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Production of highly ionized plasma by micro-dot array irradiation and its application to compact X-ray lasers

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Abstract

A plasma production method using the irradiation of an array of small spots has been investigated from the point of view of soft X-ray laser generation in the recombining plasma scheme pumped by a pulse-train laser. The expansion geometry of highly ionized ions produced by the micro-dot array irradiation method has been measured and compared with that by a simple line irradiation. Spatial distribution of gain coefficients of the Li-like Al ion transition lines have also been measured for both irradiation methods. Highly ionized ions were observed to spread wider in the micro-dot array irradiation method. It is expected that rapid expansion and efficient cooling are achieved in plasmas produced by the micro-dot array irradiation method, which is consistent with the experimental results on the spatial structure of the X-ray laser gain region.

Keywords: Micro-dot array irradiation; Pulse-train laser; Recombining plasma scheme; Soft X-ray spectra; X-ray lasers

1. INTRODUCTION

We have been developing a compact X-ray laser based on the recombining plasma scheme, in which a pulse-train YAG (yttrium aluminum garnet) laser is used as a pump source. The pulse-train laser irradiation method was originally proposed as a method of achieving a compact X-ray laser by Hara *et al.* (1991) in RIKEN (Institute of Physical and Chemical Research), where an Nd:glass laser system was used and the recombining plasma scheme was also adopted. The focusing system was a conventional one, a combination of a convex lens and a cylindrical lens, because the output beam from the RIKEN laser system had a uniform intensity profile over its cross section and delivered enough energy to trim the circular beam cross section into a rectangular one. On the other hand, our pumping system is a YAG laser that would open a possibility of high-repetition-rate X-ray lasers, though the beam size of the YAG laser output is small and the intensity profile is not flat over its cross section. Therefore the irradiation pattern will not be smooth along a line focus when the conventional line focus system is used. A new line focusing system with a segmented prism array should be introduced to perform X-ray laser experiments without losing laser energy. The idea of segmented array optics is as follows (Villeneuve *et al.*, 1991). The incident laser beam is split into several parts. Each part of the split beam is then separately focused to a line and all these individual line foci overlap at the same place, a common line focus. Superposition of the individual beamlets leads to averaging out of the intensity variation in the incident beam. Also, the irradiation pattern has a small scale modulation due to interference between divided beams that results in formation of an array of microdots on a target. Recently, we demonstrated performance of our new line focus system and the production of highly ionized plasma with an array of small dots (Yamaguchi *et al.*, 1999*c*, 2000). This irradiation method would be effective in producing highly ionized ions with a small input energy. Rapid cooling might take place in expanding plasmas originating from microdots, which could be effective to pump X-ray lasers through recombination processes.

It would be worth clarifying the effect of microdot plasma production for pumping recombination X-ray laser by comparing properties of X-ray laser media pumped through the micro-dot irradiation and that by the simple line irradiation

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in the same pulse-train laser method. In this work, we have measured spatial distribution of soft X-ray emission from highly ionized ions and have analyzed the spatial structure of gain region in the expanding plasma from spatially resolved soft X-ray spectral data. We found a clear difference among plasmas produced by the above two irradiation methods. The results are qualitatively consistent with the expanding geometry in plasmas from an array of microdots.

2. EXPERIMENTAL SETUP

Our standard pulse-train laser consists of 16 pulses of 100-ps laser pulse with a 200-ps interval. The envelope of the pulse-train is shaped so that the earlier eight pulses are more than four times as intense as the later ones. For the microdot array irradiation, a YAG laser system at T. T. I. (Toyota Technological Institute) was used, which consisted of a mode-locked YAG oscillator, a regenerative amplifier, and four-stage YAG amplifiers. It delivered laser output of 1.5 to 2 J energy with 25 mm diameter. The lens assembly consists of a segmented prism, a beam expander, and a cylindrical lens. The line focus was 11 mm long on an Al slab target. In detail, the irradiation pattern had small dots aligned with the line focus, which were about 50-μm diameters with a spacing of 140 μm. The power density for each pulse was estimated as $1.0–1.3 \times 10^{12}$ W/cm^2. The detailed description of the new line focusing system is reported elsewhere (Yamaguchi *et al.*, 1999*c*).

For the simple line irradiation, an Nd:glass laser system at RIKEN was used, which consisted of a mode-locked YLF oscillator, a regenerative amplifier, and six Nd:glass amplifiers. The diameter of the output laser beam was 6.5 cm. A mask having a rectangular opening to produce a uniform line focus was used to trim the central part of the beam. The laser was focused onto an Al slab target via a line-focusing system, a combination of a cylindrical lens and a spherical lens. The irradiation pattern was a line 25 mm long and 14 μm wide. The power density was $1.0–1.5 \times 10^{12}$ W/cm^2.

