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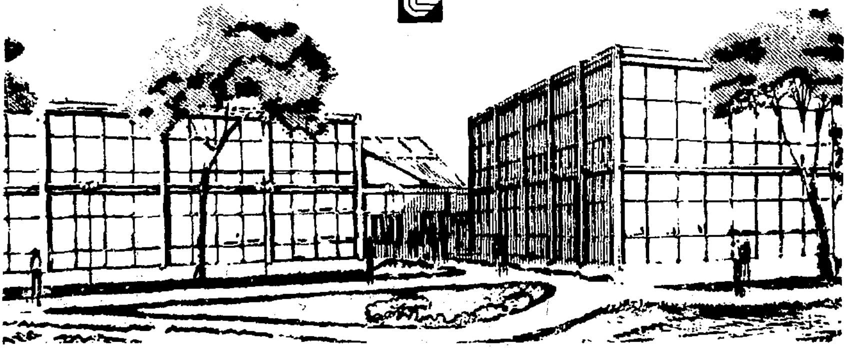

ULTRA-FAST IMAGE CONVERTER STREAK CAMERAS FOR LASER FUSION DIAGNOSTICS*

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Summary

The design and operation of a 10-ps resolution optical streak camera used to characterize laser pulses and other transient optical signals in fusion research is discussed. Performance characteristics are presented. The design, operation, and application of an x-ray streak camera used to study laser-produced plasmas in the x-ray spectral region of 1 to 10 keV with temporal and spatial resolutions of ∿ 20 ps and ∿10 μm is also discussed.

Introduction

The development and application of detailed, high-resolution diagnostic instrumentation for laser and laser-target interaction studies is an important aspect of laser fusion research. Measurements with temporal and spatial resolutions on the order of picoseconds and microns over a wavelength range extending from the infrared to the x-ray region of the spectrum are required. At present, laser-plasma interaction experiments are neither totally reliable nor reproducible. The data acquisition techniques must be as complete as possible on each shot. Sampling methods requiring the accumulation of data from many events are to be avoided.

Optical Streak Cameras

Background

In the performance of experiments on laser-plasma interactions, it is essential to characterize the pulse of laser energy that is applied to the target. A number of diagnostics techniques are applicable to this problem. Photodiodes, two-photon fluorescence, three-photon fluorescence, and the Duguay shutter are useful but all suffer from disadvantages that eliminate them as serious candidates for solving the complete fast diagnostics problem.[1]

Another approach employs a streak camera. In this method the image of a slit apertured beam is swept across a recording film. Mechanical cameras are limited to resolution times greater than 10 ns.[2] The creation of the ultra-fast image converter streak camera has successfully reduced the resolution time to less than 10 ps. This device has also proven to have both a linear response and a high sensitivity. These features make it possible to obtain the maximum time-resolved information from a single event.

Operation

The Livermore ultra-fast streak camera (UFSC) (Fig. 1) can be divided into five basic functional packages: the front end optics, the image converter tube, the image intensifier tube, the requisite electronic and mechanical subsystems, and the recording film pack. Figure 2 shows a schematic of these packages in some detail.

Light from the transient event under study comes from the left. A small fraction of the main beam is split off to trigger the camera. The main beam is attenuated, delayed, and diffused, and then illuminates a narrow slit. The lens assembly relays the image of the slit onto the photocathode of the image converter tube. The photoelectrons produced by the incident photons are accelerated into the image converter by a high positive potential (with respect to the cathode) applied to the fine wires of the grid. The electron beam is further accelerated by the field between the grid and the anode. The electrode structure in the tube provides electrostatic focusing as the electrons travel through the anode aperture. A suitable voltage pulse, optically triggered by the earlier split-off portion of the input beam, is then applied to the deflecting electrodes. This causes the beam of electrons, which after being refocused represents an image of the input slit, to be swept across the output phosphor screen on the back face of the image converter tube.

Fig. 1. Livermore ultra-fast, image-converter streak camera.

