論文 / 著書情報
Article / Book Information

論題(和文)	
Title(English)	Analysis of Highly Ionized N Plasma Spectra under the Effect of an External Magnetic Field in Fast Capillary Discharge
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出典(和文)	Physics and Application of Plasmas Based on Pulsed Power Technology, NIFS-PROC-90, pp. 67-72
Citation(English)	Physics and Application of Plasmas Based on Pulsed Power Technology, NIFS-PROC-90, pp. 67-72
発行日 / Pub. date	2012, 4

Analysis of Highly Ionized N Plasma Spectra under the Effect of an External Magnetic Field in Fast Capillary Discharge

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ABSTRACT

It is considered that lasing of a H-like N Balmer α soft X-ray laser (SXRL) at wavelength of 13.4 nm might be possible by utilizing an expansion phase of Z-pinch discharge plasma. To realize the SXRL, we studied the soft-x-ray amplification in discharge-produced plasma under an externally applied axial magnetic field. The purpose of this technique is to make the concave electron density distribution at the time of lasing and amplify the radiation by guiding effect.

I. Introduction

Quantum soft X-ray laser (SXRL) has been investigated for a few decades due to its narrow bandwidth, high coherence and directivity. It becomes a tool to elucidate the problem of solid state physics, nanotechnology, and life science. The main x-ray laser medium is plasma produced by laser irradiation or capillary discharges. In comparison with a laser-pumped x-ray laser, the capillary discharge scheme has the advantages of relatively high efficiency, large gain volume, and long gain duration.

In 1994, utilizing a fast capillary Z-pinch discharge to generate a plasma column efficiently, Ne-like Ar SXRL at a wavelength of 46.9 nm was demonstrated by Rocca et al. [1]. In addition, suppressing the growth of magnetohydrodynamic (MHD) instability by use of predischarge, lasing of Ne-like Ar laser became to be reproducibly observed [2].

Concerning the generation of a shorter wavelength SXRL pumped by capillary discharge scheme [3, 4, 5], we investigated possibility of lasing the H-like N Balmer recombination SXRL at a wavelength of 13.4 nm. The wavelength of 13.4 nm is in an extreme ultraviolet range, therefore a Mo/Si multilayer mirror can be applied to the capillary discharge for SXRLs.

To realize the SXRL, we studied the soft-x-ray amplification in discharge-produced plasma in an externally applied axial magnetic field. Applying an axial magnetic field to the plasma is a well-known technique to suppress plasma instabilities during implosion, and has been used in several experiments including generation of high density plasma [6]. In this experiment, the purpose of this technique is to generate a concave plasma density distribution at the time of lasing. At and after the maximum pinch, a convex electron density distribution will be formed in usual Z-pinch plasma. This electron density distribution refracts the ray of light off the axis, as shown in Fig.1. Refraction decreases the effective gain coefficient and limits the maximum gain-length product that could be obtained. For this reason, we aimed to make the concave electron density distribution at the time of lasing by applying axial magnetic field and amplify the radiation by guiding effect. In this paper we discuss the results of the study of soft x-ray amplification in a discharge-produced plasma column under the influence of an axial magnetic field.

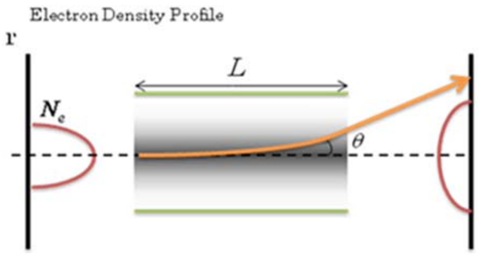

Fig.1. Refraction effect of electron density gradient

II. Experimental setup

Capillary discharge plasma was generated by utilizing a triangular current with peak amplitude of about 50 kA and a pulse width of about 50 ns. A pulsed power supply system with a pulse shaping transmission line as shown in Fig. 2 was used [7, 8]. An alumina (Al_2O_3) ceramics capillary with an inner radius of 1.5 mm and a length of 150 mm was filled with initial nitrogen molecular gas at pressure of about 600 mTorr.

