Divergence Measurements of Soft-X-Ray Laser Beam

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The divergence of the C VI 182-Å lasing line generated in a rapidly recombining, magnetically confined plasma column was measured with soft-x-ray spectrometers equipped with multichannel detectors. In addition to measurements of the relative divergence, an absolute divergence of ~9 mrad at a magnetic field of 20 kG and ~5 mrad at a magnetic field of 35 or 50 kG was obtained by a direct scan of the 182-Å axial radiation. Based on these data a peak 182-Å power of ~100 kW is obtained. Calculations of the spatial distribution of gain in the plasma were in very good agreement with the experimental data.

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Since the announcements by Lawrence Livermore National Laboratory and Princeton University groups at the American Physical Society meeting in Boston (November 1984) of the achievement of high gain in Se XXV at 206–209 Å[1] and in C VI at 182 Å,[2] respectively, significant progress in the development of soft-x-ray lasers is apparent in both laboratories as well as in a number of other institutions.[3] In the Princeton experiment, where amplification of stimulated emission by a factor of 100 (a one-pass gain length of $kl \approx 6.5$) was reported earlier,[2] gain is generated in a recombining plasma column which is confined by a magnetic field and cooled by radiation losses. Plasma is created by the interaction of a commercially available 1-kJ transversely excited atmospheric CO_2 laser with a carbon-disk target in a strong (90 kG) magnetic field. The CO_2-laser pulse duration was ~80 nsec and maximum gain was obtained at an energy of ~300 J. Rapid recombination, after the laser pulse, creates a population inversion between levels 3 and 2 in hydrogenlike carbon (C VI). Installation of a soft-x-ray mirror[4] in a double-pass arrangement provided an additional demonstration of the amplification of stimulated emission. With a measured normal-incidence reflectivity of 12% at 182 Å, a 120% increase in axial stimulated emission was observed.[2]

In this paper we present recent measurements of the relative (to nonlasing lines) and absolute divergence of the C VI 182-Å lasing line, one of the key parameters characterizing the soft-x-ray laser beam. We also present calculations of the radial profile of the gain in the plasma using a one-dimensional computer code which provides a theoretical interpretation of our earlier results as well as an insight into the present data.

A general description of the experimental device can be found in Ref. 2 and in references therein. However, the present experimental system differs from the previous one as a result of the installation in the axial and transverse soft-x-ray spectrometers of multichannel detectors, and also the addition of a device for a precise horizontal scan of the axial spectrometer. The multichannel detectors are based on microchannel-reticon arrays and permit the recording of emission spectra in the axial and transverse directions in a single laser shot. The transverse instrument views most of the plasma; more details are given in Ref. 2. One example of the emission spectra is shown in Fig. 1. In the transverse spectrum, the spontaneous C VI 182-Å

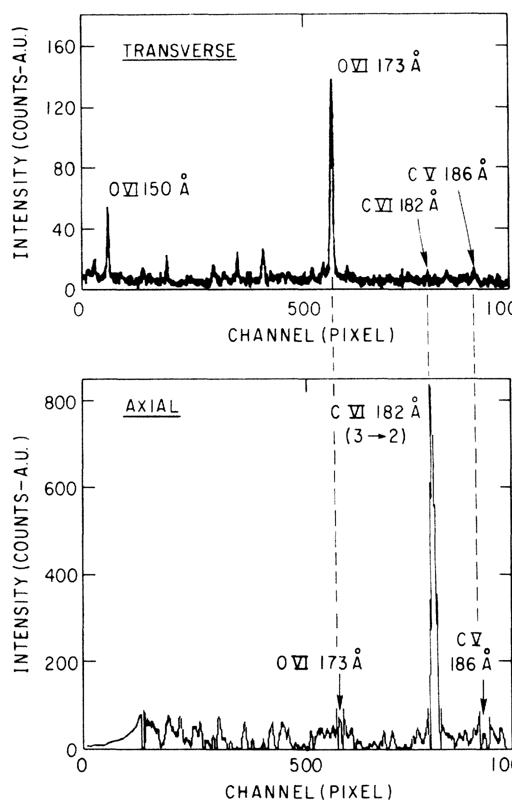

FIG. 1. Transverse and axial spectra in the region near 182-Å from a carbon-disk target with four carbon blades. The laser energy was 500 J.

emission is weak compared with the strongest line in the spectrum, C VI 173 Å. However, in the axial direction, the stimulated 182-Å emission dominates the spectrum.

