UCRL--69119

CONF-83015-42

UCRL-69119
PREPRINT

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This paper was prepared for submittal
at the IEEE 1983 Nuclear Science Symposium
San Francisco, Calif.
October 19-21, 1983

November 1, 1983

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Livermore
National
Laboratory

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ULTRAFAST GATED INTENSIFIER DESIGN FOR LASER FUSION X-RAY FRAMING APPLICATIONS*

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A major challenge for laser fusion is the study of the symmetry and the hydrodynamic stability of imploding fuel capsules. Streaked x-radiography, in one space and one time dimension, does not provide sufficient information. Two (spatial) dimensional frames of 10-100 ps duration are required with good image quality, minimum geometrical distortion (approximately 1%), dynamic range greater than 1000 and greater than 200 x 200 pixels. A gated transmission line imager (TLI) can meet these requirements with frame times between 30 and 100 ps. An instrument of this type is now being developed. Progress on this instrument including theory of operation, ultrafast pulse generation and propagation, component integration, and high resolution phosphor screen development are presented.

The Concept of Laser Fusion

The concept of Laser Fusion is to use a large (0.1 to 10 MJ) short pulse (1 to 10 ns) laser to ablate the outer surface of a capsule containing deuterium and tritium fuel and implode it, compressing and heating the fuel to a density of $>100 \text{ gm/cm}^3$ and a temperature of $>10^8 \text{ }^\circ\text{C}$. If these conditions can be reached the fuel will ignite and burn in a thermonuclear reaction, releasing large amounts of energy which can then be used in a variety of ways. The ablation of the target surface creates pressures $>10^8$ atmospheres, far exceeding the strength of materials. The shell is accelerated inward at more than 10^{12} gravities and reaches velocities $>3 \times 10^7 \text{ cm/s}$. Under these extreme conditions it is clear that the forces on the capsule must be exerted very symmetrically and uniformly or the capsule will fail to converge to a small high density point. The problem is somewhat akin to trying to squeeze a child's balloon down from its original diameter ($\sim 8 \text{ in}$) to the volume of a pea while keeping it perfectly symmetrical.

Hydrodynamic Instabilities and Symmetry

The problem of imploding the fuel capsule is further complicated by the large accelerations and the fact that the low density ablating material is accelerating the high density shell. Under these conditions the shell is potentially unstable against small perturbations via the Rayleigh-Taylor and Richtmeyer-Meshkov instabilities. Figure 1 shows a gas bubble [1] undergoing Rayleigh-Taylor instability. This gives an

*Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.

idea of how damaging the instability is to symmetry and suggests what a photo of an unstable imploding fuel capsule might look like. There are several methods by which these instabilities can be controlled, including (among others) adjusting the shell thickness and grading the density of the shell. All of these methods involve increases in capsule complexity and loss in implosion efficiency. Since it is desirable to implode the capsule with the minimum amount of energy it is very important to be able to establish the boundary of the parameter space between capsule stability and instability.

Thus one of the challenges which must be met by Laser Fusion is to produce a hydrodynamically stable and symmetric implosion. This in turn leads to a major challenge for Laser Fusion diagnostics; to develop a method to measure the symmetry and stability of the imploding shell and the symmetry of the compressed core.

X-ray Backlighting

The method which holds the most promise for measuring the symmetry and stability of the imploding capsule is x-ray backlighting. Figure 2 is a schematic of how an x-ray backlit photo of the imploding target might be taken. The sample shown is the fuel capsule to be radiographed. Under conditions of interest it would be irradiated by a number of laser beams, not shown here for simplicity. The x-rays used to radiograph the fuel capsule are produced by a laser driven x-ray source which consists of a small (1 mm x 1 mm) foil of material which has the desired characteristic emission lines. It is irradiated by one of the laser beams not used to irradiate the target. The x-rays pass around and through the fuel capsule and are collected by an x-ray focusing optic, here shown schematically as a lens, but which in reality is a grazing incidence x-ray mirror. The x-ray optic focuses the transmitted x-ray image onto an imaging detector which records it on a recording medium, such as film or a CCD array. In this case the imaging detector is a high speed framing camera and the subject of this paper.

Framing Camera Requirements

The fuel capsule implodes from its initial radius to its final radius in roughly the length of the laser drive pulse, ~ 1 -10 ns. Thus it is necessary to have an exposure time much shorter than this to resolve the image of the capsule without serious blur. With an implosion velocity of $\sim 3 \times 10^7$ cm/s and a desired resolution at the target of a few microns, it is necessary to have a shutter time of 10-100 ps. The requirement for spatial resolution of a few microns is determined by the fact that symmetry errors of less than 1% of the initial capsule radius can cause degradation of burn efficiency. Resolution of a few microns is also consistent with the fact that the wavelength of maximum growth rate for the Rayleigh-Taylor instability is on the order of the capsule wall thickness, again typically a few microns. This requirement has several implications for the framing camera design:

- 1) The image must have a distortion of less than 1%, or be easily and convincingly correctable to that level.
- 2) With magnifications of 10-20 for the x-ray optic the camera resolution must be in the range of 20-60 microns.
- 3) The camera must have $\sim 200 \times 200$ pixels to measure symmetry errors of 1% convincingly.

