Time-resolved extreme ultraviolet emission from a highly ionized lithium capillary discharge

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A fast discharge current pulse (50 ns FWHM) was used to create a highly ionized plasma in a 500-μm-diam lithium hydride capillary 3.8 cm in length. Time-resolved extreme ultraviolet spectra of the capillary plasma show simultaneous line emission from highly ionized (O VI) and singly ionized (O II) species, indicating the existence of a hot-core plasma ($Te > 25$ eV) surrounded by a significantly cooler plasma near the walls. The intensity of the 72.9 nm emission corresponding to the Li III 3–2 transition was observed to increase during the decay of the current pulse, consistent with excitation by electron-ion recombination. The results are relevant to the possibility of amplification of extreme ultraviolet radiation in a discharge-pumped device.

Several types of discharges have been used to excite electron-ion recombination laser transitions in the infrared, visible, and near ultraviolet.[1-6] The generation of denser and more highly ionized plasmas, which rapidly recombine at the end of the excitation, might enable recombination laser action at extreme ultraviolet wavelengths in a discharge-pumped device. Pulsed capillary discharges can produce dense highly ionized plasmas and have been used as spectroscopic sources in the study of multiply ionized species and in the generation of x-ray radiation.[7-9] We have proposed the use of a fast capillary discharge plasma as a medium for the amplification of extreme ultraviolet radiation following electron-ion recombination. In this scheme a nearly totally ionized plasma with a large length to diameter ratio ($l/d \sim 100$) is initially created by a fast capacitive discharge. Electron heat conduction to the capillary walls in addition to other energy losses is expected to rapidly cool the plasma at the decay of the current pulse resulting in a large recombination rate.[10] Under optimized plasma conditions amplification might occur in several transitions, for example, in the 3–2 transition of hydrogenic ions. Besides the interest in capillary plasmas for the direct discharge excitation of short wavelength laser transitions, laser-heated capillary plasmas have also been recently suggested as x-ray laser media.[11]

Herein we discuss time-resolved measurements of the extreme ultraviolet spectral emission of a 500-μm-diam lithium hydride capillary discharge excited by a fast current pulse with a full width at half maximum (FWHM) of about 50 ns. The study was designed to gain understanding of the lithium capillary plasma regarding the possibility of amplification of the Li III 72.9 nm line following electron-ion recombination. Time-integrated spectra of larger diameter (2 mm) lithium capillary plasmas have been previously reported for excitation pulses one order of magnitude longer (0.6 μs FWHM).[2] To our knowledge, this letter is the first report of time-resolved spectra from a highly ionized capillary discharge. The use of a gated dual plate intensified array detector provided the required sensitivity to obtain extreme ultraviolet spectra with 5 ns resolution in a single-shot discharge.

A 500-μm-diam lithium hydride capillary 38 mm in length is excited by discharging a low inductance ring of ceramic capacitors. Lithium hydride was selected to build an electrically nonconducting capillary from which lithium is ablated to create a plasma.[2] The material for the construction of the capillary was obtained pressing LiH pellets at 40 tons/cm^2 to produce cylinders of 1 cm diameter. A hole 500 μm in diameter was then machined in these solid pieces of LiH. Three of these cylinders were finally assembled and potted together in low vapor pressure epoxy to form a 38-mm-long capillary. The discharge setup is schematically represented in Fig. 1. A 6.6 nF ring of ceramic capacitors is directly connected to two hollow graphite electrodes positioned at each end of the capillary. No additional current switch other than the capillary itself was included in series with the capillary discharge to minimize the circuit inductance, which was found to be 70 nH. The capacitors are charged to a value below the breakdown voltage of the capillary. Values in excess of 50 kV can be reached after firing the discharge several times. Discharge initiation is achieved by the plasma which is produced by switching a third electrode located in the proximity of the cathode to negative high voltage. The discharge setup is evacuated from both ends of the capillary using a turbomolecular pump. A solenoid surrounding the capillary can produce an axial magnetic field of up to 100 kG with the purpose of providing additional control over the plasma evolution. However, the results report-

