Dynamics of laser-irradiated shell targets

N. G. Basov, P. P. Volosevich, E. G. Gamaliĭ, S. Yu. Gus'kov,
Yu. A. Zakharenkov, O. N. Krokhin, V. B. Rozanov,
G. V. Sklizkov, and A. S. Shikanov

P. N. Lebedev Physics Institute, USSR Academy of Sciences
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Experimental results are presented of the measurements, on the "Kal'mar" installation, of the time of compression of shell targets by a laser pulse. The agreement between the experimental data and the theoretical dependence of the compression time on the target and pulse parameters indicates that at laser radiation fluxes $< 10^{14}$ W/cm^2 the "corona" and the shell-compression dynamics can be described within the framework of a hydrodynamic model with near-classical thermal conductivity.

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A density $\rho_{D_2} \approx 6$–8 g/cm^3 and a neutron yield $\sim 3 \times 10^6$ particles per flash were obtained earlier[1] by laser-mediated compression of gas-filled microspheres. In this paper we compare the experimental investigation, performed with the "Kal'mar" installation, of the microsphere compression dynamics with numerical calculations and with an analytic model that establishes the similarity laws for this process.

The experimental procedure consisted of determining the R–t diagram of the motion of the critical-density surface[1] from a time scan of the image of the plasma luminosity region at the second harmonic of the heating radiation.[2] The shell collapse time (the time to stop its inner boundary) t^* was determined from the instant t^*_{cr} corresponding to the minimal radius R_{min}. According to numerical calculations, in these experiments we had $t^*_{\text{cr}} - t^* \approx 0.1$–$0.15$ nsec.

The experiments were numerically simulated in accord with the "Luch" program whose physical and mathematical model was described in[3]. We disregarded anomalous absorption mechanisms and the preliminary heating of the target by fast electrons.

In the hydrodynamic-compression regime, when $\tau_u \gtrsim t^*$, the shell motion described by the equation

$$M\frac{dv}{dt} = 4\pi R^2 P_{\text{cr}} , \tag{1}$$

where M and v are the mass and velocity of the shell, and P_{cr} is the pressure in the "corona" near the critical density. According to[4], under the conditions of the discussed experiments, the critical-density surface coincides with the Jouguet surface, so that $P_{\text{cr}} = 2n_{\text{cr}}kT_{\text{cr}}$. The temperature T_{cr} can be easily determined in the approximation wherein the energy absorption, the energy transport by the electronic thermal conduction, and the motion of the material are assumed stationary. As a result we obtain for P_{cr}

$$P_{cr} = \left[\frac{2^{1/2} E_{abs}(t)\rho_{cr}^{1/2}}{4\pi R^2}\right]^{2/3} . \tag{2}$$

TABLE I.

No. of experiment	Shell parameters			absorbed energy E_{abs}, J	t_c^*, nsec, experiment	t_c^*, nsec numerical calculation	t_a^*, nsec Eq. (3)
	Diameter $2R_0$, μm	Thickness Δ, μm	pressure P_D atm				
1	125	2,25	0	15 ± 3.0	1.5 ± 0,15	1.50	1.02
2	125	2.10	15	9 ± 1.5	1.8 ± 0,15	1,70	1.10
3	100	1,20	0	13 ± 2.5	1,25 ± 0.12	1,10	0.75
4	98	1.40	0	12 ± 2,0	1,4 ± 0.15	1.30	0.86
5	90	1.10	22	11 ± 2.0	1.1 ± 0.10	0.95	0.66
6	75	0,90	15	10 ± 2.0	0.9 ± 0.10	0.80	0.53

Laser pulse duration $\tau_{las} = 2.5$ nsec.

Integration of (1) with allowance for (2) yields

$$t^* = A\,\frac{2.5}{(32\pi\rho_{cr})^{1/4}}\left[\frac{M_0^3\,R_0}{E_{abs}(t^*)}\right]^{1/4}, \tag{3}$$

where R_0 is the initial shell radius, E_{abs} is the absorbed energy, and ρ_{cr} is the critical density.

Table I lists the shell collapse times in six experiments, as well as the values of t^* obtained in numerical calculations (using the Spitzer thermal-conductivity coefficient κ_{Sp}) and those obtained from formula (3). In Figs. 1(a) and 1(b) the experimental and the analytic results are compared with the calculated ones. It is seen that formula (3) accounts well for the dependence of t^* on the parameters and on the absorbed energy and thus determines the systematization of the collapse times measured in different experiments. The coefficient $A = 1.5$. The good agreement with the numerical calculations indicated that the pressure of the "corona" and the unevaporated shell mass M_{unev} were close in the experiments to the calculated values. We used in the calculations $P_{cr} \sim 10^5$–10^6 atm, $T_{cr} \approx 0.5$–0.7 keV, an average degree of ionization ~ 10, $M_{unev} \approx (60$–$70)\%\ M_0$, and a hydrodynamic transfer coefficient $\eta \approx 5$–10%. The "corona" temperature determined in the experiment by various methods[5] was also ≈ 0.5–0.7 keV.

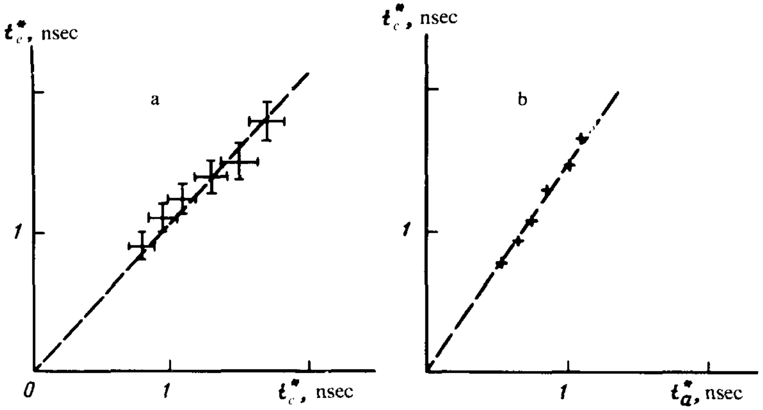

FIG. 1.

