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SOFT-X-RAY AMPLIFICATION IN AN ABLATIVE CAPILLARY DISCHARGE

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ABSTRACT Soft x-ray amplification in CVI 18.2nm line is observed in an ablative UHMW-PE capillary discharge. The gain coefficient is measured to be 1.9cm^{-1}. The electron density is about $2 \times 10^{19}\text{cm}^{-3}$.This indicates that capillary discharge pumping device can be a source for a compact soft x-ray laser.

I. INTRODUCTION

Matthews et al. [1] reported laser amplification at wavelengths of 20.6 and 20.9 nm in SeXXV and Suckewer et al. [2] demonstrated of lasing action at wavelengths of 18.2 nm in CVI in 1984. All these have been demonstrated in plasmas created by high-energy lasers. However, their large size, complexity and cost have hampered the widespread use of these laser sources in a number of importance applications. For practical applications a more efficient and compact device need to be developed. With this objective, in 1988 Rocca, Beethe and Marconi [3] proposed the development of the soft x-ray recombination laser by direct excitation of a capillary plasma column with a fast discharge current pulse. The advantage of discharge pumping is that it is technically simpler and has a higher efficiency than a large-scale laser driver.

The present setup is based on a recombination pumping scheme utilizing $2 \leftarrow 3$ transition in hydrogen-like carbon ions. The discharge starts by surface flashover on the capillary walls. Plasma current sheath, which is formed by the ablated material from the surface breakdown, will then implode radially toward the capillary axis. Carbon atoms are fully ionized to C^{6+} ions. Plasma temperature drops rapidly during the expansion of the plasma and eventually collides with the capillary wall. Collisional recombination of C^{6+} ions into ions of lower charge, produce population inversion and amplification.

In the present study, we report unambiguous observation of an amplified spontaneous emission in the CVI 18.2nm H_α transition. The result is obtained from time integrated spectral data, using an Ultra High Molecular Weight Polyethylene (UHMW-PE) capillary discharge. Comparing the spectral line intensities of the gain and non-gain lines by varying the capillary length, the gain in the CVI 18.2nm transition is directly verified.

II. EXPERIMENTAL ARRANGEMENT

The discharge setup is the same as that described in Ref. 4 and 5.The capillaries are excited by discharging a low inductance capacitor array to provide a short ringing period (250ns) together with a sufficiently high input energy (20J at 20kV) (Fig. 1). Twenty-eight ceramic capacitor of 3.6nF nominal capacitance each (total capacitance $=0.1\mu\text{F}$) are placed in the periphery of a square (45cm x 45cm) having as center the capillary axis. The capacitors are directly connected to the carbon capillary electrode through a parallel plate transmission line. The discharge electrodes are made out of graphite, and are bored axially to a diameter of 2 mm to allow for the exit of the radiation from the capillary plasma. A negative trigger pulse between the trigger electrode and the cathode, which is grounded, initiates the discharge.

Throughout the experiment, UHMW-PE capillaries with a 1.0mm bore diameter are used. The capillary length is varied from 10 to 20mm. The capillaries were evacuated to pressure of 10^{-6} mbar. The range of charging voltage used in this experiment is 12-20 kV. A Rogowski loop is used to monitor the evolution of the discharge current. A maximum current of approximately 40 kA is attained with a risetime of about 30 ns and FWHM about 100ns(Fig.4). Throughout the experiment, the input power density [(stored energy)/(capillary volume) x (FWHM of the discharge current)] of the capillary volume is kept constant by adjusting the capacitor charging voltage for different capillary lengths. The output spectral for input power densities of $1.0 \times 10^{10}$and 1.5×10^{10} Wcm^{-3} are monitored using a 1 m focal length grazing incidence spectrograph (McPherson 248/310G with gold coated grating, 600 grooves/mm blaze at 1°, grazing angle at 87°). The spectrograph uses a multichannel intensified array detector that can be displaced tangentially to the Rowland circle. A Helium-Neon laser beam is directed through the capillary to align its axis with the entrance slits of the spectrograph. The monitoring system is shielded from electromagnetic interference through the use of a Faraday cage.