Taken together, these imply an active photocathode area of 4-12 mm. Generally speaking, it is easier to gate a small image quickly than a large one. Many framing camera designs use deflection systems to displace the image from place to place on the screen between frames. We have not chosen this method in the belief that an electrostatic deflection system offers too much opportunity for distortion of the image and will compromise credibility of symmetry measurements at the 1% level. This problem is avoided by using the proximity focused geometry which inherently has small distortion. The residual distortion is fixed and can be easily and convincingly corrected. In a proximity focused gated intensifier, however, the gate time is limited to transit time of the gating pulse across the photocathode at the speed of light. Thus the resolution of the camera and the number of pixels in the frame limit the speed of a proximity focused gated imager. With a photocathode dimension of 4-12 mm the limiting gate time is 13-40 ps.

Other important considerations for viewing backlit targets and other laser fusion phenomena are dynamic range and edge response. Typically the target is dense and quite attenuating to the backlighting x-rays, but the backlighter extends beyond the edge of the fuel capsule so that one is faced with the problem of viewing a small dark object against a large bright background. The background from the x-ray backlighter may be more than 100 times brighter than the x-rays transmitted through the target. Any scatter in the x-ray optical system or the gated intensifier will tend to flood the shadow image of the target with background and destroy the dynamic range of the image. To record this type of scene one needs a dynamic range $>1000:1$ and an edge response which drops nearly the full dynamic range within a few pixels.

A similar problem arises in the time domain in that both the backlighter and the target emit intense background for a long time compared to the gate time. If the "shutter" of the gated intensifier is not opaque enough, leakage through the device will fog and blur the recorded image. For this reason the shutter ratio must be greater than 10,000:1.

Although the laser driven backlighter source which we plan to use is one of the brightest available, the high resolution of the instrument in both space and time divides up the emitted energy so finely that intensity becomes a problem. Thus we require that the photocathode quantum efficiency be as high as possible and that electron transport through the camera also be as high as can be achieved.

The framing camera requirements are summarized in Table I.

Table I

Framing Camera Requirements

Time resolution: 10-100 ps
Spatial resolution: 20-60 μm
Image distortion: <1%
Image size: >200 x 200 pixels
X-ray energy range: 1-8 keV
Dynamic range: >1000:1
Shutter Ratio: >10,000:1
Edge response: $\sim$ 1000:1 in 50 μm
Quantum Efficiency: >5%

Gated Imaging Status

Fast gating of electro-optic imaging tubes has been the objective of researchers for many years. Kotecki and Lear [2] summarize the technology using microchannel plate (MCP) intensifier tubes. They conclude that the gating speed of conventional MCP image tubes is currently limited to slightly under a nanosecond. Laviro, et al., [3] of LEP in France described a tube which was designed to minimize lead inductance and photocathode resistivity and was driven through two parallel 50 ohm inputs. This tube achieved 300 ps FWHM gating for visible light inputs. Only recently has an effort been made to construct an imaging tube with the propagation of a fast gating pulse as a prime design criterion. Workers at LEP in France [4] have built a sealed tube with 50 ohm characteristic impedance between the front surface of an active MCP and a phosphor screen. The 7 kV gating pulse is capacitively divided between the MCP ($\sim$ 1 kV) and the MCP-screen vacuum gap ($\sim$ 6 kV). The MCP is used as the x-ray converter/detector. This structure was among the first to include the gated gap as part of a transmission line and achieved a gating time of a few hundred picoseconds. J. D. Kilkeny, et al., [5] at Imperial College (London) produced an x-ray imaging tube which is gated between an x-ray photocathode and an extraction grid. These designs, however, have spatial resolution and dynamic range that is insufficient for many laser fusion applications. The gating time is also constrained by the need to convert from coaxial to planar geometry in order to be compatible with external pulse generators. From this background a device called a Transmission Line Imager (TLI) has evolved to serve the needs of LLNL's Laser Fusion Program.

The Transmission Line Imager, designed to meet the requirements described earlier, is shown schematically in Figure 3. Its principal features are: an integral, geometrically matched pulse generator; a parallel-plate transmission line operating above its normal cutoff frequency; a photocathode and phosphor screen anode integrated into the transmission line non-disruptively; and an integral thick-film termination resistor to minimize electrical reflections. The

Implementation of the complete TLI design is a combination of innovative electro-optical design, a blending of electrical and mechanical technologies, and careful attention to selection of materials compatible with each other and the required fabrication process.

