J. Plasma Fusion Res. SERIES, Vol. 8 (2009)

The possibility of a capillary discharge soft X-ray laser with shorter wavelength by utilizing a recombination scheme

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(Received: 12 September 2008 / Accepted: 23 December 2008)

The capillary discharge soft X-ray laser is a promising scheme with its long capillary plasma column that is efficiently generated by the fast current pulse of about several 10s ns. In this study, the possibility of a recombination soft X-ray laser will be discussed in anticipation of realizing a 13.4 nm H-like N EUV laser. Evolution of EUV emission from nitrogen plasma with number density of 10^{18}cm^{-3} was measured and analyzed with MHD calculation. Comparing the experimental and the calculation results, it is considered that in order to initiate the collisional ionization effectively in a few ns and to obtain many fully-stripped nitrogen ions enough for lasing, much higher electron number density is required. The possibility of realizing a recombination soft X-ray laser pumped by the capillary discharge is discussed.

Keywords: Capillary discharge, Soft X-ray laser, Recombination laser, Pulsed power and Z-pinch.

1. Introduction

The capillary discharge soft X-ray laser is a promising scheme with its long plasma column of about a few 10s cm in which the radiation is amplified along the plasma column efficiently. It is considered that such a high gain-length product could be achieved using a wave guide effect due to the concave electron density profiles in the implosion phase. Owing to these advantages, discharge current of about a few 10s kA with a half cycle duration of about 100 ns can stably generate the Ne-like Ar 46.9 nm collisional soft X-ray laser up to saturation regime[1-3]. However, there is a strong demand to shorten the wavelength of the laser down to 13.5 nm EUV range in order to use the Mo/Si multi-layer mirror for wider application. Utilizing a Balmer α line of hydrogen-like nitrogen (H-like N) ion, it may be possible to generate a 13.39 nm recombination soft X-ray laser by the use of expansion phase after the maximum pinch, during which rapid cooling of the plasma initiates[4]. To realize the H-like N recombination laser, a plasma column of higher density and higher temperature is required. At the instant of maximum pinch, electron temperature of 100-200 eV is necessary to fully strip the nitrogen atom and in the expansion phase, electron number density of about the order of 1×10^{20} cm^{-3} is required in order to obtain the gain $G > 1$ cm^{-1} [5]. In this study, time evolution of radiation characteristics were measured with an X-ray photo diode and discussed by utilizing MHD calculation results.

2. Experimental set-up

In this study, to investigate the possibility of the recombination laser, high efficient pulsed power system has been developed, which consists of a 2.2 µF LC generator, a 2:54 step-up transformer, a 3 nF water capacitor, a gap switch and a capillary plasma load of about 130 nH as shown in Fig. 1. The pulsed power system generates the fast current pulse with rise time of about 30 ns and decay time of about 30 ns. EUV emission from the nitrogen plasma was measured by using an IRD AXUVHS5 Mo-Si with 40 pF capacitance. The time resolution of the photo diode is about 2 ns and the wavelength range of 12-15 nm can be measured. A pinhole of 2 mm in diameter was set at a distance of 150 mm from the photo diode to reduce the background radiation in order to measure the coherent radiation. In addition to this, an X-ray diode with gold cathode, which has high quantum efficiency for the wavelength in the range of about 20 nm to 100 nm, was used to measure the radiation of longer wavelength. Location of the each diode was at 600 mm from the end of the capillary. In this experiment, discharge current amplitude was 18 kA and an initial filling nitrogen molecule number density was 2×10^{16} cm^{-3}. The plasma was pre-ionized by utilizing an RC discharge with current amplitude of 10 A and time constant of 10 µs to generate an axially uniform pinched plasma by suppressing growth of an instability[2].

