Soft X-ray amplification in 3- and 4-mm-diameter capillaries

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Laser pulses with energy of ~10 μJ are generated at 46.9 nm on the $3p-3s$ transition of the Ne-like Ar by a fast capillary discharge setup in both 3- and 4-mm channels. The dependence of the laser output pulse energy on the pressure of Ar gas is measured for 3-mm-diameter capillaries at currents of 25, 30, and 35 kA. Under the same discharge conditions used in 3-mm capillaries, experiments indicate that higher and faster current pulses are required to produce soft X-ray amplification in 4-mm-diamater capillaries.

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Besides the normal properties of lasers, X-ray laser has its special advantages, such as short wavelength, excellent monochromaticity, nice directivity, and high brightness, which make it widely used in biological imaging, atomic physics, micro-technology, diagnostics of nuclear fusion plasma, etc.. Notable progress has been made in X-ray laser since collisional excitation amplified spontaneous emission (ASE) in Ne-like Se was first demonstrated by large laser facilities in 1984. However, these X-ray laser sources are generally pumped by large facilities, their use in a number of important applications is hampered by the large size, complexity, and cost. With the goal of demonstrating table-top soft X-ray laser, Rocca *et al.* proposed to excite soft X-ray amplifications by use of a compact capillary discharge due to its enhanced efficiency, compact size, and low cost. They reported the first demonstration of a large soft X-ray amplifier at 46.9 nm on the $3p-3s$ $(J=0-1)$ transition in Ne-like Ar plasma by capillary discharge in 1994[1]. At the International Conference on X-ray Laser in 1995, the capillary discharge soft X-ray laser was considered to be one of the most possible schemes to realize table-top soft X-ray laser. In 1999, they obtained impressive results[2−4], operating this laser at 4 Hz with an average energy value of 0.88 mJ. More recently, three other groups also reported the amplification at 46.9 nm by capillary discharge[5−7].

The influence of pre-discharge on soft X-ray amplification and the performance of 46.9-nm laser had been studied by E. Hotta group[8]. Herein we would like to present the dependence of the laser output pulse energy on the initial pressure of Ar gas in a 3-mm-diameter capillary channel. The soft X-ray amplification in a 4-mm-diameter capillary on the same experiment setup is also obtained by using higher and faster discharge current pulses. To our knowledge, this is the first report on soft X-ray amplification in both 3- and 4-mm capillaries on the same experiment setup.

The capillary discharge setup is schematically illustrated in Fig. 1. The system consists of a Marx generator, a 2:30 step-up transformer, a pulse-forming line (PFL), a gap switch, and a pre-pulse circuit. This device was designed to excite electron collision pumping scheme extreme ultraviolet (XUV) laser in Ne-like Ar at 46.9 nm.

The PFL is a pure-water coaxial line. It is charged by a three-stage Marx generator, the output voltage of which is 40 kV; subsequently 600-kV voltage can be achieved at the output of the PFL with a half period of 100−120 ns. The gap switch is composed of four trigger electrodes filled with SF_6 gas. The equivalent electrical circuit diagram of the capillary discharge system is shown in Fig. 2.

A ceramic capillary is placed on the axis of the device connecting to the gap switch. An anode in various lengths is inserted into the capillary to change the length of the Ar gas column; a cathode with a hole in its axis enables the radiation from the capillary to enter the

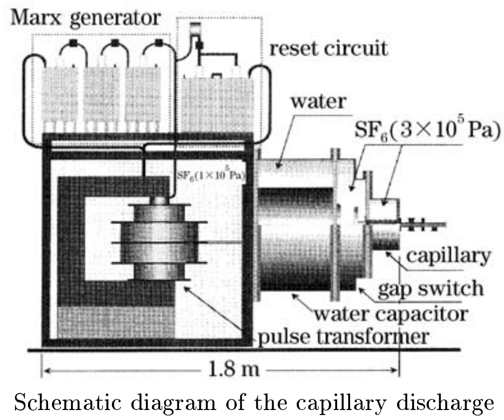

Fig. 1. Schematic diagram of the capillary discharge setup.

