Discharge-pumped soft-x-ray laser in neon-like argon*

J. J. Rocca,† F. G. Tomasel, M. C. Marconi,[a] V. N. Shlyaptsev,[b] J. L. A. Chilla, B. T. Szapiro, and G. Giudice
Department of Electrical Engineering, Colorado State University, Fort Collins, Colorado 80523

(Received 14 November 1994; accepted 9 February 1995)

Starting with the discovery of x-ray lasers in 1984, laser-created plasmas remained for almost a decade, the only medium in which large amplification of soft-x-ray radiation could be obtained. In this paper the recent first demonstration of large soft-x-ray amplification in a discharge-created plasma column, realized utilizing a fast capillary discharge to collisionally excite the 46.9 nm transition of Ne-like, Ar is reviewed. Results of the parametrization of the Ar IX discharge-pumped amplifier, the study of the dynamics of its plasma column, and the measurement of the time history of the laser pulse are reported. Prospects for laser operation at shorter wavelengths are also discussed. © *1995 American Institute of Physics.*

I. INTRODUCTION

Recent x-ray laser reviews[1-3] summarized the significant progress achieved in this field, following the first successful demonstration of collisionally excited[4] and recombination pumped[5] soft-x-ray lasers in plasmas generated by powerful laser drivers. Such progress includes the expansion of the spectral range covered by x-ray lasers, the demonstration of saturation of the small signal gain, and the characterization of the spectral and spatial properties of these lasers. Also, efforts have been made to improve their coherence properties and to shape their pulselength for specific applications. These bright sources have also been successfully utilized in a number of proof-of-principle experiments in x-ray microscopy, x-ray holography, and in the diagnosis of dense plasmas.[6]

However, the most recent reviews on this field[1-3] stress in their conclusions, the need for the development of more compact, higher efficiency soft-x-ray lasers that, being more affordable and accessible to users, could make their use widespread in important applications. With this objective, efforts have recently been devoted to explore soft-x-ray laser excitation schemes that make use of tabletop laser drivers. Experiments have been conducted in both collisional excitation and recombination schemes.[7-11] These experiments have yielded, to date, gain-length products of $\leqslant 4$, with the exception of a recent experiment in which a 100 fs pulse from a terawatt laser was used to pump Pd-like Xe, resulting in $gl \sim 11$ at 41.8 nm.[11]

Alternatively, pulsed-power-driven plasmas have also received significant attention, both theoretical and experimental, as potentially high efficiency laser sources. However, despite the success in the development of discharge-pumped lasers at wavelengths as short as 116.1 nm as early as in 1972,[12] the 100 nm barrier remained insurmountable for the development of shorter-wavelength discharge-pumped lasers for over 20 yr. A major obstacle has been axial inhomogeneities in the plasma produced by nonsymmetric compressions and instabilities that severely distort the plasma, thus destroying the amplification. For example, Kr pinches produced plasmas with an adequate ionization balance to explore for gain by collisional excitation in transitions of the Ne-like ion, yet no amplification was observed.[13,14] To circumvent the limitations imposed by the plasma inhomogeneities, schemes have been explored that make use of large x-ray fluxes produced by plasmas created by powerful pulsed-power machines to photopump a separate, more quiescent plasma by resonant photoexcitation or by photoionization followed by recombination.[14-18] Resonant photopumping of He-like Ne ions by He-like Na line emission, and of Be-like Mg IX ions by Li-like Al XI line radiation produced in pinch plasmas, has resulted in fluorescence in the laser lines and in the generation of population inversion.[17,18] However, further experiments are still needed to demonstrate amplification in these pulsed-power-driven photopumped schemes.

As a route to compact, efficient, and simpler soft-x-ray lasers, we have proposed the direct generation of an axially uniform plasma column by a fast discharge in a capillary channel.[19] Discharges in evacuated capillaries had been previously studied as sources of continuum radiation in the soft-x-ray region for spectroscopy, microscopy, and lithography.[20-22]

Several experiments were recently conducted in both capillary discharges[23-27] and pinch plasmas[28,29] to explore for amplification by collisional recombination. While gain[23,27,29] and anomalous line intensity ratios indicative of population inversion[25] have been reported, only limited exponentiation has been observed, with the laser line intensity remaining comparable to that of the surrounding lines for the longest plasma columns explored. Alternatively, it has been recognized that capillary discharges could also create adequate plasma conditions for soft-x-ray amplification by collisional excitation.[30-33] We suggested, based on preliminary experiments,[30,32,33] that fast discharge excitation of a capillary channel filled with a selected mass density of uniformly preionized material would lead to amplification in Ne-like and Ni-like ions.

---

*Paper 6IA2, Bull. Am. Phys. Soc. **39**, 1660 (1994).

†Invited speaker.

[a] College of Exact and Natural Sciences, University of Buenos Aires Argentina. Member of the National Council for Scientific and Technological Research CONICET.

[b] P. N. Lebedev Physical Institute, Moscow, Russia.

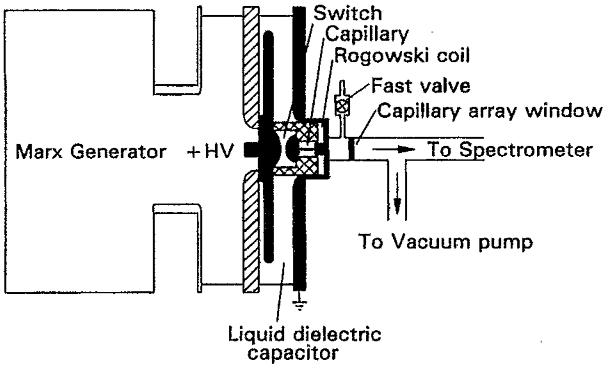

FIG. 1. Schematic diagram of pulse generator and capillary discharge setup.

