Laser Amplification at 18.2 nm in Recombining Plasma from a Laser-Irradiated Carbon Fiber

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(Received 29 April 1987)

Extreme-ultraviolet laser amplification has been observed for the C VI Balmer-α transition at 18.2 nm, with use of a novel optical system to irradiate up to 1 cm length of carbon-fiber target. The measurements were time resolved and indicated peak single-transit amplification of about 30 times.

PACS numbers: 52.55.−s, 32.30.Rj, 32.70.−n, 52.50.Jm

The development of extreme-ultraviolet (XUV) lasers is progressing rapidly through a variety of schemes that use laser-produced plasmas as the amplifying media.[1] Strong exponential behavior was first reported for $3p$-$3s$ transitions in Se XXV.[2] High gain on the C VI Balmer-α transition has been observed with a solid target in a strong magnetic field.[3] Smaller gain has been seen in Li-like Al XI with solid targets[4] and in C VI with thin-film targets.[5] Our work has concentrated on recombination to C VI,[6] including the use of short carbon-fiber targets.[7,8]

The present experiment was designed to produce significant amplification by the irradiation of longer fibers under optimized conditions. The laser used was a neodymium-glass system, Vulcan at the United Kingdom Science and Engineering Research Council Rutherford Appleton Laboratory, which can generate up to 10^{12} W in 70-ps, 0.53-μm pulses. A new six-beam target-irradiation facility was devised, combining focusing via $f/2.5$ aspheric doublet lenses with 13° off-axis reflection at $f/2.5$ spherical mirrors to produce 7-mm-long, 25-μm-wide aberration-free line foci.[9]

Carbon-fiber targets were supported horizontally at one end and positioned with $\simeq$5-μm spatial accuracy and 10^{-3}-rad angular accuracy.[9] The laser beams were focused in opposed pairs to a common line focus. One pair was used to irradiate lengths up to 5.5 mm. The free end of the fiber was placed in a fixed position close to one end of the line focus with an overlap to ensure its irradiation at high intensity. Masking of the two beams was used to produce a sharp cutoff in the irradiation pattern and thus to vary the irradiated length. For lengths between 5.5 and 9.5 mm, two pairs of beams were used to produce a longer line focus by the superposition of axially displaced overlapping foci. It was impractical to increase the irradiated length beyond 9.5 mm because of vibration and bending of the fibers.

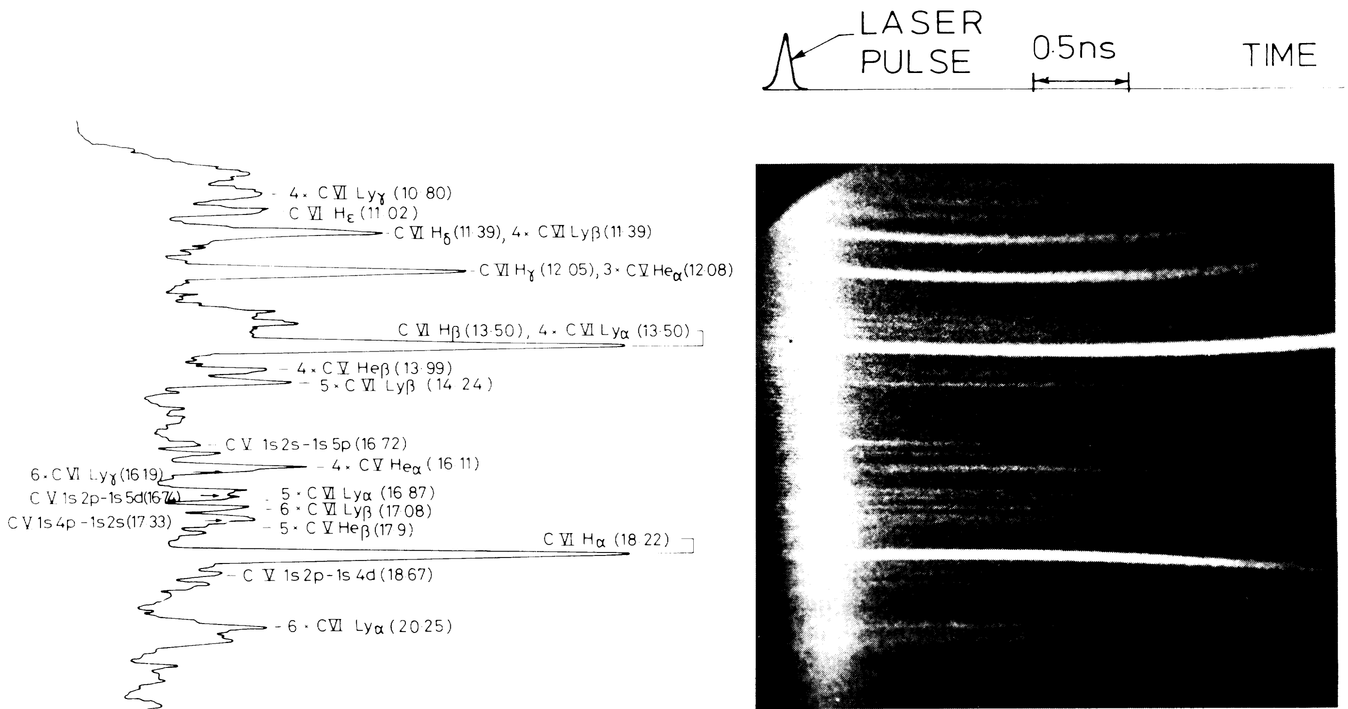
A time-resolving XUV spectrometer observed the axial emission from the free end of the fiber.[10] The instrument used a variable-periodicity grazing-incidence diffraction grating to focus XUV spectrum to a flat field at the transmission photocathode of an XUV streak camera. Spectral resolution was 0.5 Å and the temporal resolution was 0.4 nsec. An XUV pinhole-camera image, filtered to $h\nu \simeq 500$ eV, recorded images of the plasma, and the absorbed energy was measured with plasma calorimeters.

