Four-frame gated optical imager with 120-ps resolution

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Abstract

In this paper we describe the operation and applications of a framing camera capable of four separate two-dimensional images with each frame having a 120-ps gate width. Fast gating of a single frame is accomplished by using a wafer image intensifier tube in which the cathode is capacitively coupled to an external electrode placed outside of the photocathode of the tube. This electrode is then pulsed relative to the microchannel plate by a narrow (120 ps), high-voltage pulse. Multiple frames are obtained by using multiple gated tubes which share a single bias supply and pulser with relative gate times selected by the cable lengths between the tubes and the pulser. A beamsplitter system has been constructed which produces a separate image for each tube from a single scene. Applications of the framing camera to inertial confinement fusion experiments are discussed.

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I. INTRODUCTION

The criterion for the time resolution of a framing camera is given by the required spatial resolution divided by the speed at which the object is moving. The plasmas studied in inertial confinement fusion (ICF) are typically 100 to 1000 μm in size and are moving at velocities of 1×10^7 cm/sec. If we require spatial resolution of approximately 10 μm, this implies frame times on the order of 100 picoseconds. Present laser pulses of interest to ICF are one to several nanoseconds in duration, so one would also like to have multiple frames to study the evolution of the plasma. The time delay between frames should be easy to adjust.

Short exposure times can be obtained using active probing techniques. Since laser pulses as short as 6 femtoseconds are possible[1], one can easily meet our criterion. There are, however, many sources of emission in laser-produced plasmas that one would like to directly image. These include parametric scattering processes (e.g. stimulated Brillouin scattering, stimulated Raman scattering, half-harmonic emission) or thermal emission which appear in the visible to near uv regions of the spectrum. Studies of the deposition of laser energy into solid materials require one to observe directly the appearance of shock waves breaking through the target. Framing techniques using Kerr cells[2], which require linearly-polarized and nearly collimated light, are usually not applicable: the light sources of interest are not necessarily linearly polarized and the f-number of the imaging system will be relatively small ($f/2$ to $f/10$). Mechanical shutters are clearly too slow. Fast gate times require electro-optic techniques.

Image intensifiers convert photons to electrons with an appropriate photocathode. The signal is amplified by a microchannel plate (MCP), and then the electrons are converted back to photons by a phosphor and the image is recorded (e.g. on film or by CCD readout). One-dimensional spatial information can be recorded with high temporal resolution if the photocathode is masked with a narrow slit and the electron beam is rapidly swept across the MCP by electrostatic deflecting plates; time resolution of less than 10 femtoseconds has been reported[3]. Indeed, streak cameras have been the work horses of time-resolved optical ICF diagnostics. There are, however, many applications (we will give an example later) in which two-dimensional time-resolved pictures complement those obtained with the streak camera.

An early approach towards a fast optical framing camera is the shutter tube[4,5]. Shutter tubes resemble the streak camera intensifier tubes with the time resolution obtained by gating off the photocathode between frames. The electron beam between the photocathode and the MCP is deflected between frames to a new spatial region of the MCP in order to obtain multiple frames. This procedure requires that a complex, time-dependent voltage be generated to gate and deflect the frames. The frame rate of the camera is typically limited to 400 ps by the transit time of the electron beam through the deflection plates.

The frame rate of a shutter tube can be improved by modifying the deflection plate geometry. A traveling wave deflection structure[6] has been demonstrated which allows the voltage pulse to propagate at the same velocity as the electron beam; effective transit times can be reduced to 50 ps. The limiting factor then becomes the rise time of the staircase voltage applied to the deflection plate which has limited the frame rate to 500 ps.

Image dissector tubes[7,8], on the other hand, require simpler ramped voltages to sweep the electron image past a slit to convert spatial information into time information. A separate electrode further downstream is swept in the opposite manner to reconstruct the 2-D images on the phosphor. The frame times can be as fast as 100 ps, but the image resolution is more dependent on the quality of the electron optics since the dissecting slit is imaged onto the MCP. Also, the specially-built tube is physically quite large.

The electron transit time can also be reduced by using proximity-focused tubes[9-11]. The tube has no electron-focusing optics which requires the cathode to be within a few millimeters of the phosphor. Fast frames can be obtained by applying a short electrical pulse between the cathode and the phosphor. The gate time is proportional to the RC time of the cathode-phosphor circuit. One can increase the conductivity of the cathode by placing a metallic coating on the substrate of the cathode. The coating cannot be made too thick without compromising the transmission of the tube. This limits the conductivity of the substrate. The gate time is also limited by the inductance of the circuit. Connections into the tube to the conducting layer have been found to contribute significantly to the total inductance of the gating circuit and gate times have been limited to 200 ps.

