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Progress in the Development of Table-Top Discharge-Pumped Soft X-Ray Lasers

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Abstract. The demonstration of large soft x-ray amplification in a discharge-created plasma has opened a new path to the development of compact and practical soft x-ray lasers. We review our progress in the development and study of these ultrashort wavelength lasers. The field has advanced from the first observation of large amplification in a discharge-created plasma in Ne-like Ar [J.J. Rocca, V.N. Shlyaptsev, F.G. Tomasel, O.D. Cortazar, D. Hartshorn, and J.L.A. Chilla, *Phys. Rev. Lett.* 73, 2192 (1994)], to the demonstration of an extremely compact saturated laser at 46.9 nm. In this paper we give an overview of these and other selected results. They include the observation of large amplification (gain-length product of 7.5) in Ne-like S at 60.8 nm in material ablated from a solid target by a discharge, and preliminary results of the search for gain at a shorter wavelength in Ne-like Ca. A recent study of the spatial coherence of the capillary discharge 46.9 nm Ne-like Ar laser, which provides the first experimental measurement of a monotonic increase of the spatial coherence with length in a soft x-ray amplifier, is also summarized.

1. INTRODUCTION

Following the first demonstrations of soft x-ray lasing in plasmas generated by large laser facilities in 1984 [1,2], the goal of realizing more compact and efficient soft x-ray lasers that could have widespread use in applications has received much attention. With this motivation considerable effort has been devoted to explore amplification schemes that use smaller laser drivers, leading to significant progress in the past few years [3-7]. Alternatively, it has been recognized that direct discharge excitation of the gain medium could result in increased laser efficiency and simplicity. However, in pulse-power driven plasmas a major obstacle has been axial inhomogeneities produced by non-symmetric compressions and instabilities, which result in severe distortion of the plasma column that destroys the amplification. To efficiently generate axially uniform plasma columns with the large densities of multicharged ions necessary for soft x-ray amplification we have proposed the use of fast capillary discharges [8, 9]. This approach was successful in obtaining for the first time large soft x-ray amplification in a discharge-created plasma [10], and has led to the demonstration of the first saturated table-top soft x-ray laser, in Ne-like Ar [11].

In the capillary discharge scheme an elongated, needle-like plasma with remarkable axial uniformity is created by a fast current pulse that excites preionized material contained in a capillary channel defined by insulating walls. In the fast capillary discharges we use for excitation of collisional soft x-ray lasers, the electromagnetic forces of the rapidly rising current pulse compress the plasma creating a shock wave. The current distribution is influenced by the wall plasma created by plasma radiation and heat conduction [11, 12]. Following the initial phase of the discharge, the soft x-ray emitting region of the plasma is rapidly compressed to form a plasma column 200-300 μm in diameter [13]. The optimum plasma temperature and density for lasing occur several nanoseconds before stagnation, when the first compression shock wave reaches the axis. Subsequently, the plasma density continues to increase as the plasma stagnates, and laser action ceases due to increased refraction and collisional thermalization. The high efficiency with which these fast capillary discharges can generate highly ionized plasma columns is illustrated by the remarkable similarity of the two argon spectra shown in Fig.1. The spectrum in Fig.1a) corresponds to a 43 kA, 30 ns full width at half maximum (FWHM) discharge through a 2.5-mm-diam Ar-filled capillary channel, while the spectrum in Fig. 1b) is for a 1 MA current implosion in a multi-Terawatt pulse power generator (Gamble II, see Ref. [14]). Moreover, the capillary discharge structure has the advantages of providing a very good initial plasma

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symmetry, and a short compression time which leads to stable plasma columns. This has allowed us to generate axially uniform plasma columns with a very large length-to-diameter ratio (*l/d*=500-1000) and up to 20 cm in length.

In the following two Sections we summarize laser results obtained in Ne-like Ar using these discharges, and the following Section discusses lasing in Ne-like S. Preliminary results of the search for gain in Ne-like Ca are reported in Section 5, followed by a discussion of the measurement of the spatial coherence of the Ne-like Ar laser.