Extensive analytic and numerical modeling was used to determine the optimum target and laser irradiation parameters. Practical constraints were included in the modeling in the form of a lower limit of 70 psec for the pulse duration from Vulcan and a lower limit of 7 μm for the fiber diameter due to the problems of bending and vibration referred to previously. A new analytical model combined earlier work, defining optimum energy input as a function of plasma mass and duration of heating,[6] with a more recent understanding of the process of ablation by laser irradiation which relates absorbed energy and pulse duration to plasma mass.[11] The model predicted higher gain for lower plasma mass and shorter heating time; thus 70-psec pulses and 7-μm fibers were chosen. The required absorbed energy was given as

$$E/(1\ \text{J cm}^{-1}) = 0.11[r/(1\ \mu m)]^{2.4}\tau/(100\ \text{psec}),$$

in terms of fiber radius r and laser pulse duration τ, suggesting a requirement of 1.6 J cm^{-1}. Numerical modeling, discussed later, refined these conclusions and suggested that for an absorbed energy of 2 J cm^{-1}, a maximum gain coefficient of 15 cm^{-1} could be achieved. Experiments were conducted at incident energy levels of about 10 times the required absorbed energy because of the 10% absorption fraction for fiber targets.

The absolute and relative intensities of the Balmer lines were determined by calibration of the detector with synchrotron radiation. Line blending of H_β with $4\times Ly_\alpha$ was assessed by the recording of spectra showing simul-



(a) (b)

FIG. 1. (a) Streak-camera record of the emission spectrum along the axis of a 7-μm carbon-fiber target with 8 mm irradiated length and 2.5 J cm^{-1} absorbed energy. (b) Densitometry from (a) 975 psec after the peak of the laser pulse, with wavelengths labeled in nanometers.

taneously $H_\beta + 4\times Ly_\alpha$ and $3\times Ly_\alpha$, both with and without a 1000-Å Al filter to cut out the H_β component of the blended line. The results showed that the fraction of the observed intensity due to H_β was 75%. There was no blending for the H_α line. The detection sensitivity was 8 times higher for H_β relative to H_α.

An experimentally recorded streak spectrum is shown in Fig. 1. The main spectral feature is the C VI Balmer series. Weaker lines are C VI and C V resonance lines in higher orders and some C V $1s2l$ to $1snl$ transitions as indicated by the labeling.

Figure 2 shows H_α and H_β intensities for a range of lengths from 1.5 to 9.5 mm, 975 psec after the peak of the laser pulse. In Fig. 2 the exponentially increasing H_α intensities are fitted by the function $\exp(gl)-1$ (appropriate for small values of gl where gain narrowing of amplified spontaneous emission is not important). The method used was linear least-squares fitting for data points $\ln[I(l)/C+1]$, using C as a free parameter to obtain a fit passing through the origin, for which the slope g gave the gain. The resulting best fit is $g=4.1\pm0.6$ cm^{-1} corresponding to a maximum single-transit gain of 49. Lengths l were taken from the x-ray pinhole-camera images of the irradiated fibers. The data have average absorbed energy per unit length E/l of 2.6 J cm^{-1} with rms variation ±0.6 cm^{-1}. The incident energy was 10 times the absorbed energy. Least-squares fitting showed no systematic change in E/l with l.

