Enhancement of soft x-ray emission using prepulses with 2ω and 4ω laser plasmas

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Dependence of x-ray emission efficiencies on a plasma volume were obtained for a 527 nm laser with Cu targets and for 263 nm with Cu and Au targets using the same prepulse technique as the one used by Kodama *et al.* [Appl. Phys. Lett. **50**, 720 (1987)]. 4ω results indicate that a maximum of three times increase was observed in soft x rays ($h\nu = 100$–200 eV), while no appreciable increase was observed in hard x rays ($h\nu = 1$–3 keV). From 2ω results, a factor of 2 for the soft x rays and a factor of 3 for the hard x rays were observed.

The study of x-ray emissions from laser-produced plasmas is currently a subject of great interest,[1–7] since the emissions may be utilized as an energy driver of indirect drive targets of inertial confinement fusion and an exposure source of x-ray lithography. It is particularly important for both purposes to study details of x-ray spectra[1,3,6] and to know how to increase the x-ray emissions.

We measured soft ($h\nu = 100$–280 eV) and hard ($h\nu = 1$–3 keV) x-ray emissions from 2ω and 4ω laser plasmas with long density scale lengths using a double-pulse technique. In the 4ω experiment, the soft x rays from Au targets showed a maximum increase of three times compared to the value taken without a prepulse, while the hard x rays did not show any appreciable amount of increase. Similar but less pronounced features of the x-ray emissions were observed for Cu targets. In the 2ω experiment the soft x rays from Cu targets showed an increase by a factor of 2, while the hard x rays demonstrated a factor of 3 increase. In this communication we focus our attention mainly on the soft x rays because detailed discussions of the hard x rays have already been published.[8]

Experiments were carried out using three beams of the Gekko IV Nd:glass laser four-beam system: a first beam for a 1053 nm prepulse, a second for a 527 nm main pulse, and a third for a 263 nm main pulse. In the 2ω experiment the 527 nm main laser pulse of 200 ps full width at half maximum (FWHM) preceded by the 1053 nm prepulse (200 ps FWHM) were focused onto Cu targets through aspherical lenses of $f/1.6$ and $f/8$ with incidence angles of 35° and 22.5° to the target normal, respectively. Intensity of the main laser pulse (2ω) was fixed at 10^{14} W/cm^2. In the 4ω experiment, the 263 nm main laser pulse (200 ps FWHM) and the 1053 nm prepulse (200 ps FWHM) were focused through $f/8$ spherical lenses with incidence angles of 0° and 45° onto Cu or Au targets. Intensity of the main pulse was 10^{14} W/cm^2. For both experiments prepulse laser intensities were varied from 2 to 8×10^{13} W/cm^2. Time delay from the prepulse to the main pulse was also varied from 1 to 3 ns.

X-ray energy measurements were conducted with an Al photocathode biplanar x-ray diode (XRD) with various filters.[1] Since the XRD's temporal resolution was 350 ps, x-ray pulses from pre- and main pulses could be discriminated. The x-ray conversion efficiency discussed in this paper is defined as 100 times the ratio of the measured x-ray fluence divided by the main laser energy per unit solid angle. X-ray pinhole pictures were taken to monitor the coalignment of the focal spots created by the pre- and main pulses on the target.

Figures 1(a) and 1(b) show soft ($\eta_{\rm soft}$) and hard

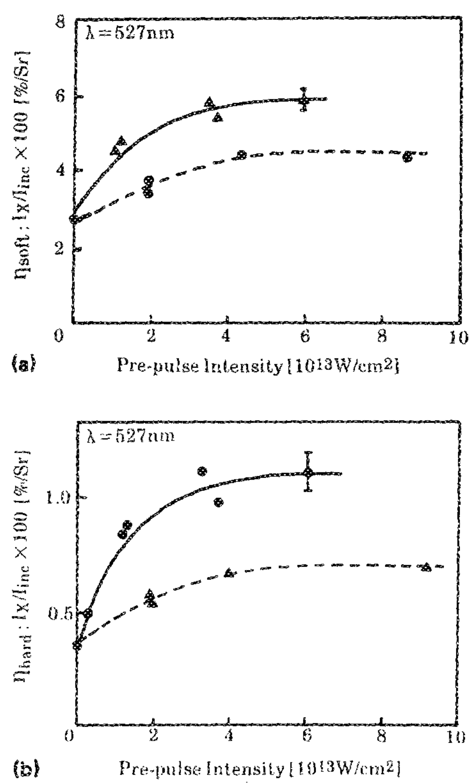

FIG. 1. (a) X-ray conversion efficiency ($\eta_{\rm soft}$: $h\nu = 100$–280 eV) from Cu target as a function of prepulse intensity for variable delays (▲ 1.1 ns and ● 1.8 ns). The 2ω main pulse intensity was at 10^{14} W/cm^2. (b) X-ray conversion efficiency ($\eta_{\rm hard}$: $h\nu = 1$–3 keV) from Cu target as a function of prepulse intensity for variable delays (▲ 1.1 ns and ● 1.8 ns). The 2ω main pulse intensity was at 10^{14} W/cm^2.

