Influence of current prepulse on capillary-discharge extreme-ultraviolet laser

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In this paper the influence of the prepulse current on a capillary-discharge 46.9 nm Ne-like Ar extreme-ultraviolet laser is reported. A current pulse with a typical RC shape (decay time of ~30 μs) was used as a prepulse. Measurements indicate that when the filling pressure is low, the output can be improved by reducing the time delay between the application of the prepulse current and the onset of the main discharge current. For high pressure the reverse is true. This change is most significant for time delays between 2 and 4 μs, and beyond these time delays, the effect is less significant. This effect is attributed to the changes in the capillary channel pressure and also to the absorption of the laser emission by the plasma plume ejected during the prepulse. Thus, apart from ensuring a minimal amount of prepulse current to prevent nonuniformity effects, the timing of the application of the prepulse current is also important.

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The short wavelength and high peak power of amplified spontaneous emission sources in the extreme-ultraviolet (EUV) and soft x-ray regimes make them very attractive for many applications in science and technology, and they have been extensively explored in past decades [1,2]. Of particular interest and importance is the development of compact, higher efficiency and low cost systems that are more affordable and accessible to make their use more widespread in important applications. The first observation of large amplification in the transitions of Ne-like ions in capillary-discharge plasma [3] and the subsequent demonstration of the saturated operation of the tabletop amplifier [4] opened up such a possibility and has attracted much attention since. In this capillary-discharge scheme, an elongated plasma column with high aspect ratio (~1000:1) is created by a fast current pulse injected into a low pressure (~1 mbar) argon-filled capillary channel. The magnetic force induced by the current together with the high kinetic pressure gradients near the capillary wall compress the plasma, creating a shock wave. This compressional discharge leads to the formation of a hot and highly ionized plasma column 100–200 μm in diameter. A few nanoseconds before stagnation, when the first compression shock wave reaches the axis, the plasma attains a temperature (~60–80 eV) and mean electron density (~5×10^{18} cm^{-3}) necessary for lasing [5,6]. This condition creates a high abundance of Ne-like argon ions in the plasma, and population inversion between the 3p \(^1S_0\) and 3s \(^1P_1\) levels is achieved through collisional electron impact excitation of the ground state Ne-like argon ions, resulting in a gain at 46.9 nm wavelength. An important criterion for soft x-ray amplification in a discharge created plasma is the existence of a stable plasma column with good axial uniformity. Axial inhomogeneities usually accompany high power electrical discharges as a result of nonuniform initial conditions and slow compression [7]. To circumvent this plasma uniformity problem, the capillary channel is filled with a certain amount of preformed plasma just before the injection of the fast main current pulse. This preformed plasma allows the main current pulse to flow homogeneously through the plasma column. To date, in successful capillary-discharge laser systems [3,8–11], this preionization of the argon gas is achieved by the application of a “prepulse” current pulse with a peak value of tens of amperes for several microseconds prior to the onset of the main current pulse. Herein we report the experimental results showing the influence of the prepulse current on the operation of a capillary-discharge soft x-ray laser.