The H_β data have a best-fit g value of 1.57 ± 0.17

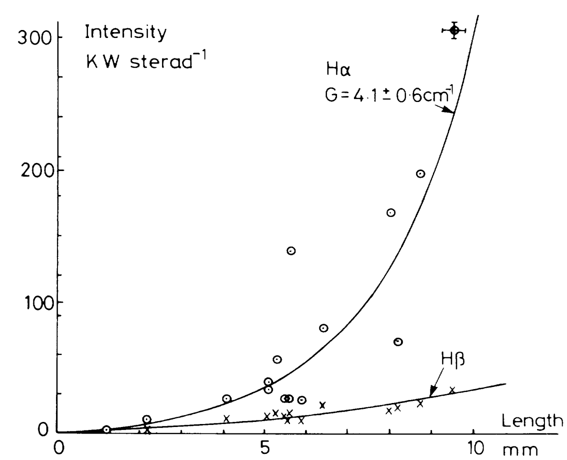


FIG. 2. Ordinate: absolute intensity of axial H_α and H_β emissions measured from streaked spectra 975 psec after the peak of the laser pulse. Abscissa: irradiated length. A typical measurement error bar is shown for H_α. Theoretical fits to the experimental data are also plotted.

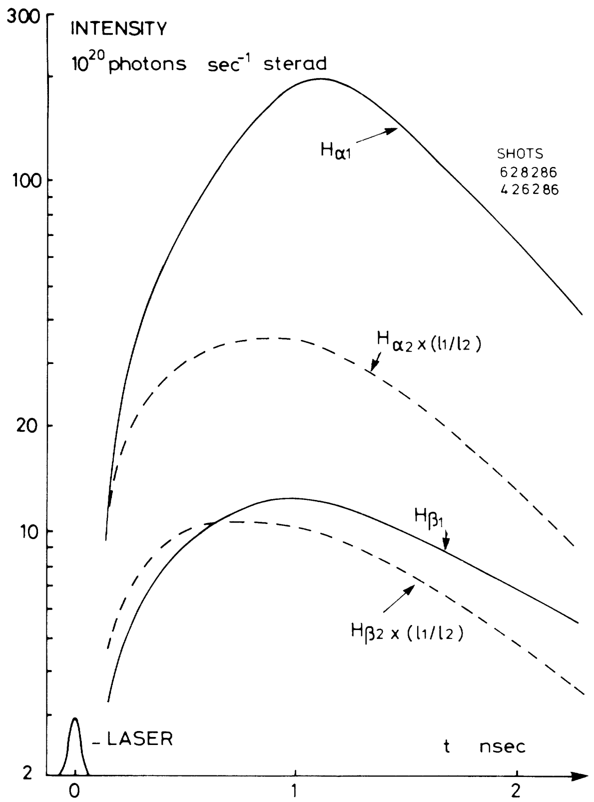


FIG. 3. Time history of the absolute intensities of H_α and H_β from two streak spectra. $H_{\alpha 1}$ and $H_{\beta 1}$ are for length $l_1=8$ mm and $H_{\alpha 2}$ and $H_{\beta 2}$ are for $l_2=2.2$ mm.

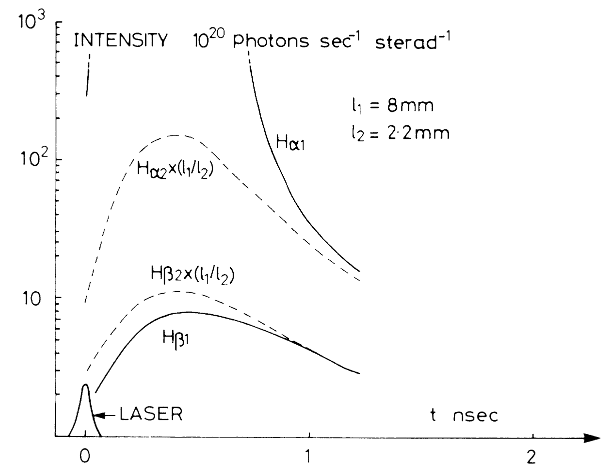


FIG. 4. Gain coefficient as a function of time deduced from Figs. 3 and 5 as explained in the text.

cm $^{-1}$. The H_β line is not expected to show gain and the small nonlinearity is attributed to systematic error in the data set, though there was no statistically significant variation in E/l with l, as noted earlier. To estimate the possible effect of this error on the gain coefficient deduced for H_α, the H_α data were scaled by a factor $gl/[\exp(gl)-1]$ with $g=1.57$, which gives zero gain if applied to the H_β data. The resulting g value for H_α is found to be $g=3\pm0.5$ cm $^{-1}$ and represents a lower bound on the gain. The single-transit gain is therefore about 30 if we take the median of these two estimates.

