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X-Ray-Interference Mirrors to Investigate
Energy Transport in Laser-Plasma Applications

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STREAKED SPECTROMETRY USING MULTILAYER X-RAY-INTERFERENCE
MIRRORS TO INVESTIGATE ENERGY TRANSPORT IN LASER-PLASMA APPLICATIONS*

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ABSTRACT

Transport of energy in laser-produced plasmas is scrutinized by devising spectrally and temporally identifiable characteristics in the x-ray emission history which identify the heat-front position at various times in the heating process. Measurements of the relative turn-on times of these characteristics show the rate of energy transport between various points. These measurements can in turn constrain models of energy transport phenomena. We are time-resolving spectrally distinguishable subkilovolt x-ray emissions from different layers of a disk target to examine the transport rate of energy into the target. A similar technique is used to measure the lateral expansion rate of the plasma spot. A soft x-ray streak camera with 15-psec temporal resolution is used to make the temporal measurements. Spectral discrimination of the incident signal is provided by multilayer x-ray interference mirrors. These synthetic x-ray crystals have been characterized for reflectivity and bandwidth and exhibit resolutions $\frac{E}{\Delta E}$ of 10 to 90.

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INTRODUCTION

The rate of energy transport in laser irradiated targets can be studied using spectrally-distinguishable x-ray emitting materials to signal the time-dependent heating rate at different positions in the target. Experiments can be designed with either axial or lateral variations in target materials, e.g. layered targets or annular target designs. Time-resolved measurements of the x-ray emission at appropriate photon energies can then establish the history of energy propagation in the experiment. Such measurements add additional experimental information to the active research areas of energy transport modeling and hydrodynamic simulation in the inertial confinement fusion community.

THE STREAKED SPECTROMETER

This paper describes a new instrument capable of the detailed measurements required for such experiments with five time-resolved narrow-band energy channels below one kilovolt. The energy channels consist of Bragg diffraction bands on the order of ~ 10 eV wide obtained from sputtered multi layer x-ray interference mirrors.¹ A soft x-ray streak camera^{2,3} is used to simultaneously time resolve the five side-by-side energy channels. A schematic representation of this streaked spectrometer and the layered target experiment are shown in Fig. 1. X-rays from the emitting plasma are diffracted from five separate multilayer strips onto the photocathode slit of a soft x-ray streak camera. The diffracted beams are passed through absorption filters before reaching the photocathode. This instrument combines the strengths of both multilayer interference mirrors and soft x-ray streak camera technology. The multilayer synthetic crystals can provide high reflectivity (1-40% in the subkeV region), narrow channel width, and versatile channel energy selection (variable d-spacing). When coupled with the temporal resolution (15 psec),^{3,4} large dynamic range⁵ (10^3), multichannel detection capability and shot-noise limited

sensitivity of the soft x-ray streak camera, a powerful diagnostic combination is produced for a variety of x-ray measurement requirements. Multi-channel, narrowband, temporally resolved data from recent energy transport experiments of the design described above are presented. Full analysis of these data will be published at a later time.

The energy channel positions of the five-channel streaked spectrometer system are very flexible. The initial system was designed to provide coverage of the subkilovolt region at 102-eV, 267-eV, 653-eV, 737-eV, and 943-eV photon energies. Multilayer designs used in this system are based upon Bragg angles near 25° . Relatively large Bragg angles decrease surface reflection and allow convenient alignment and instrument positioning. The multilayer materials are selected to give optimum reflectivity at the desired photon energies and the d-spacings are specified by the Bragg equation,

$$m\lambda = 2d_0 \sin \theta (1 - \delta/\sin^2 \theta)$$

Here δ is $1-n$, the index of refraction decrement, θ is the Bragg angle of diffraction, m is the diffraction order, λ is the x-ray wavelength, d_0 is the actual d-spacing of the material and $d_0(1-\delta/\sin^2 \theta)$ is the index-of-refraction-dependent effective d-spacing of the multilayer for the x-ray wavelength of interest.

