Optimization of laser parameters for the maximum efficiency in the generation of water-window radiation using a liquid nitrogen jet

B. Kim
Department of Physics, Pohang University of Science and Technology (POSTECH), Pohang 790-784, Korea

B. Ahn, D. Lee, and J. Kim
Vacuum and Measurement Technology, Pohang 790-320, Korea

D. Kim
Department of Physics, Pohang University of Science and Technology (POSTECH), Pohang 790-784, Korea

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A laser-produced plasma is a suitable compact x-ray source that can be of broad band or quasimonochromatic with a proper choice of material and filter. To address the maximum conversion efficiency for an efficient, quasimonochromatic source at 2.88 nm (N VI $1s^2$-$1s2p$ transition) using liquid nitrogen jet for soft x-ray microscopy, the radiation characteristics such as absolute intensity, spectra, and angular distribution have been investigated for different laser pulse durations (picosecond and femtosecond pulses) and laser energies The comparison of conversion efficiencies between picosecond [120 ps full width at half maximum (FWHM)] and femtosecond (40–500 fs FWHM) lasers indicates that the picosecond laser would provide better conversion efficiency, which is 1.6% at 2×10^{13} W/cm^2. The investigation shows that the laser intensity for the maximum conversion efficiency scales as $I_m \propto 1/\tau^{\alpha}$, where $\alpha=0.9\pm0.15$. This empirical formula is useful to choose the laser parameters properly for a given pulse width. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2192088]

Due to the development of high-power laser technology, laser-produced plasmas have become excellent compact short-wavelength sources for various purposes.[1–6] To make an efficient source, the condition for maximum conversion efficiency at a desired wavelength should be found.[7–9] The desired wavelength varies, depending on an application. For example, the 13 nm radiation is needed for extreme ultraviolet (EUV) lithography, the water-window radiation for soft x-ray microscopy, and the hard x-ray radiation for medical imaging. The optimal conditions for the 13 nm radiation have been actively investigated. In these works, various experimental parameters such as laser pulse duration, laser intensity, laser focal spot size, and target material were searched to improve efficiency.[7,8] The laser intensity dependence of conversion efficiency to 0.6–1.4 nm radiation from copper plasma was studied using 4 and 150 ps lasers.[9–11] The prepulse effect on the generation of 0.2 and 0.8 nm radiations was investigated using a 90 fs laser.[12] In the water-window region, not only solid targets[6] but also liquid jets and droplets[13–15] of ethanol, methanol, and nitrogen have recently been investigated due to debris problem. The generation of the water-window radiation versus the pulse duration of a femtosecond laser has been studied using carbon and Al plasmas.[16,17] However, there is still a lack of information about the characteristics of the conversion efficiency related to laser parameters, which helps one to select the laser parameters for the maximum efficiency.

In this letter, we present the study of the dependence of the conversion efficiency on laser parameters such as energy and pulse duration for the 2.88 nm radiation from a liquid nitrogen jet. For this purpose, a series of the experiments has been performed for the measurement of the absolute intensity of the 2.88 nm radiation from a liquid nitrogen jet for various laser parameters. The study results in an empirical formula that tells us what laser parameters should be used to efficiently generate 2.88 nm radiation for a given laser pulse duration in the range of femtoseconds to nanoseconds.

The experimental apparatuses used in this study are shown schematically in Fig. 1. A high-purity and high-pressure nitrogen gas was fed into a gas line and then into a capillary with a tapered nozzle at the other end. The nitrogen gas was cooled and liquefied by two liquid nitrogen cooling stages. Especially the first cooling stage further removes residual water vapor in the nitrogen gas. This removal is important to form a stable liquid jet for a long duration because tiny ice pieces from water vapor may block the nozzle. The liquid nitrogen was then injected into a vacuum chamber through a capillary nozzle. For a stable jet, a nozzle has to be tapered. The tapering of a nozzle with an angle at least larger than 15° was recommended.[18] We used the nozzle that has a tapering angle of 20°.

