Measuring and increasing the safety margin of high-gain shock-ignited targets

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1. Introduction

Shock ignition [1] is a laser direct-drive inertial confinement fusion scheme, in which the stages of compression and hot spot formation are partly separated. The fusion fuel is first imploded at somewhat lower velocity than in conventional schemes, reducing the risks associated to Rayleigh-Taylor instability (RTI). The hot spot is created at the end of the implosion by a converging shock-wave driven by a final spike of the laser pulse. Significant research activity has been devoted to assessing the feasibility of shock ignition [2, 3]. In particular, we studied an all-DT target (the HiPER target), by means of analytical models and 1D and 2D radiation-hydrodynamics simulations [4]. In shock ignition, the separation of fuel compression and ignition allows some design flexibility [5, 6], when targets are up-scaled from a (theoretically) marginally igniting small target to larger dimensions. We determined scaling laws for different scaling options, and computed gain curves by 1D simulations of families of scaled targets [6]. The unavoidable modeling uncertainties (well evidenced, e.g., by the recent NIF experiments [7, 8]) indicate that any credible design has to include large safety margins [9]. For high-gain shock ignition we use a 1D safety factor, ITF^*, analogous to the 1D ignition threshold factor, ITF, used to characterize NIF indirect drive targets [7]. In ref. [10] we computed ITF^* for the HiPER target, and determined its dependence on implosion velocity and spike power. We then generated gain curves at given ITF^*.

In this paper we report further studies, aiming at improving design realism, and at increasing target robustness. In addition to the HiPER target, we consider a target originally proposed by G. Schurtz and the CELIA-Bordeaux group [5], consisting of a relatively thick DT layer and a plastic ablator. The simulation code DUED [11] has been used in all the simulations reported here.

2. Evaluating and increasing target ITF^*; Gain curves vs ITF^*

We refer to the targets shown in Fig. 1, irradiated by the laser pulses schematically shown in Fig. 2, with wavelength of 350 nm. The *foot* power determines the fuel in-flight isentrope parameter $a_{\rm if}$ (or adiabat, ratio of pressure to the pressure of a fully degenerate electron gas at the same density), the pulse *plateau* the implosion velocity, the *spike* contributes to hot spot

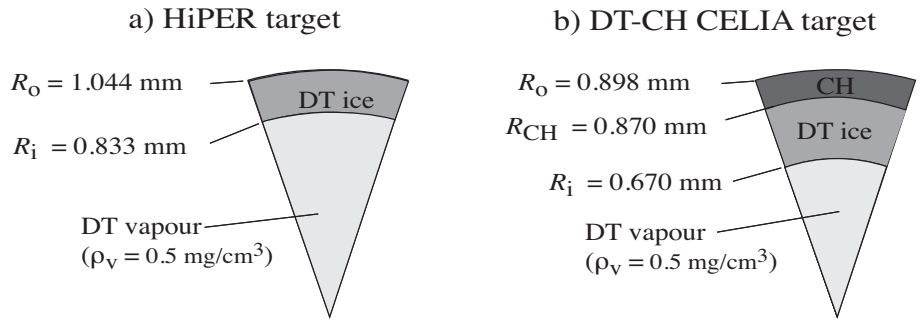

Figure 1: *Reference (scale $s = 1$) targets considered in this paper.*

formation. The initial *picket* serves to shape the adiabat in space, in order to reduce RTI growth rate.

