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ABSTRACT

The plasma produced by focussing the output beam of a 1 Gigawatt CO_2 laser onto solid targets was observed with a grazing incidence spectrograph. Measurements of electron temperature, density and ion velocity are reported.

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INTRODUCTION

The output beam of a carbon dioxide laser was focused onto solid targets situated in vacuo so that a power density of 6×10^{11} watts cm^{-2} was incident on the target surface. The spectrum emitted from the resulting plasma was recorded with a two metre grazing incidence spectrograph. The electron temperature of the plasma was estimated from measurements of both the recombination continuum of C V and the wavelength of the peak intensity of the bremsstrahlung continuum. In addition Stark broadened C IV lines conveyed information regarding electron density, whilst stigmatic spectra permitted the determination of the spatial distribution of electron temperature.

Previous spectroscopic observations of laser produced plasmas have been made mainly on plasma heated by 0.694 μm ruby or (more often) 1.06 μm neodymium giant-pulse lasers, with output powers up to 100 GW (Feldman and Doschek, 1975). Some early studies are referred to by Fawcett (1974) and Donaldson et al (1973). Examples of recent papers are Galanti and Peacock (1975) and Fawcett and Hayes (1975). It was of interest to extend these spectroscopic observations to CO_2 laser-produced plasmas, where a somewhat different physical situation exists due to the substantially longer wavelength of the CO_2 laser radiation (10.6 μm) compared with ruby (0.694 μm) and neodymium (1.06 μm). This is because reflection of laser radiation in the plasma takes place at a critical layer where the radiation frequency equals the plasma frequency. Since the plasma frequency is proportional to the square of the electron density, it follows that this critical layer for the longer wavelength CO_2 laser radiation will be at a lower density than the critical layer for neodymium radiation.

APPARATUS

The carbon dioxide laser was of the double discharge type and consisted of a 375 megawatt oscillator and two amplifiers providing a (saturated) amplification of 4. The output beam had a rectangular cross section of 5 cm by 10 cm. Both the risetime and the half width of the output pulse were 50 nanoseconds. An off-axis paraboloid mirror of focal length 16 cm (made of magnesium alloy and with its surface polished to a tolerance of 25 μm) focussed the laser beam onto solid target surfaces. After reflections from connecting optics and transmission through a sodium chloride crystal window the measured power available at the target surface was 1 GW, and the power density of the focussed beam was 6×10^{11} watts cm^{-2} $\pm$ 50%. A two metre grazing incidence spectrograph viewed the target. It had an angle of incidence of 88^{o} and contained a 600 line per mm grating. Ilford Q2 photographic plates recorded the spectra. For the first exposures the target surface was placed in a plane perpendicular to the length of the 5 μm entrance slit and 3 cm away from it. For the other exposures the length of the slit was in the same plane as the target surface and at a distance of 16 cm. To obtain spatially resolved records of the plasma radiation parallel to the entrance slit, a second slit was placed perpendicular to the entrance slit half way between it and the grating. For the first exposures its width was 0.5 mm; and for the second 150 μm. Spatial resolution perpendicular to the entrance slit was determined by the aperture of the instrument which was 0.3 mm at 3 cm and 1.6 mm at 16 cm from the entrance slit. Spectral emission from the plasma produced by between 10 and 100 laser pulses was recorded on each photographic plate. The laser power was sufficiently reproducible to permit multiple exposures without introducing a large error. It was necessary to move the target after every 20 pulses due to minor surface damage.

OBSERVATIONS

Spectra of carbon and iron were obtained with flat targets of the pure iron or graphite. The most highly ionized spectra on the plates were of Fe XVI but Fe IX and Fe X were more intense with Fe VII and Fe VIII emitted more strongly than Fe IX at distances greater than 1 mm from the focal spot. The carbon plasma was chosen for diagnostic analysis because the C V recombination continuum provides a method of electron temperature measurement. The illustration shows two carbon spectra taken with the split parallel and perpendicular to the target surface respectively. Notable features which convey information are the strong recombination continuum of C V, the bremsstrahlung continuum close to the target surface, and the intense lines of C VI near the focal spot which become less intense relative to the C V lines at radial distances greater than 2 mm from the focal spot. In addition there are Doppler and Stark broadened lines. Some C IV lines have large Stark widths close to the target surface which become narrower further out.

