The effects of the pre-pulse on capillary discharge extreme ultraviolet laser

M. Shuker*, A. Ben-kish, R. A. Nemirovsky, A. Fisher and A. Ron
Department of Physics, Technion - Israel Inst. of Tech., Haifa 32000, Israel

In the past few years collisionally pumped extreme ultraviolet (XUV) lasers utilizing a capillary discharge were demonstrated. An intense current pulse is applied to a gas filled capillary, inducing a magnetic collapse (Z-pinch) and formation of a highly ionized plasma column. Usually, a small current pulse (pre-pulse) is applied to the gas in order to pre-ionize it prior to the onset of the main current pulse. In this paper we investigate the effects of the pre-pulse on a capillary discharge Ne-like Ar XUV laser (46.9nm). The importance of the pre-pulse in achieving suitable initial conditions of the gas column and preventing instabilities during the collapse is demonstrated. Furthermore, measurements of the amplified spontaneous emission (ASE) properties (intensity, duration) in different pre-pulse currents revealed unexpected sensitivity. Increasing the pre-pulse current by a factor of two caused the ASE intensity to decrease by an order of magnitude and to nearly disappear. This effect is accompanied by a slight increase in the lasing duration. We attribute this effect to axial flow in the gas during the pre-pulse.

PACS numbers: 42.55.Vc,42.60.Lh

In the last decades the possibility of achieving Amplified Spontaneous Emission (ASE) in the soft X-ray and XUV regimes was extensively explored [1]. One of the realizations utilizes a homogenous column of highly ionized plasma created by a fast capillary discharge [2]. Specifically, a fast (~50ns) and intense (~50kA) current pulse is applied to a capillary filled with low pressure (~1Torr) argon gas. The current induces magnetic forces that attract the gas towards the capillary axis. During the self-collision of the gas on the axis a column of highly ionized Ar plasma is formed (this technique to create high temperature plasmas is called Z-Pinch). Careful design of the experimental parameters results in high abundance of Ne-like Ar ions in the plasma, and population inversion between the 3P and 3S electronic configurations. The population inversion is due to excitations by collisions with hot electrons in the plasma and spontaneous emission - i.e. the collisional excitation scheme [1]. Strong amplification was observed in the 3P - 3S transition at 46.9nm [2-6]. The timing of the amplification (that lasts about 1ns) is close to the pinch time (i.e. the collision of shock waves on the capillary axis). Obviously, for efficient amplification the plasma column must be relatively stable and homogeneous (at least up to the amplification time). Several effects might cause instabilities or inhomogeneity in the Z-pinch process (see Ref. [6] and references therein). One of the possible reasons for inhomogeneity is the initial electrical breakdown through the gas column. At the onset of the main current pulse, high voltage across the capillary (hundreds of kV), may result in channel-like breakdown along the capillary walls (channel sparks) [6]. A technique to overcome this inhomogeneity is to pre-ionize the gas by a slow, low intensity current pulse ("pre-pulse"). In Refs. [2-6] a small current (typically 10 - 100A) is applied for a few µs before the onset of the main current pulse. The pre-pulse current creates sufficient amount of pre-ionization in the argon gas, allowing the main current pulse to flow homogenously (i.e. with an axial symmetry). In this paper we report experimental results showing the effect of the pre-pulse current on the operation of capillary discharge X-ray lasers. We investigate the homogeneity of the gas column during the pre-pulse itself, and during the plasma collapse. Finally we show the influence of the pre-pulse on the laser pulse properties.

Our experimental setup consists of a 1MV Marx type generator connected to a 7Ω transmission line. A self triggered spark gap connects the line and the capillary load (5mm inner diameter, filled with 500mTorr of Ar gas). A sine-shaped, 50kA peak current pulse is typically used with 100 - 120ns half cycle time (depending on the length of the capillary). Before the onset of the main current pulse a so-called "pre-pulse" current is applied. The pre-pulse current is created by a discharge of a small capacitor and has a typical RC shape with a decay time of ~20µs - see figure 4. The maximum current of the pre-pulse is controlled by a current limiting resistor. We note that prior to the pre-pulse a small spark was initiated at one end of the capillary ("pre-pre-pulse"). This spark, initiated across a 0.3mm long surface of alumina, increases the number of electrons in the gas providing easy breakdown conditions for the pre-pulse. In the experiments reported in this paper we used glass or alumina capillaries with various length (5 - 16.5cm). The exact properties of the capillary are stated before the description of each experiment.