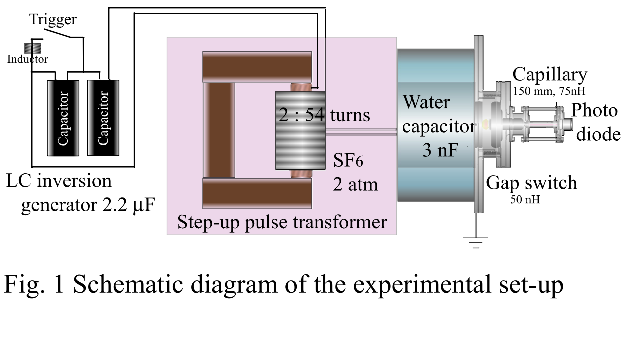

Fig. 1 Schematic diagram of the experimental set-up

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3. MHD calculation model

Dynamics of capillary Z-pinch plasma was calculated by one dimensional single-fluid, two temperature MHD equations in the 1D Lagrangean cylindrical coordinate. The basic equations are as follows. The continuity and the momentum conservation equations are given by,

$$\frac{\partial \rho}{\partial t} + div\ \rho u\ . \qquad (1)$$

$$\frac{\partial \rho u}{\partial t} + div\,(P + Q_{vis}) = 0\ . \qquad (2)$$

Where, ρ is density, u is velocity of the fluid, P is the pressure and Q_{vis} is artificial viscosity. The internal energy of the electron and the ion was solved by the following energy conservation equations,

$$\frac{\partial E_e}{\partial t} + div\,(Pu - k\nabla T) + Q_{joule} - Q_{ie} - Q_{atom} = 0\ . \quad (3)$$

$$\frac{\partial E_i}{\partial t} + div\,(Pu + Q_{vis}u - k\nabla T) + Q_{ie} = 0\ . \quad (4)$$

Here, k is thermal conductivity perpendicular to the magnetic field[6], Q_{joule} is energy loss due to Joule heating of the electron gas, Q_{atom} is energy loss through the atomic processes and Q_{ie} is exchange energy between electrons and ions[6]. The magnetic field B is determined by an induction equation by combining the generalized Ohm's law,

$$\frac{\partial \rho u}{\partial t} = curl\left(\frac{1}{\sigma\mu_0} curlB\right) - curl\left(u \times B\right). \qquad (5)$$

Consequently, the current density and the magnetic field are related through the Ampere's law,

$$curlB = \mu_0 j\ . \qquad (6)$$

In these equations, j is the current density, μ_0 is the permeability of vacuum and σ is the conductivity of the plasma. The following rate equation is coupled with the MHD equations.

$$\frac{dN_i}{dt} = \sum_m R_{li} N_{mi} - R_{mi} N_i\ . \qquad (7)$$

Where, R_{mi} is the net rate describing the transition including the collisional ionization, 3-body recombination and radiative recombination[7, 8]. Each charge state was calculated for ground state.

3. Experimental result and calculation analysis

Time evolution of the radiation emitted from the nitrogen plasma produced by a capillary discharge was measured as shown in Fig. 2. In this experiment, maximum discharge current amplitude was 18 kA and pulse width was about 70 ns. In Fig. 2, the green line indicates the radiation intensity in the range from 20 nm to 100 nm, the black line indicates the EUV radiation intensity and the brown line indicates the discharge current wave form. Radiation in the range from 20 nm to 100 nm is increasing rapidly 30 ns after the initiation of the discharge. This indicates that the maximum pinch occurs at around 30 ns. Meanwhile, the radiation signal in the EUV range gradually stars to increase after 30 ns. It is considered that it takes time to ionize the nitrogen into higher charge state. Then, the radiation in the EUV range continuously increases. At this time, the recombination radiation takes in larger part of radiation and in which may exist Balmer α line.

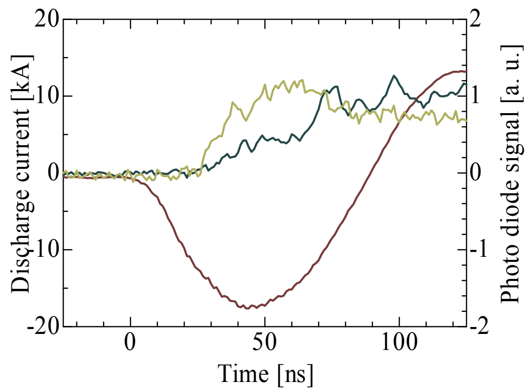

Fig. 2 Measured time evolution of radiation intensity. Green line: Radiation intensity in the range from 20 nm to 100 nm. Black line: EUV radiation intensity. Brown line: Discharge current wave form.