Time-integrated soft X-ray emission from laser-produced plasmas was analyzed using a space-resolving spectrograph consisting of a toroidal mirror, a flat-field grazing incidence spectrometer with an aberration-corrected concave grating (1200 grooves/mm, Hitachi 001-0437), and a back-illuminated X-ray CCD camera (Princeton Instruments, Inc., SX-TE/CCD 512TKB or SX-TE/CCD 1024AB). This spectrograph was designed to form an image of the source with a 1× magnification in the horizontal direction at the entrance slit and with a 3× magnification in the sagittal direction at the flat-field output plane. The spatial resolution in each direction is 10–100 μm depending on the entrance slit width or approximately 50 μm, respectively. The measured wavelength range was 9–16 nm. Observations of plasma X-ray emission were performed with the two different sight directions. When the sight axis coincides with that of the line focus, the axial view, one observes brightness distribution at one end of the elongated source. On the other hand, when the sight axis is rotated by 90°, the transversal view, an X-ray intensity distribution along the line is observed.

3. EXPERIMENTAL RESULTS

Some soft X-ray spectra from the Li-like ion are often expected as lasing lines in compact X-ray lasers using the recombination plasma scheme. Especially, the 3*d*–4*f* and 3*d*–5*f* transition lines of Li-like ions were well investigated (Jamelot *et al.*, 1985; Hara *et al.*, 1989; Kawachi *et al.*, 1997; Yamaguchi *et al.*, 1999*b*). In this report, analyses on spatial distributions have been concentrated on the 3*d*–5*f* (10.57 nm) and 3*d*–4*f* (14.47 nm) lines of Li-like Al ions.

In the microdot array irradiation, we measured the spatial distribution of soft X-ray spectra along the line focus measured at the target surface in the transversal view (Yamaguchi *et al.*, 2000). Then we confirmed that highly ionized ions of aluminum originated from an array of small dots corresponding to the irradiation pattern. In Figure 1 are shown the intensity distributions of the 15.47 nm line (Al XI 3*d*–4*f* transition) along the line focus measured at the different distance, z, from the target surface. The modulation of X-ray intensity can be clearly seen at the target surface, $z = 0$ mm. The period of the modulation is 130–140 μm and the width is 50–70 μm. The spatial modulation is smoothed out quickly beyond $z = 0.1$ mm as shown in Figure 1.

Expansion characteristics of plasmas produced by the two different irradiation methods have been investigated by observing the source size variation of spectral lines of highly ionized ions when the view point is moved away from the target surface in the axial view. The source size along the vertical direction to the target normal, the axis of plasma blow-off, was determined as the FWHM of the spatial distribution of each spectral line. The source size of the Li-like Al 3*d*–4*f* transition line (15.47 nm) or the 3*d*–5*f* transition

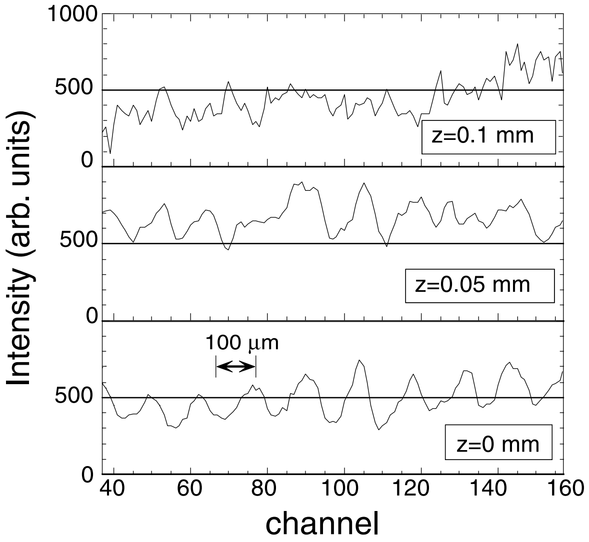


Fig. 1. Intensity distribution of 15.47 nm line along the line focus in the microdot array irradiation.

