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CAPILLARY DISCHARGE EXTREME ULTRAVIOLET LASERS

Progress Report

for period December 15th, 1991 - December 14th, 1992

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Capillary Discharge Extreme Ultraviolet Lasers

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Abstract

The project objective is to explore the generation of soft X-ray laser radiation in a plasma column created by a fast capillary discharge. The proposed capillary lasing scheme offers the potential for compact, simple and efficient soft X-ray laser sources. For this purpose we constructed a compact, fast pulse generator which produces 100 kA current pulses with a risetime of 11 ns. Initial experiments were conducted in evacuated capillaries, in which the plasma is produced by ablation of the capillary walls. We studied the soft X-ray emission from discharges in polyethylene capillary channels, to investigate the possibility of amplification in the 3-2 transition of CVI, at λ = 18.2 nm. We have obtained time-resolved spectra in which this transition appears anomalously intense respect to the 4-2 transition of the same ion. To date, however, this phenomena could not be confirmed as gain, as the intensity of the 18.2 nm line has not been observed to exponentially increase as a function of the capillary length.

Encouraging results have been obtained by fast pulse discharge excitation of capillaries filled with preionized gas. High temperature (Te > 150 eV), small diameter (~200 μm) plasma columns have been efficiently generated. Fast current pulse excitation of a selected low mass density of uniformly preionized material filling the capillary was observed to rapidly detach the plasma from the capillary walls, forming a plasma channel of a diameter much smaller and significantly hotter than those produced by a similar current pulse in evacuated capillaries of the same size. Discharges in argon-filled capillaries at currents between 20 and 60 kA produced plasmas with ArX-ArXIV line emission, and with spectra that are similar to those of plasmas generated by ≥ 1 MA current implosions in large pulsed power machines. The characteristic of these plasmas approach those necessary for soft X-ray amplification in low Z elements.

Publications

1. "Fast Discharge Excitation of Small Scale Soft X-Ray Lasers", J.J. Rocca, B.T. Szapiro, D. Cortázar, F.G. Tomasel, M.C. Marconi, J. Hung and K. Floyd. To be published in Proceedings of the Third International Colloquium on X-Ray Lasers. May 18-22, 1992, Schliersee (Germany).

2. "Study of the Soft X-Ray Emission from Carbon Ions in a Capillary Discharge", J.J. Rocca, M.C. Marconi and F. Tomasel. Accepted for publication in IEEE Journal of Quantum Electronics.

3. "Generation of Hot (Te>150 eV) Capillary Plasma Columns for Soft X-Ray Amplification", F.G. Tomasel, J.J. Rocca, D. Cortázar, B. Szapiro and K. Floyd. Thirty-fourth Annual Meeting of the Division of Plasma Physics. November 16-20, 1992, Seattle (Washington).

4. "Towards Small Scale Soft X-Ray Lasers Excited by Fast Capillary Discharges", J.J. Rocca, B. Szapiro, D. Cortázar, F.G. Tomasel, J. Hung, J. Meyer and K. Floyd. Invited paper in the IEEE Laser & Electro-Optics Society 1992 Annual Meeting. November 15-20, 1992, Boston (Massachusetts).

5. "Soft X-Ray Radiation of H-Like and Li-like Ions in a Fast, High Power Capillary Discharge", J.J. Rocca, B. Szapiro, D. Cortázar, F. Tomasel, J. Hung and K. Floyd. 1992 IEEE International Conference on Plasma Science. June 1-3, 1992, Tampa (Florida).

6. "Fast Discharge Excitation of Hot Capillary Plasmas for Soft X-Ray Amplifiers", J.J. Rocca, O.D. Cortázar, B. Szapiro, K. Floyd and F.G. Tomasel. Submitted for publication (August 1992).

7. "Experiment on Soft X-Ray Laser Development in a Table-top Capillary Discharge", J.J. Rocca, M.C. Marconi, B.T. Szapiro and J. Meyer. In *Ultrashort Wavelength Lasers*, SPIE Vol. 1551, 275 (1991).

8. "Progress Towards the Development of a Compact Capillary Discharge Soft X-Ray Lasers, J.J. Rocca, M.C. Marconi, B.T. Szapiro and J. Meyer. In *Short Wavelength Coherent Radiation: Generation and Applications*, OSA Proceedings Vol. 11, 106 (1991).

9. "Soft X-Ray Emission Spectroscopy of a High Power Capillary Discharge for a Recombination Laser Scheme", J.J. Rocca, B. Szapiro, M.C. Marconi, O.D. Cortázar, J. Meyer and F.G. Tomasel. 1991 Annual Meeting of the Division of Plasma Physics. November 4-8, 1991, Tampa (Florida).

10. "Study of the Soft X-Ray Emission from Carbon Plasmas Excited by Fast Capillary Discharges", B. Szapiro, J.J. Rocca, M.C. Marconi, D. Cortázar and F. Tomasel. 44th

Annual Gaseous Electronics Conference. October 22-25, 1991, Albuquerque (New Mexico).

11. "Experiments on a Capillary Discharge Soft X-Ray Scheme", J.J. Rocca, M.C. Marconi, B.T. Szapiro, O. Buccafusca and J. Meyer. Conference on Quantum Electronics Laser Science. May 12-17, 1991, Baltimore (Maryland).

Fast Discharge Excitation of Hot Capillary Plasmas for Soft X-Ray Amplifiers

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Abstract

High temperature ($T_e > 150$ eV), small diameter (~200 μm) plasma columns have been efficiently generated by very fast (11 ns risetime, 25 ns FWHM) pulsed discharge excitation of capillary channels filled with preionized gas. Discharges in argon filled capillaries at currents between 20 and 60 kA produced plasmas with ArX - ArXIV line emission, in which the degree of ionization was controlled by the magnitude of the current pulse. The characteristics of these plasmas differ from those created in evacuated capillaries and approach those necessary for soft x-ray amplification in low Z elements.

In this communication we report the efficient generation of hot ($T_e > 150$ eV) plasma columns of small diameter (~200 μm) by fast current pulse excitation of capillary channels filled with preionized gas. These plasmas are of smaller diameter and significantly hotter than those observed in evacuated capillaries excited by a similar current pulse. Soft x-ray spectra from argon plasmas created by these relatively compact capillary discharges at currents $I < 60$ kA are similar to those of plasmas generated by ≥1 MA current implosions in large pulsed power machines. This efficient generation of highly ionized capillary plasma columns can potentially impact the development of small-scale soft X-ray lasers.

Capillary discharges have been initially studied as sources of soft X-ray radiation for spectroscopy, X-ray lithography and microscopy [1-3]. More recently these discharges have been proposed as gain medium for compact, high efficiency soft x-ray lasers [4]. Recombination and collisional excitation laser schemes both require the generation of hot, highly ionized plasma columns with a large optical length in order to achieve a significant amplification. The recombination scheme, in addition, requires rapid cooling of the plasma. A small plasma diameter is also crucial in both cases to avoid quenching of the population inversion by trapping of resonant radiation.

The possibility of obtaining soft X-ray amplification by plasma recombination in a capillary discharge has recently motivated several experimental studies of the soft x-ray emission from evacuated polyacetal and polyethylene capillaries 0.5-1 mm in diameter [5-8]. Spectra from these experiments are consistent with plasma temperatures in the range of 15-70 eV. In evacuated capillaries the discharge starts by surface flashover on the capillary walls, and the plasma column is composed of material ablated from the capillary walls. In discharges such as those in the experiments mentioned above, in which the risetime of the current pulse was ≥ 50 ns, the plasma remains coupled to the walls during the course of the current pulse. The material injected into the plasma by wall ablation and the electron heat conduction from the plasma column to the walls limit to relatively low values the temperature that can be achieved. An increase of the excitation current does not necessarily result in a significantly higher plasma temperature, as an increase in the discharge energy results in more ablated material and in a higher plasma density. In effect, high current pulses (500 kA) of 300 ns risetime injected through narrow capillary channels have created cold (T_e = 10 eV), high density plasmas which have been used for the study of transport coefficients in partially degenerate, strongly coupled plasmas [9].

