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**X-RAY BACKLIGHTING SOURCES OF
4 TO 10 keV FOR LASER-FUSION TARGETS***

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ABSTRACT

High-intensity, short-duration x-ray pulses are necessary to diagnose the compression of laser fusion targets. Present target designs are such that backlighting sources ranging from a few thousand electron volts to 100 keV will be necessary. The desired source durations range from a few tens of picoseconds for flash radiography to several nanoseconds for streaked backlighting, and the source occurrence must be tightly synchronized to that of the target-irradiating laser pulse. For the latter reason, a laser-induced x-ray pulse is preferred.

An initial study of the K lines of Ti, Ni, and Zn as possible backlighting sources was conducted. The conversion efficiency of laser light into line radiation was obtained as a function of laser intensity, pulse length, and wavelength. A threshold laser intensity for x-ray line production was identified. Information was obtained on the size and location of the x-ray emission source, in relation to laser parameters. The experimental results, and their impact on backlighting capability for the present laser fusion targets, are discussed.

Introduction

As laser fusion progresses toward higher-density final fuel conditions, x-ray backlighting has emerged as one of the few diagnostic methods available for determining the symmetry, stability, and the compressed size of imploding shells. The backlighting sources required for this diagnostic work are defined by the characteristics of the targets that are to be radiographed.¹

Target-Dependent Backlighter Requirements

An example of the type of target for which x-ray backlighting will be required is the New York University (NYU) double-shelled target, the parameters of which are discussed below.

The outer shell is the target consists of a low-Z ($Z =$ atomic number) ablator and a higher-average-Z pusher; a typical ablator is AlD, and a likely candidate for the pusher is TaD₂. The typical outer diameter of the shell is approximately 2 mm, and the time during which the motion of the shell is of interest is approximately 5 ns. To study shell stability, imploding velocity, and symmetry, spatial and temporal resolutions of 5 to 10 μ m and 50 to 100 ps, respectively, are required.

The inner shell, with a diameter of approximately 300 μ m, includes a high-Z pusher (e.g., gold) and a low-Z fuel comprising a mixture of deuterium and tritium (D-T). The characteristic implosion time is approximately 2 ns. The spatial and temporal resolutions required to

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study the inner-outer pusher collisions are 2 μm and 10 ps, respectively; a temporal resolution of 20 to 40 ps is required to study the stagnation conditions of the inner pusher.

While the required temporal and spatial extents of the backlighting sources (and the corresponding resolution limits of the imaging instruments) are delimited by the target parameters discussed above, the backlighter wavelength is defined both by the relative transmission characteristics of the various shells and by the level of x-ray self-emission of the target as a whole. Preliminary computations show that backlighters in the 8- to 10-keV range (below the Ta L edge) are well suited to follow the motion of a TaCOH outer shell almost up to the time of collision with the inner shell. However, the rapid increase in areal density ($\rho\Delta R$) near collision time requires backlighting at or above 25 keV to follow the interaction of the two shells, and an ability to probe deeper into the target will require sources with energies as high as 100 keV.

Although it will ultimately be necessary to image targets designed for high yield, such as the target described above, much of the data necessary to validate the computed behavior of laser fusion targets can be obtained with simpler target designs. In particular, targets that are thought at this time to best match the two-arm Novette laser, which will be built as a test-bed for the Nova laser design, will require backlighting at approximately 4.5 keV. In addition, some data on shock propagation through the ablator should be obtainable at 2.7 keV.

One additional constraint, synchronization, needs to be folded into the requirements for a backlighting source. It is necessary to synchronize, to within a few tens of picoseconds, the time at which the target irradiation occurs and the time at which the "picture" is obtained. This severe timing constraint is difficult to satisfy other than by using an optical pulse, synchronized with the main laser irradiation pulse, to generate the necessary x-ray backlighter. Consequently, our program has been investigating x-ray emissions from laser-irradiated plasma targets as possible backlighting sources. In particular, line emitters have been investigated,³ principally because the large concentration of energy in a very narrow frequency window can be tuned to the particular part of the target under investigation by a proper choice of material. Since the opacities of the target components change rapidly with frequency, a source with a narrow bandwidth has the additional advantage of simplifying the data analysis.