Diffraction characteristics of the sputtered-multilayer synthetic crystals are measured using fluorescent line emission⁶ near the channel energies at which the multilayers are used. The effective d-spacings are obtained from the angle of the first-order Bragg peak. Integrated reflectivity (over diffraction angle) and the rocking curve width provide peak reflectivity (P%) and Bragg peak FWHM (ΔE) characteristics. These quantities are tabulated in Table 1.

Surface reflection, particularly at low x-ray energies, can impose a significant background of broad spectral character on the total signal in each detected channel. This low-energy background is reduced to acceptable levels using absorption filtering and large Bragg angles.

Figure 2 demonstrates the need and effectiveness of this filtering

technique for the 267-eV channel. The reflectivity of Ti/C multilayer at 25° is approximated by the reflectivity of a uniform 1:1 mix of carbon and titanium calculated using a semiclassical dispersion theory.⁷ This reflectivity added to the Bragg diffraction response of the multilayer is shown in the left-most box of Fig. 2. When the total multilayer response is multiplied by the transmission efficiency of a 2.65- μm thick carbon absorption filter, the transmitted contribution outside the Bragg peak at 267 eV is negligible as shown in the right box of Fig. 2. Absorption filters used to filter the five channels are listed in Table 1.

The five energy channels shown in Fig. 3 are calculated using the measured Bragg diffraction characteristics of the multilayers, calculated estimates of surface reflectivity, filter transmission efficiencies and the streak camera photocathode response. The CsI photocathode response is approximated here by an $E_p(E)$ energy deposition model⁸ scaled by the 50- $\mu\text{g}/\text{cm}^2$ carbon-foil-substrate transmission efficiency. Absolute calibration of the complete system response remains to be done.

ENERGY TRANSPORT MEASUREMENTS

Time-resolved measurements of x-ray emission from laser irradiated targets have been made at the Argus laser facility. The streaked spectrometer is positioned with 98-cm target-to-multilayer path and a 47-cm separation between the multilayers and the photocathode. Figure 4 is a streaked image of x-ray emission in the five channels from a 31-J, 1.06- μm , 735-psec laser irradiation of a Au disk at $\sim 3 \times 10^{14} \text{ W}/\text{cm}^2$ peak intensity. This raw data, originally recorded on Royal X Pan film, is converted to temporal profiles of x-ray intensity using a density-to-exposure stepwedge calibration of each piece of film. These temporal profiles, averaged over the spatial extent of the channel, are displayed in Fig. 5.

Experiments were performed to examine energy transport both into the disk target (radial transport) and in the lateral direction. Disk targets of Al with Be coatings at a variety of thicknesses were shot at

an intensity of $3 \times 10^{14} \text{ W/cm}^2$. Clear and repeatable temporal modulation of the emitted x-ray flux was observed from the layered targets. The character of the modulation changes with Be thickness and is consistent from shot to shot. Figure 6 is an example of ~ 450 -psec large scale structure on the emitted x-ray temporal profile. The target was an Al disk with a $0.27\text{-}\mu\text{m}$ Be coating. The incident $1.06\text{-}\mu\text{m}$, 89-J Gaussian laser pulse had a 720-psec FWHM. The temporal profiles in each of Figs. 6 and 7 are absolutely timed with respect to each other and are normalized to unit peak intensity for convenient comparison of relative temporal shapes. The 102-eV, 737-eV, and 943-eV channels are shown. The 267-eV and 653-eV channels exhibit similar structure. The emission history from a bare Al disk irradiated with a 742-psec, $1.06\text{-}\mu\text{m}$, 90-J laser pulse at $3 \times 10^{14} \text{ W/cm}^2$ is displayed in Fig. 7 for comparison. Again the 102-eV, 737-eV and 943-eV channels are shown. The temporal profiles from Al disks are much flatter on top than the Au disk data shown in Fig. 4 and have significantly longer emission times.