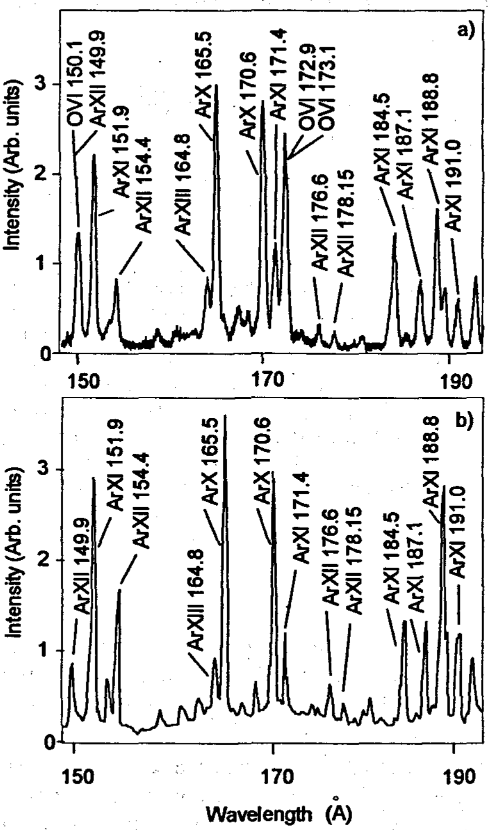

Figure 1. Argon spectra corresponding to a) 43-kA, 30-ns FWHM discharge current pulse through a 2.5-mm-diam capillary [9], b) 1 MA current implosion in the Gamble II generator [14]. Transition wavelengths are in Å.

2. AMPLIFICATION IN Ne-LIKE Ar

The first observation of large soft x-ray amplification in a discharge-pumped amplifier was realized in the *J*=0-1 line Ne-like Ar at 46.9 nm [10, 15]. In this initial experiment a fast discharge, having a half-period of 60 ns and a peak current of approximately 40 kA, was used to excite Ar plasma columns in 4-mm-diameter channels drilled in polyacetal. The capillary channel was placed in the axis of a 3 nF liquid-dielectric circular-parallel-plate capacitor. The capacitor was charged by a Marx generator and rapidly discharged through the capillary channel by closing a spark gap switch pressurized with SF_6. The gain at 46.9 nm was determined by measuring the integrated line intensity as a function of plasma column length. The spectra of Fig. 2 show the dramatic increase of the laser line intensity as a function of capillary length. In the spectrum of the 3-cm-long capillary, the intensity of the *J*=0-1 line of the Ne-like Ar is observed to be smaller than the intensity of the surrounding lines. In the 6-cm-long capillary amplification makes this line more intense than the many neighboring lines, and in the 12-cm-long plasma column the laser line totally dominates the spectrum. Analysis of the data of this first experiment yielded a gain coefficient of 0.6 cm^{-1} and a gain-length product of 7.2 for the 12-cm-long capillaries. As summarized in the next Section, subsequent experiments conducted utilizing longer plasma columns under optimized discharge conditions and double-pass amplification yielded an effective gain-length product of 27, the largest reported to date for a table-top soft x-ray amplifier [11]. Also, spectra we obtained for different capillary lengths in the wavelength region corresponding to the *J*=2-1 line of Ne-like Ar at 69.8 nm showed a supralinear increase of this line, indicative of gain. However, the gain in this line was much smaller than for the *J*=0-1 line [15], and a significant increase in the amplification is still required to make it of practical interest. Small amplification in this line in a capillary discharge was more recently also observed by Hildebrand *et al.* [16].

3. SATURATED OPERATION OF THE Ne-LIKE Ar AMPLIFIER

A major step in the development of compact ultrashort wavelength lasers consists in saturating the gain in the amplifier and in demonstrating substantial output energies. At this condition, which occurs when the laser intensity reaches the saturation intensity, an important fraction of the energy stored in the laser's upper level can be extracted. Depending on the specific amplifier characteristics, this amounts to overcome barriers that are imposed by the small gain volumes and short plasma lengths, by the short duration of the gain, or by plasma inhomogeneities and limiting refraction effects. To reach gain saturation in our discharge-pumped Ne-like Ar laser we conducted experiments in longer plasma columns, and used an iridium mirror to implement double-pass amplification measurements. This resulted in the first clear observation of gain saturation in a table-top soft X-ray amplifier [11, 17].

The experiments were conducted exciting 4-mm-diam capillaries filled with 700 mTorr of Ar gas with currents pulses of approximately 39 kA peak current having a half cycle duration of about 70 ns. A detection system consisting of a 2.2 m grazing incidence spectrograph with a microchannel plate (MCP) intensified CCD array detector was used to measure the relative variation of the laser energy as a function of plasma column length. Absolute measurements of the laser output pulse energy were performed using a fast vacuum photodiode having a calibrated Al photocathode [11]. The results of single-pass amplification measurements for capillary plasma columns up to 15.8 cm in length are shown as open circles in Fig. 3. At these discharge conditions, the energy of the laser pulse is observed to increase exponentially for lengths up to about 12 cm, where it begins to saturate. A fit of the data corresponding to plasma columns up to 11.5 cm with the Linford formula [18] yields a gain coefficient of 1.16 cm^{-1}. Saturation of the intensity is observed at gain-length products of about 14. Laser pulse energies of 6 μJ were measured to exit the 15.8-cm-long plasma columns.

