

Gain measurements at 18.22 nm in C VI generated by a Nd:glass laser

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We present recent gain measurements in C VI at 18.22 nm for a soft-x-ray amplifier produced by a line-focused glass laser (1.053 μm) on a solid carbon target. The maximum gain measured was $8 \pm 2 \text{ cm}^{-1}$ in the recombining plasma column, with additional radiation cooling by iron impurities.

Recent research in soft-x-ray laser development is progressing in the direction of obtaining shorter wavelengths. Significant advances are also being made in the XUV region. Much attention is being devoted to the first applications of these lasers. The possibility of using soft-x-ray lasers for the microscopy of living cells has stimulated research in the development of x-ray lasers operating in the wavelength region of 2.33–4.37 nm, the so-called water window.^{1,2} Impressive advances in longer-wavelength XUV lasers, such as the one recently demonstrated at 108.9 nm,^{3,4} have significant potential applications in chemistry. An important point, however, that is rarely discussed is the laser energy required for these applications. For example, in order to record a high-resolution image of a biological cell on a photoresist, substantial laser beam energy is required. This is a significant concern in our current soft-x-ray microscopy experiments,⁵ even for the maximum output energy of our current 18.22-nm laser.⁶

We have, therefore, applied a significant effort to increase the energy of the 18.22-nm soft-x-ray laser. One approach has been to develop additional amplifiers. This technique can also be applied to the shorter-wavelength region, where our current goals include the generation of lasing action near 10.0 nm, using ions in the Li-like sequence,⁷ and down to 1.0 nm, using a powerful picosecond laser for selective excitation.⁸

In this Letter we present the first step in developing such amplifiers by the generation of gain in C VI at 18.22 nm using a Nd:glass laser beam brought to a line focus on a solid carbon target in a strong magnetic field (field lines parallel to the line focus). The role of the magnetic field is considered to be less important here than in our research in generating gain at 18.22 nm using a CO₂ laser that is point focused along the magnetic-field axis because of a much higher initial electron density for the 1- μm Nd:glass laser than for the 10- μm CO₂ laser. However, in the future we plan to combine this amplifier with our CO₂-laser-pumped, magnetically confined soft-x-ray laser; thus it is necessary that the Nd:glass-laser-pumped amplifier also work in a magnetic field and have a similar transverse dimension.

In the experiments the maximum pumping laser energy used was 40 J, which was limited by the area of the beam input optics, and the pulse duration was 3 nsec. The 5.1-cm-diameter laser beam was line focused onto the cylindrical target by the combination of a 67-cm focal-length spherical lens and a 450-cm focal-length cylindrical lens (Fig. 1). The dimensions of the line focus were $\sim 100 \mu\text{m} \times 5 \text{ mm}$. The length of the line focus was limited by the size of the magnet port. One of the features of the target system was the capability of rotating the target so that for every shot a fresh target surface is exposed by the laser. A similar condition was created in the experiments performed by Jaeglé *et al.*⁹ by translation of a plane aluminum target. The gain was measured by changing the target length and hence the plasma length, as shown in Fig. 1.

Another feature was a stainless-steel blade in front of the target. The 0.25-mm-thick stainless-steel blade was placed 0.8 mm from the target surface. The function of the blade was to provide an additional cooling source: fully stripped carbon ions in the laser-produced plasma interact with the blade and cool rapidly through thermal conduction and line radiation. The concept of conductive cooling by a metal plate was first suggested by Bhagavatula and Yaakobi.¹⁰

Experiments with a target without the stainless-steel blade showed significantly lower gain: with 32 J

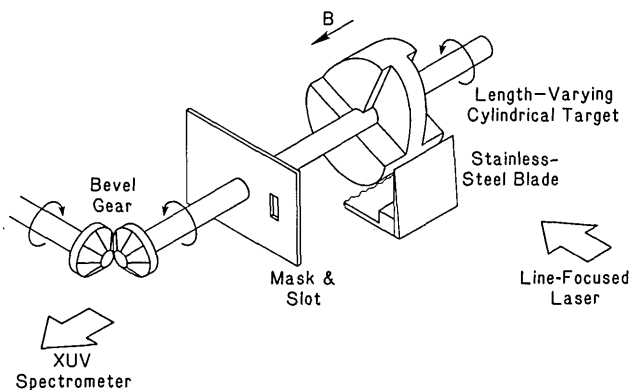


Fig. 1. The rotatable-target system. B, An axial magnetic field.