In the remainder of this paper we discuss the gated optical imager (GOI) that we have used for the first time to frame laser-produced plasmas. Development of a technique to produce a short high-voltage pulse to gate an image intensifier tube provides 100-ps frame times. The cathode is capacitively coupled to an external electrode; this configuration allows the construction of a low-inductance path to ground. Multiple frames are obtained by using multiple tubes and so the time between frames can be set arbitrarily.

The image intensifier tubes are readily available, reliable, and very compact. An example of an application of this camera at this laboratory is presented in the third section.

II. DESCRIPTION OF THE GATED OPTICAL IMAGER

A commercial framing camera[12] has been designed for four-frame operation during a single event. Each channel of the GOI uses a wafer intensifier tube[13] which has an S20 photocathode with a quartz window. (The quartz window was chosen for our particular camera to allow for pictures to be taken in ultraviolet light. A single-frame GOI was previously used successfully with a fiber-optic face plate.) In fast pulse operation, the cathode is capacitively coupled to a conducting electrode which is pulsed relative to the MCP of the tube. To turn the tube off and maintain a narrow gate pulse, the cathode is reversed-biased relative to the MCP by approximately 100 V.

The high voltage is generated by a planar triode pulse generator whose output is a 2.5 kV pulse with a risetime of less than 1.5 ns. The pulse is then shortened to approximately 100 ps by feeding it to a speed-up module which contains a reversed-biased diode which is pulse charged to operate near its avalanche breakdown point[11]. Since the avalanche breakdown process is known to occur rapidly (< 100 ps typical time scale), one can use well-characterized diodes to produce a very fast rising pulse at high voltages ($\sim$ 1 kV). The pulse is then split and fed to opposite sides of the tube to optimize impedance matching and to symmetrize the propagation of the pulse across the photocathode. Note that the large voltage pulse is required since the capacitive coupling to the tube leaves only one tenth of the applied gate voltage on the cathode-to-MCP gap.

Multiple frame operation is achieved by using multiple gated intensifier tubes. This requires that the optical system provide a separate image to each GOI channel, but this is easily accomplished (see Sec. 3). The output pulse from the planar triode pulser is fed to a single speed-up module which is split between the four tubes. The relative timing between channels is determined by the relative lengths of the cables between each tube and the speed-up module. This arrangement is illustrated in Fig. 2.

The width of the gate pulse has been verified optically using a strobe technique with a laser diode pulser (pulse width = 80 ps, wavelength = 840 nm) and using a photodiode to measure the light emitted at the phosphor (P20), as is seen in Fig. 3. This is a plot of integrated light output versus relative delay between the gate and the laser and was obtained using a sampling-type setup. The gate pulse is approximately Gaussian with a FWHM of close to 120 ps. By uniformly illuminating the tube with the diode pulser, we have examined the spatial dependence of the gate time by moving the photodiode receiver across the phosphor; the variation is less than 20 ps. The gate time is determined by the electron transit time to the MCP and the capacitance limits the diameter of the photocathode to 18 mm; a larger cathode would have a larger capacitance and a slower gate time.

Although the gate pulse is applied across the entire tube (electrode to ground), the voltage across each part of the tube is determined by the ratio of its capacitance to the total tube capacitance. The rise time of the gate pulse across each part will also be proportional to the capacitance of each section of the tube. For these reasons, the MCP provides essentially the same gain as in d.c. operation. The MCP voltage can be varied incrementally in six steps (each step = 50 V) from 920 V (radiant gain = 10^3) to 670 V (radiant gain = 30). The shutter ratio is greater than 10^6 which is indicated by the tube specifications and has been verified by comparing gated and ungated exposure times to obtain similar intensity levels with the MCP biased. The lower limit corresponds to defects in the MCP.

The spatial resolution of the gated tube has been investigated. A contrast transfer function (CTF) has been obtained (see Fig. 4) using a linear zone plate grid. The CTF is greater than 30% at 10 lp/mm which corresponds to the smallest spacing on the target grid. Comparison between the CTF obtained in the fast gate mode and that obtained by gating the MCP (300 μs gate time) shows no significant difference. The resolution is limited by the intrinsic spatial resolution of the intensifier tube and is not degraded by the external electrodes. Note that the measured CTF includes effects of recording the image onto film; the finite thickness of the emulsion degrades the system response at higher spatial frequencies.