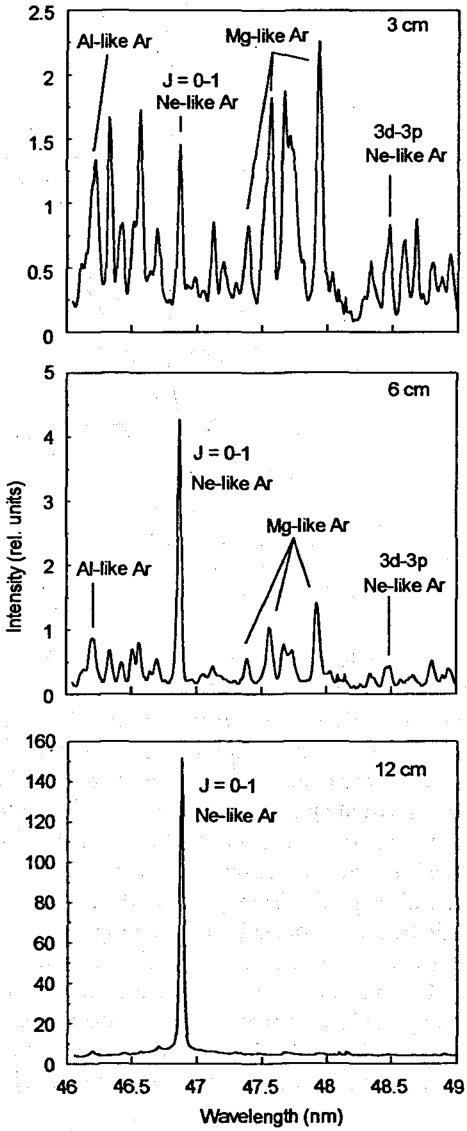

Figure 2. Axial spectra from Ar plasma columns 3-,6-, and 12-cm-long. A dramatic increase of the J=0-1 line of ArIX at 46.9 nm as a function of length is observed. The spectra correspond to 38±1 kA discharges through 4-mm-diam capillaries.

Double-pass amplification experiments allowed us to substantially increase the laser pulse energy and to study the saturation behavior for significantly longer effective plasma column lengths. The double-pass amplification measurements were performed using a flat iridium mirror for two different plasma column lengths: 9 and 14 cm. In the 9-cm-long capillaries the laser intensity enhancement due to the mirror was measured to be 63x. In contrast, the enhancement observed in the 14-cm-long capillaries was in the average only 8x. This behavior is indicative of saturation of the amplification in the second pass. The increase in the laser energy measured in the double-pass experiments in the 14-cm-long capillaries corresponds to laser pulse energies of up to 30 μJ and to beam intensities larger than the computed saturation intensities of 56-78 MW/cm^2. The saturation intensity was calculated considering an ion temperature of 100 eV, and an effective-to-radiative lifetime ratio for the laser upper level between 20 and 30 for plasma densities of 5-8x10^{18} cm^{-3}, as computed by our magnetohydrodynamic calculations for these discharge conditions [11].

The measured saturation behavior is in good agreement with the result of two independent radiation

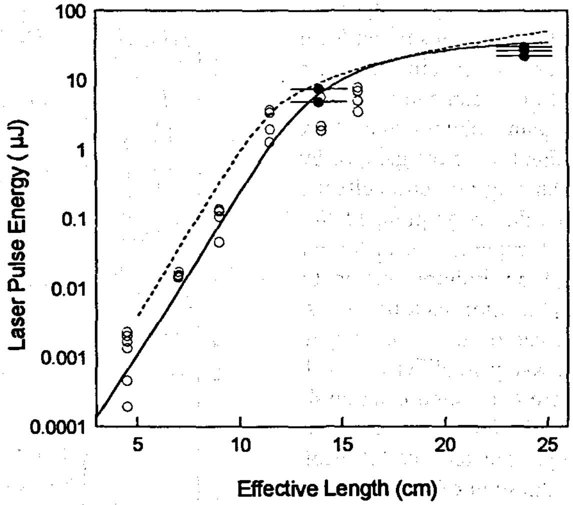

Figure 3. Measured and computed 46.9 nm laser output energy as a function of capillary discharge plasma column length. Single- and double-pass measurements are indicated by open and full circles, respectively. The solid line is the result of simple radiation transport calculations assuming parabolic gain and density profiles. The dashed line was computed with a hydrodynamic/atomic physics code.

transport models for the capillary plasma columns. Computations of the variation of the laser energy as a function of plasma column length were conducted by solving the radiation transport equation for an inhomogeneously broadened transition, taking into account line narrowing, refraction effects, and gain saturation. It should be noticed that consideration of refraction losses is essential to adequately describe the measured energy dependence on plasma column length. The solid line in Fig. 3 is the result of calculations performed assuming parabolic gain and density profiles, while the dashed line correspond to computations conducted for the time dependent electron density and gain profiles obtained from magnetohydrodynamic and atomic physics calculations conducted with the code Radex [19]. We have also studied the influence of an externally applied axial magnetic field on the capillary discharge soft x-ray laser performance. An optimized magnetic field of about 0.15 T was observed to increase the uniformity and intensity of the soft x-ray laser beam by decreasing the plasma density gradients at the time of lasing [20].