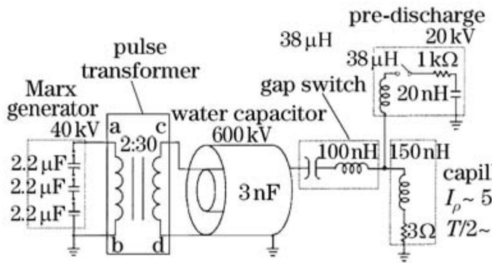

Fig. 2. Equivalent electrical circuit diagram of capillary discharge system.

detector system. A pinhole is mounted 15 mm from the end of the capillary to establish different pumping at both sides and effectively reduce the radiation absorption in Ar gas.

Firstly, the Ar gas filled in a capillary is pre-discharged by a 10−100 A current pulse with a duration of 10−20 μs, and then a large current pulse rapidly discharges through the pre-discharged gas along the capillary channel to produce a hot plasma column. The amplitude of the fast current pulse is 30−50 kA with a rising time of about 50 ns, which results in $\mathrm{d}I/\mathrm{d}t \sim 1 \times 10^{12}$ A/s, providing the possibility of pumping capillary to excite X-ray lasing in Ne-like ions. The radiation from capillary discharge is monitored by an X-ray diode (XRD), which is positioned on the axis at 72 cm from the end of the capillary. The cathode of XRD is coated with a gold layer, which is sensitive to X-rays ranging from 10 to 100 eV. The distance between the cathode and the anode of XRD is 2 mm and the bias voltage applied to the cathode is 800 V.

The experiments were conducted by using a ceramic capillary, 16 cm in length and 3 mm in diameter, filled with pre-ionized Ar gas. The main current pulses used in the experiments had an amplitude of ~30 kA and a rise time of approximately 50 ns. They were preceded by a pre-pulse of about 20-A amplitude and several microseconds duration to produce a uniform pre-ionization. A little spike pulse with potential for amplification was measured in XRD output pulses at 220—450 mtorr (1 mtorr = 0.133 Pa) Ar pressures at 33 ns after the initiation of the current pulses, the result is shown in Fig. 3(a). A large increase in the amplitude of the spike pulse was obtained at the Ar pressure of 340 mtorr, as shown in Fig. 3(b). The full-width at half-maximum (FWHM)

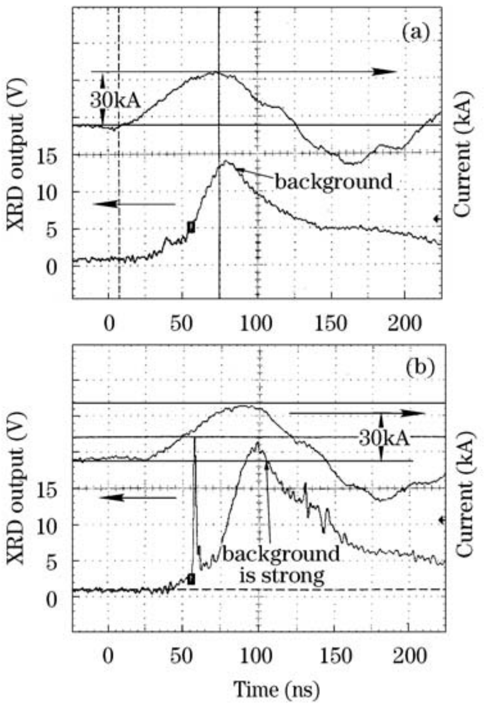

Fig. 3. Waveforms of the main current pulse and the XRD output pulses for a 16-cm plasma column excited by pre-pulses of 20 A and main current pulses of 30 kA. (a): Under the pressure of 450 mtorr; (b): 340 mtorr.

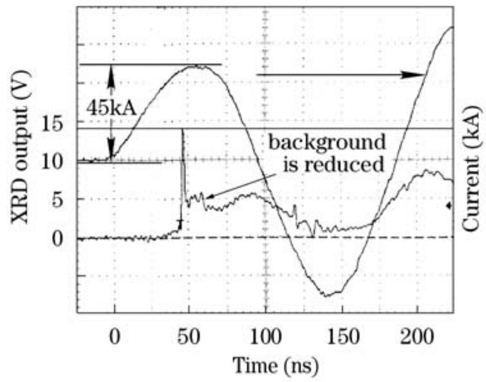

Fig. 4. Waveforms of the main current pulse and the XRD output for a 16-cm plasma column under Ar pressure of 340 mtorr and current of 54 kA.

