EUV spectroscopy of ultrafast capillary discharges

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ABSTRACT

The observation of EUV spectra of multiply charged ions excited by an ultrafast capillary discharge suggest the possibility of developing an intense compact source of soft x-ray and EUV radiation for practical applications (EUV lithography, microscopy, etc.). The discharge is driven by a compact water transmission line having a very fast current pulse (12 ns FWHM, rise time~1 ns). Spectra of OV-OVI ions from a polyacetal capillary and ArVII-ArVIII ions from an Ar filled capillary were observed and investigated in a spectral range of 100-300 Å using a 1-m grazing incidence spectrograph. The resulting capillary discharge plasmas have an electron temperature of ~25-35 eV, which could be increased to ~100 eV using a more powerful transmission line.

Keywords: EUV spectroscopy, capillary discharge plasmas, EUV lithography.

1. INTRODUCTION

A capillary discharge plasma can be used as a soft x-ray source [1,2] and as an active medium for soft x-ray lasers [3-7]. For, example, large soft-x-ray amplification (gl=7.2-27) [5,6,7] and achievement of the saturation limit at the wavelength 469 Å [7] was observed in an Ar capillary discharge plasma. These works and the results of ultra-fast capillary discharge experiments reported here suggest that a capillary discharge plasmas could serve as an alternative source of intense soft x-ray radiation for contact microscopy and lithography [2] and for projection lithography [8]. Black body emission was obtained with emission efficiencies exceeding 30% of the input power [2]. An emission yield of 6 J/pulse at 13.5 nm (Ly_α transition in Li^{+2} ion) was measured in a fast LiH capillary discharge [8]. This yield is comparable to the yield/pulse at 13.5 nm produced in a KrF laser plasma soft x-ray source [9] used for EUV lithography. For this reason further development of more effective and compact capillary devices is needed. Technology is available for the development of a powerful compact driver with a short current pulse and effective energy input. One possible approach is the use of a transmission line driver. Earlier a large water transmission line driver was used for to create a capillary discharge plasma in which a high electron temperature–T_e=150-200 eV–was achieved and spectra of FIX, FVIII ions were observed [10]. A water transmission line was used to investigate XUV amplification in a recombining z-pinch plasma [11]. In ref. 6 capillary discharge plasmas driven by a water transmission line were used as active media for an extremely compact tabletop soft-x-ray laser.

The purpose of our investigations is the development of a compact source of spontaneous soft x-ray and EUV radiation–wavelength from "water window" ~20 Å to several hundred Å–for practical applications–microscopy, lithography, fluorescence analysis, etc.–and for fundamental research–spectroscopy, solid-state physics, etc. In this paper we describe a compact and very fast water transmission line driver applied to capillary discharge plasmas. This device could be considered as a prototype of a compact and effective EUV source. EUV spectroscopy is the most informative diagnostic of the capillary discharge plasmas (see, for example, references 1,2,8,10,12-14). For this reason we report here EUV spectroscopic observations made with different geometries and various parameters of capillary discharges.

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2. DESIGN

The schematic diagram of the capillary discharge device is shown in Fig.1. The high voltage needed to produce the discharge is generated with a Marx generator. The Marx generator used in these experiments has three stages, each consisting of a 35 nF capacitor. Each capacitor is charged to a voltage U_0 of 30-40 kV. Arc switches separate each stage from the next and the final stage from an output terminal. When the arc switches are triggered, the output terminal rises to $U=3U_0$ and then discharges through a 48 μH resonant inductor to a water transmission line. The resonant inductor uncouples the transmission line from the capacitor bank to protect the bank from voltage spikes.

