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DEVELOPMENT OF SMALL SCALE SOFT X-RAY LASERS

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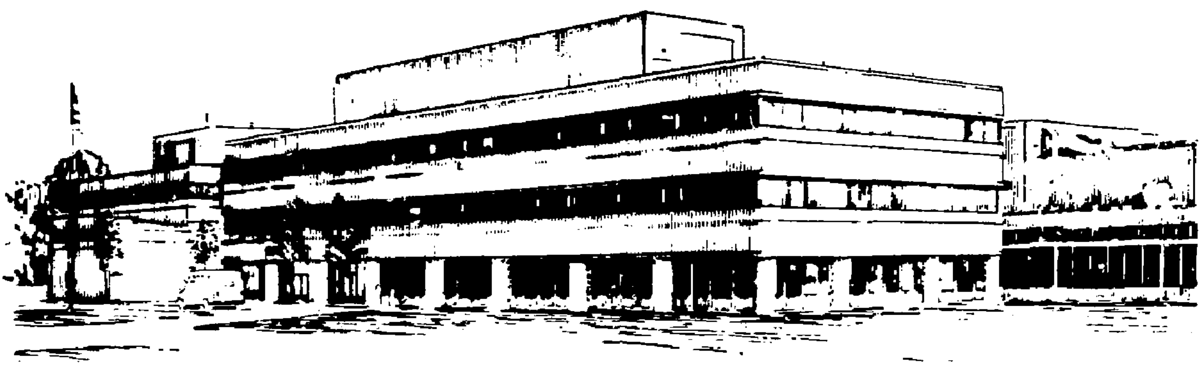

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DEVELOPMENT OF SMALL SCALE SOFT X-RAY LASERS

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ABSTRACT At present rapid progress is being made in the application of soft x-ray lasers to fields such as microscopy and microlithography. A critical factor in the range of suitable applications is the scale and hence cost of the soft x-ray lasers. At Princeton, gain at 182Å has been obtained with relatively low pump laser energies (as low as 6J) in a 'portable' small-scale soft x-ray laser system. We will also discuss aspects of data interpretation and pitfalls to be avoided in measurements of gain in such systems.

1. INTRODUCTION

When the first laser was demonstrated by Maiman in 1960, the directionality and brightness of these new sources caught the public imagination but they were slow to find applications. In fact, there was an extended period when they were known as "solutions looking for a problem." Today of course 30 years later the situation is very different with laser scanners in widespread use in shops and compact disk players and even in dentists' offices.

It is now six years since the first demonstration of high gain in the soft x-ray region, and we are now in a period between demonstrations of gain in different systems and the acceptance of x-ray lasers as practical and useful devices. Of course research on soft x-ray lasers is expensive and if it was going to take 20 years or so for applications to emerge then the funding prospects might indeed be limited. Fortunately the development of applications of soft x-ray lasers is in progress and it is very important to demonstrate as soon as possible that soft x-ray lasers are not just exotic and expensive specialized laboratory phenomena but can be practical tools with important applications.

This work is part of a larger effort at Princeton of which an overview is given in the paper by Suckewer(1990). Work on the two laser approach aimed at generating lasing in the 10Å region is reported by Tighe(1990). This paper is about the work at Princeton to develop small scale soft X-ray lasers for applications. A review of the application of soft x-ray lasers to x-ray microscopy is given in this proceedings (Suckewer 1990) and in (Skinner 1990a).