III. APPLICATIONS

The four frame GOI is presently a routine diagnostic used in conjunction with the Nova laser. Nova is a ten-beam laser; each beam is able to deliver focused 2.0 kJ of energy in the form of 0.35 μm wavelength light to solid targets of various materials. Pulse lengths range from 100 ps to 5 ns. One mission of this facility is to study plasmas under conditions similar to those expected in an inertial confinement fusion reactor. With the GOI one can study the spatial and temporal evolution of thermal emission around the target or look at light scattered by parametric processes driven in the laser-produced plasmas.

The image is relayed to the GOI by a Cassegrain telescope which has a magnification of 8.47 and has an input f-number of 10 (the telescope is 2 meters from the target); this means that the diffraction-limited object plane resolution at a wavelength of 450 nm is 9 μm/lp. In the image plane, the resolution is therefore larger than 76.2 μm/lp or 13 lp/mm. This is comparable to the image resolution of the tube. Four images of the target of nearly equal intensity are provided by the system of beamsplitters and mirrors shown in Fig. 5. Small differences in the relative channel intensities can be compensated by adjusting the MCP gain of each tube individually.

An example of the use of the GOI is illustrated in Fig. 6. In this experiment, two beams of Nova were focused onto one side of a 63.7-μm-thick planar aluminum slab. The focused energy produces a shock wave in the target which, when it reaches the other side, shows up as a bright flash. Shown in Fig. 6 are four frames taken during a single event; the frames are separated by 200 ps. The first frame shows emission due to preheat, then the shock breakout has begun by the second frame and continues in the remaining frames. Note that although the beams were intended to be overlapping, two distinct spots were observed instead of a single spot. Alignment errors in the target positioner were later determined to be the cause of this; note that this sort of information would be difficult to obtain using a streak camera alone without fortuitious alignment.

IV. SUMMARY

We have demonstrated the usefulness of an optical framing camera which provides four two-dimensional images per event with 120-ps gate widths on each frame. Changing the interframe timing is a simple procedure. The camera has a good spatial resolution and cathode area for a wide range of imaging applications. The imager has proved to be a useful and reliable diagnostic on the Nova laser system.

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FIGURE CAPTIONS

1. a) A view of the rear of the framing camera showing the physical connections with the speed-up module (far right), the d.c. bias supply (lower center) and the planar triode pulse generator. b) A view of the framing camera showing the arrangement of the four gated intensifier tubes.