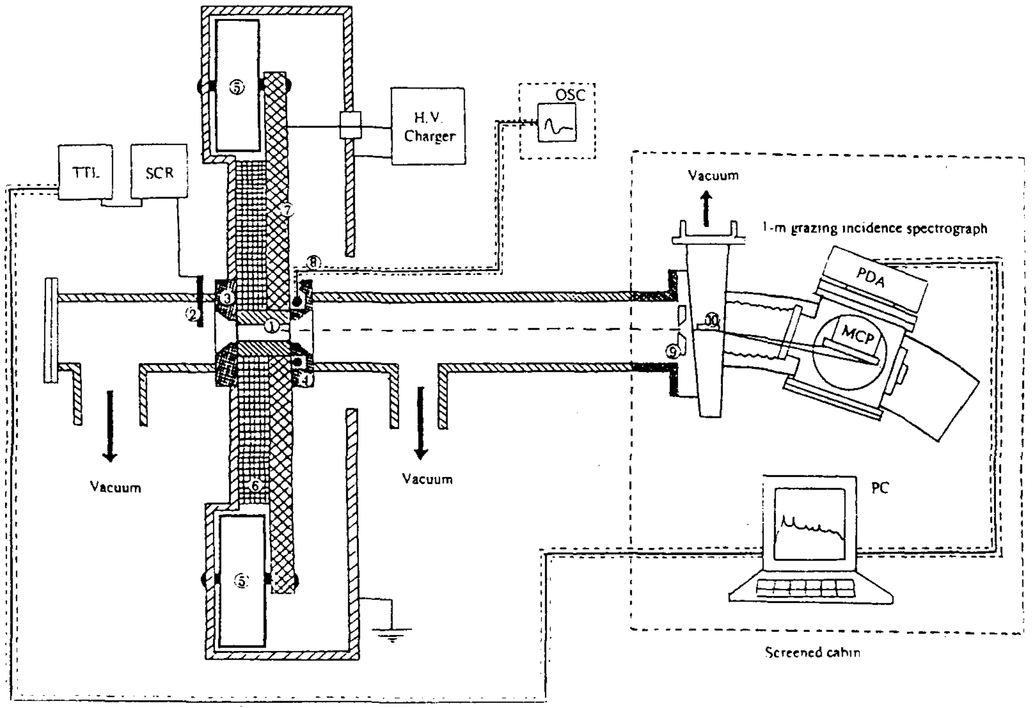


Fig.1 Experimental setup : 1 capillary, 2 trigger electrode, 3 grounded electrode, 4 high voltage electrode,5 ceramic capacitors, 6 insulator, 7 high voltage plate, 8 Rogowski coil, 9 entrance slit, 10 gold coated grating.

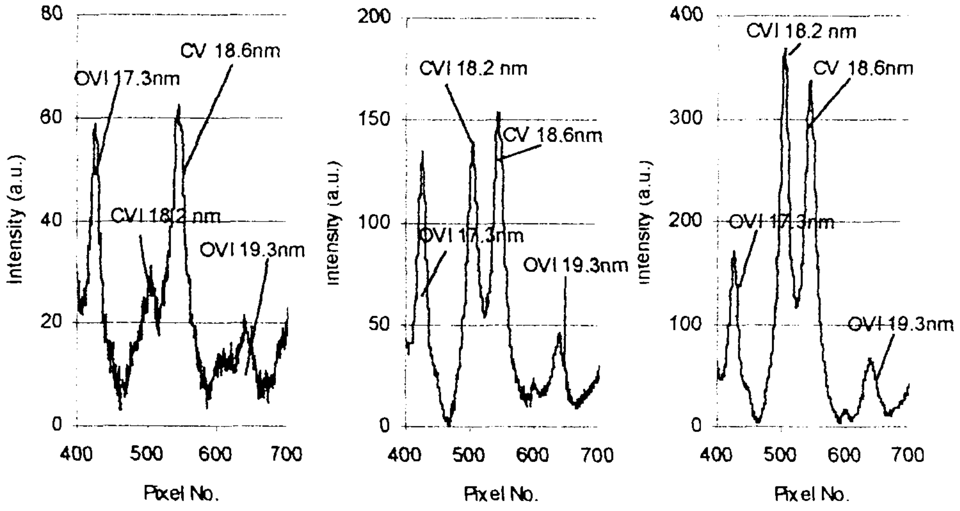
III. RESULTS AND DISCUSSION

An input power density of 1.0 x 10^{10}Wcm^{-3} for the spectrum in the wavelength range from 17.0 to 20nm is shown in fig. 2. For the 10mm length capillary, the CV 18.6nm and OVI 17.3nm dominate in the region being observed. However, the CVI 18.2nm line is very weak and can just be barely differentiated from background radiation. With increasing length the CVI 18.2nm line increase rapidly, become more intense than the CVI 18.6nm line. The intensity of various lines plotted against the capillary length is given in fig. 3. The intensity of CVI line increase exponentially with increasing capillary length. From the formula given by Linford et. [6]

