NE-LIKE AR SOFT X-RAY LASER PUMPED BY CAPILLARY DISCHARGE WITH DIFFERENT CURRENT PULSES

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ABSTRACT

Two capillary discharge devices with different current waveforms were used to excite Ar plasma columns up to 35 cm in length in 3.2 mm diameter channel. The Ne-like Ar lasers at 46.9 nm, 69.8nm and 72.6 nm were obtained with one capillary discharge device with current amplitude of 12-17 kA and a half period of 110 ns. The lasers at 69.8nm and 72.6 nm in Ne-like Ar ions were achieved with low current of 12 kA. The experimental results with different initial pressure show that the 69.8 nm and 72.6 nm lasers can be realized with lower pressure than the pressure of 46.9 nm laser. In addition, the saturated soft x-ray laser at 46.9 nm was generated with the initial pressure of 22 Pa and peak current of 17 kA. The gain coefficient is 0.58 cm^{-1}. On the other capillary discharge device, the highly saturated soft x-ray laser at 46.9 nm was realized with the current amplitude of 27 kA and a half period of 170 ns. The gain coefficient of 1.0 cm^{-1} has been achieved with the initial pressure of 60 Pa.

1. INTRODUCTION

There is significant interest to develop compact and efficient soft x-ray laser. One of the promising approaches is the capillary discharge scheme, which has the advantages of a relatively high efficiency, large gain length and long gain duration. The first demonstration of soft x-ray laser of Ne-like Ar at 46.9 nm pumped by capillary discharge was realized by American group in 1994[1]. In the experiment, the gain coefficient of 0.6 cm^{-1} and gain length product of 7.2 was observed with polyacetal capillaries and current amplitude of 39 kA[1]. Since then, significant progresses have been made in increasing the energy of laser, realizing new wavelength laser and applying the 46.9nm laser. Besides Ne-like Ar 46.9 nm laser, Ne-like S 60.8 nm laser[2] and Ne-like Cl 52.9 nm laser [3] have been realized with capillary discharge scheme by American group. In 2011, the Ne-like Ar 69.8 nm laser was first demonstrated by our group[4].

In order to increase laser energy at 46.9 nm and reduce the peak current, polyacetal capillary was replaced by alumina capillary in 1998. With ceramic capillary 18.2cm in length, lasing was obtained with an average energy of 135 μJ at a repetition rate of 7 Hz[5]. In 1999, increased laser energy was achieved by increasing the length of capillary to 34.5 cm. Average laser energy of 0.88 mJ was obtained at a repetition rate of 4 Hz[6]. In addition, the discharge parameters such as initial pressure, peak current were varied to obtain the optimum parameters of 46.9 nm laser[7,8]. With the saturated 46.9 nm laser, many application experiments have been conducted such as dense plasma diagnostics, laser ablation and so on[9].

In the capillary discharge scheme, a fast current pulse rapidly compresses the plasma, creating a hot dense plasma column. The soft x-ray amplification can be obtained in the plasma column. The state of plasma column and the laser pulse depend on the current pulse. In this paper, two capillary discharge devices with different current pulses were used to study Ne-like Ar lasers.

2. NE-LIKE AR LASER CORRESPONDING TO CURRENT AMPLITUDE OF 12-17 KA

The details of the experimental setup have been described in publication [10]. The power supply of main pulse consists of Marx generator, Blumlein line and main switch. The Blumlein line with capacitance of 7nF is pulse-charged by a Marx generator and is discharged through main switch into a capillary channel containing the pre-ionized Ar gas. The Ar gas is pre-ionized by pre-pulse power supply with voltage of 20kV and current of 20A. An Al_2O_3 capillary with an inner diameter of 3.2 mm and a length of 35 cm was utilized in the experiment. A x-ray diode (XRD) was used to detect the laser pulse and a grazing-incidence x-ray spectrograph (McPherson 248/310G) having 600 lines/mm gold coated grating was used to measure the soft x-ray spectrum.