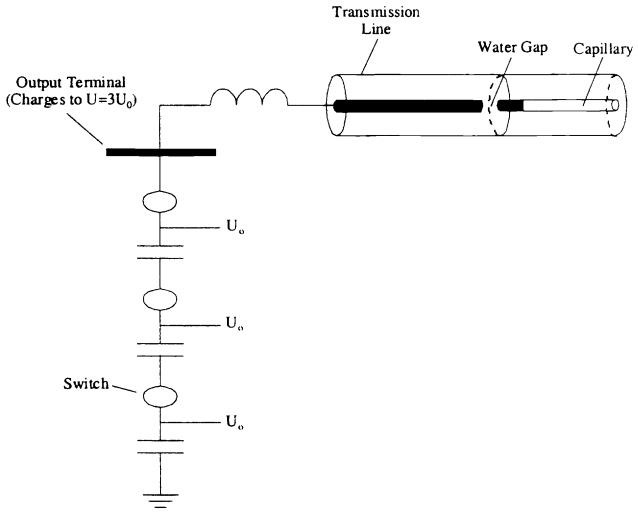


Fig.1. The schematic diagram of the capillary discharge device.

The transmission line stores energy for the discharge and controls its duration. The length ℓ of the line is 20 cm. It has a coaxial geometry and is filled with a water dielectric (ε_r=80). The transmission line has a capacitance of 600 pF, which, if charged to a voltage U of 120 kV, allows it to store 4.3 J of energy (E). The FWHM pulse width τ of a pulse produced by this transmission line is given by $\tau = 2(\ell\sqrt{\varepsilon_r})/c$ = 12 ns. The average power transmitted through the capillary is 720 MW.

The transmission line is separated from the capillary by an adjustable water breakdown switch. As the voltage on the transmission line rises, the switch breaks down and current flows into the capillary. The calculated impedance Z of the transmission line is 11 Ω, and the capillary impedance is negligible. The expected peak current is 12 kA.

3. EXPERIMENT AND DISCUSSION

Two types of the capillaries were used in the experiments: 1) a polyacetal $(CH_2O)_n$ capillary of two different dimensions: 2-mm-diameter 20-mm-long and 0.5-mm-diameter 10 mm long; 2) an Ar filled capillary of dimensions 2-mm-diameter 20-mm-long with an Ar pressure of 50-200 mTorr. The axially emitted XUV radiation from the capillary discharges was studied using a 1-m grazing incidence spectrograph. A gold-coated grating with 600 grooves/mm was installed at a 4° grazing incidence angle. An off-Rowland geometry was used: the spectra were recorded in a plane perpendicular to the diffracted rays (see Fig.2). In this method, the exact focusing takes place at only one wavelength λ_0, which corresponds to the intersection point of the registration plane with the Rowland circle. However due to the small numerical aperture of the spectrograph, it is possible to record the spectrum in a wide spectral range $\lambda_0 \pm \Delta\lambda$. The value $\Delta\lambda$ is connected with the observed spectral resolution $\lambda/\delta\lambda$—the wider $\Delta\lambda$ the lower $\lambda/\delta\lambda$ because of defocusing. For example, for the cases reported an entrance slit of width of 20 μm results in a spectral resolving power ($\lambda/\delta\lambda$) of 100 - 200 and a resolvable spectral range ($\Delta\lambda$) of ~$\lambda_0/2$. The alignment to a different λ_0 was produced by changing the distance between the plane of registration and the grating. A detailed description of the spectrograph will be published elsewhere. Earlier, this type of spectrograph was used for EUV spectroscopy of a KrF laser plasma source [8] intended for EUV lithography.