ELECTRON TEMPERATURE

The electron temperature was determined as a function of distance from the focal spot by measuring the intensity of the C V recombination continuum as a function of wavelength for the two plates illustrated. The frequency interval over which the continuum intensity falls by a factor of e is a direct measure of electron temperature. Instrument and plate calibration permitted the conversion of photographic density into intensity. The method used for determining the absolute sensitivity of the grazing incidence spectrograph is described by Morgan et al (1968). It made use of an X-ray source of discrete K-lines, the intensity of which was monitored by a flow proportional counter acting as an absolute photon flux detector. Fig. 1 shows three microdensitometer traces of the continuum centred at distances of 0.75 mm, 3 mm and 9 mm from the target surface. Over this range the measured electron temperature falls from 68 to 10 eV, as illustrated in Fig. 2. (The error bars indicated are standard errors, calculated from experimental uncertainties in continuum density, spectrograph and plate calibrations). The highest measured temperature relates to the plasma within 1 mm of the focal spot and was observed with the length of the entrance slit of the spectrograph in the plane of the target surface. The temperature deduced from this observation, (Fig. 1 top trace), was 58 ± 4 eV. This temperature is time averaged along the line of sight and weighted in favour of the dense part of the plasma-history by the square of the electron density, N_e. After corrections for contributions from the cooler outer plasma layers (by Abel inversion) a temperature of 68 ± 7 eV was obtained. The other points shown in Fig. 2 were derived from observations with the spectrograph entrance slit perpendicular to the target plane, but were not corrected in this manner.

An independent measurement of electron temperature was derived from the observation that, within 1 mm of the focal spot, the bremsstrahlung continuum intensity peaks at a wavelength $\lambda_{max} = 95 \pm 10$ Å, and since

$$\lambda_{max} = 6200\ (kT_e)^{-1}\ \text{Å},\ kT_e = 65 \pm 7\ \text{eV}.$$

The highest temperature estimates apply to a region extending 350 μm radially from the laser input axis with sharp boundaries (see the illustration) in this direction and 1.5 mm axially from the centre of the focal spot. The temperature is also time-averaged, but the 70 eV region could be expected to cool rapidly after the laser pulse has terminated because of conduction to the target surface, so that most of the C V continuum emission close to the surface should only last for a time comparable with the duration of the laser pulse. (Further from the surface, the measured temperatures are averaged over longer times and are also space-averaged). Although some part of the plasma could thus be considerably hotter than 70 eV at maximum laser intensity, considerations of ionisation balance between the strong C V and weaker C VI lines suggests that any element of plasma at higher temperatures could only exist for a few nanoseconds. Furthermore it should be noted that since the time averaged electron temperature is weighted by N_e^2, low density, hotter or cooler plasma regions, may not contribute appreciably to the photographic records.

ELECTRON DENSITY

Some carbon IV lines emitted from a region of up to 2 mm from the focal spot have large Stark widths; these widths decrease at larger radii. The transition 2p ^2P - 4d ^2D for example, has a half width of 0.5 Å. The application of a Z extrapolation formula from Griem (1974) to previous calculations for the same transition in O VI made by Burgess et al (1967) indicates electron densities of 10^{20} cm^{-3}. Although this is not a measure of the electron density in the 70 eV region, it does indicate that parts of the plasma have exceeded the critical density (10^{19} cm^{-3}) for reflection of the 10.6 μm laser light. An average electron density near 10^{19} cm^{-3} was estimated for the 70 eV region from the absolute intensities of the C V recombination continuum and the bremsstrahlung continuum.

The maximum absorption of laser light should occur just outside the critical density surface, and consequently the highest temperature in the plasma should exist near this position. It follows that this surface at 10^{19} cm^{-3} lies somewhere in the region with average temperature 70 eV, with a steep temperature and density gradient between it and the target surface. The region encloses at least some C V plasma at densities in excess of 10^{19} cm^{-3}, with a larger volume of 70 eV plasma outside the surface. An ion velocity in the radial direction of 5×10^{6} cm^{-1} ± 50% was derived from the Doppler widths of C V lines.