Some exciting results were obtained recently by a scanning of the position of the axial spectrometer in the transverse direction (perpendicular to the axis of the plasma column). The axial emissions are imaged by a grazing-incidence mirror onto the entrance slit of the axial spectrometer. The mirror is constructed by bending of a glass strip, and so consequently the optical quality of the system is not ideal. Hence a transverse scan of the axial spectrometer gives information of the relative divergence of the lasing line radiation in comparison to nonlasing lines. This may be seen in Fig. 2 where the 182-Å emission on axis was so intense that the detector was saturated whereas the C V 186-Å and O VI 173-Å lines remained weak with flat spatial profiles.

The axial spectra presented in Fig. 1 were obtained at a position of the spectrometer corresponding to $x = 250\ \mu m$ in Fig. 2. This spectrometer horizontal position was established for all earlier measurements[2] by alignment of the system (CO_2-laser focusing mirror, target slot, and spectrometer entrance slit) with a He-Ne laser beam. However, from Fig. 2 we can see that the maximum gain is near $x = 200\ \mu m$ with a corresponding amplification of the 182-Å radiation of approximately a factor of 5 larger than presented earlier[2] (i.e., $kl \approx 8$). The sensitivity of the axial instrument for the data of Fig. 2 was higher than in Fig. 1 in order to measure intensity changes of nonlasing lines.

To obtain information about the absolute divergence of the soft–x-ray laser beam, the grazing-incidence mirror was removed. In its place a 1-mm-wide and 10-mm-high collimating slit was installed to block reflections from the walls of the vacuum chamber. Figures 3 and 4 show the results of a shot-by-shot transverse scan of both the collimating slit and the axial soft–x-ray spectrometer. The angular resolution, given by the ratio of the spectrometer entrance-slit width to the plasma-to-spectrometer distance, was 20 μrad. The principle of the experiment is presented schematically on the right-hand side of Fig. 3, and on the left-hand side is shown the intensity distribution of the C VI 182-Å, C V 186-Å ($4d$-$2p$), and O VI 173-Å ($3d$-$2p$) lines for a magnetic field $B = 20$ kG. For

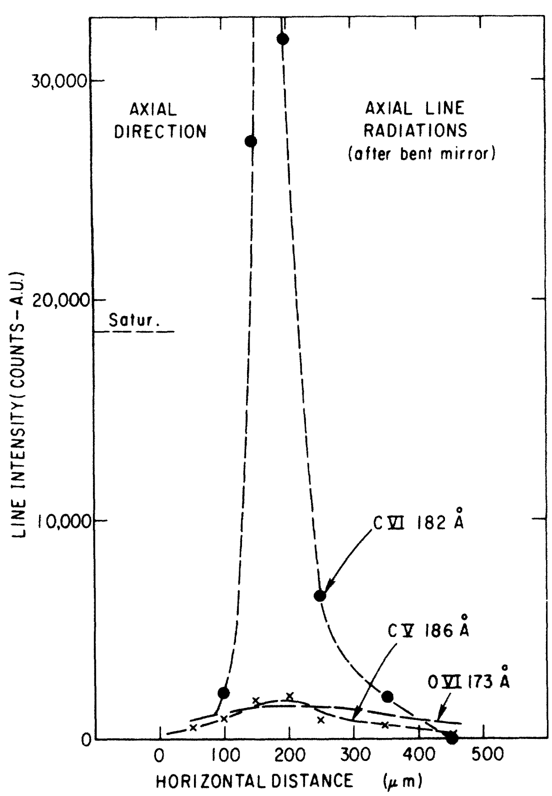

FIG. 2. Transverse scan of C VI 182-Å, C V 186-Å, and O VI 173-Å emission showing a strong central peak for the C VI 182-Å stimulated emission. "Satur." indicates the level above which the detector is saturated. Intensities above this level were obtained by comparing the nonsaturated regions of the 182-Å spectral profiles.