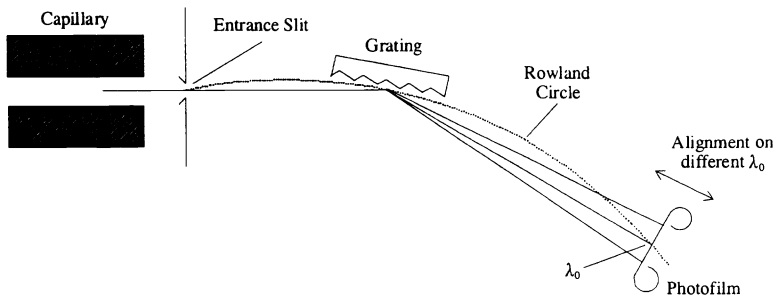


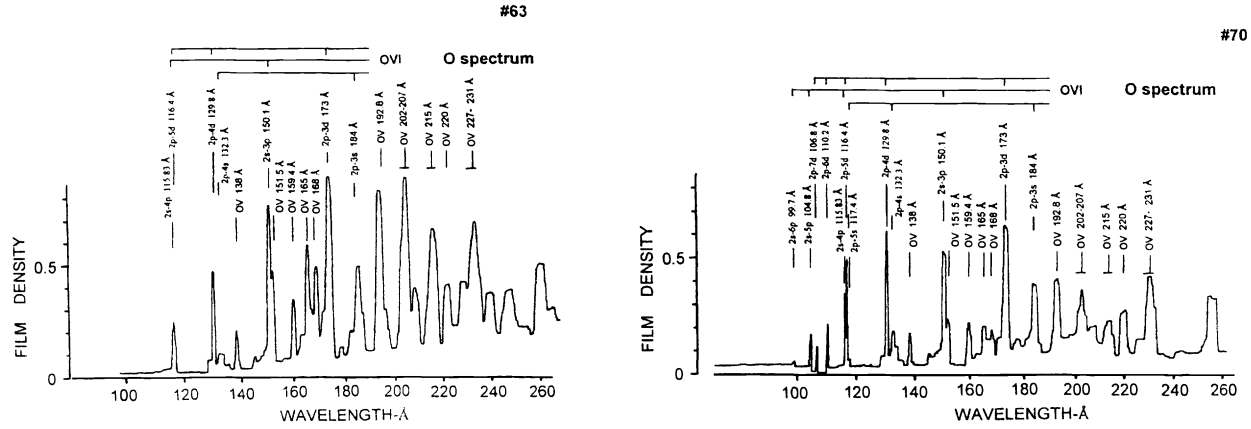
Fig.2. The spectrograph used to analyze the EUV radiation produced in the capillary

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The spectra were recorded on calibrated UF-4 photofilm [15]. The distance between the capillary exit and the entrance slit of the spectrograph was 10 mm. To record each spectrum it was necessary to produce 1-5 discharge shots. Time-integrated EUV spectra of highly charged ions excited in the fast capillary discharge plasmas were investigated in the spectral range 100-300 Å. Spectra of OVI and OV ions from a polyacetal capillary and ArVIII and ArVII ions from an Ar filled capillary were observed. Ref. 16,17 were used for the line identification. Spectra were recorded at different capillary geometries, at different applied voltages and various Ar pressures.

3.1. Polyacetal capillary

Typical spectra of OVI and OV ions excited in capillaries of two geometries (a "big" capillary: 2-mm-diameter 20-mm-long; and a "small" capillary: 0.5-mm-diameter 10-mm-long) are shown in Fig.3. Intense 2l-nl' transitions with n up to 7 were



a) 2-mm-diameter 20-mm-long capillary, 5 shots, U_0=40 kV

b) 0.5-mm-diameter 10-mm-long capillary, 1 shot, U_0=35 kV

Fig. 3. Spectra of the polyacetal capillary discarge at different capillary gemometries and conditions

observed in OVI ions. Overall line intensities of OVI ions are increased when the capillary volume is decreased. The intensity ratio of OVI/OV ion lines and relative intensities of high transitions in OVI ions are also increased. This factor indicates a higher electron temperature in a "small" capillary, when the input energy per unit volume is increased.

Relative intensities of the 2p-3d (λ=173 Å) and 2p-4d (λ=130 Å) transitions in OVI ions and the 2s2p-2s3d (λ=192.85 Å) transition in OVI ion versus applied voltage U_0 are shown in Fig.4. An increase of voltage U_0, the OVI lines show a very rapid increase in intensity. This dependence is strong—intensity of the 2p-4d transition is increased by one order of magnitude when U_0 is changed from 30 to 40 kV. Thus the intensity yield in this spectral range can be increased by increasing U_0.

