Efficient generation of highly ionized calcium and titanium plasma columns for collisionally excited soft-x-ray lasers in a fast capillary discharge

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Fast discharges through 1.5-mm-diam capillaries have produced dense Ca and Ti plasma columns with an abundance of Ne-like ions, which are of interest for the development of small-scale, collisionally excited soft-x-ray lasers. Current pulses of 30 ns full width at half maximum and peak currents of less than 70 kA produced plasmas with line emission from ions with charge up to the F-like state. Line emission at the wavelengths of the $3p$-$3s$ and $3d$-$3p$ transitions of the Ne-like ions has been observed.

High-power lasers, of the type employed in inertial-confinement fusion research, have been successfully utilized to generate highly ionized plasmas with an abundance of Ne-like and Ni-like ions for soft-x-ray amplification [1,2]. Soft-x-ray lasing in collisionally excited Ne-like ions was demonstrated in these plasmas in several elements ranging from Ti ($Z=22$) to Ag ($Z=47$) [1,2]. Multiterawatt pulsed power machines producing current pulses in the range of mega amperes have been considered as alternative drivers for collisionally excited lasers [3]. However, the widespread use of soft-x-ray lasers in a number of interesting applications remains largely inhibited by the size, cost, and complexity of the soft-x-ray sources.

Recently, significant efforts have been devoted to the utilization of smaller laser drivers in the development of small-scale soft-x-ray lasers based on both collisional excitation and recombination laser schemes [4–6]. Gain-length products of 2.5 and 2 have been reported at 20.4 nm in Ni-like Nb and at 18.2 nm in C VI, respectively, utilizing table-top laser drivers [4,5]. A proposed alternative approach toward compact, efficient, and simpler soft-x-ray lasers consists in the direct generation of the amplifying plasma columns by a fast discharge through a capillary channel [7,8]. In this Rapid Communication we report the efficient generation of dense Ca and Ti plasma columns by a fast capillary discharge in which modest currents are required to reach the Ne-like ionization state. Ca and Ti plasmas in which atoms are ionized up to the F-like state were produced by currents of less than 70 kA in 1.5-mm capillaries. These capillary discharges are unique in generating elongated plasma channels with those characteristics, using such small currents. Emission from the $3p$-$3s$ and $3d$-$3p$ transitions of Ne-like ions in a capillary discharge plasma is reported.

Discharges in plastic and Teflon capillaries that produce plasmas, in which C, O, and F ions are the dominant species, have been studied as sources of continuum and soft x rays for spectroscopy, microscopy, and lithography [9], and, more recently, as possible plasmas for soft-x-ray recombination lasers [10]. However, the development of collisionally excited soft-x-ray lasers in the Ne-like and Ni-like sequences requires the generation of

highly ionized plasma columns in heavier elements. Recently we reported the generation of hot ($T_e > 150$ eV) dense Ar plasma columns of small diameter by fast discharge excitation of a preionized gas-filled capillary [8]. The creation of elongated capillary plasma columns in elements with $Z > 18$ is of significant interest because the gain in the $3p$-$3s$ lines of Ne-like ions increases with the nuclear charge, having a maximum near Se ($Z = 34$) [11]. However, in this case the generation of capillary plasmas requires the development of a different approach, as, in contrast with Ar, these elements are solid at room temperature.

The Ca and Ti plasmas reported herein were produced by ablation of the walls of capillary channels perforated through insulating solid materials containing these elements. The fast current pulses rapidly detach the plasma from the walls, limiting both the amount of material ablated and the heat conduction losses, to form a hot, compressed plasma channel. Capillaries were made by binding calcium hydride powder, CaH_2, with epoxy resin (80%-20% by weight). Similarly, the Ti plasmas were created by ablation of the walls of capillaries made out of titanium hydride, TiH_2, and epoxy resin. Alternatively pure CaH_2 capillaries, which do not contain resin, were developed by pressing CaH_2 powder to 0.7 GPa. In all these capillary structures multiple discharge shots can be performed on a single capillary.