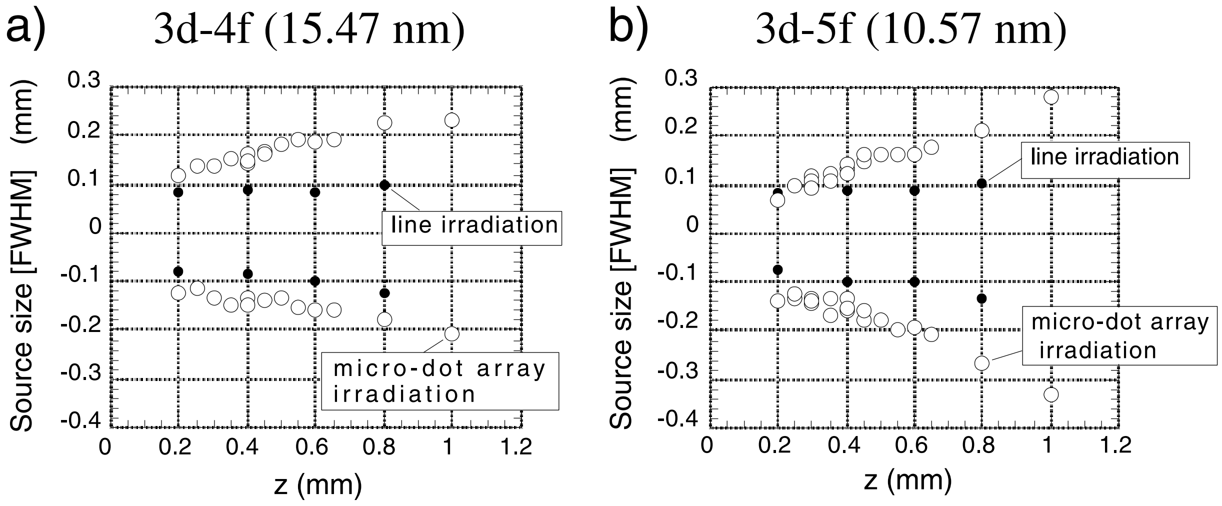


Fig. 2. Source size of the Li-like Al ion transition line as a function of distance from the target surface. The target surface is at $z = 0$. (a) The $3d$–$4f$ line (15.47 nm). (b) The $3d$–$5f$ line (10.57 nm). Open circle: microdot array irradiation. Closed circle: line irradiation.

line (10.57 nm) is plotted as a function of distance from the target surface, *z*, in Figure 2a or b, respectively. The half angle of divergence is about 8–14° for the case of microdot array irradiation, while the value is about 2–5° for the case of line irradiation. It can be thought that the highly ionized plasma produced by using the microdot array irradiation method expands wider from the target than that produced by the simple line irradiation.

Finally we performed an X-ray laser gain measurement in the axial view by changing the plasma length. Several soft X-ray transition lines of the Li-like and Be-like Al ions were observed as the lasing lines pumped by the pulse-train laser through the recombining plasma scheme, those being the Al XI $3p$–$5d$ (10.38 nm), Al XI $3d$–$5f$ (10.57 nm), Al X $3d$–$5f$ (12.35 nm), Al XI $3p$–$4d$ (15.06 nm), Al XI $3d$–$4f$ (15.47 nm), and Al X $3d$–$4f$ (17.78 nm). In this experiment, the spatial profiles of the gain coefficient have been investigated for the Al XI $3d$–$5f$ and $3d$–$4f$ lines. The two-dimensional mapping of gain coefficient for the $3d$–$4f$ line is shown in Figure 3. The gain mapping in the case of the microdot array irradiation is shown in Figure 3a, where it shows that the gain region exists at a 0.3–0.5-mm distance from the target surface. On the other hand, the gain region extends up to 0.8 mm in the case of the line irradiation as shown in Figure 3b. The spatial profile of the gain was nearly the same for the $3d$–$5f$ lines.

4. DISCUSSION

In the recombining plasma scheme, it is an important issue to complete the heating and ionization before the plasma has expanded freely from the target and to cool down efficiently

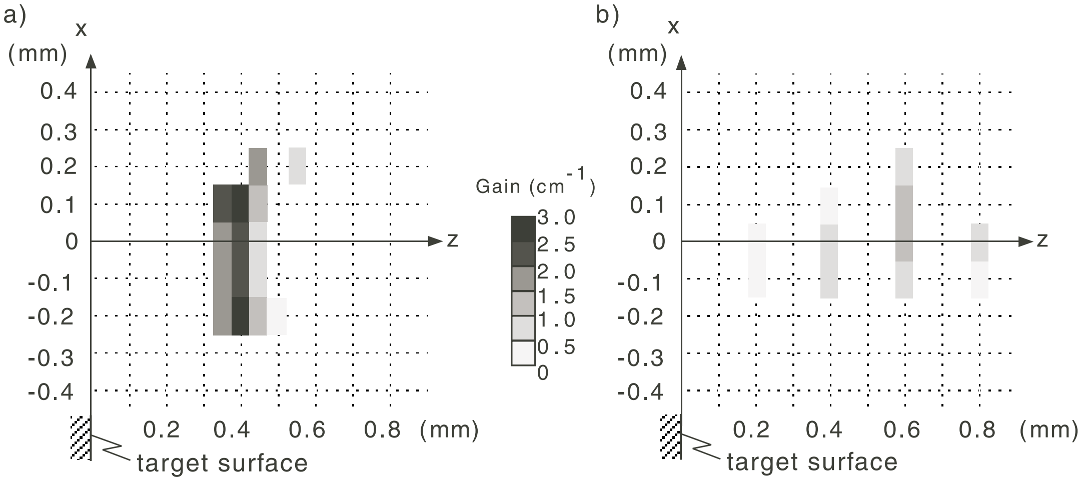


Fig. 3. Two-dimensional mapping of gain coefficient of the Al XI $3d$–$4f$ transition line. (a) The microdot array irradiation. (b) The line irradiation.