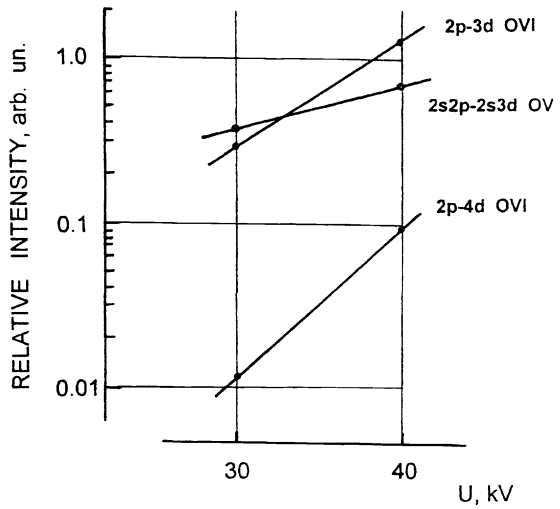


Fig. 4. Relative OV, OVI line intensities in polyacetal capillaries versus U_0

3.2. Ar filled capillary

The spectra for the Ar filled capillary at different Ar pressures are show in Fig.5. Maximum line intensities are observed at Ar pressure near 100 mTorr (Fig.5b). Intense 3d, 3p-nl' transitions up to n=10 (3d-10f) are observed in ArVIII ions. Relative intensities of different lines versus Ar pressure are shown in Fig.6. The data for 3p-4d, 3p-4s, 3d-4f transitions in ArVIII are in good agreement with one another (Fig.6a). A discrepancy is observed for ArVIII 3s-4p (159 Å) line—the intensity is increased when the Ar pressure is decreased (Fig.6b). It is caused by a contribution to the intensity of some oxygen lines, for example, OV (159 Å) $2p^2$-2p4d. The influence of the wall materials on the observed spectra is illustrated in Fig.6c—at small

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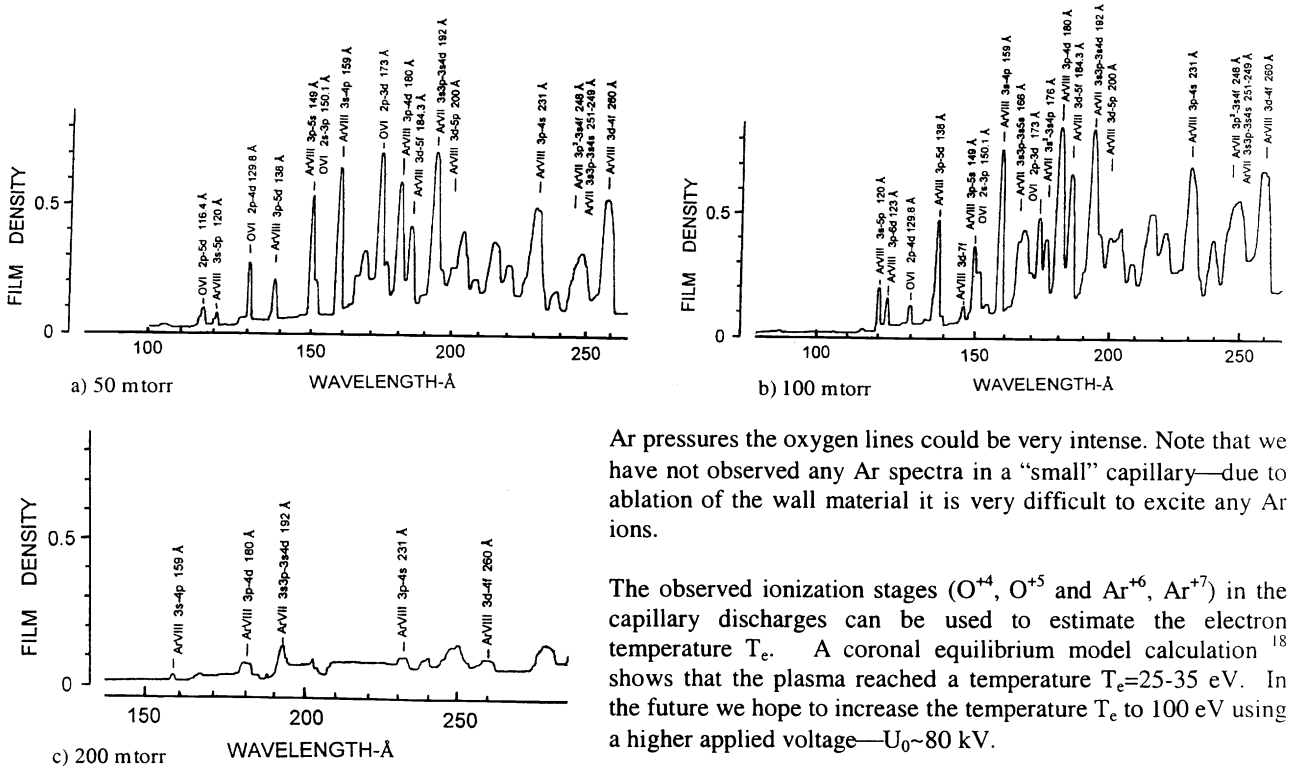