The capillary plasmas were excited by a fast, high-voltage pulse generator that produced current pulses with a 10–90% risetime of 13 ns and a full width at half maximum of 30 ns through a 1-cm-long capillary load. The pulse generator consisted of a 3-nF circular parallel-plate capacitor that, for the experiments reported herein, was charged by a six-stage, $V \leq 600$ kV Marx generator. A schematic diagram of the pulse generator and discharge configuration is shown in Ref. [11]. The capillary, which was placed in the axis of the capacitor, was evacuated to a pressure below 2×10^{-5} Torr and then excited by discharging the capacitor through a low-inductance circuit that included the capillary channel and an SF_6 pressurized spark-gap switch. The fast discharge pulse was preceded in a few microseconds by a preionization spark

produced by discharging a small (3 nF, 12 kV) capacitor between a closely spaced third electrode and the anode electrode, with the purpose of enhancing the uniformity of the breakdown, and it was immediately preceded by a discharge prepulse having a current of approximately 1 kA and a duration of 50 ns.

The axial soft-x-ray emission from the capillary plasmas was focused by a grazing-incidence mirror into the slit of a grazing-incidence spectrograph. The first part of the study, consisting in the determination of the degree of ionization of the plasma as a function of current and the study of its temporal evolution, was conducted with a 1-m spectrograph utilizing either a 600- or a 1200-lines/mm gold-coated grating blazed at 1° and mounted at an angle of incidence of 86°. The identification of the $3p$-$3s$ transitions of Ne-like species, which required increased spectral resolution, was accomplished utilizing a 2.2-m grazing-incidence spectrograph provided with a 1200 lines/mm gold-coated grating set at 85.8°. In both instruments the detection system consisted of a multichannel-plate intensifier (MCP), a phosphorous screen, and a linear diode array detector. Time-resolved spectra with approximately 5-ns resolution were obtained by gating the MCP with a high-voltage pulse.

The soft-x-ray emission from Ca capillary plasmas is discussed next. Figure 1 shows the time-resolved spectra, obtained at 6 ns after the peak of the current pulse, of the

soft-x-ray emission from Ca plasmas generated in a 1.5-mm-diam, 1-cm-long capillary by current pulses of three different amplitudes. For the 44-kA discharge the most intense lines in this spectral region correspond to Na-like Ca, Ca X, and to F-like Ca, Ca XII, an indication that in a 1.5-mm-diam capillary this relatively small current is sufficient to generate Ne-like Ca ions. Ca IX and Ca XIII lines are also observed. As the current increases, the plasma becomes more ionized, as shown by the increase in intensity of the Ca XIII lines and by the relative decrease of the Ca X lines. At a current of 67 kA the Ca XIII 131.2-nm line dominates the spectrum. These results show that the degree of ionization of these plasmas can be selected by adjusting the magnitude of the current pulse. Similar spectra were obtained with capillaries of the same diameter and length of 3 and 5 cm, by increasing the discharge voltage to compensate for the decrease in discharge current caused by the larger inductance associated with a longer capillary.

Figure 2 is a sequence of time-resolved spectra displaying the temporal evolution of the soft-x-ray emission for a 65-kA discharge through a CaH$_2$ capillary. The time of each spectrum relative to the current pulse is indicated. In the first spectrum, obtained at 8 ns after the initiation of the current pulse, only Ca IX and Ca X, as well as O
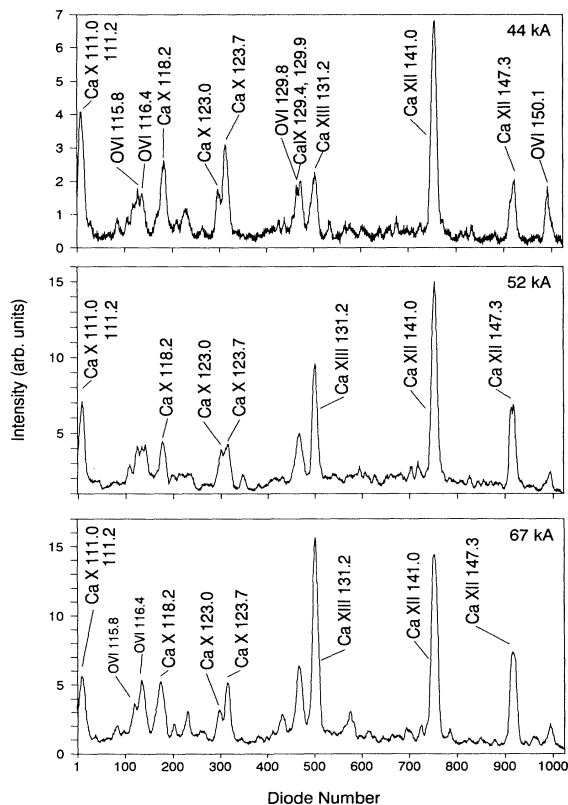