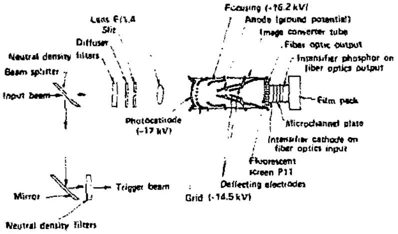

Fig. 2. Schematic of the Livermore ultrs-fast, image-converter streak camera.

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The intensity of the blue light emitted by the phosphor depends upon the electron current striking it. This current, in turn, depends upon the intensity of the light incident on the photocathode. Intensity versus time information from the incident pulse is thus transformed into intensity versus position information along the phosphor screen.

To realize the extremely short time resolution required, it is necessary to operate the image converter tube at the lowest possible level of photocathode illumination. Therefore, a high-gain image intensifier must be employed to amplify the weak phosphor image to levels that can be conveniently photographed. This intensifier is proximity focused and directly coupled to the fiber optic output of the image converter tube. Photographic film is then directly contacted to the fiber optic output of the intensifier by the film pack mechanism. The film is exposed, developed, and the resulting photograph either visually analyzed or further processed using an isodensitometer.

Performance Parameters

Spectral Sensitivity

The spectral sensitivity of the UFSC is dependent upon the type of photocathode in the image converter tube. Cameras with S-1 photocathodes are used primarily for diagnostics of 1.06-μm radiation from Nd lasers. Cameras with S-20 photocathodes are used for diagnostics in the visible and near ultraviolet region of the spectrum.

Threshold Sensitivity

Tests have been conducted with the UFSC to determine the threshold sensitivity of the image converter photocathode. Streak photographs were taken of 30-ps, 1.06-μm laser pulses of decreasing intensity. The film exposure threshold of the camera system was found to vary, depending on the tube being tested, between 2×10^{-9} and 1×10^{-11} J incident on the 25-μm slit. This translates into an S-1 photocathode sensitivity of about 300 W/cm^2.

Streak Velocity

The streak velocity is easily measured by generating a train of ultra-short light pulses of known separation in time and photographing this pulse train with the streak camera. The required pulse train may be formed by passing a single ultra-short laser pulse through a pair of accurately spaced, partially transmitting mirrors. The pulse bounces back-and-forth between the mirrors with a small fraction leaking out at each bounce. Each pulse is separated by the time required for light to make one round trip in the mirror cavity. The resulting pulse train is photographed with the UFSC and the position of each pulse is plotted against the time separation between that pulse and the first pulse. The reciprocal slope of this curve is a measure of the streak velocity. The curve shape is a measure of its linearity. This streak velocity can be varied to suit a particular experiment by changing the capacitance across the deflection plates of the image converter tube. With the camera adjusted for maximum linear sweep velocity, a plot of the data yeilds a slope of 32 ps/mm. The sweep velocity is, therefore, 3.1×10^9 cm/s and is linear within 3% over 80% of the 40-mm output aperture.

Dynamic Range

The dynamic range, an extremely important characteristic of the UFSC, can be determined using the same experimental approach employed to measure streak velocity. This setup produces a train of pulses that are not only evenly spaced in time, but also constantly decreasing in intensity. A photograph is again taken of this pulse train with the UFSC, and the film exposure of each succeeding pulse is measured with a microdensitometer. These film exposure levels are then plotted against their corresponding intensity levels that have been calculated from the reflection and transmission characteristics of the cavity mirrors.

Figure 3 shows overlaid densitometer traces of a single 150-ps pulse (inset photo) after it had passed through an etalon that produced factor of 2 output amplitude ratios. Seven pulses are recorded on the original photo (only six are shown on the graph) giving a dynamic range in excess of 2^7 or 128. Figure 4 shows the average of data from several measurements, corrected for film characteristics. These data verify the large linear intensity response range of the ultra-fast, image converter camera.

