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Capillary discharge soft X-ray lasing in Ne-like Ar pumped by long current pulses

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Abstract. A capillary discharge soft X-ray laser operating at 46.9 nm on the transition $3p$–$3s$ ($J = 0$–1) of the Ne-like Ar has been realized by exciting the active medium with a long half-cycle duration current pulse of 140 ns. The current is produced by discharging a 10 nF water dielectric capacitor, initially charged to voltages lower than 200 kV by a six stage Marx generator, through a 15-cm long capillary channels. The laser amplification has been obtained by properly adjusting all the other experimental parameters. Utilizing a 3-mm in diameter Al_2O_3 capillary channel initially filled with 0.3 torr of Ar pressure, a laser beam, which has a 4-mrad divergence and a time duration of 1.3 ns, is characterized by a gain of 0.6 ± 0.1 cm^{-1}. The stability of the plasma compression followed by the laser emission is verified.

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1 Introduction

Few years ago, a successful experiment, conducted by Rocca *et al.* [1], showed large laser amplification at 46.9 nm in argon plasma pumped by a z-pinch capillary discharge. In this efficient X-ray pumping scheme, a current flowing through a capillary channel creates the active medium. The high current pulse compresses the plasma column towards the capillary axis, causing the plasma heating and the increasing of the electron density. If particular plasma conditions (density, temperature and dimensions) are reached during the plasma compression [2], laser amplification can be obtained at 46.9 nm between the $3p$–$3s$ levels of the Ne-like argon ions. Such conditions critically depend on the initial discharge parameters: the current pulse amplitude and rise time, the initial gas pressure, the capillary diameter, the capillary material and the preionization process. For such reason, since the first demonstration of lasing in a capillary discharge in 1994, only recently, successful experiments were reported by two other groups [3,4]. In this context it is important to fix which one of several parameters determining the plasma dynamics is the most critical and which of them can guarantee the reproducibility of the lasing action. Fast $\mathrm{d}I/\mathrm{d}t$ current slope (higher than 10^{12} A/s) has been considered one of the most crucial condition necessary to reach a good plasma compression and a proper electron heating needed for the population inversion avoiding plasma cooling and material ablation from the capillary walls. To achieve such slope, current pulses with half-cycle duration smaller or of the order of 100 ns have been utilized in other experiments [1,3–5]. These currents are generated by discharging low capacitance capacitors (of the order of few nF) through the capillary tube initially charged to a voltage higher than ≈300 kV. In our laboratory we succeeded in achieving generation of the stimulated emission at 46.9 nm in the Ar filled capillary discharge. In this brief report we show that the lasing action can be obtained using relatively long rise time (45 ns) and half cycle duration (≈140 ns) current pulses, by properly adjusting the other experimental parameters and utilizing a 10 nF capacitor charged with a voltage lower than 200 kV.

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2 Experimental setup

A detailed description of the experimental setup has been published elsewhere [6]. Figure 1 shows a schematic picture of the apparatus. A current pulse, having a peak value ranging from 26 to 40 kA and a half-cycle duration of 140 ns is used to excite the active medium. The relatively long current rise time (measured from 10% to

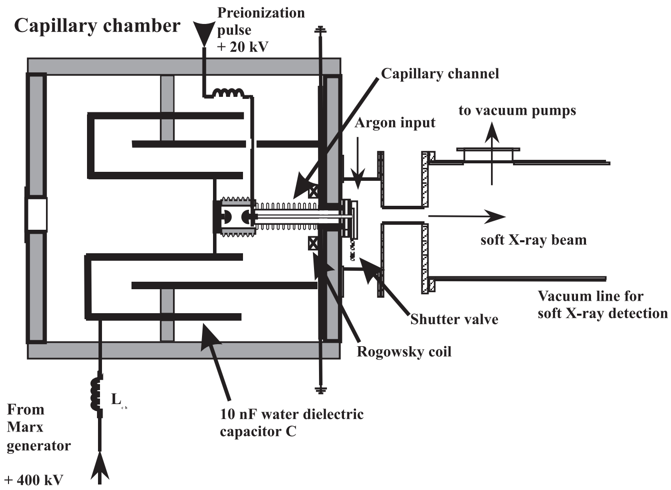


Fig. 1. A schematic diagram of the capillary discharge apparatus.