Based on these results, we have succeeded in developing a very compact saturated 46.9 nm laser of size comparable with that of many widely utilized visible and ultraviolet gas lasers. This laser generates subnanosecond pulses with energies up to 25 μJ and with a beam divergence that varies between 3.5 and 6.5 mrad depending on the discharge conditions [21].

4. DEMONSTRATION OF LASING IN VAPOR CREATED BY ABLATION OF A SOLID MATERIAL: AMPLIFICATION IN Ne-LIKE S

Recently, we have also demonstrated lasing in the J=0-1 transition of Ne-like sulfur ions at 60.8 nm in vapor produced by discharge ablation of a solid target [22]. This result is of particular interest because it shows the feasibility of also obtaining ultrashort wavelength amplification by discharge excitation in materials that are solid at room temperature. For this experiment our original discharge setup [9] was modified to allow the injection of the sulfur vapor into the capillary channel through a hole in the ground electrode. The sulfur vapor was produced ablating the wall of a 5-mm-diam, 2-cm-long secondary capillary channel drilled in a sulfur rod with a slow current pulse delivering 200 J in about 50 μs. The vapor generated by this capillary discharge was injected into the main capillary channel and was subsequently excited by a fast current pulse of 35-37 kA peak amplitude to generate a narrow plasma column with the necessary conditions for amplification.

Under optimized conditions, strong lasing was expected to occur in the $3s\ ^1P^0_1$ - $3p\ ^1S_0$ line,.as is the case in the discharge pumped Ne-like Ar laser [10]. This J=0-1 line has been accurately identified at 60.84 nm in spectra obtained from laser-created sulfur plasmas [23], and has recently been observed to lase in laser-created plasmas generated using the Asterix iodine laser facility at the Max Planck Institute for Quantum Optics [24]. Figure 4 shows a spectrum obtained under optimized laser conditions in the spectral region spanning from 58.8 to 61.2 nm using a tin filter. The spectrum corresponds to a 37 kA discharge through a 4-mm-diam, 16.8-cm-long channel filled with 460 mTorr of sulfur vapor. The spectrum is completely dominated by the J=0-1 line transition of Ne-like sulfur, which appears at 60.84 ± 0.015 nm. Another line of Ne-like sulfur (the $3p\ ^1P_1$ - $3d\ ^1P^0_1$ transition at 60.12 nm [23]), that in absence of amplification should have similar intensity, also falls in the spectral range of Fig. 4. The fact that in our plasma column the intensity ratio of these two lines is observed to be at least 100 is clear evidence of amplification in the J=0-1 line.

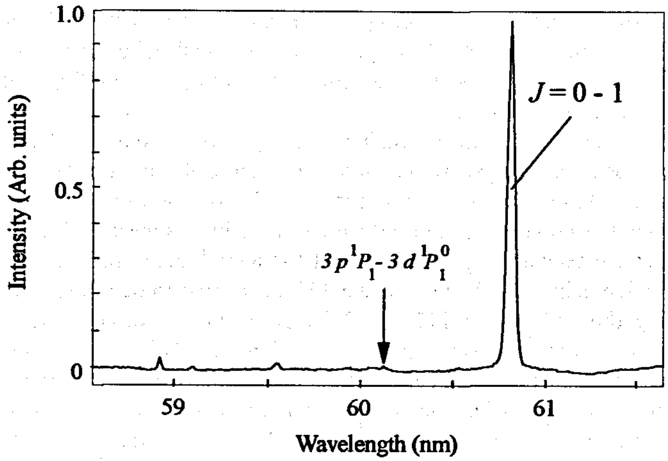

Figure 4. Spectrum of the axial emission of the sulfur plasma column in the region between 58.5 and 61.5 nm. The spectrum corresponds to a 37 kA discharge through a 4-mm-diam, 16.8-cm-long capillary filled with 460 mTorr of ablated sulfur vapor. The $3s\ ^1P^0_1$ - $3p\ ^1S_0$ line of Ne-like sulfur completely dominates the spectrum, while the 60.12 nm $3p\ ^1P_1$ - $3d\ ^1P^0_1$ line of the same ion, that in absence of amplification should have similar intensity, is not observed.