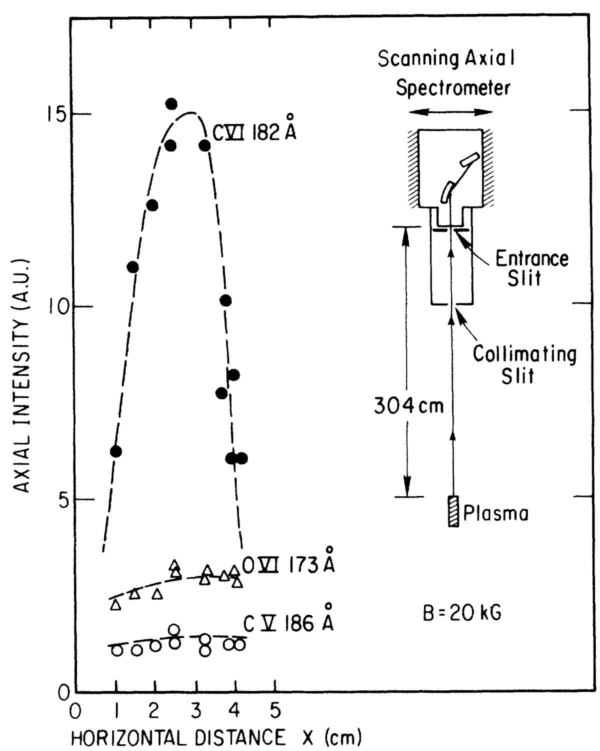

FIG. 3. Absolute divergence measurements (~9 mrad) of the 182-Å lasing radiation for a magnetic field $B = 20$ kG. For comparison the intensities of nonlasing lines O VI 173 Å and C V 186 Å are shown, recorded simultaneously with the 182-Å line.

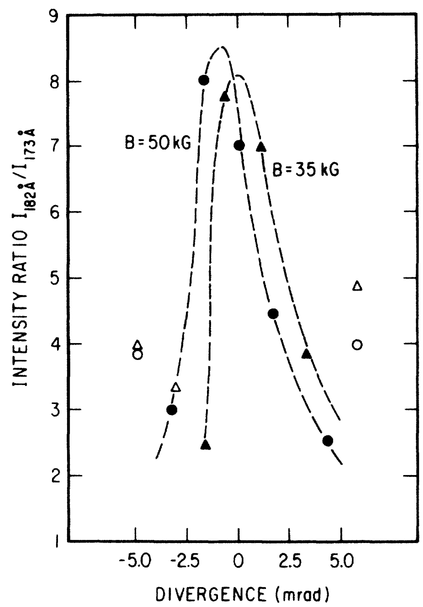

FIG. 4. Divergence measurements (~5 mrad) of the 182-Å radiation (relative to the O VI 173-Å line) for $B=35$ and 50 kG.

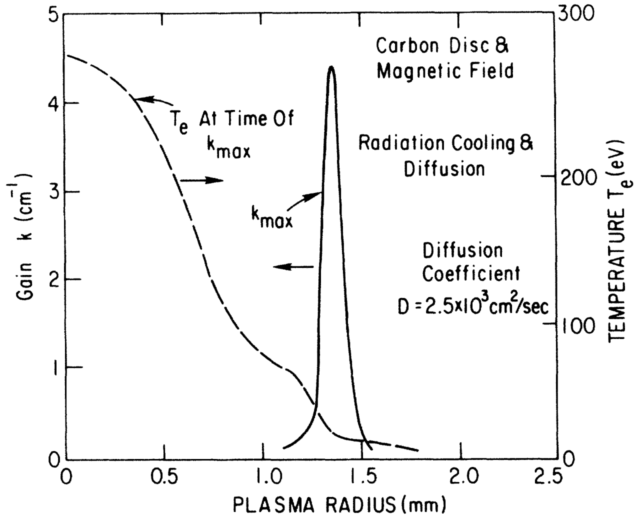

FIG. 5. Radial profiles of C VI 182-Å gain, k_{max}, and electron temperature, T_e, vs radius in the plasma column as predicted by a 1D code.

every shot the intensities of all three lines were recorded simultaneously on the multichannel detector of the axial soft–x-ray spectrometer. One may see that the lasing line, C VI 182 Å, is strongly peaked on axis with FWHM ≈ 2.7 cm at a distance of 304 cm from the plasma (target), which corresponds to a horizontal divergence of the beam of ~9 mrad. At the same time the intensities of the nonlasing lines O VI 173 Å and C V 186 Å are quite constant over the scan region ~3 cm.