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(η_{hard}) x-ray conversion efficiencies versus prepulse intensity in the 2ω experiment. η_{soft} increases with the prepulse intensity. A 100% increase from the single pulse case is observed for different time delays [Fig. 1(a)]. Figure 1(b) shows a case for η_{hard}. In contrast to η_{soft}, η_{hard} shows an increase of 2 to 3 times the value with a single pulse, depending on the time delay.

Shown in Fig. 2 are x-ray generation efficiencies of Au targets as a function of prepulse laser intensity in the 4ω experiment. Figure 2 elucidates cases for two energy bands: Fig. 2(a) for $h\nu = 100$–280 eV and Fig. 2(b) for $h\nu = 1$–3 keV. In Fig. 2(a), η_{soft} shows some increase with the prepulse laser intensity for the time delays of 1.5 and 2 ns. At the highest prepulse intensity of 8×10^{13} W/cm^2, η_{soft} doubles the value taken without the prepulse for a 2 ns delay and triples for a 1.5 ns delay. For the 3.5 ns time delay η_{soft} was independent of the prepulse intensity. A plasma created by a prepulse could well expand in a three-dimensional way and then the plasma might not affect the x-ray production anymore when the separation between the two pulses became too wide. We consider that the distinctive difference of η_{soft} for the 2.0 and 3.5 ns delay is due to the above effect. In Fig. 2(b) there is no pronounced increase of x rays (η_{hard}), but η_{hard} is rather constant. For the 2 ns separation one might see a slight increase with prepulse laser intensity. Similarly in Fig. 3, η_{soft} and η_{hard} of Cu targets are shown. Overall trends with prepulse intensity are very close to the ones with Au

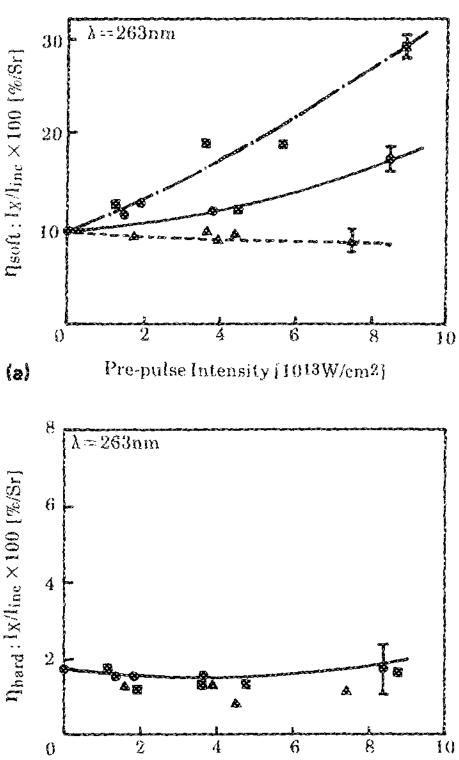

FIG. 2. (a) X-ray conversion efficiency (η_{soft}: $h\nu = 100$–280 eV) from Au target as a function of prepulse intensity for variable delays (■ 1.5 ns, ● 2.0 ns, and ▲ 3.5 ns). The 4ω main pulse intensity was at 10^{14} W/cm^2. (b) X-ray conversion efficiency (η_{hard}: $h\nu = 1$–3 keV) from Au target as a function of prepulse intensity for variable delays (■ 1.5 ns, ● 2.0 ns, and ▲ 3.5 ns). The 4ω main pulse intensity was at 10^{14} W/cm^2.