Backlighter Parameters Defined by Imaging Diagnostics

While the targets define the parameter space within which a backlighting source might be selected, the instruments used to diagnose a backlit target operate in restricted regions of this space. Therefore, different matrices of energy, duration, extent, and intensity of the source are required, depending on the imaging system used.

Two broad categories of instrumentation are being considered. The first category is designed to provide excellent time resolution, so that the motion of selected parts of the target can be followed over an extended period. An x-ray image is obtained by an x-ray microscope with a spatial resolution of a few micrometres at the target, and this image is projected onto the slit of a streak camera.⁴ In this way, temporal resolutions of about 10 to 15 ps can easily be obtained for streak times as long as 4 ns. However, this scheme provides information in one spatial direction only. (Note that pinhole cameras might also be used instead of the microscope if an acceptable tradeoff between spatial resolution and backlighter intensity can be found.) Mirrors for the x-ray microscope

can be made from special artificial crystals currently fabricated by Dr. Troy Barbee of Stanford University; these crystals provide narrowband ($E/\Delta E = 30$) channels for up to 10- to 12-keV x rays. The x-ray microscope requires a backlighter with a long duration (several nanoseconds). In one direction, the dimensions of the required source are defined by the projection of the slit width back through the optics to the backlighter location (typically 100 to 200 μm); in the other direction, the dimensions are defined by the required uniform backlighting of the target. Since the x-ray emitting region of a laser-irradiated disk target roughly corresponds to the laser-illuminated region, a cylindrical lens (or even an astigmatic lens) could be used to obtain a roughly elliptical emission region of the required size. This elliptical shape maximizes the laser intensity on the backlighter for a given input energy. However, this shape also makes alignment of the backlighter with the target and with the x-ray imaging optics more critical than if a more extensive circular beam pattern were used.

The second type of imaging scheme being considered is designed to provide two-dimensional images, which are particularly useful for assessing the symmetry and stability of the target implosion. These images can be obtained with x-ray microscopes, Fresnel lenses, or pinhole cameras coupled to either film or a CCD (charge-coupled device) array in the image plane. All of these systems require the use of extended backlighting sources. Alternatively, point-source projections can be used; such devices are being developed at LLNL under the acronym PIX (Point Imaging of X rays). The PIX systems require sources having a minimum extent, since the source size defines the spatial resolution.

Both the extended and point-source systems used for two-dimensional imaging require a means of freezing the target motion. This can be achieved either by using fast shutters (e.g., microchannel plates gated by Aston switches) or by using streak-camera framing techniques. In either case, a relatively long-duration x-ray backlighting source is usable. However, these systems are expected (at this time) to provide, at best, 100- to 200-ps frames. Therefore, it is desirable, to investigate the option of very short-duration (10- to 20-ps) x-ray backlighting sources that would act as a flash. In all cases, the power density of the x-ray backlighter on the recording medium defines the dynamic range of the instrument.

To assess whether appropriate sources are available for providing x-ray information on laser-irradiated high-density targets, a systematic study of the K lines of Ti, Ni, and Zn was performed. Further experiments with higher-energy lines are planned for a later time.

Backlighter Characterization Experiment

To a large degree, the usefulness of a backlighting diagnostic hinges on the amount of laser energy, E_L , required for the backlighter. For high-energy x-ray line emission, this laser energy can become significant, since line production exhibits a laser-intensity threshold that increases with line energy. The laser pulse duration also plays a significant role. Long pulses create enough hot plasma to allow the copious production of highly ionized atoms, which radiate He- and Li-like lines. Short pulses produce suprathreshold electrons, which induce fluorescence lines in cold matter; these lines dominate the radiated x-ray spectrum.

A knowledge of the spatial, spectral, and temporal behaviors of the line-emission source is necessary to determine which detection schemes can be used. As discussed above, streaked radiography requires a long-duration backlighter, while flash radiography requires very short

backlighting flashes to freeze the motion of imploding shells. It is the short-pulse technique that prompts our interest in the relative durations of the x-ray line emission and the heating laser pulse. The different imaging systems also impose different requirements on the extent of the backlighter; i.e., that it be either a point source or an extended region. Whether the latter option is viable depends on the relative sizes of the target and the backlighting region.

Experimental Setup

The 10 upper beams of the Shiva laser⁵ were used to irradiate the candidate backlighter disk targets. These targets, nominally 1000 μm in diameter and 25 μm thick, were tilted at 45° with respect to the laser beam-cluster axis to optimize the lines of sight of the diagnostic instruments.