Higher temperatures in evacuated capillaries can result from utilizing a very fast rise of the current pulse to limit the amount of material ablated from the capillary walls before the magnetic field of the current pulse compresses the plasma detaching it from the walls. High temperature plasmas, with emission from FVIII and FIX have been reported to result from the excitation of 1 mm diameter evacuated teflon capillaries with 120 kA current pulses having a fast (≤ 10 ns) risetime [10]. However, experiments we have conducted in teflon capillaries of the same diameter excited by 11 ns risetime current pulses of up to 86 kA have produced colder plasmas, with emission from FVII and FVIII. The different degree of ionization observed in the two experiments is probably not caused by the difference in peak currents, but more likely by the specific shape of the current pulse, which determines the amount of mass ablated at the onset of the discharge. The characteristics of the plasmas generated in evacuated capillary discharges depend on this and other conditions, such as the uniformity of the breakdown, which are difficult to control.

In the experiments reported herein hot plasma columns of diameter much smaller than the capillary diameter are generated by tailoring the conditions at the initiation of the discharge to allow for a rapid detachment of the plasma from the capillary walls. A fast rising current pulse encounters a selected low mass density of uniformly preionized material filling the capillary. The rapid compression that results produces a highly ionized plasma column which is shown to be of smaller diameter and significantly hotter than those produced by a similar current pulse in evacuated capillaries of the same size.

The development of the discharges in the capillaries filled with the preionized gas resembles the formation of a compressional z-pinch by a rapidly rising current pulse [11-14]. However, in the capillaries the initial diameter of the plasma is nearly an order of magnitude smaller than those commonly used in low density z-pinch experiments, and hot plasmas with small diameters are produced utilizing only modest discharge energies. The argon spectra reported herein for currents $I < 60$ kA resemble those of argon plasmas produced by mega-amp driving currents in the Gamble II and Python multiterawatt pulse generators [12,15].

The experiments were conducted utilizing a recently developed high voltage fast pulse generator which produces current pulses having a 10 to 90% risetime of 11 ns and a full width at half maximum of 25 ns. The pulse generator and capillary discharge set up are schematically illustrated in Figure 1. The capillary is in the axis of a 3 nF circular, parallel plates capacitor containing ethylene glycol as dielectric. The capacitor was charged by a 7 stage, 700 kV, Marx generator. The capillaries were excited by discharging this capacitor through a low inductance circuit which includes the capillary and a spark gap switch controlled with SF_6. The current pulse was monitored with a Rogowski coil having a response time of less than 2 ns. To conduct the experiments reported herein the pulse generator was designed to also produce a preionization pulse with a current of 20-40 A and a duration of approximately 2 μs immediately preceding the fast discharge pulse. The studies were conducted in polyacetal and in teflon capillary channels having either 1 cm or 5 cm in length and diameters of 1.5 mm and 2.5 mm. The capillaries were evacuated to a pressure below 2×10^{-5} Torr and argon gas was injected shortly before the initiation of the current pulse utilizing a fast valve. Several hundred shots were fired in a single 2.5 mm polyacetal capillary without observing any significant sign of deterioration of the capillary structure.

The axial soft X-ray emission from the plasma was observed through a hole in the anode electrode. The radiation from the plasma was collected and focused in the slit of a 1 m grazing incidence vacuum spectrograph by a gold coated cylindrical mirror positioned at 86 degrees with respect to the incoming radiation. The spectrograph contained a gold coated grating ruled at 1200 lines per millimeter with a blaze angle of 1 degree. The dispersed radiation was detected by a windowless multichannel plate intensified diode array which was gated to obtain spectra with a temporal resolution of approximately 5 ns.

Figure 2 a-c shows time resolved soft X-ray spectra covering the spectral range between 150 Å and 193 Å from a 2.5 mm diameter, 1 cm long polyacetal capillary filled with approximately 100 Pa of preionized argon gas for three values of the discharge current. All the spectra shown in this Figure were obtained at the time indicated in Figure 1b, 6 ns after the peak of the current pulse. Comparison of the spectra corresponding to the different currents shows that it is possible to select the degree of ionization by varying the amplitude of the current pulse.

The spectrum in Figure 2a, which corresponds to a 23 kA current pulse, is dominated by line emission from fluorine-like argon, ArX. Emission from ArXI lines, and from OVI lines are also observed. The spectrum of a 43 kA discharge, shown in Figure 2b, corresponds to a higher degree of ionization. At this current the ArXI transitions are more intense and emission from ArXII lines is also observed. Similar spectra were observed from discharges in 5 cm long capillaries of the same diameter. The features of the 43 kA spectrum are remarkably similar to those reported for an argon z-pinch implosion driven by a 1 MA current pulse from the Gamble II generator (see Fig. 6 in Ref. 12). Figure 2c shows that further increase of the discharge current to 56 kA caused the appearance of ArXIII transitions and a decrease in the abundance of ArX.

A calculation of the ionization times of argon utilizing the ionization coefficients of Lotz [16] for the value of the electron density given below indicates that the electron temperature must be higher than 120 eV for ArXIII lines to be observed 30 ns after the beginning of the discharge current pulse, as shown by the spectra of Figure 2c. The electron density was estimated from the ratio of intensities of the 197.95 Å and 171.86 Å lines of ArXI, which is sensitive to the electron density in the range from 1×10^{17} cm^{-3} to about 1×10^{19} cm^{-3} [17]. For a 55 kA discharge in argon at about 100 Pa this intensity ratio was measured to be 0.6, corresponding to an electron density of about 5×10^{18} cm^{-3} in the region of the plasma where the ArXI emission occurs, based on computations for an optically thin plasma at 170 eV [17].

A higher degree of ionization corresponding to a hotter plasma was observed in the argon discharges conducted in a 1.5 mm capillary. The time resolved spectra of Figure 3, which corresponds to a 51 kA discharge current pulse in that capillary, shows the emission from ArXIV lines. Strong transitions corresponding to ArXIII are also observed, while the emission from ArXII lines is weak, an indication that the population of this ion nears complete ionization. Calculations of the ionization times [16] show that in this discharge the electron temperature surpasses 150 eV. These temperatures are significantly higher than those observed in evacuated capillaries excited by a similar current pulse. The spectra from discharges in evacuated teflon capillaries 1.5 mm and 2.5 mm diameter were dominated by FVII lines, and FVIII lines were either absent or extremely weak, an indication that the plasma temperature remained under 30 eV. As discussed below, time resolved soft X-ray pinhole images confirm a contrasting difference in the spatial distribution of the plasma reported herein and those of a conventional evacuated capillary discharge excited by the same current pulse.

End-on soft X-ray images of the capillary plasmas were obtained utilizing a pinhole camera consisting of a 90 μm diameter pinhole placed at 38 cm from the capillary, and a vacuum soft x-ray image intensifier consisting of a multichannel plate (MCP) and a phosphorous screen. The camera has a calculated magnification of 3, which was verified experimentally by recording the extent of the emission from a direct current low pressure helium capillary lamp 1 mm in diameter placed for the purpose of this calibration at the location of the capillary. The spectral sensitivity of the imaging camera was limited to wavelengths below approximately 350 Å by a 100 nm thick carbon foil filter placed over the pinhole and by the photoelectric emission response of the MgO coating utilized on the MCP. Two dimensional images of the plasma were recorded in photographic film. The radial intensity profile of the soft X-ray image was also recorded directly from the phosphorous screen utilizing a linear diode array detector. In both cases a temporal resolution of approximately 7 ns was obtained by gating the gain of the MCP intensifier.

Figure 4 compares the measured time integrated soft X-ray radial intensity profile from a 44 kA discharge in a 2.5 mm diameter capillary filled with pre-ionized argon to that corresponding to a vacuum discharge in the same capillary. In the first case the plasma that emits the soft x-rays occupies the central region of the capillary and has a FWHM of approximately 0.26 mm. In contrast, the soft X-ray emission from the evacuated capillary is less intense and originates from a significantly broader plasma column, having a FWHM diameter of approximately 1.1 mm.

