Study of the supercritical region in a CO_2-laser plasma in the x-ray spectra of multiply charged ions

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The profiles of the electron density and the temperature in the supercritical region of a plasma produced by a CO_2 laser have been measured. A plateau forms on the density profile at $q \sim 5 \times 10^{14}$ W/cm^2.

X-ray spectral diagnostic methods[1] have proved highly effective in studies of laser heating of plasmas at various wavelengths, primarily studies of the relationship between such plasma properties as n_e and T_e and the characteristics of the heating laser beam (its wavelength, energy power density, etc.). The previous experiments, however, have been carried out for the plasma corona ($n_e < n_c$) and for spherical compression ($n_e \sim n_{\rm solid}$). The supercritical region of a laser plasma ($n_c < n_e < n_{\rm solid}$), on the other hand, has been studied in experiments on plasma heating by light with $\lambda = 10.6\,\mu$m ($n_c = 10^{19}$ cm^{-3}) only by interferometric methods,[2] which, although very informative with regard to the spatial distribution $n_e(r)$, can tell us nothing at all about the plasma temperature in the zone under study.

In this letter we report the first use of x-ray spectroscopy of multiply charged ions for simultaneous measurements of the profiles of the temperature and density in the supercritical region of the plasma produced by the light from a CO_2 laser.

The experiments were carried out in the TIR-1 device, which is described in detail in Refs. 3 and 4. Two groups of experiments were carried out. 1) A laser beam with an energy ~ 50 J and a length at half-maximum ~ 2 ns is focused by a NaCl lens with a focal length $f = 1$ m to a spot $\sim 300\,\mu$m in diameter, which provides a power density $q \sim 3 \times 10^{13}$ W/cm^2 at the bombarded surface. 2) Light with an energy ~ 100 J is focused by an aspherical NaCl lens with $f = 550$ mm to a spot $\sim 100\,\mu$m in diameter ($q \sim 5 \times 10^{14}$ W/cm^2).

The targets are bulk aluminum targets—flat plates.

The line emission of the A1XI and A1XII ions is measured by a spectrograph with a plane quartz crystal or a crystal of CsAP, whose optic axis is directed parallel to the bombarded surface. The spatial resolution along the normal to the surface results from the use of an entrance slit $\sim 100\,\mu$m wide, oriented parallel to the dispersion of the crystal. The spectra are recorded on UF-VR film.

Figure 1 shows some typical densitometer traces of the spectra of the A1XI and A1XII ions at various distances (r) from the bombarded surface for the two laser power densities. Comparison of the results reveals a characteristic distinction between the spectra in these two cases: At the lower power density q the intensities of the resonant line of the He-like aluminum ion (I_R), of the intercombinational line (I_I), and

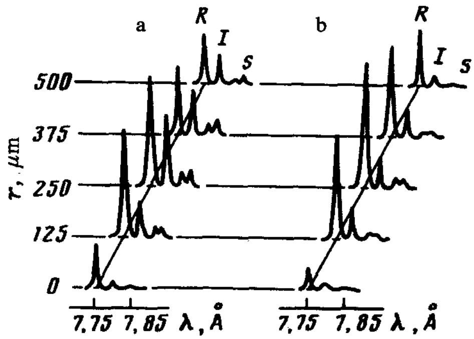

FIG. 1. Typical densitometer traces of the emission spectra of the A1XI and A1XII ions at various distances (r) from the bombarded surface. a—$q \sim 3 \times 10^{13}$ W/cm^2; b—$q \sim 5 \times 10^{14}$ W/cm^2.

of the satellites (I_S) are approximately the same at large distances from the surface, but at the higher power density we find $I_R > I_I \gg I_S$. The qualitative conclusion which follows from this fact is that the temperature and density of the plasma are higher in the second case.

The plasma properties are measured by the following procedure. The electron temperature T_e is determined from the intensity ratios of the k, l, j, q, and r satellites and the resonant line of the He-like aluminum ion.[1,5] The component of the intensity of the resonant line due to recombination processes is unimportant, since the plasma in the critical and supercritical regions is an ionizing plasma ("superheated"), and these are the regions that were studied in these experiments. Capture of the resonant radiation is also insignificant in this case, since the transverse dimension of the plasma in our experiments is $\cong 100\ \mu$m, considerably smaller than the distance[1] (l_{cr}) over which self-absorption begins to have a significant effect on the intensity of the resonant line.

Figure 2 shows the measured time-average profiles $T_e(r)$ for $0 \leqslant r < 500\ \mu$m. We see from this figure that the maximum values of T_e at $q \sim 5 \times 10^{14}$ W/cm^2 occur ~ 500 μm from the bombarded surface and are ~ 700 eV. The reason for this behavior of the temperature is that the critical point, at which the laser light with $\lambda = 10.6\ \mu$m is absorbed, lies at a certain distance from the bombarded surface. In this case the maxi-

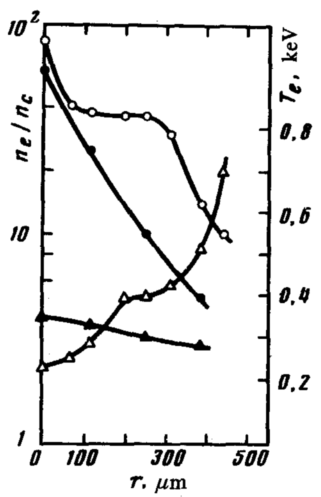

FIG. 2. Profiles of the electron density n_e (circles) and of the temperature T_e (triangles). Filled points—$q \sim 3 \times 10^{13}$ W/cm^2; open points—$q \sim 5 \times 10^{14}$ W/cm^2.

mum temperature should be near the critical surface, while in the supercritical region the plasma heating is much weaker and occurs by thermal conductivity. At $q \cong 3 \times 10^{13}$ W/cm^2 the temperature is essentially constant over the region 0-400 μm, within the experimental error; this result may be due to an increased effect of the electron thermal conductivity with decreasing plasma density.

The electron density n_e is determined from the ratio of the resonant and intercombinational lines of the He-like ion,[1] A1XII. The measured density profiles $n_e(r)$ are also shown in Fig. 2. At $q \sim 5 \times 10^{14}$ W/cm^2 there is a plateau at $n_e \sim 3.7 \times 10^{20}$ cm^{-3}, i.e., at $\sim 37 n_e$. The reason for this shape of the density profile is that at high power densities q the radiation pressure of the heating beam becomes comparable to the pressure of the plasma itself. The role played by radiation pressure in shaping a plasma density profile was first pointed out in Ref. 6. It was subsequently demonstrated in numerical calculations,[7,8] and it was first confirmed experimentally in Ref. 2, where methods of picosecond interferometry at a power density $q \sim 10^{14}$ W/cm^2 of the CO_2 heating laser beam revealed the effect at $n_p \sim 7 n_c$. An estimate based on the balance of the radiation pressure and the plasma pressure yields a plateau height

$$n_p \sim E_0^2 / 8\pi T_e \approx 25 n_c$$

in our case.

In summary, these results show that the shape of the density profile in the supercritical region during the heating of a plasma by a CO_2 laser beam depends strongly on the power density of the beam; at $q \sim 5 \times 10^{14}$ W/cm^2, a plateau is observed on the density profile. The theory of the mechanisms by which the density profile is modified requires further development. More-detailed experiments are also necessary.

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