Figure 5 shows the measured variation of the integrated line intensity of the J=0-1 line of Ne-like sulfur as a function of plasma column length. An increase of about 1.6 in the plasma column length is observed to increase the integrated intensity of the line by a factor 13. This corresponds to a gain coefficient of 0.45 cm^{-1}, and a gain-length product of 7.55 for 16.8-cm-long capillaries. Strong amplification was observed for a broad range of pressures, from 300 to 700 mTorr and for currents between 33 and 38 kA.

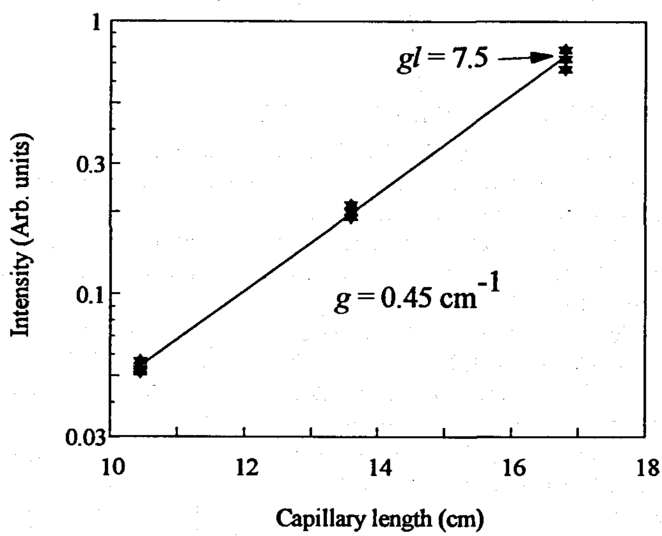

Figure 5. Variation of the integrated intensity of the J=0-1 line of Ne-like sulfur as a function of plasma column length. The line is a fit with the Linford formula [18], which results in a gain coefficient of 0.45 ± 0.01 cm^{-1}, and to a gl product of 7.5 ± 0.15 for the 16.8-cm-long plasma column.

Lasing occurs shortly before stagnation of the plasma column, as in the case of Ne-like Ar [11]. The region of gain is a narrow plasma column of about 0.03 cm in diameter surrounded by a lower-density plasma containing sulfur ions of a lower degree of ionization, which in turn is surrounded by material ablated from the capillary walls. The deceleration of the plasma column near the axis prior to stagnation results in a velocity gradient that, due to motional Doppler broadening, considerably facilitates the radial escape of the lower laser level radiation. At the time of lasing, which for our discharge conditions is observed to occur near the time of maximum current, the electron density and temperature in the gain region are computed to be about 2-3x10^{18} cm^{-3} and 60-80 eV, respectively. As described below, this temperature corresponds to a plasma that is overheated with respect to the temperature range T_e=20-40 eV for maximum Ne-like sulfur abundance in a steady-state plasma.

According to the approximate scaling laws of atomic kinetics valid for lasing in Ne-like ions in steady-state conditions the gain scales for ions of charge Z approximately as $G \sim Z^{4.5}$ [25]. Consequently for sulfur, a gain ~3 times smaller than that for the J=0-1 line of argon could be estimated. As mentioned above, in the case of the J=0-1 line of argon the effective gain was measured to reach 1.16 cm^{-1} [11], value that is smaller than the maximum computed gain of 1.5-1.8 cm^{-1} due to refraction. According to the above scaling law the effective gain in Ne-like sulfur would be expected to be rather small, less than 0.3 cm^{-1}. Our computations using the code Radex [12, 19, 26] indicate important contributions to the generation of the population inversion by plasma overheating and transient population effects. Due to the exponential dependence of the excitation rates on the electron temperature, a larger population inversion and, consequently a larger gain, arises from overheating. Such overheating of the plasma respect to steady-state ionization conditions can be more easily achieved in low-Z elements like sulfur, due to a large decrease of the ionization time with ion charge. In addition, in this sulfur laser transient population effects are found to play a more important role than in the argon laser. A transient increase in the population inversion can arise when the characteristic time of the rise of the excitation is of the order of the effective lifetime of the laser upper level [27]. While in these relatively long-lived discharge plasmas transient effects are not nearly as dramatic as in plasmas produced by subpicosecond lasers [4], their contributions to the gain can be noticeable. The computations indicate that, in the case of sulfur, transient population effects can increase the gain by 20-40%. As a result of plasma overheating and transient population effects the maximum gain in the J=0-1 line of Ne-like sulfur is computed to approach 1 cm^{-1}, a value which taking into account refraction losses is in satisfactory agreement with the measured effective gain of 0.45 cm^{-1}.