The gas was pre-ionized by RC discharge with amplitude of about 10 A and a decay time constant of 3 μs. Schematic diagram of time integrated spectrum pinhole imaging set-up is illustrated in Fig. 3. The measurement of radiation from the nitrogen plasma was carried out using a transmission grating spectrometer with a lattice constant of 1/1000 mm^{-1} in combination with an X-ray CCD camera which has 1024×1024 pixels. Each pixel has an area of 13-μm square. The transmission grating was placed at a distance of 600 mm from the end of capillary and a distance between the grating and the CCD camera was 425 mm. In addition, two slits of 1 mm×5 mm were placed between the capillary and the transmission grating, and the diameter of the transmission grating was 50 μm.

The axial magnetic field was generated by using a 4-cm diameter, 15-cm long coil positioned concentrically with the capillary channel. The coil, which was excited by a DC power supply, produced magnetic fields up to 15 mT.

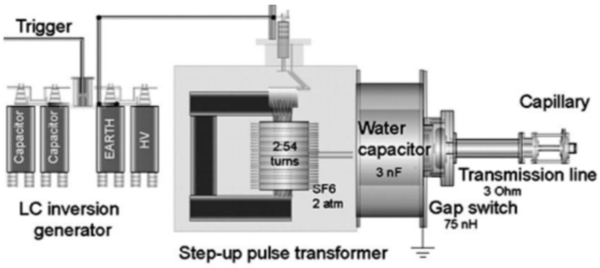

Fig. 2. Experimental setup for lasing H-like N soft X-ray laser

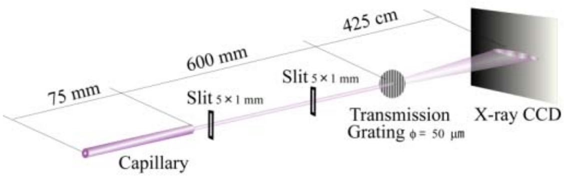

Fig. 3. Time integrated spectrum pinhole imaging set-up

When an axial magnetic field is applied to plasma, the magnetic flux is conserved in the plasma because of induced azimuthal current in plasma shell. The magnetic flux is collected by the imploding plasma, which leads to increase of the magnetic field strength inside the plasma. When the plasma is compressed to a radius of r, the magnetic flux density inside plasma, B, is given by

$$B = \frac{\eta B_0 r_0^2}{r^2} \qquad (1)$$

where $B_0, r_0,$ and η are the initial magnetic flux density of the external field, initial plasma radius, and leakage of the magnetic flux during implosion.

From previous experimental results, the plasma is compressed to one tenth of initial plasma radius at maximum pinch. Therefore, the multiplication factor of 100 in the magnetic flux density is expected.

III. Experimental results and discussions

The effects of the axial magnetic field [9, 10] on the time-resolved XRD signals radiated from fast capillary Z-pinch discharge plasma are illustrated in Fig. 4. Axial magnetic field inside the plasma opposes the compression force driven by the plasma current. This phenomenon prevents the plasma compression and the increase of the electron temperature and density, which may lead to the decrease of radiation intensity. However no change is observed in radiation intensity with an axial magnetic field. This result indicates that an externally applied axial magnetic field of 15 mT does not significantly affect the evolution of the plasma. The cause may be the negligibly small compressed axial magnetic field strength $B_z/r^2 \approx 1.5$ T compared with the self-generated azimuthal magnetic field $B_\theta = \mu_0 I/2\pi r = 33$ T.

