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Space-resolving spectroscopy of X-ray amplifying laser-produced plasma

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1. Introduction

Tabletop X-ray lasers which operate at wavelengths shorter than 20 nm are promising tools for many important applications such as X-ray photoelectron spectroscopy, X-ray microscopy, X-ray holography. We observed soft X-ray amplification of Li-like Al transition lines in recombining Al plasmas produced by a pulse-train YAG laser with an input energy of only 1.5 J [1, 2]. An unstable cavity X-ray laser was demonstrated with a clear enhancement of intensity and a narrow divergent X-ray beam, which would be lead to realization of compact and high repetition rate X-ray lasers [3]. Consequently, an advanced experiment to improve X-ray laser output substantially has been performed, in which an X-ray lasing in the saturated-gain regime and production of highly coherent X-ray radiation are expected. We intended to prolong the X-ray laser medium in a cavity by using a double-target configuration.

In this scheme, knowledge on spatial and temporal interactions of X-ray radiation and laser-produced plasmas, that is propagation, amplification and absorption of X-rays, is important to perform successful X-ray laser amplification. In this report, we observed two-dimensional distributions of soft X-ray laser (3d-4f transition line of Li-like Al) in the various configurations of plasma medium.

2. Experimental Setup

A 100 ps laser pulse from a mode-locked YAG oscillator, 1064 nm, was transformed into a linearly polarized 16-pulse train through an optical stacker and a delay line component, the interval of each pulse was 200 ps. A YAG laser system with four-stage amplifiers delivered output energy of about 0.7 J. A Nd:Glass amplifier having a 25-mm-diameter rod was added to the YAG laser system, the output laser energy was increased up to 2.1 J. A schematic drawing of the experimental setup is shown in Fig. 1. The laser beam was divided into two beams through a half mirror, and each beam was irradiated on an Al target by using a segmented lens system [4]. Each lens assembly forms an 11-mm-long focused line on the target. Therefore, the Al plasmas produced in this experiment had a total length of up to 22 mm. X-ray emission from the plasma was analyzed using a space resolving flat-field graz-

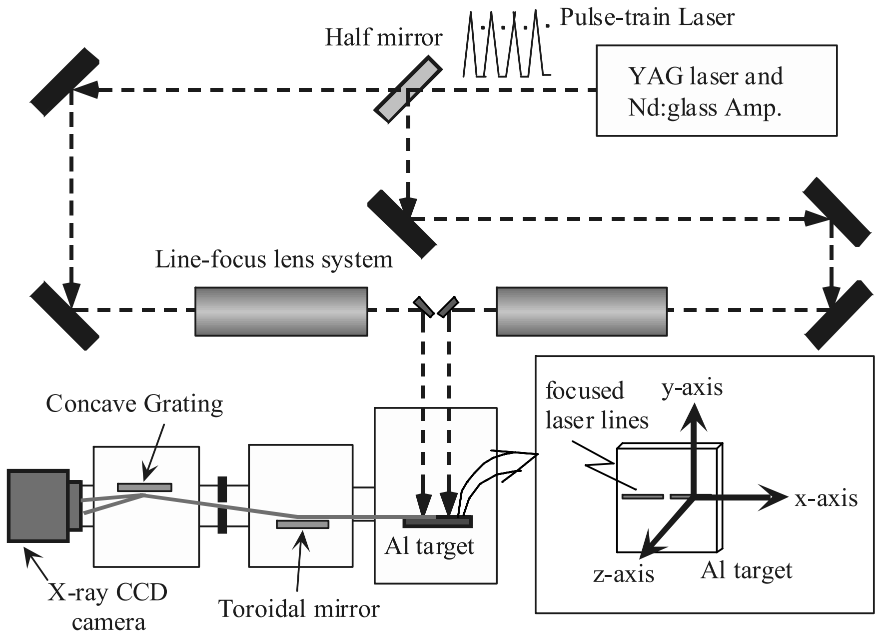

Fig. 1 Schematic drawing of the experimental setup. The coordinate system with respect to the target surface are shown in the inset.