The primary diagnostics used in these experiments were

- o A crystal spectrometer, the configuration of which was set to measure line emission in the appropriate range (from around 4.7 keV for Ti to around 9 keV for Zn) at 21° from the target normal.
- o The X-1 streak camera, which monitored the x-ray emission duration at a location 32° from the target normal.
- o A zone plate camera, located at 21° from the target normal, which was used to determine the camera response for various backlighter/target size ratios.
- o Two x-ray microscopes, one located at 45° and one located at 48° from the target normal in two orthogonal planes, which monitored the extent of the x-ray emission region below 2 keV. These microscopes provided an indication of where the laser beams were aligned on the target.

The laser was operated in either a long-pulse or a short-pulse configuration. For the long-pulse experiments, the oscillator was tuned to produce a pulse length (τ_L) of 600 ps (FWHM of a Gaussian pulse). The laser energy on target was varied from 500 to 3800 J. By adjustments to the laser-beam diameters at the target location, laser intensities (I_L) on target ranging from 10^{14} to 10^{17} W/cm² were explored.

For the short-pulse operation, the oscillator was tuned to produce a nominal $\tau_L = 100$ ps. Laser energy on target varied from 200 to 900 J, while I_L again spanned the range from 10^{14} to 10^{17} W/cm².

Conversion Efficiencies

Throughout this paper, ξ_x is the conversion efficiency for an x-ray line emitter and is defined as the number of photons per line (or line cluster, including the K $_{\alpha}$ and He- and Li-like lines) divided by the incident laser energy. For all the materials and laser-irradiation configurations tested during this experiment,

$$\xi_x \sim 10^{11} \text{ to } 10^{12} \text{ photon/J,}$$

in agreement with similar data obtained elsewhere.⁶ Typical energy conversion efficiencies ($\eta_x = \xi_x$ times line energy) are shown in Table 1.

Table 1. Line conversion efficiencies--fraction of incident energy.

Target	Line energy (keV)	Laser intensity (W/cm ²)	FWHM (ps)	Energy conversion (%)
Ti	4.8	3×10^{15}	600	0.06
Ni	7.8	3×10^{16}	600	0.08
Zn	9.0	3×10^{16}	600	0.02

To estimate the scaling of ϵ_x with laser energy, two titanium disks were irradiated at 3×10^{15} W/cm², but with different energies on target. (To maintain the same intensity, the size of the beams at the target location was changed.) In this pair of experiments, the measured conversion efficiencies were

$$\epsilon_x = 5.6 \times 10^{11} \text{ photon/J at 530 J.}$$

$$\epsilon_x = 5.7 \times 10^{11} \text{ photon/J at 2380 J.}$$

It thus appears that scaling with laser energy is linear; consequently, the balance of the experiments concentrated on determining the scaling of ϵ_x with laser intensity.

Variations in ϵ_x with I_L are best illustrated by the Ti data (Fig. 1) that were obtained over a wide range of laser intensities, pulse durations, and wavelengths. Whenever x-ray lines were obtained, the conversion efficiency increased with decreasing laser intensity. At a chosen laser intensity, some slight differences were observed (within error bars) between the data obtained at various laser wavelengths, with somewhat higher conversion efficiencies observed for shorter wavelengths. However, for a 1.06- μ m laser irradiation, no significant differences in ϵ_x were seen when the pulse length was varied from 100 ps to 2 ns at a fixed laser intensity. The observed variation in ϵ_x as a function of I_L is probably due to decreased laser absorption.

At short pulses ($\tau_L \sim 100$ ps), no Ti lines were observed for laser intensities lower than 3×10^{16} W/cm². At long pulses ($\tau_L = 600$ ps), Ti lines were obtained over the full range of intensities explored (1×10^{14} to 3×10^{16} W/cm²). We can speculate that some threshold laser intensity, I_T , exists at all pulse lengths, but lies below 3×10^{14} W/cm² for 600-ps irradiations. Interestingly, when frequency-doubled laser light is used at $\tau_L = 100$ ps, the threshold intensity lies below 10^{15} W/cm².