2. SMALL SCALE SOFT X-RAY LASERS

The original recombination pumped 182Å laser at Princeton was based on a magnetically confined CO_2 laser produced plasma. While this laser continues to be used for applications development, efforts have begun to improve its performance by increasing the energy with additional amplifiers. To this end we are developing amplifiers pumped with a line focussed neodymium laser. Initial results yielded a gain of $8cm^{-1}$ on the CVI 182Å transition using a pump laser energy of only 15J on target (Kim 1989a). In other experiments (Skinner 1990b) gain of $4.5cm^{-1}$ at 182Å was obtained with only 6 J of driving laser energy. This is a remarkably low pump energy and has very favorable implications for the future widespread use of these devices. The target length in this case was limited by the diameter of access ports

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in the magnet. Although the gain was high, the relatively short target length limited the gain-length to GL≈2-3 and hence the output intensity of the stimulated emission was only several times that of the spontaneous emission. Clearly, from the point of view of applications we would like to be in the region of GL = 5 or more where the output is orders of magnitude higher than spontaneous emission. Practical obstacles such as plasma uniformity and refraction of the stimulated emission beam need to be overcome in order to maintain gain over larger lengths.

To address theses issues, a new target chamber was installed outside the solenoidal magnet which enabled longer length targets to be used. In order to maximize the gain and confine a plasma, the interaction region of a target was surrounded by a miniature chamber with stainless steel walls (see Figure 1). Gain is generated by recombination after the plasma is first ionized by the drive laser. The recombination rate and hence gain generated depend strongly on the cooling rate. The stainless steel walls confine the plasma and provide additional cooling both by radiation losses from iron impurities in the plasma and by thermal conduction.

A 67-cm focal-length spherical lens and two cylindrical lenses were operated to produce a ≤ 100 μm x 11 mm line-focus on a length-varying cylindrical target. A square apodiser was used to control the Nd laser beam cross section to improve the uniformity of the line focus. The target lengths used in this experiment were 2.5, 5.0, and 7.5 mm. A 0.2 x 2 mm slot in a mask located 10 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 0.4 - 0.6 mm from the target surface.

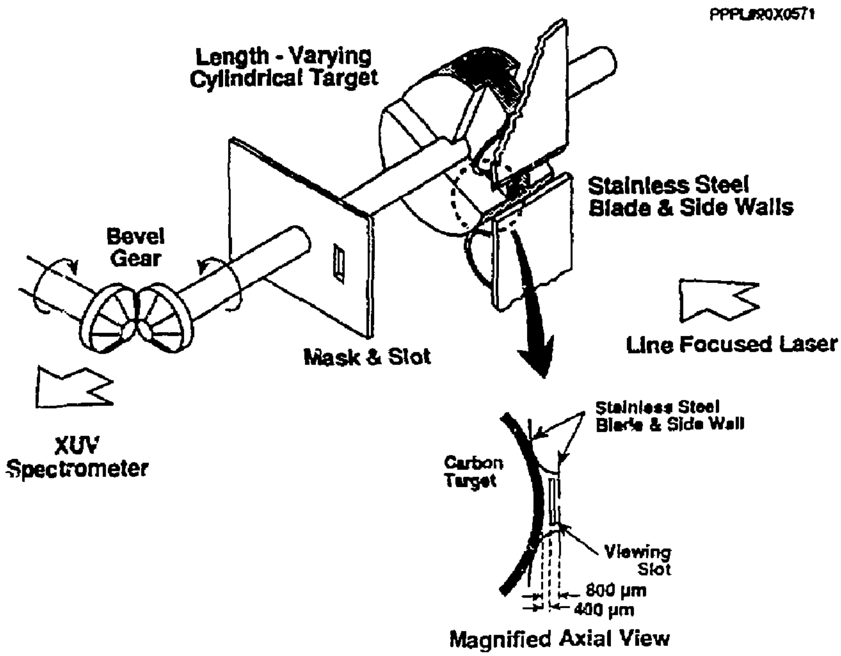

Fig. 1 The rotatable target system. The Nd laser enters through a stainless steel slot 400μm wide. The plasma is surrounded by flexible stainless steel walls to provide additional cooling and the view of the axial spectrometer is restricted to the region shown in the lower axial view. Part of the upper blade and side wall has been cut away in the drawing to display the target.