Detailed Description of the TLI

A side view of the TLI design is shown in Figure 4. It will be described in detail from left to right.

The basis for the very short electrical gating pulse is the photo-conductive (Auston) switch [6-10]. This is a piece of near intrinsic, high resistivity ($>10^7$ ohm-cm) GaAs cut to the same width as the transmission line. It has two Au-Ge contacts [11-13] plated and annealed on one surface and attached with Au-Sn or Ag-Sn solder to the transmission line. The gap between the contacts is approximately 2 mm wide, adequate to hold off 20 kV for several tens of nanoseconds. Surface breakdown is prevented by encapsulating the area above the gap in transparent nonconductive epoxy. The photo-conductive switch behaves as an insulator until carriers are available to conduct between the contacts. It is possible to create a great number of carriers very quickly by illuminating the gap with a high energy laser pulse (~ 1 mJ), turning the GaAs into a quasi-metal for a period corresponding to the carrier recombination time, about 1 ns. One characteristic by-product of the Laser Fusion Program is the availability of laser pulses coincident with the experiment and of sufficient energy to cause the GaAs to conduct. The speed with which the device "switches" is the same as the width of the illuminating pulse. In our case, a 20 ps, $1.06 \mu\text{m}$ laser pulse or a 5 ps dye laser pulse will be available.

Near uniform illumination of the switch gap (2 mm x 25 mm) is achieved by a fiber optic geometry changer, round at one end and rectangular at the other. Experiments at LLNL have shown the damage threshold of step-index fibers to be approximately $5 \times 10^{10} \text{ W cm}^2$, well above the power required to drive the switch. As the GaAs becomes suddenly conductive, the charge line and the transmission line are connected electrically. The charge line has been pulse charged to a potential of -20 kV and the transmission line has been biased slightly positive to deter photoelectrons from crossing the gap. The result is a pair of 10 kV waves moving away from the switch at the speed of light, one down the transmission line and one down the charge line. The duration of the pulse is limited to the round trip propagation time of the charge line; for our work from ~ 30 ps to about 300 ps, depending on the phenomenon being diagnosed. The plane wave generated by switching along the full width of the switch gap is carried along a 25 mm wide transmission line. The cutoff frequency of this line is 6 GHz, but so long as the wave remains plane, pulses with rise times corresponding to much higher frequencies can be successfully transmitted. As an example, Figure 5 shows the leading edge of a 2.4 kV pulse transmitted 10 cm down a 35 mm wide (4 GHz cutoff) transmission line. The laser pulse width was 50 ps. Deconvolving the oscilloscope response yields a rise time of approximately 60 ps. The same pulse was viewed after reflection from the open transmission line end after an additional 20 cm of travel and had a

deconvolved rise time of 100 ps. Our TLI design requires pulse fidelity be maintained for only 5-10 cm, so a rise time of 30-40 ps is anticipated (with the 20 ps laser excitation pulse).

After generation and transmission, the pulse reaches the active region of the device, the x-ray photocathode. The photocathode will be either gold or CsI on a 25 μm beryllium substrate. The cathode emits photoelectrons with a quantum efficiency in the range of 0.1 to 1 [14] and varying kinetic energy, typically 1 to 10 eV for gold, 0.5-4 eV for CsI. The lower energy spread of the CsI electrons is much preferred due to their smaller transverse velocities, but gold will be used initially for ease of handling.

The importance of small transverse velocities is due to our means of improving the dynamic range of the imager. The photocathode is essentially transparent to the x-rays being measured, allowing most of them to continue onto the phosphor screen. X-rays stopped by the phosphor will create noise in the image, as there is no gating mechanism for the x-rays. Our solution to this is to install an electron collimator in front of the screen. This collimator is essentially a thin, 0° bias angle MCP without gain. Electrons normal to its surface will pass through it to the phosphor, if there is not too much transverse electron energy. By illuminating the photocathode at a slight angle, about 5° , x-rays will be absorbed in the high-lead content MCP glass. MCP attenuation is calculated to be >500 in the operating energy range.

After passing the photocathode, the gating pulse must be absorbed in some manner that keeps reflections to an acceptable level. The wide line and narrow spacing precludes discrete resistors. Working in collaboration with F. Uribe of Sandia National Laboratory in Livermore, large area thick film resistors have been built which appear to have both the high-frequency performance and short pulse, high-current capability. The terminating resistor will be approximately 25 mm square and have a resistance of about 18 ohms, the characteristic impedance of the TLI. Tests are incomplete but results thus far are encouraging.

The length of the terminating resistor is long compared to the wavelength of significant frequencies in the pulse. In order to minimize reflections, the local characteristic impedance will be controlled nearly equal to the resistance remaining. This will be done by an inclined ground plane under the resistor. The ground plane will stop short of actually touching the "ground" end of the resistor. Instead, there will be a small gap with relatively large surface area. This, in conjunction with discrete capacitors, will form a AC ground and still allow for a DC reverse bias to be applied across the gap.

