is diagrammed in Fig. 2. The image from the fluoro is captured by unique, fast TV cameras, then digitized and transmitted uphole to be stored in computer memories. The digital data are combined with calibration information to produce pictures that show the size, shape, and density distribution of fission or fusion materials. Imaging experiments can resolve x-ray, gamma ray, fission neutron, or fusion neutron images to 0.10 mm. Images from the different types of radiation can be separated by filtering to remove the undesired radiation species or by use of time-of-flight techniques in which cameras are shuttered on only

FIG. 2. The pinhole assembly formed in a 20-in.-long steel block. The central element is 0.004-0.025 in. ID by 0.250 in. OD and 1-3 in. long. This portion is formed of a solid piece of gold and controls the experimental resolution. The remainder of the assembly controls the image contrast by following, in a stepped manner, the penumbra established by the central element.

during the arrival of the desired radiation species. The image is integrated during the entire device history.

Various forms of time-dependent imaging are also becoming an important part of the diagnostics used in underground nuclear testing. Time-dependent imaging applications include both measurements of material motion and spatially resolved time-of-flight measurements from which spatially resolved fusion temperatures are determined. These applications combine pinhole imaging either with fast framing cameras that use nanosecond camera shutters or with streaking cameras. Digital or analog fiber optic data links are also frequently an integral part of time-dependent imaging experiments. This paper will discuss some of the experiments and hardware used by the Nuclear Test Program.

Fast Framing Cameras

Fast framing camera applications require shutter times ranging from 1 ns for material motions studies, to 500 ns for some neutron time-of-flight applications. Performance requirements for these camera shutters are shown in Table 1.

This desired performance is achievable with gated (pulsed biased) wafer-type microchannel plate image intensifier tubes. These tubes consist of a photocathode, which is proximity-focused to a microchannel plate (MCP) electron multiplier, which is in turn proximity-focused to a phosphor screen (Fig. 3). Optical shuttering is achieved by pulse biasing either the photocathode-to-microchannel

FIG. 1. PINEX (PINhole EXperiment) focused radiation from a nuclear source through a "pinhole" and onto a plastic fluoro. Light from the fluoro is focused onto special high-speed TV cameras, which digitize the data downhole and send them uphole to be stored in a computer memory. The data are later combined with calibration data to produce a quantized image.

Table 1. Shutter performance requirements.

Spatial resolution	$> 10^4$ pixels
Temporal resolution	1 ns to 500 ns
Optical gain	10^3
Shutter ratio	$10^6:1$
Dynamic range	$> 200:1$ linear
Response uniformity	No dynamic distortion
Spatial distortion	No dynamic distortion

FIG. 3. Image intensifier tubes. The tube is gated by reverse biasing between the photocathode and the microchannel plate, then supplying a pulsed forward bias voltage.

plate or the MCP itself. We have experimented with gating the photocathode in both a coaxial termination geometry and in a microstripline transmission geometry.

Optical Shutter Characterization

Figure 4 is a diagram of the laboratory we use to characterize these shutters. An Electro-Photonics Limited flashlamp pumped-dye laser is passively modelocked to provide a train of 100–200 laser pulses, each separated by 5 ns. Each pulse has a duration of approximately 15 ps with an output wavelength centered at 600 nm. The ratio of the selected pulse to a nonselected pulse is approximately 400:1. Part of the energy of the selected pulse is split off and used both to generate the trigger signal for the pulser driving the intensifier tube and to provide a monitor of the laser output to ensure proper laser performance. In this way, the electrical pulser used to gate the tube is synchronized to the selected laser pulse. The remainder of the laser pulse is sent through an optical delay before being directed to the photocathode of the intensifier tube. The laser pulse is walked through the optical gate in steps of 100 ps by varying the length of the optical delay path. At each step, the output from the intensifier tube phosphor is recorded by a solid-state camera built around the Reticon 100 × 100 array. The camera is fiber-optically coupled to the phosphor faceplate of the intensifier tube. The output of the camera is digitized and sent to a Digital Equipment Corporation LSI-11 minicomputer, where the recorded image is saved on disk. Image-processing routines are used to analyze the data and to determine the performance parameters of the optical shutter.

When possible, the light level input to the tube is adjusted to produce at least 100 counts above background on the recording camera in order to achieve a system-dynamic range (maximum recordable signal/minimum recordable signal) of at least 100:1. The total optical gate length is defined as the time from when the output from the intensifier tube can first be detected above the camera noise to when the intensifier tube output is down to a level that cannot be distinguished from the camera noise. The turn-on time is defined as the time from detection of the output at the edge of the intensifier tube to the time when the output from the center of the tube is the same intensity as the output at the edge. The turn-off time is defined as the time from the beginning of drop-off of the output at the edges of the intensifier tube to the time when the intensifier tube is completely off.

