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Recombination X-ray Laser Experiments Using Exploding Ribbon Al Targets

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ABSTRACT

We present data obtained from recent recombination x-ray laser experiments carried out at the Nova and Phebus lasers using exploding ribbon Al targets irradiated with 100 ps pulses of 0.53-μm light. Spatially and temporally resolved x-ray and soft x-ray spectra will be shown. These spectra revealed the plasma to be insufficiently ionized so as to produce inversions in H-like Al. Conditions were found to be appropriate for inversion in He- and Li-like Al, however, and evidence for amplification of the AlXI 105.7 Å (5f-3d) and AlXII 88.9 (5f-3d) and 130.1 Å (4f-3d) lines was seen. These results will be discussed in detail and related to other work regarding the discrepancies between expected and measured electron temperatures in plasmas of this type.

I. Introduction

Much progress has been made in developing shorter wavelength x-ray lasers since the first demonstrations of x-ray lasing in 1984. Colliosional excitation and recombination are the two primary schemes to shorter wavelength lasers that have been examined in the past few years. Recently, Ni-like x-ray lasers have been extrapolated to wavelengths as short as 35 Å. In this paper, we discuss recent experiments carried out on the Nova and Phebus lasers whose aim was to demonstrate recombination pumped gain on the 3-2 transition in H-like Al at 39 Å.

II. Experimental Setup

Figure 1 shows the experimental setup used in this work. Two beams of the Nova laser were used to irradiate a strip type target, discussed in further detail below. Soft x-ray emission along the intended axis of x-ray lasing was observed by two McPigs spectrographs. One of these was operated in the imaging mode, which allowed spectra spatially resolved in the plane of the incident beams to be obtained. Time resolved x-ray crystal spectrometers were also used to monitor the plasma ionization balance.

The targets used in these experiments are shown in Fig. 2; they consisted of 100μm wide strips of Al deposited between two 500 Å thick Formvar sheets. This sandwich type geometry was used in order to attempt to maintain a higher plasma density at time of peak recombination and thus increase the gain. The targets employed were quite thin and are intended to "burn through" during the laser pulse.

The Al layer used in these experiments varied between 1000 and 4000 Å in thickness. 0.53-μm laser light was used in this work, with the total intensity on target ranging from 1×10^{14} W/cm^2 to 1×10^{15} W/cm^2. The pulse width was generally 100 ps; several shots were carried out at longer pulse as described below.

The x-ray and soft x-ray spectra taken in these experiments basically supported the primary conclusion drawn from the data, namely that the plasma ionization balance peaked out at H-like and thus the H-like emission was due primarily to collisional excitation. As a fully stripped plasma is required to produce recombination in H-like Al, this result implies that conditions were not appropriate to produce gain in H-like Al. However, conditions were closer to optimum for He- and Li-like Al. The data and how it supports this conclusion is discussed further below. This discussion will be broken into considering i) x-ray spectra and ii) soft x-ray spectra and gain measurements.

III. X-ray Spectroscopy

Figure 3 shows a typical time resolved x-ray spectra obtained. Note the presence of both He-like and H-like emission. The ratio of the lyman beta to helium beta transitions was observed to fall between 0.75 and 2.5, as shown in the figure. This is consistent with the value expected from simple atomic models for a plasma peaking out in ionization at H-like. More convincingly, Fig. 4 shows the time history of the helium beta and lyman beta lines. The relatively short time history of the H-like line implies that the H-like stage is relatively short lived in the plasma and consequently most of its emission occurs during the time when the plasma is hot and ionizing. In contrast, the He-like radiation has a "tail" which occurs well after the laser pulse when the plasma is recombining. This indicates a substantial portion of the He-like emission occurs due to recombination and thus is appropriate to look for gain in He- (and Li-like) Al. For comparison to Figure 3, Figure 5 shows a time integrated Al spectra obtained in this same series of experiments.

IV. Soft X-ray Spectroscopy and Gain Measurements

Figure 6 shows a typical time integrated Al soft x-ray spectra obtained from the non-imaging McPigs spectrograph. This is essentially time integrated data, as McPigs was gated off at t=2.2 ns (the pulse width was 100 ps). Note emission from H-, He-, and Li-like Al, as well as H-like O. We will comment on gain measurements for some of these lines shortly.

Figure 7 shows a time integrated, space resolved soft x-ray Al spectra obtained from a 1000 Å thick strip irradiated at $2x10^{14}$ W/cm^2. Note the different spatial extent of emission from H-, He-, and Li-like Al. The spatial extent of the H-like 110.8 Å, He-like 88.9 Å, and Li-like 105.7 Å lines are 70 µm, 300 µm, and 1 mm, respectively. The relatively narrow extent of the H-like emission implies that it was short lived; indeed, for reasonable expansion velocities (1- 2 $x10^7$ cm/sec) the observed extent implies an emission time of several hundred picoseconds, which is in accord with Fig. 4. Similarly, longer emission times are inferred for He-like and Li-like Al. As the emission duration for He- and Li-like is much longer than the pulse duration, a signficant fraction of the total radiation from these stages represents recombination and thus implies the possible presence of gain. The implied time history of plasma emission shown in Fig. 7 has been corroborated by time resolved data to be presented later.