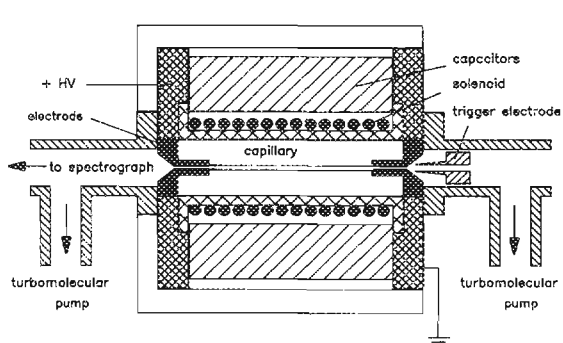

FIG. 1. Schematic diagram of the capillary discharge setup.

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ed herein were obtained in the absence of an externally applied magnetic field.

The axial emission of the discharge in the extreme ultraviolet was analyzed with a 1 m focal length normal incidence vacuum spectrograph using gratings of 600 and 2400 lines/mm. Time-resolved spectra were obtained by gating a windowless intensified multichannel plate diode array detector. The spectrograph and the detection electronics were placed inside a Faraday enclosure to protect the electronics from the electromagnetic noise generated by the short discharge pulses. The distance between the capillary and the entrance slit of the spectrograph was 1.3 m. Efficient light collection was achieved using an aluminum-coated spherical mirror placed 0.56 m from the discharge at an angle of 13° with respect to the axis of the discharge. The mirror focuses the capillary radiation in a line approximately 100 μm wide allowing the collection of sufficient radiation to easily obtain single-shot spectra with an entrance slit of 20 μm and a 5 ns FWHM optical aperture. The signals from a Rogowski coil used to monitor the discharge current pulse and the gating pulse which activates the multichannel plate were digitized and recorded by a 200 MHz dual channel transient digitizer for every discharge pulse. The 45 ns FWHM discharge current pulse produced from capacitors charged to 40 kV is illustrated in Fig. 2. The peak current is 5 kA and the excitation energy is 5.3 J, corresponding to a power density deposition of 1.6×10^{10} W cm^{-3}.

Figure 3 is a time-resolved spectrum of the axial emission of the capillary discharge in the 68–110 nm spectral region taken 3 ns after the peak of the current pulse. Intense O VI transitions at 103.2 and 103.8 nm are seen at the right of the spectrum. Also visible is the emission from the Li III 3–2 transition at 72.9 nm and oxygen-impurity lines corresponding to all the degrees of ionization from O VI down to O II. Unfortunately, the spectral resolution of this instrumentation does not allow unambiguous discrimination between the Li III 3–2 line at 72.89 nm and a possible contribution from the O V transition at 72.87 nm. Nevertheless, the major part of the observed emission at 72.9 nm is expected to correspond to the Li III line since the temporal evolution of its intensity differs from O V lines. The higher resolution spectrum at 83 nm also shown in Fig. 3 was obtained with the 2400 lines/mm grating allowing assignment of the emission in this spectral region to the O III and O II transitions. The simultaneous emission from species with such a different degree of ionization as O VI and O II cannot occur in a plasma of uniform temperature. A simple collisional-radiative plasma model calculation shows that in steady state O VI is the dominant species only for temperatures above 15 eV. However, we have a nonstationary excitation regime, and to make possible the existence of large numbers of O VI ions at the time of the peak current, the time constant for ionization from O V to O VI must be of the order of the current rise time. This means that the plasma must reach a temperature of about 27 eV. On the other hand, significant emission from O II lines will only occur at temperatures below 6 eV. This suggests the existence of a hot-core plasma surrounded by a much cooler boundary plasma (5 eV) near the capillary walls at the time of the peak current. This picture is consistent with the capillary discharge model developed by McCorkle in which ablation of the wall material is described to form a dense, cold boundary plasma that surrounds a less dense highly ionized plasma core.[9] Assuming Bennet equilibrium in the core plasma the electron density of this plasma is estimated to be about 1×10^{18} cm^{-3} for a 40 kV discharge. The electron density for amplification of the Li III 3–2 transition should be less than 1×10^{17} cm^{-3} at the time of the peak recombination to avoid excessive deexcitation of the upper level by electron collisions.[12]

