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Observation of a Population Inversion in a Possible Extreme Ultraviolet Lasing System

R. J. Dewhurst,* D. Jacoby, G. J. Pert, and S. A. Ramsden
Department of Applied Physics, University of Hull, Hull HU6 7RX, England

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Spectrographic observation of a population inversion between the levels $n = 3$ and $n = 2$ in a rapidly expanding C VI plasma is reported. These and other results are shown to be in good agreement with a computer model, which is used to predict the conditions required to obtain laser action at 182 Å.

For some time now there has been considerable interest in obtaining laser action at extreme ultraviolet and x-ray wavelengths and a large number of schemes by which this might be achieved have been proposed.[1,2] Although Jaeglé *et al.*[3] have reported gain at 114 Å on the $2p^5 4d\,^3P_1$-$2p^6\,^1S_0$ intercombination line in Al^{3+}, the mechanism producing the inversion is unclear and the interpretation of the results has been disputed by other workers.[4] A population inversion in the extreme ultraviolet region has been observed in a laser produced carbon plasma by Irons and Peacock[5] but at densities too low to obtain useful gain.

In this work we have achieved a population inversion of the $n = 3$ to $n = 2$ transition of C VI at 182 Å, using the recombination scheme,[6] which is sufficiently high to allow a laser to be constructed. The basic difficulty in this scheme is the need to obtain extremely rapid expansion and cooling of a fully ionized plasma[7]; recombination then leads to a preferential population of the upper states and hence to an inversion. In this work we have used very thin cylindrical carbon fibers irradiated in vacuum by a Nd glass laser; such targets allow a limited number of particles to be uniformly heated which then rapidly expand in all directions.

The carbon fiber, 5.3 μm in diameter, was supported vertically at the focus of the laser beam 13 cm in front of the horizontal entrance slit of a 2-m grazing incidence spectrograph (Hilger and Watts type E580). The spectrograph was carefully calibrated for absolute intensity measurements over the wavelength range 10–100 Å using the calibrated x-ray source and proportional counter system described by Morgan, Gabriel and Barton[8] and it is of interest to note that the calibration was practically identical to that reported for similar instruments by both Morgan, Gabriel, and Barton,[8] and Hobby and Peacock.[9] Irons and Peacock[10] have also demonstrated that in this wavelength range, there is no reciprocity failure for the photographic emulsion used (Ilford Q2). An auxiliary vertical slit between the fiber and the spectrograph gave a spatial resolution of 100 μm. Without this slit, spectra could be obtained with a single laser shot, whereas with it in position thirty shots were needed to obtain a satisfactory exposure.

The laser was a conventional Nd-glass system giving up to 0.5 J in a pulse of 140-ps duration although energies of only 150 mJ were used in these experiments. Streak-camera measurements[11] showed that the pulse width was reproducible to ± 10 ps and that there were no spurious or satellite pulses. The single-pulse extinction ratio was at least 10^{-4} and the fiber was further protected from spontaneous emission and stray flash-lamp light by a saturable absorber. The laser energy was reproducible to ± 30 mJ for about 75% of the shots; on the remaining 25% there was an oscillator malfunction leading to a very weak output pulse. The contribution of these weak pulses in multishot experiments was less than the 10% of the total plate intensity and can be neglected; this is confirmed by the good agreement of single-shot and multishot intensity ratios of the Lyman lines.

We have found it necessary to use a small prepulse to break the fiber and form a dense cold plasma with which the main pulse interacts. Since the fiber is broken by a laser-driven shock, the prepulse must have a duration greater than the shock transit time, which is found experimentally to be about 100 ps, in good agreement with computation simulation. In these experiments the prepulse was obtained by irradiating the fiber with a fraction (8%) of the main pulse 200 ps beforehand. The prepulse allows the plasma to expand and more nearly fill the focal spot, of radius 20 μm, and also enables the plasma heating to take place at densities nearer to optimum.[7]

The width of the main laser pulse is determined by the time required to heat and ionize the plasma. Such long pulses also have the advantage that the focused laser intensity is kept below that at which heat-flux limitation occurs. This is an important condition since the fiber must be uniformly heated by thermal conduction to obtain the most rapid expansion; ion-probe measurements do indeed show a uniform radial velocity independent of azimuth, and good front-to-back symmetry is also shown in the spatially resolved spectra.

The presence of an inversion can be deduced from the relative intensities of the Lyman series lines when these are optically thin. Thus, in Fig. 1 we plot the reduced line intensity $I_n/A_n\omega_n$ (where I_n is the intensity, A_n the Einstein coefficient, and ω_n the statistical weight of the upper state for the nth Lyman transition) against the energy E_n of the upper state, averaged over six plates. Near the fiber axis the density is so high that the plasma is optically thick giving rise to a negative slope in this region. Farther out all the lines become optically thin and the negative slope corresponds to an inversion. The distance at which this occurs may be roughly calculated to be ~100 μm from estimated values of the density, temperature, and velocity obtained from particle and energy balance considerations.