CONCLUSIONS

The electron temperature for the CO_2 laser-produced plasma can be compared with that measured for plasmas generated using neodymium lasers at similar power densities (Donaldson et al 1973, Galanti and Peacock 1975) and also of ruby (Boland et al 1968). Higher experimental accuracy is required to establish whether or not they are significantly different. The low running cost of CO_2 lasers and the more extended plasma generated, which is spectroscopically visible over 1 cm from the target, means that this plasma offers an interesting source for spectroscopic studies. Further photometric and time-resolved measurements are under way to investigate the dynamics of such plasmas.

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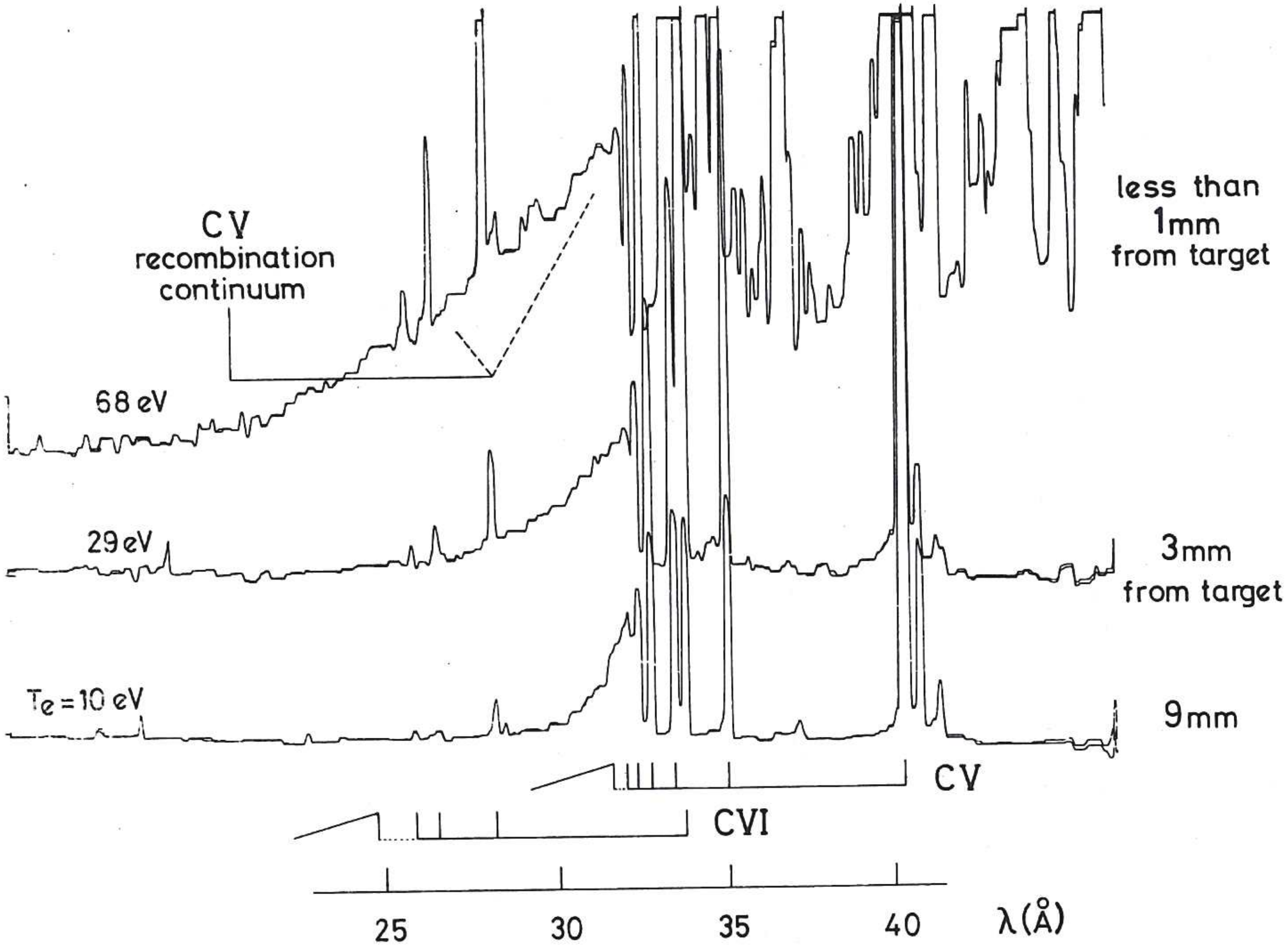

Fig.1 Densitometer traces of spatially-resolved spectra of carbon plasma generated with the CO_2 laser at 6×10^{11} Watts cm^{-2}.

