

## Studies on dynamical shell formation for direct-drive laser fusion

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**Summary.** — We consider a recently proposed target concept for laser-driven inertial confinement fusion (GONCHAROV V. *et al.*, *Phys. Rev. Lett.*, **125** (2020) 065001). A homogeneous sphere is irradiated by an appropriately timed laser pulse, leading to the (dynamic) formation of a dense shell. This shell is then imploded to high velocity to achieve the conditions needed for thermonuclear ignition. Here we study, by means of one-dimensional and two-dimensional simulations, a scaled-down target suitable for a proof-of-principle experiment, which can be performed on the laser OMEGA at the Laboratory for Laser Energetics, Rochester University.

### 1. – Introduction

Conventional targets for direct-drive laser fusion consist of a spherical shell with a thin inner layer of frozen deuterium-tritium (DT) fuel. Such targets can be effectively imploded at the velocities required for thermonuclear ignition by the ablation pressure generated by collisional absorption of laser light [1]. The use of hollow shells, rather than homogeneous spheres, is dictated by the need of reducing laser power and, at the same time, allowing for longer implosion time [2]. However, fabrication of thin shells with highly uniform DT layers is difficult and expensive. In addition, they are expected to be more susceptible to instabilities and asymmetries than homogeneous spheres. Recently, a new concept of spherical target has been proposed [3]. Irradiation of this target by an appropriately timed sequence of laser pulses leads to the formation of a shell of dense fuel and, possibly an outer layer of other materials, containing lower density fuel. Such a dynamically formed hollow shell target is then irradiated by a properly shaped laser pulse, driving fuel implosion, and the subsequent formation of the hot-spot required for ignition.

In this paper we first describe the main features of such target concept by means of a 1D simulation (sect. 2), and then report studies on the preliminary design of a scaled-down proof-of-principle experiment (sect. 3).

## 2. – The concept

We illustrate the target concept by means a one-dimensional (1D) simulation using the radiation-hydrodynamics-nuclear code DUED [4]. We consider a liquid DT sphere, with radius  $R_0 = 1200 \mu\text{m}$ , surrounded by a shell of DT-wetted plastic foam  $100 \mu\text{m}$  thick, irradiated uniformly by a laser pulse with the temporal power dependence shown in fig. 1. The initial moderate power pulse drives an imploding shock wave, which bounces at the center at  $t \sim 42 \text{ ns}$ . The subsequent blast wave progressing in the compressed fuel causes its expansion (at about  $t \sim 55 \text{ ns}$ ). Expansion of the material continues until its ram pressure becomes lower than the ablation pressure generated by the laser pulse. At this time, a shock is generated near the ablation front. It decelerates the expanding fuels and leads to the formation of a hollow shell configuration (with outer radius  $R_f \sim 1600 \mu\text{m}$ ) at  $t \sim 140 \text{ ns}$ . Such a dynamically created shell is then accelerated inward using the conventional central hot-spot direct drive laser fusion approach. Fuel is imploded to velocity  $u_{imp} = 4 \times 10^7 \text{ cm/s}$ , a central hot spot is formed and fuel ignites and burns. More details on target predicted performance have been presented in ref. [3], where it is shown that large energy gain (ratio of fusion energy to laser energy) of the order of 75 can be obtained with laser pulses of 1.15 MJ.

## 3. – A proof-of-principle experiment

The concept illustrated above requires laser pulses of more than 1 MJ and duration in excess of 150 ns, which are not feasible with presently available lasers for inertial fusion. However, a fundamental aspect, namely the generation of low entropy, high density, adequately symmetrical shell, could be tested in scaled-down experiments, using laser pulses shorter than 4 ns and with total energy of about 15 kJ, as currently available at the University of Rochester OMEGA laser [5]. We present here a few preliminary results on the design of such experiment.

We consider a spherical foam target ( $R_0 = 320 \mu\text{m}$ , density  $\rho_0 = 0.2 \text{ g/cm}^3$ ) acting as a surrogate for the liquid DT. This target develops a thermally expanding plasma cloud

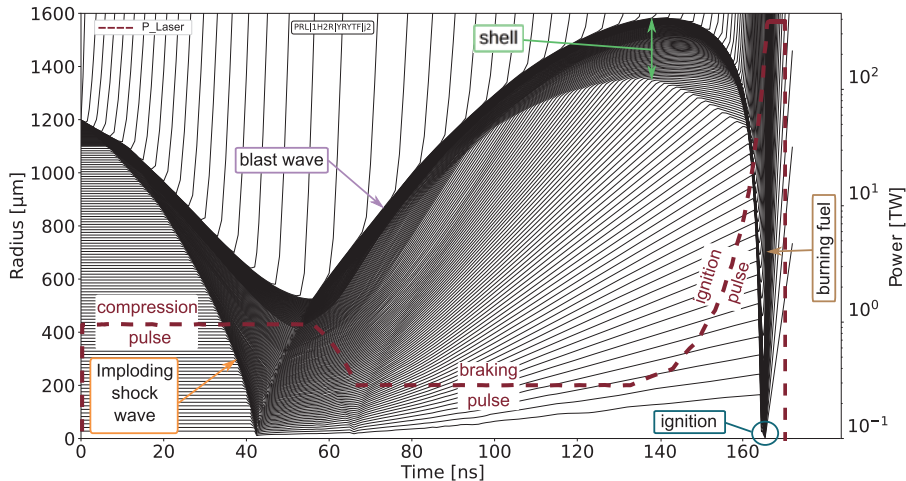


Fig. 1. – Implosion diagram. The black lines refer to particle trajectories (left-hand side axis) and the dashed line to the laser power (right-hand side axis).

after shock bounce from the center and the formation of a blast wave. The cloud expansion is slowed down and finally reversed so as to lead to its compression by a sequence of convergent shocks, which are launched by a sequence of laser *pickets*. (Pickets replace a continuous pulse to reduce the growth of Rayleigh-Taylor instability [6]). Figure 2(a) shows the temporal profile of laser power, as well as the evolution of the shock and rarefaction waves leading to the formation of the shell. The figure shows that a dense shell, with radial density profile, as shown in fig. 2(b), is generated at  $t = 3.9$  ns.