In order to interpret these spectra further we have compared them with the predictions of the computer model described by Pert.[12] Since the plasma is created under conditions where the temperature is nearly uniform, as a result of thermal conduction, the hydrodynamics can be described by a simple similarity model, and the relative populations described by average values constant over the plasma. The ionization rate equations are integrated consistently with the hydrodynamics, and are treated by means of the collision limit approximation for all ionization stages except C VI for which a complete collisional-radiative model with ten states is used. The

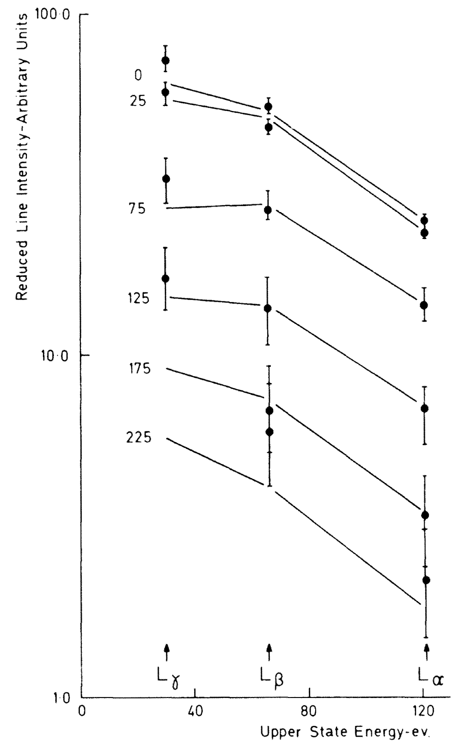

FIG. 1. The reduced line intensity $(I_n/\omega_n A_n)$ of the Lyman series lines of C VI plotted logarithmically against the upper-state binding energy, at different spatial distances from the fiber axis. The points represent the values obtained by averaging the measurements from six spectral plates, and the lines are obtained by computational predictions. Each set of values is designated by its distance of measurement from the fiber axis in microns.

code includes radiative energy loss by line, recombination, and bremsstrahlung radiation in the energy balance, together with absorption by inverse bremsstrahlung, and a dump at the critical density. It has been tested against analytic and numerical solutions[13] for the hydrodynamics, and against calculations by McWhirter and Hearn[14] and by Seaton[15] for the ionization routines.

During the early stages of expansion radiative trapping is quite severe but since the transit time of radiation in the plasma is short (<1 ps) and the plasma is nearly uniform, we have used the simple device of a trapping factor to describe this effect. While we appreciate the nature of this approximation, we feel that little serious error is incurred in calculating excited-state populations, which is our primer concern, since the role of radiation trapping is rather that of a switch; furthermore, comparison with experimental data indicates that the approximation is

TABLE I. Comparison of single-shot emission results with computed values.

Line	Total emitted energy (10^4 ergs) Measured	Computed
L_α	1.5 ± 0.5	1.7
L_β	0.9 ± 0.3	1.0
L_γ	0.5 ± 0.2	0.5

satisfactory. The trapping factor takes into account thermal[16] and motional[17] Doppler effects and both ion quasistatic and electron-impact Stark broadening.

In Table I we compare the total energy emission in the Lyman lines in single-shot experiments, which do not involve any errors associated with the laser shot-to-shot reproducibility, with those predicted by the computer model. In Fig. 2 we compare the spatially resolved multishot experiments with the computed spatially resolved spectra, taking into account the finite slit width. It can be seen that in each case the computer model satisfactorily predicts the experimental results and we therefore feel reasonably confident in using the computer simulations to interpret the data.

Figure 3 shows the computed behavior of the states $n = 1-3$ of the hydrogenic ion C VI: We plot the reduced population in each state, defined as the fraction of the total number of ions, q_n, divided by the statistical weight of that state, against time measured from the onset of the laser prepulse. The inversion is established at about 900 ps, when the plasma radius is 150 μm. At this time the ion density is about 5×10^{18} cm^{-3} and the peak inversion density $(n_3/\omega_3 - n_2/\omega_2) \approx 3 \times 10^{14}$ cm^{-3}. Figure 4 shows the computed gain-length product (αl) along the fiber axis with a peak value of 2×10^{-2}. This was calculated taking into account both the plasma expansion along this axis and Doppler and Stark effects on the linewidth.