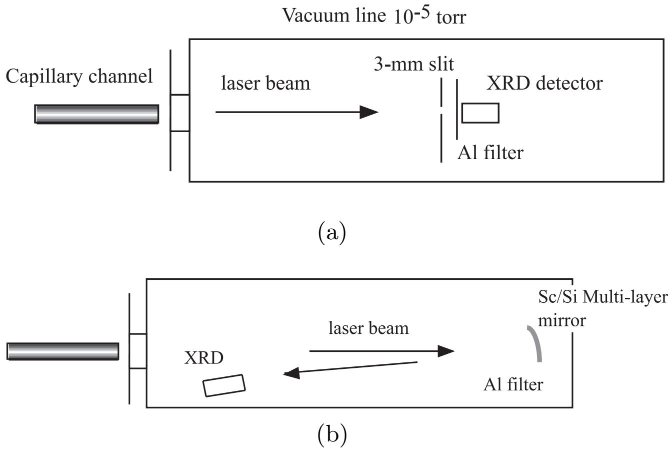
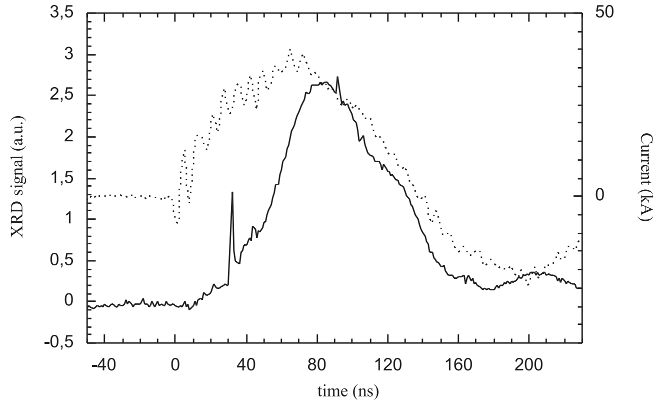


Fig. 2. (a) Schematic diagram of the first diagnostic arrangement with the XRD on axis at 100 cm from the capillary output and (b) the second diagnostic arrangement with the Sc/Si multilayer mirror positioned on axis at 170 cm far from the capillary output and the XRD out of focus at 80 cm from the mirror.

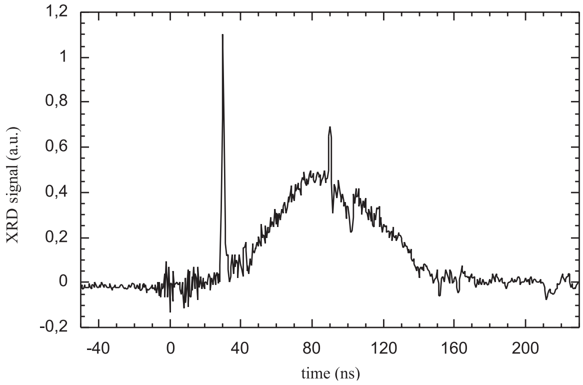
90% of the peak value) of about 45 ns, leads to an average $\mathrm{d}I/\mathrm{d}t = 0.6 \times 10^{12}$ A/s with a 30 kA current peak value. The current was produced by discharging a 10 nF water dielectric capacitor, through a low impedance circuit, which contains the capillary tube and a water spark-gap. The capacitor is initially charged typically only up to 200 kV by a six stages Marx generator. An independent circuit produces a 3−5 μs long preionization current, which was fixed at 20 A in the present experiments. The measurements have been performed in a 7.6−15 cm long, 3.0−3.4 mm in diameter capillaries, which were realized both in alumina and polyacetal. The capillaries have been statically filled with pure Ar to a pressure, ranging from from 0.1 to 1 torr. During the capillary filling a shutter valve provides to separate the capillary tube from the detection line. The opening of the valve, which takes roughly 1 ms, by appropriate trigger signals, drives both the preionization current and the main capillary discharge circuits and allows the radiation to escape from the capillary tube up to the detection system. A small reservoir chamber placed between the capillary exit and the shutter valve prevents a significant Ar pressure non-uniformity along the capillary during the shutter opening time. To detect the radiation we have used a fast vacuum photodiode (XRD) with a detection area of 200 mm^2, having a copper photo-cathode, which was polarized by a negative voltage of 560 V with respect to the grounded anode grid. A 1 GHz (Tektronix DSA602) digital oscilloscope has been used to monitor the signal from the photodiode. Such oscilloscope limited the time resolution of the measured signal to less than 0.5 ns. This resolution is still sufficient to measure the laser emission duration, which, as it has been reported in the other experiments [3,4,7], is expected to be of about 1−1.5 ns at FWHM. To perform our experiments we used two different diagnostic arrangements, (Figs. 2a and 2b). The first arrangement (Fig. 2a) is used both to measure the laser beam divergence and the amplifying gain, while the second one to spectrally select the $3p$−$3s$ ($J = 0$−1) transition of the Ne-like Ar ions. The first configuration consists of the detector directly positioned on the capillary axis at 100 cm far from the capillary output. A 0.8 μm thick Al foil on the XRD cuts the visible and ultraviolet radiation. A 3-mm wide slit was successively positioned in front of the XRD and transversally shifted (together with the XRD) in order to characterize the laser divergence. The second configuration (Fig. 2b), containing a Sc/Si multi-layer mirror, allowed the spectroscopic identification of the laser emission. The mirror is characterized by a normal incidence reflectivity of about 35% at 46.9 nm, and a bandwidth of ±2 nm centered at this wavelength, as reported in [8]. We used a 75-cm focal length mirror, positioned at 170 cm from the capillary exit (slightly tilted) and the XRD detector out of focus, at 80 cm from the mirror.