The schematic diagram of the capillary-discharge laser system used in our experiments is shown in Fig. 1. A four-stage double Marx generator, which is capable of producing 150–300 kV at erection, pulse charges a 5-Ω, 3-nF water-filled coaxial pulse-forming line (PFL). The PFL then discharges via a self-breaking spark gap pressurized with SF\(_6\).
into the capillary load resulting in a main discharge current pulse with a rise time of about 35 ns and peak values ranging from 9 to 19 kA. This fast excitation current produces \( \varepsilon \)-pinch capillary-discharge plasma in the 3-mm-diam and 20-cm-long ceramic (\( \text{Al}_2\text{O}_3 \)) capillary channel. The effective plasma length can be varied by using cathode pins of varying lengths. A field shaper is employed at the high voltage end of the capillary to prevent surface flashover along the insulator surface. Depending on the requirement, the filling argon gas pressure in the capillary was maintained in the region of 0.1–0.4 mbar by continuously injecting the gas through the 3 mm axial hole of the ground discharge electrode. The axial soft x-ray emission was monitored with a 1 m grazing incidence spectrograph (McPherson 248/310G) having a 600 lines/mm gold coated grating placed at 87°. A micro-channel plate (MCP) intensified charge coupled device (CCD) array detector was used for detecting the soft x-ray radiation. The radiation emanating from the axial hole of the ground electrode propagates through a 1 mm aperture installed 10 mm away from the hollowed ground electrode and then through a collimator (1 mm diam and 46 mm long) before it reaches the 30 \( \mu \text{m} \) spectrograph entrance slit situated 52 cm away. All the spectra and line intensity collected in this work were time integrated. These narrow openings allow for a differential pumping scheme which is necessary for the use of an MCP image intensifier at the spectrograph. The MCP works at pressures lower than 10\(^{-6} \) mbar while the argon pressure in the capillary channel is \( \sim 1 \) mbar. In fact, due to the poor transmission of EUV (soft x-ray) radiation in a gas such a pumping setup is indispensable if the laser is to be coupled to any detection system or experiment. For example, 80% of the radiation at 46.9 nm is absorbed after propagating through a 2 cm path of 1 mbar argon gas [12]. Therefore, contraptions with a similar function are found in all capillary-discharge soft x-ray lasers. The distance between the first aperture and the hollowed ground electrode is kept as short as possible to reduce reabsorption of the laser output by the argon gas. The collimator was also used as an aid in the alignment of the spectrometer to the laser system.

The main discharge current is preceded by an exponentially decaying \( (RC \sim 30 \mu \text{s}) \) prepulse current [Fig. 2(a)]. The amplitude of the current from this separate capacitor discharge circuit is controlled by varying a current limiting resistor. The synchronization between the main and prepulse currents is measured from relative timings of the onsets of the two current pulses.

Qualitative side-view observations of the prepulse plasma had been performed using simple visible light photography. A transparent boron-silicate glass capillary (inner diameter 4 mm and outer diameter 6 mm) was used to permit side-view imaging using a digital camera. Figure 2(b) shows a typical image taken with a peak prepulse current of 16 A, and an argon pressure of 0.22 mbar. Only a length of about 30 mm of the capillary was viewable through the side port of the load chamber. It can be seen that the column is a homogeneous glow discharge indicating that the plasma is heated in a uniform manner. As expected, for low prepulse currents (4 A or less) the emission was faint and the glow discharge plasma was inhomogeneous. A series of measurements was conducted changing only the peak prepulse current while the other parameters were kept constant. Strong and reproducible laser emissions were obtained with peak prepulse currents in the range of 10–23 A. For prepulse currents larger than 23 A, the laser emissions were not intense while none was observed below 4 A. Similar results had been observed elsewhere and plasma instabilities have been shown to be the main cause for the disruption of the laser performance [8,9]. In most of the experiments reported here, a peak prepulse current of 16 A was found to be most suitable, giving strong and stable laser output.

To measure the soft x-ray laser line amplification, the axial output spectra were taken for different plasma column lengths. Figure 3 shows the typical time-integrated axial output spectra for three lengths (10, 12, and 14 cm). The grating of the spectrograph was adjusted to the spectral region spanning from 38 to 57 nm. These spectra correspond to 16 kA discharges at 0.22 mbar argon. Strong amplification of the 46.9 nm \( 3p \rightarrow 3s \) (\( J=0–1 \)) line is evident. In the spectrum of the 10-cm-long plasma column, the intensity of the Ne-like Ar line is stronger than the intensity of the surrounding lines by slightly more than two times. In the 14-cm-long plasma column, as a result of amplification, the laser line completely dominates the spectrum. A plot of the integrated intensity of the \( J=0–1 \) line of the Ne-like Ar as a function of the plasma column length shows an exponential increase. A gain coefficient of 1.2 cm\(^{-1} \) is obtained when these data are fitted to the Lindford formula [13]. As a calibrated detector was not available, absolute measurement of the laser pulse energy could not be carried out.