ing incidence soft X-ray spectrograph with a toroidal mirror as a pre-focusing optics. The detector was an X-ray CCD camera (SX-TE/CCD 512TKB, Princeton Instrum.) using a back-illuminated CCD of 512×512 pixels with 24×24 μm pixel size. This spectrograph was designed to image X-rays from a source with a 1× magnification in a horizontal direction (z-axis) at the entrance slit and with a 3× magnification in a sagittal direction (y-axis) at the flat-field output plane. A spectral image taken for each shot consists of spatially-resolved spectra along the y-axis from a field of view in the z-direction limited by the width of the entrance slit. After taking a set of spectrophotographs by changing the view position along the z-axis, one can reconstruct a two-dimensional distribution for each individual spectral line. The spatial resolution in this experiment is about 10 μm for both axes. We observed two-dimensional distributions of soft X-ray radiation viewed from the axis of plasma column under various plasma configurations as follows; i) half-target configuration (plasma length of 5.5 mm), ii) single-target configuration (11 mm), iii) double-target configuration (22 mm). The plasma length was varied by changing the width of an opening in a mask settled in front of the target.

3. Experimental Results

X-ray emissions from Li-like ions, Al XI 3d-4f (15.47 nm) and Al XI 3d-5f (10.57 nm) were observed near the target surface with the less spatial extent in the y-axis. In Fig. 2, spectral line distributions as a function of distance from the target surface (z-axis) are displayed in the vicinity of the Al XI 3d-4f line for the half-target case (Fig. 2 (a)) and the sin-

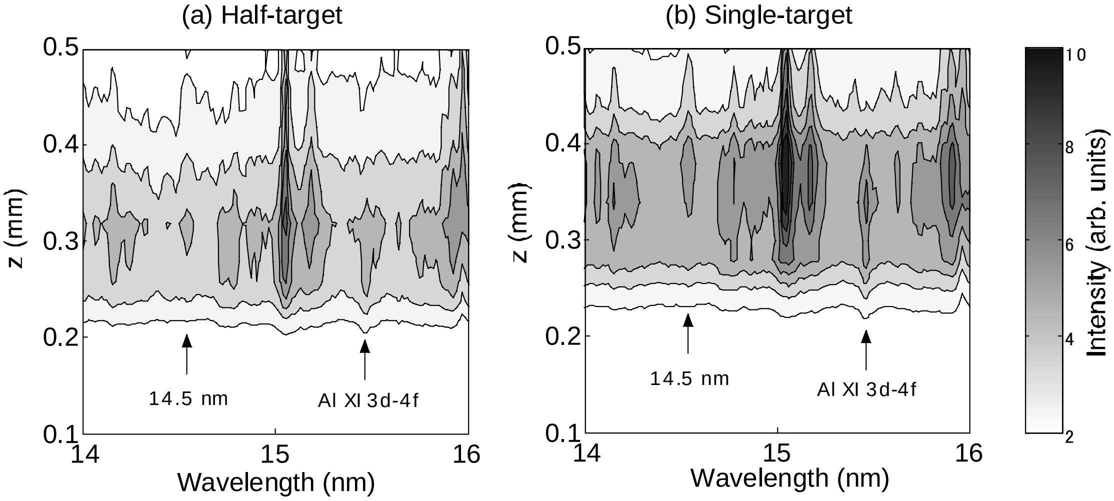

Fig. 2 Spatial distributions of soft X-ray spectra near the Al XI 3d-4f line as a function of distance from the target surface. (a) Half-target (5.5 mm) and (b) single-target (11 mm) configurations.

gle-target case (Fig. 2 (b)), respectively. It was found that the highly ionized ion emissions appear at a region nearer from the target. On the other hand, emission lines of lower ionized ions distribute far from the target. One can distinguish amplifying lines from ordinary emission lines by analyzing the intensity enhancement when the length of the plasma was doubled. It can be found that the 3d-4f line has an enhancement factor more than 2 in the region z= 0.33-0.38 mm. Furthermore, it is observed that the line at around 14.5 nm seems to be also amplified in the region z= 0.35-0.48 mm, though there has been no report on amplifications for this line. Ion species for this line might be assigned to Al II or O V ion according to the NIST Atomic Spectra Database, though the mechanism producing population inversion for these transitions is not clear. It is necessary to accumulate data on this line.