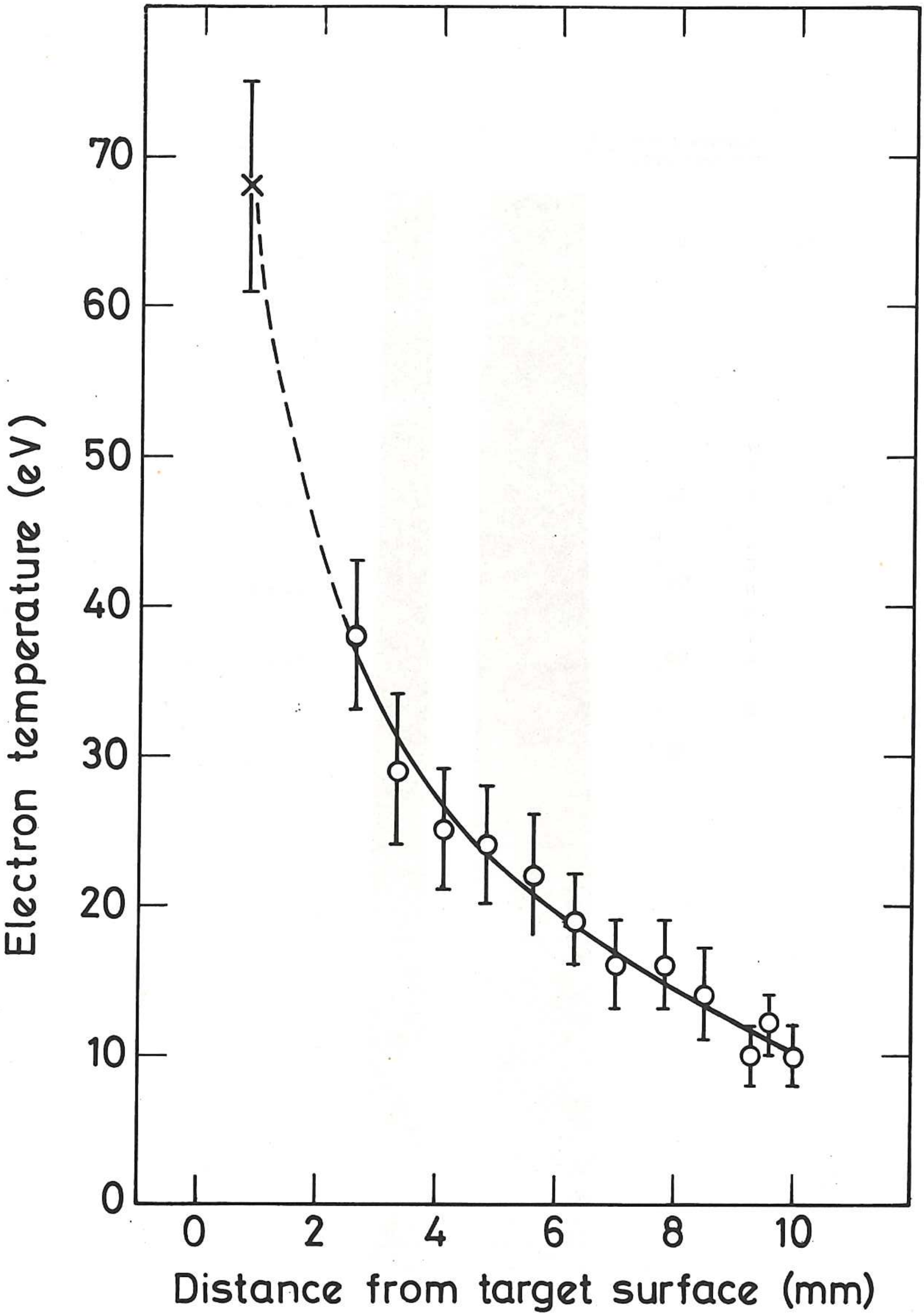

Fig.2 Axial electron temperature variation (for explanation of symbols see text).