FIG. 1. Time-resolved spectra (110–150 Å) from a 1.5-mm-diam, 1-cm-long CaH$_2$ capillary corresponding to three different values of the discharge current pulse.
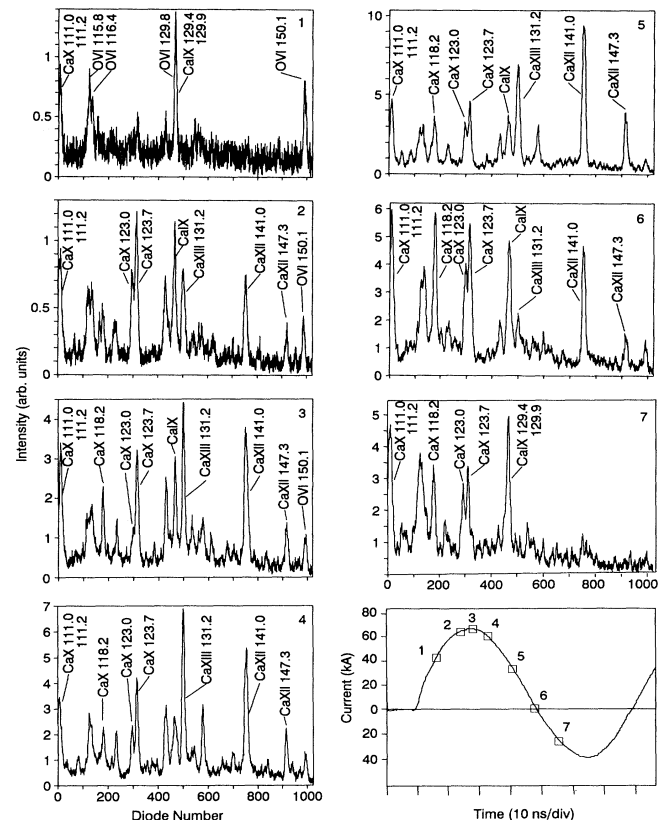

FIG. 2. Sequence of time-resolved spectra (110–150 Å) from a 1.5-mm-diam, 1-cm-long capillary containing CaH$_2$ excited by a 65-kA current pulse. The time at which each spectra was obtained with respect to the discharge current pulse is indicated.

impurity lines, are observed. The degree of ionization of the plasma increases to reach a maximum shortly after the peak of the current pulse, when Ca XIII emission is observed. By the time of the end of the first half-cycle of the current pulse the Ca XIII line has practically disappeared, and again Ca IX and Ca X lines dominate the spectra. During the second half-cycle of the current pulse the plasma continues to cool, as more ablated material from the capillary walls is injected into the plasma column.