The time evolution of the axial extreme ultraviolet emission in the 50–90 nm spectral region for a 40 kV discharge is shown in Fig. 4. The marks on the current pulse of Fig. 2 indicate the times at which the spectra were taken. The earliest time with respect to the initiation of the current pulse at which a spectrum could be obtained was limited by the intrinsic delay of the gating circuit. At the time corresponding to the peak of the current pulse O V impurity lines are observed to be more intense than the Li III 3–2 transition at 72.9 nm. During the decay of the current pulse, the intensity of the 72.9 nm line increases significantly with respect to the other lines and becomes dominant, reaching its maximum 26 ns after the peak of the current pulse. During the decay of the

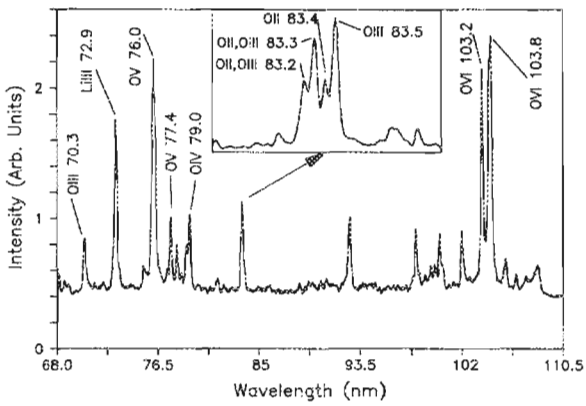

FIG. 3. Time-resolved axial emission spectra of the lithium capillary plasma corresponding to 3 ns after the peak of the current pulse. The excitation voltage was 35 kV. The wavelengths are indicated in nm.

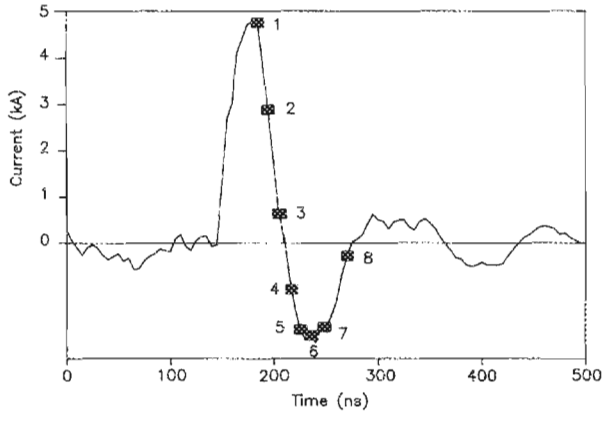

FIG. 2. Discharge current pulse corresponding to a 500-μm-diam lithium hydride capillary 38 mm in length excited by a 6.6 nF capacitor charged to 40 kV. The marks indicate the times at which spectra were obtained. The horizontal dimension of the marks represents the time error bars.