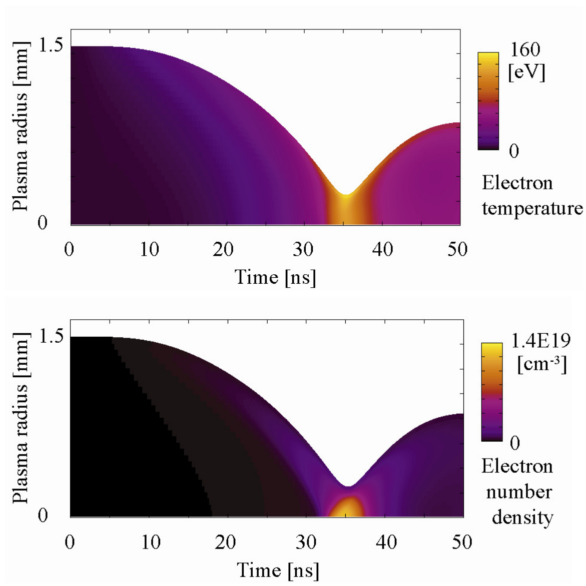

Fig. 3 Calculated electron temperature (up) and electron number density (down). Peak discharge current amplitude: 18 kA. Pulse width of discharge current: 70 ns. Initial number density of NII: 4×10^{16} cm^{-3}.

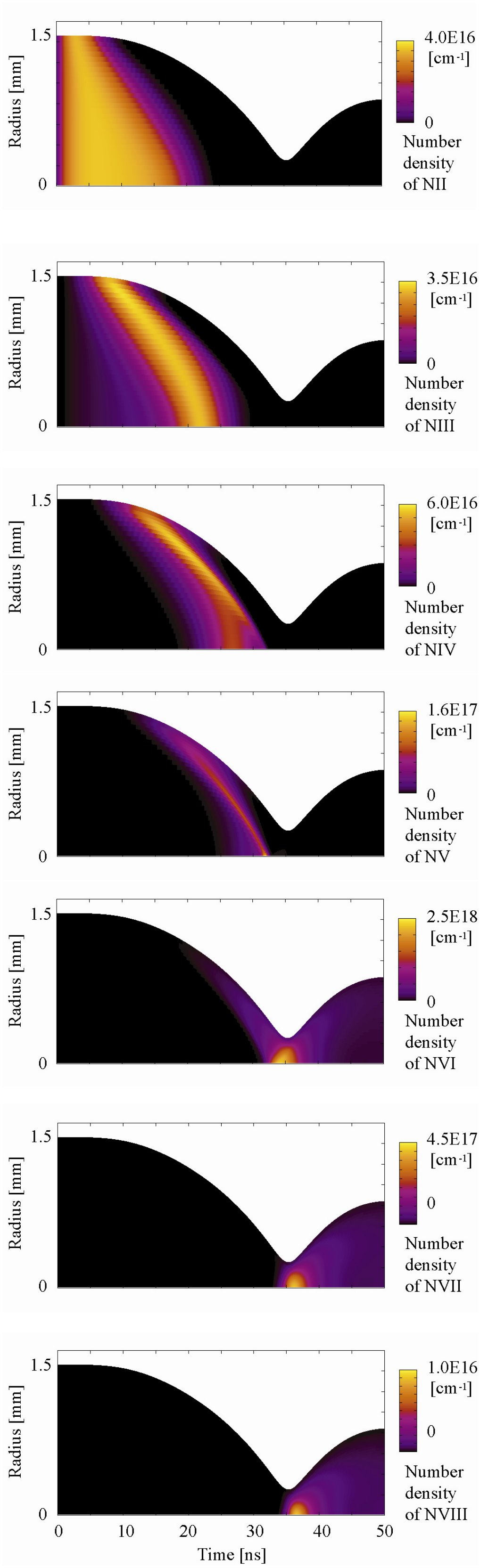

Fig. 4 Time evolution of respective nitrogen ion density distributions. Peak discharge current amplitude: 18 kA. Pulse width of discharge current: 70 ns. Initial number density of NII: 4×10^{16} cm^{-3}.