Time resolved pinhole images describing the evolution of the argon plasma column are shown in Figure 5. All of the soft x-ray pinhole images obtained during the first half cycle of the current pulse are highly reproducible, axially symmetric and smooth, an indication that the plasma column is well behaved and free of instabilities. The fast current pulse rapidly detaches the plasma column from the capillary walls and collapse of the plasma occurs before the earliest time at which we could obtain a time resolved pinhole image, 8 ns after the peak of the current pulse. At this time, the FWHM diameter of the soft X-ray emitting region of the plasma column is measured to be approximately 0.19 mm. The diameter of the plasma column is observed to expand continuously and without disruptions to 0.42 mm by the end of the first half cycle of the current pulse. The expansion continues during the first part of the second half cycle of the current. At the time of the end of the first half cycle of the current the plasma is measured to expand at a velocity of approximately $1.5\text{x}10^7$ cm/sec. The rapid expansion phase can be of interest for the population inversions by collisional recombination. As described below, the short lived, small diameter hot capillary plasmas reported herein have characteristics that approach those necessary for amplification of soft X-ray radiation by collisional excitation of low Z ions of the Ne-like and Ni-like sequence.

The Ne-like sequence has been very successfully utilized in laser produced plasmas to generate soft X-ray lasing from electron-collisional excitation pumping of 3p-3s transitions in elements with Z as low as 22 (titanium) [18-21]. The favorable scaling to low Z of the also successful Ni-like sequence has been predicted theoretically by Hagelstein [22]. The latter ions have the advantage of requiring reduced excitation energy for lasing in a given wavelength range, and are promising laser candidates for the capillary plasmas described above. ArIX and KrIX are the two gaseous elements of the Ne-like and the Ni-like sequences for which the required plasma conditions for gain fall within the range of those of the capillary discharges described herein. To explore for gain in argon, a plasma temperature of approximately 80 eV and densities between 10^{18} and 10^{19} cm^{-3} are required. For argon, however, the predicted gains are small; a gain of 0.16 cm^{-1} has been predicted for the J=2-1 ArIX lines [23], while a gain of 2 cm^{-1} has been computed for the $(1S_0\text{-}1P_1)$, 468.9 Å line of ArIX [24]. The latter value however is probably optimistic, as the difficulty in modeling the J=0-1 transition in Ne-like ions has frequently resulted in an overestimate of the gain as compared with the experiments [25].

To estimate the gain in the 4d-4p $(^1S_0 - {}^1P_1)$, 337 Å transition of Ni-like KrIX, we utilized the three-level model developed by Hagelstein [22]. A predicted gain of 1.4 cm^{-1} results from assuming a plasma with an optimum electron density of 7.1×10^{17} cm^{-3} and an electron temperature of 100 eV, in the case in which 50 percent of the ions are in the Ni-like ground state [26]. Moreover, the plasma conditions necessary for optimum gain in heavier elements of these sequences, in which the gain are predicted to be significantly larger, appear to be within the reach of this type of discharge. Plasma temperatures of approximately 150 eV and 200 eV are required for maximum gain in the 3p-3s transition of Ne-like calcium and titanium [25], while also a temperature of approximately 200 eV and an electron density of 1×10^{19} cm^{-3} are required for Ni-like molybdenum [22].

In summary, we have demonstrated the efficient generation of hot, dense capillary plasmas with a diameter of ~ 200 μm and aspect ratios up to 250:1 by fast discharge excitation of a preionized capillary column. The fundamental elements in the development of these well behaved hot plasma columns are a small diameter capillary structure initially filled with a low mass density, plasma and a very fast risetime excitation pulse which rapidly detaches the plasma from the capillary walls. These capillary plasmas have characteristics that approach those necessary for soft x-ray amplification in low Z elements, and consequently are of interest for the development of small-scale soft X-ray amplifiers.

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FIGURE CAPTIONS

Figure 1. a) Schematic illustration of the fast capillary discharge setup.

b) Typical current pulse corresponding to a discharge through a 2.5 mm diameter, 1 cm long argon filled capillary. The mark identifies the time at which the spectra of Figures 2 and 3 were obtained.

Figure 2. Time resolved spectra of the soft x-ray emission (150 - 193 Å)from a discharge through a 2.5 mm diameter capillary filled with approximately 100 Pa of argon for three values of the excitation current. The spectra have a temporal resolution of 5 ns and were obtained 6 ns after the peak of the current pulse.

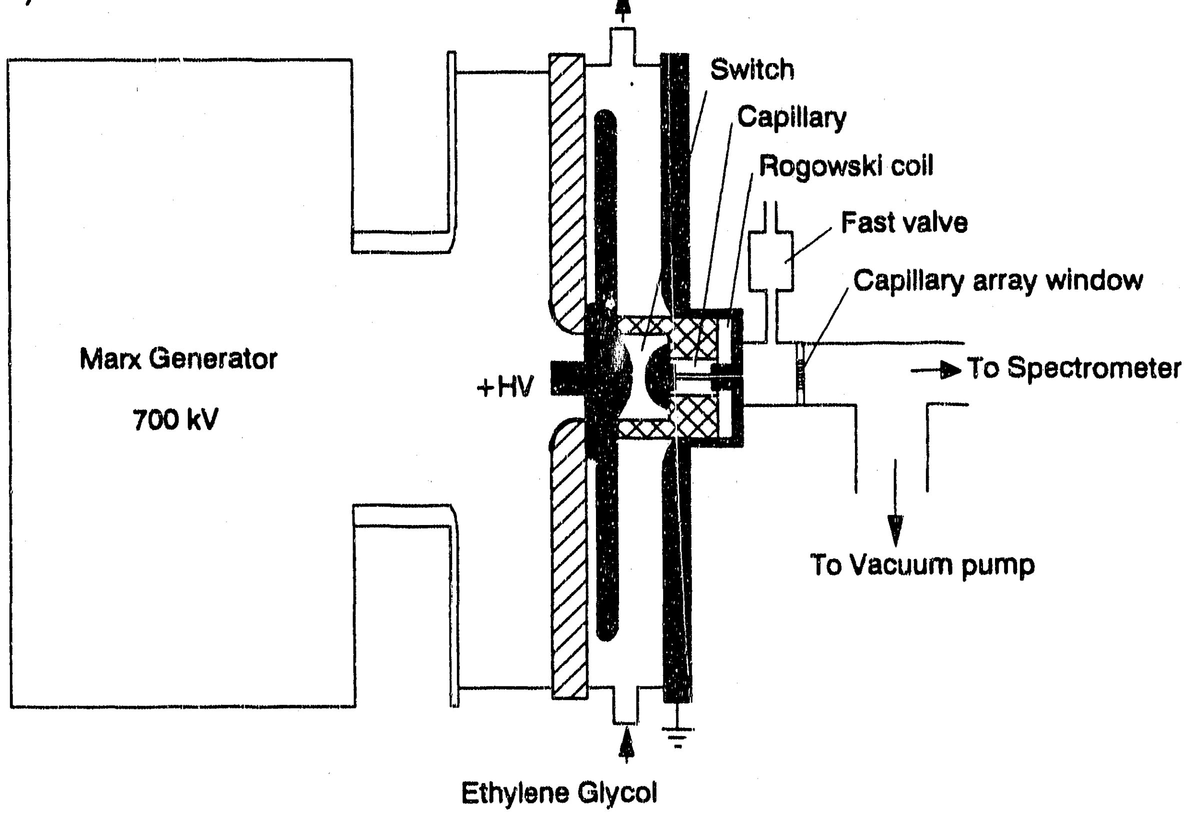
Figure 3. Time resolved spectrum of the soft x-ray emission (150 - 193 Å) from a 1.5 mm diameter capillary excited by a 51 kA current pulse. The spectra was obtained at the time indicated in Figure 1, 6 ns after the peak of the current pulse.

Figure 4. Radial intensity profiles of time integrated pinhole camera images of the axial soft x-ray emission from a 2.5 mm diameter capillary excited by a 44 kA current pulse for: a) capillary filled with approximately 100 Pa of preionized argon gas, b) evacuated capillary.