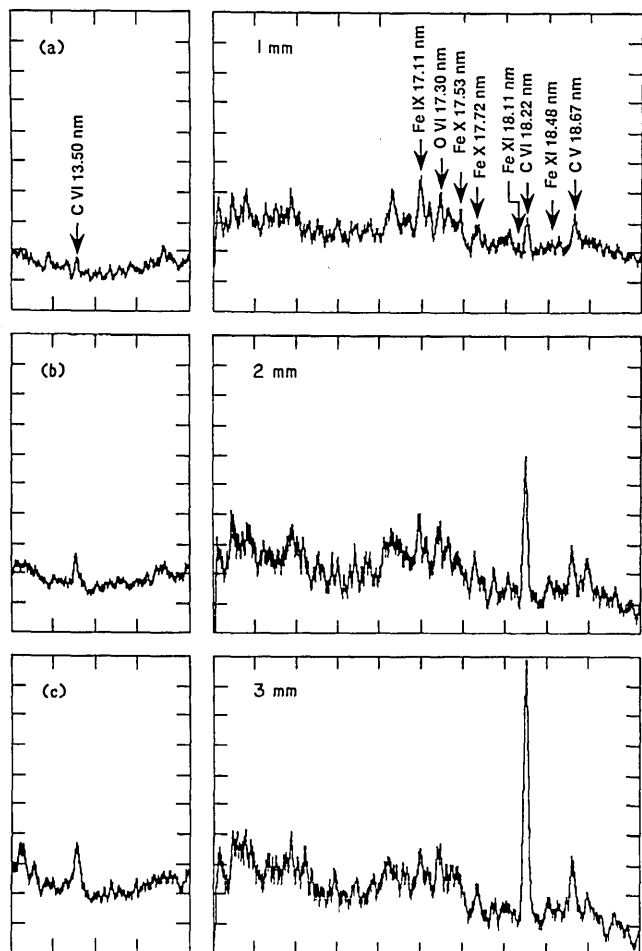


Fig. 2. Experimental spectra obtained by a XUV spectrometer for plasma lengths of (a) 1 mm, (b) 2 mm, and (c) 3 mm with 25 J of laser energy and a magnetic-field strength of 50 kG.

of laser energy a gain of 4.5 cm^{-1} was measured with the blade, compared with $0.4\text{--}0.8 \text{ cm}^{-1}$ without the blade. A limited spatial region is selected by a slot in a mask 1.5 cm from the target in the axial direction and viewed by a soft-x-ray spectrometer located 2.6 m from the target in the axial direction. For the data presented below the slot size was $0.8 \text{ mm} \times 2 \text{ mm}$, and the near edge of the slot was 0.5 mm from the target surface. Hence the region selected by the slot included an area surrounding the blade.

Experiments in which the radial distance from the edge of the slot to the target was varied indicated that C VI was abundant in the region 0–2 mm from the target surface. The region selected by the slot for the gain measurements (0.5–1.3 mm from the target surface) was judged to have the most favorable conditions for gain.