Recent experiments conducted at Colorado State University accomplished the first demonstration of large soft-x-ray amplification in a discharge-created plasma, utilizing a relatively compact discharge setup.[34] A gain length of gl=7.2 was measured in the 46.9 nm $J=0-1$ line of Ne-like argon in a 12 cm long plasma column generated by a fast capillary discharge. In the next section we summarize these results and present measurements of the variation of the laser line intensity as a function of the discharge parameters. In the following sections we discuss both the study of the evolution of the capillary plasma column at the conditions at which lasing is observed, and the measurement of the time history of the laser pulse. In Sec. V we discuss the prospects for the operation of discharge-pumped lasers at shorter wavelengths.

II. DEMONSTRATION OF AMPLIFICATION IN NE-LIKE ARGON

Experiments designed to search for amplification in Ne-like Ar were conducted utilizing the fast capillary discharge setup schematically shown in Fig. 1. Argon plasma columns were generated by discharging, through a spark gap pressurized with SF_6, a 3 nF liquid dielectric capacitor into 4 mm diam capillary channels filled with preionized gas.[32,34] The capacitor was pulse charged by a Marx generator. A system composed by a toroidal copper mirror placed at 82° and a 2.2 m grazing incidence spectrograph with a 1200 l/mm grating was used to analyze the radiation axially emitted by the plasma column through the hollow grounded electrode. Following the identification of the $J=0-1$ line in Ne-like Ar at 46.875±0.015 nm, measurements of its intensity were conducted as a function of capillary length to search for amplification. In these experiments special care was taken in maintaining constant the characteristics of the excitation, defined by the amplitude and period of the current pulse, as the capillary length was varied. The first observation of large amplification in Ar IX at 46.9 nm was realized both in pure argon and in Ar–H_2 gas mixtures at pressures near 700 mTorr excited by a current pulse with a half-period of about 60 ns and an amplitude near 39 kA.[34] More recently, it was realized that the H_2 fraction used in the Ar–H_2 experiments was, due to incomplete mixing of the gases in the gas manifold used in the experiment, significantly smaller than the 1:2 ratio reported, and amounted to be less than 10%. This and the fact that larger laser intensities were observed in pure argon discharges rule out a possible crucial role of H_2 in the laser population mechanism, confirming this is a collisionally excited laser. Figure 2 shows the dramatic increase of the intensity of the 46.9 nm transition of Ne-like Ar observed when the plasma length is increased from 3 to 12 cm. In the spectrum of Fig. 2(a), corresponding to a 3 cm long capillary, the $J=0-1$ line is observed to be less intense than the surrounding lines of Mg-like Ar, and to have only about twice the intensity of the neighboring $3d-3p$ Ne-like Ar line at 48.5 nm. In the spectrum corresponding to the 6 cm long plasma, the intensity of the $J=0-1$ line surpasses those of all surrounding lines, and, in the case of the 12 cm plasma column, this line totally dominates the spectrum. At this point the intensity of the lasing line was measured to exceed that of the 48.5 nm line by more than 300 times. A plot of the integrated line intensity of the $J=0-1$ line as a function of the capillary length shows an exponential increase. A fit of these data to the Lindford formula[35] yields a gain coefficient of $0.6\pm0.04\ \text{cm}^{-1}$, corresponding to a gain-length product of 7.2 for the 12 cm column. Preliminary measurements conducted with a 16 cm long plasma column, indicate that the intensity of the laser line continues to increase with capillary length. A quantitative measurement of the gl product in this case, however, has not yet been obtained, since the line intensity saturated the detector when attenuated by the thickest aluminum filter we had available for the experiment.

It should be noticed that the measured gain coefficient of $0.6\ \text{cm}^{-1}$ is the effective gain, having a reduced value with respect to the maximum gain coefficient $g_0=\sigma\,\Delta N$ due to refraction effects. The role of refraction can be estimated by modifying the beam optics analysis by London,[36] for the cylindrical geometry of the plasma column of the capillary discharge. In the case of a cylindrical plasma column larger than the characteristic refraction length L_r, the effective gain coefficient, α, can be shown to be related to the gain coefficient g_0 by

$$\alpha=g_0-\frac{2}{L_r},$$

where L_r can be calculated from the gradient of the index of refraction by

$$L_r=\sqrt{\frac{\partial^2 n}{\partial r^2}}.$$

Assuming a plasma density of $5\times10^{18}\ \text{cm}^{-3}$ and parabolic density and gain profiles with a full width at half-maximum (FWHM) of ~300 μm it results that $L_r=6.7$ cm and $g_0\sim0.9\ \text{cm}^{-1}$, corresponding to a decrease of the gain due to refraction of $\sim0.3\ \text{cm}^{-1}$. While the refraction effects are estimated to be non-negligible, they are, nevertheless, according to this approximation sufficiently small (corresponding to a refraction gain length $G_r=g_0\ L_r\sim6>1$) to allow for maintained exponential growth of the intensity with plasma column length,[36] as observed in the experiments.

Measurements of the integrated intensity of the 46.9 nm Ar IX line were also conducted as a function of discharge current and pressure to determine the dependence of the am-