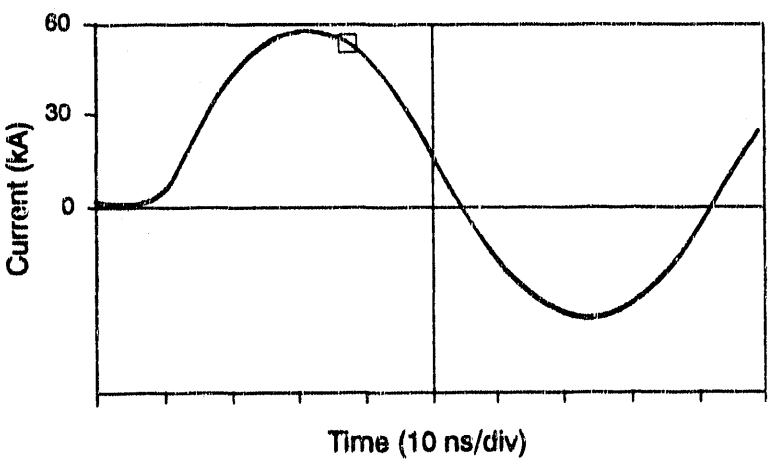
Figure 5. Radial intensity profiles from a time resolved sequence of on-axis soft x-ray pinhole images from an argon capillary discharge plasma. The discharge

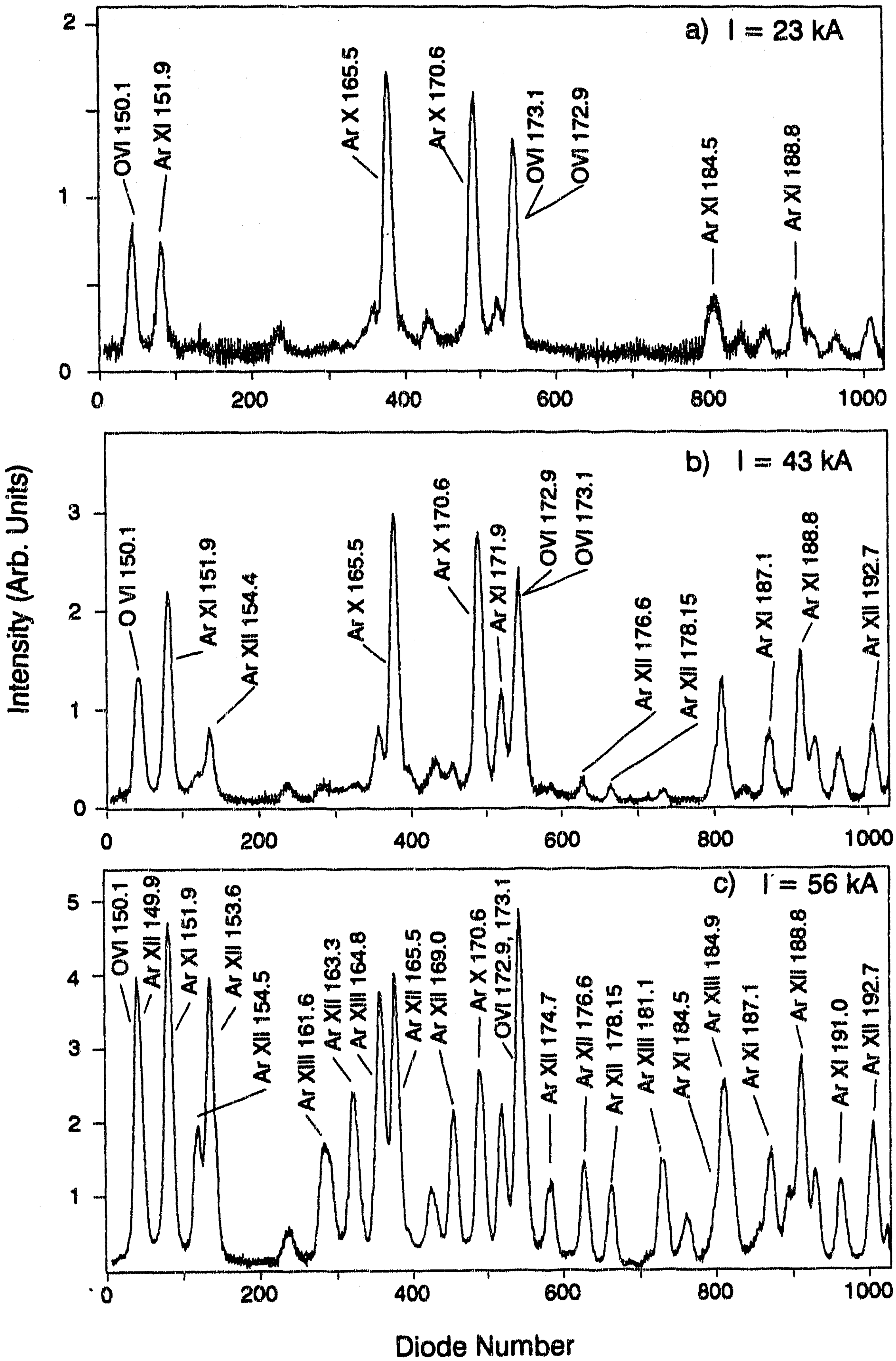
conditions are the same than those of Fig. 4a. The current pulse at the bottom of the figure illustrates the timing of each pinhole image. The times indicated are measured relative to the peak of the current pulse.

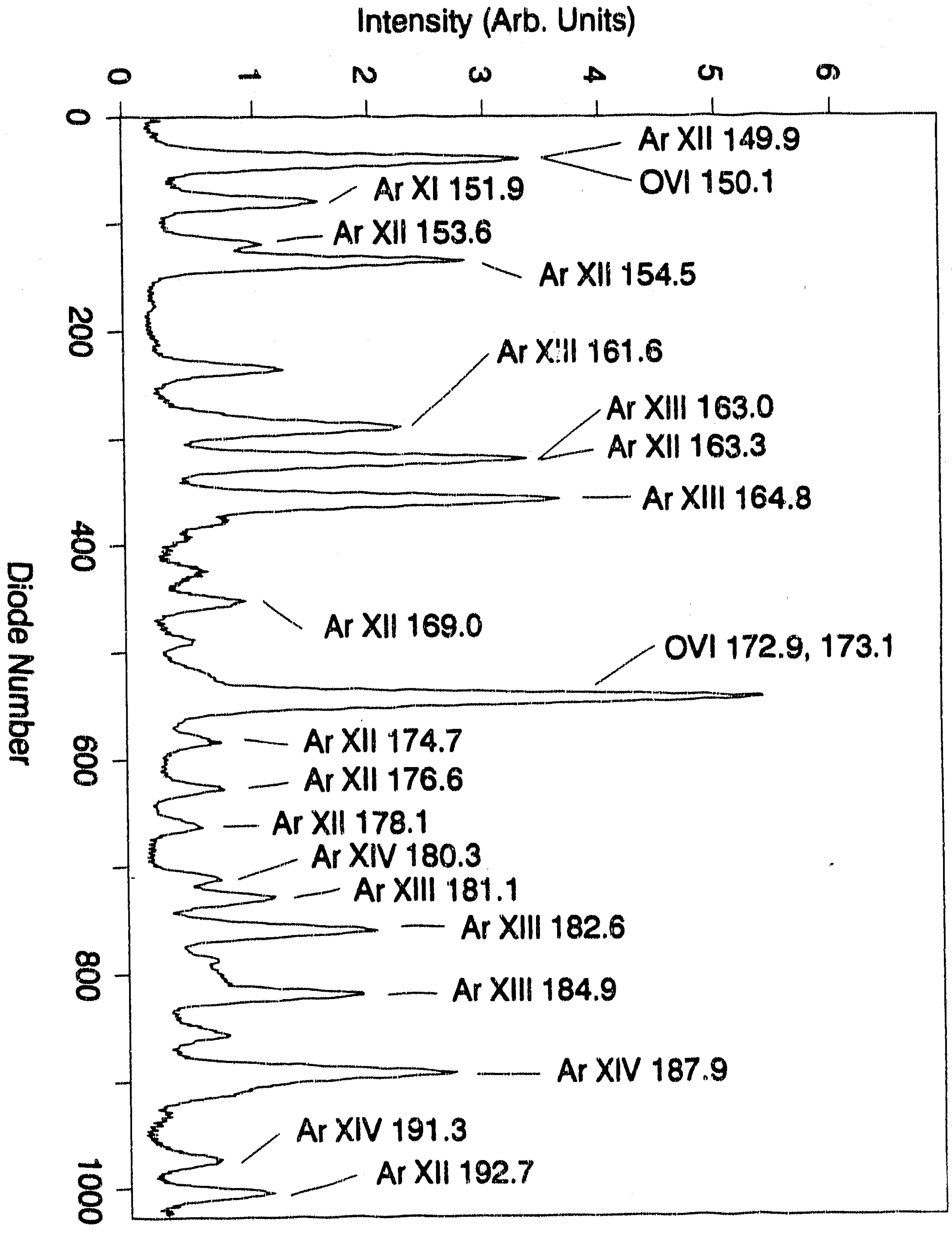
a)