For the higher-energy backlighters (Ni and Zn), this threshold intensity, even at $\tau_L = 600$ ps, lies above 10^{16} W/cm² for 1.06- μ m irradiation. It thus appears that the emission lines of Ni and Zn will be useful only for systems requiring point sources if the laser energy necessary for producing these lines is to be kept within reasonable

Fig. 1. Conversion efficiency for Ti K lines.

limits. However, preliminary experiments at $\lambda = 0.35 \mu\text{m}$ have shown that the threshold intensity for Ni at $\tau_L = 600 \text{ ps}$ has decreased to below $2 \times 10^{15} \text{ W/cm}^2$, while ξ_x remains essentially the same. Hence, shorter-wavelength lasers may be considered for backlighter irradiation when high-energy extended sources are required.

Within the limited set of data available, the maximum ξ_x obtained for each tested backlighter decreases with x-ray line energy. At $1.06 \mu\text{m}$, no significant differences are apparent between yields of K and M shell radiation.⁷ However, K emission is preferred for backlighting purposes, since it provides a large line/continuum ratio.

Nature of Line Emission

The relative intensities of He- and Li-like lines from highly stripped ions and of K_{α} lines from essentially cold matter is a function of both laser pulse duration and laser wavelength.

Figure 2 shows a prominent nickel K_{α} line for $1.06\text{-}\mu\text{m}$ irradiation at $\tau_L = 100 \text{ ps}$ and $I_L = 5 \times 10^{16} \text{ W/cm}^2$. By contrast, at the same wavelength and about the same laser intensity ($\sim 3 \times 10^{16} \text{ W/cm}^2$), shots at $\tau_L = 600 \text{ ps}$ show a much larger relative intensity of the He- and Li-like lines. Similar behavior occurs for the other materials tested (Ti and Zn). These differences in types of emission indicate that, as the pulse duration increases, the laser is more efficient at heating the plasma, and the (volume) scale length of the highly ionized plasma increases. At the short pulse length and at high intensities, a large number of suprathermal electrons are available to excite lines in the cold matter,⁸ while the short time scale limits the degree of ionization into He- and Li-like states.

Spectral differences as a function of laser wavelength are displayed in Fig. 3 for Ti. Since the level of hot electrons decreases with

Fig. 2. Ni spectrum for
1.06- μ m irradiation.

Fig. 3. Ti spectrum for
100-ps irradiation.

decreasing wavelength,⁹ the spectra at shorter wavelengths show no sign of the cold K _{α} line that had been seen at 1.06 μ m. Even at the short pulse length, no cold lines are detected.

The lowering of the threshold intensity for line production with decreasing laser wavelength may be related to a weakening of transport inhibition.¹⁰ In addition, the increased electron density at the critical-density surface causes a decrease in collisional ionization time and, therefore, improves the probability of producing highly ionized and excited atoms that give rise to the He- and Li-like lines.

Temporal Behavior of the X-Ray Emission

A streaked crystal spectrograph is being built to investigate the duration of x-ray line emission. The present experiments used a filtered x-ray streak camera¹¹ with seven relatively broad channels ranging from 2.8 to 25.5 keV. Each individual line that was studied was contained in a specific channel and could be detected by the increase in brightness of that channel relative to the surrounding channels.

At a laser pulse length of 100 ps, Ti lines, which were predominantly He- and Li-like lines, followed the thermal x-ray channel behavior, while Ni and Zn lines occurred later in time (τ). It can be seen from Fig. 4 that, compared to continuum emission, the line emission occurred later in time and was of shorter duration. (In Fig. 4, E_x = x-ray energy.)

In all the shots for which streak-camera data were obtained, the high-energy x-ray channels ($h\nu > 4$ keV) lagged the thermal channel ($h\nu < 2$ keV) by 50 to 100 ps.

Fig. 4. X-ray streak record of emission from a Ni disk.

The timing of the lines shown in Fig. 4 might imply a delay in suprathedral electron production; alternatively, the timing could be an indication that these electrons have traveled on the order of a millimetre in the corona before interacting with the cold matter. This effect is not well understood at this time.

In all cases, the FWHM of the x-ray emission exceeded the laser pulse duration. In the channel containing the lines,

FWHM x-ray emission $\sim$ (1.4 to 2.4) laser-pulse FWHM.