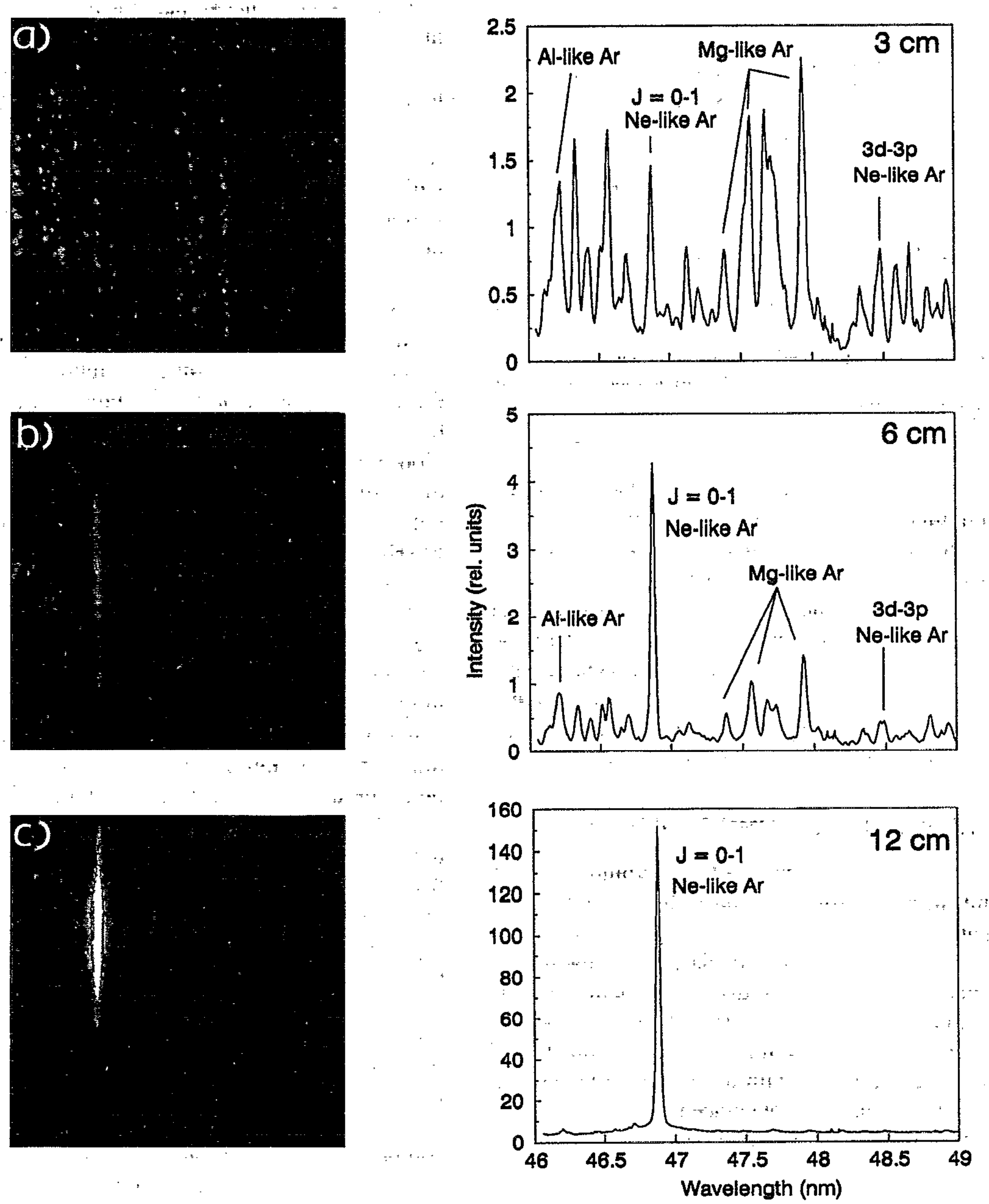

FIG. 2. Axial spectra from Ar plasma columns 3, 6, and 12 cm long. A dramatic increase in the intensity of the $J=0-1$ line of Ar IX at 46.9 nm as a function of capillary length is observed. The spectra correspond to 38±1 kA discharges in 4 mm diam capillaries.

plification on these discharge parameters. Figure 3 shows the dependence of the amplified line intensity on the discharge current for an operating pressure of 700 mTorr. Amplification of the $J=0-1$ line was observed at currents between 34 and 41 kA, with a maximum occurring near 39 kA. All of the measurements were conducted with a wide gate pulse (~30 ns) in the detector, to allow for time integration of the amplified radiation independently of any variation in the time of occurrence of the laser pulse as the discharge parameters were varied. Figure 4 shows the dependence of the amplified line intensity as a function of the filling gas pressure. The data, obtained from discharge shots at approximately the same current, 39 kA, show that adequate conditions for amplification are obtained at pressures approximately between 500 and 750 mTorr.

Spectra were also obtained in the wavelength region corresponding to the $J=2-1$ line of the Ne-like Ar at 69.8 nm, which is theoretically predicted to have a lower gain.[37] Measurements of the variation of the intensity of this line is complicated by the fact that it appears blended with the $2p^5 3p^3 D_3 - 2p^5 3s^3 P_2$ Ar IX transition, which cannot be inverted.[38] A comparison of averages of series of spectra from 3 and 12 cm capillaries shows a superlinear increase of the intensity of the 69.8 nm line, indicative of gain in the $J=2-1$ transition of Ar IX. However, the intensity of this line remains smaller than that of neighboring Ar VIII resonant

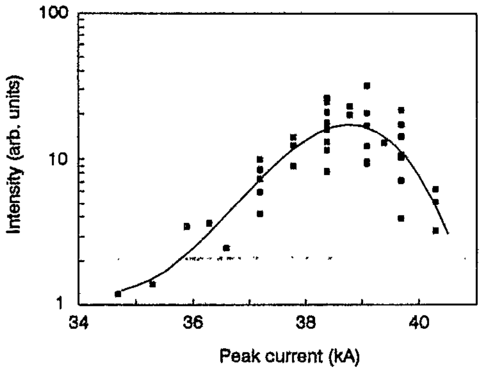

FIG. 3. Variation of the integrated intensity of the 46.9 nm Ar IX line as a function of discharge current. The data were taken from 4 mm diam, 12 cm long capillaries filled with 700 mTorr of argon.

lines, even in the 12 cm capillaries. The absence of strong amplification in this $J=2-1$ line is in agreement with results obtained in laser-created plasmas for low-Z Ne-like ions at Livermore, where in the case of Ti XIII only the $J=0-1$ line was observed to lase.[39] It should be noticed, however, that due to the good reflectivity of materials in the 70 nm region the utilization of a mirror, or eventually an optical cavity, provided the inversion can be maintained for a sufficiently long time, might allow for significant amplification of the $J=2-1$ lines, despite their smaller gain coefficients.