Several measurements were carried out to investigate the role of pre-pulse current in the dynamics of the discharge and lasing processes. First, we measured the uniformity of the gas column illumination during the pre-pulse by means of visible light fast photography [6]. A 5cm long glass capillary was used in these experiments to allow side-view imaging. The visible light emission of the gas in the capillary is indicative of current flow, ionization...
and heating of the gas. Therefore a non-uniform emission indicates that the volume of the gas is heated in a non-uniform manner. Experiments were carried out with pre-pulse peak currents in the $5 - 50A$ range, and the emission was monitored up to $20\mu s$ after the pre-pulse started. A $5A$ pre-pulse current caused a channels-like emission pattern in the gas (even after $20\mu s$ the emission of the gas was inhomogeneous). On the contrary, a $50A$ peak current pre-pulse induced a homogenous emission in the gas. The homogenous emission was achieved $6\mu s$ after the onset of the pre-pulse current.

In order to further investigate the effect of the pre-pulse current on the stability of the plasma column collapse, an off-axis pinhole camera was used. This camera consists of an array of four pinholes placed in front of the capillary, with each of the holes located slightly off the capillary axis. The position of the pinholes allowed imaging of the entire length of the plasma column from four different directions (an $8cm$ long alumina capillary was used in these experiments). The images from all four pinholes were obtained on a gated multi-channel plate (with $3ns$ gating time) that was coupled to a CCD camera. A thin Mylar filter was used to limit the spectral response of the detector ($\sim 2 - 5nm$), so only radiation from highly ionized Ar ions ($Ar^{8+}, Ar^{9+}$) was measured. We have performed a series of pinhole measurements with different pre-pulse conditions. Usually, the image was taken at the instance the plasma column self-collided on the capillary axis (the pinch time). The pinhole images were analyzed using a simple ray-tracing code. Figure 2a shows a pinhole image taken with a relatively low $5A$ peak current pre-pulse, displaying an instability of the plasma column (the cone shape of the column is a result of the measurement geometry, causing different optical magnification along the plasma column).

In figure 2b a reconstruction of the experimental image is demonstrated using a ray-tracing code. The best reconstruction was achieved by displacing a $2cm$ long segment in the middle of the plasma column by $150\mu m$ from the axis. This instability obviously diminishes the amplification as the gain region diameter is of the order of $100\mu m$. Note that the magnitude of the instability has a large shot to shot variation and some shots display relatively stable collapse even with $5A$ pre-pulse current. This is consistent with the fact that occasionally we measured strong XUV amplification even with low pre-pulse currents. Repeating the same measurement with a pre-pulse peak current of $50A$ showed a stable collapse in every shot. These measurements indicate that in case the pre-pulse current is too low, an instability develops during the plasma collapse. Its magnitude depends on the initial conditions of the column (that are slightly different in every shot).

The two measurements discussed above indicated that minimal pre-pulse current must be used in order to ensure instabilities free collapse of the plasma column. Indeed, appropriate pre-pulse conditions resulted in strong lasing at the $3S \rightarrow 3P$ transition of the Ne-like Ar ion. A Carbon X-ray diode was placed in front of the capillary to measure the temporal history of XUV radiation during the main current pulse. The response of the Carbon photo-cathode is in the spectral range $40 - 100nm$ ($\sim 12 - 30eV$). Special care was taken to ensure high bandwidth of the entire measurement system (The overall bandwidth was $\sim 1GHz$). The signal was measured on a $5GS/s$ digitizing oscilloscope. In this set of experiments we used a $16.5cm$ long alumina capillary to obtain a laser pulse strong enough to be easily measured in this time-resolved technique. A typical signal from the X-ray diode (XRD) shows a combination of two physical effects. A relatively slow radiation pulse (typical time $\sim 50ns$) starts $\sim 20ns$ after the onset of the main current and peaks after $60 - 70ns$. On top of the slow pulse an extremely fast and intense radiation pulse is observed (typical time of $\sim 1ns$). The latter pulse appears $45 - 50ns$.
after the onset of the main current. We attribute the slow pulse to the radiation of the heated plasma in the capillary, while the fast pulse is attributed to the lasing action in the plasma. Figure 3 displays typical main current and XRD signals. We have chosen to display an experiment with a relatively weak laser signal so the less intense signal of the plasma radiation is evident.

