Development of small-scale soft-x-ray lasers: aspects of data interpretation


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The widespread application of soft-x-ray laser technology is contingent on the development of small-scale soft-x-ray lasers that do not require large laser facilities. Progress in the development of soft-x-ray lasers that are pumped by a neodymium laser of energy 6–15 J is reported. Some aspects of data interpretation and gain measurements in such systems are discussed.

1. INTRODUCTION

The field of x-ray laser technology has recently matured to the stage in which the application of these devices to fields such as x-ray microscopy is under way, and commercial units are being planned with a view to industrial applications such as micro lithography. A critical factor in such developments is the scale and hence the cost of these devices. The collisionally pumped soft-x-ray laser in neonlike ions, developed at the Lawrence Livermore National Laboratory, requires a large-scale laser facility such as Novette or Nova to create a plasma of appropriate conditions. At Princeton University a 3-mJ, 182-Å soft-x-ray laser, based on a recombining plasma, was developed that had an efficiency almost 2 orders of magnitude higher than the collisionally pumped one. However, the required pump laser, a 300-J CO₂ laser, was still large. In order to increase the output energy and efficiency of the 182-Å soft-x-ray laser, we have been developing soft-x-ray amplifiers. A gain of 8 cm⁻¹ was measured in a 3-mm-long carbon plasma that was transversely pumped by a 3-nsec neodymium laser pulse with an energy of 25 J, of which only 15 J impinged upon the target. We have also demonstrated an amplification of 4.5 cm⁻¹ on the C vi m = 3 to n = 2 transition at 182 Å in a recombining carbon plasma when pumped by only 6 J. In this paper we present the initial gain measurements at 182 Å. We also present some measurements that show a nonlinear rise of intensity with length in an aluminum plasma pumped by a 6- or 12-J laser pulse. We discuss data interpretation and gain measurements in such systems.

2. AMPLIFICATION AT 182 Å WITH A 6-J PUMP LASER

In this section we present gain measurements on the C vi 182-Å transition in a carbon plasma produced with a 6-J, 3-nsec Nd:glass laser pulse. The laser creates a plasma with a large fraction of totally stripped carbon ions. Rapid recombination after the laser pulse leads to a collisional radiative cascade and high populations in the excited levels of hydrogenlike carbon. The population in level n = 2 decays rapidly by Lyman-α radiation, and hence a population inversion builds up between level 3 and level 2 with gain at the m = 3 to n = 2 transition at 182 Å. The experimental setup was the same as that presented in an earlier paper. Figure 1 shows the rotatable-target system used. A 67-cm focal-length spherical lens and a 450-cm focal-length cylindrical lens were utilized to produce an approximately 100 μm × 5 mm line focus on a length-varying cylindrical target. The target lengths used in this experiment were 1, 2.5, and 4.5 mm (limited by the diameter of the access ports in the target chamber). A 0.8 mm x 2 mm slot in a mask that was located 1.5 cm away from the target in the axial direction selected a limited spatial region, which was viewed by an axial soft-x-ray spectrometer equipped with a multichannel detector. In the experiments the slot was placed in such a way that it selected a spatial region 0.0–0.8 mm from the target surface. The axial emission was imaged by a grazing-incidence mirror onto the entrance slit of the spectrometer. The mirror was constructed by bending a glass strip; thus the optical quality was not ideal. The plasma region viewed by the spectrometer could be changed by translating it perpendicular to the optic axis. These spatial scans indicated that the spectrometer viewed an ~200-μm wide region in the plasma within the limits of the 800-μm-wide mask.