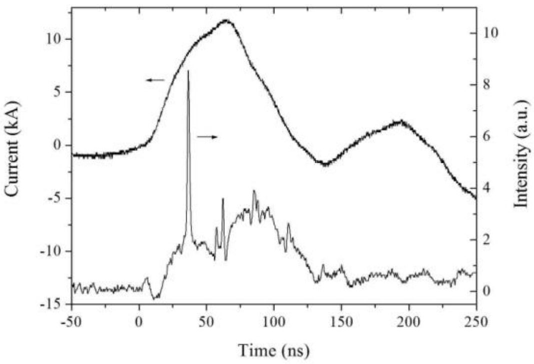

Fig. 1 Discharge current pulse and temporal evolution of soft x-ray emission detected by XRD. The Ar pressure was 12.5 Pa

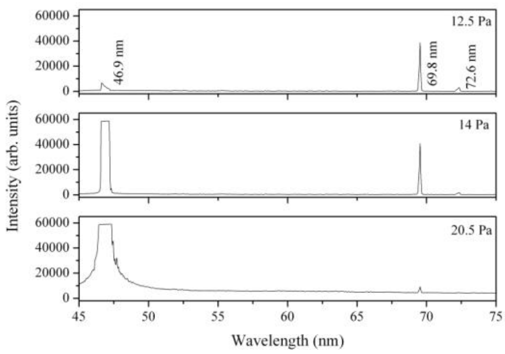

Fig. 2 Time-integrated axial emission spectra, showing three Ne-like Ar laser lines at 46.9 nm, 69.8 nm and 72.6 nm.

Figure 1 shows the main current waveforms and the XRD signal at initial Ar pressure of 12.5 Pa. The discharge current pulse has an amplitude of 12 kA, a rise-time of 43 ns and a half period of ~110 ns. A laser spike with the duration of 1.7 ns was observed at 36.5ns after the beginning of the discharge current. In order to measure the wavelength of the laser spike, soft x-ray emission in the axial direction was measured with a grazing-incidence x-ray spectrograph. Figure 2 shows the time-integrated axial emission spectra for three initial pressures of 12.5 Pa, 14 Pa and 20.5 Pa. In the pressure of 12.5 Pa, the laser line of Ne-like Ar at 69.8 nm totally dominates the spectrum. In addition, there are two weak laser lines at 46.9 nm and 72.6 nm. As the pressure increases from 12.5 Pa to 14 Pa, the intensity of 46.9 nm laser line becomes larger than the 69.8 nm and 72.6 nm laser lines. In the pressure of 20.5 Pa, the laser line of Ne-like Ar at 46.9 nm totally dominates the spectrum, and the laser line at 69.8 nm is weak. These results show that the high pressure is benefit to the 46.9 nm laser. The electron density of compressed plasma increases with the increase of initial pressure. Therefore, the high electron density is good for the 46.9 nm laser.

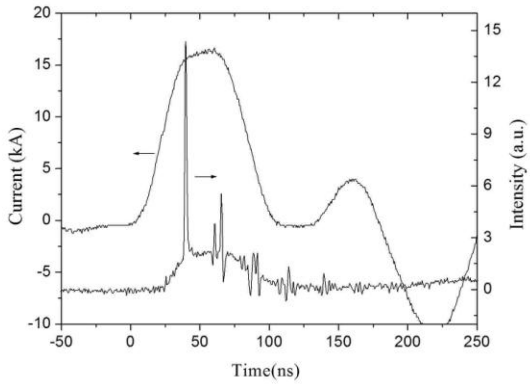

Fig. 3 Discharge current pulse and temporal evolution of soft x-ray emission detected by XRD

