Prepulse effect on laser-induced water-window radiation from a liquid nitrogen jet

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The authors show the prepulse effect on the conversion efficiency of a visible laser into water-window (λ=2.3–4.4 nm) x ray from a liquid nitrogen jet. It is observed that a prepulse of only 2 mJ enhances the conversion efficiency by 10–15 times for the main pulse of 15–60 mJ at a delay of 3–6 ns. The photon flux is $\sim 1.2 \times 10^{12}$ photons/pulse sr at a delay of 4 ns for a main pulse of 60 mJ with a prepulse of 4–8 mJ. It is noticed that the conversion efficiency increases with the delay up to 3 ns and is then saturated. © *2007 American Institute of Physics*.
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Along with the development of high-power laser technology, the interactions of high-power lasers with various targets have been studied for radiation sources, because laser-produced plasmas are promising compact x-ray sources that can be broadband or quasimonochromatic with an appropriate choice of materials and lasers. For example, a 13 or 13.5 nm radiation has been investigated with extreme ultraviolet (EUV) lithography,[1–7] the water-window (λ=2.3–4.4 nm) radiation with soft x-ray microscopy,[8–13] and the hard x-ray radiation with medical imaging or material testing.[14–18]

It has been known that the conversion efficiency (CE) is enhanced by the introduction of a prepulse.[2–6,12–18] To obtain an optimal lithography source at 13.5 nm, Rajyaguru *et al.* reached the maximum CE at a delay of 100–130 ns between the main pulse and the prepulse for a Li-contained water-based continuous jet using a 10 ns, 532/1064 nm Nd:YAG laser (YAG denotes yttrium aluminum garnet).[3] Also using a similar laser, Higashiguchi *et al.* obtained the optimized CE at a delay of 100 ns for a SnO_2-contained liquid jet,[4] and at a delay of 20–50 ns for a planar lithium.[5] For the same purpose, Dunne *et al.* used a 170 ps, 1064 nm Nd:YAG laser to obtain the maximum CE of (4.8±1.5)% into 3% bandwidth at 8.8 nm for a 10% Ce-doped glass target at a delay of 5.1 ns (Ref. 6) and Düsterer *et al.* has studied the prepulse effect on the generation of 13 nm radiation from water droplets for different parameters of a prepulse such as pulse width, energy, and delay.[2] For an optimal water-window source, Berglund *et al.* has used a ultraviolet prepulse to enhance the soft x-ray flux at 3.37 nm from ethanol droplets.[13] These results indicate that proper conditions for a prepulse such as prepulse energy and delay time depend sensitively on the laser specification and target.

Recently a liquid nitrogen jet plasma[9,10] has drawn attention as source for a water-window x-ray microscope because it can emit a strong monochromatic radiation at 2.88 nm and is inherently debris-free. The prepulse effect in the case of the liquid nitrogen jet target[12] has not been known much, so the systematic investigation of prepulse effect in terms of a prepulse and main pulse energy, and the delay between two pulses has been carried out in this letter. The experimental arrangement is schematically shown in Fig. 1. A high-purity nitrogen gas was cooled and liquefied through the cooling stages to make a liquid nitrogen jet.[9] In this study we used a 13 μm diameter nozzle to form a 12 μm liquid nitrogen jet and a 532 nm, 120 ps Nd:YAG laser operating at 10 Hz. The laser was split by a beam splitter (BS, $R_s \sim 70\%$ and $R_p \sim 30\%$) into two laser beams. The energies of the laser beams can be controlled by rotating the polarization of the laser beams with a wave plate. One beam (main pulse) goes through a delay line. The other (prepulse) goes through another set consisting of a wave plate and a polarizer ($T_s \sim 0\%$ and $T_p > 95\%$) which further controls the beam energy. The prepulse is polarized horizontally to the optical table. The polarization of the main beam is the mixture of horizontal and vertical polarization, depending on the energy: 15 mJ for pure horizontal polarization, 60 mJ for pure vertical polarization, and in between for mixed polarization. These two pulses with intended energies and a delay between them