3 Experimental results

Figure 3a shows both the photodiode signal, measured with the first experimental configuration (with full XRD aperture), and the current pulse shape. The signal has been obtained utilizing 0.3 torr of Ar pressure and a 3-mm in diameter ceramic (Al_2O_3) capillary channel. Here, we can distinguish a peak at 31 ns after the current onset (much before the maximum of the current) which has a duration of 1.3 ns at FWHM, and a long lasting (>150 ns) soft X-ray spontaneous emission, having its maximum at about 85 ns. In Figure 3b it is shown the XRD signal obtained with the 3-mm slit in front of the detector. It can be seen that while the intensity of the spontaneous emission has been reduced by a factor 5 with respect to the previous measurement because of the reduced exposed detection area of the XRD, the short peak intensity remained unchanged demonstrating its much lower divergence. The divergence, measured by shifting the slit (Fig. 4), resulted



(a)



(b)

Fig. 3. (a) Time evolution of the soft X-ray emission (solid line) measured with the XRD detector (full aperture) positioned at 100 cm from the capillary output and the current pulse shape (dotted line). (b) Time evolution of the soft X-ray emission measured with the XRD detector with the 3-mm wide slit. Experimental parameters: initial Ar pressure: 0.3 torr, capillary length: 151 mm, capillary diameter: 3.0 mm, current pulse amplitude: 32 kA. The peak at 91 ns after the starting of the current is due to a reflection of the laser pulse on the XRD.

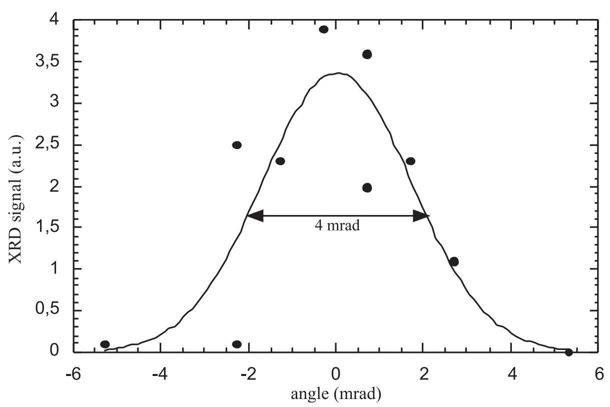


Fig. 4. Intensity of the laser emission as a function of the detection angle. Experimental parameters: Ar pressure 0.3 torr, capillary length: 151 mm, capillary diameter: 3.0 mm, current pulse amplitude: ≈32 kA.

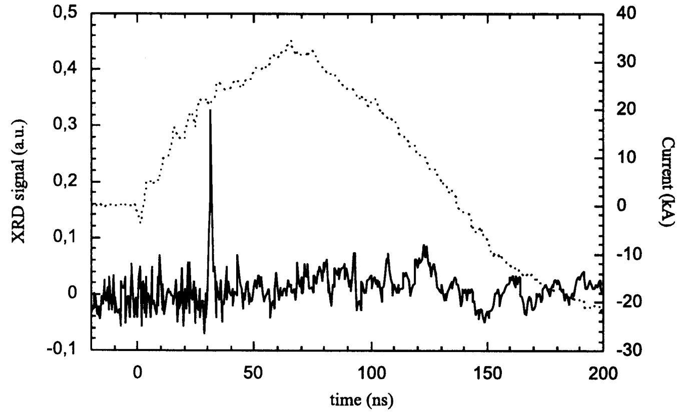


Fig. 5. Time evolution of the laser emission at 46.9 nm selected by the Sc/Si multi-layer mirror (solid line) and the current pulse (dotted line). Experimental parameters: initial Ar pressure 0.3 torr, capillary length 151 mm, capillary diameter: 3.0 mm, current pulse amplitude: ≈32 kA.

