Study of the dynamics of a laser plasma on the basis of the x-ray spectra of multiply charged ions

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The structure of images of a laser plasma formed in optically thick x-ray spectral lines has been studied. Analysis of these images yields information on the average expansion velocity of the plasma, the hydrodynamic efficiency of the compression, and the rate at which the target mass evaporates.

Methods of x-ray spectroscopy have been used in experiments on laser fusion[1] to determine the electron density N_e, the temperature and ionization state of the plasma, and, when impurity gases are used in the target, the confinement parameter ρr, where ρ is the density and r the dimension of the plasma.[2,3] In the present letter we report experiments carried out on the Del'fin-1 device,[4] in which we have determined the mass evaporation rate m and the hydrodynamic efficiency (η) of the target compression from the shift of the intensity peak on images of the plasma formed in optically thick x-ray spectral lines.

Experiments on the spherical compression and heating of shells are carried out at a laser energy of 1–1.5 kJ. The absorption efficiency is 35–40%. The glass shells are 400–500 μm in diameter with a wall thickness $d = 0.5$–4 μm. An image of the plasma is formed in the intrinsic emission of the plasma in x-ray spectral lines with the help of a spectrograph with a plane quartz crystal, $Q\,[10\bar{1}0]$, and a slit along the dispersion direction. The spectral resolution, determined by the crystal, is $\sim 8.8 \times 10^3$, and the spatial resolution at the object in the direction perpendicular to the dispersion is ~ 30 μm. It thus becomes possible to study the structure of the spectral line in various cross sections of the image of the plasma.

Figure 1 shows a typical K spectrum of the x-ray emission of silicon in the interval 5–7 Å, integrated over the plasma lifetime, along with a characteristic two-dimensional image in the line of the helium-like silicon ion. At the center of the image of the plasma we see a shift of the emission peak along the dispersion direction. The magnitude of this shift, $\Delta\lambda$, is taken to be the difference between the wavelengths of the geometric center of the image of the plasma of the spherical target and the intensity peak.

The basic physical cause of the observed phenomenon appears to be the Doppler effect in the plasma, which is expanding in a radially symmetric fashion. If we assume that the plasma is optically thick with respect to the emission in resonant lines, i.e., if the side of the target opposite the observer is screened during the shaping of the image, the wavelength shift of the emission will depend on the projection of the expansion velocity vector onto the observation axis. At the center of the image, where the expansion direction coincides with the observation axis, we find a maximum of the shift, while in the peripheral parts of the plasma image, where the expansion direction is perpendicular to the axis, there is no shift. The magnitude and sign of the shift should therefore be related to the expansion velocity and to the optical thickness of the plasma for the light beam detected. We do in fact observe such a relationship in the experiments.

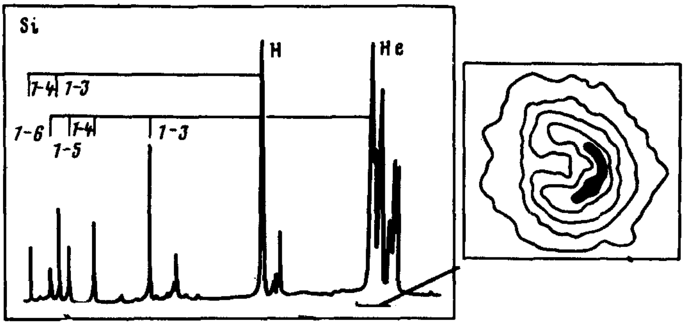

FIG. 1. The x-ray emission spectrum of silicon and densitometer image of the plasma in the resonant line of the helium-like silicon ion ($1s^2$–$1s2p$).