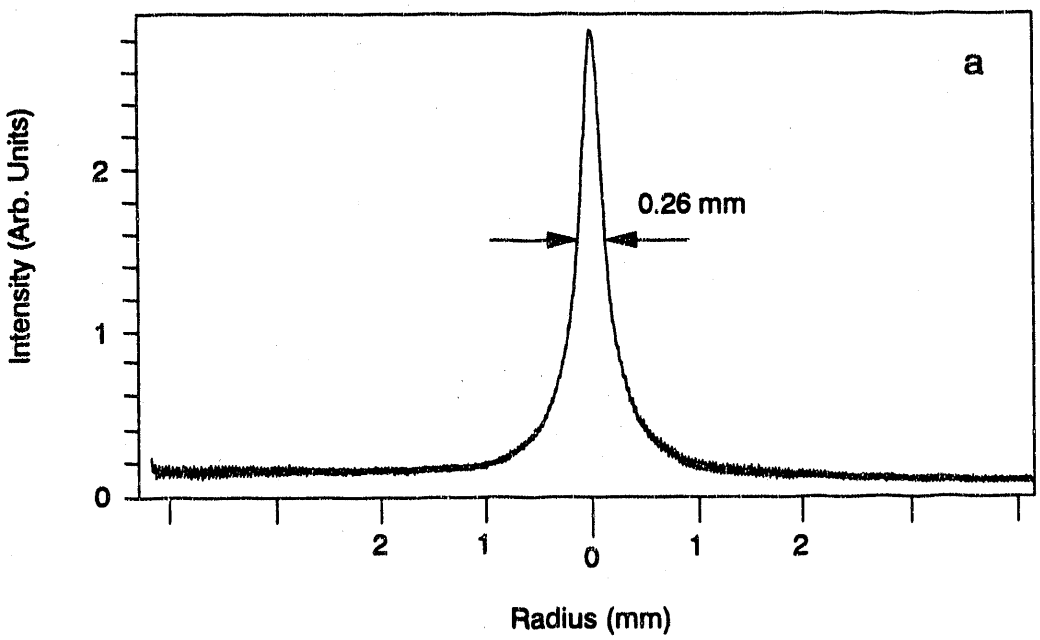

Switch
Capillary
Rogowski coil
Fast valve
Capillary array window
Marx Generator
700 kV
+HV
To Spectrometer
To Vacuum pump
Ethylene Glycol

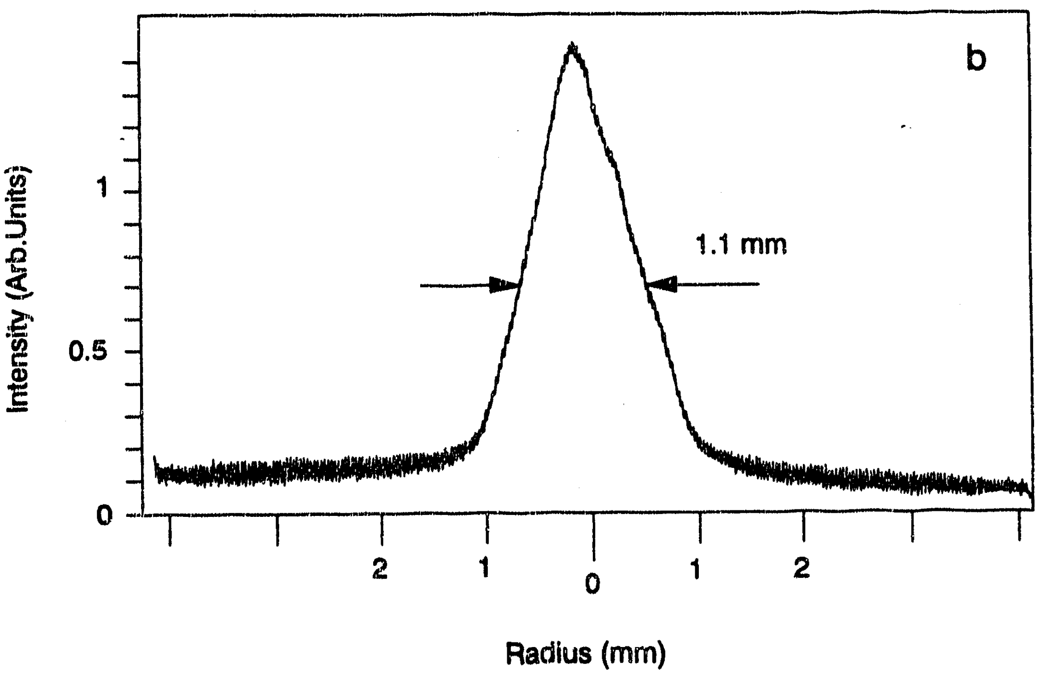
b)

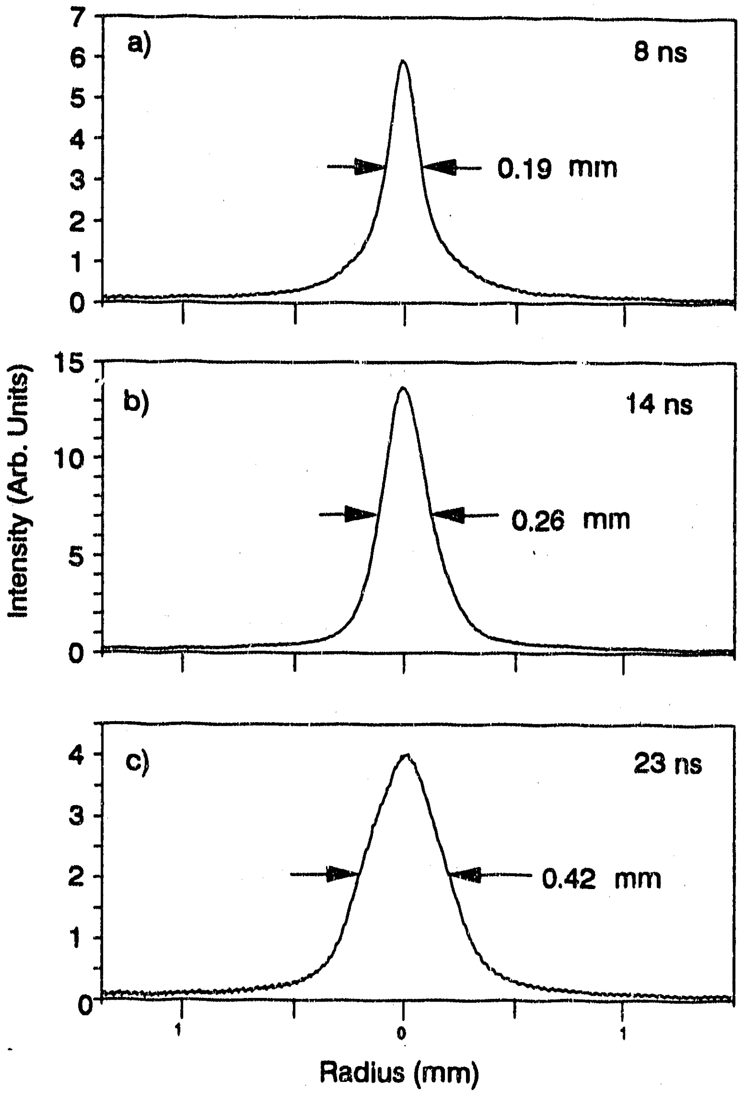

60
30
0
Current (kA)
Time (10 ns/div)

