Effects of pre-pulse current on Ne-like Ar laser at 72.6 nm excited by capillary discharge

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Received: 27 April 2022 / Accepted: 11 July 2022 / Published online: 10 August 2022
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Abstract
At present, research on the capillary discharge plasma Ne-like Ar 72.6 nm laser is insufficient, and additional experimental studies are supposed to determine the experimental parameters of the laser. Thus the effects of the pre-pulse current and the delay time between pre-pulse and main-pulse on the 72.6 nm laser are investigated in this paper. Before the experiments, the plasma parameters during the Z-pinch process were simulated. We employed 3.2 mm inner diameter capillaries with 35 cm and 45 cm lengths in the experiment. The experiment was conducted with the main-pulse current amplitude of 17.5 kA, the initial Ar pressure of 14–21 Pa, the pre-pulse and main-pulse delay time of 3.5–54.5 μs, and the pre-pulse current amplitude of 9.0–66.8 A. The intensity of the 72.6 nm laser was measured with different experimental parameters. The experimental results indicate that the intensity of 72.6 nm laser is maximum with the initial Ar pressure of 16 Pa, the pre-pulse and main-pulse delay time of 20 μs, and the pre-pulse current amplitude of 18.4 A in the 45 cm long capillary.

1 Introduction
X-ray lasers are primarily utilized for coherent diffraction imaging [1], dense plasma diagnosis [2], material surface research [3], etc. Highly ionized plasma is most often employed as the gain medium. Due to the small size and high conversion efficiency, the capillary discharge produced plasma is commonly utilized in X-ray lasers. The capillary discharge scheme was first proposed by Rocca et al. for generating soft X-ray lasers [4]. The 46.9 nm laser output was demonstrated utilizing a capillary 12 cm long and 4 mm inner diameter filled with a Ne-like Ar plasma as the gain medium [5]. Figure 1 shows the energy level structure of the Ne-like Ar ion. Since then, several research groups have also followed up and achieved the output of the 46.9 nm laser [6–9]. It is also significant to study lasers at wavelengths other than 46.9 nm between the $2p^5 3s$ and $2p^5 3p$ configurations. Kim et al. established a collision excitation model for Ne-like Ar ions and calculated the populations and gain coefficient of the transitions between the $2p^5 3s$ and $2p^5 3p$ configurations. It was found that the transition $2p^5 3p^1 S_0$ $- 2p^5 3s^1 P_1 (J = 0–1)$ corresponding to the 46.9 nm laser was not the only one to produce the laser. When the electron density was between $10^{18}$ and $10^{19}$ cm$^{-3}$, the $2p^5 3p^3 D_2 - 2p^5 3s^3 P_1 (J = 2–1)$ transition also had the possibility to generate the 72.6 nm laser [10].

From the energy level structure of Fig. 1, it can be known that the upper and lower energy levels of the 46.9 nm and 72.6 nm lasers are completely different. This leads to a significant difference in the experimental conditions required to output the two wavelengths. In the study by Jiang et al., the 46.9 nm laser intensity was the highest when the pre-main pulse delay was 12 μs, and higher delays weakened the intensity [11]. In addition the experimental results obtained by Muhammad et al. [12] and Tan and Kwek [13] both showed that with the increase of the main-pulse current amplitude, the optimal initial pressure and the peak intensity of the 46.9 nm laser increased. In this paper, the experimental conditions required to output the 72.6 nm laser are completely different from those of the 46.9 nm laser. It is found that there are two peaks of laser intensity in the process of increasing the pre-main pulse delay under partial pre-pulse current amplitude. In addition, it is difficult to obtain the 72.6 nm laser for high main current.

In 2011, our research group utilized a main-pulse current with a rise time of 43 ns and an amplitude of 12 kA to...
pinch the plasma in a 3 mm inner diameter and 35 cm long alumina capillary. The 72.6 nm laser output of the \(2p^33p^3D_2\) \(-2p^53s^3P_1\) \((J=2–1)\) transition was observed for the first time at the initial Ar pressure of 12.5 Pa. At the initial pressure of 13 Pa, the intensity of the 72.6 nm laser increased, demonstrating the possibility of its growth [14]. In 2016, our research group further measured the gain coefficient of 72.6 nm laser as 0.22 cm\(^{-1}\) and the gain-length product as 7.3 at the initial pressure of 16 Pa [15].

To the best of our knowledge, other international research groups have not reported on the 72.6 nm laser except for our research group. Our research group has only studied the effects of the initial pressure on the laser output so far [15]. Thus the study of 72.6 nm laser is not yet comprehensive. According to the experimental results of Niimi et al., the pre-pulse current impacts the initial plasma state [6], which may affect the 72.6 nm laser intensity. In this paper, we investigate the effects of the pre-pulse current amplitude and delay time between pre-pulse and main-pulse on the 72.6 nm laser intensity and determine the optimal conditions for laser generation. At the same time, the results of this paper are significative to guide other groups to obtain and optimize the 72.6 nm laser.