III. CAPILLARY PLASMA COLUMN EVOLUTION

We previously reported a study of the evolution of the plasma column in a fast argon capillary discharge,[32] but at conditions that differed from those in which amplification was recently demonstrated.[34] To elucidate the dynamics of the capillary plasma column at the discharge conditions corresponding to amplification in the $J=0-1$ line of Ne-like Ar, time-resolved end-on soft-x-ray images were obtained. The measurements were conducted with a x-ray pinhole camera, consisting of a 45 μm diam pinhole placed at 36 cm from the end of the capillary and a gated multichannel plate (MCP) intensified coupled charge device (CCD) array detector. The camera has a calculated magnification of 3.14, a spatial resolution limited to ~60 μm by the finite size of the pinhole, and a temporal resolution of approximately 5 ns. Pinhole images of the plasma were obtained using a 1000 Å thick carbon foil filter, which limits the radiation observed to wavelengths below ~30 nm. Images were also obtained without a filter to allow for the observation of cooler plasma regions. In the latter case the wavelength of the radiation observed is limited to $\lambda \leq 1300$ Å by the spectral response of the MCP.

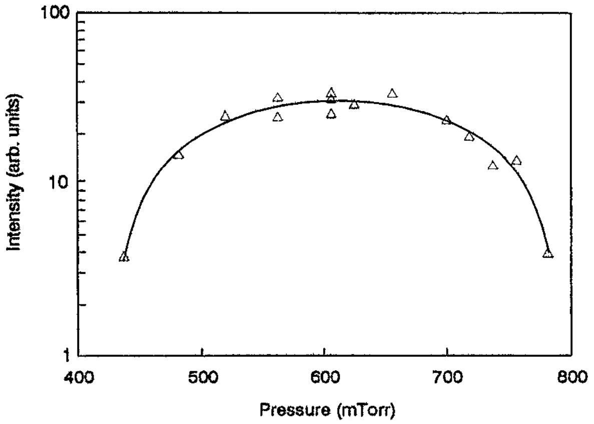

FIG. 4. Variation of the integrated intensity of the 46.9 nm Ar IX line as a function of discharge pressure on a 4 mm diam, 15 cm long capillary filled with argon. The discharge current was maintained constant at approximately 39 kA.

The data confirm that the rapidly rising current in the capillary channel gives origin to the formation of a strong shock that evolves, forming a compressed plasma column at the center of the capillary.[40] Figure 5 shows a sequence of time-resolved pinhole images of the soft-x-ray emitting region of the plasma column as a function of time for a 39 kA discharge through a 4 mm diam, 12 cm long capillary filled with 700 mTorr of argon. The corresponding evolution of the FWHM diameter of the soft-x-ray emitting region of the plasma column relative to the current pulse is shown in Fig. 6. The dynamics of the plasma is in good qualitative agreement with hydrodynamic calculations for a fast argon capillary discharge. The images obtained at 26 ns from the beginning of the current pulse show the emission from a cylindrical shell, caused by the current distribution determined by the skin effect, with an outer diameter that approaches that of the capillary channel. The subsequent images show that the plasma shell is detached from the wall by the forces of the electromagnetic pressure produced by the fast current pulse, causing its rapid collapse with a velocity that reaches $\sim 2\times 10^7$ cm/s. Besides the compressional heating, Joule heating is calculated to make a significant contribution in heating the central region of the capillary plasma. Hydrodynamic/atomic model calculations show that in the final stage of compression near optimal parameters for gain formation in the $3p-3s$ transitions of Ne-like Ar are reached: an electron temperature of 70–90 eV, and an electron density of $0.3-1\times 10^{19}$ cm^{-3}. Due to the high-velocity compression, the electron density abruptly increases to reach or surpass the noted values, giving rise to a gain peak that has a duration of 1–2 ns. Also, when the kinetic energy of the shock wave reaches the capillary axis, it causes an abrupt increase in the ion temperature. Overionization of the dense plasma, increased Doppler broadening, and collisional thermalization lead then to a decrease in the gain, thus terminating the laser pulse. The FWHM diameter of the radiating region of the plasma column at the time of maximum compression is measured to be ~200 and ~300 μm with and without a filter, respectively. The plasma column is observed to maintain a diameter close to that achieved at the time of maximum compression for about 15 ns, and to subsequently expand continuously until shortly after the peak of the second half-cycle, when the diameter of the emitting region is measured to be about 3 mm. The column suffers a second collapse by the time of the end of the first cycle of the current (not shown in Fig. 5), but reaching this time a diameter of about 1 mm, that results in a cooler plasma which is not of interest for collisionally excited soft-x-ray lasers.

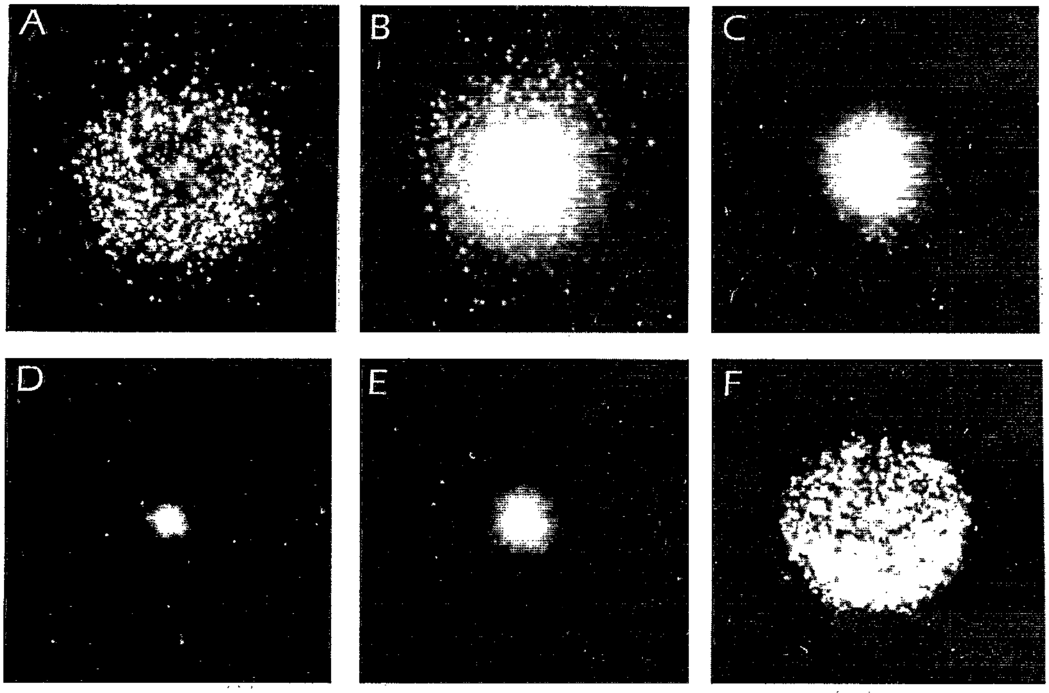

FIG. 5. Series of time-resolved end-on images of the plasma column at discharge conditions near the optimum for amplification in the $J=0-1$ line of Ar IX in Figs. 3 and 4, for an argon discharge in a 4 mm diam capillary. The diameter of the emitting region in the first image (a) is 3.5 mm. The timing of each image with respect to the current pulse is shown in Fig. 6.