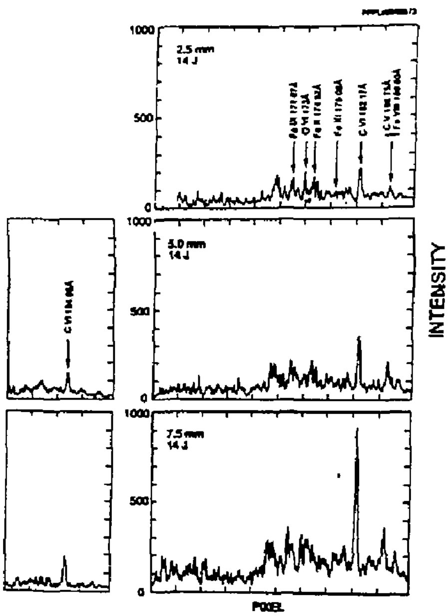

Fig. 2 Spectra obtained with 14J laser energy from carbon plasmas of length: (a) 2.5mm, (b) 5mm and (c) 7.5 mm.

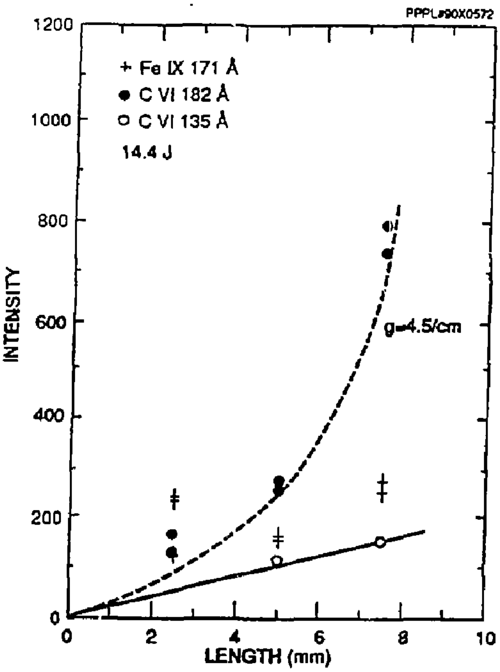

Fig. 3 Intensities of the CVI 182Å and 135Å lines versus plasma length and (dashed line) a least squares fit to the gain equation (eqn. 1) with a gain of 4.5 cm^{-1} for the 182Å line.

Preliminary results, obtained with a 14J, 3nsec laser pulse are shown in Figures. 2 and 3. A contribution from a FeXI 182.17Å line has been subtracted from the data. The Fe contribution was estimated from the intensity of the FeXI 178.1Å line. This line shares the same upper level ($3p^3 3d\ ^3D^o_2$) with FeXI 182.17Å and the relative intensity of these two lines is given by Kelly (1987). The CVI 182.17Å line (3-2 transition) increased non-linearly while the CVI 134.95Å and some other lines increased linearly as expected from optically thin spontaneous emission from a homogeneous plasma of length equal to the length of the target. This was a clear indication of gain on the 182.17Å line. The difference in the length dependence of the 182.17Å and 134.95Å lines here is very important. The data were fitted by a nonlinear regression model which performed a least-square fit of the data to the relation (Linford 1974) :

$$I(L) \propto \frac{(\exp(GL) - 1)^{3/2}}{(GL \times \exp(GL))^{1/2}} \qquad (1).$$

This 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 cm^{-1} on the CVI 182.17Å line. These results at remarkably low driving laser energy augur 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

A new target chamber has been constructed with improved access for the drive laser so that plasmas of length of 1cm or more could be produced (Skinner 1990b). Because of concern about deviations of the beam due to refraction, this system also had much more flexibility for positioning and angular adjustment of the target and detector. In this section we present some results from this system showing non-linear increase of intensity with length of AlX and AlXI lines in an aluminum plasma. The lithium sequence ions such as AlXI were first used in soft x-ray laser development by Jaeglé (1990); however the present work on aluminum plasmas created with a low energy Nd laser was primarily stimulated by the surprising results of Hara (1989) indicating gain on almost all AlX and AlXI lines observed. It was a simple task to repeat the experiments of Hara *et. al.* by changing the target material to aluminum.