In general, the duration of the x-ray emission increased with intensity on target at fixed z and decreased with z at given intensity. Closer examination of the data suggests that the FWHM of the line emission might be somewhat shorter than that of the continuum emission. The actual value of the FWHM cannot be determined, however, until experiments can be run with the streaked crystal spectrograph.

In the long-pulse experiments, only two shots yielded time information. Both of these shots showed an x-ray emission time that was shorter by approximately 25% than the laser pulse duration. Since no absolute timing was available, it is not possible to state unambiguously when the x-ray emission occurred with respect to the laser pulse.

Spatial Extent of the Line-Emission Region

Little information was gathered on the extent of the line-emission region in the plane of the backlighter, but additional experiments are being planned to determine this extent. Continuum x-ray emission in the 2-keV region was monitored with two x-ray microscopes, and the diameter of the x-ray emission region was found to closely match that of the laser spot size. For backlighting purposes, however, the x-ray emission of interest is not the thermal part of the spectrum. In particular, Ni and Zn lines, which are predominantly generated by hot electrons when short laser pulses are used, could emanate from a much larger region than the directly irradiated by the laser. The observed delay in x-ray line emission is compatible with the hypothesis that the lines are excited by electrons that have been reflected at some corona boundary and, therefore, could impact the target over a much wider area than the one in which they were generated. Zone plate camera data indicate that, at short laser pulses, the x-ray emission region is indeed larger than the nominal spot size. However, the camera imaged an x-ray backlit cold ball in these experiments, so the size of the x-ray line-emission area cannot be accurately determined; further experiments will be required to study this parameter.

On a few shots, an imaging spectrograph was used to determine the spectral characteristics of the x-ray emission as a function of distance along the normal to the disk. The data show a relatively large region of He-like line emission that compares well with computed estimates.¹² The cold K_{α} emission is confined to the disk surface, as would be expected from the hypothesis of hot electrons ionizing the cold matter.

For T_1 at $I_L \sim 4 \times 10^{14}$ W/cm², a wavelength of 1.06 μ m, and $\tau_L = 600$ ps, the measured x-ray emission scale length was 125 μ m. At $I_L \sim 2 \times 10^{15}$ W/cm², with wavelength and pulse length remaining the same, the Ni line (Fig. 9) exhibits a FWHM of 60 μ m. For these two cases, the laser spot size was 920 μ m and 100 μ m, respectively, on target.

For a given laser intensity on target, the x-ray emission scale length appears to increase with laser pulse duration. It is not known to what extent the observed increase is due to the smearing of a small emission region traversing the viewing zone of the spectrometer and to what extent it is due to a genuine increase in plasma scale length.

Summary

In terms of defining the potential of a method for backlighting laser fusion targets, the most important results of the backlighter characterization experiments are the existence of a laser intensity

threshold for x-ray line emission and the dependence of this threshold on laser wavelength. Indeed, for 8- to 9-keV backlighting, streak radiography is constrained by this threshold. A typical Nova target that would be investigated by a 12:1-magnification streaked x-ray microscope would require that the backlighter be irradiated with 10 kJ of 0.53- μ m laser light. This level of irradiation, which could be accomplished by using 1 of the 10 Nova beams, would provide a dynamic range capability of three orders of magnitude for the imaging system. At 1.06- μ m irradiation, the required energy would be prohibitive. Similarly, two-dimensional imaging with extended sources at 8 to 9 keV would be only marginally possible with a shuttered system (>100 ps) and would not be viable for flash systems (<100 ps), even with 0.53- μ m irradiations.

The data discussed above show that, with 1.06- μ m light, streaked radiography at 4.5 keV will require 1 TW for double-shelled Nova-type targets or 300 GW for smaller single-shelled targets. A 22:1 streaked microscope system would then provide a dynamic range of three orders of magnitude. Similarly, flash radiography at 8 to 9 keV using a PIX system will require 2.5 TW of 1.06- μ m irradiation to obtain a 10- μ m spatial resolution. Better focusing of the laser light on the backlighter could considerably reduce this power requirement.

Additional experiments will be performed to increase our knowledge of backlighter characteristics and, in particular, to determine the potential of shorter laser wavelengths for generating x-ray lines. Lowering the threshold of line excitation will allow either streaked or framing radiography to be performed at higher backlighting energies. At this time, however, it appears that, by allowing for frequency doubling of one of the Nova beams, both streaked and flash radiography at 8 to 9 keV will be possible.

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