Symmetry and stability of laser-driven compression of thermonuclear targets

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An analysis is presented of the instability of laser-driven compression of thermonuclear targets. Estimates made for shell targets with large energy gains show that the compression can be stable at a definite initial-perturbation level.

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1. The problem of the stability of laser-driven compression of thermonuclear targets was investigated both by numerical simulation of the system of equations of two-dimensional hydrodynamics and thermal conductivity,[1,2] and in the linear approximation.[3,4] An investigation of closely related problems in[3] and[4] yielded different results. It was concluded in[2] that shell targets are absolutely unstable, but an appreciable compression of a similar target was registered in experiment[5] and no asymmetry was noted. We present below, for the instability processes, an analysis that is applicable to different compression regimes and different types of targets and makes it possible to interpret the results of[3–5] from a unified point of view. Estimates were made of the growth of the perturbations in shell targets with large energy gains.[6]

2. There are two compression stages in which the motion is hydrodynamically unstable in the Rayleigh-Taylor sense[7] (see the figure). The first stage is acceleration of the unevaporated part of the target by the hot and low-density ablation layer. The second stage is the deceleration of the denser peripheral

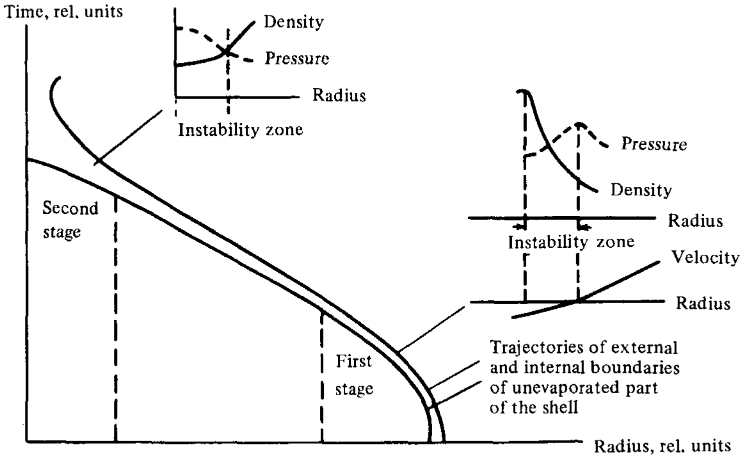

FIG. Stages of hydrodynamic instability in the course of compression of a shell target.

layers of the target by its heated core. The stages are separated in time by a region of a stable flow with constant velocity. In both stages, the motion is unstable in a certain region. When calculating the growth increments of the perturbations it is therefore necessary to use the expression obtained in[8], which is more general than that in[7]:

$$\gamma^2 = \rho^{-1} \nabla p \, \nabla \ln \rho \, (\nabla \ln \rho >> \nabla \ln p). \tag{1}$$

The motion is stable if the pressure and density gradients are oppositely directed, as in the situations singled out in the figure. The two instability stages exist for compression of all target types considered in the literature.

The flow will deviate significantly from spherically-symmetrical if the instability in the first stages leads to perturbation amplitudes that are comparable with the dimensions of the regions covered by the motion. The instability in the second stage can lead to a turbulent mixing[9] of the target material, which is not critical for a homogeneous or quasi-homogeneous target, such as in[6], in which the mass of the thermonuclear fuel exceeds the mass of the inhomogeneous intrusions. We shall therefore dwell on the instability of the first stage

3. The instability zone moves into the interior of the medium with the velocity of the evaporation wave, and more and more new particles of the medium pass through the zone and are then carried away to the periphery of the target with the expanding corona. Thus, a given particle will stay in the instability zone for a time

$$t_{\text{instab}} = \Delta r / v_{\text{evap}}, \tag{2}$$

where Δr is the width of the unstable zone and v_{evap} is the velocity of the evaporation wave. Consequently, the amplitude of the perturbation in a Lagrangian particle during the compression time is

$$\Delta(t)/\Delta_0 = \exp(\gamma t_{instab}). \tag{3}$$

We note that t_{instab} can be much shorter than the acceleration time, i. e., than the lifetime of the unstable situation. The quantities ∇p, $\nabla \rho$, and v_{evap} are determined entirely by the target-heating regime.

The influence of the width of the instability zone can be illustrated by the results of[3,4], where a study was made of the stability of compression of a spherical target (target radius 400 and 500 μ, laser-pulse energy 60 and 50 kJ). In the former case, when a steeper laser pulse was used, the growth of the perturbation led to appreciable distortion of the one-dimensional picture, while in the latter case a Gaussian pulse was used and the growth of the perturbation was negligible. These results can be explained by estimating the size of the instability zone (from the temperature and density distributions given in these papers), which turned out to be much larger in the former case than in the latter.