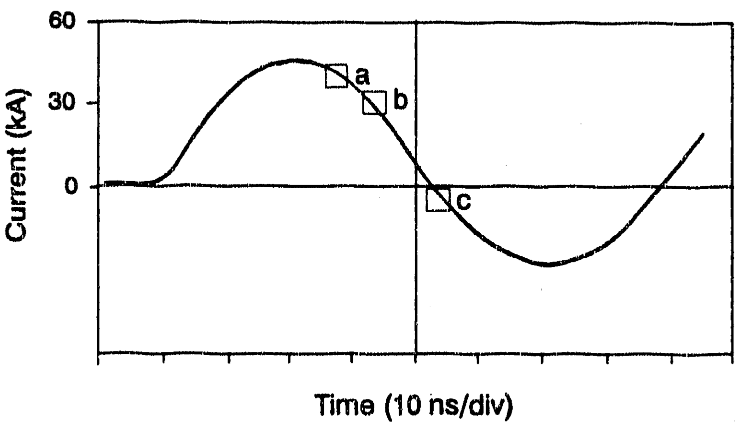

a) I = 23 kA
OVI 150.1
Ar XI 151.9
Ar X 165.5
Ar X 170.6
OVI 173.1
OVI 172.9
Ar XI 184.5
Ar XI 188.8
b) I = 43 kA
O VI 150.1
Ar XI 151.9
Ar XII 154.4
Ar X 165.5
Ar X 170.6
Ar XI 171.9
OVI 172.9
OVI 173.1
Ar XII 176.6
Ar XII 178.15
Ar XI 187.1
Ar XI 188.8
Ar XII 192.7
c) I = 56 kA
OVI 150.1
Ar XII 149.9
Ar XI 151.9
Ar XII 153.6
Ar XII 154.5
Ar XIII 161.6
Ar XII 163.3
Ar XIII 164.8
Ar XII 165.5
Ar XII 169.0
Ar X 170.6
OVI 172.9, 173.1
Ar XII 174.7
Ar XII 176.6
Ar XII 178.15
Ar XIII 181.1
Ar XI 184.5
Ar XIII 184.9
Ar XI 187.1
Ar XII 188.8
Ar XI 191.0
Ar XII 192.7
Intensity (Arb. Units)
Diode Number
0
200
400
600
800
1000


Intensity (Arb. Units)
0
1
2
3
4
5
6
0
200
400
600
800
1000
Diode Number
Ar XII 149.9
OVI 150.1
Ar XI 151.9
Ar XII 153.6
Ar XII 154.5
Ar XIII 161.6
Ar XIII 163.0
Ar XII 163.3
Ar XIII 164.8
Ar XII 169.0
OVI 172.9, 173.1
Ar XII 174.7
Ar XII 176.6
Ar XII 178.1
Ar XIV 180.3
Ar XIII 181.1
Ar XIII 182.6
Ar XIII 184.9
Ar XIV 187.9
Ar XIV 191.3
Ar XII 192.7


a
Intensity (Arb. Units)
0.26 mm
0
1
2
2
1
0
1
2
Radius (mm)


b
Intensity (Arb.Units)
1.1 mm
0
0.5
1
2
1
0
1
2
Radius (mm)


7
6
5
4
3
2
1
0
a)
8 ns
0.19 mm
15
10
5
0
b)
14 ns
0.26 mm
Intensity (Arb. Units)
4
3
2
1
0
c)
23 ns
0.42 mm
1
0
1
Radius (mm)


60
30
0
Current (kA)
a
b
c
Time (10 ns/div)

Fast Discharge Excitation of Small Scale Soft X-Ray Lasers

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ABSTRACT: We are investigating the development of compact and efficient soft X-ray lasers by discharge excitation of capillary plasmas with fast high current pulses. These discharges generate highly ionized plasma columns with adequate characteristics to explore both recombination and collisional excitation laser schemes. In relation to the first scheme, herein we discuss soft X-ray spectra from Li-like ions. We also report the generation of hot plasma columns by fast pulse excitation of a capillary filled with preionized material. As compared with discharges in evacuated capillaries, this new scheme allows for increased control of the plasma density and temperature, and can generate hotter plasmas. Discharges in argon filled capillaries produced plasmas with ArX-ArXIV line emission, in which the ionization degree was controlled by the magnitude of the current pulse. The use of these discharges for collisionally excited Ne-like and Ni-like laser schemes is discussed.

1. INTRODUCTION

The development of more compact, higher efficiency and less costly soft X-ray lasers is currently receiving increased attention [Hagelstein (1991), Kim et al (1991), Schäfer et al (1992)]. We have proposed for this purpose the use of highly ionized capillary plasmas columns created by direct excitation with a fast discharge [Rocca et al (1988)]. Capillary discharges have been previously used to generate highly ionized plasmas for spectroscopy, continuum generation and microscopy [Bogen et al (1968), McCorkle (1981)]. Several inherent characteristics of capillary discharges make them attractive for extreme ultraviolet (EUV) and soft X-ray (XUV) amplification: the high power density deposition (which can be greater than 1×10^{11} W/cm^3), the large length-to-diameter ratio and the possibility of creating small diameter plasma columns with reduced radiation trapping. In addition, for the implementation of recombination laser schemes, the proximity of the capillary walls provides enhanced plasma cooling [Rocca et al (1988)].

Recently, experiments motivated by the possibility of obtaining gain by collisional recombination have been conducted in capillary plasmas excited by current pulses with pulsewidths of the order of 100 ns FWHM and currents between 5 and 50 kA [Marconi and Rocca (1989), Steden and Kunze (1990), Marconi et al (1990), Morgan et al (1991), Rocca et al (1991,1992)]. Steden and Kunze reported the observation of short bursts of 18.2 nm radiation, which were interpreted as amplified spontaneous emissions, near the peak of the second half cycle of the current pulse in a low voltage (V = 7-16 kV) polyacetal capillary discharge. Our study of similar discharges (100 nF, 15-23 nH) has showed that the spectra of polyacetal capillary plasmas are dominated by oxygen lines, with weak CVI emission for discharge voltages above 10 kV. In contrast, discharges in polyethylene capillaries were found to emit strong CVI lines. In both cases however, the CVI emission was observed to peak shortly after the maximum of the current pulse and to vanish before the end of its first half cycle, indicating that in these discharges the decay rate of the current pulse is slow compared with the loss rate of the highly charged ions caused by diffusion and recombination.

Herein we report results of experiments conducted with a significantly faster discharge, with pulses having a 10-90% current risetime of 11 ns, a FWHM of 25 ns and currents up to 100 kA. We are utilizing this fast discharge to study the possibility of amplification by collisional recombination in H-like and Li-like ions. We have recently reported time resolved spectra in 1 mm diameter polyethylene discharges in which the 18.2 nm 3-2 transition of hydrogenic carbon appears anomalously intense respect to the 4-2 transition of the same ion [Rocca et al (1991)]. To date however, this phenomena could not be confirmed as gain since it has lacked reproducibility and the intensity of the 18.2 nm line has not been observed to have an exponential increase as a function of the capillary length. The next section discusses time-resolved spectra of the soft X-ray emission from Li-like ions. Section 3 reports the generation of hot capillary plasmas that are adequate to explore XUV and EUV amplification by collisional excitation of Ne-like and Ni-like ions.