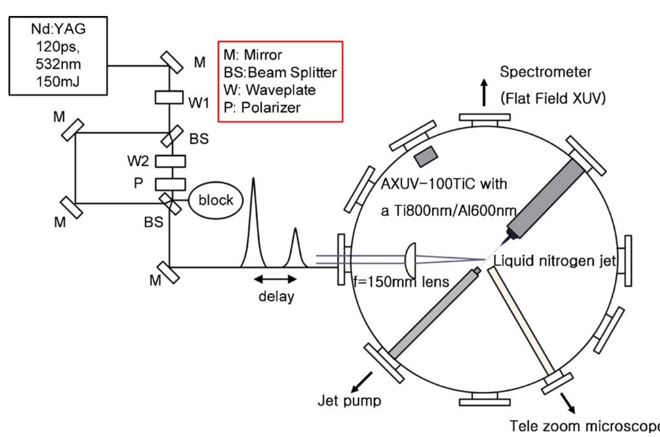

FIG. 1. (Color online) Schematic experimental setup for water-window plasma sources using a liquid nitrogen target. The angle between the jet direction and the laser propagation was 135° due to the experimental arrangement.

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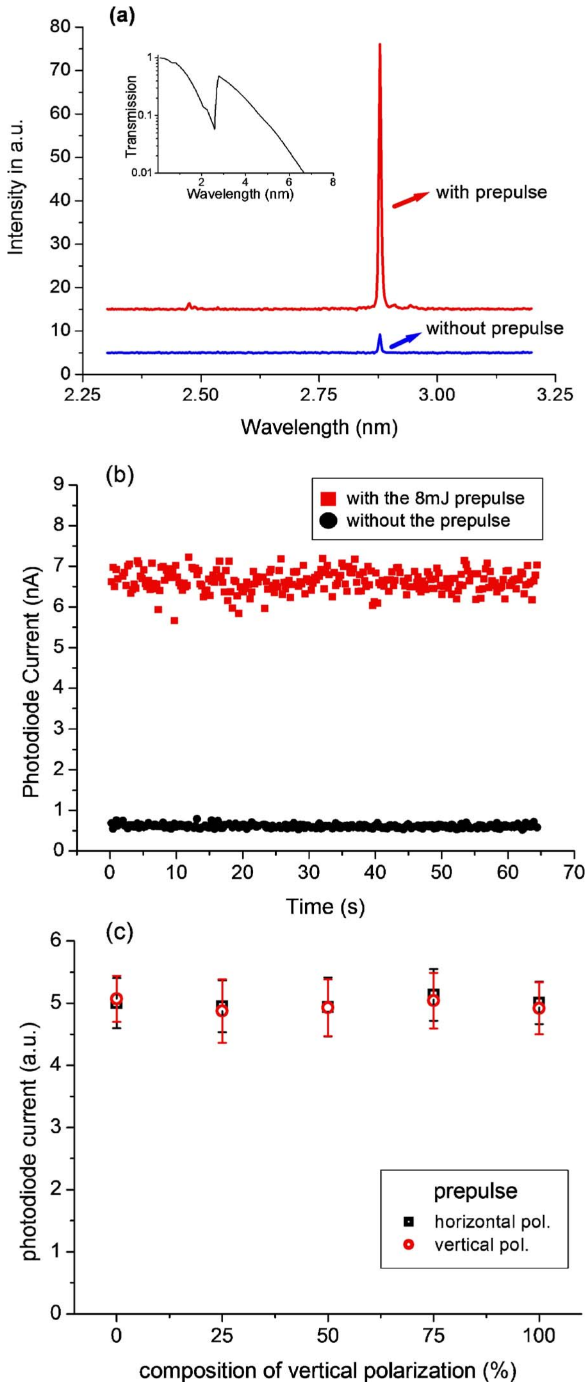

FIG. 2. (Color online) Spectra (a) and photodiode current (b) with and without the prepulse: 60 mJ main pulse, 8 mJ prepulse, 6 ns delay. The spectra of the water-window region were obtained with Ti 200 nm/Al 150 nm filter. [The transmission of this filter is shown in the inset of (a)]. The AXUV-100TiC (Ref. 21) photodiode current was obtained with an additional Ti 800 nm/Al 600 nm filter. (c) The effect of the polarization of main pulse and prepulse on the emission intensity. The photodiode currents (proportional to the emission intensity) is shown as a function of the polarization composition for a main pulse energy of 30 mJ at a delay of 3 ns.

were combined at another BS, forming a train of two pulses. The delay time was varied from zero to 6 ns. This pulse train was focused by a $f=150$ mm lens onto a jet at an angle of 135°, as shown in Fig. 1. The focal spot size was measured to be about 20 μm full width at half maximum in diameter.