IV. LOCATION OF THE GAIN REGION AND TIME HISTORY OF THE LASER PULSE

Model calculations conducted utilizing a hydrodynamic/atomic code of the capillary discharge plasma[37] indicate that gain can be obtained on both a cylindrical shell at times shortly before the plasma column collapses, and/or on the axis of the capillary, depending on the discharge conditions. While time-resolved spectra obtained with a 5 ns gate pulse indicate that lasing occurs near the time of the collapse of the plasma at the axis of the capillary, the very rapid compression of the plasma column makes it difficult to determine the spatial location of the gain from a combination of the data in Fig. 6 and the timing of the laser pulse. To experimentally determine the location of the gain region, the far-field pattern of the beam was recorded in the presence of pinholes, placed in close proximity to the end of the plasma column, at selected locations along the plasma diameter. The laser radiation emitted through the pinholes was recorded at 2.2 m from the end of the capillary, utilizing as a spectral filter the grazing incidence spectrograph, with the slit widely opened to ~300 μm.

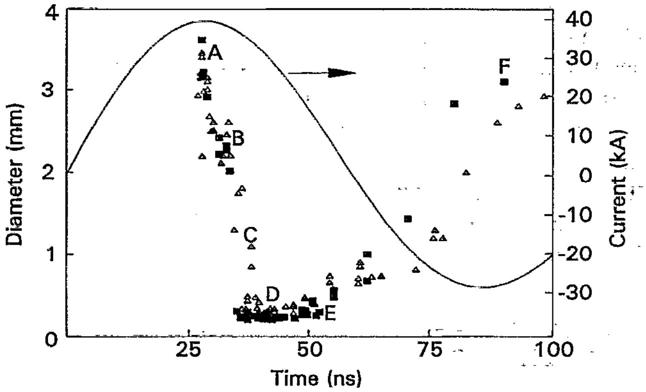

FIG. 6. Evolution of the outer diameter (defined as FWHM of the intensity) of the XUV soft-x-ray emitting region of the plasma column as a function of time. The solid squares correspond to data obtained interposing a 1000 Å thick carbon foil, which filters out radiation with $\lambda > 30$ nm.

Figure 7(a) shows an image obtained with a single 150 μm pinhole centered on the capillary axis and placed at 1.5 cm from the end of the plasma column. It was obtained at near optimum conditions for lasing in a 12 cm long capillary. Figure 7(b) shows a beam profile obtained by placing in the same location a linear array of three 150 μm pinholes, having 300 μm center-to-center separation, and positioned such that the center hole is concentric with the capillary. In both figures the intense emission emanating from the central pinhole indicates that strong amplification is present in the central region of the capillary. While fluctuations of the central lobe relative to the sidelobes have been observed for different shots, in the vast majority of the shots the maximum amplification was observed to originate from the central region of the capillary. In some occasions, however, we have recorded beam patterns having a slight depression in the center, an indication that in those shots the optimum plasma conditions for amplification might occur off axis.

The pinholes also define specific known locations at the end of the plasma column, which, assuming a Gaussian beam and with the knowledge of the ray matrix of the detection system, allow for an estimate of the beam diameter at the end of the plasma column. The radius of the wave front and the beam diameter in the plane of the pinhole mask, parameters

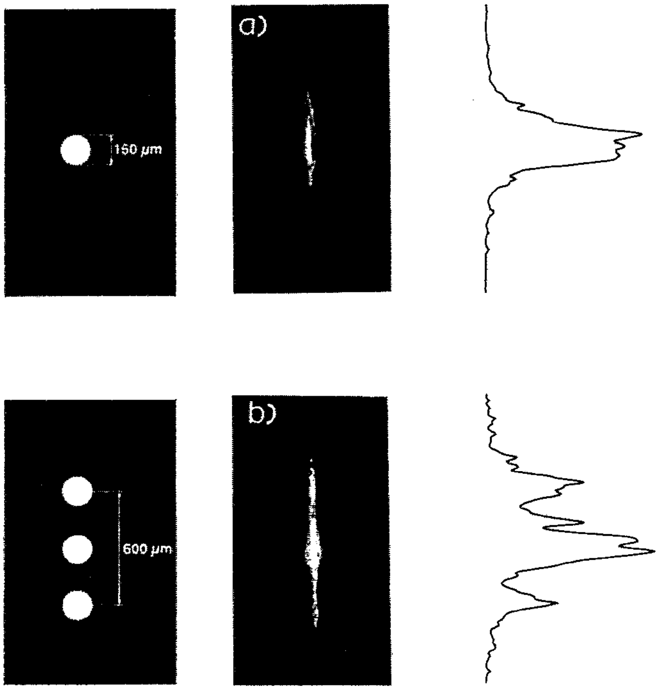

FIG. 7. The far-field pattern of the 46.9 nm laser radiation emitted through configurations of 150 μm pinholes placed at 15 mm from the end of the plasma column. The radiation was recorded at 2.2 m from the capillary, after being filtered by the grazing incidence spectrograph. (a) Image corresponding to a single pinhole, aligned with the capillary axis. (b) The image corresponding to a linear array of three pinholes separated 300 μm between centers, as illustrated in the figure.

that completely characterize the beam, can be determined from the separation and relative intensity of the peaks, respectively. Analysis of the intensity profile of Fig. 7(b) results in a time-integrated beam diameter at the end of the 12 cm plasma column of 360 μm FWHM, and a beam divergence of approximately 5.8 mrad. Nevertheless, a series of beam profiles obtained with another capillary consistently displayed a relatively larger intensity in the central lobe, corresponding to a smaller plasma column diameter. This indicates that the extent of the gain region is highly sensitive to the plasma conditions that govern its formation. A more precise determination of the laser beam divergence and diameter was obtained by measuring its intensity profile at three different locations along the beam path. For this purpose, the beam profile was recorded in the presence of an array of fiduciary slits. Series of measurements conducted placing the slit array at 1.5, 15, and 38 cm from the end of a 12 cm long capillary plasma column yielded a beam divergence of 5.5 mrad and a FWHM beam diameter at the end of the amplifier of ~300 μm.