$$I = I_0\left[\frac{e^{\alpha L}-1}{\alpha L}\right]e^{-\frac{\alpha L}{2}},$$

where L= plasma length,
α=gain coefficient,
I=Spectral intensity,
I_0=Spectral intensity emitted without amplification,

a gain curve is plotted for CVI 18.2nm line as shown in fig 4 (solid line). A gain coefficient of 1.9 cm^{-1} is obtained. This corresponds to a gain-length gl product of 3.8 for a 2cm long capillary. The other lines are observed to increase only linearly (dotted line).



(a) (b) (c)

Fig.2 Time-integrated axial emission from a 1.0 mm diameter with input power density of 1.0 x 10^{10}Wcm^{-3} UHMW-PE capillary discharge in the 17 – 22 nm spectral region for different capillary length (a) 10mm, (b) 15mm and (c) 20mm.

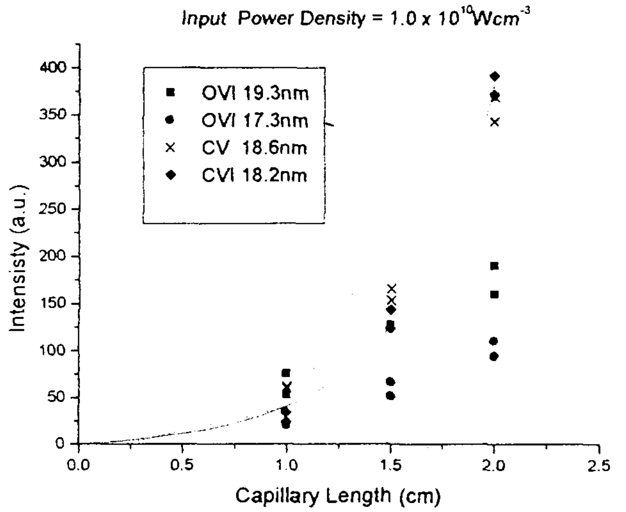


Fig.3 Relative intensities of CVI18.2nm, CV18.6nm, OVI 19.3nm and OVI 17.3nm line as a function of capillary length with constant input power density 1.0 x 10^{10}Wcm^{-3}.The solid line indicates the calculated gain curve with g=1.9cm^{-1}.