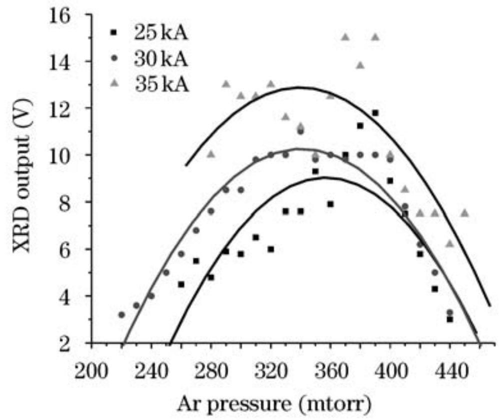

Fig. 5. Intensity of the laser emission as a function of the Ar pressure for currents of 25, 30, and 35 kA.

of the spike pulse is determined to be ~2 ns. When an aperture of 3 mm in diameter was placed on the axis at 20 cm from the XRD, the background emission was reduced greatly, while the amplitude of the spike changed little, as shown in Fig. 4. This result indicates that the spike pulse appears to have a good directivity, which is one of the characteristics of a laser line. Actually, this spike has been proved to attribute to the lasing of $3p-3s$ transition ($J = 0-1$) in Ne-like Ar with a wavelength of 46.9 nm[1,7].

The amplitude of the laser spike on the output of XRD was measured to reach the maximum value of 13.8 V by use of 16-cm-long capillary plasma columns at the discharge current of 35 kA and Ar pressure of 380 mtorr. The estimated output laser energy of laser is 10 μJ and the corresponding energy conversion efficiency is estimated to be 3×10^{-8}. Previous experiments and simulations[1,8] indicated that the laser spike is usually obtained before the collapsinng plasma column reaches the axis, when the value of the main current approaches the peak value[2]. In our experiments, the laser spike took place at nearly half the value of the current pulse, where the value of the current was 18 kA. This result suggested that the amplification of the soft X-ray could be realized at a lower discharge current, as low as 18 kA.

The intensity of the laser emission as a function of the initial pressure of Ar gas for different current pulses was measured. The results are shown in Fig. 5. In the case of

25-kA current, the pressure range for lasing is in a narrow region from 250 to 440 mtorr. As the current amplitude increased from 25 to 35 kA, the pressure region for lasing became wider. The intensity of the laser under the same pressure also increased as the peak value of the current pulses increased from 25 to 35 kA. The intensity of the laser emission was measured to be 8.8, 10.1, 12.8 V, respectively, for 25, 30, and 35 kA under the pressure of 340 mtorr. Actually, with the increase of the current amplitude, the value of $\mathrm{d}I/\mathrm{d}t$ approaches 1×10^{12} A/s, which is considered to be one of the most necessary conditions to avoid the great ablation of the capillary wall and to reach a proper electron temperature for the population inversion. Therefore, it can be predicted that higher intensity of the laser spike can be achieved if the current amplitude exceeds 35 kA.

The lasing experiments were also performed in a 4-mm-diameter channel. The results are shown in Fig. 4. In this case, the value of the pre-discharge current pulse was improved from 20 to 60 A, and an aperture with the diameter of 3 mm was placed on the axis at 20 cm from the XRD. Though the discharge voltage of the Marx generator was kept at the same value with that for the 3-mm capillary, the amplitude of the current pulse was measured up to 54 kA with half cycle duration of 100 ns. The great increase of the current amplitude may be attributed to the adequately pre-discharge of Ar gas and the diminishment of the impedance in the discharge circuit.

In the case of the 4-mm capillary, the laser output pulse took place at 50 ns from the beginning of the current pulse, while it appeared at 33 ns for the 3-mm capillary. Moreover, the peak value of the laser spike for the 4 mm capillary (15.3 V) is higher than that for the 3-mm one (8.4 V) under the same Ar pressure of 340 mtorr and the same length of plasma column. To produce soft X-ray amplification in 4-mm-diameter channels, faster and higher discharge current pulses should be used. These discharges provide the advantage of producing necessary hot plasma columns, which can result in the larger amplification in transitions of Ne-like ions.

In conclusion, soft X-ray amplification in Ne-like Ar at 46.9 nm has been observed in a low pressure range from 220 to 440 mtorr when discharged by a fast current pulse of 25 kA. The pressure range becomes wider when the current amplitude increases from 25 to 35 kA. The experimental results indicate that higher and faster current pulses are needed for 4-mm-diameter capillaries to excite soft X-ray lasers.

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