A Nd glass laser, operated at 6J or 12J, was brought to a line focus by a combination of 4 lenses. Two spherical lenses with a combined focal length of 60cm and two cylindrical lenses produced a sharp line focus 12mm long with a width of 50μm (FWHM) on a rotatable aluminum target with sectors of differing length (2, 6, 10mm). Axial emission was detected by a soft X-ray multichannel spectrometer "SOXMOS" (Schwob 1989) SOXMOS was attached to a rotatable arm pivoted under the target so that the angle it viewed could be varied by $\pm 2°$ with respect to the target. The target assembly was on a platform that could also be rotated $\pm 2°$ around a vertical axis. By combining the two motions, emission over a $\pm 4°$ axial range in the horizontal plane could be recorded. This system was designed to allow the most precise alignment of the target with respect to the spectrometer and also enable the detection of a stimulated soft X-ray beam that had been deviated from the nominal axial direction by refraction in the plasma. A slot with open area 3mm high and 0.35mm wide was placed on axis 4 cm from the target to limit the view of the spectrometer. The position of the slot could be adjusted to view regions of the plasma at different distances from the target surface.

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 with length is commonly regarded as conclusive evidence for stimulated emission.

Some very interesting results emerged very quickly in the experiments. At 6J drive laser energy a very dramatic increase in the AlX and AlXI lines was seen with the 10mm target as compared to 2mm, while the AlIV and OVI lines show a sub-linear increase. The data could be fitted to the Linford (1974) relation with a gain of 4/cm for the Al XI 154Å line and the 3.3/cm for AlX 177Å. We repeated the experiments at 12J and observedan even more dramatic effect (Figures 4 and 5).

All the AlXI and AlX lines observed show an non-linear increase with length in an almost perfect fit to the Linford relation for gain. For instance the AlXI 141Å (3s-4p) intensity increases by a factor of x50 from 2mm to 10mm and is an excellent fit to the gain equation for a gain of $G = 5.1$/cm. The AlXI 150Å (3p-4d), 154Å (3d-4f) and AlX 177Å (3d-4f) lines also show a length dependence which is a very close fit to the gain equation at comparable values of gain. Similar results were obtained for the AlXI 105.7Å (3d-5f) and 103.8Å (5d-3p) lines.

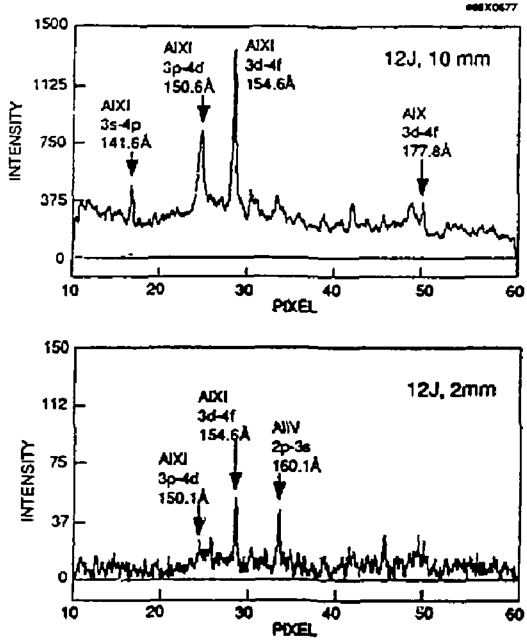

Fig. 4 Spectra obtained at 12J laser energy with target length 2mm and 10mm. Note the x10 scale change from the 2mm to 10mm graph.