Resolution is measured using a 100% contrast target in contact with the fiber-optic faceplate of the intensifier tube. To ensure uniform input, a milk glass diffuser is placed approximately 6 in. in front of the photocathode of the intensifier tube. A CTF (contrast transfer function) value is then read off the intensity profile of the digitized image recorded by the Reticon camera.

FIG. 4. Diagram of the characterization setup used to characterize the temporal and spatial performance of MCP intensifier tubes.

Electrical Pulsers

Fast electrical pulsers are needed in order to quickly gate intensifier tubes.¹ Applications involving 1–5 ns optical gates require very low jitter. An ideal photocathode pulser would be capable of supplying 100–200 V into a low impedance (approximately 17 ohms) with a rise and fall time of 200–300 ps, would have a full width at half maximum (FWHM) of approximately 500 ps, and would exhibit 30-ps jitter.

Avalanche transistors, or avalanche transistors combined with step recovery diodes, are used to provide the electrical gate pulse for photocathode gating. Voltage pulses of 200 V with a rise time of 1.1 ns can be generated by Raytheon RS 3500 avalanche transistors in a charge-line pulse. Step-recovery diodes can be used to sharpen the rising and falling edges of the pulses.² A pulser manufactured by Power Spectra, Inc. (formerly Picosecond Enterprises, Inc.) delivers 170 V with a rise and fall time of 500 ps into a 17-ohm microstrip transmission line. We have used especially packaged step-recovery diodes to deliver 200-V pulses with a 300-ps rise time and a 450-ps fall time into a 50-ohm load. We are continuing with further repackaging to reduce package capacitance and inductance and to provide a better impedance match between the diode package and the microstrip transmission line.

The photoconductive switch is another currently available technique to produce voltage pulses of several hundred volts or even kilovolts, with rise and fall times on the order of a few hundred picoseconds.^{3–6} However, a laser that is capable of providing several microjoules is needed for driving the switch. Such systems are not suited for field applications, where portability and reliability are essential, although they are useful for laboratory evaluations. Photoconductive switches may find future uses in the field if laser diodes can be made to drive them.

Characterization Results

Figure 5 shows the results of gating an 18-mm intensifier tube that has a standard S20 photocathode. The picture in the upper left corner shows the electrical driving pulse; the other pictures show the intensity recorded along a diameter of the tube at various times during the optical gate. The photocathode was reverse biased to +50 V, and a -200 V pulse with an FWHM of 38 ns was applied in a termination

FIG. 5. Measured optical gate of an 18-mm intensifier tube with a standard S20 photocathode. The first picture is the electrical pulse measured into 50 Ω . The electrical pulse had a peak voltage of 200 V with an FWHM of 38 ns. The intensity profiles show the recorded intensity across the diameter of the phosphor output of the intensifier tube as a function of time. Note that the intensity of the input light was increased at 75 ns into the gate. As can be seen, the optical gate is much longer than the electrical driving pulse.

geometry. The highly resistive surface of the photocathode produces an "iris" effect as the electrical pulse propagates across its surface. The intensifier tube responded with a turn-on time of 40 ns, a full-on time of 35 ns, and a turn-off time of 45 ns, thus producing a total optical gate of 120 ns. If the FWHM of the electrical pulse is decreased to 10 ns, this intensifier tube never fully turns on in the center (Fig. 6).

When an ITT Model F4111 18-mm intensifier tube that contains a metallic undercoating on the photocathode is used, the length of time for the electrical pulse to propagate from the edge to the center of the tube is greatly reduced. Figure 7 shows both the electrical pulse, which was coupled to the tube in a termination-type coupling, and the measured intensity profiles of an ITT F4111 intensifier tube with an undercoating of twice the standard thickness. When a -150 V pulse with a 2-ns FWHM was applied, the intensifier tube responded with a turn-on time of 0.4 ns, a full-on time of 3.4 ns, and a turn-off time of 0.5 ns, giving a total optical gate of 4.3 ns.

We compared the termination coupling with the microstrip transmission line coupling method. The same tube described in Fig. 7 in a termination coupling was also mounted in a 17-ohm microstripline pulser. The voltage pulse was adjusted to give approximately the same peak voltage and FWHM as were used in the termination geometry. Figure 8 shows the electrical pulse and measured intensity profile for

the microstripline geometry. A total optical gate of 2.9 ns was obtained at a resolution of 40% CTF at 3 lp/mm. This performance is compared with the 4.3-ns shutter obtained in the termination geometry. When the electrical pulse width was shortened to 1.2-ns FWHM with 50 V cross-over width of 1.5 ns, the total optical gate decreased to 1.9 ns as shown in Fig. 9.