2. Diagram illustrating the connections used for four-frame operation of the camera.

3. Measured gate width of the camera.

4. Measured contrast transfer function of the GOI using a linear zone plate grid (minimum spacing = 10 lp/mm).

5. Scheme for providing images of nearly equal intensity and at the same time to all four GOI channels.

6. Data obtained with the four-frame GOI showing breakout of a shock wave produced in an aluminum slab target.

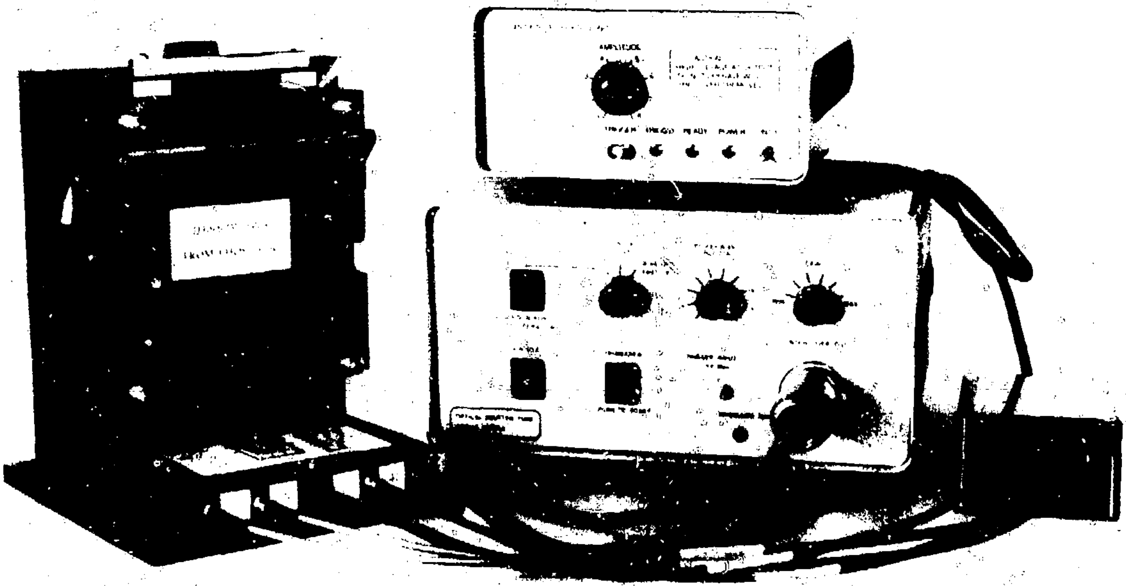


Figure 1a

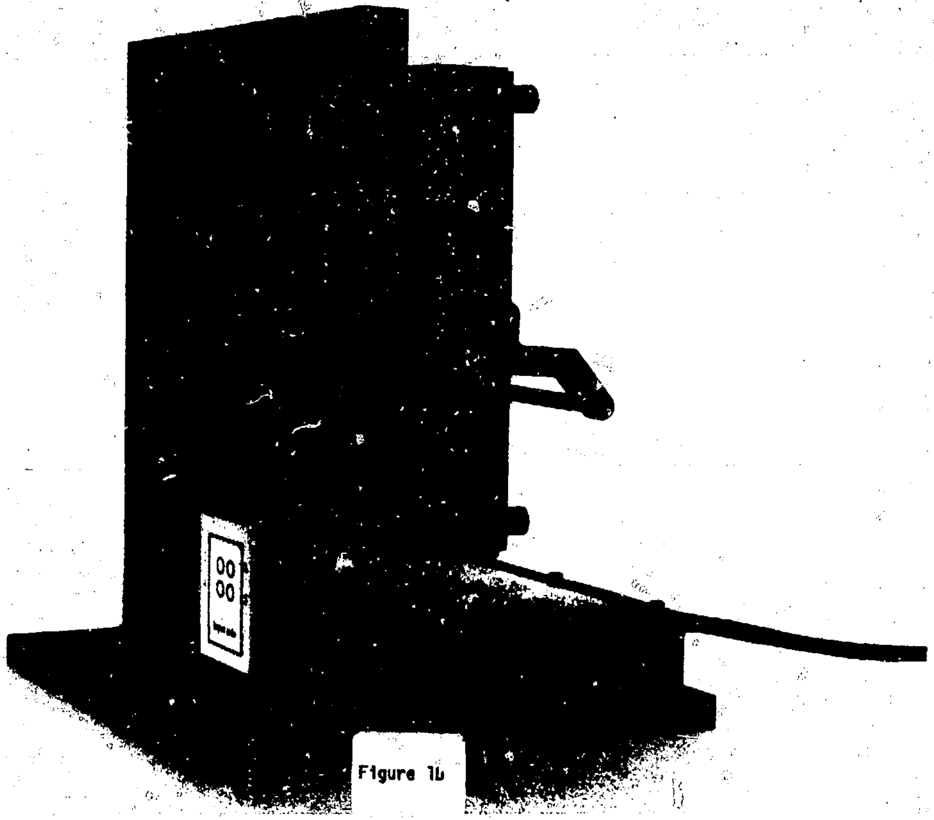
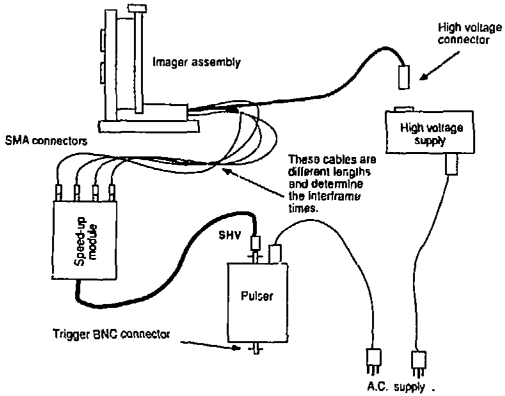


Figure 1b



Imager assembly
High voltage connector
SMA connectors
High voltage supply
These cables are different lengths and determine the interframe times.
Speed-up module
SHV
Pulser
Trigger BNC connector
A.C. supply

Figure 2

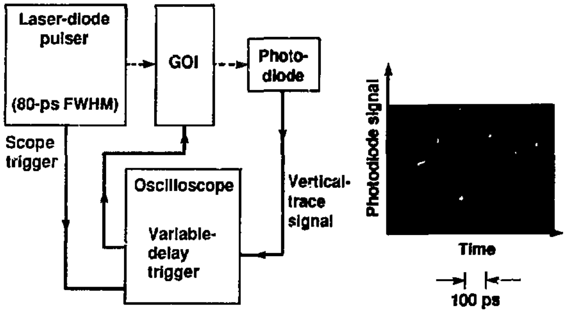

Laser-diode pulser
(80-ps FWHM)
GOI
Photo-diode
Scope trigger
Oscilloscope
Variable-delay trigger
Vertical-trace signal
Photodiode signal
Time
100 ps