Figures 2(a) and 2(b) show R–t diagrams of the critical surface in two experiments. To determine the pressures in the target it is important to investigate the stages of its expansion. Figures 3(a) and 3(b) show the calculated R–t diagram of the inner surface of glass and the time dependences of the ratio of the pressures of the compressed gas and of the corona during the expansion stage. The expansion of the second shell (Fig. 2b), whose collapse time ($t^* \sim 1$ nsec) is much shorter than the laser-pulse

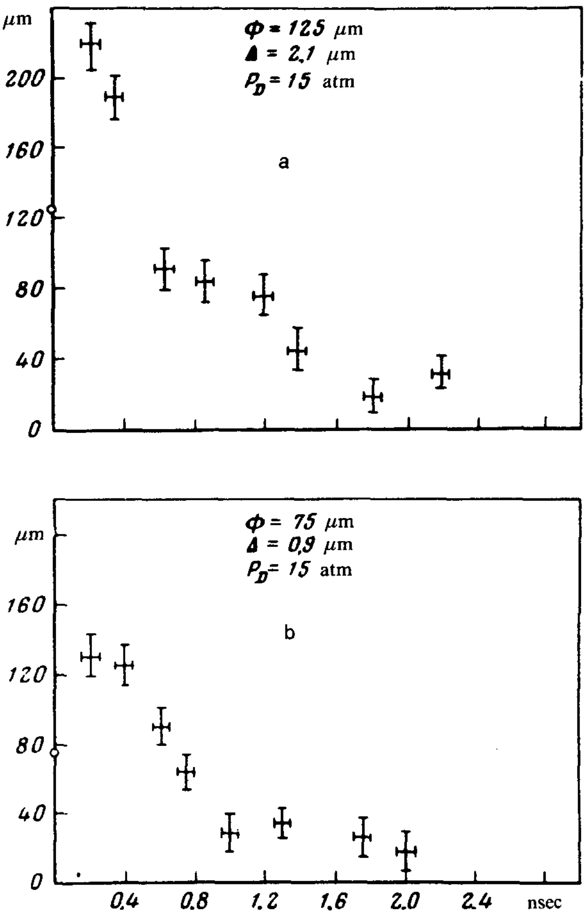
μm
Φ = 125 μm
Δ = 2,1 μm
P_D = 15 atm
a
200
160
120
80
40
0
μm
Φ = 75 μm
Δ = 0,9 μm
P_D = 15 atm
b
160
120
80
40
0
0.4
0.8
1.2
1.6
2.0
2.4
nsec

FIG. 2.

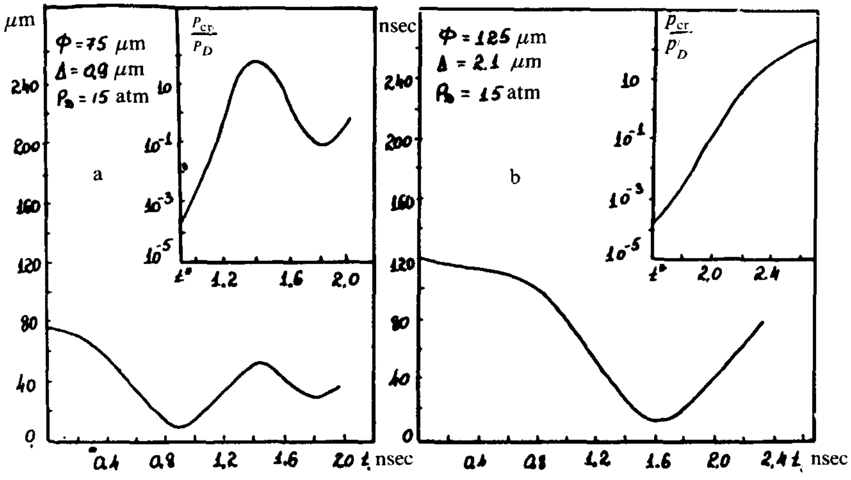
μm
Φ = 75 μm
Δ = 0,9 μm
P_D = 15 atm
a
$P_{cr.}/P_D$
10
10^{-1}
10^{-3}
10^{-5}
t^*
1.2
1.6
2.0
240
200
160
120
80
40
0
0.4
0.8
1.2
1.6
2.0
t, nsec
nsec
Φ = 125 μm
Δ = 2.1 μm
P_D = 15 atm
b
$P_{cr.}/P_D$
10
10^{-1}
10^{-3}
10^{-5}
t^*
2.0
2.4
240
200
160
120
80
40
0
0.4
0.8
1.2
1.6
2.0
2.4 t, nsec

FIG. 3.

duration, has an interesting feature. By the instant when the pulse action stops its manages to become compressed again. The agreement between the experimental and calculated *R–t* diagrams suggests that the pressure distributions in the target during the shell expansion stage are close to the calculated ones.

We note in conclusion tht the described analysis of the model experiments with the "Kal'mar" installation leads to the important conclusion that in large-scale experiments, at flux densities $\sim 10^{14}$ W/cm^2, the state of the "corona" and the dynamics of the shell compression can also be described within the framework of the hydrodynamic model with a thermal conductivity close to classical.

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