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**SOFT X-RAY LASER GAIN MEASUREMENTS
IN A RECOMBINING PLASMA COLUMN**

By

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ABSTRACT

An enhancement of ~ 100 of stimulated emission over spontaneous emission of the CVI 182 Å line (one-pass gain ≈ 6.5) was measured in a recombining, magnetically confined plasma column by two independent techniques using intensity calibrated XUV monochromators. Additional confirmation that the enhancement was due to stimulated emission has been obtained with a soft X-ray mirror.

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The recombination scheme proposed by Gudzenko et al.¹ for the development of a soft X-ray laser and the experimental observation of a population inversion in CVI in a recombining plasma by Irons and Peacock² have attracted much interest.³⁻⁸ The principle of the recombination scheme is, first, to create and heat a multi-Z, high density plasma in order to ionize atoms to the proper stage of ionization, and next, to cool the plasma rapidly to create a strong nonequilibrium (recombination) regime. In such a regime, the ions recombine with the electrons by a three-body process with a rate that is the highest for highly excited levels (high n -quantum number). The lower levels are populated by collisional cascading processes. Hence, in a recombining plasma the process of population occurs from higher to lower levels. At the same time, depopulation of low- n levels is predominantly by radiative (spontaneous) transitions: in hydrogenlike ions this has the highest rate for the resonance $2 + 1$ transition. In this way, in hydrogenlike ions for example, a population inversion can occur for levels $n = 3$ and 4 relative to level 2 , with higher gain on the $3 + 2$ transition (in CVI this transition corresponds to the wavelength $\lambda = 182.2 \text{ \AA}$).

Most of the work on the recombination scheme has been based on fast adiabatic cooling due to free expansion of the plasma into a vacuum or cold gas. In parallel, there were, of course, intensive theoretical and experimental studies of other approaches to soft X-ray laser development⁹⁻¹⁸ with impressive results, recently from Livermore in electron, collisionally pumped, neonlike Se.^{19,20} One advantage of the recombination

scheme is the relatively rapid decrease of wavelength with (isoelectronically) increasing Z-charge of the working element. However, the disadvantages of the scheme based on plasma recombination during free expansion are the rapidly decreasing electron density, the difficulty of obtaining a relatively long and uniform plasma column, and control of the cooling rate.

To avoid these problems, it was proposed²¹ to create a plasma column with a relatively large ratio of plasma length to radius ($l/r > 10^2$) in a strong solenoidal magnetic field and cool it by radiation losses. Because the spectral line radiation losses are proportional to Z^4 , and three-body recombination is proportional to n_e^2 , such cooling can produce very rapid recombination in a plasma with high enough Z and n_e . We have shown experimentally²² that radiation cooling of a magnetically confined plasma column can be more efficient than adiabatic cooling of an expanding plasma. The magnetic field prevents the radius of the column from increasing and hence prevents a rapid decrease in electron density.

In this paper we present measurements of enhancement of up to $E = 100$ of stimulated emission over spontaneous emission for the CVI 182 Å line in a recombining plasma column, confined by a magnetic field, $B = 90$ kG. We also report the first demonstration of increased stimulated emission with the use of a soft X-ray mirror. The plasma was created by the interaction of a 1 kJ CO_2 laser with a solid carbon target (the maximum enhancement was measured for a laser energy = 0.3 kJ, power density = 5×10^{12} W/cm², and pulse FWHM = 75 nsec). The plasma