While investigating the properties of the laser a strong sensitivity to the pre-pulse peak current was observed. A series of consecutive measurements was performed changing only the peak pre-pulse current (by changing the current limiting resistor in the pre-pulse circuit). The rest of the experimental parameters were kept constant. In all the shots reported below the peak of the main current was $52 \pm 1kA$ and the Ar pressure in the capillary was $500 \pm 10mTorr$. The properties of the laser pulse were analyzed in the following manner. The background plasma radiation in the vicinity of the pulse was subtracted, and the pulse was fitted to a Gaussian (using a least squares minimization algorithm). The properties of the laser pulse (intensity, time, FWHM) were deduced from the Gaussian fit. This technique of analysis is required to reduce the experimental errors caused by the limited sampling rate. We have investigated the relation between the laser pulse properties and the pre-pulse peak current. The timing of the laser pulse (relative to the onset of the main current) was not influenced by the change in the pre-pulse peak current (in all the measurements the lasing time was within a range of $1ns$). However, both the intensity of the laser pulse and its duration show a systematic dependence on the pre-pulse peak current. In figure 3 the intensity and duration of the laser pulse are plotted against the pre-pulse peak current in the range $50 - 100A$. When the pre-pulse current is increased - a rapid decrease in the laser pulse intensity is observed. It is important to note that a relatively small increase in the pre-pulse (from $50A$ to $100A$) reduced the intensity of the laser by an order of magnitude. Another experimental observation is that while the laser intensity decreases, the duration of the laser pulse increases.

The purpose of the pre-pulse current in the capillary discharge experiment is to heat and ionize the gas column. This pre-ionization allows the main current to flow uniformly in the gas column (i.e. with axial symmetry) and prevents channel like breakdowns. Therefore, it is not surprising that a minimal level of pre-pulse current is required to prevent non-uniformity effects. The pre-pulse current, being three orders of magnitude lower than the main current, is usually assumed to have no effect on the Z-pinch dynamics (other than insuring a stable collapse). However we found that increasing the pre-pulse current can reduce substantially the lasing intensity. The fact that the timing of the laser pulse stayed constant for all the pre-pulse currents we tested, suggests that the radial dynamics of the collapse is not affected by the pre-pulse amplitude (in the range $50 - 100A$). The decrease in the intensity of the laser can be attributed to several effects. In our experimental system the axial magnetic field is determined by the pre-pulse current, hence the change might be due to the different axial magnetic field. Another possibility is that the pre-pulse causes radial perturbations in the gas column (skin effect, radial motion) that later effects the main collapse. Finally, the heating of the gas column during the pre-pulse might cause axial flow of the gas through the hole in one of the electrodes (through which the laser radiation exits). The part of the capillary affected by the axial flow will have different initial gas density, and therefore very low gain $\tilde{c}$. Furthermore, the flow of gas out of the capillary will increase the absorption of the laser radiation when it exits the capillary.

The maximal axial magnetic field generated by the pre-pulse currents tested here is relatively low ($\sim 1.5kG$),
not in the range that should effect the lasing. In order to estimate the radial dynamics during the pre-pulse current a series of one-dimensional MHD simulations was performed. Even the maximal pre-pulse current used in our experimental investigation (100A) caused negligible radial non-uniformity in the plasma column (the uniformity was better than 1.5% during the entire pre-pulse). Finally, the axial motion during the pre-pulse was estimated by calculating the sound velocity of the heated gas from the electron temperature found using the MHD simulation. The simulation results show that during the 6µs, 100A pre-pulse the argon is heated to \( T_e = T_i \approx 1.5eV \) and reach mean ionization of \( Z \simeq 1 \).