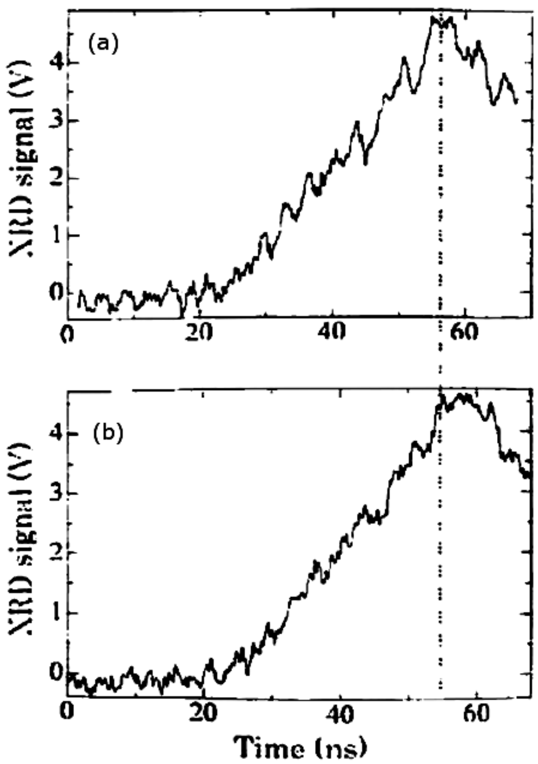

Fig. 4. XRD signals radiated from fast capillary Z-pinch discharge plasma. (a) Without external magnetic field. (b) With axial magnetic field of 15 mT.

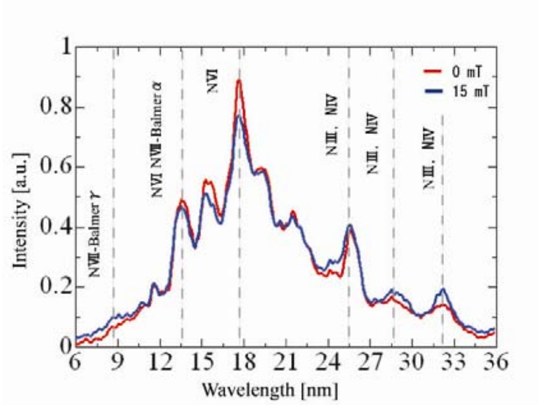

Fig. 5. Emission spectrum profiles without and with axial magnetic field of 15 mT