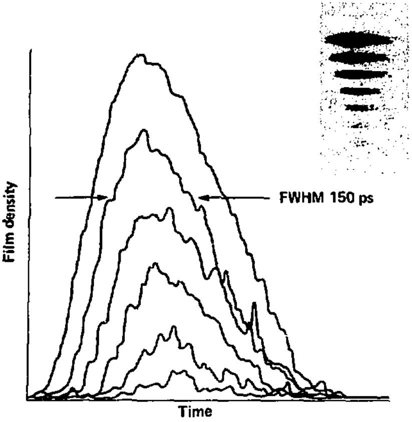

Fig. 3. Overlaid densitometer traces of pulses produced by a 2:1 amplitude ratio etalon from a single 150-ps pulse (inset). The illustrated dynamic renge is > 128.

Spatial Resolution

The spatial resolution of the UFSC depends on many factors including electron focusing in the image converter tube, the graininess of the output phosphor, and the spatial resolution of the image intensifier. It has been determined by placing a resolution chart in the plane of the camera slit, illuminating it with a laser pulse, and taking a streak photograph of the image. The limiting spatial resolution, as determined by this method, is seven line pairs per millimetre.

Temporal Resolution

Three factors combine to influence the total camera time resolution, T_c: the slit resolution, T_1; the

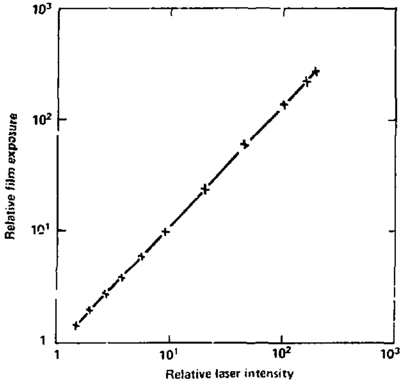

Fig. 4. Average of streak camera dynamic range data showing large linear intensity response range of camera.

electron transit time spread, T_2; and the technical time resolution, T_3. These are related to T_c by

$$T_c^2 = T_1^2 + T_2^2 + T_3^2 \ . \tag{1}$$

The slit resolution, T_1, is the time required to streak the slit image through a distance equal to its width. It may be calculated from

$$T_1 = d/v \ (\mathrm{ps}) \ , \tag{2}$$

where v is the streak velocity (mm/ps) and d is the width of the slit image (mm). Using the normal slit width of 0.025 mm, a total camera system magnification of 1.35X and the previously determined streak velocity of 3.1×10^{10} mm/s, the slit resolution is found to be 1 ps. Although this value depends upon three quantities that vary depending upon the camera setup, it is usually small and can be neglected.

The second limitation to the total time resolution arises because the electrons emitted from the photocathode have a spread in kinetic energies. This distribution of energies (velocities) causes electrons emitted from the photocathode at the same time to arrive at the output phosphor at slightly different times. This contribution to the total time resolution, the electron transit time spread, T_2, can be calculated from[3]

$$T_2 = 2.34 \cdot 10^{-8} \sqrt{\Delta u}/E \ (\mathrm{ps}) \ , \tag{3}$$

where Δu is the spread of electron velocities (eV) and E is the magnitude of the accelerating electric field at the photocathode (V/cm). For normal operating conditions of the UFSC with 1.06-μm light incident on an S-1 photocathode, Δu is 0.3 eV and E is estimated to be 3600 V/cm. Thus the electron transit time spread is found to be 3.6 ps. Equation (3) shows that to minimize this effect it is necessary to operate with the maximum possible field E between the photocathode and the grid. This is the most important factor in obtaining picosecond resolution when using an image converter tube.