To obtain the absolute intensity of the 2.88 nm radiation, the spectrum was measured using a flat field spectrometer[19] and an absolutely calibrated soft x-ray photodiode

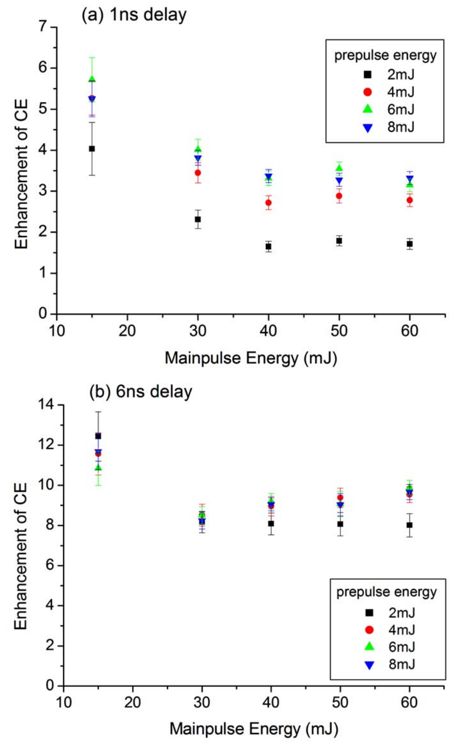

FIG. 3. (Color online) Enhancement of the CE as a function of the main pulse energy at the 1 ns delay (a) and at 6 ns delay (b).

(AXUV-100TiC[21]) with a Ti 800 nm/Al 600 nm filter. The spectra served us by providing the information on the relative ratios between spectral lines integrated by the x-ray photodiode and by monitoring the change of the spectral components with the change of laser parameters.

Figures 2(a) and 2(b) show typical quasimonochromatic spectra and photodiode currents obtained with and without a prepulse. The main pulse energy was 60 mJ. The fluctuation of the current signal is less than 10%. The spectrum clearly shows that the main contribution to the photodiode current comes from the 2.88 nm light, indicating that the enhancement of the 2.88 nm light is responsible for the increase of the photodiode current by a factor of about 11. We have done a series of experiment to study the effect of polarization on the production of emission. It was done at a delay of 3 ns with a main pulse energy of 30 mJ and a prepulse energy of 4 mJ. An additional wave plate and a polarizer were inserted to the main pulse beam line to set a polarization composition for a given main pulse energy. For a given polarization of the prepulse (horizontal or vertical), the composition of the polarization of the main pulse changed from pure vertical to pure horizontal polarization. The results, as shown in Fig. 2(c), reveal that the emission intensity is independent of the polarization.

We investigated the prepulse effect by changing the prepulse energy, the main pulse energy, and the delay between the two pulses. The enhancement of CE (the ratio of the CE with a prepulse to that without a prepulse; CE is evaluated assuming the emission of the radiation is isotropic, as demonstrated in the previous work[9]) is a function of the prepulse and the main pulse energy and is shown in Fig. 3. Figures 3(a) and 3(b) are the plots of the CE enhancement versus the main pulse energy at different delays of 1 and 6 ns, respectively. Note that a higher enhancement is achieved for lower main pulse energy. The enhancement at