Measurements of the time-integrated intensity of the \( J=0–1 \) line of Ne-like Ar at 46.9 nm as a function of the initial gas filling pressure and the main discharge current were carried out in detail to determine the dependence of the
amplification on these discharge parameters. Figure 4 shows the experimental results for a capillary length of 19 cm and prepulse current of 16 A applied 12 µs before the main current. For clarity the data for only three discharge currents are shown. Each data point represents the intensity readout from the MCP intensified CCD array detector of the spectrograph. For each pressure scan, discharge shots were collected while the main discharge current was maintained approximately constant. At 19.0 kA, adequate plasma conditions for strong amplification for the 46.9 nm line was obtained over a broad pressure range from 0.15 to 0.35 mbar with an optimum pressure of about 0.24 mbar. As the amplitude of the discharge current was reduced, this pressure range narrowed down. At 10.5 kA the optimum pressure was about 0.13 mbar while the pressure range was from 0.10 to 0.15 mbar. Initial investigations showed that the variation in the average output intensity was less than 20% for time delays between 14 and 30 µs, and dropped drastically beyond 30 µs. There appears to be significant sensitivity to time delays below 14 µs. In the more detailed results reported below, time delays below 14 µs were used.

The dependence of the integrated intensity of the laser line on the time delay between the prepulse and the main currents was then studied. Figure 5 shows the variation of the integrated intensity of the 46.9 nm Ne-like Ar line as a function of the initial gas filling pressure for two different time delays. (a) 16 kA and (b) 12 kA. The prepulse current was set at 16 A for all the experiments.

The dependence of the integrated intensity of the laser line on the time delay between the prepulse and the main currents was then studied. Figure 5(a) shows the variation of the integrated intensity of the 46.9 nm Ne-like Ar line with initial filling pressure for the 16 kA main current. The experiment was conducted for two different time delays at 2 and 12 µs with the prepulse current fixed at 16 A. While the operating pressure range is unaffected by the time delay, the laser output intensity for pressures beyond the optimum pressure is lower for the case of 2 µs time delay. However, when the main current was changed to 12 kA [Fig. 5(b)], the output intensity is higher for pressures below the optimum pressure for the case of 2 µs time delay. This increase in intensity at the lower pressure end is larger when the main current was reduced further.

Figure 6 shows the dependence of the integrated intensity of the 46.9 nm Ne-like Ar line on time delay for four different filling pressures of 0.12, 0.14, 0.16, and 0.24 mbar. The main and prepulse currents were fixed at 16 kA and 16 A, respectively. For each shot, the prepulse and the main current...
signals were recorded and the time delay was measured as accurately as possible from the oscilloscope. For all the pressures shown, the output emission exhibits two characteristics as the time delay was reduced: a relatively gradual variation from 12 μs to about 4 μs, and a sharper change for time delays below 4 μs. However, the characteristic for 0.12 mbar filling pressure is different from the rest. For the higher pressures (0.14–0.24 mbar), the output emission reduces as the time delay decreases but this trend is reversed for 0.12 mbar. The four intensity curves appear to converge to a common level at a time delay of about 2 μs. These measurements indicate that when the filling pressure is low, the output can be improved by reducing the time delay between the application of the prepulse current and the onset of the main discharge current. For high pressure the reverse is true. This change is most significant for time delays between 2 and 4 μs, and beyond these time delays, the effect is less significant. Thus, apart from ensuring a minimal amount of prepulse current to prevent nonuniformity effects, the timing of the application of the prepulse current is also important.