Based on these experimental conditions, the electron temperature and the electron density were calculated as shown in Fig. 3. These results show that the maximum pinch occurs at about 30 ns after the initiation of the discharge. The maximum electron temperature reaches 160 eV, which is high enough to generate NVIII according to the Saha's equation while the maximum electron density is 1.4×10^{19} cm^{-3} at the most. Time evolution of ion density distribution for respective ionization charge states, which is in ground state, is shown in Fig. 4. Ion charge number increases gradually to NVI as the plasma sheet is accelerated toward the capillary axis by the Lorenz force. After the implosion of the plasma sheet on the axis, ionization to NVII occurs in a few ns. Consequently, after the instant of maximum pinch, about 5 % of the nitrogen ions become NVII. Subsequently, only 2 % of NVII are ionized to NVIII. In this case, according to the Saha's equation, electron temperature is high enough to fully strip the nitrogen. Although ionization to NVIII is not performed effectively because it needs more time in such a low-density plasma to ionize the nitrogen up to NVIII. As a result, the obtained density of NVIII is not enough to generate a population inversion for lasing. Thus, in order to obtain the required number density of NVIII at the maximum pinch time, higher electron number density is needed to increase the electron collisional ionization rate. In addition to these facts, to realize a recombination laser by the use of effective three body recombination, it is necessary to obtain higher electron number density, because three body recombination rate is proportional to the square of electron number density.

4. Discussions

Based on the above results, the possibility of realizing the lasing of a recombination soft X-ray laser is discussed. At the initial NII number density of 3×10^{17} cm^{-3}, the MHD equations were solved for a discharge current of 50 kA with a pulse width of about 70 ns. Calculated time evolution of the temperature and the electron number density are shown in Fig. 5. From these results, the maximum pinch occurs at about 35 ns after the initiation of the discharge and the obtained maximum electron temperature is 160 eV. In this case, the maximum electron number density reaches 9.0×10^{19} cm^{-3}, which is several times higher than that of calculation results for a discharge current of 18 kA mentioned above. The time evolution of the density distribution of the nitrogen ions is shown in Fig. 6. Nitrogen ions up to NVI were continuously ionized to the next charge states in a similar way as shown in the low-density plasma case. A few ns before the maximum pinch, when imploding shock reaches the plasma column axis, population of the NVI greatly increased and the almost all of the ions becomes to NVI. In the maximum pinch phase, that is a few ns after the generation of NVI, population of the NVII starts to dominate. Additional heating of the plasma by the magnetic pinch compression and thermalization of the pinched plasma generates NVIII and number density of NVIII reaches 1.2×10^{19} cm^{-3}, which is 1000 times higher than that of calculation results for a discharge current of 18 kA. In this case, at the instant of maximum pinch, electron density is high enough to initiate the collisional ionization of NVII to NVIII effectively. Finally, electron temperature rapidly goes down to several tens of eV by the expansion of the plasma column. In this recombination phase, several ns after the maximum pinch, the electron number density keeps still in the order of $10^{19}cm^{-3}$. Such a high electron number density is suitable for three body recombination scheme which leads to the generation of inversion population between n=2 and n=3 of NVII. Therefore, theoretically, it is possible to obtain the gain of 1 cm^{-1}. But, in this expansion phase, it is difficult to form the concave electron density profile which leads to the wave guide of the laser radiation. In addition to this, the m=0 instability may grow after the maximum pinch, which also prevents the amplification of radiation. Therefore, it is necessary to consider the radiation transport of the Balmer α line in the expansion phase. However, we still expect that it is possible to obtain the gain by utilizing the capillary discharge recombination pumping scheme.

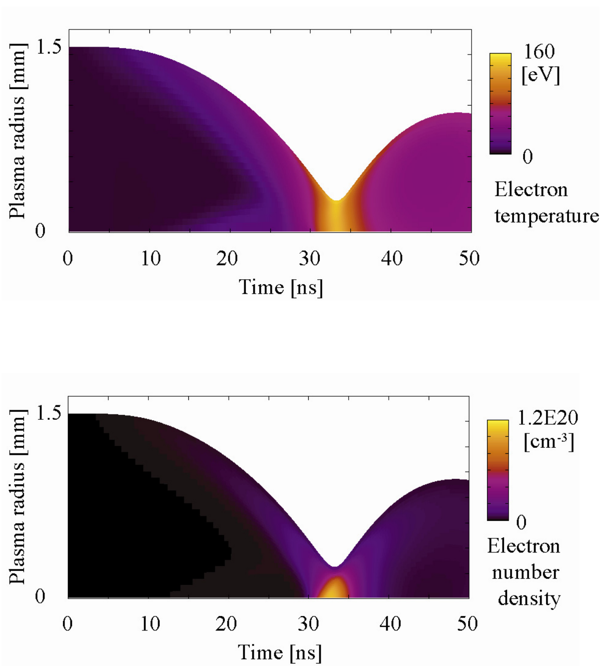

Fig. 5 Calculated electron temperature (up) and electron number density (down). Peak discharge current amplitude: 50 kA. Pulse width of discharge current: 70 ns. Initial number density of NII: 3×10^{17} cm^{-3}.