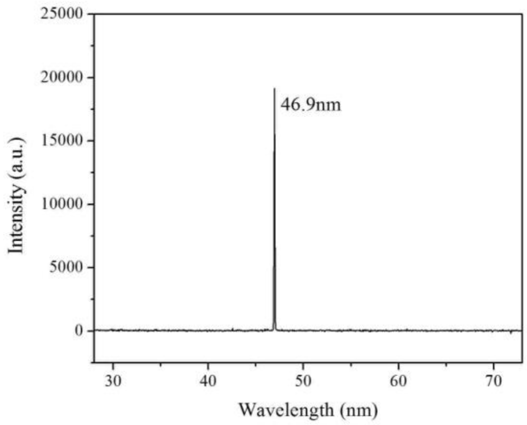

Fig. 4 Time-integrated axial emission spectrum, showing Ne-like Ar laser line at 46.9 nm.

In order to increase the electron density, the amplitude of the main current was enhanced to 17 kA as shown in figure 3. The half period of the current is about ~110 ns and the rise-time is 27ns. A typical temporal evolution of soft x-ray emission at the initial pressure of 24.5 Pa is shown in figure 3. A laser spike with the duration of 1.7 ns was observed at 40ns after the beginning of the discharge current, as shown in figure 3. The time of lasing onset of 40 ns is larger than the one of 36.5 ns in figure 1. Figure 4 shows the spectrum from the plasma, corresponding to the same conditions of figure 3. In the spectrum ranging from 30 nm to 70 nm, the 46.9 nm laser line completely dominated the entire 40 nm wide spectrum and the 69.8 nm and 72.6 nm laser lines were not observed. Experimental results show that the largest intensity of 46.9 nm laser can be obtained at Ar pressure of 22 Pa. Therefore the gain coefficient was determined at 22 Pa by measuring the 46.9 nm line intensity as a function of capillary discharge, as shown in figure 4. The intensity of 46.9 nm line was observed to increase exponentially for length up to 27 cm, where it begins to saturate. A fit of these data with Linford formula yields a gain coefficient of 0.58 cm^{-1}. The saturated 46.9 nm laser has been realized..

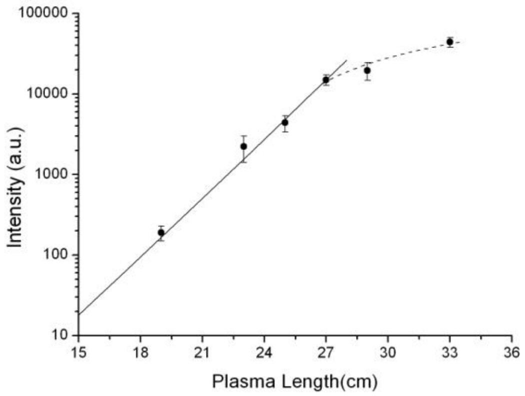

Fig. 5 Variation of the intensity of 46.9 nm line as a function of plasma column length. The gain coefficient determined by Linford formula is 0.58 cm^{-1}.

3. NE-LIKE AR LASER CORRESPONDING TO CURRENT AMPLITUDE OF 27 KA

In order to increase the energy of the 46.9 nm laser, the amplitude of the main current was enhanced to 27 kA. This experiment was conducted with the other capillary discharge device. The main pulse power supply was described in a previous publication [11]. It consists of a ten-stage Marx generator, a main switch and a 3 nF water-insulated capacitor as intermediate energy storages. The pre-pulse power supply, discharge chamber, vacuum system and detection system are similar to the device described in the last section. An identical capillary described in the last section was used in the experiment. The plasma in the capillary was generated with current pulses having a first cycle duration of 170 ns as shown in figure 6. An intense laser spike with the duration of 1.8 ns was observed at optimum pressure of 60 Pa as shown in figure 6. The onset of the laser pulse occurs at 36.5 ns after the beginning of the current pulse. The spectrum ranging from 30 nm to 70 nm was also measured. The results show that the spectrum is completely dominated by 46.9 nm laser line.