CONCLUSION

In summary, important narrow-energy-band, temporally-resolved information about energy transport in laser plasmas has been obtained using multilayer x-ray interference mirrors coupled to a soft x-ray streak camera. This diagnostic technique should stimulate much additional experimentation and analysis with emphasis on the spectrally-resolved temporal emission characteristics of the plasma to indicate energy transport properties.

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Table 1. Multilayer Interference Mirrors and Filter Characteristics

<u>Channel energy</u>	<u>102 eV</u>	<u>267 eV</u>	<u>653 eV</u>	<u>737 eV</u>	<u>943 eV</u>
Bragg Angle	25°	25°	27.1°	23.8°	25°
d-spacing (Å) ($d_{\text{eff}} = 143 \text{ Å}$)	178	55	21	21	15
Scattering material/ spacer	V/C	Ti/C	W/C	W/C	W/C
Width ΔE (eV)	10	7	8	8	10
Integrated reflectivity (mrad)	3.6	1.89	0.46	0.46	0.12
Peak reflectivity (%)	10.8	10.6	5.1	5.1	1.6
Filter material/ thickness	Be/1 μm	C/2.65 μm	Al/7000 Å	Al/7000 Å	Al/7000 Å

Figure Captions

- Figure 1 The streaked spectrometer system provides narrow-band, time-resolved, measurement of x-ray emission from laser plasmas. A Be-on-Al layered target is shown here. X-rays emitted from the laser-irradiated target are diffracted by five separate sputtered multilayer synthetic crystals onto the photocathode slit of a soft x-ray streak camera. The diffracted beams are filtered through thin absorption foils before reaching the photocathode.
- Figure 2 Absorption filters are used to eliminate the surface (Fresnel) reflection contribution to the diffracted signal. The 267 eV 55-Å spacing Ti/C channel is shown here. Surface reflection is approximately calculated with a semi-classical model using a 1:1 mix of titanium and carbon. The Bragg diffraction peak superimposed on this surface reflection is shown in the first box. The transmission function of a 2.65- μm thick carbon foil (second box) is used to filter the signal from the multilayer. The combined response of the channel in the third box shows that the reflective background is reduced to a negligible level.
- Figure 3 Spectral response of five narrow-band Bragg diffracted energy channels below one kilovolt. Measured Bragg peak characteristics of the multilayers are combined with calculations of surface reflectivity, filter absorption and CsI photocathode efficiency to obtain these estimates of the total system response.
- Figure 4 Raw data streaks in five channels obtained from the x-ray emission of an Au disk target. The target was heated by a 1.06- μm , 31.5-J, 735-psec laser pulse at $\sim 3 \times 10^{14} \text{ W/cm}^2$ peak intensity.
- Figure 5 Temporal x-ray emission profiles of the data displayed in Fig. 4. Raw film density data is converted to intensity using individualized stepwedge calibration of the Royal X Pan film. This technique preserves the large dynamic range characteristics of the data.
- Figure 6 Temporal emission history of a 0.27- μm Be coated Al disk in three spectral channels. Large scale temporal modulation is clearly evident in the two higher-energy channels. The three channels are normalized to unit peak intensity. The target was heated by a 1.06- μm , 89-J, 720-psec gaussian laser pulse at $3 \times 10^{14} \text{ W/cm}^2$.
- Figure 7 Temporal emission history of a bare Al disk in three spectral channels. Channels are normalized to unit peak intensity. The target was irradiated by a 1.06- μm , 90-J, 742-psec gaussian laser pulse at $3 \times 10^{14} \text{ W/cm}^2$.

Fig. 1

Fig. 2

Fig. 3

Argus/1.06 μm
31.5 J/735 psec
3 $\times 10^{14}$ W/cm²
Au disk
No. 31051214
SX-8/CsI

102 eV
287 eV
943 eV
953 eV
737 eV

ΔE 10 eV
Time
500 psec

Fig. 4

Fig. 5

Fig. 6

Fig. 7