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Abstract. In this paper, we report on the realization of a capillary discharge soft x–ray laser operating at 46.9 nm pumped by a 30 kA peak value, 150 ns half cycle duration current pulse (corresponding to a mean current slope of about 5 10^{11} A/s). The slope of the pumping current is sufficiently high to produce the plasma compression and laser amplification on the 3p-3s, J=0-1 transition of Ne-like Ar, in 2.4-4 mm in diameter alumina capillary channels. We have analyzed the output pulse characteristics of the produced laser beam, such as the lasing time and the pulse duration, the saturation and the output pulse energy, the near field image as a function of different experimental parameters. Using the same current pulse, the lasing effect has not been observed in polyacetal capillaries, demonstrating the damning role of the wall capillary ablation in the heating and in the stability of the plasma column during the z-pinch compression.

INTRODUCTION

The demonstration of a capillary discharge soft x-ray laser operating at 46.9 nm in Ne-like Ar by Rocca et al. in 1994 [1], opened the possibility of the actual realization of compact and high repetition rate soft x-ray lasers. However, since that time, in spite of the fast developments of the capillary-discharge soft x-ray laser in Ne-like Ar carried on by that group [2], in other laboratories, it has been very difficult for a long time just to reproduce those original experiments. The reason resides on the fact that, in order to produce an optimal plasma column during the capillary discharge with the required temperature and density for the population inversion many experimental parameters should be determined. Consequently, only very recently, in 2000 and 2001 [3-4], some other group started to report some result.

Recently [5], we also reported on the demonstration of the soft x-ray laser amplification in Ne-like Ar using a capillary discharge device. In the present paper we

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will show further results concerning the optimization of the laser beam intensity as a function of some of the main experimental parameters of the capillary discharge: the current pulse amplitude, the initial gas pressure, the capillary diameter and material. Moreover, we have characterized the output pulse parameters of the laser beam such as the gain-length product and the saturation, the output pulse energy and duration, the divergence and the near field structure of the beam.

EXPERIMENTAL DEVICE

The electrical pumping device has been described in detail elsewhere [6]. The high current pulse through the capillary channel is produced by discharging a 10 nF water dielectric capacitor initially charged to high voltage by a six-stage Marx generator. This electrical device can generates current pulses with a peak value ranging between 26 and 36 kA. Due to the high value of the capacitor, the current has a relatively long half cycle duration, which changes with the capillary length between 135–150 ns. These parameters correspond to a current rise time ranging between 45 and 50 ns and to a mean current slope of ~ 0.5 10^{12} A/s. A 20 A pre-ionization current, having a duration of 3–4 µm, precedes the main discharge and it is produced by an independent circuit. In the actual setup the capillary channel is separated from the detection line through a shutter valve, opening 1 ms before the discharge is fired. This system allows us to fill the capillary channel with Ar at the desired pressure, avoiding the gas outflow into the detection line. On the other hand, this arrangement actually limits the repetition rate of the capillary discharge device to 1 shot every 1 or 2 minutes.

Different detection lines have been used to analyze the radiation. A 1-m grazing angle spectrometer having a toroidal reflection grating with 550 g/mm has been used to spectrally analyze the soft x-rays with a spectral resolution of about 2 Å (with a 100-µm entrance slit). Another detection line has been used to acquire the near field images of the laser beam. It consists of a couple of two 75-cm focal length Sc/Si multi-layer mirrors, having a nominal peak reflectivity of 30% at 46.9 nm and a bandwidth of ±2 nm. The mirrors have been positioned in order to reproduce on the detector a 1:1 image of the laser beam at the capillary output. In both cases the detector, which is characterized by a spatial resolution of about 20 µm, consists of a MCP coupled to a CCD camera. At the present state, the MCP is gated with a 500 ns long voltage pulse so that it acquires time-integrated images. The time evolution and the laser pulse duration have been studied using a fast vacuum photodiode, positioned at 1 m far from the capillary output and coupled with a 1 GHz Tektronix digitizing oscilloscope. A calibrated silicon p-i-n diode detector has been utilized to estimate the laser output energy.

EXPERIMENTAL RESULTS

The measurements of the spectra, which have been obtained utilizing a 20-cm long, 3-mm in diameter alumina (Al_20_3) capillary channel, gave the results shown in fig.1. In a very narrow region of both current and initial gas pressure the line of the Ar at 46.9

dominates the spectra in the spectral region analyzed (43– 49 nm). This clearly demonstrates the laser amplification on the 3p–3s (J=0–1) transition of the Ne-like Ar.