Based on these results we calculate that a system with an $\alpha l \sim 10$ may be constructed with an input laser energy of about 100 J. Such a device should be capable of laser operation in a traveling-wave mode although, as the pumping efficiency is very low, output energies of not more than

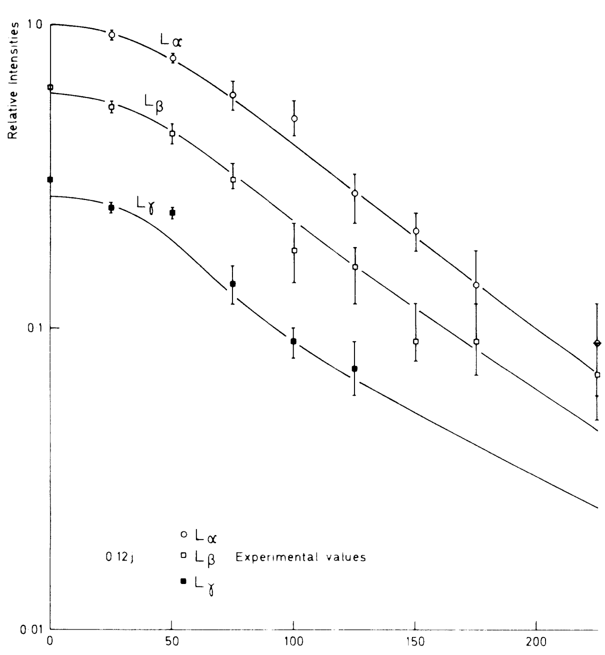

FIG. 2. Comparison of the experimental and computational spectral radial distributions. The points represent the experimentally measured intensities and the curves those obtained computationally.

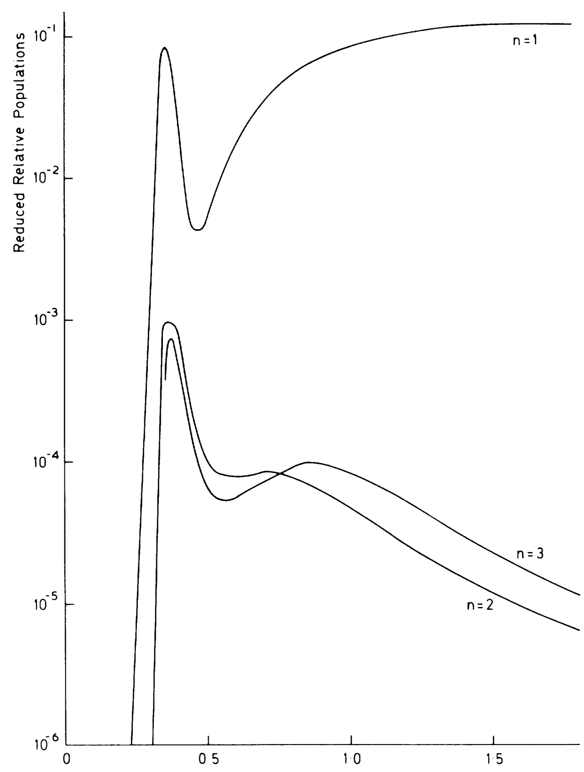

FIG. 3. The growth of population in the levels $n = 1-3$ obtained from the computer prediction. Since the populations are plotted as reduced population (q_n/ω_n), the onset of inversion of the Balmer α transition at 0.9 ns can be seen.

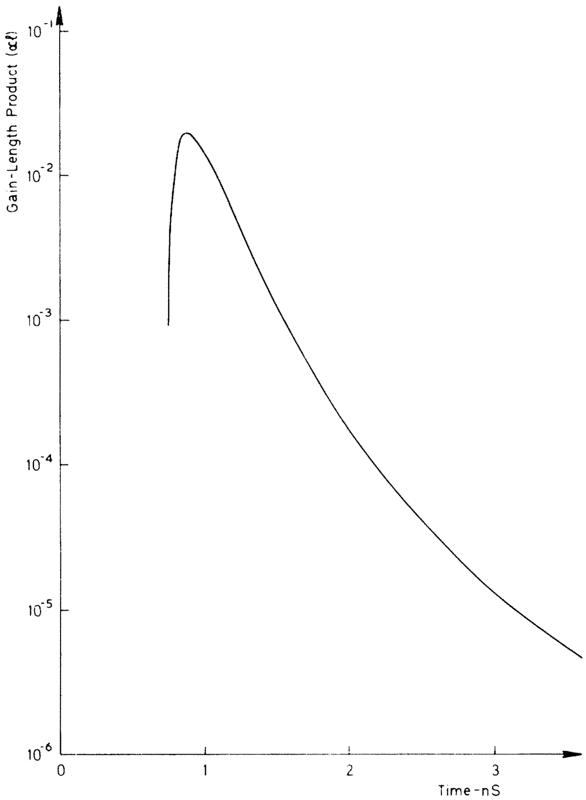

FIG. 4. The computed gain-length product (αl) of the Balmer α line of C VI plotted against time measured from the arrival of the prepulse.

1 mJ are predicted. These devices may be scaled with wavelength by using ions of higher atomic number. We have shown elsewhere[12] that the gain varies rapidly with the charge number Z, as $Z^{7.5}$. Unfortunately, the initial conditions of operation do not scale as conveniently, and one must both increase the density at which heating occurs and decrease the fiber radius as Z increases. For elements up to aluminum ($Z = 13$) one can envisage heating at or below solid density, but at higher atomic numbers schemes using laser compression must be considered.[18]

*Now at Department of Natural Philosophy, University of Strathclyde, Glasgow, Scotland.

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