Amplification of Stimulated Soft-X-Ray Emission in a Confined Plasma Column

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An enhancement of ~ 100 of stimulated emission over spontaneous emission of the C VI 182-Å line (one-pass gain ~ 6.5) was measured in a recombining, magnetically confined plasma column by two independent techniques involving intensity-calibrated extreme-uv monochromators. Additional confirmation that the enhancement was due to stimulated emission has been obtained with a soft-x-ray mirror; with 12% measured effective reflectivity of the mirror, a 120% increase in intensity of the C VI 182-Å line in the axial direction was observed.

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The recombination scheme proposed by Gudzenko and Shelepin[1] for the development of a soft-x-ray laser and the experimental observation of a population inversion in C VI in a recombining plasma by Irons and Peacock[2] 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 parallel to the works on the recombination scheme, there were, of course, intensive theoretical and experimental studies of other approaches to soft-x-ray laser development (see, e.g., Waynaut and Elton[9] and references therein) with impressive results, recently from Lawrence Livermore National Laboratory in which a gain-length product of 6–7 was achieved at 206 and 209 Å in electron-collisionally pumped, neonlike Se.[10] One advantage of the recombination scheme with a $\Delta n = 1$ lasing transition (n is the principal quantum number of the level) is the relatively rapid decrease of wavelength with (isoelectronically) increasing charge of the atomic-core Z (hence ionization potential) 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, a proposal was made[11] to create a plasma column 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 the square of the electron density, n_e^2, such cooling can produce very rapid recombination in a plasma with high enough Z and n_e. We have shown experimentally[8] 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. Our approach differs in this way from Ref. 4 which relies on adiabatic cooling due to free plasma expansion.

In this paper we present measurements of enhancement of up to $E \approx 100$ of stimulated emission over spontaneous emission for the C VI 182-Å line ($3 \rightarrow 2$ transition) in a recombining plasma column, confined by a magnetic field, $B \approx 90$ 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 $\approx 5 \times 10^{12}$ W/cm^2, and pulse FWHM ≈ 75 nsec). The plasma emission in the axial direction was measured by an extreme-uv (xuv) grazing-incidence monochromator equipped with a sixteen-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 $\Delta t \approx 20$ nsec and approximately twice shorter for the transverse one. Both instruments were operated in the spectral range 10–350 Å and were absolute-intensity calibrated. Total line intensities were measured as the resolution of xuv instruments was not high enough to measure the line profiles. More details about the experimental arrangement, instrumental setup, and calibration were presented by Milchberg and co-workers.[8, 12–14] There we also presented observations of the C VI 182-Å line in time-integrated spectra and time-resolved measurements with an enhancement of up to $E \approx 10$ of stimulated emission over spontaneous emission in the axial direction (corresponding to a gain-length product of $G = kl \approx 3.5$).[14] In those experiments, a carbon disk with a 1.5-mm hole in the center was used and gain was measured along the axis of the plasma column. However, radial profiles of the C VI line radiation measured with the transverse xuv duochromator[13] indicated that better conditions for maximum gain should exist in the off-axis region of the plasma column. 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.[15] In this way, C^{6+} ions are created mainly in the center of the plasma column and recombine to C^{5+} in the outer region. In Fig. 1 a carbon disk is shown, 2 mm thick with a horizontal slot 0.8×4 mm^2 located 1.3 mm below the center of the disk and a thin carbon blade attached. In some experiments a disk without a blade was used. The role of the carbon blade was to create a more uniform plasma in the axial direction and to provide additional cooling by heat transport from the plasma to the blade. A mask with a slot (0.3 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 disk.

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

$$E=\frac{I(182)_{\text{axial}}}{I(182)_{\text{transv}}}\left[\frac{I(135)_{\text{axial}}}{I(135)_{\text{transv}}}\right]^{-1}. \tag{1}$$

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 C VI 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 C VI 33.7-Å line (2 → 1 transition) to monitor the reproducibility of C VI emission in the discharges. The contribution (close to 30%) of the fourth order of the 33.7-Å line intensity to the intensity of 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, and 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 C VI 135-Å is expected from theoretical calculations[11] (of the order of $E\approx 1.5$–2) and can be taken into account by the second method described below.

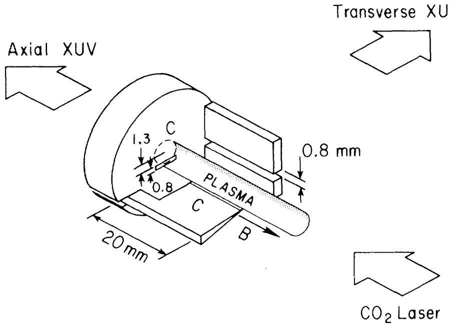

FIG. 1. Scheme of experiment with a carbon-disk target with a 0.8×4-mm^2 horizontal slot and with a thin carbon blade 2 cm long.