Fig.5. Spectra of Ar filled capillary discharges (U_0=40 kV, 5 shots) at different Ar pressures

Ar pressures the oxygen lines could be very intense. Note that we have not observed any Ar spectra in a "small" capillary—due to ablation of the wall material it is very difficult to excite any Ar ions.

The observed ionization stages (O^{+4}, O^{+5} and Ar^{+6}, Ar^{+7}) in the capillary discharges can be used to estimate the electron temperature T_e. A coronal equilibrium model calculation [18] shows that the plasma reached a temperature T_e=25-35 eV. In the future we hope to increase the temperature T_e to 100 eV using a higher applied voltage—U_0~80 kV.

4. CONCLUSIONS

Intense EUV radiation in a spectral range of 100-300 Å was observed in capillary discharge plasmas. The fast discharge was driven by a compact water transmission line. Spectra of OV-OVI ions from a polyacetal capillary and ArVII-ArVIII ions from an Ar filled capillary were investigated for different geometries and various parameters of capillary discharges. The resulting capillary discharge plasmas have the electron temperature ~25-35 eV, which could be increased up to ~100 eV using a more powerful transmission line. This device could be considered as a prototype of a compact and effective EUV source for different practical applications (EVU lithography, microscopy, etc.).

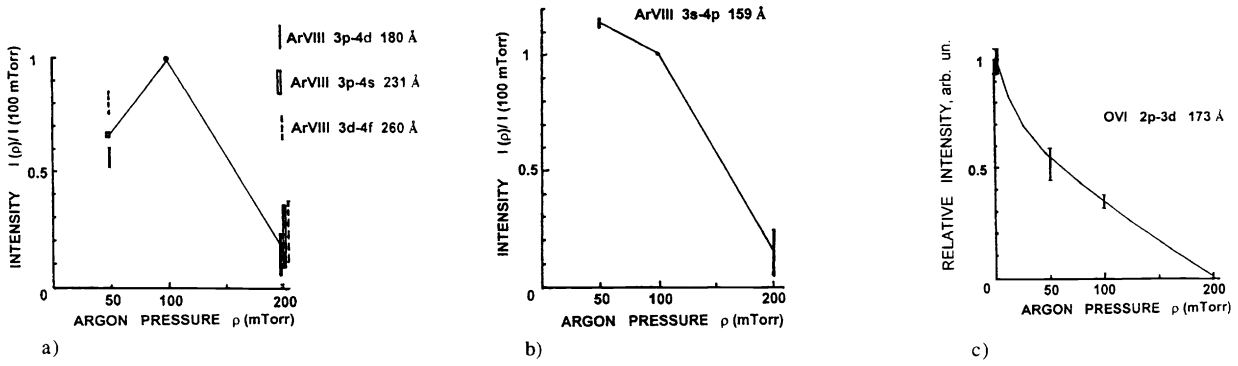


Fig.6. Relative intensities of ArVIII and OVI lines in Ar filled capillary discharges (U_0=40 kV) versus different Ar pressure