Figure 2 shows the intensity variation of the C v 135-Å, O v i 173-Å, C vi 182-Å, and C v 186-Å lines with respect to the plasma length with a 6-J, 3-nsec laser pulse. Unlike in earlier work, no stainless-steel blade or magnetic field was used here. The C vi 182-Å line (3–2 transition) increased nonlinearly, while the C vi 135-Å (4–2 transition) and some other lines increased linearly, as was expected from optically thin spontaneous emission from a homogeneous plasma of length equal to the length of the target. This result is a clear indication of gain on the 182-Å line. The difference in the length dependence of the 182- and 135-Å lines here is very important. The contribution of the fourth order of the C vi 33.74-Å line to 135 Å was small and was estimated from measurements of the second- and fifth-order 33.74-Å line to be approximately three counts from 1-mm targets and seven counts for 4.5-mm targets (~10% of the total 135-Å signal). This contribution was subtracted from the 135-Å data in Fig. 3.
The target chamber was modified to provide easier control of the target and slot position and was relocated outside the existing magnet assembly. The dimensions and

![Fig. 1. Rotatable target system.](image)

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Within the experimental uncertainty, the intensity contribution of the fourth-order 33.74-Å line did not change significantly with length. The contribution is small because of the large opacity of this line even in a 1-mm plasma. The intensity of optically thick lines in plasmas that are much larger than the optical depth is substantially independent of the plasma size, and hence the small contribution of the fourth-order 33.74-Å line to the 135-Å intensity is proportionally less at a 4.5-mm length than at a 1-mm length.

The data were fitted by a nonlinear regression model, which was used to perform a least-squares fit of the data to the relation

\[ I(L) = \frac{[\exp(GL) - 1]^{5/2}}{[GL \times \exp(GL)]^{1/2}} \]  

Equation (1) describes the output intensity of a Doppler-broadened, homogeneous source of amplified spontaneous emission of gain–length product GL. The fit yielded a value of the gain of 4.5 ± 0.5 cm⁻¹ on the C vI 182-Å line and of 0.5 cm⁻¹ on the C vI 135-Å line (see Fig. 3).

![Fig. 3. Intensities of C vI 182- and 135-Å lines versus plasma length and (dashed curves) least-squares fits to the gain equation [Eq. (1)] with a gain of 4.5 cm⁻¹ for the 182-Å line.](image)

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![Fig. 4. Intensities of C vI 182-Å and C v 186-Å lines versus plasma length and (dashed curves) least-squares fits to the gain equation [Eq. (1)] with a gain of 4.4 cm⁻¹ for the 182-Å line.](image)

**Fig. 4.** Intensities of C vI 182-Å and C v 186-Å lines versus plasma length and (dashed curves) least-squares fits to the gain equation [Eq. (1)] with a gain of 4.4 cm⁻¹ for the 182-Å line. Each point represents the peak intensity of a spectral line from one laser shot.
position of the slot were varied in a series of experiments further to isolate the gain region from the surrounding plasma. Gain was typically observed in the region 600–800 μm from the target surface. For Fig. 4 the slot was reduced to 400 μm and positioned to view the region 600–1000 μm from the target surface. The nonlinear increase of the 182-Å stimulated emission is clearly seen in contrast to the linear dependence of the spontaneous emission from the C v 186-Å 4d 3P–2p 3P transition. The gain at 182 Å was estimated to be 4.4 ± 0.5 cm⁻¹ by means of Eq. (1). Extensions of this work to longer plasma lengths are in progress. The above result augurs well for the commercial availability in the near future of relatively inexpensive soft-x-ray lasers for a variety of novel applications.