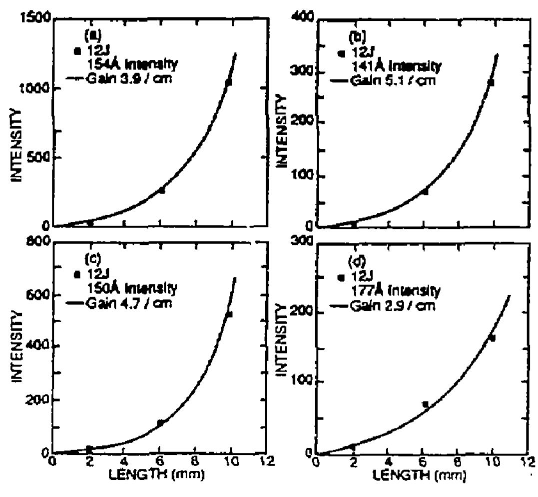

Fig. 5 Dependence of the AlXI 141Å, 150Å,154Å and AlX 177Å axial line intensity on length. The line represents a theoretical fit of the experimental points to the gain equation (Eq. (1) in the text).

DATA ANALYSIS

There are some unexpected features to the data in Figures 4 and 5. First of all, every AlX and AlXI line observed, without exception, showed a non-linear increase with length. In general the gain coefficient depends on the factors shown in Eq.(2):

$$G = \frac{1}{8\pi c} \frac{\lambda^4}{\Delta\lambda} g_i A_{ik} \left\{ \frac{N_i}{g_i} - \frac{N_k}{g_k} \right\} \qquad (2).$$

Here G is the gain coefficient, and λ the wavelength. g is the statistical weight, A_{ik} the radiative transition probability and N the population of the upper level i and lower level k. The highest gain was expected on the 3-4 transition with the largest gA value (3d-4f at 154Å); however, the data shows high gain on all the AlXI and AlX lines observed, similarly to Hara *et. al.* (1989). Particularly surprising was the strong increase apparent on the AlXI 141Å line which has a gA value much lower than the 150Å and 154Å transitions. In fact in previous work in magnetically confined, CO_2 laser-produced systems (Kim 1989b), where the AlXI 154Å transition exhibited stimulated emission; the 141Å line emission was solely spontaneous. In the present experiment the time history observed with a streak camera showed no difference between the time evolution at 154Å and the continuum background at 162Å and is not delayed as might be expected in a recombination system. Another unexpected feature is the apparent 'gain' in the background continuum emission, from 5-10 counts at 2mm to ~200 counts at 10mm, an increase of ~30 for a factor of 5 change in length. All these features raised concerns about the homogeneity of the plasma along its length. Specifically, were the level populations in the region of the 2mm plasma viewed by the spectrometer identical to the conditions in the 10 mm section? The 2, 6 and 10mm sections shared a common boundary on the spectrometer end of the target wheel. To test if the plasma was homogeneous, a target was built with the 2mm sections on both ends of the target and the 6mm section on the end of the target away from the spectrometer. First the conditions were arranged so as to reproduce the previous 10mm spectra and then the emission from the two 2mm sections at each end of the target was compared.