Discharges in TiH_2 capillaries produced plasma containing highly ionized Ti ions. Figure 3 shows a time-resolved spectrum covering the 97–134-Å region corresponding to a 61-kA discharge through a 1.5-mm-diam, 3-cm-long capillary containing TiH_2. Line emission from Na-like Ti, Ti XII, and F-like Ti, Ti XIV, is observed. Other Ti transitions, as well as chlorine lines corresponding to ionization states ranging from Cl IX to Cl XIII, have also been identified in the spectra of these capillaries in other wavelength regions. Cl is found as an impurity in the epoxy resin used to bind the TiH_2. Due to the relatively low Cl concentration, approximately 300 ppm, most of these lines can be expected to be optically thin, and therefore constitute a good diagnostic tool. The ratio of intensities of the Cl X resonant lines was verified to be very close to the optically thin value. An estimate of the electron density was obtained from the line intensity ratio of selected Cl XI lines that are sensitive to the electron density and relatively insensitive to variations in the electron temperature [12]. The intensity ratio of Cl XI $2s^22p^3\,^2D^o_{3,2}-2s2p^4\,^2D_{3/2}$ (209.18 Å) and $2s2p^4\,^2D_{5,2}-2p^5\,^2P^o_{3/2}$ (195.69 Å) lines, selected for this purpose, was computed as a function of the plasma density from the relative populations of their upper levels resulting from solving a set of rate equations for the $2p^5$, $2s2p^4$, and $2s^22p^3$ levels. The collisional and radiative rates coupling the population of these levels were computed utilizing the transition probabilities given by Cheng, Kim, and Desclaux [13], assuming an electron temperature of 150 eV. The majority of a set of 15 spectra obtained 8 ns after the peak of the current pulse for excitation currents between 40 and 66 kA yielded line intensity ratios that correspond to densities in the range of 4×10^{18} to 2×10^{19} cm^{-3}.

The 3p-3s laser candidate transitions and the 3d-3p lines in the Ne-like ions are normally very weak, but they have been previously identified in spectra from laser-create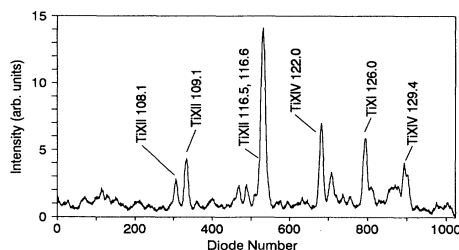d plasmas and beam-foil experiments [14,15]. In Ca XI some of the 3p-3s transitions fall in between the strong Ca X resonant lines at 557.74 Å and 574.01 Å, which provide for a convenient wavelength calibration. The calibration of this spectral region was completed utilizing the Ar II lines from a low-pressure dc discharge. Figure 4(a) shows an average of 14 spectra in this wavelength region, corresponding to CaH_2 capillaries 1.5 mm in diameter and 3 cm in length, obtained 8 ns after the peak of current pulses of the order of 50 kA. Lines were observed at 565.40±0.15 Å and 567.10±0.15 Å, which correspond well with the wavelengths of the $3s\,^1P_1-3p\,^3P_2$ (565.32 Å) and $3s\,^3P_2-3p\,^3D_3$ (566.98 Å) lines of Ne-like Ca [14]. The first of these lines, the $J=2-J=1$ transition, is a candidate for amplification. Also, spectra obtained in the wavelength region corresponding to the three 3d-3p Ca XI transitions $3p\,^3D_2-3d\,^3F_3$ (427.05 Å), $3p\,^3P_2-3d\,^3D_3$ (431.50 Å) and $3p\,^3D_3-3d\,^3F_4$ (435.00 Å) [14], two of which contribute to populate the upper levels of the above-mentioned 3p-3s lines by radiative cascade, show lines whose wavelengths agree to within 0.1 Å with those of the above-mentioned 3d-3p transitions.