2 Experimental setup

The experimental setup has been described in detail in references [11, 16]. Its fundamental structure is shown in Fig. 2, including a main-pulse power, a pre-pulse power, a control system, a discharge chamber, a vacuum chamber, a detection system, etc. The capillary material is \(\text{Al}_2\text{O}_3\), and its end close to the main switch is inserted with a molybdenum electrode. The other end is the ground electrode and is connected to the vacuum chamber. Before the experiment started, the capillary was in a vacuum environment. Initially, the Ar gas with different initial pressure controlled by adjusting the valve was filled in the capillary. When the main-pulse charging system charges the capacitors in the Marx generator to the specified voltage, the pre-pulse power receives a trigger signal from the control system and generates a 9.0–66.8 A pre-pulse current. The pre-pulse current ionizes Ar and produces the initial plasma consisting of low ionization Ar ions. Figure 3 shows the pre-pulse current waveform with an amplitude of 29.0 A and a decay time constant of 29.6 \(\mu\)s. The capacitors of the Marx generator are discharged in serial following the specified delay. After the rectification by the water capacitor, the main-pulse current is generated as the main switch self-breakdown. With the Z-pinch action of the main-pulse current, the initial plasma is compressed to form a plasma state appropriate for the laser output. The laser in this paper has no resonant cavity. After the single-pass amplification in the plasma, the laser is output in the form of amplified spontaneous emission (ASE). Figure 4 shows...
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3 Experimental results and discussion

The experiment first employed a capillary with an inner diameter of 3.2 mm and a length of 35 cm, similar to the previous research [15]. Although the 72.6 nm laser output was successfully produced, the intensity was low. Therefore, a capillary with an inner diameter of 3.2 mm and a length of 45 cm was selected to increase the gain-length product. The intensity of the 72.6 nm laser increased significantly. Thus we mainly reported the experimental results using the 45 cm long capillary. Before exploring the effects of the pre-pulse current on the 72.6 nm laser, it was necessary to determine the optimum Ar pressure. Figure 5 shows the variation of the 72.6 nm laser intensity with the initial Ar pressure when the main-pulse current amplitude is 17.5 kA and the pre-pulse current amplitude is 18.4 A and 29.0 A, respectively. Compared with the intensity variation at the pre-pulse current amplitude of 29.0 A, the laser intensity increased and decreased more rapidly at the pre-pulse current amplitude of 18.4 A. While at both pre-pulse amplitudes, the laser intensity was maximal at the 16 Pa initial Ar pressure.

The plasma state was simulated by the magnetohydrodynamics (MHD) program in this paper. As shown in Fig. 6, the radial distribution of electron density was calculated when the inner diameter is 3.2 mm, the initial pressure is 16 Pa, and the main-pulse amplitude current is 17.5–23.5 kA. In the radial range of 0.05–0.25 mm off-axis, the increase of the main pulse current amplitude increases the electron density. When the main-pulse current amplitude is 17.5 kA and the initial pressure is 14–20 Pa, the radial distribution of electron density is shown in Fig. 7. In the radial range of 0.05–0.25 mm off-axis, the electron density rises with the increase of the initial pressure. When the main-pulse current amplitude is 17.5 kA and the initial pressure is 16 Pa, it is consistent with the electron density corresponding to the maximum relative gain coefficient at the wavelength of 72.6 nm obtained by Kim et al. [10]. This also explains that the 72.6 nm laser output is the highest under this condition.

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Fig. 3 Pre-pulse current waveform with the amplitude of 29.0 A

Fig. 4 Main-pulse current waveform with the amplitude of 17.5 kA

Fig. 5 The time-integrated intensity of 72.6 nm laser versus Ar pressure when the pre-pulse current amplitude is 18.4 A and 29.0 A
in the experiment. The effects of pre-pulse current amplitude and delay time between pre-pulse and main-pulse on the laser intensity were further investigated at the initial Ar pressure of 16 Pa.

Figure 8 shows the variation of the 72.6 nm laser intensity with pre-pulse and main-pulse delay time when the pre-pulse current amplitudes are 18.4 A, 29.0 A, 35.6 A, and 49.0 A, respectively. Hayashi et al. discovered that as delay time increased, preionized plasma was sequentially divided into three states: uniform plasma column, non-uniform and moving striations, and composite state. The demarcation delay time between the first two states decreased as the initial Ar pressure dropped [17]. According to the results in reference [17], we consider that the initial plasma may be a uniform column at 20 μs. Because the initial plasma is uniform, the Z-pinch process will be stable when the main-pulse arrives, which is advantageous to the laser output. When the pre-pulse and main-pulse delay time is greater than 20 μs, the striations fringe state of the initial plasma may cause the instability of the Z-pinch process, resulting in a rapid decrease of the 72.6 nm laser intensity.