5. SEARCH FOR GAIN IN Ne-LIKE Ca

The natural extension of the work summarized in the previous Sections is the search for gain in capillary plasmas at shorter wavelengths [15]. The demonstration of lasing in Ne-like sulfur at 60.8 nm showed the feasibility of obtaining amplification by collisional excitation in discharge-created plasmas produced by ablation of solid targets. To obtain lasing by collisional excitation at wavelengths shorter than that of the Ne-like Ar, 46.9 nm, it is necessary to search for amplification in elements heavier than Ar [15]. We have obtained spectra of Ca plasmas with the objectives of identifying the J=0-1 line of Ne-like Ca and searching for amplification. The $3s\ ^1P^0_1$- $3p\ ^1S_0$ line of Ne-like Ca at 38.327 nm was first identified in laser created-plasmas [28], and later observed by us in a discharge-created plasma [29]. It was also observed to lase in plasmas created in the Asterix iodine laser [30].

For the calcium experiments discussed herein, capillaries were made by pressing a mixture of CaO and Ca_3N_2 powder in a 2:1 ratio to 65 MPa. Plasmas containing Ca were produced by ablating the walls of these capillaries with a slow current pulse, followed by a fast high current pulse that ionizes and compresses the plasma as in the previous experiments. Figure 6 shows a time-resolved spectrum of the axial plasma emission in the neighborhood of

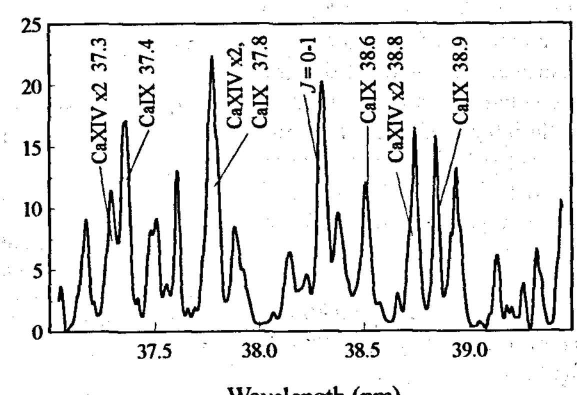

Figure 6. Time-resolved spectrum of capillary plasma containing Ca ions in the region between 37 and 39.5 nm showing line emission at 38.3 nm, the wavelength of the J=0-1 line of Ne-like calcium.

38.3 nm for a 75 kA discharge through a 3.5-mm-diam, 5-cm-long capillary channel. The first half-cycle duration of the current pulse was 56 ns. The spectrum corresponds to the emission 33 ns after the initiation of the current pulse and has a time resolution of about 5 ns. A strong line is observed at 38.33 ± 0.015 nm, which corresponds well with the wavelength of the J=0-1 laser line of Ne-like Ca. The line has an intensity comparable to that of neighboring resonant lines of CaIX (Mg-like Ca) and CaX (Na-like Ca). The second order of CaXIV (N-like Ca) lines is also observed, confirming that the plasma is sufficiently hot to create a high abundance of Ne-like Ca. Experiments with CaH_2 capillaries have yielded similar spectra, encouraging further experiments.

6. STUDY OF THE SPATIAL COHERENCE OF THE Ne-LIKE Ar LASER

Good transverse spatial coherence will be essential in realizing the full potential of these sources in some important applications. Current soft x-ray lasers face the difficulty of achieving a good coherence without the aid of an optical cavity, mainly due to their short gain duration. Measurements of the spatial coherence of laser pumped soft x-ray lasers have been reported [31-33], but most of them correspond to a single amplifier length of the particular laser studied. Several theoretical studies have been conducted to understand the spatial coherence of soft x-ray amplifiers [34-38]. In general, they predict an improvement of the coherence with amplifier length. This is the result of a decreasing number of modes guided along the amplifier column due to gain guiding and refractive anti-guiding [34]. Such build-up of the coherence is essential in achieving very good spatial coherence in cavity-less soft x-ray amplifiers. However, this monotonic increase of the spatial coherence with amplifier lengths had not been previously experimentally observed in soft x-ray lasers. We have measured a monotonic increase of the spatial coherence as a function of plasma column length in a capillary discharge soft x-ray amplifier.

The measurements were conducted in the 46.9 nm line of Ne-like Ar for capillary plasma column lengths up to 16.4 cm. The spatial coherence was measured recording the diffraction produced when the soft x-ray laser beam intersects a knife edge (Fig. 7, left) [39]. This technique has been recently utilized to observe an improvement in the coherence of a laser pumped Ne-like Zn laser when a reflecting multilayer mirror was used [40]. It has the advantage of determining in a single shot the degree of coherence for any two points on the illuminated region of the detector plane that correspond to a line perpendicular to the knife edge. The interference fringes were recorded with a gated detector consisting of the combination of a gated MCP, phosphor screen, image intensifier, and a CCD array. To conduct the measurements of the spatial coherence as a function of plasma column length, the knife edge was placed in a radial position respect to the beam. This gives a measurement of the coherence in the tangential direction. The measurements were conducted in 4-mm-diam polyacetal capillaries filled with Ar gas at pressures of 600 mTorr. The plasma was excited by current pulses of approximately 37 kA peak current, having a first half cycle duration of about 70 ns.