emission in the axial direction was measured by an XUV grazing incidence monochromator equipped with a 16-stage electron multiplier, and emission in the transverse direction was measured by an XUV grazing incidence duochromator equipped with two-channel electron multipliers. The rise time of the axial instrument was $\Delta t = 20$ nsec and approximately twice shorter for the transverse one. Both instruments were operated in the spectral range 10-350 Å. The emission in the axial and transverse directions was simultaneously observed by two absolute intensity calibrated air monochromators. Beam splitters were utilized so that each pair of XUV and air instruments observed essentially the same region of the plasma. In this way, it was possible to use the branching ratio method to provide an in situ absolute intensity calibration for the XUV instruments using both the laser produced plasma and, independently, a high voltage vacuum spark specially built for calibration purposes²³ In addition, the relative sensitivity of the axial and transverse instruments was obtained for the CVI 182 Å and CVI 33.7 Å lines by viewing simultaneously with both instruments the plasma created by the interaction of the CO₂ laser with the top of a vertical fiber (the diameter of the fibers was 70-300 μ), similar to a calibration performed at Hull University.⁴ More details about the experimental arrangement, instrumental setup and calibration are presented in Refs. 22 - 25. There we also presented observations of the CVI 182 Å line in time-integrated spectra and time-resolved measurements with an enhancement of up to 10 of stimulated emission over spontaneous emission in the

axial direction (corresponding to a gain length product of $G = k_L \approx 3.5$).²⁵ In those experiments, a carbon disc with a 1.5 mm hole in the center was used. Gain was measured along the axis of the plasma column (the axis of the column was close to the center of the hole). However, radial profiles of the CVI line radiation measured with the transverse XUV duochromator by a shot-to-shot vertical scan²⁴ indicated that better conditions for maximum gain should exist in the off-axis region of the plasma column in agreement with theoretical expectations. In the center of the plasma column, the temperature is at a maximum and decreases rapidly in the outer region, whereas the electron density reaches a maximum off-axis.^{26,27} In this way, C^{6+} ions are created mainly in the center of the plasma column and recombine to CVI in the outer region where n_e is at a maximum and T_e is significantly lower than on the axis. The carbon disc target was masked to enable the axial and transverse spectrometers to observe only the off-axis region of the plasma. In Figs. 1a and 1b are shown two carbon discs, 2 mm thick. Each had a horizontal slot 0.8 mm x 4 mm located 1.3 mm below the center of the disc. The disc in Fig. 1b had a thin carbon blade attached, 2 cm long with the blade edge ~ 0.5 mm to the left of the central axis. Each disc was mounted in the vacuum chamber inside the magnet, with its surface perpendicular to the axis of the CO_2 laser beam. A mask with a slot (0.8 mm wide, and 2 cm long) parallel to the plasma column limited the view of the transverse spectrometer to the off-axis region at the same height as the slot in the disc. A grazing incidence mirror focused light from the center of the slot in the disc to the axial XUV monochromator.

The enhancement (E) of stimulated emission over spontaneous emission of the CVI 182 Å line was measured in two ways and the consistency of enhancement (gain) was checked with the relative population of level $n = 3$ obtained from measurements of intensities in axial and transverse directions. The first method was based on the comparison of the ratio of the intensities of the CVI 182 Å line recorded simultaneously by the axial and transverse XUV instruments (first laser shot) with the ratio of the intensities of the CVI 135 Å line ($4 \rightarrow 2$ transition) also recorded simultaneously by the axial and transverse XUV instruments (second laser shot) as follows:

$$E = \frac{I(182)_{\text{axial}}}{I(182)_{\text{transv.}}} / \frac{I(135)_{\text{axial}}}{I(135)_{\text{transv.}}} . \quad (1)$$

In Eq. (1), $I(\lambda)$ is the intensity of a line of wavelength λ integrated over the spectral profile and over length. The subscripts "axial" and "transv." refer to the direction of emission. The CVI 135 Å line was chosen for such a comparison because it has the same lower level and an upper level close in energy to the 182 Å line. One channel of the transverse duochromator recorded the CVI 33.7 Å line ($2 \rightarrow 1$ transition) to monitor the reproducibility of CVI emission in the discharges. The contribution of the fourth order of the 33.7 Å line to the 135 Å line was subtracted. The transverse intensities of the 182 Å and 135 Å lines compared to the 33.7 Å line indicated a population inversion of levels 3 and 4 relative to level 2, hence the 182 Å and 135 Å lines are not affected by optical trapping.