Figures 8-10 show time integrated spectral lineouts taken at distances of 0, 550µm, and 1250 µm from the center of the target. (These spectra are obtained from the raw data used to generate Fig. 7). Note the preponderance of H-like emission at the plasma center, while in contrast the emission 1250 µm from plasma center is dominated by Li-like Al and H-like O.

Figure 11 shows time resolved data that corroborates the spatially resolved data shown in Fig. 9. This data was obtained at the Phebus laser using the SPARTUVIX diagnostic. Note the emission times for H-, He-, and Li-like Al, which are consistent with the spatial extent of emission shown in Fig. 9.

Figure 12 contrasts the differences between the soft x-ray emission for 100 ps and 750 ps pump pulses. This experiment was done in order to contrast the soft x-ray spectra for these two cases, as it is expected that the emission for the 750 ps case should come primarily from hot, collisinally excited plasma. Note that in the short pulse case, bright emission is observed on the H-like O and Li-like Al lines at 102.4 and 105.7 Å. In contrast, for 750 ps irradiation these two lines are relatively weak, while 2-3 emission from He-like Al is quite strong. Overall, these spectra imply the presence of recombination dominated conditions for the 102.4 and 105.7 Å lines. Note the similar intensity of the H-like Al 110.8 Å 4-3 line for both cases, implying that this line arises due to collisional excitation in both cases.

The results presented above imply that a significant fraction of the He-like and Li-like emission occurs due to recombination, while H-like Al emission is due primarily to collisional excitation. Thus, there is reason to look for evidence of gain on the He-like and Li-like Al lines. Figure 13 shows two spectra obtained from a length study carried out for 1000 Å thick strip targets irradiated at $2x10^{14}$ W/cm^2. In these experiments, the transitions at 105.7 Å (Li-like Al 5f-3d), 102.43

Å (H-like O 3-2) , and 88.9 Å (He-like Al 5f-3d) were observed to show some nonlinear behavior with target length. The gains inferred from this data were of the order of 0.5-1.0 cm^{-1}. Subsequent attempts to reproduce this result were unsuccessful, presumably due to the relatively low gain and experimental issues related to target and alignment reproducibility.

Figure 14 shows the McPigs spectra obtained for thin (1000 Å Al) and thick (4000 Å Al) strips irradiated at $1x10^{15}$ W/cm^2. Note the much higher degree of ionization for the latter, presumably due to the increased energy absorption. Unfortunately, it was not possible to do a length study under these conditions due to the lack of available intensity from Nova- 0.5 cm long targets were the longest that could be irradiated at this intensity.

V. Discussion

As is evident from the above, the plasma ionization was inferred to peak at H-like instead of the fully stripped stage required to produce gain in H-like Al. This was in contrast to LASNEX simulations, which predicted the plasma to be ionized to the fully stripped stage. The reason for this discrepancy is presumably due to LASNEX computing a higher T_e than actually obtained. This behavior has indeed been observed in other experiments, as shown in Figs. 15 and 16. Here we show results from dot target experiments carried out at KMS Fusion for conditions similar to those used for the Nova results discussed previously. In this KMS work, T_e was measured as a function of time using the slope of the recombination continuum and compared to LASNEX results. A significant discrepancy was observed, and this is under continuing investigation.

Future work in this area will concentrate on the use of shorter pulses and time resolved diagnostics. The latter is especially important, as late time gain could be masked by early time spontaneous emission in a time integrated spectrum.

VI. Summary

A series of recombination x-ray laser experiments has been carried out on Nova using 100 ps pulses of 0.53-um light. The targets employed were Al strips ranging in thickness from 1000 to 4000 Å of Al sandwiched between 500 Å sheets of Formvar. Conditions were hoped to be optimum for producing gain in H-like Al. It was found, however, that the H-like Al emission arose primarily due to collisional excitation, not recombination. Recombination induced emission was observed in He- and Li-like Al, however. Attempts to measure gain on transitions in He- and Li-like Al resulted in some evidence for nonlinear behavior of the He-like 88.9 Å 5f-3d and Li-like 105.7 Å 5f-3d lines. Some evidence for gain was also seen on the H-like O 102.43 Å 3-2 line as well. Nonetheless, no reproducible gains were measured. In general, the plasma was observed to be less ionized than predicted by LASNEX simulations. This is in accord with other recent measurements which show consistently lower electron temperatures than would be expected.

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