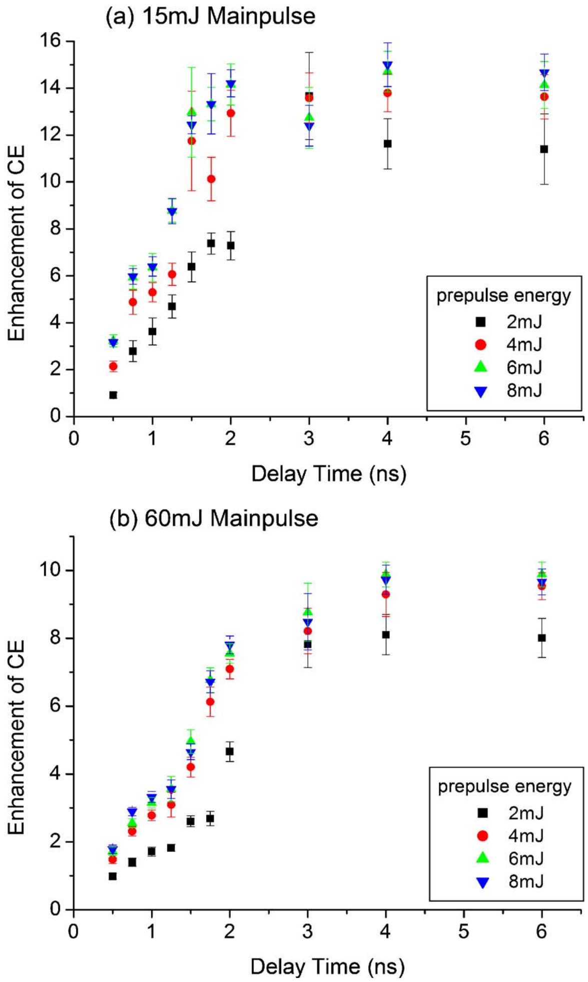

FIG. 4. (Color online) Enhancement of the CE as a function of the prepulse energy and the delay time (a) at 15 mJ main pulse and (b) at 60 mJ main pulse.

1 ns delay is smaller than that at 6 ns delay, indicating that the 1 ns delay is too short for a proper preplasma to be formed. At 1 ns delay, 2 mJ of the prepulse energy is not sufficient, and at the 6 ns delay, the enhancements are more or less the same for the prepulse energy of 2–8 mJ. Especially, the enhancement in the case of 15 mJ main pulse is conspicuous. The results indicate that the main pulse energy is not a critical parameter when the main pulse energy is larger than 30 mJ.

Figure 4 shows the enhancement of CE as a function of the delay time and the prepulse energy for the main pulse energy of 15 and 60 mJ. The largest enhancement of 15 is observed for a prepulse energy of 8 mJ and a main pulse energy of 15 mJ at a delay of 4 ns, while for 60 mJ main pulse energy the enhancement by a factor of about 10 is obtained. This large enhancement has been understood in terms of the increased inverse-bremsstrahlung absorption due to the expanding preplasma volume enhancement.[13] Note that the prepulse of 2 mJ is not enough to make the proper preplasma as the delay time get shorter. The CE enhancement by the 2 mJ prepulse is lower by 20% for the delay longer than 3 ns and even by 100% for the delay of 0.5 ns than that by higher prepulse energies. The results also reveal that the enhancement increases with the delay of up to 3 ns and is then saturated. Düsterer *et al.*[2] has observed the similar behavior in their experiments with 20 μm diameter water droplets. They have carried out the simulation using one-dimensional hydrodynamic code MEDUSA (Ref. 20) and atomic physics codes. The simulation results showed the large enhancement but failed to explain the monotonic increase of CE for short delays: the three-dimensional (3D) expansion is speculated to play a role. The 3D hydro-atomic simulation is under preparation.

The number of photons has been estimated by using the photocurrent of an absolutely calibrated soft x-ray photodiode, and the spectrum for relative intensities of spectral components integrated by the said photodiode. The photon flux estimated is $\sim 1.2 \times 10^{12}$ photons/pulse sr at a delay of 4 ns for a main pulse of 60 mJ with a prepulse of 4–8 mJ.

In summary, we investigated the prepulse effect, using 12 μm diameter LN_2 jet, to enhance the x-ray emission into water window for soft x-ray microscope. We observed the improvement of the CE by a factor of 10–15 for main pulse energies of 15–60 mJ by introducing the prepulse of more than 2–8 mJ at 3–6 ns delay between the main pulse and the prepulse. At the delay shorter than 3 ns, the proper preplasma is not formed so that the CE enhancement is lower than that at 3–6 ns delay for any prepulse energy. The enhancement is higher for small main pulse energy than for large main pulse energy.

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