The third contribution to the total camera time resolution is the technical time resolution, T_3. This is the time required to streak through a distance equal to one spatial resolution unit. It can be calculated from

$$T_3 = \frac{1}{v\delta} \ (\mathrm{ps}) \ , \tag{4}$$

where v is the streak velocity (mm/ps) and δ is the effective spatial resolution of the camera system (line pairs/mm). The effective spatial resolution is determined by dividing the true resolution found by streaking the resolution chart by the linear magnification (1.35X) of the camera system. Using the values of v and δ previously determined, the technical time resolution is found to be 6.2 ps. Because the slit resolution is small, large changes in the streak velocity have little effect on its contribution to the total time resolution. However, because the technical time resolution is a much greater quantity, changes in streak velocity cause it to have a significant role in influencing the camera's total time resolution. Returning to Eq. (1) and using the three resolution factors just determined, the total camera time resolution can be calculated to be 7.2 ps.

The task of unfolding the actual pulse width that the UFSC detects requires an additional step. Assuming a quadratic summation, the width of a single laser pulse as recorded by the camera, T, is related to the total time resolution, T_c, and the actual pulse width, T_p, by the expression

$$T^2 = T_p^2 + T_c^2 \ . \tag{5}$$

As an illustration of the UFSC's ability to resolve closely spaced pulses, consider the data presented in Fig. 5 taken with an S-20 camera. A double pulse train was created by passing a single ultra-short pulse from a mode-locked dye laser through a 9.9-ps etalon made from glass microscope slides. The resulting streak photograph was scanned using a small, computer-controlled microdensitometer. The densitometer output was further processed by computer

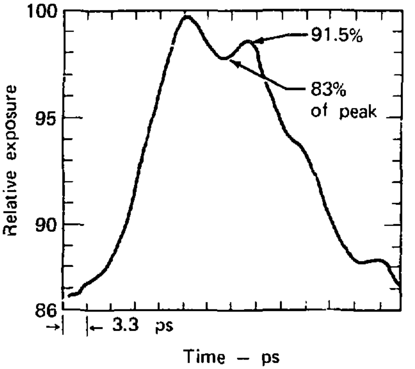

Fig. 5. Realtive film density vs time curve obtained after microdensitometer and computer processing of streak photograph. Illustrates clear resolution of two pulses 9.9 ps apart.

to remove unwanted system noise. The resulting curve illustrates that not only were the two pulses clearly resolved but the amplitude ratios were also as expected.

Applications

The UFSC has been used to perform a variety of diagnostics tasks in the LLL Laser Fusion Program. One obvious application is the analysis of laser pulse quality. Figure 6 shows a photodiode oscillogram of what was originally believed to be a clean, 2-ns pulse from an early stage of the Livermore Long Path Laser. Figure 7 is a streak photograph (10-ps resolution) of the laser pulse. The 2-ns envelope contains a regular, deep 28-ps modulation and a weaker 300-ps modulation. The source of this structure was traced to reflecting surfaces in the oscillator that produced subcavity modes.

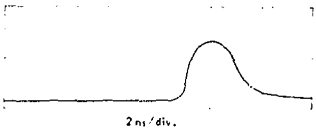

Fig. 6. Photodiode oscillogram of a 2-ns laser pulse from the Livermore long path laser.

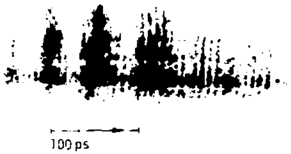

Fig. 7. Streak photograph of "smooth" pulse shown in Fig. 6 shows 28-ps and 300-ps modulations.

The UFSC's have also been used to study the results of nonlinear optical effects on high-power laser pulse propagation.[4] We have observed the time-dependent self-focusing of pulses. More recently a time-resolved interferometric technique has been employed to measure the refractive index changes in optical materials induced by the passage of a high-power light pulse.

X-ray Streak Camera

Background

The study of laser produced plasmas for fusion research has emphasized the need for a detection and recording system that is sensitive at x-ray wavelengths and has temporal and spatial resolutions on the order of picoseconds and microns. Details of the x-ray emission characteristics of laser heated targets with time resolutions comparable to the plasma heating times and spatial resolutions comparable to fractions of a target diameter will yield data that address the questions of the optical-absorption, plasma-heating and implosion processes. Unfortunately, nearly all observations to date have been time integrated because of the absence of suitable time-resolved x-ray detectors. Spatially resolved data have also been unobtainable.