In the transverse direction, the intensities of both lines are mainly due to spontaneous emission because of the small plasma thickness. In the axial direction, some small enhancement of line CVI 135 Å is expected from theoretical calculations²¹ (in the order of $E \approx 1.5-2$) and can be taken into account (with only small corrections in the gain) by the second method described below.

In the second method the intensity of a given line in the axial direction relative to the same line in the transverse direction (after adjustment for the distribution of the CVI 182 Å line intensity along the column and its approximate radial profile) was compared using the relative intensity calibration data from spark and vertical fiber plasmas.²³

$$E = \frac{I(182)_{\text{axial}} \times V_{\text{axial}}^{-1}}{I(182)_{\text{transv.}} \times V_{\text{transv.}}^{-1}} \quad (2)$$

where V is the volume of the plasma observed by the axial and transverse XUV monochromators.

The enhancement, E , is related to one-pass gain, G , averaged over line profile by

$$E = (\exp G - 1)/G. \quad (3)$$

In order to find the radial region of the plasma column with the maximum one-pass gain, G , the CO_2 laser was focused on the target (Fig. 1a) at different radial positions. Figure 2 shows the results of these measurements for $B = 90$ kG and laser energy $P_L = 450$ J. One may see that, for this laser energy, the

enhancement rises rapidly near $r \approx 1.5$ mm (Fig. 2 suggests that a higher resolution scan may reveal the maximum gain to be near $r \approx 2$ mm). For a lower laser energy, $P_L = 300$ J, which we found to be optimum in experiments with the C-disc, the maximum enhancement was observed in a relatively thin cylindrical shell of radius $r \approx 1.3$ – 1.5 mm with enhancement close to 10 near $r = 0$, in agreement with our earlier results.²⁵

In Fig. 3 are shown intensities of 182 Å and 135 Å lines (first and second column respectively) measured in axial and transverse directions. The intensity of the CVI 33.7 Å line was similar for both shots. The energy of the CO₂ laser was $P_L = 300$ J, and magnetic field $B = 90$ kG. The CO₂ laser was focused at $r = 1.3$ mm from the edge of the slot on the C-disc, which corresponded to the maximum enhancement region. The maximum enhancement $E \approx 100$ was measured from intensity ratios of the 182 Å and 135 Å lines in the axial and transverse directions (first method) at the time of peak intensity of the 182 Å line. The one-pass gain $G \approx 6.5$ was deduced from Eq. (3).

The peak of the CVI line intensities was observed during plasma recombination.²³ In the recombination phase, the electron temperature $T_e \approx 10$ – 20 eV was measured from the slope of CVI and CV recombination continua. In the same phase, the maximum electron density of $n_e \approx (6-7) \times 10^{18}$ cm⁻³ was measured from the intensity ratio of CV satellite lines from $2p^{23}P - 1s2p^3P$ and $2s2p^3P - 1s2s^3S$ transitions.

In experiments with a thin C-blade (Fig. 1b), the intensities of 182 Å and 135 Å lines increased typically by a

factor of 4 in the axial direction. However, the enhancement (gain) of the 182 Å line did not increase. In Fig. 4 is shown an example from a series of measurements of the time evolution of CVI 182 Å and CVI 135 Å line intensities in axial and transverse directions for the C-disc with a C-blade target. The enhancement $E = 95$ for the CVI 182 Å line (corresponding to a gain of $G = 6.5$) was measured by the first method. The intensity and time behavior of the CVI 33.7 Å line was reproducible for both laser shots. Due to the increased intensity of the 135 Å line, the effect of background radiation was much smaller than in Fig. 3. The transverse instrument viewed 5 mm of plasma length (the region 1-6 mm from the disc surface), where intensity of the CVI lines was strongest. Measurement of the CVI line intensities at different distances from the C-disc (using a 1 mm wide vertical mask) revealed that the effective length of the plasma where the CVI ion density was sufficiently large and uniform to produce significant gain, was $l_{\text{eff}} = 1$ cm. However, the plasma column observed by a streak camera (in visible light, i.e., in light from ions of lower stage of ionization) was significantly longer.