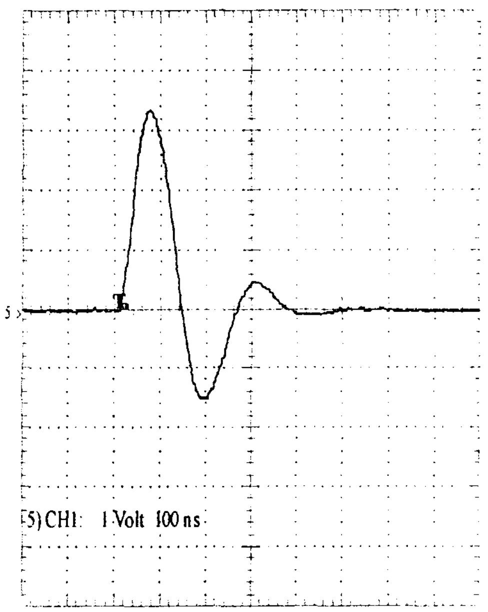


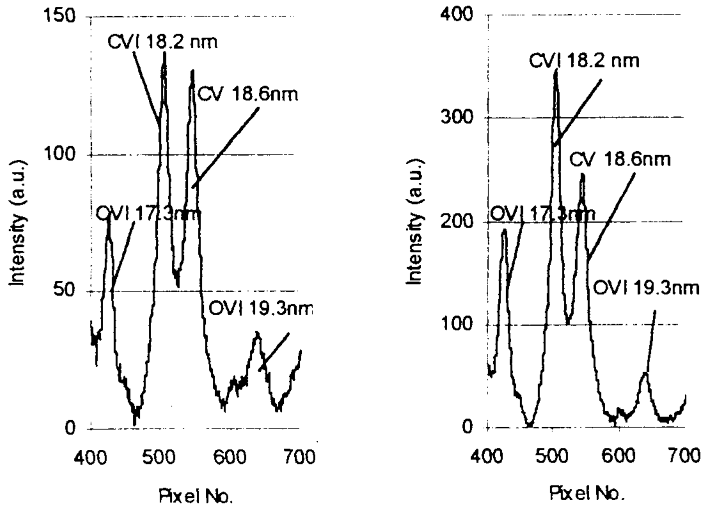
Fig.4 Current pulse for a 100 nF, 20 kV capillary discharge.
Vertical axis: 10kA/div;
Horizontal axis: 100ns/div.

Fig. 5 shows the spectra for the 10mm and 15mm capillary length with input power density raised to 1.5 x 10^{10}Wcm^{-3}. With higher input power density, a hotter plasma is obtained. The CVI 18.2 line can be clearly differentiated from the background radiation, and the intensity is comparable to the CV 18.6nm line although the capillary length is 10mm. By increasing the length to 15mm the CVI 18.2 line becomes more intense than the CV 18.6nm line. A graph of intensity versus capillary length has been plotted and the gain curve of 1.9cm^{-1} has been obtained (fig. 6).

High density and high temperature plasma are often Stark broadened. The half width Δλ of the higher member of hydrogen-like level is given by [7]

$$\Delta\lambda = 6\times10^{-11}\times n^{2/3}\lambda^{2}u^{2}\frac{1}{Z}$$

where u is the quantum number of the upper state and Z the effective charge of the emitting ion . Plasma density n = $n_e + Z_i^{3/2}n_i$, where n_e is electron density and n_i is the density of ion with nuclear charge Z_i. For the CVI 18.2nm line u=3, Δλ=1 x 10^{-8}cm (measured) and Z=4 [8] the electron density works out to be 2 x 10^{19}cm^{-3}. The electron density is close to the value required for the amplification of the CVI H_α line by collisional recombination [9].



(a) (b)

Fig.5 Time-integrated axial emission from a 1.0 mm diameter with input power density of 1.5 x 10^{10}Wcm^{-3} UHMW-PE capillary discharge in the 17 – 22 nm spectral region for different capillary length (a) 10mm and (b) 15mm.

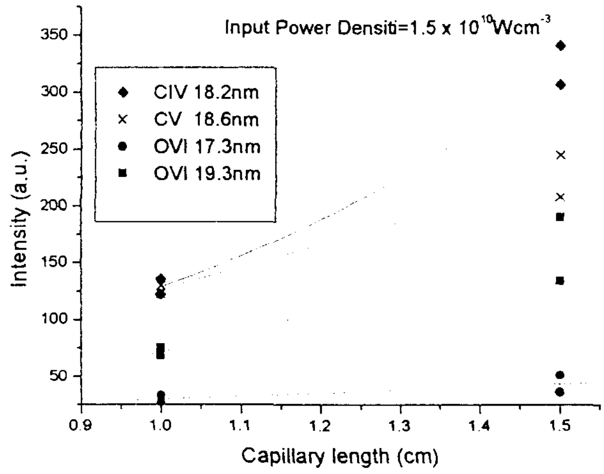


Fig.6 Relative intensities of CVI18.2nm, CV18.6nm, OVI 19.3nm and OVI 17.3nm line as a function of capillary length with constant input power density 1.5 x 10^{10}Wcm^{-3}.The solid line indicates the calculated gain curve with g=1.9cm^{-1}.

IV. CONCLUSION

Intense CVI 18.2nm line emission is observed to increase exponentially with length in a 1.0mm diameter UHMW-PE capillary discharge. In contrast, emission of other lines increases linearly with the capillary length. A gain-length product of 3.8 have been observed with input power intensity of 1.0 x 10^{10}Wcm^{-3}. An electron density of 2 x 10^{19}cm^{-3} is estimated from the spectrum. This indicates that the capillary discharge-pumping scheme is able to produce plasma conditions similar to that of laser-produced plasma. Experiments are still being carried out to demonstrate higher amplification in such a system. Using such a recombination-pumping scheme, capillary discharges can become attractive sources for compact X-ray lasers.

Acknowledgments

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