With increasing magnetic field ($B=35$ and 50 kG) we observed further narrowing of the soft-x-ray laser beam down to ~5 mrad (Fig. 4). This indicates that with higher magnetic field maximum gain is created in a more narrow plasma region (less than 50 μm transversely). We also observe a slight shift of the peak intensity of the 182-Å radiation at higher magnetic field, which may be caused by a small tilt of the magnet at high currents. Another interesting feature is the rise of the 182-Å line intensity near the geometrical limits of scan (indicated by open circles and triangles in Fig. 4). The limits are determined by the diameter of the vacuum tube between the target and the soft–x-ray spectrometer. In order to decrease the effect of shot-to-shot line-intensity fluctuations, the 182-Å radiation was normalized to the O VI 173-Å line intensity in Fig. 4 (the 173-Å line intensity was quite uniform across the scan as can be seen in Fig. 3). Our initial interpretation was that this rising intensity of 182-Å radiation near the edges of the scan was due to diffraction effects on the edges of the target slot. However, a more probable effect may just be the reflection of the 182-Å radiation (grazing-incidence reflection) inside the vacuum tube. In the future, we plan to reinstall the grazing-incidence mirror and relocate the axial soft–x-ray spectrometer with the entrance slit in the focal plane of the mirror in order to measure the divergence of 182-Å radiation in the far field.

Knowledge of the divergence allowed us to estimate the total power of the soft–x-ray beam, ~100 kW, from measurements (using absolute-intensity-calibrated spectrometers[2]) of the total intensity of the 182-Å radiation (4×10^8 W sr^{-1}) and pulse duration (~10–30 nsec). This corresponds to a pulse energy of 1–3 mJ.

In order to understand better our earlier measurements of the radial dependence of the gain profile in the plasma column and the effect of this profile on the divergence, a one-dimensional hydrodynamic plus atomic-physics model has been developed.[5]

A key element in obtaining a high gain length was the realization, from measurements of the radial profiles of the C VI line radiation, that the most favorable conditions for maximum gain should exist in the off-axis regions of the plasma column. By variation of the position of the laser focus on the carbon-disk target with respect to the observation volume of the axial and transverse monochromators, it was possible to measure the gain as a function of radius, r, in the plasma column. It was seen that with increasing r there was a rapid rise in gain which reached a maximim near $r \approx 1.3$ mm for optical plasma conditions and decreased rapidly for larger r.

In the computer model a single mean flow velocity was used to describe the ion mass motion. After solution of time-dependent equations for the ion density, momentum, and electron energy, the gain was calculated by a postprocessor code from the electron density, temperature, and number density of the ground-state populations of fully stripped and hydrogenlike carbon. Because the laser pulse length is longer than the compressional Alfveń transit time, radial pressure balance is quickly established in the plasma. Strong heating on the cylindrical axis of symmetry (at the laser focus) leads to a centrally peaked temperature profile with a corresponding electron density minimum. On the other hand, off axis, strong radiative cooling by C IV leads to low-temperature, high-density conditions conductive to a fast recombination rate and high 182-Å gain. With the introduction of an ion diffusion rate an order of magnitude greater than the classical value, totally stripped ions were transported from the center to the cold, off-axis region where fast recombination generated high gain.

Figure 5 shows the predicted gain versus radius and it can be seen that high gain occurs in a narrow $\sim$50–100-μm-wide annulus at a radius of 1.4 mm. This is in excellent agreement with previous experimental measurements[2] of the radial distribution of gain in the plasma. Refraction of the 182-Å emission in the plasma is negligible because the electron density ($n_e \lesssim 10^{19}$ cm^{-3}) is too low and thus an estimate of the divergence of the stimulated emission in single-pass amplification can be obtained from ray tracing. With an annular width of 50 μm and a plasma length of 1 cm, the angular range of rays that pass through the gain region is 10 mrad. With a peak in the gain profile at a particular radius the divergence will be even less and thus the 1D calculations provide a good understanding of the remarkably low value of the measured divergence.

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[1]D. L. Matthews *et al.*, Phys. Rev. Lett. **54**, 110 (1985).

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

[3]See, for example, Proceedings of the Conference on Short-Wavelength Radiation: Generation and Application, Monterey, California, March, 1986 (American Institute of Physics, New York, to be published); also Proceedings of International Conference on X-ray Lasers, Assois, France, April, 1986, J. Phys. (Paris) (to be published).

[4]T. W. Barbee, Jr., S. Mrowka, and M. C. Hettrick, Appl. Opt. **24**, 883 (1985).

[5]E. J. Valeo, C. Keane, and R. M. Kulsrud, Bull. Am. Phys. Soc. **30**, 1600 (1985); also S. Suckewer *et al.*, in Proceedings of the International Conference "Laser 85," Las Vegas, Nevada, December 1985 (to be published).