Of greater interest is the identification of the $J=0-J=1$ lines, which have been observed for low-Z elements to have the largest gain in laser-created plasmas [2], in agreement with calculations. Wavelength calibration in the spectral region corresponding to the $3s\,^1P_1-^3P\,^1S_0$ Ca XI transition was obtained utilizing Ca IX lines from the same discharge, as well as the 3d-2p

FIG. 3. Time-resolved spectrum from a 1.5-mm-diam, 3-cm-long capillary containing TiH_2. The spectrum was obtained 10 ns after the peak of a 61-kA current pulse.
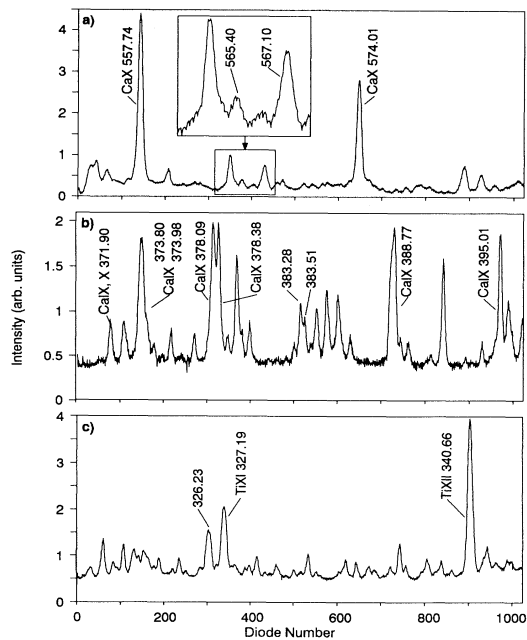

FIG. 4. (a) Average of 14 spectra from compressed CaH_2 capillaries, covering the region between the strong 557.74- and 574.01-Å resonant lines of Ca X. (b) Spectrum from a compressed CaH_2 capillary in the neighborhood of 383 Å. (c) Spectrum from capillary containing TiH_2.

C IV lines from a low-current polyethylene discharge and Na VII lines. The major impurity in the CaH_2 is known to be O, and an analysis of the material performed to identify heavy metal impurities found only Mg and Al at concentrations greater than 0.01 ppm. None of these elements has known lines in the vicinity of 383.3 Å. The spectrum of Fig. 4(b), which corresponds to a 56-kA discharge through a 2.5-mm capillary made out of pure CaH_2, shows a line at 383.28 ± 0.10 Å and a wavelength which is in good agreement with the only previous measurement of the $3s\,^1P_1 - 3p\,^1S_0$ transition of Ca XI (383.27 Å) [14] in a laser-created plasma. Also, as previously observed by Ragozin [16], this $J = 0$-1 laser candidate transition appears closely spaced from a line at 383.51 Å. In our spectra these two transitions, which were also observed in 1.5-mm-diam capillaries, often appeared blended into a single feature at approximately 383.4 Å, having an intensity up to that of the strong Ca IX neighboring lines [17]. Experiments were also conducted to identify its isoelectronic equivalent in Ti.

For this purpose, spectra covering the vicinity of 326 Å were obtained from TiH_2 capillary discharges. This region of the spectra was calibrated using P XI and P XII lines. Figure 4(c) shows a time-resolved spectrum from a 3-cm-long, 1.5-mm-diam TiH_2 capillary discharge excited by a 50-kA current pulse. The line observed in this spectrum at 326.23 ± 0.10 Å corresponds well with the calculated (326.24 Å, Ref. [2]) and previously measured wavelength (326.29 ± 0.05 Å, Ref. [15]; 326.3 ± 0.5 Å, Ref. [2]) of the $J = 0$-$J = 1$ transition of Ne-like Ti. It should be noticed nevertheless that in this case the most accurate measurement of this Ti XIII line, a beam-foil experiment

(Ref. [15]), inferred the contribution of a blended line at 326.1 Å that could also be contributing to our spectra. The other two clearly observed lines in the spectrum of Fig. 4(c) are assigned to the Ti XI 327.19-Å and the Ti XII 340.66-Å transitions.

In conclusion, we have generated dense, highly ionized Ca and Ti plasma columns, using a fast capillary discharge and identified line emission at wavelengths corresponding to the $3p$-$3s$ and $3d$-$3p$ lines in the Ne-like ions. The relatively small currents required to ionize the atoms to the Ne-like state could potentially lead to small-scale, discharge-pumped ultrashort-wavelength lasers by collisional excitation. Similar discharges in capillaries containing elements of the next row of the periodic table are expected to produce highly ionized plasma columns containing large concentrations of Ni-like ions, which will allow for the exploration of gain in this sequence. Ni-like ions, which have the advantage of requiring a reduced excitation energy for lasing in a given wavelength range, and which have been predicted [18] to scale favorably to low Z, constitute very attractive candidates for lasing in a capillary discharge.