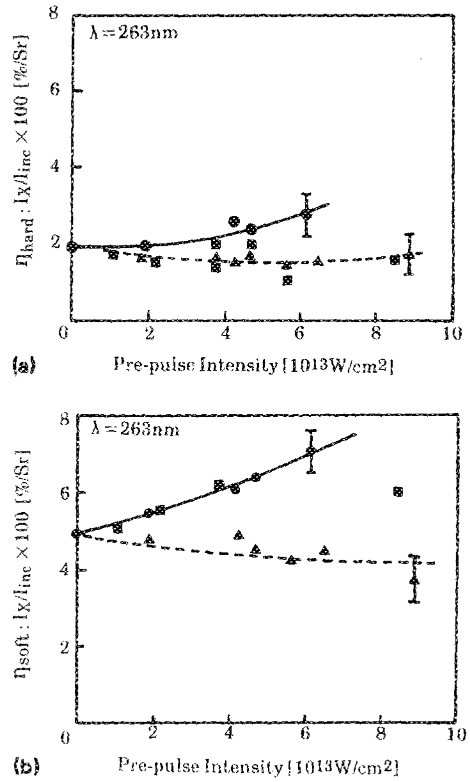

FIG. 3. (a) X-ray conversion efficiency (η_{soft}: $h\nu = 100$–280 eV) from Cu target as a function of prepulse intensity for variable delays (■ 1.5 ns, ● 2.0 ns, and ▲ 3.5 ns). The 4ω main pulse intensity was at 10^{14} W/cm^2. (b) X-ray conversion efficiency (η_{hard}: $h\nu = 1$–3 keV) from Cu target as a function of prepulse intensity for variable delays (■ 1.5 ns, ● 2.0 ns, and ▲ 3.5 ns). The 4ω main pulse intensity was at 10^{14} W/cm^2.

targets. η_{soft} increases with the prepulse intensity for both 1.5 and 2.0 ns time delays, while η_{hard} is rather insensitive to the prepulse intensity. The maximum amount of increase for the 2.0 ns time delay is about 50%. η_{hard} shows an increase when the prepulse intensity exceeds 3×10^{13} W/cm^2.

We discuss physical aspects about the increase of η_{soft} and then those of η_{hard}. η_{soft} was found in the 4ω experiment to increase with the prepulse intensity. X-ray pinhole camera images also indicated that the x-ray emitting volume was lengthened along the main laser axis only when the prepulse was introduced. While η_{soft} in the 2ω experiment showed an increase comparable to those in the 4ω experiment, η_{hard} in the 2ω showed a distinctive difference from η_{hard} in the 4ω. In the 4ω plasmas, however, soft x rays are the primary product because of their high critical density ($n_c^{4\omega} = 1.6\times10^{22}$ cm^{-3})[2] and short absorption length. The absorption length is defined as $L_{\mathrm{abs}} \sim c/\nu_{ei}$ for classical absorption, where c is the speed of light and ν_{ei} is the electron-ion collisional frequency. Noting that $L_{\mathrm{abs}} \propto \lambda_L^2$ (λ_L: laser wavelength) 4ω laser light could be absorbed within a plasma whose scale length is four times smaller than that for a 2ω laser, assuming that plasma temperatures are the same for both laser wavelengths. This explains that the hard x ray ($h\nu = 1$–3 keV) does not increase until a relatively long density scale length is prepared for the main pulse. Plasma temperature is another major factor to determine the x-ray emissivity. From numerical calculation results,[9] electron temperatures around the critical density at the peak of the main pulse are not affected by plasma sizes of up to 50 μm, in those scalelengths in both 2ω and 4ω experiments, indicating that the x-ray emissivity is mainly a function of the emitting volume. In the 4ω experiment it is primarily soft x-ray emission that increases 2–3 times when the emitting volume is lengthened, while it is both soft and hard x rays that showed factors of 2–3 increase in the 2ω experiment. The above difference in the photon energies should be due, solely, to the difference in the critical densities of the two (2ω and 4ω) lasers.

In the 4ω experiment, η_{hard} ($h\nu = 1$–3 keV) starts increasing at above 3×10^{13} W/cm^2 of the prepulse intensity. This is clearly seen for the Cu target in Fig. 3(b). For x rays above 1 keV to be emitted effectively, a large and hot corona region is required.[10] As the extent of the preplasma increases with the prepulse intensity, first η_{soft} shows an increase because the emitting volume becomes larger. Then, underdense plasmas with density scale lengths longer than the ones at around the critical densities begin to absorb the incoming laser flux. In plasma densities lower than the critical density, the plasma could be heated to higher temperatures for a given absorbed laser flux, resulting in an increase of η_{hard}.

The dependence of the x-ray conversion efficiencies on the plasma-emitting volume was obtained for the 2ω laser with Cu targets and for the 4ω with Cu and Au targets using a prepulse technique. The 4ω results indicate a maximum factor of 3 increase in the soft x rays ($h\nu = 100$–280 eV), while the 2ω results showed a threefold increase of hard x rays ($h\nu = 1$–3 keV) and an increase by a factor of 2 for soft x rays. There was an indication in the 4ω experiment that the hard x rays may increase when very long density scale lengths were created by the highest prepulse intensity.

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