Figure 8 also shows that at a pre-pulse current amplitude of 18.4 A, another laser intensity peak is visible at the pre-pulse and main-pulse delay time of approximately 11 μs. The peak intensity was less than that at 20 μs. When the pre-pulse current amplitude was 29.0 A, the laser intensity peaked at 11 μs delay time as well. However, it was significantly weaker than the peak at 18.4 A. In contrast, the peaks were not significant at other pre-pulse current amplitudes. It may be due to the fact that the radial electron density gradient in the Z-pinch process is minimal when the delay time is 11 μs. The refraction effect has a weak influence on the light. So the smaller refraction loss results in the laser intensity peak at this delay time.
The intensity of 72.6 nm laser peaked at pre-pulse and main-pulse delay times of 11 μs and 20 μs when the pre-pulse current amplitude was 18.4 A. So we investigated the effects of pre-pulse current amplitude on 72.6 nm laser intensity at the delay time of 11 μs and 20 μs. Figure 9 shows the variation of the 72.6 nm laser intensity with the pre-pulse current amplitude for both delay times. At delay times of 11 μs and 20 μs, the laser intensity increased by 437% and 284% as the pre-pulse current amplitude increased from 9.0 to 18.4 A, respectively. However, as the pre-pulse current amplitude grew from 18.9 to 35.6 A, the laser intensity decreased. In the pre-pulse current amplitude range from 35.6 to 66.8 A, the laser relative intensity gradually decreased between 1700 and 1000 at the delay time of 11 μs. But it stabilized at about 3000 at the delay time of 20 μs.

Shuker et al. reported that increasing the amplitude of the pre-pulse current resulted in a more uniform distribution of gas heating and preionized plasma, which was advantageous for Z-pinch process stabilization. When the pre-pulse current amplitude exceeded a critical value, increasing it within a specified range was difficult to improve the uniformity of gas heating and preionized plasma distribution [18]. The conclusions of reference [18] can be used to explain the positive correlation between the laser intensity at 72.6 nm and the pre-pulse current amplitude in 9.0–18.4 A. When the pre-pulse current amplitude exceeds 18.4 A, it becomes difficult to improve the uniform distribution of gas heating and preionized plasma further. The 72.6 nm laser absorption due to the increased gas escape velocity may become the main factor of the laser intensity reduction.

In addition, Shuker et al. also believed that the change of the axial magnetic field and the radial motion of the plasma column may also lead to the reduction of the laser output under the condition of high-amplitude pre-pulse current [18]. Pre-pulse current with different amplitudes will generate different axial magnetic fields in the capillary. The changes of the axial magnetic fields have a certain influence on the distribution of the plasma, which in turn affects the output of the laser in the subsequent Z-pinch process. Similar to the main pulse, the high-amplitude pre-pulse may also induce radial motion of the plasma, but the process may be unstable, resulting in the same instability of the subsequent Z-pinch.

### Conclusion

In summary, we reported the 72.6 nm laser output of the \(2p^53p^3D_{2}–2p^73s^3P_{1} (J=2–1)\) transition of Ne-like Ar ions in a 3.2 mm inner diameter and 45 cm long alumina capillary. After determining the optimum Ar pressure of 16 Pa at the main-pulse current amplitude of 17.5 kA, the effects of the pre-pulse current amplitude and delay time between pre-pulse and main-pulse on the 72.6 nm laser output

\[ C_s = (\gamma Z k T_e/m_i)^{1/2} \]  
where \(\gamma\) is the adiabatic index, and its value is 5/3 for Ar gas, \(Z\) is charge state, \(k\) is Boltzmann’s constant, \(T_e\) is electron temperature, and \(m_i\) is ion mass. The gas escape velocity is given by [21]:

\[ v_e = \frac{2}{\gamma - 1} C_s. \]
were investigated. When the pre-pulse current amplitude was varied, the peak laser intensity occurred at 11 μs and 20 μs delay times. However, the peak laser intensity was higher at the 20 μs delay time. Meanwhile, the experimental results showed that laser intensity increased at first and then decreased as the amplitude of the pre-pulse current increased in both delay times. Eventually, the optimal conditions for 72.6 nm laser generation were determined to be 16 Pa initial Ar pressure, 18.4 A pre-pulse current, and 20 μs delay time between pre-pulse and main-pulse at 17.5 kA main-pulse current. This study has the guiding significance for the future investigation of the effects of initial plasma on the 72.6 nm laser. The above results are expected to optimize the experimental parameters further to obtain a more intense 72.6 nm laser output.

**Author contributions** YZ contributed to the conception of the study; YB, YZ, BA performed the experiment; YB, YZ, DZ, HC contributed significantly to analysis and manuscript preparation; YB performed the data analyses and wrote the manuscript; LL, JL helped perform the analysis with constructive discussions.

**Funding** This research was funded by the National Natural Science Foundation of China (Grant numbers 61875045, 62005066).

**Declarations**

**Conflict of interest** The authors declare no competing interests.

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