**3.1. Effects of low-mode asymmetries in laser illumination.** – One of the crucial aspects of the proposed experiment is assessing the sensitivity of the concept to timing (and power level) errors, as well as to target initial inhomogeneity, departure from sphericity and non-uniform irradiation. Here, we present the first results of a study on the effects of non-uniform irradiation, based on 2D simulations with DUED. For simplicity, we assume radial laser beams (while in the previous 1D simulation we used a more realistic 2D model for laser-target interaction), with angular-dependent intensity,

$$(1) \quad I(\theta, t) = I_0(t) \left[ 1 + \sum_{l_{min}}^{l_{max}} A_l \times \mathcal{P}_l(\cos \theta) \right],$$

where  $I_0$  is the unperturbed laser intensity,  $A_l$  the amplitude of the perturbed mode  $l$  and  $\mathcal{P}_l(\cos \theta)$  the Legendre polynomial of order  $l$ . A systematic study on the effects of low-modes is in progress. We illustrate here a case with  $A_1 = -0.05$ ,  $A_2 = 0.07$  and  $A_4 = 0.06$ . The density map at  $t = 3.9$  ns is shown in fig. 3(a). The figure clearly shows a departure from symmetry with respect to  $\theta$  and a significant displacement to the right of the shell center due to negative amplitude  $A_1$  of the first Legendre polynomial  $\mathcal{P}_1$ . The enclosed cavity is still quite uniform. An important quantity for inertial confinement fusion is confinement parameter [1],  $\langle \rho R \rangle = \int \rho dr$ . We then consider its Legendre-mode analysis

$$(2) \quad \langle \rho R \rangle(\theta, t) = c_0(t) \left[ 1 + \sum_{l=0}^{l_{max}} \frac{c_l(t)}{c_0(t)} \mathcal{P}_l(\cos \theta) \right].$$

In fig. 3(b) we show the time evolution of  $c_0(t)$  and a few normalized coefficients  $c_l(t)/c_0(t)$ . The peaks of  $\langle \rho R \rangle$  in correspondence to the convergence of the first shock

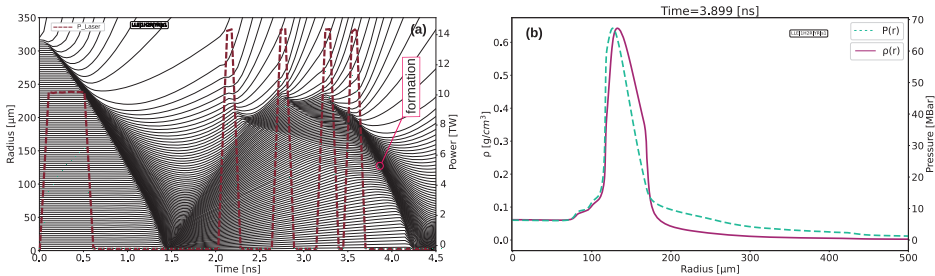


Fig. 2. – (a) Implosion diagram of the surrogate target: the black lines refer to particle trajectories (left-hand side axis) and the dashed line refers to the laser power (right-hand side axis). (b) Density and pressure profile of the formed shell.

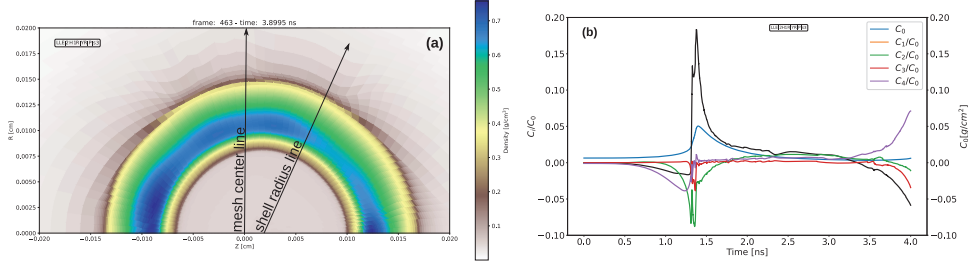


Fig. 3. – (a) 2D density map of the target at  $t = 3.9$  ns. (b) Time evolution of Legendre modes of confinement parameter  $\langle \rho R \rangle$ .

and the formation of the shell are apparent, as the growth of the perturbed modes. To be noted, in particular, the large amplitude of mode  $l = 1$ .

#### 4. – Conclusion

In this paper we reported preliminary design studies of a proof-of-principle experiment of a target for inertial fusion with dynamic shell formation. Studies are now in progress to make the design more realistic, and to assess the sensitivity of shell formation to deviations of laser and target parameters from their nominal values. In addition, synthetic diagnostics, coupled with hydrodynamic simulations, will be used to define the parameters of the experimental diagnostics.

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