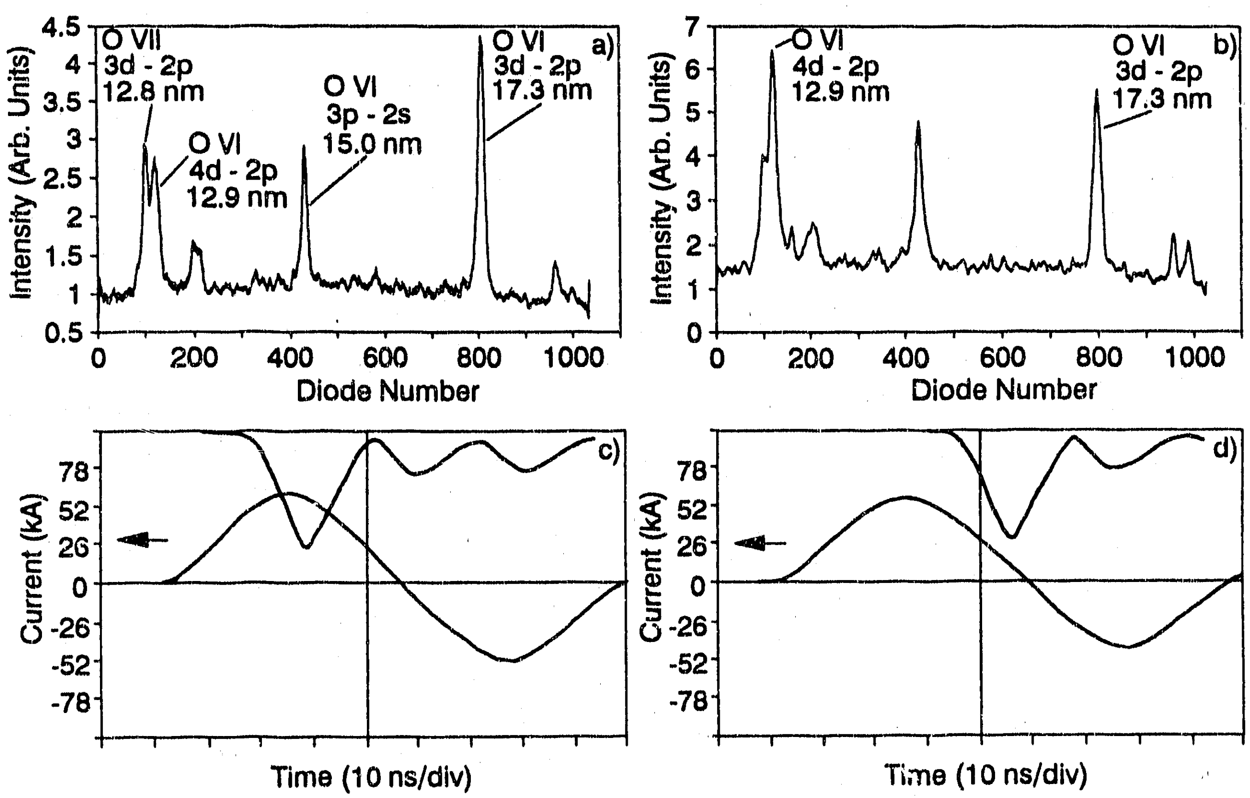

Figure 1. The spectra illustrate the relative intensity of the 4d-2p and 3d-2p OVI transitions at times corresponding to a) peak of the current pulse and b) end of the first half cycle of the current pulse for a 1 mm diameter, 1 cm long polyacetal capillary excited by a 62 kA current pulse. The current pulse and relative timing of the detector gate pulse for spectra a) and b) are shown in c) and d) respectively.

2. STUDY OF ANOMALOUS LINE INTENSITY RATIOS IN LI-LIKE IONS.

Soft X-ray spectra from polyacetal $(COH_2)_n$ capillaries excited by the fast discharge pulses described above show that the line emission is dominated by oxygen ion lines. In spectra corresponding to the 100-200 Å region, lines from helium-like (OVII) and lithium-like (OVI) oxygen are observed. Figure 1 shows a time-resolved spectra of the emission from a 1 mm polyacetal capillary excited by a 62 kA pulse, corresponding to two different times during the current pulse. The collisional recombination of OVII ions into OVI ions can lead to population inversion in the 4f-3d transition (λ = 51.8 nm) of this ion. A population inversion in this transition can be monitored by the intensity ratio of the 4d-2p (λ = 12.9 nm) and the 3d-2p (λ = 17.3 nm) transitions. The 4d and 4f levels are separated by 0.02 eV and it can be assumed that collisions ensure equal populations per unit of statistical weight in both levels.

In an optically thin plasma the ratio between the intensities of the 4d-2p and 3d-2p transitions is related to the population per unit of statistical weight n_{4d}, n_{3d} of the 4d and 3d levels by

$$I_{4d\text{-}2p}/I_{3d\text{-}2p} = 0.32\ n_{4d}/n_{3d}$$

Comparison of the time-resolved spectra of Figure 1a) and 1b) shows a large increase in the intensity of the 4d-2p line respect to the 3d-2p line at the end of the current pulse, when the plasma is expected to cool and recombine. For the case of an optically thin plasma the measured intensity ratio of the 12.9 nm to the 17.3 nm lines would represent a population inversion per unit of statistical weight of n_{4d}/n_{3d} = 3. Time-resolved spectra obtained at shorter wavelengths show that also the 5d-2p line becomes anomalously intense with respect to the 3d-2p transition

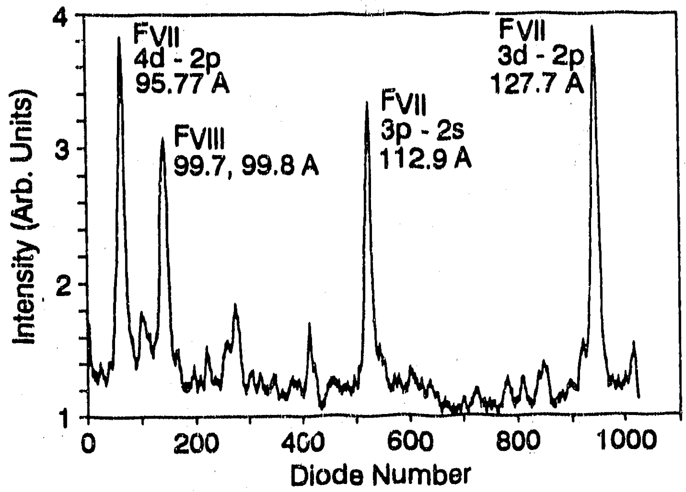

Figure 2. Spectra from a 1 mm diameter, 1 cm long teflon capillary excited by a 67 kA current pulse showing the emission from helium-like and lithium-like fluorine transition.

at the end of the current pulse. The anomalous relative intensity of these lines as in the spectra in Figure 1b) could however be caused by self absorption of the 17.3 nm line. To estimate the effect of self absorption the relative intensities of the fine structure components of the 3d-2p transitions were measured. These measurements however were not conclusive because while in a few spectra an intensity ratio between the two fine structure components at 172.93 Å and 173.08 Å was measured to be 0.56, which is very close to the optically thin, statistically distributed value of 0.55, other spectra had ratios as low as 0.43. Nevertheless, time-resolved electron density measurements suggest that the anomalous intensity ratio of Figure 1a) might be caused by the larger self absorption of the 17.3 nm line. The electron density was measured to increase as a function of the time during the current pulse, reaching values between $2x10^{19}$ and $3x10^{19}$ cm^{-3} at the end of the first half cycle of a 70 kA current pulse. These densities are more than an order of magnitude larger than the value at which collisional electron impact deexcitation is expected to cause an equilibration of the state populations. A scheme that can provide increased control of the plasma density is described in the next section. The Z^7 scaling of the maximum density necessary to avoid collisional mixing of the populations with the nuclear charge Z suggest the conduction of similar studies of the populations of Li-like ions in heavier elements. We are currently conducting experiments in teflon capillaries to study the populations in FVII following the recombination of FVIII ions. The spectrum in Figure 2, which correspond to a 1 mm diameter capillary excited with a 67 kA current pulse, shows abundance of He-like fluorine as is necessary to investigate inversions in FVII.

