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DIVERGENCE MEASUREMENTS OF SOFT X-RAY
LASER BEAM

By

S. Suckewer, C.H. Skinner, D. Kim,
E. Valeo, D. Voorhees, and A. Wouters

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PLASMA
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Divergence Measurements of Soft X-Ray

Laser Beam

MASTER

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Abstract

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The divergence of the CVI 182 Å lasing line generated in a rapidly recombining, magnetically confined plasma column was measured using 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 this data a peak 182 Å intensity 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 Livermore and Princeton groups at the APS meeting in Boston (November 1984) of the achievement of high gain in Se XXV at 206-209 Å and in CVI at 182 Å, 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.¹ In the Princeton experiment, where amplification of stimulated emission at 100 (a one-pass gain length of $k \approx 6.5$) 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 TEA CO₂ laser with a carbon disc target in a strong (90 kG) magnetic field. The CO₂ 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 hydrogen-like carbon (CVI). Installation of a soft X-ray mirror³ 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 and absolute divergence of the CVI 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 due to 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. One example is shown in Fig. 1. In the transverse spectrum, the spontaneous CVI 182 Å emission is weak compared to the strongest line in the spectrum, OVI 173 Å. However, in the axial direction, the stimulated 182 Å emission dominates the spectrum.

Some exciting results were obtained recently by scanning 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 a glass strip, 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 non lasing lines. This may be seen in Fig. 2 where the 182 Å emission on axis was so intense the detector was saturated whereas the CVI 186 Å and OVI 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 $x = 250\mu$ in Fig. 2. This spectrometer horizontal position was established for all earlier measurements² by aligning the system: CO₂ laser focusing mirror, target slot, and spectrometer entrance slit using a He-Ne laser beam. However, from Fig. 2 we can see that the maximum gain is near $x = 200\mu$ with a corresponding amplification of the 182 Å radiation of approximately a factor of 5 larger than presented earlier.² 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 horizontal scan of both the collimating slit and the axial soft X-ray spectrometer. 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 CVI 182 Å, CV 186 Å, and OVI 173 Å lines for a magnetic field $B = 20$ kG. For 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, CVI 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 ~ 9 mrad. At the same time the intensities of the nonlasing lines OVI 173 Å and CV 186 Å are quite constant over the scan region ~ 3 cm.

With increasing magnetic field ($B = 35$ kG 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 μ transversely). We also observe a slight shift of the peak intensity of 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 $182 \text{ \AA}$ radiation was normalized to the OVI $173 \text{ \AA}$ line intensity in Fig. 4 (the $173 \text{ \AA}$ line intensity was quite uniform across the scan as can be seen in Fig. 3). Our initial interpretation was that this rising intensity of $182 \text{ \AA}$ 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 $182 \text{ \AA}$ 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 $182 \text{ \AA}$ radiation in the far field.

Knowledge of the divergence allowed us to estimate the total power of the soft X-ray beam $\sim 100 \text{ kW}$ from measurements of the total intensity of the $182 \text{ \AA}$ radiation ($\sim 1\text{--}3 \text{ mJ}$) and pulse duration ($\sim 10\text{--}30 \text{ nsec}$).

In order to better understand 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.⁴

A key element in obtaining a high gain length was the realization, from measurements of the radial profiles of the CVI line radiation, that the most favorable conditions for maximum gain should exist in the off-axis regions of the plasma column. By varying the position of the laser focus on the carbon disc 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 maximum near $r \approx 1.3 \text{ mm}$ for optimal 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 hydrogen-like carbon. Because the laser pulse length is longer than the compressional Alfvén 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 CIV leads to low temperature, high density conditions conducive to a fast recombination rate and high $182 \text{ \AA}$ 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 $\sim 50\text{-}100\mu$ wide annulus at a radius of 1.4 mm. This is in excellent agreement with previous experimental measurements² of the radial distribution of gain in the plasma. Refraction of the $182 \text{ \AA}$ emission in the plasma is negligible because the electron density ($n_e \sim 10^{19} \text{ cm}^{-3}$) 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 50μ 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.

Acknowledgments

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References

1. See, for example, Proc. of Conf. on Short Wavelength Radiation: Generation and Application, Monterey, CA (March 1986), AIP Conf. Proc. to be published; also Proc. of Int. Conf. on X-Ray Lasers, Assois, France (April 1986), to be published in J. Phys.
2. S. Suckewer, C.R. Skinner, H. Milchberg, C. Keane, and D. Voorhees, Phys. Rev. Lett. 55, 1753 (1985).
3. T.W. Barbee, Jr., S. Mrowka, and M.C. Hettrick, Appl. Opt. 24, 883 (1985).
4. E.J. Valeo, C. Keane, and R.M. Kulsrud, Bull. Am. Phys. Soc. 30, 1600 (1985); also S. Suckewer et al. in Proc. Int. Conf. "Laser 85," Las Vegas, NV (December 1985).

Figure Captions

Fig. 1 Transverse and axial spectra in the region near $182 \text{ \AA}$ from a carbon disc target with four carbon blades. The laser energy was 500 J.

Fig. 2 Transverse scan of CVI $182 \text{ \AA}$, CV $186 \text{ \AA}$, and OVI $173 \text{ \AA}$ emission showing a strong central peak for the CVI $182 \text{ \AA}$ stimulated emission. In this figure, "Satur." indicates the level above which the detector is saturated. Intensities above this level were obtained by comparing the nonsaturated region of the $182 \text{ \AA}$ spectral profiles.

Fig. 3 Absolute divergence measurements ($\sim 9 \text{ mrad}$) of the $182 \text{ \AA}$ lasing radiation for a magnetic field $B = 20 \text{ kG}$. For comparison are shown the intensities of nonlasing lines OVI $173 \text{ \AA}$ and CV $186 \text{ \AA}$, recorded simultaneously with the $182 \text{ \AA}$ line.

Fig. 4 Divergence measurements ($\sim 5 \text{ mrad}$) of the $182 \text{ \AA}$ radiation (relative to the OVI $173 \text{ \AA}$ line) for $B \approx 35 \text{ kG}$ and 50 kG .

Fig. 5 Radial profiles of CVI $182 \text{ \AA}$ gain, k_{max} , and electron temperature, T_e , versus radius in the plasma column as predicted by a 1D code.

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SPECTRA NEAR C VI 182 Å LINE (C-Disc With 4 C-Blades)

Fig. 1

Fig. 2

Fig. 3

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Fig. 4

Fig. 5

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