Available online at www.sciencedirect.com
ScienceDirect
Physics Letters A 370 (2007) 154–157
PHYSICS LETTERS A
www.elsevier.com/locate/pla

Space-resolved soft X-ray emission from laser produced lithium plasma

P. Nica [a,b,*], S. Miyamoto [b], S. Amano [b], T. Inoue [b], A. Shimoura [b], T. Mochizuki [b]

[a] *Department of Physics, Technical "Gh. Asachi" University, Blvd. Mangeron, Iasi 700029, Romania*
[b] *Laboratory of Advanced Science and Technology for Industry, University of Hyogo, Hyogo 678-1205, Japan*

Received 23 February 2007; accepted 18 May 2007

Available online 6 June 2007

Communicated by F. Porcelli

Abstract

Space-resolved emission spectroscopy was used to study the evolution of 13.5 nm line intensity and electron temperature of the plasma generated by laser ablation of lithium target. Two emitting regions were observed, their intensities depending on laser fluency. Plasma image is discussed in the frame of a Gaussian model of particle expansion.

PACS: 52.50.Jm; 52.38.Mf; 47.27.Nf; 81.30.Fb

Keywords: Lithium laser produced plasma; Space-resolved spectroscopy

1. Introduction

In the last years, a special attention was given to the development of a high brightness soft X-ray source for the next generation of extreme ultraviolet lithography (EUVL). Two possibilities were widely investigated, namely gas discharge-produced plasmas, and laser-produced plasmas (LPP) [1]. Recently, a high conversion efficiency (CE) was demonstrated by using Li target for LPP [2,3]. In a previous work [4], the maximum CE which we experimentally obtained was $1.2\%/2\pi sr/2\%$ bw, and it was comparable with that of Sn. Some advantages arise from efficient emission of the Li^{2+} ion at 13.5 nm (Lyman-α line) which is the practical wavelength of the lithography based on Mo/Si multilayer-coated optics. By using low laser fluencies, low energy ions are generated and in return the collector optics lifetime is extended [3]. Understanding the plasma dynamics dependence on laser parameters such as intensity and spot size is of great importance since it provides the path towards the optimal emission of the radiation of interest. Meantime, the emission profile is also an important input for the design of an illumination system of an extreme ultraviolet tool in order to achieve the desired illumination uniformity [1].

In the present Letter we report our experimental results on the space-resolved soft X-ray emission from laser produced lithium plasma. The features of interest are the space dependence of the 13.5 nm line intensity and of the plasma temperature, source size and spectral distribution.

2. Experiment description

The plasma was generated by laser ablation of a lithium foil target using 1.06 μm radiation pulses from a Q-switched Nd:YAG laser (for more details see [4]). The typical pulse energy was 0.5 J in a pulse width of 10 ns. The laser beam was focused on the target by an f/500 lens with a 45° incidence angle. By adjusting the lens position (LP), various spot diameters were obtained. Thus, the laser intensities on the target were $I_L = 2.2 \times 10^{11}$, 3.8×10^{10}, 1.8×10^{10}, 9.8×10^{9}, 6.3×10^{9} W/cm^2 for LP = 0, 4, 6, 8, and 10 mm, respectively, where LP = 0 mm corresponds to the best focusing condition. For the sake of simplicity, instead of laser intensities, only the lens positions will be specified in the followings. For spectroscopic studies, a grazing incidence soft X-ray spectrograph with flat-field image focusing and back-illuminated CCD cam-

* Corresponding author.
E-mail address: pnica@ch.tuiasi.ro (P. Nica).

0375-9601/$ – see front matter
doi:10.1016/j.physleta.2007.05.105

era was used in the incidence plane, at 90° relative to the target normal. The spectrograph covers the spectral range of 5–22 nm with moderate wavelength resolution. By placing a 50 μm pinhole at 50 mm in front of the entrance slit, the plasma was imaged to obtain a 100 μm overall space resolution. Simultaneously, the plasma was also ×2 imaged by a Flying Circus (FC) system at −90° relative to the target normal. It had a spectral sensitivity in the 13.5 nm region and 4% bandwidth [5].

3. Experimental results

For the laser intensities previously mentioned, the soft X-ray emission in the analyzed wavelength domain is dominated by the resonance lines of Li^{2+} ion. The line of interest, Ly-α, is emitted in a wide space domain of approximately 5 mm. By integrating over the line profile, the space dependencies of the Ly-α line intensity are plotted in Fig. 1 for various lens positions, where the origin corresponds to the target position. Two regions of emission were observed and their intensities depend on the laser fluencies. Thus, for high laser intensity (LP = 0 mm), the fully stripped ions are dominant near the target (A-region, see Fig. 1), where the strong inverse Bremsstrahlung occurs. Then, the recombination takes place in the expansion region (B-region in Fig. 1) to give Li^{2+} ions, which emit stronger in this domain. On the other hand, for low laser fluency (LP = 10 mm) the maximum intensity is observed in the high density region, indicating a lower excitation temperature. The strongest emission occurs for moderate laser fluency (LP = 6 mm) and a maximum CE is achieved [4]. All the analyzed laser intensities give an emission intensity peak located at 0.3 mm from the target, while the dominant emission results from the expansion region.