3. EXPERIMENTS ON ALUMINUM PLASMAS, ASPECTS OF DATA INTERPRETATION

In the above experiment the plasma length was limited to 4.5 mm by the internal diameter of the ports available in the target chamber inside the magnet. A new target chamber was constructed in which plasmas of length of 1 cm or greater could be produced. This system also had much greater flexibility for positioning and angular adjustment of the target and detector (Fig. 5). In this section we present some results from this system that show a nonlinear increase of intensity with length of Al x and Al xi lines in an aluminum plasma. The lithium sequence ions, such as Al xi, were first used in soft-x-ray laser development by Jaeglé and co-workers; however, the present work on aluminum plasmas that were pumped with a low-energy neodymium laser was stimulated primarily by the surprising results of Hara et al., which indicated gain on almost all the Al x and Al xi lines observed. It was a simple task to repeat the experiments of Hara et al. by changing the target material to aluminum. Gain can be produced in lithiumlike aluminum in a way analogous to that for hydrogenlike carbon by collisional radiative cascade in a rapidly recombining plasma. For lithiumlike aluminum the fast 3p–2s radiative transition depletes the 3p level and can produce a population inversion and gain on the 4d–3p transition at 154 Å.

A Nd:glass laser, operated at 6 or 12 J with a 3-nsec pulse length, was brought to a line focus by a combination of four lenses. Two spherical lenses with a combined focal length of 60 cm and two cylindrical lenses produced a sharp line focus 12 mm long with a width of 50 μm (FWHM) on a rotatable aluminum target with sectors of differing length (2, 6, and 10 mm). Axial emission was detected by a soft-x-ray multichannel spectrometer. The spectrometer was attached to a rotatable arm that was pivoted under the target so that the angle that it viewed could be varied by ±2° with respect to the target. The target assembly was on a platform that could be rotated ±2° around a vertical axis, so that by combining the two motions emission over a ±4° axial range in the horizontal plane could be recorded. This system was designed to permit the most precise alignment of the target with respect to the spectrometer and also to enable us to detect a stimulated soft-x-ray beam that had been diverted from the nominal axial direction by refraction in the plasma. Gain was expected to occur over a limited plasma region; hence a slot with an open area 3 mm high and 0.35 mm wide was placed on axis 4 cm from the target in order to limit the view of the spectrometer. The position of the slot could be adjusted to permit viewing of regions of the plasma at different distances from the target surface. For the data presented below, emission from region 0.75–1.1 mm from the target surface was detected.

In the experiment a search for gain was performed by varying the experimental parameters (including the target length) and looking for conditions in which the intensity of candidate lines increased with length at a rate that was faster than linear. A faster-than-linear rise of intensity

Fig. 5. Improved experimental setup for gain measurements showing range of angular adjustments available.

Fig. 6. Aluminum spectra obtained at 6-J laser energy with target lengths of 2 and 10 mm.
period and 250-μm entrance slit dispersed the axial plasma emission along the entrance slit of an x-ray streak camera. The entrance slit was 12-mm long and 1-mm wide and was coated with a 200-A-thick aluminum photocathode. This grating-and-streak-camera arrangement resulted in a source-size-limited spectral resolution for these experiments of ~3 Å. The spectral range of the instrument extended from 110 to 190 Å.

Figure 6 shows axial spectra of Al iv, O vi, Al x, and Al xi lines at 2- and 10-mm target lengths. A dramatic increase of the intensities of the Al x and Al xi lines is seen with the 10-mm target as compared with the 2-mm target, while the Al iv and O vi lines show a sublinear increase. Figure 7 shows peak intensities taken at 2-, 6-, and 10-mm target lengths and a curve fitted to the data. The theoretical fit was derived from a nonlinear regression model,⁶ as in the C vi case. In general the transition linewidth will be a convolution of the Stark and the Doppler broadenings, but for present purposes we have used the gain equation based on the Doppler broadening.

A higher laser energy was used in order to increase the output intensity. Data taken at 12 J are shown in Figs. 8 and 9. Here the increase with the length is even more dramatic; for instance, the Al xi 141-Å (3s-4p) intensity increases from 2 to 10 mm by a factor of 50 and is an excellent fit to the gain equation for a gain of G = 5.1 cm⁻¹.