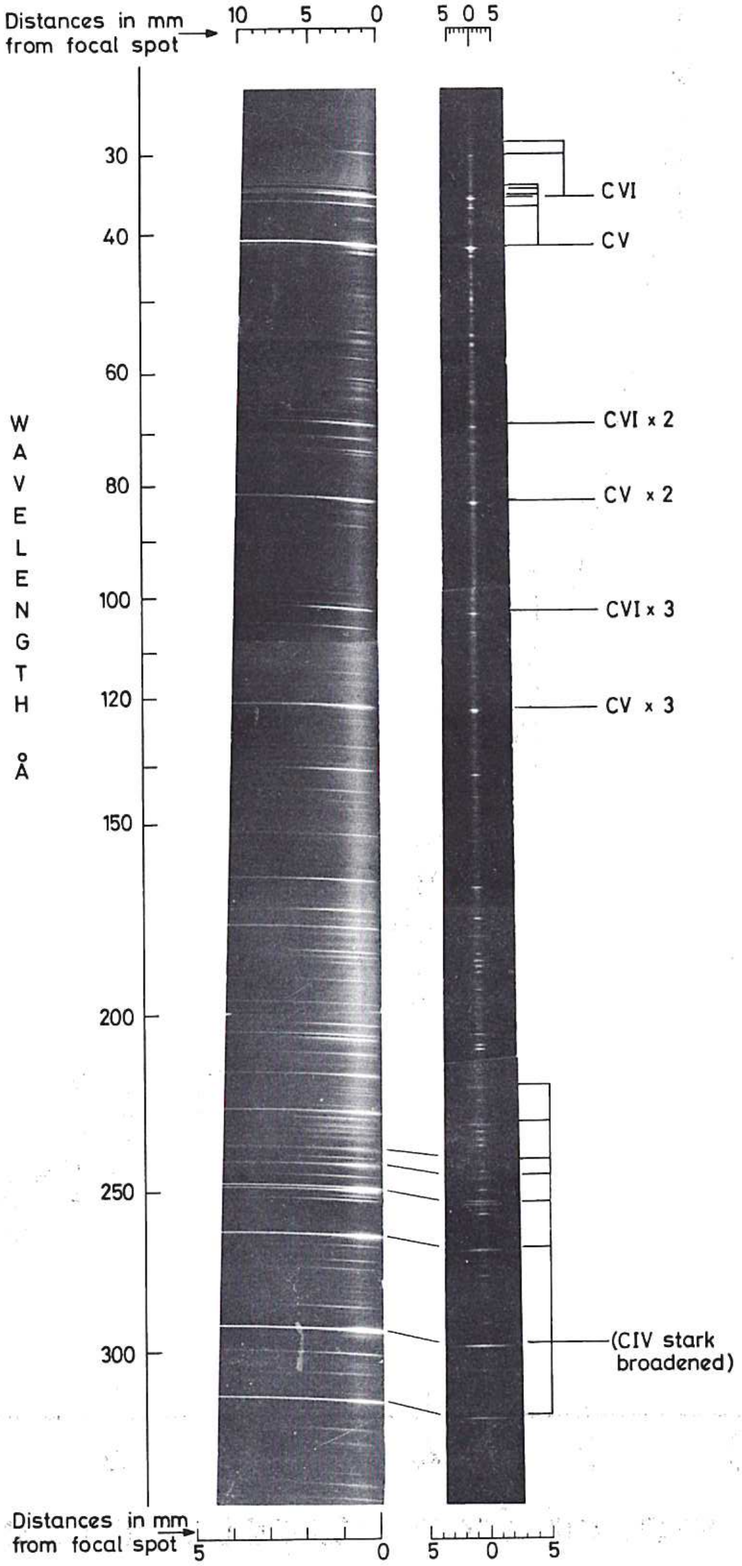

Illustration:

Spectra emitted from the plasma produced with a CO_2 laser focused onto carbon (power density 6×10^{11} Watts cm^{-2}).