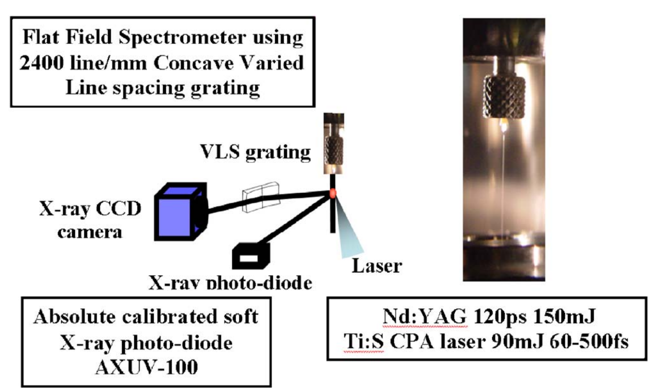

FIG. 1. Experimental setup for water-window source using a liquid nitrogen jet target.

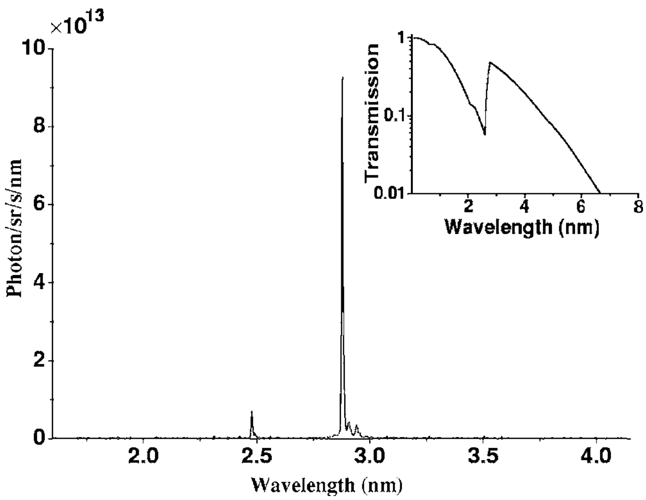

FIG. 2. Spectrum in the water-window region produced from liquid nitrogen at a laser intensity of 1.5×10^{14} W/cm^2 of 120 ps pulsed Nd:YAG laser. A Ti 200 nm/Al 150 nm filter was used for quasimonochromatic spectrum. The inset is the transmission curve of the filter.

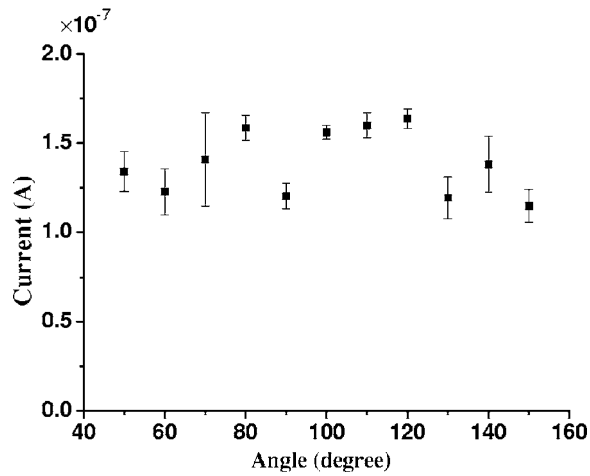

FIG. 3. Angular distribution of the 2.88 nm radiation at a laser intensity of 1.5×10^{14} W/cm^2 of 120 ps pulsed Nd:YAG laser.

The backing pressure and nozzle diameter are also important factors for a stable operation. The investigation tells us that the backing pressure of 0.5–3.0 MPa for 10–30 -μm-diam nozzle is a suitable condition for a stable liquid nitrogen jet. For example, for a 12-μm-diam nozzle with a backing pressure of 0.5 MPa, a stable jet region of about 700 μm length was obtained. This region is so stable that it vibrates less than 2 μm. By increasing the backing pressure, the stable region can be extended to several millimeters at the cost of the vacuum. The higher pumping speed is needed to maintain a vacuum of a few mTorr. The data presented below were obtained using a nozzle with a diameter of 12 μm. The diameter of the formed jet was about 10 μm.

Two different high-power laser systems were used in this work. The first one is Nd:YAG (yttrium aluminum garnet) laser at 532 nm at 10 Hz whose pulse duration is 120 ps and maximum energy of 150 mJ/pulse. The other one is a Ti:S laser at 10 Hz that has a tunable pulse duration from 40 to 500 fs and a maximum energy of 90 mJ/pulse. The pulse width is controlled by the grating separation in a compressor. A $f=150$ mm lens was used for the Nd:YAG laser and $f=200$ mm lens for the femtosecond laser. The focal spot size measured was about 20 μm in diameter for both lasers.