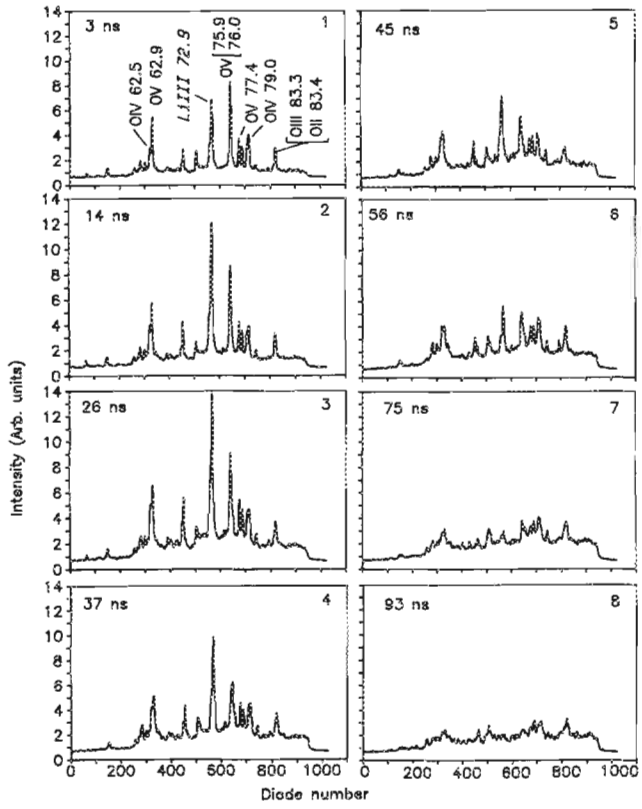

FIG. 4. Time-resolved x-ray ultraviolet spectra corresponding to the capillary discharge current pulse shown in Fig. 2. The time delay respect to the time of the peak current is indicated in each spectrum. The numbers on the right correspond to the marks in Fig. 2. All wavelengths are indicated in nm.

current pulse, the ratio of the sums of the intensities of O V to O IV lines, which is indicative of the degree of ionization of the plasma, is observed to decrease. Such observations are consistent with the excitation of Li III 3–2 transition following three-body electron-ion recombination during the decay of the current pulse which is enhanced as the plasma cools.

A highly ionized plasma was created with only 5 J of excitation energy from a fast discharge in a 500-μm-diam LiH capillary. Time-resolved spectra indicate the coexistence of a hot, highly ionized plasma core surrounded by a significantly cooler boundary plasma. Diffusion of totally stripped ions from the core plasma into the cooler boundary plasma might lead to an annular region of high recombination rates, similar to that observed in laser-created plasmas,[13] in which x-ray ultraviolet gain might occur under optimized plasma density conditions.

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[1] V. Zhukov, E. Latush, V. Mikhalewskii, and S. Sem, Sov. J. Quantum Electron. **7**, 407 (1977).
[2] S. Silfvast, L. Szeto, and O. Wood, II, Appl. Phys. Lett. **36**, 615 (1980); S. Silvast, O. Wood, II, and J. Macklin, *ibid.* **42**, 347 (1983).
[3] M. S. Butler and J. A. Piper, Appl. Phys. Lett. **42**, 1008 (1983); **43**, 823 (1983).
[4] E. M. Campbell, R. G. Jahn, W. F. Von Jaskowsky, and K. E. Clarck, Appl. Phys. Lett. **30**, 575 (1977); J. Appl. Phys. **51**, 109 (1980).
[5] J. J. Rocca, H. Mancini, and B. Wernsman, IEEE J. Quantum Electron. **QE-22**, 509 (1986).
[6] J. J. Rocca, Appl. Phys. Lett. **47**, 1145 (1985).
[7] H. Conrads, Z. fur Physik **444**, 200 (1967).
[8] P. Bogen, H. Conrads, G. Gatti, and W. Kohlhaas, J. Opt. Soc. Am. **58**, 203 (1968).
[9] R. A. McCorkle, Appl. Phys. A **26**, 261 (1981).
[10] J. J. Rocca, D. C. Beethe, and M. C. Marconi, Opt. Lett. **13**, 565 (1988).
[11] A. Zigler, M. Kishenevsky, M. Givon, E. Yarkoni, and B. Ared, Phys. Rev. A **35**, 4446 (1987); R. W. Lee and A. Zigler, Appl. Phys. Lett. **53**, 2028 (1988).
[12] O. Wood and W. Silfvast, Appl. Phys. Lett. **41**, 121 (1982).
[13] C. H. Skinner, D. Kim, A. Wouters, D. Voorhes, and S. Suckewer, SPIE **831**, 262 (1987).