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REFERENCES

1. P.Bogen, H.Conrads, G.Gatti, and W.Kohlhaas, "Continuum Radiation Source of High Intensity", *JOSA* **58** (2), pp. 203-206, 1968.
2. R.A.McCorkle "The High-Power Sliding-Spark Capillary Discharge in Vacuum: Variations and Applications", *Appl.Phys.* **A 26**, pp. 261-270, 1981.
3. C.Steden, and H.-J.Kunze "Observation of gain at 18.22 nm in the carbon plasma of a capillary discharge", *Phys.Lett.***A151**, pp. 534-537, 1990.
4. Hyun-Joon Shin, Dong-Eon Kim, and Tong-Nyong Lee, "Soft-x-ray amplification in a capillary discharge", *Phys.Rev.* **E 50**, pp. 1376-1382, 1994.
5. J.J.Rocca, V.Shlyaptsev, F.G.Tomasel, O.D.Cortazar, D.Hartshorn, and J.L.A.Chilla, "Demonstration of a Discharge Pumped Table-Top Soft-X-Ray Laser", *Phys.Rev.Lett.* **73**, pp. 2192-2194, 1994.
6. B.R.Benware, C.H.Moreno, D.J.Burd, and J.J.Rocca, "Opreration and output pulse characteristics of an extremely compact capillary-discharge tabletop soft-x-ray laser", *Opt.Lett.* **22**, pp. 796-798, 1997.
7. J.J.Rocca, D.P.Clark, J.L.A.Chilla, and V.N.Shlyaptsev, "Energy Extraction and Achievement of the Saturation Limit in a Discharge - Pumped Table - Top Soft X-ray Amplifier", *Phys.Rev.Lett.* **77**, pp. 1476-1479, 1996.
8. M.A.Klosner, H.A.Bender, W.T.Silfvast, and J.J.Rocca, "Intense plasma discharge source at 13.5 nm for extreme-ultraviolet lithography", *Optics Letters* **22**, pp. 34-36, 1997.
9. A.P.Shevelko, L.A.Shmaenok, S.S.Churilov, R.K.F.J.Bastiaensen, and F.Bijkerk, "Extreme Ultraviolet Spectroscopy of a Laser Plasma Source for Lithography", *Phisica Scripta* **57**, pp. 276-281, 1998.
10. S.M.Zakharov, A.A.Kolomenskii, S.A.Pikuz, and A.I.Samokhin, "Soft x-ray emission in a high-current capillary discharge", *Sov.Tech.Phys.Lett.* **6**, pp. 486-487, 1980.
11. T.Wagner, E.Ebert, K.Frank, W.Hartmann, D.H.H.Hoffmann, and R.Tkotz, "XUV Amplification in a Recombining z-Pinch Plasma", *Phys.Rev.Lett.* **76**, pp. 3124-3127, 1996.
12. J.J.Rocca, M.Marconi, and F.G.Tomasel, "Study of the Soft x-ray Emission from Carbon Ions in a Capillary Discharge", *IEEE QE* **29**, pp. 182-191, 1993.
13. C.A.Morgan, H.R.Griem, and R.C.Elton, "Spectroscopic measurements of electron density and temperature in polyacetal-capillary-discharge plasmas", *Phys.Rev.* **E 49**, pp. 2282-2290, 1994.
14. C.A.Morgan, H.R.Griem, and R.C.Elton, "Radially resolved spectral observations of polyacetal capillary discharge plasmas", *Phys.Plasmas* **2**, pp. 2847-2852, 1995.
15. A.P.Shevelko, "Absolute measurements in the VUV spectral range using a luminescent detector", *Quantum Electronics* **26**, pp. 729-731, 1996.
16. R.L.Kelly, "Atomic and ionic spectrum lines of hydrogen through krypton", *J.Phys.Chem.Ref.Data* **16**, Suppl.1, pp. 105-109 and 401-402, 1987.
17. B.C.Fawcett, A.Ridgeley and G.E.Bromage, "The Spectrum ArIX and Extended Spectral Classification in ArV to ArVIII and ArX", *Physica Scripta* **18**, pp. 315-322, 1978.
18. M.Arnaud and R.Rothenflug, "An updated evaluation of recombination and ionization rates", *Astron.Astrophys.Suppl.Ser.* **60**, pp. 425-457, 1985.

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