The x-ray source size was measured by a pinhole camera with x-ray charge coupled device (CCD) camera at an intensity of 1.5×10^{14} W/cm^2 of the 120 ps laser. The x-ray emitting area was observed to be about 20×10 μm^2, elongated due to the fact that the diameter of the nozzle is smaller than the diameter of the focal spot size of the laser.

A flat field spectrometer (FFS) and an absolutely calibrated x-ray photodiode[19] were used to characterize radiations. The FFS is equipped with a 2400 line/mm grating and a soft x-ray CCD. Figure 2 shows a typical quasimonochromatic spectrum obtained with a Ti 200 nm/Al 150 nm filter (the inset shows the transmission of the filter). A strong single line is N VI $1s^2$-$1s2p$ transition at 2.88 nm and the weak one N VII $1s$-$2p$ transition at 2.48 nm. This quasimonochromatic radiation is well suited to an imaging with zone plates. The angular distribution of the radiation was measured by rotating the x-ray photodiode around the jet. The results obtained using the 120 ps pulsed Nd:YAG laser at an intensity of 1.5×10^{14} W/cm^2, shown in Fig. 3, reveal that the emission of the radiation is isotropic. The FFS spectrum gives the relative ratios of spectral lines and the signal from the absolutely calibrated x-ray ultraviolet (XUV) photodiode gives the total intensity of XUV photons. A straightforward manipulation of these two pieces of information leads to the absolute intensity of the 2.88 nm radiation. The estimated photon number of 2.88 nm light is 4×10^{11} photons sr^{-1}/pulse at an intensity of 1.5×10^{14} W/cm^2 of the 120 ps laser. This estimation is comparable with the report of Jansson *et al.* of 1×10^{12} photons sr^{-1}/pulse.[15] The difference is due to the difference in the details in experiments such as laser, focal spot, jet diameter, etc. Our estimation of the photon number could be higher if the jet diameter and the focal spot size had been matched better. The upgrade is under progress for this point.

The estimation of the photon number allows us to estimate the conversion efficiency. The estimated conversion efficiencies are shown in Figs. 4 and 5 for picosecond and femtosecond lasers, respectively, with respect to different laser intensities. The conversion efficiency is defined by the total x-ray radiation energy per the total input laser energy illuminating a target. The maximum conversion efficiency of

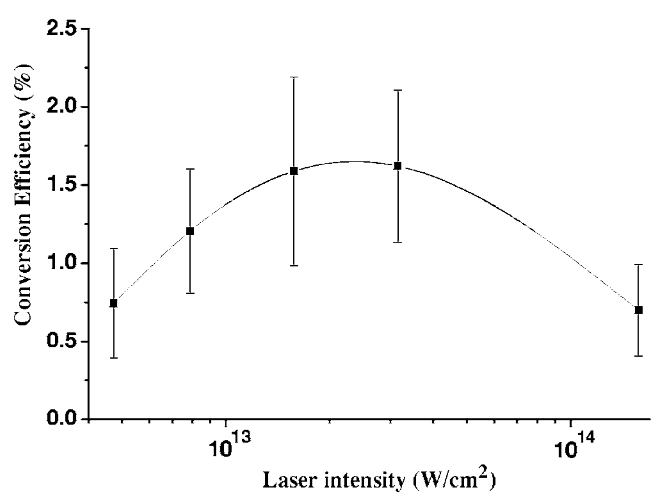

FIG. 4. Conversion efficiency of 532 nm, 120 ps laser light to the 2.88 nm radiation for different laser intensities. The data are connected by a line for the better visibility.

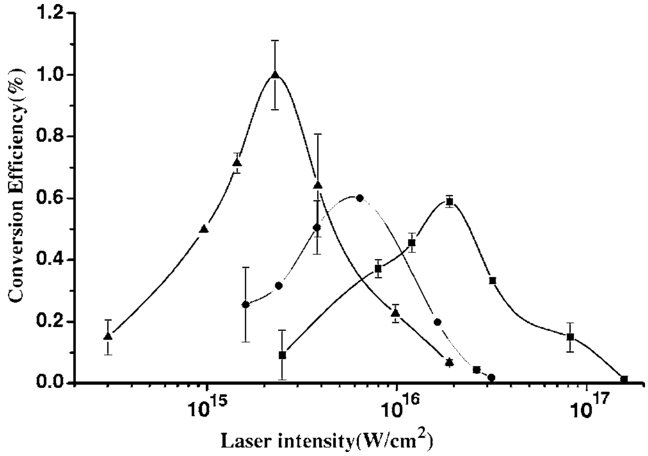

FIG. 5. Conversion efficiency of 800 nm, femtosecond laser light to 2.88 nm radiation (■: 60 fs, ●: 300 fs, and ▲: 500 fs). Data are connected for the better visibility.