The time history of the laser pulse was also studied utilizing an internally intensified x-ray streak camera developed in house. For this measurement, the streak camera was coupled to the 2.2 m grazing incidence spectrograph, positioning the photocathode on the Rowland circle. The spectrometer imaged the laser line onto the photocathode of the camera and the streak was performed in the direction perpendicular to the entrance slit of the spectrometer.

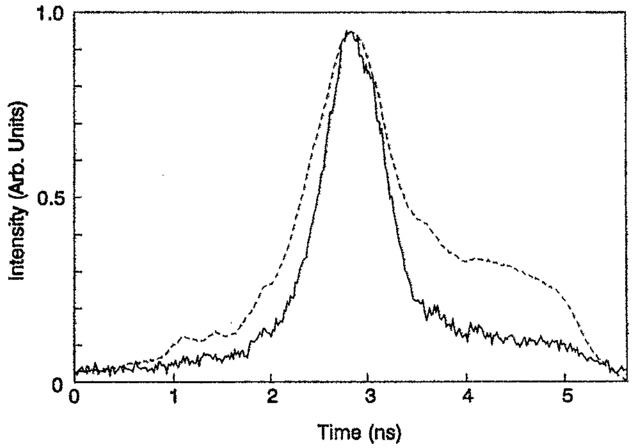

FIG. 8. Time history of the laser intensity measured at the center of the detected beam pattern (solid line) and of the spatially integrated laser line intensity (dashed line), corresponding to a ~39 kA discharge through 12 cm long, 4 mm diam capillary channel filled with 700 mTorr of argon.

Figure 8 shows the measured time history of the laser intensity at the discharge conditions described as near optimum for amplification in Figs. 3 and 4. The time dependence of both the spatially integrated laser intensity and the intensity near the center of the beam pattern, where the intensity is maximum, are illustrated. It should be noticed that, due to the stigmatic characteristic of our optical system, even the latter measurement is not completely spatially resolved. The FWHM time duration of the laser pulse is approximately 1 ns, while at the 25% value of the peak intensity the spatially integrated pulse is 2.8 ns wide. The observed time extent of the amplified pulse is in agreement with the predictions of hydrodynamic/atomic code calculation of the capillary discharge plasma column, which show that for the optimum value of the parameters discussed in Sec. II the duration of the gain is about 1–2 ns.

The soft-x-ray laser power and energy that could be obtained assuming saturation will be reached (e.g., via mirrors) can be estimated from the measured values of the gain coefficient (0.6 cm^{-1}), the laser pulsewidth (~1.2 ns), and the estimated extent of the gain region (~300 μm diam). For a 16 cm long plasma column such estimate yields a laser pulse energy of the order of 0.1 mJ and a power of about 80 kW. Considering a capacitor energy of about 100 J, this corresponds to a soft-x-ray laser to discharge power ratio of $\sim 10^{-4}$, and to a laser energy efficiency of $\sim 10^{-6}$. In comparing this efficiency value to that of laser-pumped soft-x-ray lasers having similar efficiencies, it should be noted that in the latter case the wall-plug efficiency is further reduced by more than two orders of magnitude by the efficiency of the laser driver.

V. PROSPECTS FOR LASING AT SHORTER WAVELENGTHS

A natural approach that can be followed to demonstrate lasing in a discharge-created plasma at shorter wavelengths consists in the Z scaling of the collisional excitation laser experiment discussed above along the neon isoelectronic sequence. Starting from the recent Ar IX ($Z=18$) result, Ca XI ($Z=20$), and Ti XIII ($Z=22$) are the next two ions of this sequence that, due to their even Z and consequently small hyperfine splitting,[42] are good candidates for amplification. Lasing in Ti XIII has already been demonstrated in laser-created plasmas at the Lawrence Livermore National Laboratory.[39,41] Inversion of the populations corresponding to the $J=0-1$ line in these ions will result in amplification at 383 and 326 Å, respectively. It can be expected, according to the gain scaling relation $g \sim Z^{4.5}$,[43] that, if optimum plasma conditions can be achieved, the gain of the $J=0-1$ line in these elements will be higher than in Ar IX, and of the order of 1.5 and 3 cm^{-1} for Ca XI and Ti XIII, respectively. An additional experimental complication arises here from the fact that these, as well as the next several elements of the Ne-like sequence, are solid at room temperature. Several techniques, however, can be used to generate a vapor column of these elements, including injection of material vaporized by a secondary discharge into the capillary channel,[44] and discharge ablation of the wall of a capillary containing these materials.[33]

We have recently reported the observation of the $J=0-1$ and $J=2-1$ lines of Ca XI and possibly of the $J=0-1$ line of Ti XIII in a fast capillary discharge in plasmas created by discharge ablation of capillaries containing CaH_2 and TiH_2.[33] Rapid excitation of 1.5 and 2.5 mm diam capillaries made out of these materials with current pulses of less than 70 kA have produced Ca and Ti plasmas in which atoms are ionized up to the O-like and F-like state, respectively. To be able to tailor the conditions of these plasmas for amplification, we propose the utilization of two discharge pulses: a prepulse designed to ablate material from the capillary wall, creating a cold plasma with the necessary mass density in the capillary channel, followed by a fast, high-current pulse to do the excitation. In this scheme both the amplitude of each of the pulses and the delay between them can be adjusted for independent control of the initial density of material and of the excitation. In x-ray lasers in laser-created plasmas, two pulse excitation schemes have already been proposed[45] and successfully utilized[41,46] to tailor the plasma conditions to achieve high gain.