We also tested a specially modified intensifier tube from Varo Corporation that had all of the photocathode except for a 3-mm $\times$ 18-mm strip masked off by a heavy metal undercoating. The tube was mounted in a microstrip transmission line geometry, and the electrical pulse was adjusted to give -120 V with an FWHM of less than 1 ns when measured across the photocathode of the intensifier tube. This arrangement produced an optical shutter of 1.4 ns with a resolution of 3 lp/mm at 45% CTF.

When the back bias was raised to 110 V, so that the forward-driving bias to the tube was only 10 V, a total optical gate of less than 1 ns was obtained with a CTF of 38%. Figure 10 shows the results of this test. No iris effect was observed, and the shading distortions were constant throughout the gate time.

The linearity of the camera system has been measured for optical gate widths from 4 to 250 ns. In all cases, at wavelengths ranging from 380 to 700 nm, the camera responded linearly over a range greater

FIG. 6. Measured optical gate of an 18-mm intensifier tube with a standard S20 photocathode in which the electrical pulse is not long enough to allow the intensifier tube to fully turn on in the center. The electrical pulse had a peak voltage of 190 V and an FWHM of 10 ns. In this case, the turn-off proceeds from the center to the edges, whereas the turn-off of a fully turned-on tube proceeds from edge to center.

FIG. 7. Measured optical gate of an 18-mm intensifier tube with a metallic layer under the photocathode. The "iris" effect is greatly reduced because of the lower surface resistance of the photocathode.

FIG. 8. Measured optical gate when gating an intensifier tube in a microstrip transmission line arrangement. The upper-left picture is the measured electrical pulse after passing over the photocathode. The pictures that follow show the measured intensity profiles as a function of time.

FIG. 9. Measured optical gate when gating an intensifier tube in a microstrip transmission line arrangement with the electrical pulse adjusted for the shortest possible pulse width.

FIG. 10. Measured results of the gating performance of the modified intensifier tube when gating the intensifier tube in a microstrip transmission line geometry with a 110-V back bias. The last picture shows the resolution of 3 lp/mm at 38% CTF.

than 200:1. This linearity indicates that the microchannel plate is not being depleted of its charge when the intensifier tube is subjected to pulsed light. Figure 11 is a typical plot of the measured linearity of the intensifier-camera combination. The system saturated at 73 pJ/cm^2 into the photocathode.

FIG. 11. Measured camera linearity of a Reticon 100×100 camera with a gated MCP intensifier tube fiber-optically coupled to the array. The camera saturated at 73 pJ/cm^2 . The output responded linearly with light input levels.

Uniformity vs time for a typical ITT F4111 tube is shown by the isometric plots in Fig. 12. The shading is believed to result from the irregularities in the resistivity of the photocathode undercoating. Both this nonuniformity and the gating time demonstrate that reducing the photocathode surface resistance is essential for fast gating. The surface resistance of S20 photocathodes has been measured to be approximately 10^3 ohms/square .⁷

FIG. 12. Isometric plots of a gated MCP intensifier tube vs time show very little nonuniformity vs time, except for the iris effect.

One of the best prospects for a fast optical gate is the third-generation GaAs photocathode intensifier tubes.⁸⁻¹⁰ The resistivity of GaAs photocathodes has been reported to be less than 0.01 ohms/square , thus making it highly suited for fast gating. Preliminary results of gating these tubes confirm that optical gates with a total duration of 1 ns and no iris effect are achievable.

Downhole Streak Camera Applications

SPARTEX (SPATIally Resolved Temperature EXperiment) is an experiment that measures the spatial dependence of temperature within a fusion cavity. SPARTEX uses the same "pinhole" imaging techniques as described above to image ionizing radiation onto a plas-

tic fluorescer. The image from the fluor is focused onto a two-dimensional image-dissecting fiber-optic array that delivers the light signals to the input of a streak camera as a one-dimensional array, as shown in Fig. 13. The time dependence of each spatial point is recorded to an accuracy of 1 ns by a streak camera TV camera system, which digitizes the data and transmits them to an uphole computer memory for storage. The fluor is positioned at least 25 m from the device so that time-of-flight techniques can be used to record the neutron spectral output from these resolved spatial points. Each streak camera records the neutron time-of-flight spectrum for as many as 200 spatial points. From these data, a temperature is calculated for each point. The resultant profile of temperatures within the fusion cavity gives information about device efficiency and implosion symmetries.