The temporal variation of H_α and H_β is plotted in Fig. 3 for short (2.2 mm) and long (8 mm) plasmas. Line intensities can be measured from about 130 psec when the lines emerge from the continuum. The intensities for 2.2 mm have been scaled by the length ratio $l_1/l_2=8/2.2$, showing clearly that H_β has very similar pulse shapes for both lengths, with intensity scaling almost linearly with length at all times. The H_α pulse shape is similar to that of H_β for 2.2 mm, but for the 8-mm length the intensity rises rapidly relative to the other lines, with a ratio peaking after about 1 nsec.

The temporal variation of amplification was assessed by our measuring the time-dependent ratio of the H_α intensity for the two lengths. This ratio has the form $S_1[\exp(gl_1)-1]/S_2[\exp(gl_2)-1]$ enabling us to determine g provided that the ratio of the source function brightnesses S_1 and S_2 is known. In this case $S_1/S_2\approx 1$ as evidenced by the similarity of the scaled H_β intensities in Fig. 3.

Figure 4 presents the variation of gain with time. For times later than 1 nsec, a systematic error becomes important as the radius of the expanding short plasma becomes comparable with its length, leading to a spherical expansion and more rapid cooling. Some evidence of this is seen in Fig. 3 in the different late-time slopes of H_β emission for the two lengths. The estimated gain at late times therefore becomes systematically too high. At early times (<400 psec) the 400-psec temporal resolution in the streaks masks any sudden change of intensity ratio.

Various numerical simulations of the experiment were carried out. A one-dimensional Lagrangean hydrodynamic code was used, with a collision-radiative model for ionization and the Sobolev[12] approximation to describe the effect of Doppler decoupling on the trapping of C VI Lyman radiation. The results gave radial profiles of emission and gain as functions of radius and time, from which the total emission along the axis was computed as shown in Fig. 5. The computed values of absolute intensity of H_β for long and short plasma lengths agree well with the experimental values except that the peaks occur 300 psec earlier and decay more rapidly. The computed H_α emission for long lengths is much greater than is observed because the observed amplification is smaller. The H_α:H_β ratio at late times when gain is low is the same in both theory and experiment.

The apparent H_α gain in the numerical model was deduced by treatment of the computed intensities in the same manner used in analysis of the corresponding ex-

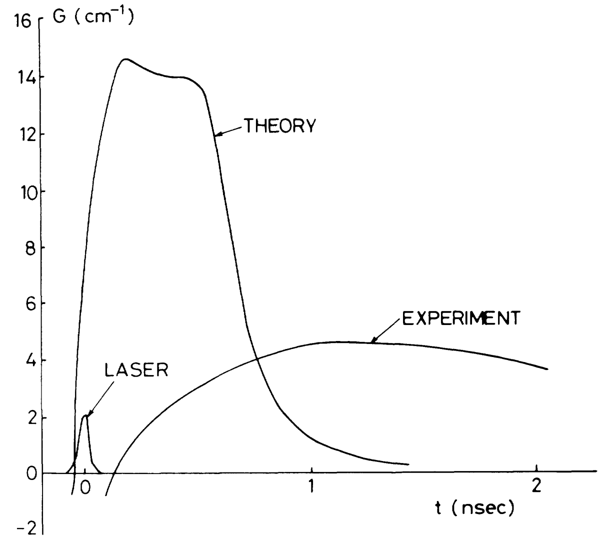


FIG. 5. Computed time history of absolute intensities of H_α and H_β for plasma lengths of 2.2 and 8 mm corresponding to the experimental data in Fig. 3.

perimental data. The finite (400 psec) temporal resolution of the streak camera was included in the simulation by a convolution procedure. Comparison of this apparent gain with experiment in Fig. 4 shows qualitative similarity. The calculated peak of 15 cm^{-1} is, however, much higher than the 4 cm^{-1} deduced from experiments and it decays more rapidly.