The width and shape of the spectral lines are extensively used for plasma diagnostic [6]. In Fig. 2 the full width at half maximum (FWHM) of the strongest lines, i.e. 13.5 nm (Li^{2+} 1s-2p, Ly-α) and 11.39 nm (Li^{2+} 1s-3p, Ly-β) are plotted vs. distance for LP = 6 mm. At approximately 0.1 mm from the target the maximum line widths were obtained, while in the expansion region the instrumental broadening is dominant, and both widths tend to the same value, i.e. 0.026 nm. Generally, after extracting the instrumental broadening, the observed full width at half maximum (FWHM) is caused by the opacity and electron impact broadening mechanisms [7,8]. For an optically thick plasma, the opacity-broadened line width increases with the oscillator strength [7,8], and a larger width of Ly-α line is expected. However, the opposite was experimentally observed. This can be explained by taking also into account the broadening of the emission process, which is given by electron impact [9,10]. Thus, assuming a constant source function, the opacity-broadened line width ($\Delta\lambda_{opac}$) is determined by the width of the function [9],

$$g(\lambda) = 1 - \exp\big[-\tau_0 \cdot f(\lambda)\big], \tag{1}$$

where τ_0 is the optical thickness at the center of the line and λ the wavelength. In the case of electron collisional emission broadening, $f(\lambda)$ is a Lorentzian function having the FWHM ($\Delta\lambda_{col}$), which depends on the quantum numbers of the upper and lower states [11]. Under these circumstances, it results the ratio

$$\Delta\lambda_{opac}/\Delta\lambda_{col} = F(\tau_0) = \sqrt{-1 - \tau_0/\ln\big[\big(1+\exp[-\tau_0]\big)/2\big]}. \tag{2}$$

One can observe that for $\tau_0 \ll 1$, $F(\tau_0) \cong 1$. Therefore, although the optical thickness of Ly-α line is larger (τ_0(Ly-α)/τ_0(Ly-β) $\cong 29$—for details see [9]), since $\Delta\lambda_{col}$ is higher for Ly-β line ($\Delta\lambda_{col}$(Ly-α)/$\Delta\lambda_{col}$(Ly-β) $\cong 1/5$ [9]), the behavior observed in Fig. 2 is possible if the plasma is optically thick at 13.5 nm, and optically thin at 11.39 nm. Moreover, the optical thickness can be evaluated. In a rough approximation, we subtracted the instrumental width to obtain $\Delta\lambda$(Ly-β)/$\Delta\lambda$(Ly-α) = 1.7 at the maximum of the width in Fig. 2. Then, by particularizing Eq. (2), it results τ_0(Ly-α) $\cong 8$. It should be noted that such estimations indicate the time-averaged local conditions rather than defining the conditions at a particular stage of plasma's evolution.

For determining the LPP excitation temperature, the common techniques which use the lines emission [7] are not applicable in the present case. Optically thin sources and thermally populated energy levels are required. In our experiment, Ly-α line is optically thick, while the expansion region of

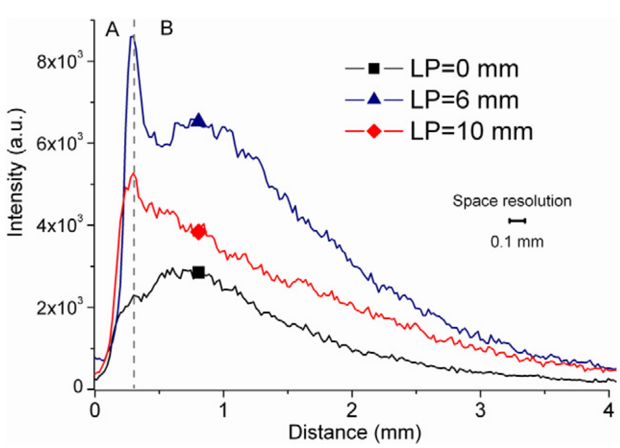

Fig. 1. The space-dependence of the Ly-α line intensity integrated on the line profile for various lens positions.

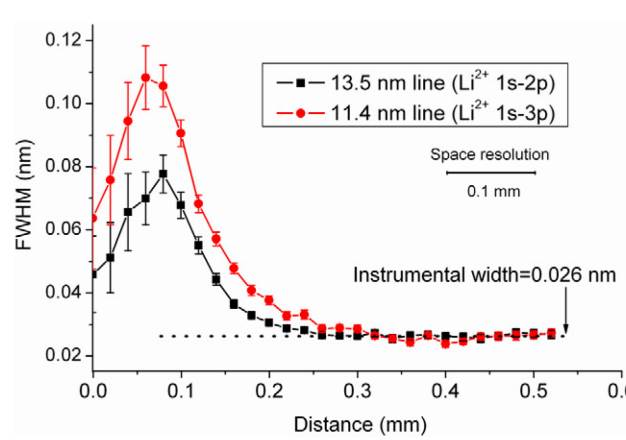

Fig. 2. The space-dependence of Ly-α and Ly-β lines widths for LP = 6 mm.