An ultra-fast image converter x-ray streak camera (XRSC) has been developed permitting study of the laser produced plasma in the x-ray spectral region of 1 to 10 keV with temporal and spatial resolutions of approximately 20 ps and 10 μm.

Operation

The x-ray streak camera is a close relative of the optical streak camera described above. The major differences are the elimination of the front end optics and the change from an infrared sensitive to an x-ray sensitive cathode in the image converter tube. Figure 8 is a schematic of the x-ray streak camera emphasizing these changes.

X rays from the laser irradiated target are incident on the gold cathode causing the emission of electrons. As in the operation of the optical streak camera, this "slit" electron beam is accelerated to the deflection plate region of the tube where the application of a suitably timed, optically triggered ramp voltage sweeps the slit image across the output phosphor screen. An intensifier is used to amplify the weak phosphor image to a photographable level.

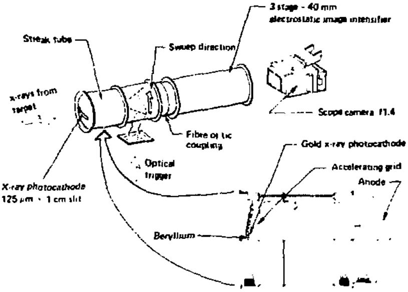

Fig. 8. Schematic of Livermore x-ray streak camera.

Performance and Applications

A fast sweep velocity and small electron transit time dispersion have reduced the temporal resolution of the XRSC to ∿ 20 ps. This value of time resolution is based on measured sweep velocities and electron dispersion values and is consistent with observed signal rise times on a number of x-ray streak records from laser heated plasmas.

The 0.125-mm by 10-mm gold slit cathode provides one degree of spatial resolution and permits time-resolved x-ray photography or time-resolved x-ray spectral measurements. To spectrally resolve the x-ray emission from laser irradiated targets, a set of K-edge absorbers are placed in front of the cathode. The insert in Fig. 9 shows a streak record of temporally and spectrally (but not spatially) resolved x-ray emission from a hollow glass ball irradiated from two sides by simultaneous laser pulses. The film is scanned to obtain density versus time profiles in each channel, and then the

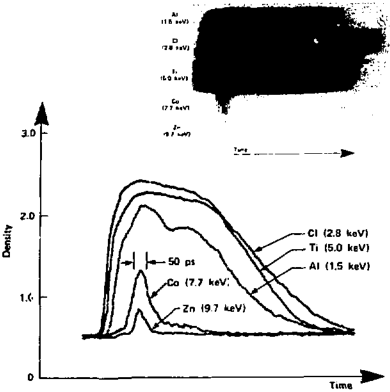

Fig. 9. Insert shows streak record of temporally and spectrally resolved x-ray emission from a laser irradiated target. Intensity vs time profiles of several spectral channels are also plotted.

characteristics of the recording film are removed with a simple computer program. The resulting intensity versus time profiles are also shown for several channels in Fig. 9. The XRSC has thus been transformed into a time-resolved x-ray spectrometer.

Up to this time laser plasma research has been limited by an absence of simultaneously spatially and temporally resolved x-ray emission diagnostics. By combining the XRSC with an x-ray pinhole camera, this need can be solved. Figure 10 shows a system that places a magnified (50X) image of the target onto the slit of the XRSC. A filter is used to limit the detected x rays to the range of interest. With this imaging scheme the x-ray emission from the irradiated target can be studied with a spatial resolution of ∿ 10 μm and a temporal resolution of ∿ 20 ps. Hardware needed to implement this extended application of the XRSC has been built and experiments will soon begin.

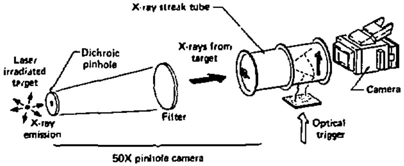

Fig. 10. Schematic of x-ray pinhole camera.

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