For the example presented in Fig. 4, the enhancement, measured by the second method, was $E = 120$, about 25% higher than measured by the first method. This small difference is due to the enhancement $E = 1.3$ ($G = 0.5$) of the CVI 135 Å line (measured by the second method). Such a small enhancement for the 135 Å line in comparison with the enhancement for the 182 Å line is in agreement with theoretical predictions.²¹

Two additional checks of the enhancement measurement were made. First, the relative population of level $n = 3$ of the CVI ion, measured from the 182 Å line emission in the transverse direction, was in good agreement with the population obtained from the 182 Å line spontaneous emission (intensity $\propto E$) in the axial direction. Second, the black-body brightness temperature, $T_B = 1.2$ keV, obtained from the 182 Å line axial brightness of $I = 10^5$ W/sr (Fig. 4; source area of 8×10^{-4} cm²) was much higher than the temperature of the recombining plasma ($T_e = 10$ -20 eV) which was emitting this radiation. The black-body temperature was estimated from the Rayleigh-Jeans formula assuming a Doppler-broadened 182 Å line width $\Delta\lambda_D = 10^{-2}$ Å.

Very recently, independent proof of the amplification of stimulated emission was obtained by using an XUV multilayer spherical mirror, developed by T. Barbee.²⁸ The experimental setup is shown in Fig. 5. The mirror available for our experiment ($\lambda = 182.2$ Å) had a radius of curvature $r = 200$ cm, which posed a difficult problem in aligning the mirror with the thin cylindrical shell where the maximum gain was expected. The XUV mirror (diameter 2.5 cm) was placed 200 cm from the carbon target in the center of the annular CO₂ laser beam (the CO₂ laser uses an unstable resonator with the central 5 cm of the beam free of laser radiation). The alignment of the XUV mirror was performed with an He-Ne laser and also with a small, pulsed HV-vacuum spark. The spark replaced the target in the vacuum chamber and was used to measure the effective reflectivity (including the ratio of solid angles towards the detector and

mirror) of the XUV mirror at 182 Å in situ. The reproducibility of spark emission was better than 4%. The effective reflectivity of the mirror at 182 Å was measured to be 12%. (In the C-disc experiments, the effective reflectivity of the mirror could be reduced due to less than perfect alignment with an elongated cylindrical plasma.) In the next two figures are shown examples from a series of preliminary measurements of the amplification of stimulated emission from the CVI 182 Å line due to the XUV mirror. To obtain better plasma reproducibility, three additional carbon blades were added to the C-disc with C-blade target in Fig. 1b. All four blades were arranged symmetrically around the plasma column with a 2.2 mm distance between opposing blades. The measured gain without the mirror (shutter closed) was in a relatively low range ($k_L \sim 4$ -4.5) due to a problem with one oscillator unit of the CO₂ laser. This caused longer rise and decay times of the CO₂ laser pulse, resulting in worse conditions for fast plasma cooling. A series of 4-5 reproducible shots was made with the XUV mirror shutter in a 'closed-open' sequence for $k_L \sim 4$ (Fig. 6) and for $k_L \sim 4.3$ (Fig. 7). Although the effective reflectivity of the mirror was less than 12%, the axial intensity of the 182 Å line increased by $\sim 100\%$ when the shutter was open while the intensity of this line in the transverse direction was essentially the same. This is a clear demonstration of the amplification of stimulated emission. With an XUV mirror of a smaller radius of curvature and further experiments at higher gain, we expect to obtain an amplification several times higher.