Figures 7a) and 7b) (right) show the measured diffraction patterns corresponding to capillaries with length between 8 and 16.4 cm. The improvement of the coherence with amplifier length is evident in the increased fringe visibility observed in the diffraction patterns corresponding to the longer plasma columns. The observed diffraction patterns compare well with those obtained numerically using the results of a wave-optics model for the generation and propagation of the radiation in the capillary plasma column, shown in Fig. 7c) (right). The model used to calculate the coherence of the beam produced by the capillary discharge soft x-ray laser is similar to that developed by Feit and Fleg [37], but takes into account the temporal variation of the electron density and of the gain coefficient, and was extended to two dimensions.

The data of Fig. 7, and that corresponding to other similar series of measurements, were analyzed to quantify the coherence function and its dependence on amplifier length. The result is shown in Fig. 8. The coherence is observed to increase monotonically with capillary length. Good agreement is observed with the result of wave-optics calculations, represented by a line in the same figure. This is, to our knowledge, the first observation of a monotonic increase of the transverse spatial coherence with amplifier length in a soft x-ray laser. For the longest capillaries studied, 16.4 cm, the coherence length in the tangential direction was determined to be about 4.5 mm in the detector plane situated at 5.89 m from the exit of the amplifier. This corresponds to an effective coherence angle of 0.8 mrad and to an effective source size of 26 μm FWHM. The total beam divergence of about 5 mrad is caused by refraction due to the electron density gradients.