The emission from the plasma was recorded on a time-resolving streaked spectrometer¹¹ that was placed on axis, on the side of the plasma opposite the spectrometer. A free-standing gold transmission grating with a 3000-Å period and 250-μm entrance slit dispersed the axial plasma emission along the entrance slit of an x-ray streak camera. The entrance slit was 12-mm long and 1-mm wide and was coated with a 200-A-thick aluminum photocathode. This grating-and-streak-camera arrangement resulted in a source-size-limited spectral resolution for these experiments of ~3 Å. The spectral range of the instrument extended from 110 to 190 Å.

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The data show high gain on all the Al xi and Al x lines with the largest $gA$ value (3d–4f at 154 Å), shown in Eq. (2):

$$G = \frac{c}{\Delta \lambda} \frac{\lambda^4}{8\pi c} g_i A_i k (N_i - N_k).$$

(2)

Here $G$ is the gain coefficient and $\lambda$ the wavelength; $g$ is the statistical weight, $A_i$ the radiative transition probability, and $N$ the population of the upper level $i$ and the lower level $k$. The highest gain was expected on the 3–4 transition with the largest $gA$ value (3d–4f at 154 Å); however, the data show high gain on all the Al xi and Al x lines observed, similar to those of Ref. 8. Particularly surprising was the strong increase apparent on the Al xi 141-Å line, which has a $gA$ value much lower than those of the 150- and 154-Å transitions. The time history observed with the streak camera showed no difference between the time evolution at 154 Å and the continuum background at 162 Å (Fig. 10). Another unexpected feature is the large rise in the background continuum emission, from 5–10 counts at 2 mm to $\sim$200 counts at 10 mm. These features raised concerns about the homogeneity of the plasma along its length. Specifically, were the level populations in the region of the 2-mm plasma viewed by the spectrometer identical to the conditions in the 10-mm section? As shown in Fig. 5, the 2-, 6-, and 10-mm sections shared a common boundary on the spectrometer end of the target wheel. In order to test whether the plasma was homogeneous, a target was built with the 2-mm sections on both ends of the target and the 6-mm section on the end of the target away from the spectrometer. First the conditions were arranged so as to reproduce the previous 10-mm spectra, and then the emissions from the two 2-mm sections at each end of the target were compared. It was immediately apparent that there was a large difference in intensity between the 2-mm section at the spectrometer end and the 2-mm section at the opposite end. When the average of the 2-mm results was taken, the best fit to the data was then a linear increase in intensity with target length, as shown in Fig. 11(a). The reason for the nonuniformity lay in a small angle between the target surface and the region viewed by the spectrometer (Fig. 12), possibly caused by refraction. In order to verify this, the target was rotated about a vertical axis to change the position of the plasma generated by the two 2-mm sections with respect to the region viewed by the spectrometer. With a 2° rotation the Al xi 154-Å emission from the two ends became equal [Fig. 11(b)]. In this configuration, however, the length dependence of the emission was linear. In conclusion, the nonlinear increase in Figs. 6–9 was caused by geometrical effects and not by stimulated emission.

As noted above, the measurement of an exponential intensity increase with length is commonly regarded as conclusive evidence for gain (see, for instance, Ref. 8). While this, of course, is clear for large gain–lengths ($GL > 4$), it can be difficult to distinguish between a general nonlinear dependence and an exponential increase at small gain–lengths ($GL < 4$). In view of the above results it is
clear that, while a nonlinear increase may be an encouraging sign of gain, it is by no means sufficient proof that gain is present. The measurements of a linear dependence of 135-Å intensity with length in the carbon study presented in Section 2 provide an essential confirmation that the nonlinear dependence of the 182-Å emission is caused by gain. As was done in some earlier studies (for example, Refs. 2, 4, 7, and 12), it is critical to monitor the emission from nearby spontaneous-emission lines in the same ion, preferably lines with a common level to the lasing line, to ensure that one is viewing a homogeneous plasma and that the comparison of plasmas of differing lengths is a valid technique for detection of gain. This is particularly important for measurements of low gain-lengths, GL < 4, where the enhancement of stimulated as compared with spontaneous emission is less than an order of magnitude.

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