In summary, we have measured an enhancement of stimulated emission over spontaneous emission larger than $E = 100$ (one-pass gain $G = 6.5$) for the CVI 182 Å line in a magnetically confined, recombining plasma column. This enhancement (averaged over the spectral line profile) was measured at a distance $r = 1.3-1.5$ mm from the column axis by two independent techniques. A black-body temperature $T_B = 1.2$ keV was calculated from the 182 Å line intensity in the axial direction ($I = 10^5$ W/sr) and exceeds the plasma temperature in the recombination stage by a factor of 60-120. Independent proof of stimulated emission amplification was obtained using an XUV mirror. With a 12% measured effective reflectivity of the mirror, a 100% increase in intensity of the CVI 182 Å line in the axial direction was observed.

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REFERENCES

- 1 L.I. Gudzenko and L.A. Shelepin, Sov. Phys. JETP 18, 998 (1964); Sov. Phys. - Dokl. 10, 147 (1965).
- 2 F.E. Irons and N.J. Peacock, J. Phys. B 7, 1109 (1974).
- 3 P. Jaeglé, G. Jamelot, and A. Carillon, Trends in Physics 1981, Ed. I.A. Durobantu (Bucharest, Central Institute of Physics, 1981) p. 445.
- 4 D. Jacoby, G.J. Pert, S.A. Ramsden, L.A. Shorrocks, and G.J. Tallents, Opt. Commun. 37, 193 (1981).
- 5 R.C. Elton, J.F. Seely, and R.H. Dixon, in Laser Techniques for EUV Spectroscopy, Eds. T.J. McIlrath and R.R. Freeman (A.I.P., N.Y., 1982), p. 277.
- 6 W.T. Silfvast and O.R. Wood, II, Ibid, p. 128.
- 7 E. Ya. Kononov, K.N. Koshelev, Yu. A. Levykin, Yu. V. Sidelnikov, and S.S. Churilov, Sov. J. Quantum Electron. 6, 308 (1976).
- 8 V.A. Bhagavatula and B. Yaakobi, Opt. Commun. 24, 331 (1978).
- 9 M.A. Dugnay and M.P. Rentzepis, Appl. Phys. Lett. 10, 216 (1967).
- 10 A.V. Vinogradov and I.I. Sobel'man, Sov. Phys. JETP 36, 1115 (1973).
- 11 R.H. Dixon and R.C. Elton, Phys. Rev. Lett. 38, 1072 (1977).
- 12 T.C. Bristow, M.Y. Lubin, J.M. Forsyth, E.B. Goldman, and J.M. Soures, Opt. Commun. 5, 315 (1972).

- 13 A.N. Zherikhin, K.N. Koshelev, and V.S. Letokhov, Sov. J. Quantum Electron. 6, 82 (1976).
- 14 R.G. Caro, J.C. Wong, R.W. Falcone, J.F. Young, and S.E. Harris, Appl. Phys. Lett. 42, 9 (1983).
- 15 T.S. Luk, H. Pummer, K. Boyer, M. Shehidi, H. Egger, and C.K. Rhodes, Phys. Rev. Lett. 51, 110 (1983).
- 16 A.V. Vinogradov and V.N. Shlyaptsev, Sov. J. Quantum Electron. 10, 754 (1980).
- 17 P. Hagelstein, Plasma Phys. 25, 1345 (1983).
- 18 U. Feldman, A. Bhatia, and S. Suckewer, J. Appl. Phys. 54, 2188 (1983).
- 19 M.D. Rosen et al., Phys. Rev. Lett. 54, 106 (1985).
- 20 D.L. Matthews et al., Phys. Rev. Lett. 54, 110 (1985).
- 21 S. Suckewer and H. Fishman, J. Appl. Phys. 51, 1922 (1980).
- 22 S. Suckewer, C.H. Skinner, D. Voorhees, H. Milchberg, C. Keane, and A. Semet, IEEE J. Quantum Electron., QE-19, 1855 (1983).
- 23 H. Milchberg, Ph.D. Thesis (Princeton University, Plasma Physics Lab.), 1985.
- 24 C.H. Skinner, C. Keane, H. Milchberg, S. Suckewer, and D. Voorhees, in Laser Techniques in the Extreme Ultraviolet, Eds. S.E. Harris and T.B. Lucatorto (AIP, N.Y. 1984) p. 372.
- 25 S. Suckewer, C. Keane, H. Milchberg, C.H. Skinner, and D. Voorhees, Ibid., p.55.