Figure 2 shows the experimental data recorded with an axial-grazing-incidence soft-x-ray spectrometer. The angle of incidence was 88° , and the intensities of multiple orders were negligible. It was equipped with a 1200-groove/mm grating at a blaze angle of 1° and a multichannel detector. The intensity dependences of the C VI 13.50-nm, C VI 18.22-nm, and C V 18.67-nm

lines with respect to plasma length are shown. The data were obtained with 25 J of laser energy and the stainless-steel blade and slot dimensions as described above. The magnetic field was 50 kG. In the experiments we found that the variation of laser intensity over the line focus limited the length of the plasma, over which gain could be achieved, to approximately 3 mm. Attempts to create a uniform plasma longer than 3 mm showed that a C VI 13.50-nm intensity increased less than linearly. This indicated that the weaker laser intensity beyond the central 3-mm-long region did not create the same plasma conditions as in the central region. For the gain measurements plasma lengths of 1, 2, and 3 mm were used, and the plasma uniformity is evidenced by the linear increase of the C VI 13.50-nm intensity with length. Emission by iron is clearly seen in the spectra. The 18.22-nm line from C VI is blended with a line of similar wavelength from Fe XI 18.22 nm. Without correction for contamination due to Fe XI 18.22 nm, the estimated gain is $5 \pm 2 \text{ cm}^{-1}$. The line intensity of Fe XI 18.22 nm is known to be approximately the same as those of Fe XI 18.11 and 18.48 nm.¹¹ Since the Fe XI 18.11-, 18.22-, and 18.48-nm lines originate from the same $3p^3d$ upper level, the use of line intensity ratios in Ref. 11 provides a reasonable approximation in estimating the contribution of Fe XI 18.22 nm. The average of the line intensities of Fe XI 18.11 and 18.48 nm is used in correcting the line intensity of C VI 18.22 nm. In Fig. 3 the corrected line intensities of C VI 18.22 nm (integrated over time and frequency) are plotted versus the plasma length.¹² The data have been fitted by the relation¹²

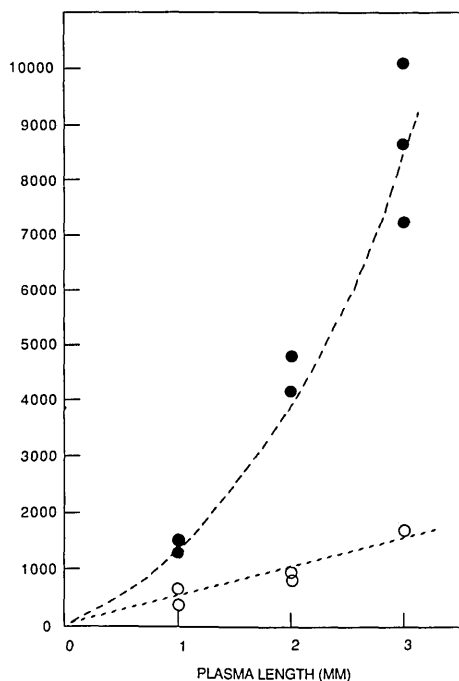


Fig. 3. Intensities of C VI 18.22 nm (filled circles) and 13.50 nm (open circles) versus plasma length with 25 J of laser energy and a magnetic-field strength of 50 kG. A stainless-steel blade was placed in front of the target for rapid cooling. The dashed curve is a theoretical gain curve of 8.1 cm^{-1} ; C VI 13.50 nm increases linearly.

$$I \sim \frac{(e^G - 1)^{3/2}}{(Ge^G)^{1/2}}, \quad (1)$$

which describes the output intensity of a Doppler-broadened, homogeneous source of amplified spontaneous emission of gain-length product G . The theoretical gain curve of $g = 8.1 \text{ cm}^{-1}$ is shown in Fig. 3. It can clearly be seen that the C VI 18.22-nm line increases exponentially and that the C VI 13.50-nm line increases linearly with the plasma length. The 13.50-nm line is expected to have much less gain than the 18.22-nm line owing to its lower transition rate and shorter wavelength.

In conclusion, we have demonstrated a high gain of $8 \pm 2 \text{ cm}^{-1}$ at 18.22 nm in C VI using the newly developed carbon target system pumped with a 25-J, 3-nsec Nd:glass laser. We plan to combine this amplifier with the present soft-x-ray 18.22-nm laser in a CO₂-laser-produced, magnetically confined carbon plasma in order to increase the beam energy. The output energy is an important issue for the application of a soft-x-ray laser to x-ray microscopy and may be a significant obstacle in the utilization of systems with a small aperture of the lasing medium.¹³

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