FIG. 13. SPARTEX (SPATIally Resolved Temperature EXperiment) uses the same pinhole imaging techniques as PINEX. Light from the fluor is focused onto a special fiber optic image disector, which converts the two-dimensional image into a line image to be delivered to a streak camera. Each resolvable point records a neutron time-of-flight spectrum from which a local plasma temperature is calculated.

We are also developing a tomographic experiment to be used with streak camera recording. Special optics will compress the image to a line. The compression will be done from several angles through the image, and all of the compressions will be recorded on a streak camera. An algorithm will be used to reconstruct a two-dimensional image at many different times along the streak camera record. A slow-motion movie can then be reconstructed from these images.

Streak Camera Design and Performance

The streak cameras used in these experiments are constructed around the RCA73435 AK and AJ series streak tubes, which have an S20 photocathode and a P11 phosphor. The extraction grid in this tube is pulse-biased as a grating grid to improve the extinction ratio of the camera. The streak tube is fiber-optically coupled to an ITT 40-mm microchannel plate image intensifier tube, which has an S20 photocathode and a P20 phosphor. The image intensifier tube serves to adjust the sensitivity of the streak camera and to shift the output wavelength of the streak camera to better match with the Si response of the recording TV camera system. Details of this digital streak camera system are described in Table 2.

The dynamic range of the system is limited to approximately 200:1 by the eight-bit digitizer of the TV camera. The spatial resolution of the system is limited by the Nyquist limit of the TV camera to

Table 2. Digital streak camera components.

Streak tube	RCA 73435AK&AJ
Photocathode	S20
Phosphor	P11
Image intensifier	ITT MCP
Photocathode	S20
Phosphor	P20
Maximum gain	10^4
Readout camera	Fairchild CCD
Spatial resolution	244 contiguous pixels
Temporal resolution	380 pixels
Frame time	5 ms (3-ms future)

approximately 125 lines per camera width. Table 3 gives details on the streak camera performance separate from the readout system.

Table 3. Streak camera performance.

Spatial resolution	4 lp/mm @ 65% CTF
Photocathode size	38 mm
Resolvable lines	300
Temporal resolution	< 1/2% of sweep
Dynamic range	> 100:1 @ 65% CTF
Sensitivity	Detects single photoelectrons at phosphor

Uphole Streak Camera Applications

We are also developing a system that will allow these data to be recorded on uphole streak cameras after being transmitted through up to 1 km of optical fiber. The technique employs wavelength multiplexing to allow sending several spatial points over each optical fiber. The data are demultiplexed uphole and presented to the photocathode of the streak camera as depicted in Fig. 14.

FIG. 14. Fiber Optic SPARTEX uses the same technology as SPARTEX except that the image disector consists of a wavelength multiplexer and several hundred meters of fibers. This allows the streak camera system to be used uphole. The downhole system is totally passive.

Wavelength Multiplexing

The wavelength multiplexer consists of a lens doublet with a wavelength dispersive element between the lenses.¹¹⁻¹³ Thus, if the light from the object has a spectral distribution, a point of light at the object plane forms a spectral line at the image plane, as illustrated in

Fig. 15. The intensity information at the objective point is reproduced at every point along the spectral output line on the image plane. The length of the spectral output line is controlled by the amount of dispersion in the optical system.

FIG. 15. A point at the objective plane is dispersed to a focused spectral line at the image plane of the multiplexer.

A diffraction grating was chosen as the dispersive element because it provides the greatest dispersion over the spectral range of the fluor. This system can also be used to encode a spatial line from the objective plane. In this case, each point along the objective line is dispersed into a spectral line at the image plane. If the grating parameters are chosen properly, the "red" portion of the spectral output from one end of the objective line will coincide with the "blue" portion of the spectral output from the other end of the objective line. This is illustrated in Fig. 16, where the blue portion of the spectrum from point P1 coincides with the red portion of the spectrum from point P2. Thus, an optical fiber located at point B collects information from each point along the objective line P1P2, by receiving each objective point as a different wavelength. Therefore, the optical fiber

FIG. 16. Each point on a spatial line at the objective plane of the wavelength multiplexer is dispersed into a spectral line at the output. The blue portion of the spectrum from point P2 is focused to the same position on the image plane as the red portion of the spectrum from point P1.

carries spatial information about all points on the objective line PIP2 by encoding spatial position into wavelength, PIP.PIP., then injecting this information onto the fiber.

The spatial image can be demultiplexed from the optical fiber by using the same wavelength-dispersive optics in reverse. The final line-image contains the same spatial information in the same position as the objective line, but each position is also displayed as a different wavelength. Therefore, if accurate contrast information is desired, the resultant line-image must be corrected for the wavelength dependence of the sensor.