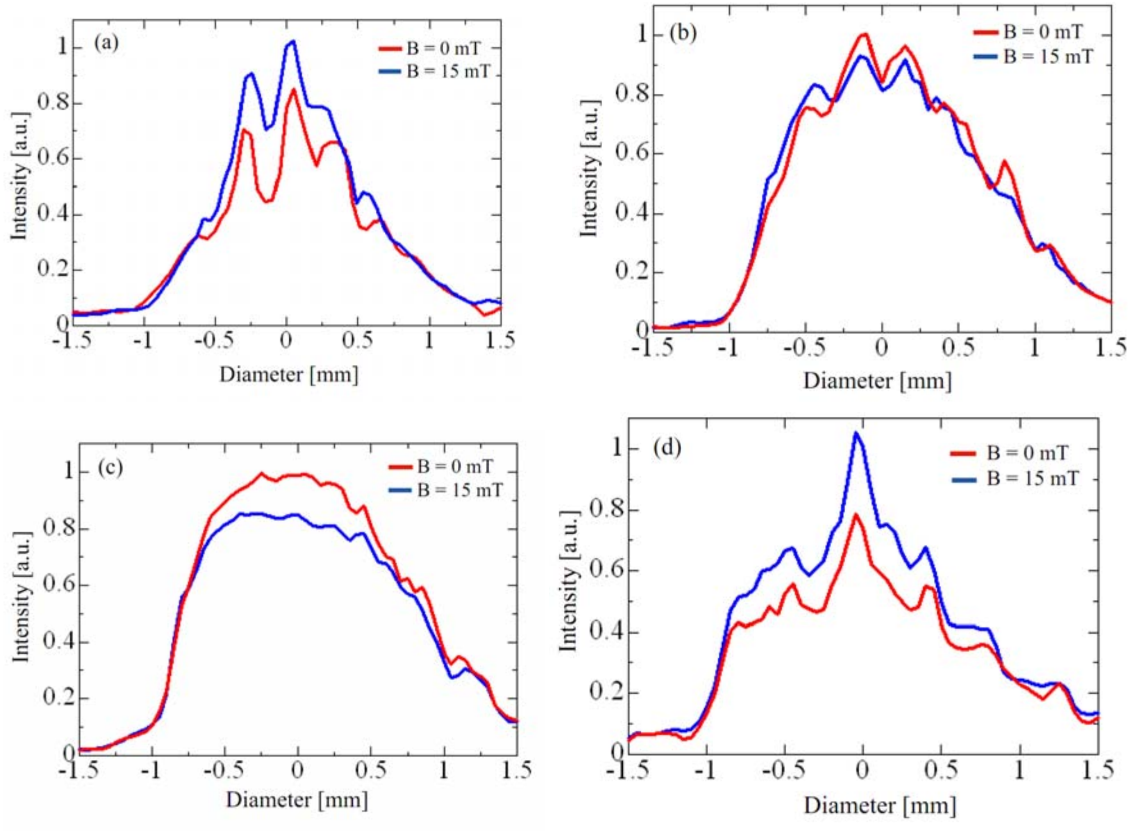

Fig. 6. Soft-x-ray profiles (a) 9 nm, (b) 13.4 nm, (c) 18 nm and (d) 27 nm corresponding to discharges of approximately 45 kA through 15-cm-long, 3-mm-diameter capillary without and with axial magnetic field of 0.15 T

The effects of the axial magnetic field on the intensity profile of the emission spectrum at wavelength of below 27 nm are illustrated in Fig. 5. As shown in Fig.5, the intensities of spectrum line at wavelengths below 6 nm and over 21 nm slightly increase by an axial magnetic field. However, intensity of spectrum line at wavelengths over 20 nm decreases.

Figure 6 shows radiation patterns recorded along the direction of the spectrometer slit under the condition of no external magnetic field applied.

(a) λ=9 nm

This line corresponds to spectrum of highly ionized NVII state. The beam profile exhibits a double peak. Since electron temperature of T_e ≈150 eV is needed in order to generate NVII ions, NVII state is considered to be obtained after maximum pinch. Therefore, this line may be affected by convex electron density distribution. The intensity of radiation in axis region obtained without axial magnetic field is lower than that with magnetic field. This result suggests that the ray of radiation is bended off the axial region by convex electron density distribution. With magnetic field, the radiation patterns sharpen and the intensity of radiation increases, suggesting the waveguide effect.

(b) λ=13.4 nm

This line corresponds to spectra of highly ionized NVI and NVII states. The beam profile also presents a double peak like that of λ=9 nm. However, the peak is not so clearly seen as that for λ=9 nm. This result suggests that NVII dominates this line, because discharge current is low (39kA) and this line is few affected by the convex electron density distribution.

(c) λ=18 nm, (d) λ=27 nm

These spectra correspond to line emissions from NIV and NIII. Ionization to NIV and NIII of low charge states, which have low ionization potentials, occurs before the maximum pinch. Therefore, these lines are not affected by the convex electron density distribution and the beam profiles also show a single peak. Change in radiation patterns of these lines caused by axial magnetic field is not thought to be induced by waveguide effect.

IV. Conclusion

To realize the SXRL, we studied the soft-x-ray amplification in a capillary discharge in an externally applied axial magnetic field.