1.6% is reached at a laser intensity of 2×10^{13} W/cm^2 in the case of a 120 ps laser. When the pulse duration is 60 fs, the conversion efficiency is maximized at a laser intensity of 2×10^{16} W/cm^2 and, in the cases of 300 and 500 fs, at laser intensities of 6×10^{15} and 2×10^{15} W/cm^2, respectively. By comparing these maximum conversion efficiencies, we note that a longer pulse has the larger conversion efficiency.

Note from Figs. 4 and 5 that the maximum conversion efficiency is achieved at a different laser intensity for a different pulse duration. A laser intensity is determined by the pulse energy, pulse duration of the laser, and its focal spot size at focus. Among these parameters, the laser pulse duration is the parameter that a laser user cannot change easily. Hence, it is useful and important to know how the laser intensity for the maximum conversion efficiency changes with respect to the pulse duration. Figure 6 shows the plot of the laser intensities of the maximum conversion efficiency with respect to pulse durations. The laser intensity of the maximum conversion efficiency decreases as the pulse duration gets longer. The data fitting reveals that $I_m \propto 1/\tau^{\alpha}$, where $\alpha=0.9\pm0.15$. The data given in Table I of Ref. 15 show that the laser intensity of 8.2×10^{12} W/cm^2 yields a higher conversion efficiency than that of 3.7×10^{13} W/cm^2 and indicates that the laser intensity of the maximum conversion efficiency is lower than 8.2×10^{12} W/cm^2 (the given data are not sufficient so that the laser intensity for the maximum conversion efficiency cannot be found). The extrapolation using the above fitting formula yields that the laser intensity of the maximum conversion efficiency is expected to be around 1.1×10^{12} W/cm^2. Considering the experimental uncertainty, this implies that the extrapolation from our fitting formula is reasonable.

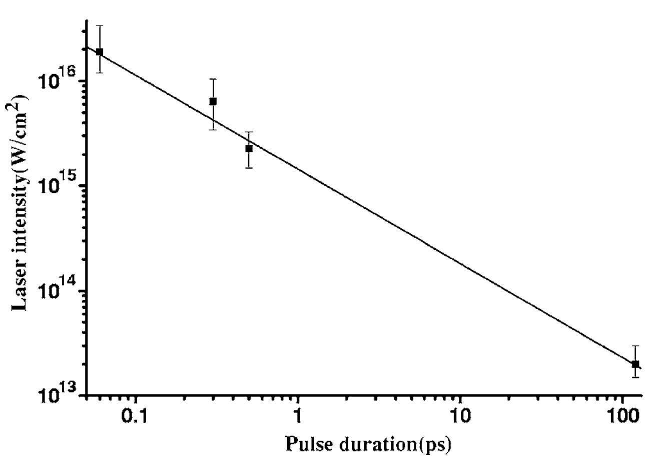

FIG. 6. The laser intensity of the maximum conversion efficiency vs the pulse duration. The data fitting shows that the laser intensity for the maximum conversion efficiency is proportional to $1/\tau^{\alpha}$, where $\alpha=0.9\pm0.15$.

In summary a very stable liquid nitrogen jet was formed in a vacuum of a few mTorr with a 10–15-μm-diam orifice nozzle with a tapering angle of 20°. At a backing pressure of 0.5–1.5 MPa, the nitrogen gas was fed into two cooling stages for liquefication. The absolute intensity of 4×10^{11} photons sr^{-1}/pulse at 2.88 nm was obtained for a 120 ps, 532 nm laser at 1.5×10^{14} W/cm^2. The conversion efficiency is 1.6% at 2×10^{13} W/cm^2 for the 120 ps laser. It was found that the laser intensity of the maximum conversion efficiency scales as $I_m \propto 1/\tau^{\alpha}$, where $\alpha=0.9\pm0.15$, with respect to pulse duration. Since high repetition of the laser intensity of the maximum conversion efficiency is necessary for the most efficient generation of x-ray photons, this formula can serve as a guide to select the laser intensity of a given pulse duration for the maximum conversion efficiency.

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