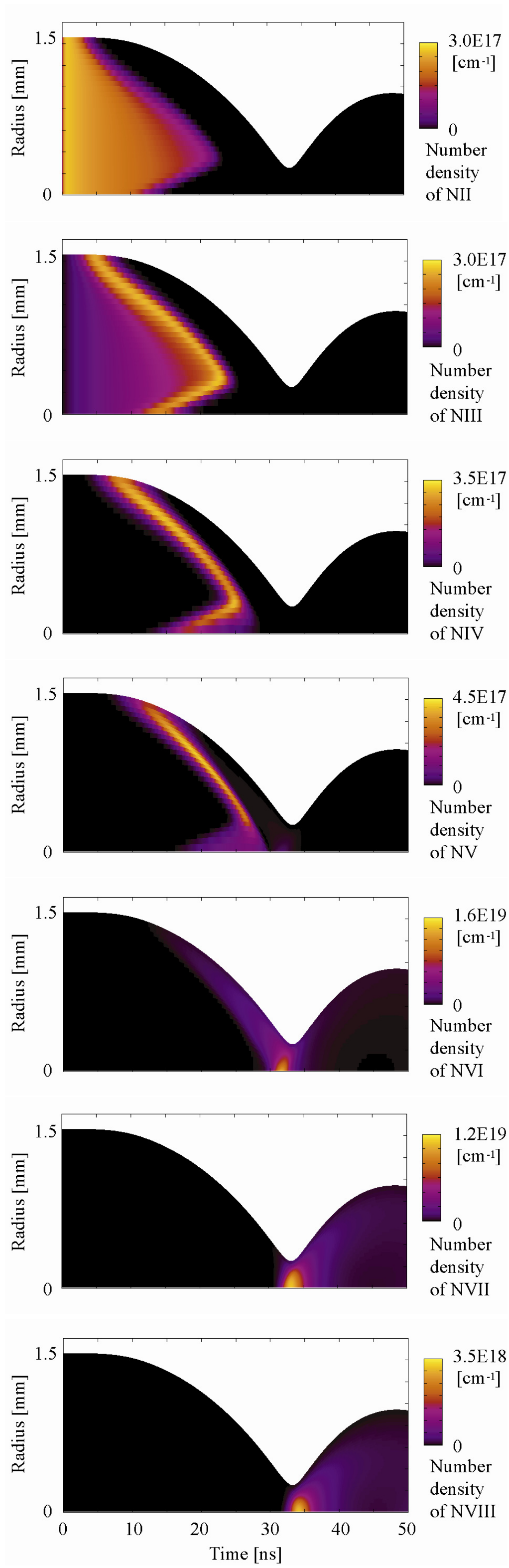

Fig. 6 Time evolution of respective nitrogen ion density distributions. Peak discharge current amplitude: 50 kA. Pulse width of discharge current: 70 ns. Initial number density of NII: 3×10^{17} cm^{-3} .

5. Conclusions

To investigate the possibility of the H-like N recombination soft X-ray laser by using a capillary discharge scheme, the evolution of the EUV emission from the nitrogen of low-density plasma was measured and discussed based on MHD calculation. Measured intensity of EUV radiation from the nitrogen plasma starts to increase gradually after the maximum pinch. The MHD calculation results, based on the experimental condition, show that in such a slightly low density plasma, required NVIII number density could not be obtained due to the lack of time to be ionized by electron impact. However, when initial gas pressure is increased and discharge current amplitude is increased to about 50 kA, it is theoretically possible to increase the NVIII ion number density up to the required value. As a result, possibility of realizing a H-like N recombination soft X-ray laser by utilizing an efficient capillary discharge scheme was shown.

Acknowledgement

The authors would like to thank the invaluable advice of Dr. Toru Kawamura and Dr. Majid Masnavi. Also, they would like to acknowledge the Seimitsu Kosaku Gijutsu Center of Tokyo Institute of Technology for their help in precision machining of device parts. This work was supported by the JSPS Research Fellowship for Young Scientists and the Grant-in-Aid for Exploratory Research, MEXT.

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