to be of about 4 mrad. The short duration of the peak together with its low divergence strongly indicates the lasing action. The second spike, appearing at 91 ns after the starting of the current, is due to a reflection of the electromagnetic signal produced by the laser pulse in the photodiode. Figure 5 shows the XRD signal obtained with the experimental setup containing the multi-layer mirror. The figure clearly demonstrates that the first high peak belongs to the $3p$–$3s$ ($J = 0$–1) transition of the Ne-like Ar at 46.9 nm. The dependence of the 46.9 nm laser line intensity has been investigated in detail *versus* the initial gas pressure and the current pulse amplitude, (Figs. 6a and 6b respectively). With a 3-mm capillary channel and a peak discharge current of 32 kA amplified spontaneous emission can be observed in a relatively small pressure interval, ranging from 0.2 to 0.4 torr and it reaches its maximum value at 0.3 torr. So, we note that in our experiment, due to the longer current rise time and half cycle duration, laser action is optimized for different values of the other parameters (in particular for the optimum gas pressure) with respect to those published by other groups. Figure 7 shows a sequence of four signals obtained by four consecutive discharges. The temporal reproducibility of the lasing spike (the jitter results to be less than 1 ns) demonstrates the stability of the plasma compression, which can be obtained in our device. Keeping close to the optimal experimental conditions (approximately 32 kA current amplitude, 0.3 torr of initial Ar pressure and 3 mm capillary diameter), the gain has been measured changing the plasma column length (Fig. 8). A gain of 0.6 ± 0.1 cm^{-1} was determined by fitting the experimental data with the Linford formula. The points measured with a 15-cm long plasma column, which deviate from the exponential behavior, can be attributed to the beginning of saturation. In order to clearly investigate such effect and improve the total energy extracted by the active medium, longer capillaries have to be used in the near future. At present state, with a 15-cm long plasma column, assuming a quantum efficiency of 10% for the copper photo-cathode, the energy

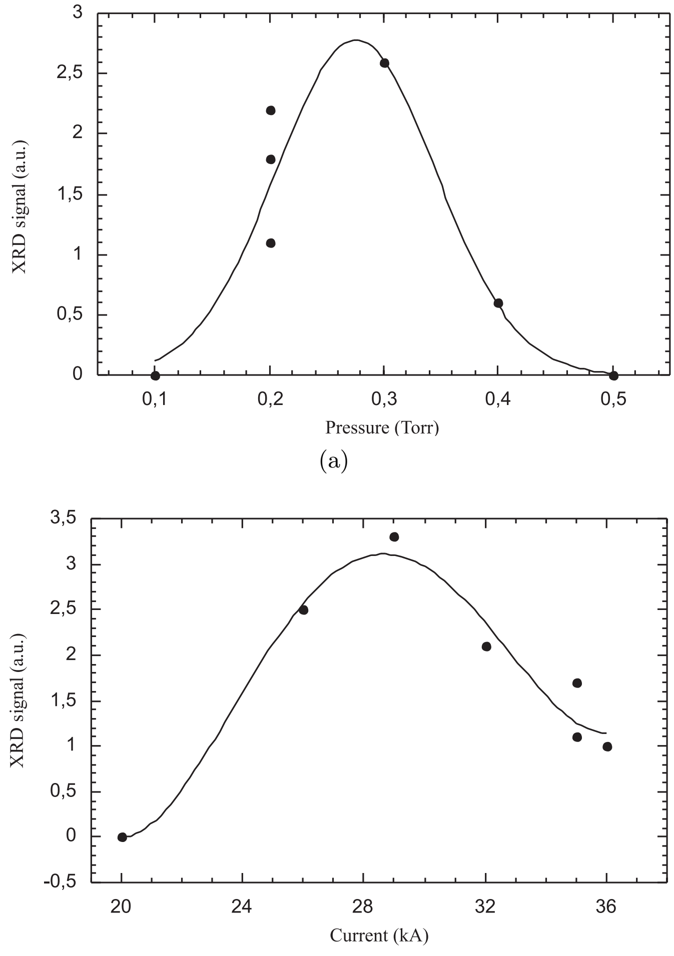


Fig. 6. (a) Intensity of the laser emission as a function of the initial Ar pressure. Experimental parameters: capillary length: 151 mm, capillary diameter: 3.0 mm, current pulse amplitude: 32 kA. (b) Intensity of the laser emission as a function of the current pulse amplitude. Experimental parameters: initial Ar pressure 0.3 torr, capillary length: 151 mm, capillary diameter: 3.0 mm.