- 26 T.K. Chu and L.C. Johnson, *Phys. Fluids* 18, 1460 (1975).
- 27 E.A. Crawford and A.L. Hoffman, in Laser Interaction and Related Plasma Phenomena, V. 6, p. 353, Eds. H. More and G. Miley (Plenum, NY, 1984).
- 28 T.W. Barbee, Jr., S. Mrowka, and M.C. Hettrick, *J.O.S.A.* (1985) in press.

FIGURE CAPTIONS

- Fig. 1 Schema of experiment with carbon disc target with 0.8 mm x 4 mm horizontal slot (a) without carbon blade, and (b) with thin carbon blade 2 cm long..
- Fig. 2 Enhancement of CVI 182 Å line measured at different distances from the center of the plasma column (corresponding to the different distances of the CO₂ laser focus from the horizontal slot).
- Fig. 3 Time evolution of CVI 182 Å and 135 Å line intensities measured with axial and transverse XUV instruments for two discharges with the same plasma conditions. The enhancement of stimulated emission for the 182 Å line was $E = 100$ (one-pass gain $k_1 = 6.5$).
Target: carbon disc with horizontal slot.
- Fig. 4 As in Fig. 3, but with a thin carbon blade attached to carbon disc. The enhancement was $E = 95$ ($k_1 = 6.5$).
Note four times higher intensities than for C-disc without C-blade.

Fig. 5 Experimental setup with XUV spherical mirror.

Fig. 6 Time evolution of CVI 182 Å line intensities in the axial direction with XUV mirror closed (first discharge; gain $k_2 \approx 4.0$) and open (second discharge). The intensities of the 182 Å line in the transverse direction are shown in the lower part of the figure. (Effective reflectivity of the XUV mirror at 182 Å is less than 12%.)

Fig. 7 As in Fig. 6, but for slightly higher initial gain (mirror closed)
 $k_2 \approx 4.3$.

Fig. 1

Fig. 2

#85X0182

$B = 90 \text{ kG}$
 $P_{\text{CO}_2} \approx 300 \text{ J}$

$$E = \frac{I(182)_{\text{axial}}}{I(182)_{\text{transv.}}} / \frac{I(135)_{\text{axial}}}{I(135)_{\text{transv.}}} \approx 100$$

1967

1966

Oct. 9/84

Fig. 3

#85X0184

C-Disc + C-Blade

B=90 kG

 $P_{CO_2} \approx 300 \text{ J}$

$$E = \frac{I(182)_{\text{axial}}}{I(182)_{\text{transv.}}} / \frac{I(135)_{\text{axial}}}{I(135)_{\text{transv.}}} \approx 95$$

#2237

2245 Oct. 23, 84

Fig. 4

EXPERIMENTAL ARRANGEMENT WITH XUV MIRROR

Fig. 5

#85X0247

C-Disc + 4 C-Blades; B = 90 kG, $P_{CO_2} \approx 300$ JXUV Mirror: ClosedXUV Mirror: Open

C VI 182 Å; Axial

C VI 182 Å; Axial

$kx \approx 4$ (Enh ≈ 13)

$$\frac{I_{182}^{AXIAL} (Open)}{I_{182}^{AXIAL} (Closed)} \approx 1.9$$

#2730

#2731

DEC. 19, 84

Fig. 6

#85X0249

C-Disc + 4 C-Blades; B=90 kG; $P_{CO_2} \approx 300$ JXUV Mirror: ClosedXUV Mirror: Open

$$k \times l \approx 4.3 \text{ (Enh. } \approx 17)$$

$$\frac{I_{182}^{\text{AXIAL}}(\text{Open})}{I_{182}^{\text{AXIAL}}(\text{Closed})} \approx 2.2$$

2752

2755

DEC. 19, 84

Fig. 7

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