Two dimensional distributions of Al XI 3d-4f line viewed from the axis of plasma column are shown in Fig.3. The emission of 3d-4f line has a peak at around z=0.25-0.35 mm and has a gain region at z=0.35-0.40 mm. It is found that X-ray amplification takes place at the front region in the expanding plasma. The region of population inversion for Al XI 3d-4f transition can be identified to have a rather small spatial extent of within 50 μm. Therefore a precise alignment is required in the double-target experiment to achieve x-ray amplification throughout the plasma length.

To examine X-ray amplification in detail, the intensity profiles in Fig.3 were analyzed at various z-positions. For example, amplification takes place almost everywhere in its source region at z= 0.36 mm, on the other hand, the absorption occurs on the plasma axis (y~0 mm) at z= 0.30 mm though the amplification is still recognized in the off-axis region (|y|>0.05 mm). The time-integrated gain coefficient were determined to be G=2.72 cm^{-1} (z=0.36 mm and y=0 mm) and G=1.81 cm^{-1} (z=0.30 mm and y=−0.07 mm).

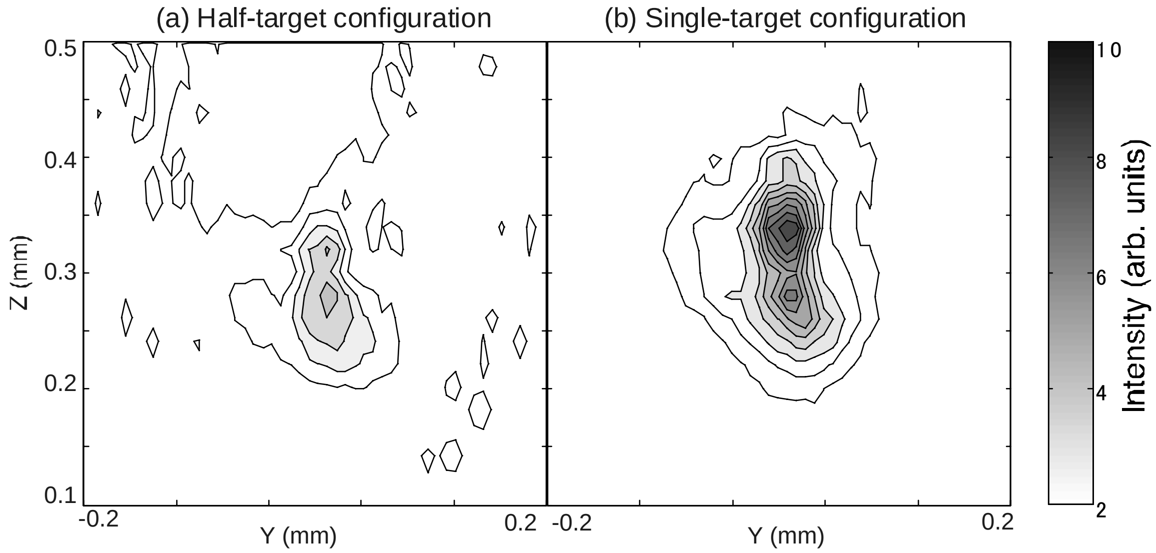

Fig. 3 Two-dimensional distributions of the Al XI 3d-4f line for (a) half-target (5.5 mm) and (b) single-target (11 mm) configurations. Clear amplification can be found in the region z=0.35-0.40 mm.

4. Summary

Two-dimensional spectroscopic observation of soft X-ray radiation has been performed in the recombination plasma scheme. The spatial distribution of population inversion was deduced for the 3d-4f line (15.47 nm). The gain region was found to have a depth of 50 μm and a width of about 100 μm which appears at the plasma front.

Further experiments in the double-target configuration have been performed utilizing the present data. The new x-ray lasing line is also under investigation.

Refference

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