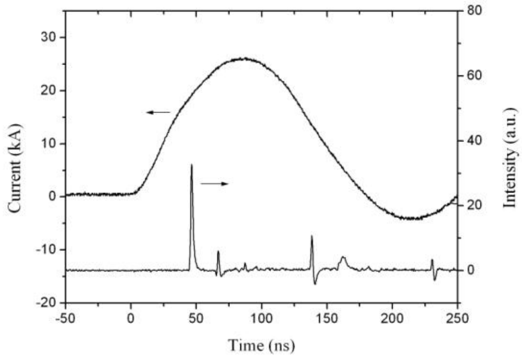

Fig. 6 Discharge current pulse and 46.9 nm laser output pulse

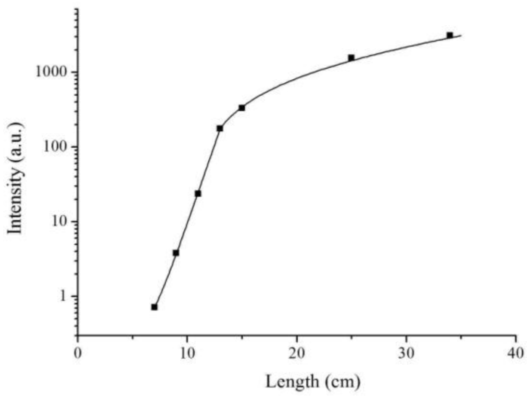

Fig. 7 Variation of the intensity of 46.9 nm line as a function of plasma column length. A fit to the Linford formula yields a gain coefficient of 1.0 cm^{-1}.

The gain coefficient of 46.9 nm laser was measured at the optimum pressure of 60 Pa. Figure 7 illustrates the measured variation of the intensity of 46.9nm line as a function of plasma column length. The intensity of 46.9 nm line increases exponentially for the plasma column length up to 14 cm, where it begins to saturate. A fit of the data corresponding to the length up to 14 cm results in a gain coefficient of 1.0 cm^{-1}. Saturation intensity is observed at a gain length product about 14. The laser intensity reaches saturation intensity 20 cm before the end of the plasma column, allowing for efficient energy extraction. The optimum pressure for 27 kA is about 60 Pa, which is much higher than the one of 22 Pa for 17 kA. Therefore, with the higher current, Ar gas with higher initial pressure can be compressed to form the higher density plasma. In this plasma, the electron density, electron temperature and Ne-like Ar abundance is high, which is benefit to enhance the gain coefficient and intensity of 46.9 nm laser. Compared the figure 7 with figure 5, the gain coefficient for 27 kA is almost two times the one for 17 kA. It means that the population inversion between upper and lower laser level is much larger for 27 kA than the one for 17 kA. Therefore, the plasma compressed by higher current pulse can emit 46.9 nm laser with larger energy.

4. CONCLUSIONS

With two capillary discharge devices, the Ne-like Ar lasers were achieved at different current pulses. At low current of 12kA, the Ne-like Ar laser at 46.9 nm, 69.8 nm and 72.6 nm were observed. The 69.8 nm and 72.6 nm laser lines become weak and disappear with the increase of the pressure from 12.5 Pa to 20.5 Pa. In addition, the 69.8 nm and 72.6 nm laser lines were not observed with current of 17 kA and 27 kA. The intensity of 46.9 nm laser increases with the pressure and current. At the current of 17 kA, the optimum pressure of 46.9 nm laser is about 22 Pa. At this pressure, the gain coefficient of 0.58 cm^{-1} has been obtained in the 46.9 nm laser line. The intensity is observed to saturate at the plasma length of 27 cm. When the amplitude of current was increased to 27 kA, the optimum pressure of 46.9 nm laser increased to 60 Pa and the gain coefficient increased to 1.0 cm^{-1}. These results show that low current is benefit to generate the 69.8 nm and 72.6 nm laser, and high current and high pressure are good to increase the energy of 46.9 nm laser.

ACKNOWLEDGMENTS

This project is supported by National Natural Science Foundation of China (Grant No. 61275139, 61078034).

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