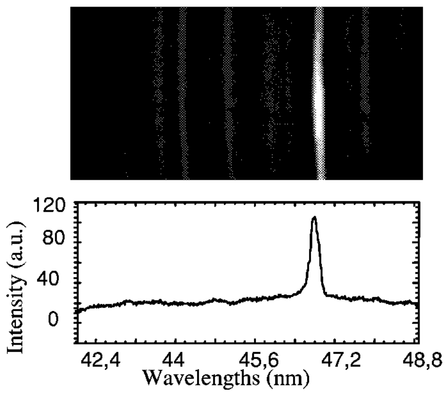

Fig.1. Measured spectra using a 3-mm in diameter 20-cm long alumina capillary channel initially filled with 320 mTorr of Ar and pumped with a 30 kA current pulse.

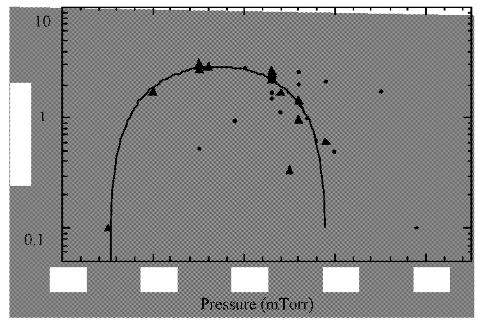

Fig.2. Dependence of the laser pulse intensity on the initial Ar gas pressure in the range of 100 – 500 mTorr. The two curves are related to two different alumina capillary channels.

The optimum current interval ranges between 27 and 32 kA, while the optimal pressure interval slightly changes from one capillary to another (see fig.2) in the interval between 200 and 450 mTorr.

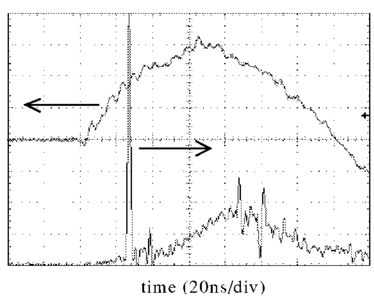

Fig.3. Time evolution of soft x-rays emitted by the discharge in a 3-mm in diameter, 20-cm long capillary channel initially filled with 0.32 Torr of Ar.

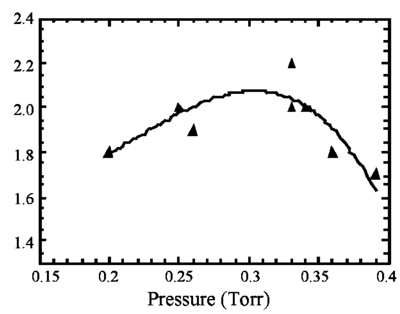

Fig.4. Duration of the laser pulse as a function of the initial gas pressure in a 20-cm long capillary.

The time evolution of the soft x-ray emission, measured with the vacuum photodiode and a 0.8 µm thick Al filter, is shown in fig.3. The laser amplification at 46.9 nm generates a short and high intensity peak appearing at 31 ns from the starting of the current pulse. This peak can be distinguished from the long lasting signal due to the spontaneous radiation emitted during the discharge by the high temperature plasma and having duration of about 100 ns. In the experimental conditions of fig.3 the laser emission has duration of about 2.2 ns at FWHM. However the pulse duration depends on the experimental discharge conditions. For example, in fig.4 the pulse duration has been analyzed as a function of the initial gas pressure. It can been seen that it reaches a maximum value of 2.2 ns at 330 mTorr and that it decreases up to 1.8 and 1.6 ns respectively at 250 and at 420 mTorr. The laser beam divergence has been roughly estimated by putting a slit on the photodiode and moving it orthogonal to the direction of propagation of the x-rays. By making several shots we have estimated a divergence of 4 mrad. This value is comparable to that also reported by other groups.

Using the same excitation current pulse and the same capillary diameter no indication of laser amplification has been observed using polyacetal capillaries instead of alumina in the pressure interval between 100 and 1000 mTorr. In spite of the fact that laser amplification has been previously reported in polyacetal capillaries [7], in our case we believe that the lack of amplification is an effect of the much slower current rise time, which allows a bigger amount of material to be ablated from the capillary walls before the laser emission.

In order to optimize the laser output intensity in alumina capillaries, the gain of the laser line has been studied as a function of the initial gas pressure, by changing the plasma column length from 10 up to 20 cm. As it can be seen in fig.5, the gain strongly changes from one pressure to another, and it jumps from 0.7 cm^{-1} at 250 mTorr up to 1 cm^{-1} at 330 mTorr.

In the same figure, it can be clearly observed the transition at 14 and 16 cm respectively at 330 and 250 mTorr between the region of the exponential increase of the laser intensity from that of saturation.