Wavelength Multiplexer Design and Performance

This system was designed to work in the spectral region from 500 to 600 nm. Two 50-mm focal length $f/1.5$ lenses are used, and the gratings are blazed for 550 nm with a spacing of 1200 grooves/in. The dispersion is adjusted so that the spectral output line from each point is 100 times longer than the 62- μ active core diameter of the optical fibers that collect the light. That is, each spatial sample is encoded into a 1-nm-wide portion of the spectrum.

The transmission losses through the multiplexer and demultiplexer are 3 db each. Encoding each spatial point into 1 nm increases the loss by 20 db. Thus, there is an expected total of 26-db loss for the multiplexing-demultiplexing system. The losses were measured to be 29 db. Typical optical fiber losses are 18 db/km at 550 nm. Thus, the optical transport system is a -47 db loss over 1 km of optical fiber.

The limiting visual resolution at the output of the multiplexer is 15 lp/mm as determined by viewing the airy image with a telescope. This resolution is consistent with the 62- μ optical fiber diameter used to sample the dispersed light at the input end of the system. The optical fiber is effectively sampling the input as if it were a 62- μ sliding aperture.

System Tests

The outputs from four optical fibers can be demultiplexed sequentially to form a line across the face of the streak tube. A 100-nm-wide bandpass filter centered at 550 nm is used in the demultiplexer so that the spatial output line from each fiber is limited to 6.2 mm (dispersion limit). At a resolution of 4 lp/mm on the streak camera photocathode, each input line is sampled 50 times.

The multiplexer system was tested by illuminating the input with a standard bar chart target, which has spatial bar patterns varying from 2 to 21 lp/mm. At the 4-lp/mm resolution desired for the streak camera input, the multiplexing system has a CTF of 90%. Thus, the total system should give a resolution of 4 lp/mm at a CTF of approximately 60% over a linear dynamic range of 100:1.

A prototype system consisting of the multiplexer and streak camera with film readout was assembled and tested. System performance is limited by the light intensity input to the wavelength multiplexer system. A power density of 103 W/cm² is required at the objective plane of the multiplexer if the full dynamic range of the streak camera is to be used. At this power density, the electron density at the phosphor of the streak tube gives 10% statistics for a resolution of 4 lp/mm. Statistics can be improved by reducing the gain of the image intensifier in the streak camera and increasing the input light (power density).

Other Imaging Experiments

Other time-dependent imaging experiments are being developed that will use the same hardware described above. Various forms of fiber optic image splitters are used in conjunction with streak cameras to measure material motion. This technique may eventually be combined with wavelength multiplexing for uphole recording.

We are also developing a time-dependent x-ray spectrometer that uses these same techniques. A special fluor is placed at the focal plane of an x-ray spectrometer. Light from this plane is focused into optical fibers and transmitted uphole to be recorded on a streak camera. The resultant data yield a time-dependent x-ray spectrum.

Conclusions

Time-dependent imaging is an important part of the diagnostics used by the Lawrence Livermore National Laboratory Test Program. Applications include material motion studies, time-of-flight background discrimination, and time-of-flight temperature measurements. Both fast framing camera and streak camera technologies are employed.

Our comparison between termination-type coupling and microstrip transmission line coupling to intensifier tubes indicates that for optical shutters with a duration of a few nanoseconds, the microstrip transmission line geometry is superior to that of the simpler termination-type coupling. Also, the width of the electrical pulse from the microstrip transmission line pulser measured after passing over the photocathode agrees with the measured width of the optical gate, when the length of time taken for the iris is added to the pulse width at the 50-V level.

Optical shutters with exposure time of less than 1 ns have been achieved over limited regions of the photocathode, and exposure times of 1.9 ns have been achieved over the entire 18-mm photocathode. We found it was essential to reduce the photocathode resistivity and to use a microstrip transmission line coupling geometry. The GaAs photocathode shows the best prospect for obtaining an optical gate of 1 ns or less from an 18-mm MCP intensifier tube. Preliminary results have shown that 1-ns gating over the entire 18-mm photocathode surface is obtainable.

We have developed a digital streak camera for remote data recording. It is capable of recording 125 lines of data over a dynamic range of 200:1 and with a time resolution of 1/2% of the sweep time. We are also developing a wavelength multiplexing system that transmits spatially resolved data over 1 km of optical fiber. The output of the multiplexer is focused on a streak camera for data recording. Prototype testing of the streak-camera-multiplexer system indicates a CTF of 60% at 4 lp/mm, with a linear dynamic range of greater than 100:1.

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