No satisfactory explanation has yet been obtained for the differences between experiment and theory, nor indeed for the lower value of gain coefficient relative to earlier experiments with shorter lengths of fiber, time-integrated diagnostics, and different irradiation conditions.[8]

In conclusion, we have successfully used new optical and diagnostic systems to measure moderately large laser gain on the 18.2-nm H_α transition of C VI.

We wish to acknowledge the technical and operational support given by the Central Laser Facility staff, including J. E. Boon, C. Brown, A. R. Damerell, P. Gottfeldt, D. A. Pepler, I. N. Ross, and P. T. Rumsby, and by the Sychrotron Radiation Facility staff, including J. West. Two of us (C.C.-P. and T.T.) received visiting fellowships from the Centre National de la Recherche Scientifique and Monbusho, respectively. The work is supported by the United Kingdom Science and Engineering Research Council.

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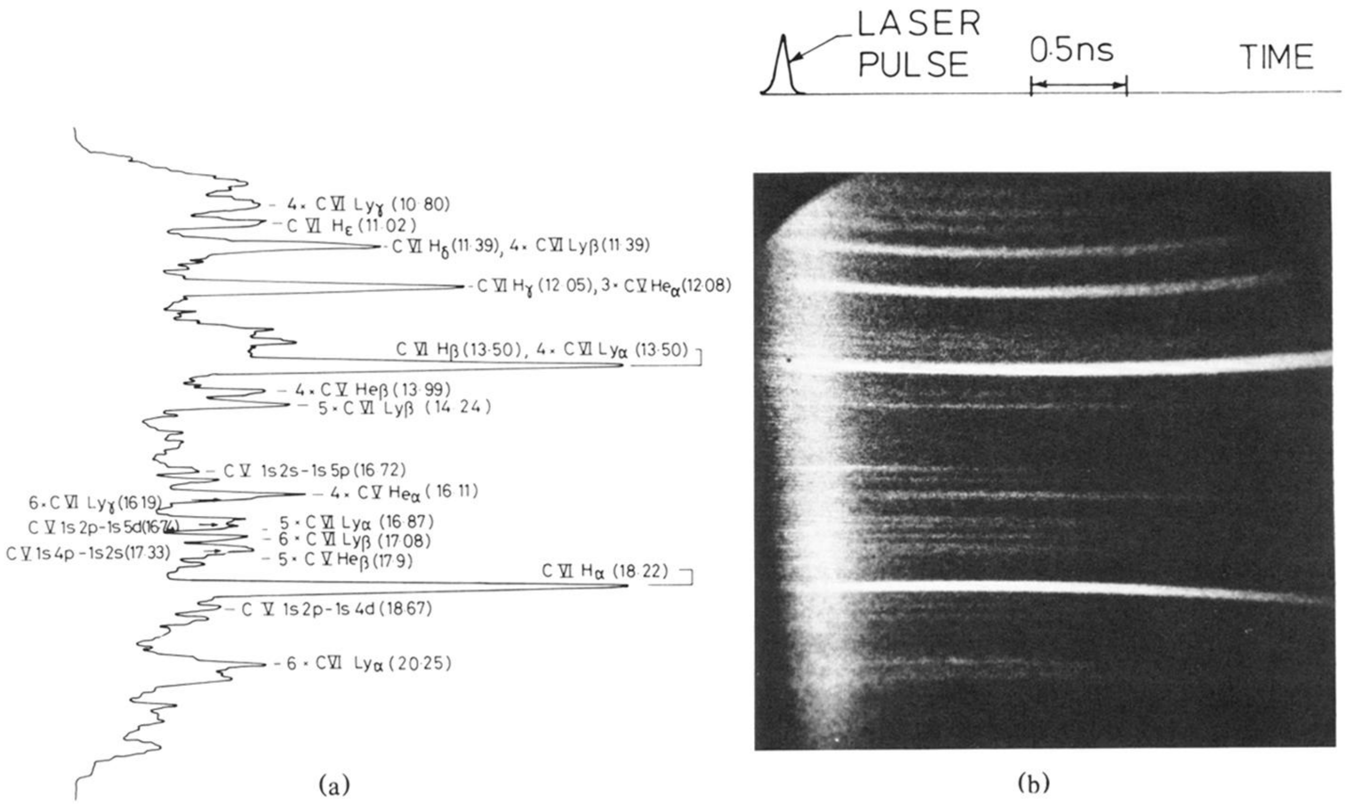

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