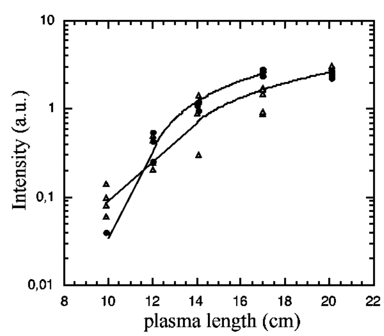

Fig.5. Intensity of the laser line at two different initial gas pressures: 330 mTorr (full circles) and 250 mTorr (triangles) as a function of the capillary length. The gain resulted to be respectively of 1 and 0.7 cm^{-1}.

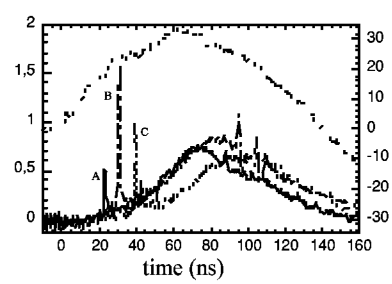

Fig.6. Soft x-ray laser emission obtained in 20-cm long capillary channel initially filled with 0.3 Torr of Ar and the current pulse. The measurements were obtained in a (A) 2.4-mm (B) 3.2-mm and a (C) 4-mm in diameter alumina capillary channel.

However, in spite of the different values of the gain the laser intensity reaches quite comparable values at the two pressures in the saturation regime. With a 20-cm long plasma column the laser output energy has been estimated to be 5 μJ. This value is much smaller than that has been obtained (about few hundreds of micro-joules) in recent Rocca's experiments [2] conducted in quite similar experimental conditions. Also in this case we think that the reduced laser output energy can be an effect of the bigger current rise time. So, investigations of the laser output energy, as a function of the current slope, will be performed in the near future. The laser pulse energy doesn't change significantly with the capillary diameter, from 2.4 to 4.0 mm (fig.6) and it reaches its maximum intensity just at 3.2 mm. In fig.6, it can be observed the interesting effect of the scaling of the time of the laser emission with the capillary diameter. Laser line is emitted respectively at 20, 31 and 40 ns from the starting of the current pulse respectively with 2.4, 3.2 and 4-mm in diameter capillary channels. However it should be noted the short time necessary to achieve the population inversion inside the plasma column, which is well below the time of the maximum of the current pulse. This behaviour let us suppose that the laser amplification can be reached with much smaller current pulse amplitudes by properly matching the capillary diameter with the initial gas pressure.

The near field images of the laser beam in 20-cm long alumina capillary channels has been analyzed as a function of the initial Ar gas pressure. The results of the measurements are shown in fig.7. The shape of the laser beam changes with the pressure from an annular one at lower pressures to a single peaked one at higher pressures. Correspondingly the laser beam dimension scales from 600 µm up to 250 µm. These values are two times bigger respect to that reported in similar experiments by Rocca [8]. Measurements of the far field structure and dimension of the laser will clarify if the large near field image, obtained in our experiment, has to be attributed to a bigger gain region or to an increased refraction of the beam.

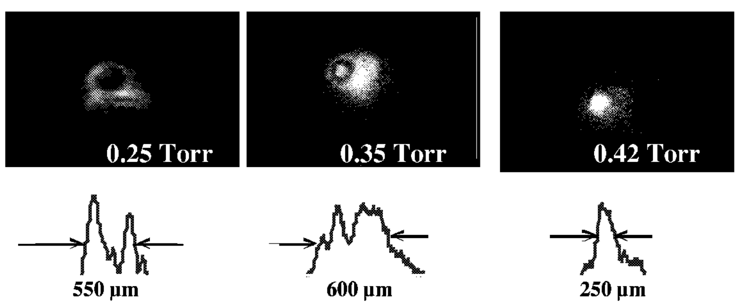

Fig.7. Near field images of the laser beam measured at different initial gas pressures. The measurements are obtained using a 30-kA current pulse through a 20-cm long, 3-mm in diameter alumina capillary channel.

CONCLUSIONS

In the present paper we have reported on the realization and the characterization of a capillary discharge soft x-ray laser operating at 46.9 nm in Ne-like Ar. Using a relatively long current pulse having a half cycle duration of about 150 ns and a peak value ranging from 27 up to 32 kA, we have measured a gain changing from 0.7 up to 1 cm^{-1} at the initial gas pressure respectively of 250 and 330 mTorr. We have clearly achieved the saturation regime, which leads us to an estimated energy of about 5 µJ in a 20-cm long capillary. All the measurements, which we have performed, show a clear evidence of the laser amplification in alumina capillary channels also using different capillary diameters. On the other side, using the same excitation current pulse no indication of lasing was observed in polyacetal capillaries.

Near field images of the laser beam has also been obtained. The shape of the laser beam changes from an anular to a single peaked shaped respectively at lower and at higher pressures. The laser beam dimension so ranges from 600 to 250 µm, giving a maximum peak spectral brigthness of 10^{21}ph/sec^{-1}mm^{-2}.

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