The ions sound velocity in the plasma is given by Ref. [12]:

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

Where \( \gamma = 5/3 \) for mono-atomic gases, \( Z \) is the ionization level, \( k_B \) is the Boltzman constant, \( T_e \) is the electronic temperature and \( m_i \) is the mass of the ion. The calculated sound velocity of singly ionized ions is therefore \( C_i \approx 2500m/s = 2.5mm/\mu s \). During our 6µs, 100A pre-pulse a length of 1.5cm of the capillary is affected by the axial flow. This can explain a drop by a factor of three in the laser intensity (assuming a gain of 0.75cm\(^{-1} \)). The escape velocity to vacuum (i.e. through the exit hole in one of the electrodes) is given by:

\[
V_e = \frac{2}{\gamma - 1} \times C_i \approx 7500m/s
\]

Hence, the gas jet that escapes the capillary during the pre-pulse propagates about 3cm outside the capillary, and cause additional absorption of the laser radiation. These two effects both cause strong decrease in the laser pulse intensity, as observed in the experiments. The axial flow of gas may also explain the increase in the laser pulse duration, as it causes slightly different pinch times along the plasma column, effectively broadening the laser pulse.

In conclusion, we studied the effect of the pre-pulse current on various aspects of capillary discharge X-ray lasers. As can be expected, low amplitude pre-pulse current (5A) results in a non uniform heating of the gas during the pre-pulse, initiating instabilities during the magneto-hydrodynamic collapse. High amplitude pre-pulse currents (50A) results in a uniform heating of the gas and stable collapse of the plasma column. However, we found that the pre-pulse also affects the properties of laser pulse itself. Increasing the pre-pulse amplitude from 50A to 100A mitigates the intensity of the laser pulse by an order of magnitude. The pre-pulse also affects the duration of the laser pulse - exhibiting longer pulses at higher pre-pulse currents. We attribute both these effects to the axial flow of gas in the capillary during the pre-pulse. Because the strong effect of the pre-pulse on the laser properties it is important to take special care in optimizing the pre-pulse in capillary discharge X-ray lasers.

This work was partially supported by the Fund for Encouragement of Research in the Technion. We acknowledge the technical assistance of Uri Avni, Shalom Aricha, and Yoav Erlich in implementing the soft x-ray laser experiment.

[1] R. C. Elton, X-ray Lasers, (Academic Press, San-diego, 1990).
[2] J. J. Rocca, V. N. Shlyaptsev, F. G. Tomasel, O. D. Cortazar, D. Hartshorn, J. L. A. Chilla, Phys. Rev. Lett., 73, 2192, (1994).
[3] A. Ben-Kish, M.Shuker, R. Nemirovsky, A. Fisher, A. Ron, J. L. Schwob, Phys. Rev. Lett., 87, 015002-1, (2001).
[4] G. Niimi, Y. Hayashi, M. Nakajima, M. Watanabe, A. Okino, K. Horioka, E. Hotta, J. Phys. D: Appl. Phys., 34, 2123, (2001).
[5] G. Tomassetti, A. Ritucci, A. Reale, L. Palladino, L. Reale, S.V. Kukhlevsky, F. Flora, L. Mezi, J. Kaiser, A. Faenov, T. Pikuz, Eur. Phys. J. D 19, 73, (2002).
[6] D. Ryutov, M. S. Derzon, M. K. Matzen, Rev. Mod. Phys., 72, 167, (2000).
[7] J. A. Rees, J. D. Craggs, Electrical Breakdown in Gases, (Macmillan, London, 1973).
[8] A. Ben-Kish, M. Shuker, R. Nemirovsky, A. Ron, J. L. Schwob, Proceeding of the 6th Intl. Conference on X-Ray Lasers, Kyoto, 1998, edited by Y. Kato, H. Takuma and H. Daido, IOP Conf. Proc. No. 159 (IOP, Bristol, 1999) p. 191.
[9] J. J. Rocca, F. G. Tomasel, M. C. Marconi, J. L. A. Chilla, C. H. Moreno, B. R. Benware, V. N. Shiyaptsev, J. J. Gonzales, C. D. Macchietto, Proc. SPIE 3156, 164, (1997).
[10] F. G. Tomasel, V. N. Shiyaptsev, J. J. Rocca, Phys. Rev. A., 54, 2474, (1996).
[11] R. Nemirovsky, A. Ben-Kish, M. Shuker, A. Ron, Phys. Rev. Lett., 82, 3436, (1999).
[12] J. Huba (Ed.), NRL Plasma Formulary, (NRL,Washington D.C., 2000).