3. FAST DISCHARGE EXCITATION OF PRE-IONIZED CAPILLARY PLASMA COLUMNS.

Here we describe a new scheme for the generation of capillary plasma columns which allows for a more independent control of the density and temperature and for higher peak plasma temperatures. It consists in very rapid pulsed discharge excitation of a capillary which has been previously filled with a selected density of a preionized material of interest. Excitation of the preionized material by a fast high current pulse is expected to rapidly detach the plasma from the walls, allowing for the creation of a hot plasma channel in which composition and density are mainly controlled by the material that has been injected into the capillary. Initial experiments were conducted injecting argon gas into a 2.5 mm diameter polyacetal capillary utilizing a fast pulsed valve. A preionization current pulse of approximately 30 A ($J \cong 600$ A/cm²) was flown through the gas filled capillary during approximately 2 μs preceding the main excitation pulse with the objective of obtaining uniform and reproducible breakdown conditions. Figure 3 shows time-resolved on-axis soft X-ray spectra of a 2.5 mm diameter polyacetal capillary channel filled with 3 Torr of argon for three different excitation currents. The spectra, which correspond to the 150-200 Å region, were obtained with a 1 m grazing incidence spectrograph containing a 1200 l/mm grating. The spectra in all cases were obtained shortly after the peak of the first half cycle of the current pulse, with the

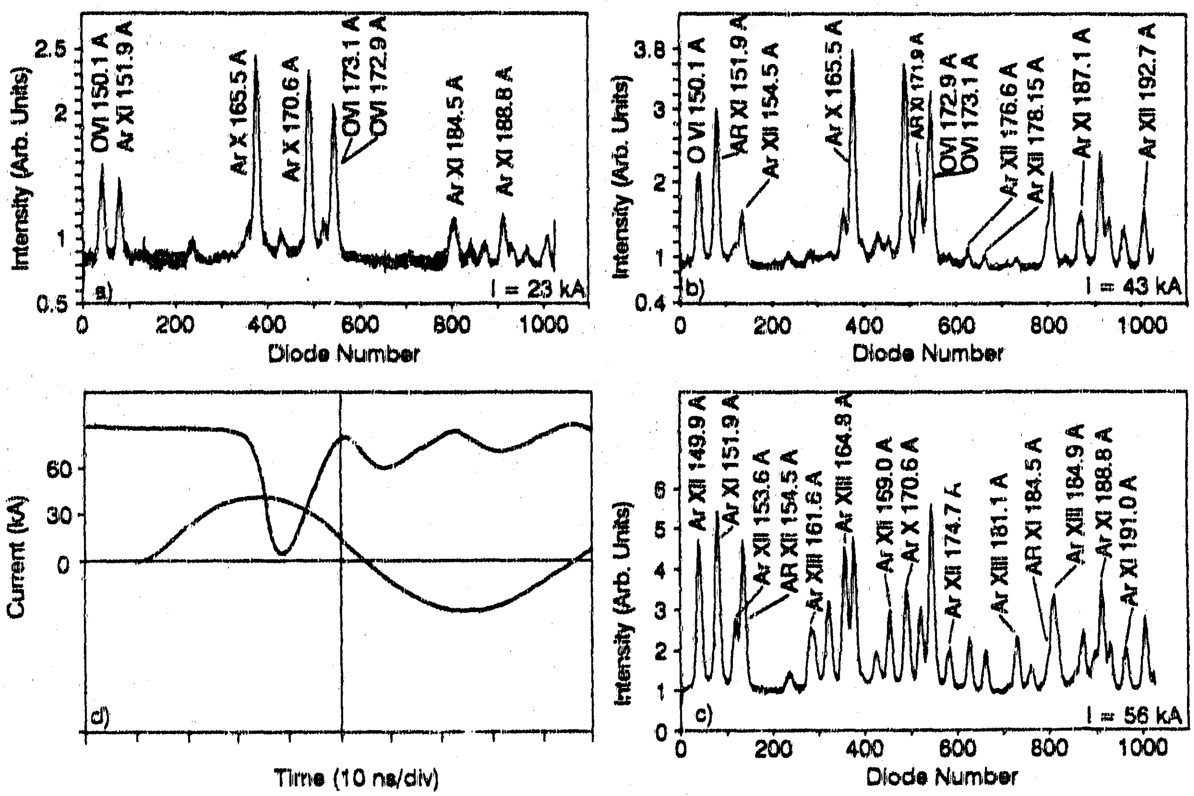

Figure 3. Time resolved spectra of the soft X-ray emission in the 150-193 Å region from a 2.5 mm diameter capillary filled with 3 Torr of argon for three values of the excitation current a) 23 kA, b) 43 kA and c) 56 kA. Figure d) shows the timing at which all the spectra were obtained respect to the current pulse. The spectra have a temporal resolution of 5 ns.

timing indicated in Figure 3d) and a temporal resolution of 5 ns. The spectrum of Figure 3a), which corresponds to an excitation current pulse of 23 kA, is dominated by line emission from fluorine-like argon, ArX. Weaker ArXI lines and emission from OVI lines originated from the material ablated from the capillary walls are also observed. Although the spatial uniformity of the plasma column has not yet been studied, the reproducibility of the spectra has been very good. Moreover, it was possible to select the dominant ion specie adjusting the discharge current as observed in Figures 3a)-c). An increase in the intensity of the ArXI lines and emission from ArXII lines are observed for 43 kA excitation. Further increase of the current to 56 kA caused the abundance of ArX to decrease and the onset of the emission from ArXIII lines.

An estimate of the electron density was obtained from the intensity ratio of the ArXI 197.95 Å line and the ArXI line at 171.86 Å, which is sensitive to the electron density in the range from 10^{17} to about 10^{19} cm^{-3} [Feldman and Doschek (1977)]. This ratio, which for a 63 kA discharge was measured to be 0.6, corresponds to an electron density of about $5x10^{18}$ cm^{-3} in the region of the plasma where ArXI occurs, according to calculations done for an optically thin plasma at 170 eV.

In Figure 3c), which corresponds to a spectrum obtained at 30 ns from the beginning of the discharge, ArXIII lines are observed. A calculation of argon ionization times utilizing the expressions given by Lotz (1969) assuming the above electron density indicates that the temperature must be higher than 120 eV for those lines to be observed. Higher degree of ionization, corresponding to hotter plasmas, were observed in 1.5 mm diameter argon discharges. Calculations of the ionization times for argon indicate that for ArXIV lines to be seen, as observed in 1.5 mm diameter capillaries excited by 55 kA pulses, the electron temperature must surpass 150 eV.

The generation of hot, highly ionized plasma channels reported herein utilizing very modest (20 - 60 kA) excitation currents could lead to compact collisionally excited lasers. The capillary plasmas described above have adequate parameters to attempt amplification in low Z components of the Ne-like sequence, which has been prolific in laser transitions between 3p and 3s levels in laser created plasmas [Matthews et al (1985,1986), MacGowan et al (1987), Lee et al (1987), Elton et al (1987)]. To explore for gain in $\Delta n = 0$ transitions of Ne-like argon [($^1S_0$ - $^1P_1$) λ = 468.9 Å, ($^1D_2$ - $^3P_1$) λ = 670.8 Å, ($^3P_2$ - $^1P_1$) λ = 697.7 Å, ($^3D_1$ - $^3P_1$) λ = 696.5 Å, ($^3D_2$ - $^3P_1$) λ = 725.8 Å], a plasma temperature of approximately 80 eV and densities between 1×10^{18} and 1×10^{19} cm^{-3} are required. A gain of 2 cm^{-1} in the ($^1S_0$ - $^1P_1$) transition has been predicted by Feldman et al (1986) at an electron density of 1×10^{19} cm^{-3}. This value however is probably excessively optimistic, as the difficulty of modeling the J = 0-1 transition in Ne-like ions has frequently resulted in an overestimate of the gain as compared with experiments. Whitten and Walling (1985) have estimated the gain of the frequently dominant (J = 2-1) lines to be 0.16 cm^{-1} in a plasma with a temperature of 80 eV and a density of 1×10^{18} cm^{-3}.

Low Z Ni-like ions are of particular interest for excitation in the capillary plasmas discussed above due to the considerable reduced excitation parameters required for amplification at a given wavelength. The favorable scaling of the Ni-like scheme to low Z has been theoretically predicted by Hagelstein (1991), who is searching for gain in plasmas generated by a small scale lasers [Basu et al (1991)]. In Ni-like krypton, Kr^{+8}, the population inversion between the 4d and 4p ($^1S_0$ - $^1P_1$) levels corresponds to a wavelength of 337 Å. Utilizing the elegant three level model developed by Hagelstein for an optimum predicted electron density of 7.1×10^{17} cm^{-3} and for a plasma temperature of 100 eV with $T_e = T_i$, we computed a predicted gain of 1.4 cm^{-1} in the 337 Å transition of Kr^{+8}, assuming that 50% of the ions are in the nickel ion ground state. The experiments in argon summarized above indicate that capillary plasmas with a length of 5-10 cm and with the required plasma parameters necessary to explore gain by collisional excitation in low Z ions can be generated by fast pulsed excitation of a gas-filled capillary.

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