In the second method the intensity of the C VI 182-Å (and 135-Å) line in the axial direction relative to the same line in the transverse direction was compared by use of the relative-intensity-calibration data from spark and vertical fiber plasmas,[12]

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

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

$$E=(\exp G-1)/G. \tag{3}$$

The peak of the C VI line intensities was observed during plasma recombination.[12] In the recombination phase, the electron temperature $T_e\approx 10$–20 eV was measured from the slope of C VI and C V 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 C V satellite lines from $2p^2\,{}^3P$–$1s2p\;{}^3P$ and $2s2p\;{}^3P$–$1s2s\;{}^3S$ transitions.

In Fig. 2 an example is shown from a series of measurements of the time evolution of the C VI 182-Å and C VI 135-Å line intensities (first and second columns) in the axial and transverse directions. The relative intensity of the 135-Å line in the transverse direction was normalized to that of the 182-Å line. Intensities in the axial direction are presented in the same units as intensities in the transverse direction, obtained by use of the relative sensitivity of the axial and transverse xuv instruments and a geometrical factor of $V_{\text{transv}}/V_{\text{axial}}\approx 1.8$. The longer tail in the relatively low axial intensity of the 135-Å line is due to background radiation.

The enhancement $E\approx 95$ for the C VI 182-Å line (corresponding to a gain of $G\approx 6.5$) was measured by the first method. The intensity and time behavior of the C VI 33.7-Å line and the CO$_2$ laser energy and power were reproducible for both laser shots. The CO$_2$ laser was focused at $r\approx 1.3$ mm from the edge of the slot, which corresponded to the maximum

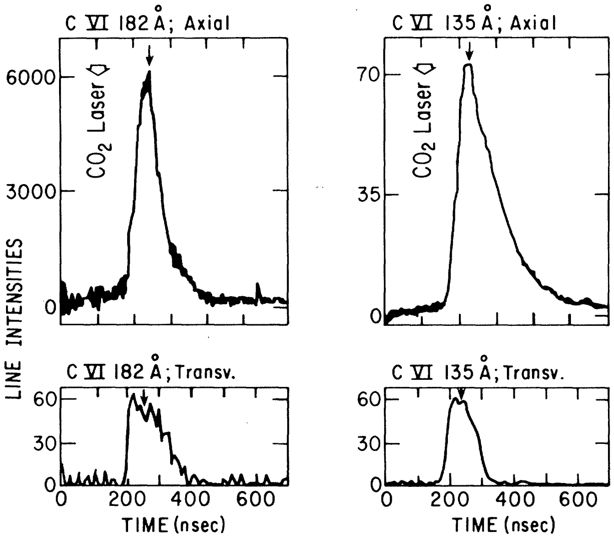

FIG. 2. Time evolution of C VI 182-Å and 135-Å line intensities measured with axial and transverse xuv instruments for two discharges with the same plasma conditions. The enhancement for the 182-Å line was $E \approx 100$; the one-pass gain was $kl \approx 6.5$.

enhancement region in the plasma column at 1.3–1.5 mm from the axis (100–200-μm layer) for the blade positions as shown in Fig. 1. The transverse instrument viewed 5 mm of plasma length (the region 1–6 mm from the disk surface), where intensity of the C VI lines was strongest. Measurement of the C VI line intensities at different distances from the C disk (with use of a 1-mm-wide vertical mask) revealed that the effective length of the plasma where the C VI ion density was sufficiently large and uniform to produce significant gain was $l_{\text{eff}} \approx 1$ cm.

For the example presented in Fig. 2, the enhancement measured by the second method was $E \approx 120$, about 25% higher than measured by the first method. This small difference is due to the enhancement $E \approx 1.3$ ($G \approx 0.5$) of the C VI 135-Å line.

The additional check of the enhancement was made by measurement of the population of level $n = 3$ of the C VI ion from the 182-Å line emission in the transverse direction, $N_{3,\text{transv}} \approx 1.1 \times 10^{15}$ cm^{-3}, which was in good agreement with the population obtained from the 182-Å line spontaneous emission in the axial direction ($\sim I_{\text{axial}}/E$), $N_{3,\text{axial}} \approx 1.3 \times 10^{15}$ cm^{-3}. Such populations correspond to the gain $k \approx 5.5$–6.5 cm^{-1} for a Doppler-broadened 182-Å line at 10 eV, and support well the measured gain.

A series of experiments was also conducted with a carbon disk without a carbon blade (disk parameters were the same as in Fig. 1). The measurements of enhancement were performed as in the above case. The maximum obtained enhancement was $E \approx 100$, although intensities of the 182-Å and 135-Å lines in the axial direction were approximately 4 times lower than for the C disk with a C blade.