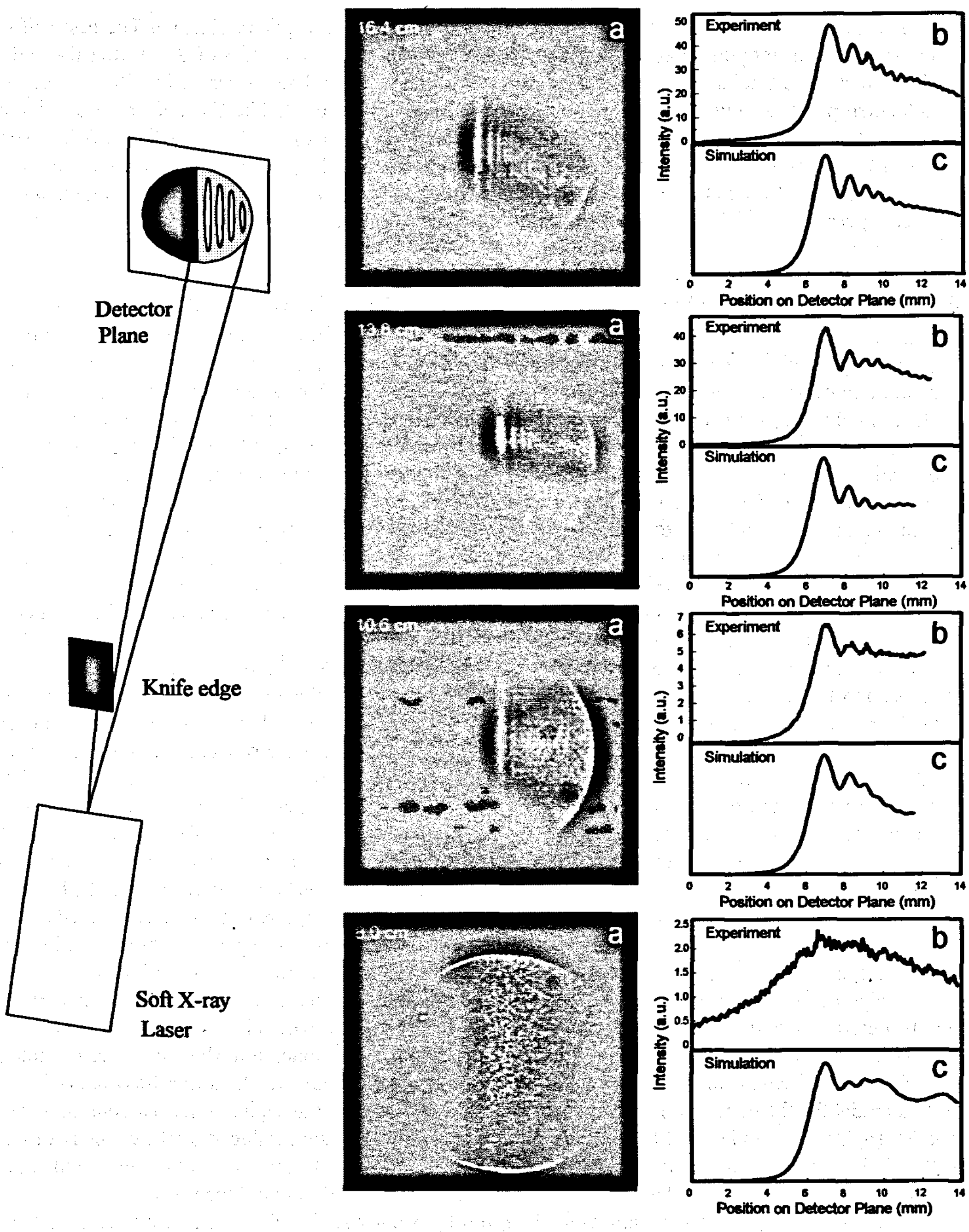

Figure 7. Left. Schematic representation of the set up used to measure the spatial coherence of the Ne-like Ar laser. The knife edge and the detector were placed at 56 cm and 589 cm from the exit of the amplifier respectively. Right a) Measured diffraction patterns corresponding to capillaries with lengths between 8 and 16.4 cm. b) Cross sections of the diffraction patterns of a) obtained by vertically integrating 50 pixels of the CCD in the region of maximum fringe visibility. c) Corresponding diffraction patterns computed using the result of the wave-optics model.

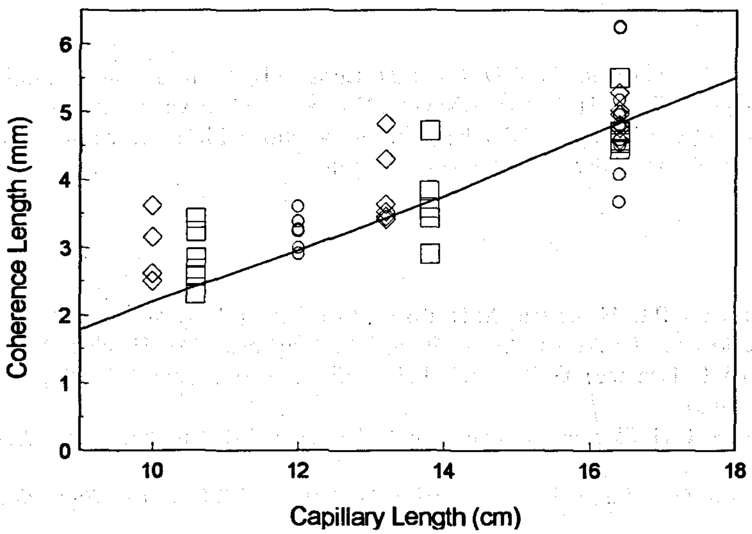

Figure 8. Variation of the coherence length in the tangential direction as a function of plasma column length. Different symbols correspond to series of measurements conducted in several identical capillaries. The line is the result of wave-model calculations.

To study the uniformity of the coherence properties across the beam profile, we performed measurements placing the knife edge in different positions relative to the laser beam. Measurementsconducted placing the knife edge along a diameter of the beam (on-axis) showed that the coherence is the same in the two orthogonal directions. Measurements off-axis showed that the coherence length in the radial direction is 30-50 % shorter than in the tangential direction. The wave-model computations suggest that a likely cause of the observed anisotropy of the spatial coherence is the change of the electron density during the laser pulse. As curves of constant phase are circles concentric with the beam, the dephasing due to a change in the curvature of the wavefront is more significant off-axis and in the radial direction. This effect is clearly shown by our simulations that use parabolic profiles and a time varying electron density. It is nevertheless possible that the observed anisotropy could be caused by a non parabolic density profile in which the curvature is radially dependent.

In summary, we have studied the spatial coherence of a discharge pumped 46.9 nm table-top amplifier for plasma columns up to 16.4 cm in length. We have observed a monotonic increase of the spatial coherence with amplifier length, in agreement with the result of wave-model computations measurement in the tangential direction yield a coherence angle of 0.8 mrad and an effective source size of 26 μm for a capillary length of 16.4 cm.

7. CONCLUSIONS

We have developed and characterized compact soft x-ray lasers based on fast discharge excitation of capillary plasmas. This was made possible by capillary discharge generation of hot and dense needle-like plasma columns of remarkable stability. A saturated 46.9 nm laser was developed by collisional excitation of Ne-like Ar and large amplification was also obtained at 60.8 nm in Ne-like S. The large amplification measured and the observed monotonic increase of the spatial coherence, both of which approach their theoretical values, are direct and clear evidence of the very high stability and uniformity of these plasma columns. These results have shattered the notion that discharge-created plasmas are insufficiently stable and uniform for soft x-ray lasing, and have opened a new road to practical soft x-ray lasers for applications.

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