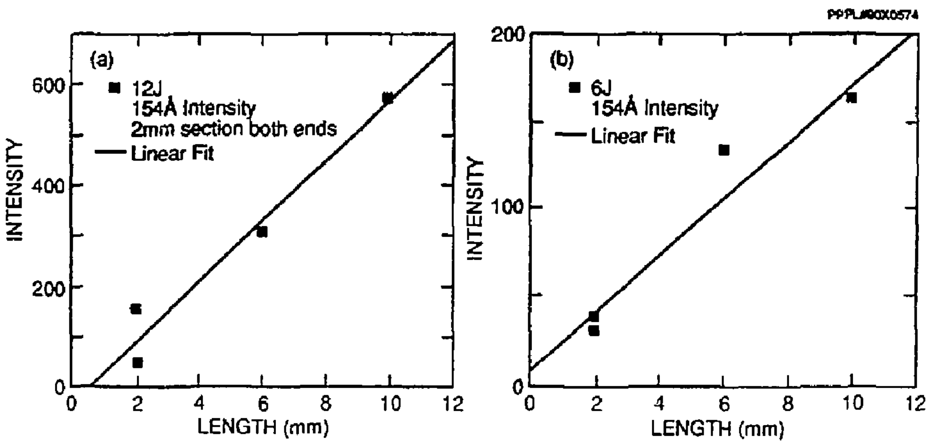

Fig. 6 (a) data showing the 154Å intensity variation with length but in this case including 2mm sections from both ends of the target. The 6mm data was from a section at the opposite end of the target to the data in Figures 4 and 5. (b) as above but with the target rotated by 2°.

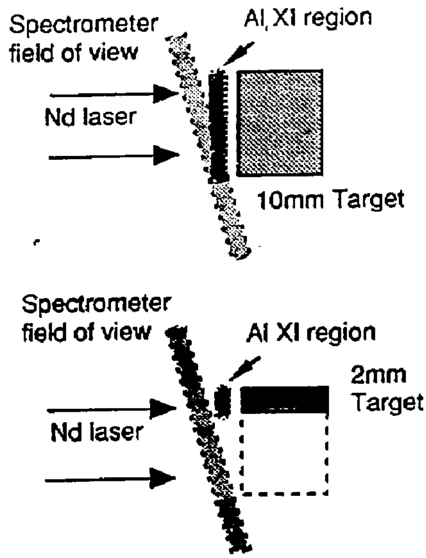

Fig. 7 Illustration of the effect of a small angle between the plasma and the region viewed by the spectrometer. The comparison of plasmas of differing lengths cannot be used for measurements of gain in this case.

It was immediately apparent that there was a dramatic difference in intensity between the 2mm section at the spectrometer end and the 2mm section at the opposite end. The target on one side of the laser beam looked much brighter than a target on the other side. Taking the average of the 2mm results, the best fit to the data was now a *linear* increase in intensity with length as shown in Fig. 6. The reason for the non-uniformity lay in a small angle between the target surface and the region viewed by the spectrometer (Fig. 7), possibly caused by refraction.

To verify this, the target was rotated about a vertical axis to change the position of the plasma generated by the two 2mm sections with respect to the region viewed by the spectrometer. With a 2° rotation the AlXI 154Å emission from the two ends became equal. In this configuration however the length dependence of the emission was linear. Basically the length scaling method to measure gain failed because the plasma was not homogeneous along the viewing region. In conclusion; the non-linear increase in Figs 4 and 5 was caused by geometrical effects and *not* by stimulated emission.

As noted before, the measurement of an exponential intensity increase with length is commonly regarded as conclusive evidence for gain (see for instance Hara 1989). However in view of the above results it is clear that while this may be an encouraging sign of gain it is by no means sufficient proof that gain is present. As was done in some earlier works (for example Matthews 1985, Jamelot 1988, Keane 1989, and Kim 1989a), it is critical to monitor the emission from nearby spontaneous emission lines in the same ion, preferably lines with the same lower level as the lasing line, to be assured that one is viewing a homogeneous plasma and that the comparison of plasmas of differing lengths is a valid. Checking that the spontaneous emission lines have a linear length dependence is particularly important for measurements of low gain-lengths, GL ≤ 4, where the output intensities are not so different to spontaneous emission levels.

SUMMARY

Soft x-ray laser technology is, at present, in a transition between demonstrations of gain in different systems and the acceptance of x-ray lasers as useful tools with practical applications. Good progress has been made in the application of soft x-ray lasers to microscopy and other fields. Gain at remarkably low pump energies has been demonstrated in CVI recombination systems and this augurs well for the development of low cost x-ray lasers for a variety of applications. Finally some pitfalls in the measurement of gain in modest gain-length systems have been demonstrated.

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