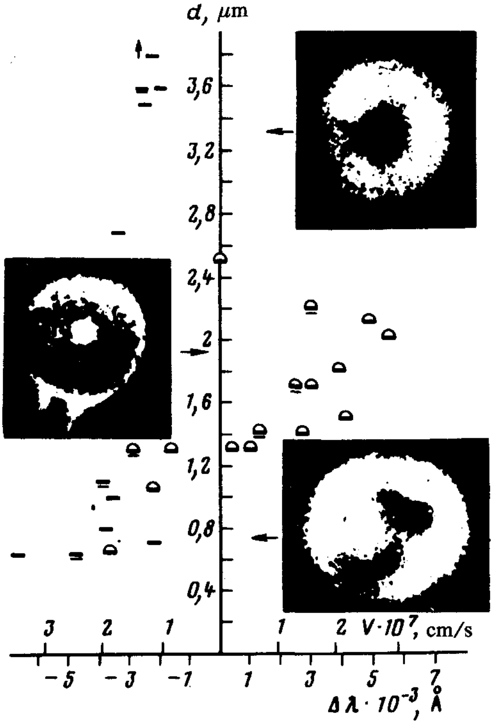

FIG. 2. *The shift* $\Delta\lambda$ *versus the shell thick*ness and x-ray pinhole photographs illustrating the optimum conditions for shell compression ($1.2 < d < 2.5$ μm), an unstable compression ($d < 1.2$ μm), and the absence of emission from the compressed shell ($d > 2.5$ μm). The arcs mark the results of experiments in which compression was detected.

Figure 2 shows the results of measurements of the magnitude and direction of the shifts of the intensity peak on images of the plasma in experiments with shells of various thicknesses. In the interval $d = 0.6$–1.2 μm we observe a blue shift ($-\Delta\lambda$) of the peak, which becomes a red shift ($+\Delta\lambda$) at a greater thickness, $d = 1.2$–2.5 μm, while at $d > 2.5$ μm we again observe a blue shift of the intensity peak on the images. The arrows here show the magnitude of the shift in experiments with a solid sphere 470 μm in diameter.

To explain the dependence of the shift on the thickness of the shells, we carried out calculations on the profiles of the temperature and density of the plasma, using the program of Ref. 5; we plotted the line shapes by the procedure of Refs. 6 and 7.

The calculations show that in the experiments with thin shells the intensity of the x-ray lines is dominated by plasma regions with a density $\sim 10^{22}$ cm^{-3}. The hot outer corona ($N_e < 10^{21}$ cm^{-3}) is almost completely transparent to light of the resonant transition, so that the blue Doppler shift on the images corresponds to the average velocity $\langle v_n \rangle$, of a layer of dense plasma.

As the shell thickness is increased, the mass of the corona increases, and the emission in resonant lines coming from the dense layers undergoes a significant self-absorption in the inhomogeneous expanding plasma. As a result, the intensity peak is shifted in the red direction on the image under these experimental conditions.

With a further increase in the shell thickness, regions with a lower density ($\sim 10^{20}$ cm^{-3}) begin to emit predominantly, and the resonant spectral lines are emitted from the plasma without any substantial self-absorption. A blue Doppler shift of the emission from the expanding plasma layers with a subcritical density is formed on the images.

The interval $d = 1.2$–2.2 μm, in which the red shift is observed, is the optimum interval for achieving high compression and heating of a DD fusion fuel in experiments in the Del'fin-1. The compression process in the experiments with these shells is highly symmetric (Fig. 2); the volume compression factor reaches 3.5×10^3, and the neutron yield ranges up to 10^7 per pulse. In experiments with thinner shells, the compression is not completely symmetric; in several experiments we observe the development of filamentation. Overall, a compression is detected in only $\sim 40\%$ of the cases. As the shell thickness is increased above 2.5 μm, no compression of the core is observed in the experiments, apparently because of its low temperature.

Comparing the value of $\langle \mathbf{v}_n \rangle$ determined from the Doppler shift in the experiments with thin shells with the shell collapse velocity $\langle \mathbf{v}_{\text{coll}} \rangle$, determined with the help of an x-ray image converter,[4] and using data on the laser energy absorbed during the collapse of the shell, we determined the hydrodynamic efficiency η and the target evaporation rate $\dot{m}$. Typical values of these quantities obtained from the Del'fin-1 experiments are $\langle \mathbf{v}_n \rangle = (1.2$–$3.3 \pm 0.1)\times 10^7$ cm/s, $\langle v_{\text{coll}} \rangle = (0.8$–$1.6 \pm 0.2)\times 10^7$ cm/s, $\eta = 5$–10%, and $\dot{m} \sim 10^5$ g/(cm^2·s). The values of η and $\dot{m}$ agree well with data from mass-spectrometric and collector measurements.[8]

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