Very recently, independent proof of the amplification of stimulated emission was obtained by use of a normal-incidence xuv multilayer spherical mirror.[16] (Theoretical modeling of the application of this type of mirror is presented by Dhez *et al.*[17] for the Orsay x-ray-laser experiment.) The experimental setup is shown in Fig. 3. The mirror had a radius of curvature $r = 200$ cm, which posed a difficult problem in alignment of 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 CO$_2$ laser beam. The alignment of the xuv mirror was performed with an He-Ne laser and also with a small, pulsed high-voltage 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% ± 4%. (In the C-disk experiments, the effective reflectivity of

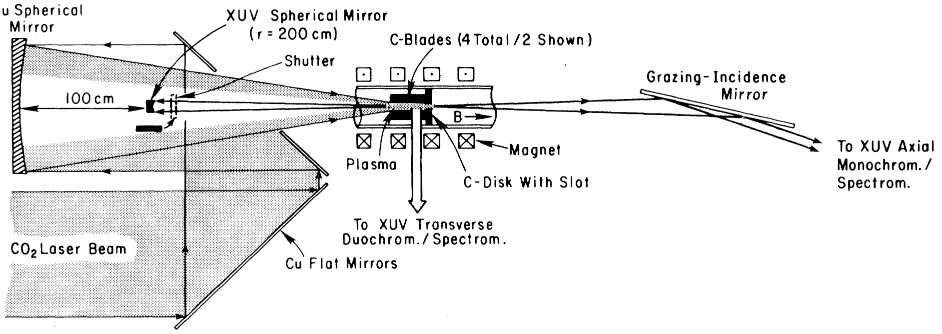

FIG. 3. Experimental setup with xuv spherical mirror.

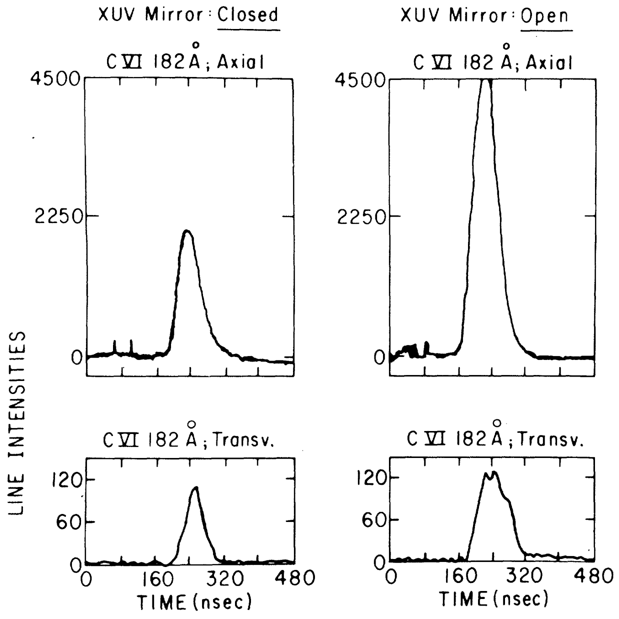

FIG. 4. Time evolution of C VI 182-Å line intensities in the axial direction with xuv mirror closed (first discharge; gain $kl \approx 4.3$) and open (second discharge); $I(182)_{\rm axial}(\text{open})/I(182)_{\rm axial}(\text{closed}) \approx 2.2$. (Effective reflectivity of the xuv mirror at 182 Å is less than 12%.) The intensities of the 182-Å line in the transverse direction are shown in the lower part of the figure. Target: C disk with four C blades.

the mirror could be reduced because of less than perfect alignment with an elongated cylindrical plasma.) In Fig. 4 an example is shown from a series of preliminary measurements of the amplification of stimulated emission from the C VI 182-Å line due to the xuv mirror. To obtain better plasma reproducibility, three additional carbon blades were added. All four blades were arranged symmetrically around the plasma column with a 2.2-mm distance between opposing blades. A series of 4–5 reproducible shots was made with the xuv mirror shutter in a "closed-open" sequence for $kl \approx 4.3$. (This gain was measured for closed shutter; gain was lower than in Fig. 2 as a result of a CO_2-laser problem.) Although the effective reflectivity of the mirror was less than 12%, the axial intensity of the 182-Å line increased by ~120% 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. In similar measurements with the C V 186-Å line, for which the reflectivity of the mirror was near 9%, the mirror had practically no effect on the line intensity. With an xuv mirror of a smaller radius of curvature placed closer to the plasma (thus easing alignment difficulties) and further experiments at higher gain, we expect to obtain an amplification several times higher.

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