The resolution and dynamic range requirements of the TLI are based, in part, on the fact that we are studying a dark image on a bright background. This is generally quite difficult due to scattering of electrons and photons from the bright areas into the dark. Elastic scattering of accelerated photoelectrons [15] from a standard phosphor screen is depicted in Figure 6. A significant fraction ($\sim 30\%$) of the electrons are scattered and eventually find their way back to the screen with a large fraction of their energy, resulting in image noise. Here we

find the second function of the electron collimator, to eliminate these scattered electrons. Electrons scattered from the top of the collimator will not make it through other channels due to their transverse velocities. Electrons scattered from the screen will be absorbed by the collimator. The overall result is a great increase in resolution with an apparent loss in efficiency of about 50%. But many of these lost electrons would have resulted in noise rather than signal so there is a net increase in the information capacity of the system.

Finally, special attention is being paid to assure that the phosphor screen minimizes loss of information due to photon scattering. The image will be coupled out of the TLI via a fiber optic faceplate either directly onto film or into an ungated image intensifier. It has been determined that the high numerical aperture (NA) of most fiber optic faceplates results in a negligible depth of field when directly coupled to a subsequent stage. As a result, the finite phosphor thickness degrades the resolution well below that found by observing the screen with low NA viewing optics. In addition, light scattered among the phosphor grains is eventually collected by fibers, possibly far from its point of creation. This can drastically impair the edge response of the imager. A new phosphor screen design, being pursued to minimize these effects, is shown in Figure 7 [16]. The two important features of this screen are:

- 1) optical isolation of phosphor islands corresponding to fiber cores, and
- 2) a monolayer of small phosphor grains.

The optical isolation is achieved by standard lithographic techniques. A method using the fiber optic face-plate as its own mask allows the webbing between the fibers of the faceplate to be coated with about $1\text{ }\mu\text{m}$ of metal while the ends of the fibers are left coated with photo-resist. The faceplate is then heated to about $150\text{--}175^\circ\text{C}$ and the resist becomes viscous. Fine grain phosphor, $0.25\text{--}1\text{ }\mu\text{m}$ is brushed on to this sticky surface which results in a monolayer of phosphor over the individual fibers. By subsequently raising the temperature of the fiber optic screen to 350°C , the resist is evaporated and the phosphor grains diffusion bond to the faceplate glass. The result is isolated islands of phosphor with little possibility of cross talk.

Fiber optic faceplates have been evaluated for internal cross talk and American Optical 2790A has been found to have very low internal fiber cross talk (see Figure 8). We anticipate that screens built using this technique will demonstrate point spread functions with widths on the order of the fiber pitch, $6\text{ }\mu\text{m}$, although overall screen resolution will be limited to the $15\text{ }\mu\text{m}$ collimator pitch.

Summary

The transmission line imager described above is now in fabrication and some of the important characteristics of its components have been tested. The design of the device addresses all of the stringent requirements for ICF framing applications and proposes solutions to many of the problems limiting the performance of other designs in use and described in the literature.

The two most important features of this device are its very short gating time and its high image quality. The high speed results from the integral photoconductive-switch pulse generator, matched vacuum transmission line geometry, and small high-conductivity photocathode. The small photocathode is made possible because of the high resolution of the proximity focused imager and the special high contrast phosphor screen. The phosphor screen incorporates the unique feature of an electron collimator which serves both to:

- 1) increase the shutter ratio by attenuating x-rays which reach the screen, and
- 2) prevent Rutherford scattered electrons from re-impacting the screen in another location, impairing the image contrast ratio and edge response.

The resolution and edge response of the screen is also enhanced by the narrow transverse electron energy distribution of the photocathode and the isolation between the islands of phosphor at the end of each fiber of the screen.

If this design is successful in all respects it will make possible short frame time quantitative images of ICF phenomenon of unprecedented quality.

Figure Captions

- Figure 1 - Target instabilities can result in a nonuniform implosion similar to this gas bubble.
- Figure 2 - Implosion instabilities and symmetry can be measured by radiographing the target with a gated imaging detector.
- Figure 3 - Gated Transmission Line Imager - Schematic.
- Figure 4 - Transmission Line Imager - Cross Section.
- Figure 5 - Experimental 35 mm wide transmission line pulse as measured by a 100-ps rise time oscilloscope.
- Figure 6 - Electrons scattered from the phosphor screen degrade imager edge response.
- Figure 7 - Electron collimator and segmented phosphor screen greatly enhance resolution and contrast ratio.
- Figure 8 - Low internal cross talk of AO 2790A fiber optic results in sharp edge response.

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