[1] D. L. Matthews et al., Phys. Rev. Lett. 54, 110 (1985); B. J. MacGowan et al., J. Appl. Phys. 61, 5423 (1983); T. N. Lee, E. A. McLean, and R. C. Elton, Phys. Rev. Lett. 39, 1185 (1987); T. Boehly et al., Phys. Rev. A 42, 6962 (1990); D. J. Fields et al., ibid. 46, 1606 (1992).

[2] J. Nilsen, B. J. MacGowan, L. B. Da Silva, and J. C. Moreno, Lawrence Livermore National Laboratory, Report No. UCRL-JC-112704 (1993).

[3] J. Davis, R. Clark, J. P. Apruzese, and P. C. Kepple, IEEE Trans. Plasma Sci. PS-16, 482 (1988).

[4] S. Basu, P. L. Hagelstein, M. Muendel, J. GoodBerlet, and S. Kaushik (unpublished).

[5] D. E. Kim, C. A. Skinner, D. Voorhees, and S. Suckewer, Proc. SPIE 1551, 295 (1991).

[6] T. Hara, K. Ando, H. Yashiro, and Y. Aoyagi, Jpn. J. Appl. Phys. 28, L1010 (1989).

[7] J. J. Rocca, D. C. Beethe, and M. C. Marconi, Opt. Lett. 13, 565 (1988).

[8] J. J. Rocca, O. D. Cortázar, B. Szapiro, K. Floyd, and F. G. Tomasel, Phys. Rev. E 47, 1299 (1993).

[9] H. Conrads, Z. Phys. 444, 200 (1967); P. Bogen, H. Conrads, G. Gatti, and W. Kohlhaas, J. Opt. Soc. Am. 58, 203 (1968); S. M. Zakharov, A. A. Kolomenski, S. A. Pikuz, and A. I. Samokhin, Pis'ma Zh. Tekh. Fiz. 6, 1135 (1980)

[Sov. Tech. Phys. Lett. 6, 486 (1980)]; R. A. McCorkle, Appl. Phys. A 26, 261 (1981).

[10] C. Steden and H.-J. Kunze, Phys. Lett. A 151, 1534 (1990); J. J. Rocca, M. C. Marconi, B. T. Szapiro, and J. Meyer, Proc. SPIE 1551, 275 (1991); C. A. Morgan, H. R. Griem, and R. C. Elton (unpublished); J. J. Rocca, M. C. Marconi, and F. G. Tomasel, IEEE J. Quantum Electron. 29, 182 (1993).

[11] A. V. Vinogradov and V. N. Shlyaptsev, Kvant. Elektron. (Moscow) 10, 2325 (1983) [Sov. J. Quantum Electron. 13, 1511 (1983)]; B. L. Whitten, R. A. London, and R. S. Walling, J. Opt. Soc. Am. B 5, 2537 (1988).

[12] U. Feldman and G. A. Doschek, J. Opt. Soc. Am. 67, 726 (1977).

[13] K. T. Cheng, Y.-K. Kim, and J. P. Desclaux, At. Data Nucl. Data Tables 24, 111 (1979).

[14] E. N. Ragozin, S. S. Churilov, E. Ya. Kononov, A. N. Ryabtsev, and Yu.F. Zayikin, Phys. Scr. 37, 742 (1988).

[15] E. Träbert and C. Jupén, Phys. Scr. 36, 586 (1987).

[16] E. N. Ragozin, private communication.

[17] J. J. Rocca, O. D. Cortázar, B. T. Szapiro, F. G. Tomasel, and D. Hartshorn, Proc. SPIE (to be published).

[18] P. L. Hagelstein, Proc. SPIE 1551, 254 (1991).