To obtain lasing at wavelengths below 300 Å in the Ne-like sequence, excitation of higher-Z ions, such as Ne-like Cr ($\lambda=285$ Å) or Ne-like Fe ($\lambda=255$ Å), is required. It is foreseeable that scaling of the excitation to achieve 50–100 μm diam plasma columns with $N_e \sim (2-5)\times 10^{20}$ cm^{-3}, and $T_e \sim 500-700$ eV could result in lasing below 200 Å in Ne-like Kr, with gains of the order of 5–8 cm^{-1}. However, the pumping requirements needed to achieve such values of the plasma parameters significantly increase the degree of difficulty of its practical realization. Alternatively, a more rapid scaling to shorter wavelengths could be achieved utilizing Ni-like ions.[8,32,37] In this case, amplification at wavelengths below 200 Å can be explored, for example, utilizing the $3d^9 4d\,^1S - 3d^9 4p\,^1P$ transition of Mo XIV ($\lambda=189.2$ Å). This transition in Mo XIV has been already identified in a laser-created plasma, and also a gl product of 3 has recently been reported in the equivalent line in Ni-like Nb ($\lambda=204.2$ Å) in a 0.9 cm long plasma created by a tabletop laser.[9] Excitation of these Ni-like transitions in a fast compressive capillary discharge should still require relatively modest currents, of the order of less than 100 kA. It is also possible that scaling of the excitation to generate plasma columns with $N_e \sim (2-5)\times 10^{20}$ cm^{-3} and $T_e \sim 300-600$ eV could produce amplification with gains of 4–6 cm^{-1} in Ni-like Xe at $\lambda \sim 91-95$ Å.

The recombination scheme also remains as a possible approach to obtain large amplification at shorter wavelengths in a fast capillary discharge,[19,25] while still maintaining moderate excitation currents.

ACKNOWLEDGMENTS

We want to acknowledge the contributions of O. D. Cortázar, D. Hartshorn, and D. Clark. We also thank Kevin Colburn and John Dorrenbacher for their work in the development of the streak camera, A. Osterheld for providing atomic data that was used in some of the gain calculations, and B. Bach from Hyperfine Inc. for technical support.

This work is supported by the National Science Foundation Grants No. ECS-9401952, No. ECS-9412916, and No. ECS-9412106, and by the Air Force Wright Laboratory. Part of the diagnostic instrumentation was developed in collaboration with Hyperfine Inc. (Boulder, CO) with the support of the Colorado Advanced Technology Institute. Previous support from the Department of Energy, Office of Basic Energy Science, and the U.S. National Research Council is also acknowledged.

[1] R. C. Elton, *X-Ray Lasers* (Academic, Boston, 1990).

[2] C. H. Skinner, Phys. Fluids B **3**, 2420 (1991).

[3] B. J. MacGowan, L. B. Da Silva, D. J. Fields, C. J. Keane, J. A. Koch, R. A. London, D. L. Matthews, S. Maxon, S. Mrowka, A. L. Osterheld, J. H. Scofield, G. Shimkaveg, J. E. Trebes, and R. S. Walling, Phys. Fluids B **4**, 2326 (1992).

[4] D. L. Matthews, P. L. Hagelstein, M. D. Rosen, M. J. Eckartr, N. M. Ceglio, A. N. Hazi, M. Medecki, B. J. MacGowan, J. E. Trebes, B. L. Whitten, E. M. Cambell, C. W. Hatcher, A. M. Hawryluk, R. L. Kaufman, L. P. Pleasance, G. Rambach, J. H. Scofield, G. Stone, and T. A. Weaver, Phys. Rev. Lett. **54**, 110 (1985).

[5] S. Suckewer, C. H. Skinner, H. Milchberg, C. Keane, and D. Voorhees, Phys. Rev. Lett. **55**, 1753 (1985).

[6] *Applications of X-Ray Lasers*, edited by R. London, D. Matthews, and S. Suckewer, San Francisco, CA, 1992, Conference No. 9206170 (National Technical Information Science, U.S. Department of Commerce, Springfield, VA, 1992).

[7] Y. Nagata, K. Midorikawa, S. Kubodera, M. Obara, H. Tashiro, and K. Tokoda, Phys. Rev. Lett. **71**, 3774 (1993).

[8] S. Basu, P. L. Hagelstein, and J. G. Goodberlet, Appl. Phys. B **57**, 303 (1993).

[9] L. Y. Polanski, C. O. Park, K. Krushelnik, and S. Suckewer, SPIE J. **2012**, 75 (1993).

[10] J. Goodberlet, S. Basu, M. H. Muendel, S. Kaushik, T. Savas, M. Fleury, and P. L. Hagelstein, "Observation of gain in a recombining H-like boron plasma," submitted to J. Opt. Soc. Am. B.

[11] B. Lemoff, G. Y. Yin, C. L. Gordon, III, C. P. J. Barty, and S. E. Harris, Phys. Rev. Lett. **74**, 1574 (1995).

[12] R. W. Waynant, Phys. Rev. Lett. **28**, 553 (1972).

[13] See AIP Document No. PAPS PHPAE-2-2547-40 for 40 pages of S. Wong, L. Koppel, L. Burr, R. Rodenburg, R. Fortner, R. Stewart, D. Dietrich, P. Egan, B. Young, and R. Dukart, Physics International Technical Report No. PITR-1549A (1984). Order by PAPS number and journal reference from American Institute of Physics, Physics Auxiliary Publication Service, Carolyn Gehlbach, 500 Sunnyside Boulevard, Woodbury, NY 11797-2999. Fax: 516–576–2223, e-mail:janis@aip.org. The price is $1.50 for each microfiche (98 pages) or $5.00 for photocopies of up to 30 pages, and

$0.15 for each additional page over 30 pages. Airmail additional. Make checks payable to the American Institute of Physics.

[14] J. P. Apruzese, in *Proceedings of the 4th International Colloquium on X-Ray Lasers*, Williamsburg, VA, 1994 (American Institute of Physics, New York, in press).