4. The effective mechanism of instability elimination, which imposes an upper limit on the number of the harmonic of the dangerous-mode band, is the electronic thermal conductivity. The characteristic time t_{eq} of equalization of the initial perturbations of amplitude Δ_0 (l is the number of the spherical harmonic of the perturbation), is

$$t_{eq} \sim \frac{C\rho x^2}{\kappa_0 T^{5/2}} \quad \frac{C\rho}{\kappa_0 T^{5/2}}\left(\frac{R_0}{l}\right)^2 , \tag{4}$$

where C is the heat capacity, κ_0 is the thermal-conductivity coefficient, ρ is the critical density, T is the temperature, and R_0 is the target radius. If we specify the compression time τ, the temperature T in the corona, and the radius R_0, then we can easily estimate from (4) a value of l_{char} such that all the perturbations with $l > l_{char}$ become equalized by the thermal conductivity in a time $t_{eq} \ll \tau$. The effectiveness of the thermal-conductivity equalization of the pressure in the corona was recently demonstrated experimentally.[10]

5. The maximum growth increment of the perturbations and the instability-zone width, determined from one-dimensional numerical calculations[6] for the target parameters indicated below and the momentum at the first stage are respectively $\gamma \sim 10^9$ sec^{-1} and $\Delta r \sim 2\times 10^{-4}$ cm, while the characteristic velocity of flow of the medium through the instability zone is $v \sim 3\times 10^5$ cm/sec. We then obtain from (3) $\Delta(t) \sim 3\Delta_0$.

A measure of the distortion of the shell shape is the ratio $\Delta(t)/\Delta R(t)$ of the perturbation amplitude to the shell thickness at a given instant of time. We note that the shell expands in the course of the acceleration, since its internal boundary moves with a velocity approximately double the velocity of the particles near the acceleration limit. Towards the midpoint of the action of the laser pulse, the thickness of the layer traveling towards the center is $\Delta R(t) \sim (5\text{—}10)\Delta R_0$, depending on the energy and on the shape of the laser pulse. Thus, the ratio $\Delta(t)/\Delta R(t)$ does not increase and the shell shape is not distorted. In addition, the speed of sound in the medium of the shell is low, $\sim 10^6$ cm/sec, so that the perturbations will be concentrated near the instability zone.

6. Let us estimate the requirements imposed on the irradiation symmetry

and on the homogeneity of a target constituting a hollow thin-wall sphere.[6] W assume that the thermonuclear fuel is symmetrically compressed if at the fina stage of the compression the surface perturbation amplitude of the compresse nucleus satisfies the condition $\Delta \ll R$, for example,

$$\Delta_{fin} \le 0.1 R_{fin}$$

R_{fin} is the final radius of the compressed target nucleus. We use for the estimates the following data: $E_{las} = 10^6$ J, $R_0 = 1$ cm, $\Delta R_0/R_0 = 10^{-2}$; $\tau = 10^{-7}$ sec, and $T \sim 1$ keV. According to[6] we have for R_{fin}

$$R_{fin} = [3R_0^{1/2}(\Delta R_0)^{5/2}]^{1/3} . \quad ($$

Then $R_{fin} = R_0/50$; $\Delta_{fin} \sim 2\times 10^{-3} R_0$, and $l_{char} \ge 30$ ($t_{eq} \sim 10^{-10}$ sec). On the basis of the results of Sec. 5, we can assume that there is no angular interaction between the spherical sections spaced a distance $x \ge R/30$ apart. We can then easily obtain the following requirements on the initial conditions: shape pertur bations $\Delta_0 \le 0.2\Delta R_0$; mass difference in the spherical sectors $(\Delta x > \Delta R_0)$ $\Delta m/m$ $\le 2\Delta_{fin}/R_0 = 4\times 10^{-3}$, time of desynchronization of the beams $\Delta t/t_0 \le \Delta_{fin}/R_0$ $= 2\times 10^{-3}$, difference between energy flux densities $(\Delta x \gtrsim R_0/30)$ $\Delta E/E_0 \le 2\Delta_{fin}/$ $= 4\times 10^{-3}$.

7. On the basis of the foregoing analysis we can expect no significant deviation of the compression process from spherically-symmetrical to take place (for $E_{las} = 10^6$ J) at a relative initial-perturbation amplitude (variations of the shell thickness, of the density, and of the mass) less than 1%. This conclusion is valid also at other laser-radiation energies and target dimensions, inasmuch as in the optical case the dimensions and the time are connected by gas-dynamic similarity relations $r, t \sim E^{1/3}$. An indirect confirmation of the much higher stability of the homogeneous shells than postulated in[2] is provid by experiments on compression of thin glass spheres with $\Delta R_0/R_0 \sim 2\times 10^{-2}$,[5] in which the shell traversed a path equal to 40 times its initial thickness witho a noticeable loss of spherical symmetry.

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