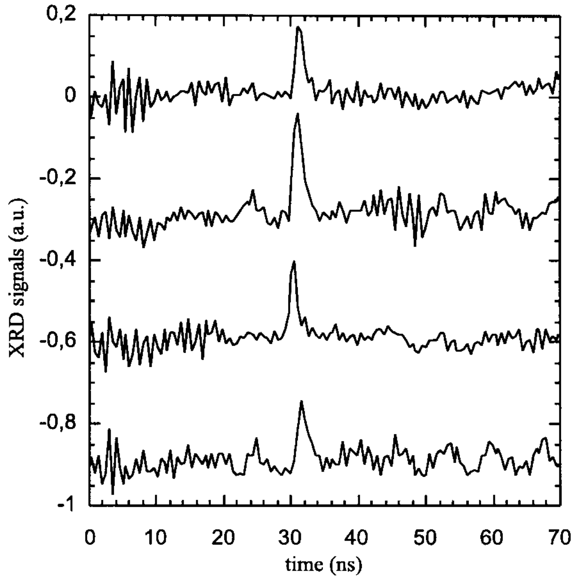


Fig. 7. Temporal evolution of laser emission obtained in four consecutive pulse discharges. The signals have been measured after reflection of the Sc/Si multi-layer mirror. Experimental parameters: initial Ar pressure: 0.3 torr, capillary length: 151 mm, capillary diameter: 3.0 mm, current pulse amplitude: 32 kA.

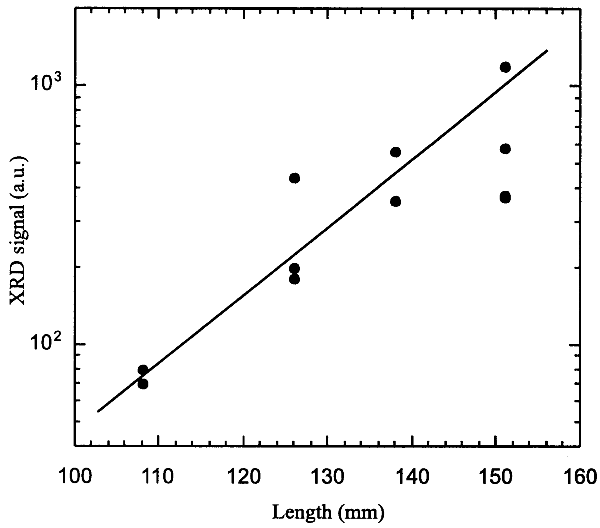


Fig. 8. Intensity of the measured laser emission (dots) as a function of capillary length. The fit of the experimental points (solid line) using the Linford formula, gives a gain of 0.6 cm^{-1}. The measurements were performed with the following experimental parameters: initial Ar pressure 0.3 torr, current pulse amplitude: 32 kA, capillary diameter of 3.0 mm.

of the laser emission was estimated of about 1 μJ. The estimation takes into account the re-absorption of the 2-cm of the neutral Ar, which is present in the reservoir chamber between the end of the capillary tube and the shutter valve. It should be noted that using a polyacetal capillary channel a big amount of material is ablated from the capillary walls, as it is demonstrated from the increase of the pressure inside the capillary after the discharge. This effect modifies the plasma properties and makes lasing action more difficult to achieve. In order to reduce such effect, polyacetal capillaries should be excited by a faster current pulse [1].

4 Conclusions

In the present report we have shown that laser operation in an argon filled capillary discharge at 46.9 nm can also be obtained by pumping the active medium with a long current pulse (140 ns of half cycle duration) properly adjusting all other discharge parameters. This allowed us to reduce the high voltage on the discharge capacitor to a value less than 200 kV. The pressure range of the laser emission has been identified in a narrow region from 0.2 to 0.4 torr in a 3-mm capillary channel and maximized at a current pulse amplitude of about 32 kA. Time duration of 1.3 ns and a divergence of about 4 mrad characterize the laser output, which takes place at 31 ns from the beginning of the current discharge. The amplified spontaneous emission has been easily achieved in an alumina capillary channel initially filled with preionized Ar gas. Amplification is difficult in polyacetal capillaries were the material ablated from the capillary walls can absorb energy and make difficult laser amplification.

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