Figure 3

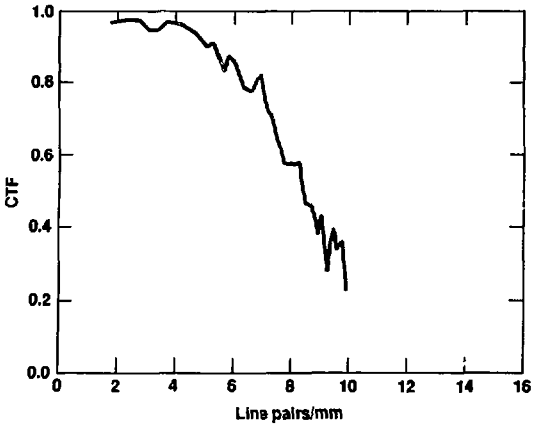


Figure 4

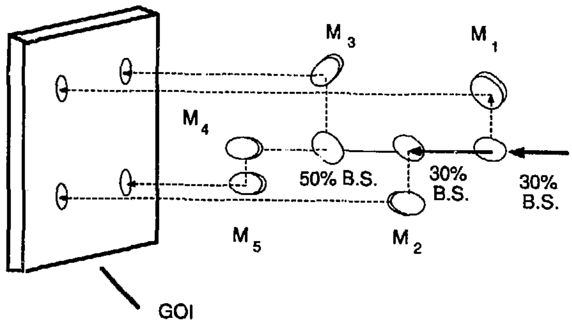


Figure 5

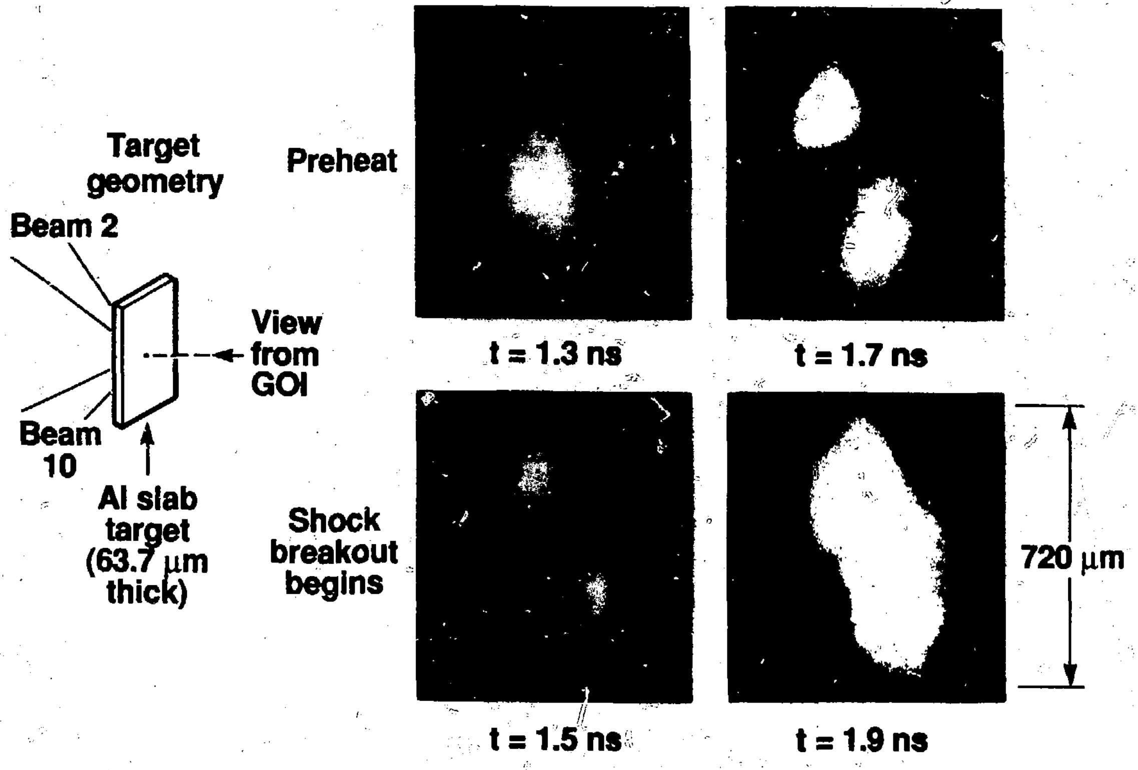

Target
geometry
Beam 2
View
from
GOI
Beam
10
Al slab
target
(63.7 μm
thick)
Preheat
Shock
breakout
begins
t = 1.3 ns
t = 1.7 ns
t = 1.5 ns
t = 1.9 ns
720 μm

Figure 6