The beam profile of λ=6 nm line (NVII) shows a double peak and the intensity of radiation increases in axis region when axial magnetic field is applied. This result suggests the waveguide effect caused by convex electron density distribution. However, soft-x-ray amplification is very low. One of the reasons may be unsatisfactory ionization by low discharge current. To realize lasing of a H-like N Balmer α soft X-ray laser, discharge current over 50kA is required [11]. In the experiment, discharge current is only 38kA to prevent breakdown near the electrodes of equipment. In fact, spectrum of NVII which is needed for lasing at wavelength of 13.4 nm is observed even though the emission is weak. To observe the definite effect of axial magnetic field and to realize the x-ray laser, improvement of insulation near electrodes and increase of the discharge current are required.

Another reason is attributed to the low axial magnetic field. Externally applied axial magnetic field of 15 mT is negligibly low compared with the self-generated azimuthal magnetic field. F. G. Tomasel et al. reported the enough soft-x-ray amplification under an externally applied axial magnetic field of 150 mT [10]. By adopting a pulsed power supply for generating axial magnetic field, we would like to obtain a compressed axial magnetic field comparable to the azimuthal magnetic field generated by the Z-pinch discharge current.

Reference

[1] J. J. Rocca, V. Shlyaptsev, F. G. Tomasel, O. D. Cortázar, D. Hartshorn, and J. L. A. Chilla, Demonstration of a Discharge Pumped Table-Top Soft-X-Ray Laser, Phys. Rev. Lett., Vol. 73, pp. 2192-2195 (1994)

[2] G. Niimi, Y. Hayashi, N. Sakamoto, M. Nakajima, A. Okino, M. Watanabe, K. Horioka, and E. Hotta, Development and characterization of a low current capillary discharge for X-ray laser studies, IEEE Trans. on Plasma Science, Vol. 30, pp. 616-621 (2002)

[3] P. Vrba, M. Vrbova, N. Dezhda, A.

Bobrova, and P. V. Sasorov, Modeling of a nitrogen x-ray laser pumped by capillary discharge, Central European Journal of Physics, Vol. 3, pp. 564-580 (2005)
[4] N. S. Kampel, A. Rikanati, I. Be'ery, A. Ben-Kish, A. Fisher, and A. Ron, Feasibility of a nitrogen-recombination soft-x-ray laser using capillary discharge Z pinch, Phys. Rev. E, Vol. 78, 056404 (2008)
[5] Y. Sakai, S. Takahashi, T. Hosokai, M. Watanabe, A. Okino and E. Hotta, The possibility of a capillary discharge soft X-ray laser with shorter wavelength by utilizing a recombination scheme, Journal of Plasma and Fusion Research Series, Vol. 8, pp. 1317-1312 (2009)
[6] Liberman M A, De Groot J S, Toor A and Spielman R B, Physics of High-density Z-pinch Plasmas, New York, Springer, 1999
[7] Y. Sakai, T. Komatsu, I. Song, M. Watanabe, G. H Kim and E. Hotta, High efficient pulsed power supply system with a two-stage LC generator and a step-up transformer for fast capillary discharge soft X-ray laser at shorter wavelength, Review of Scientific Instruments., Vol. 81, 013303 (2010)
[8] Y. Sakai, S. Takahashi, M. Watanabe, G. H. Kim and E. Hotta, Pulsed current wave shaping with a transmission line by utilizing superposition of a forward and a backward voltage wave for fast capillary Z-pinch discharge, Review of Scientific Instruments, Vol. 81, 043504 (2010)
[9] R. A. London, Beam optics of exploding foil plasma x-ray lasers, Phys. Fluids, Vol. 31, p.184 (1988)
[10] F. G. Tomasel, V. N. Shlyaptsev, and J. J. Rocca, Enhanced beam characteristics of a discharge-pumped soft x-ray amplifier by an axial magnetic field, Phys. Rev. A, Vol. 54, No. 3, pp.2474-2478 (1996)
[11] 酒井雄祐: 修士論文“高速Zピンチ放電による水素様窒素軟X線レーザー実現に向けた研究”(2010) 東京工業大学