The above behavior may be attributed to the absorption of the laser radiation by the plasma plume ejected out of the capillary and also to the resulting change in the pressure in the capillary channel during the prepulse. Before the onset of the main current, relatively “cold” plasma is created by the prepulse current. The temperature of this glow discharge plasma was inferred from a visible spectroscopic measurement of the emission from the capillary opening. This measurement took advantage of the presence of the trace of hydrogen in the argon gas used. This trace of hydrogen can be from outgassing from material surfaces [14] (this phenomena is important when the surrounding pressure is roughly equal to or less than 0.1 mbar), and also from the gas tank itself. In a low temperature regime, argon atoms (Ar I) are less radiative compared to hydrogen atoms (H I). From the Saha-LTE model [15], the H I spectra intensities are about 1–2 orders higher. This means, a presence of ~1% or less hydrogen in the argon gas will give significant H α (656.3 nm) and H β (486.1 nm) lines, and this provides a convenient way for estimating the glow discharge temperature. A plasma temperature of about 0.5 eV was estimated from the H α (656.3 nm) to H β (486.1 nm) intensity ratio obtained. It should also be noted that the trace of hydrogen does not play any crucial role in the laser population mechanism [6]. Thus, the argon gas is heated up from room temperature (~0.03 eV) to ~0.5 eV, and is ionized when the electrical current passes through. This heating creates an increase in pressure in the capillary channel. The 3 mm opening at the ground electrode of the capillary allows small amounts of this ionized gas to expand adiabatically, diffuse and escape out of the capillary channel, producing a cold plasma plume immediately in front of the capillary opening. Assuming that the plume is expanding into a vacuum, the plasma plume front end velocity can be estimated. The escape velocity into vacuum u is given by [16]

\[ u = \frac{2}{\gamma - 1} C_S, \]

where \( C_S \) is the ion acoustic velocity of the heated plasma. This velocity is related to the plasma parameters by [17]

\[ C_S = \sqrt{\frac{\gamma Z k_B T_e}{m_i}}, \]

where \( \gamma = 5/3 \) for argon gas, Z is the ionization level, \( k_B \) is the Boltzmann constant, \( T_e \) is the electron temperature, and \( m_i \) is the ion mass. Assuming the argon atoms, on the average, are ionized to Ar + (i.e., \( Z = 1 \)) during the prepulse heating, and from the estimated \( T_e \sim 0.5 \text{ eV} \), the acoustic ions velocity turns out to be \( C_S \sim 1.4 \text{ mm/μs} \). With this, the plasma jet escape velocity is estimated to be around 4 mm/μs.

The plasma plume ejected propagates about 10 mm beyond the capillary opening before it meets the 1-mm-diam aperture of the differential pumping section. The conductance of the 1 mm aperture is about an order smaller than that of the 3 mm capillary opening. Thus, the flow of the plasma plume is impeded and it begins to fill the space between the capillary opening and the 1 mm aperture. The diffusion due to the density gradient built up at the beginning of the discharge ceases. For an escape velocity estimated to be about 4 mm/μs, the 10 mm space in front of the capillary will be filled up with the cold plasma after about ~2.5 μs. This means that before the plasma plume reaches the aperture, the preionized argon pressures inside and also outside of the capillary channel change drastically. Because the laser output depends on the pressure inside the capillary channel (pinching process) and also the presence of the cold plasma plume in front of the capillary (absorption), large changes of these conditions will lead to large changes in the laser output. The time estimated above is consistent with the “transition” time of ~3–4 μs observed in the experiments.

The plasma plume will expand sideways once it reaches the aperture. This transverse expansion will have the effect of reducing the plasma plume density at later times leading to less absorption of the laser output. As is apparent from Fig. 6, the laser output for initial filling pressures larger than 0.12 mbar (i.e., 0.14, 0.16, and 0.24 mbar) increases when the onset of the main discharge is delayed longer. However,

![Figure 6. Variation of the integrated intensity of the 46.9 nm lasing line as a function of time delay for different argon pressures. The main and prepulse currents were fixed at 16 kA and 16 A, respectively.](image)
In summary, we have found that while a certain minimal amount of prepulse current is needed for the operation of a capillary-discharge EUV (soft x-ray) laser, the timing of the application of the main discharge current with respect to the prepulse current has important bearing to the level of radiation emission. The effect of this timing is dependent on the initial filling pressure. We attribute this effect to absorption of the laser output by the plasma plume, which is ejected out of the capillary, and also to the changes in the pressure in the capillary channel during the prepulse. Thus, attention has to be paid to the optimization of the prepulse in capillary-discharge EUV (soft x-ray) lasers.

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