the plasma temperature to enhance the pumping processes by electron capture into the upper state. The modified collisional-radiative (CR) model has predicted the required electron temperature for producing population inversion in the Li-like Al ions to be lower than 10 eV (Kawachi *et al.*, 1999). The degree of temperature decrease depends strongly on the volume expansion rate of the expanding plasma. The expansion geometry in each irradiation pattern investigated in this work can be modeled as a cone shape for the microdot array irradiation (A) or a column with a triangular cross section for the line irradiation (B), as shown in Figure 4. The volume expansion rate, α and β, at the distance, z, from the target is written approximately as

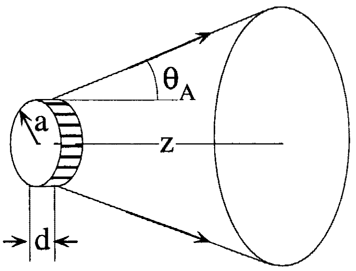
$$\alpha = \frac{\tan^2 \theta_A}{3a^2 d} z^3 \tag{1}$$

for case (A) (for $z \gg a$), where θ_A is the half angle of divergence in the plasma expansion, a is the radius of the microdot, and d is the depth of the initial plasma, or for case (B), where θ_B is the half angle of divergence in the plasma expansion, w is the width of the line focus.

$$\beta = \frac{\tan \theta_B}{2wd} z^2 \tag{2}$$

Substituting the values given by the irradiation patterns and determined from the experiments, we can state that the volume expansion rate for case (A) becomes larger than that for case (B) beyond $z \sim 0.1$ mm. It might be thought that the lower electron temperature is expected for both cases the larger the volume expansion rate becomes. Provided that the temperature of the initial plasma is equal, because the power density of the incident laser is nearly the same, the electron temperature is lower in case (A) than that in case (B) for $z > 0.1$ mm. Therefore the plasma produced by the microdot array irradiation will be cooled down to the required level for producing an X-ray laser gain faster than that produced by the line irradiation does. As a result, the distance of the gain region from the target surface is shorter in the microdot irradiation case than that in the line irradiation case. In this way, the difference of gain distribution between the two irradiation methods shown in Figure 3 could be explained by the difference in the plasma expansion geometry.

(A) micro-dot array irradiation



(B) line irradiation

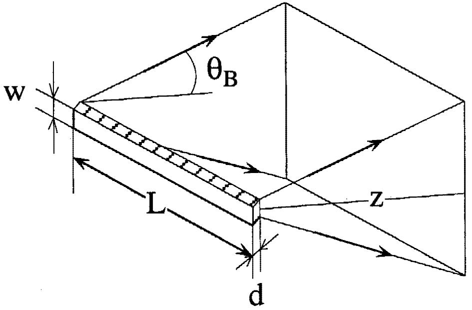


Fig. 4. Model of expansion geometry for each irradiation method. (a) The microdot irradiation. (b) The line irradiation. For case (a), only a unit microdot is shown.

5. CONCLUSIONS

Plasma production and expansion by the irradiation of an array of small spots was investigated from a point of view of soft X-ray laser generation. The array of small spots was formed by modifying the line irradiation pattern utilizing interference among line foci. The spatial distribution of highly ionized ions produced by the microdot array irradiation method or by the simple line irradiation method was measured by soft X-ray spectroscopy. The expansion natures were compared between the two irradiation methods. Spatial distributions of gain coefficient of the Li-like Al ion transition lines have also been measured. The gain region was narrower along the target normal but wider along the vertical direction to the target normal in the case of the microdot array irradiation than in the case of the line irradiation. This can be explained qualitatively from the geometrical feature of the plasma expansion. The gain coefficient produced through the microdot array irradiation is higher than that obtained by using the conventional line irradiation method. It has been clarified that rapid expansion and successive efficient cooling are achieved in plasmas produced by the microdot array irradiation method. The compact X-ray laser experiments have been successfully performed by using the microdot array irradiation of YAG laser (Yamaguchi *et al.*, 1997, 1999*a*).

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