[15] E. J. McGuire, K. Matzen, R. Spielman, M. A. Palmer, B. A. Hammel, D. L. Hansen, T. W. Hussey, W. W. Hsing, and R. J. Dukart, J. Phys. C **6**, 81 (1986).

[16] S. Stephanakis, J. P. Apruzese, P. G. Burkhalter, G. Coopertein, J. Davis, J. D. Hinshelwood, G. Mehlman, D. Mosher, P. Ottinger, V. E. Scherrer, J. Thornhill, B. Welch, and F. C. Young, IEEE Trans. Plasma Sci. **PS-16**, 496 (1988).

[17] N. Qi, D. A. Hammer, D. H. Kalantar, and K. C. Mittal, Phys. Rev. A **47**, 2253 (1993).

[18] J. L. Porter, R. B. Spielman, M. K. Matzen, E. J. McGuire, L. E. Ruggles, M. F. Vargas, J. P. Apruzese, R. W. Clark, and J. Davis, Phys. Rev. Lett. **68**, 796 (1992).

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

[20] H. Conrads, Z. Phys. **444**, 200 (1967); P. Bogen, H. Conrads, G. Gatti, and W. Kohlhaas, J. Opt. Soc. Am. **58**, 203 (1968).

[21] S. M. Zakharov, A. A. Kolomenskii, A. A. Pikuz, and A. I. Samokhin, Pis'ma Zh. Tekh. Fiz. **6**, 1135 (1980) [Sov. Tech. Phys. Lett. **6**, 486 (1980)].

[22] R. A. McCorkle, Appl. Phys. A **26**, 261 (1981).

[23] C. Steden and H.-J. Kunze, Phys. Lett. A **151**, 1536 (1990).

[24] J. J. Rocca, M. C. Marconi, and F. G. Tomasel, IEEE J. Quantum Electron. **QE-29**, 182 (1993).

[25] J. J. Rocca, M. C. Marconi, B. T. Szapiro, and J. Meyer, SPIE J. **1551**, 275 (1991).

[26] C. A. Morgan, H. R. Griem, and R. C. Elton, Phys. Rev. E **49**, 2282 (1994).

[27] H. J. Shin, D. E. Kim, and T. N. Lee, Phys. Rev. E **50**, 1376 (1994).

[28] W. Hartman, H. Bauer, J. Christiansen, K. Frank, H. Kuhn, M. Stetter, R. Tkotz, and T. Wagner, Appl. Phys. Lett. **58**, 2619 (1991).

[29] S. Glenzer and H.-J. Kunze, Phys. Rev. E **49**, 1586 (1994).

[30] J. J. Rocca, B. T. Szapiro, C. Cortázar, F. G. Tomasel, M. C. Marconi, J. Hung, and K. Floyd, in *Proceedings of the 3rd International Colloquium on X-Ray Lasers*, Schliersee, Germany, 1992 (Institute of Physics, Bristol, UK, 1992), p. 427.

[31] E. P. Ivanova, L. V. Knight, A. M. Panin, and B. G. Peterson, in *Proceedings of the International Conference on Lasers '92*, Houston, TX, 1992 (STS Press, McLean, VA, 1993).

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

[33] J. J. Rocca, O. D. Cortázar, F. G. Tomasel, and B. T. Szapiro, Phys. Rev. E **48**, R2378 (1993).

[34] J. J. Rocca, V. N. Shlyaptsev, F. G. Tomasel, O. D. Cortázar, D. Hartshorn, and J. L. A. Chilla, Phys. Rev. Lett. **73**, 2192 (1994).

[35] G. J. Linford, E. R. Peressini, W. R. Sooy, and M. L. Spaeth, Appl. Opt. **13**, 379 (1974).

[36] R. A. London, Phys. Fluids **31**, 184 (1988).

[37] V. N. Shlyaptsev, A. V. Gerusov, A. V. Vinogradov, J. J. Rocca, O. D. Cortázar, F. Tomasel, and B. Szapiro, SPIE J. **2012**, 99 (1993).

[38] R. C. Elton, R. U. Datla, J. R. Roberts, and A. K. Bathia, Phys. Rev. A **40**, 4142 (1989).

[39] J. Nielsen, B. J. MacGowan, L. B. Da Silva, and J. C. Moreno, Phys. Rev. A **48**, 4682 (1993).

[40] D. Potter, Nucl. Fusion **18**, 813 (1978).

[41] T. Boehly, M. Russotto, R. S. Craxton, R. Epstein, B. Yaakobi, L. B. Da Silva, J. Nilsen, E. A. Chandler, D. J. Fields, B. J. MacGowan, D. L. Matthews, J. H. Scofield, and G. Shimkaveg, Phys. Rev. A **42**, 6962 (1990).

[42] J. Nilsen, J. A. Koch, J. H. Scofield, B. J. MacGowan, J. C. Moreno, and L. B. Da Silva, Phys. Rev. Lett. **70**, 3713 (1993).

[43] A. V. Vinogradov and V. N. Shlyaptsev, Sov. J. Quantum Electron. **13**, 303 (1983).

[44] F. C. Young, S. J. Stephanakis, V. E. Scherrer, B. L. Welch, G. Mehlman, P. G. Burkhalter, and J. P. Apruzese, Appl. Phys. Lett. **50**, 1053 (1987).

[45] M. D. Rosen, in *Short Wavelength Coherent Radiation: Generation and Applications*, edited by P. H. Buchsbaum and N. M. Ceglio (Optical Society of America, Washington, DC, 1991), Vol. 11, p. 73; L. B. Da Silva, B. J. MacGowan, D. L. Matthews, M. D. Rosen, H. A. Baldis, G. D. Enright, B. LaFontaine, and D. M. Villeneuve, SPIE J. **1229**, 128 (1990).

[46] J. Nilsen, B. J. McGowan, L. B. Da Silva, and J. C. Moreno, Phys. Rev. A **42**, 4682 (1993); J. Nilsen, B. J. McGowan, L. B. Da Silva, J. C. Moreno, J. A. Koch, and J. H. Scofield, Opt. Eng. **33**, 2687 (1994).