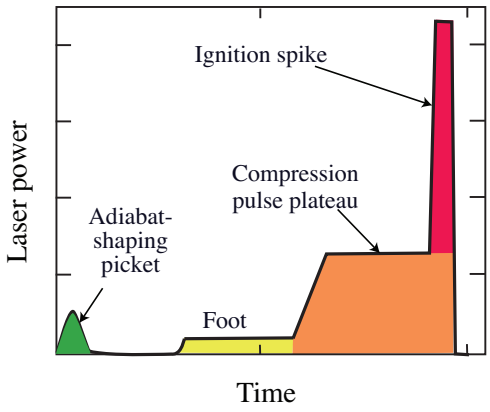

Figure 2: *Laser pulses driving the targets of Fig. 1*

At given a_{if}, ignition and gain can be achieved with different choices of plateau power and spike power, and correspondingly different ITF^*. Following ref. [12], we compute ITF^* by a set of 1D simulations with artificially reduced DT reactivity. We take $ITF^* = [\xi_G^{crit}]^{-3/2}$, with ξ_G^{crit} the minimum value of the reactivity multiplier allowing to achieve gain equal to 80% of the nominal gain. Figure 3a) shows ITF^* vs laser plateau power and spike power for the DT-CH target and $a_{if} \simeq 1.6$. [The analogous results for the HiPER target (with $a_{if} \simeq 1.4$) are also reported in Fig. 3b) for comparison; see ref. [10].] The figure shows that a compression plateau of 90 TW (resulting in implosion velocity of 250 km/s), followed by a 200 TW spike is marginally sufficient for ideal 1D ignition and high gain ($G = 70$ with laser energy of 400 kJ). However a safer (still not very large) $ITF^* \geq 2$ requires higher power, at least for the compression pulse. We have taken a pulse with compression plateau of 120 TW and spike in the range 200–330 TW as a reference. We have then upscaled target and pulse according to the laws derived in Ref. [6], in such a way to keep constant the ratio of the implosion velocity to the self-ignition velocity (minimum velocity required to ignite without the final spike). Accordingly, when linear dimensions are scaled by a factor s, times scale as $s^{1.32}$, velocity as $s^{-0.32}$, compression pulse power as $s^{1.04}$, compression laser as energy as $s^{2.32}$ spike power as $s^{1/2}$ and spike energy as $s^{1.82}$. The resulting gain curve is shown in Fig. 4. It is seen that the (1D) gain exceeds 100 at laser energy of about 1.2 MJ (with total peak power about 500 TW). Both gain and ITF^* are somewhat smaller, and peak power higherthan for the very

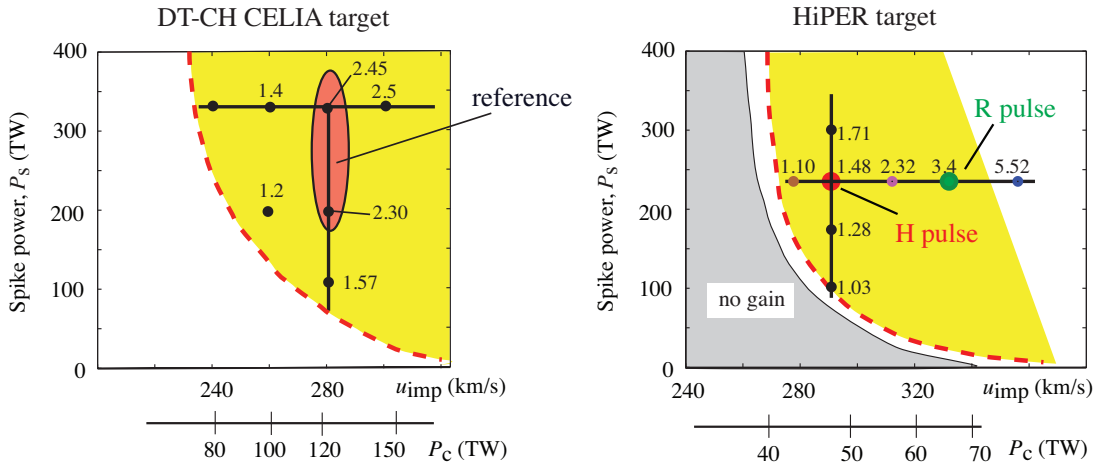

Figure 3: *ITF* for selected cases in the implosion velocity (or compression laser power) and spike power for the targets of Fig. 1. Cases in the yellow area achieve 1D gain G > 50.*

simple HiPER target. However, further optimization of this more realistic target is possible, e.g. by improving pulse shaping, or slightly reducing the thickness of the DT layer (see, e.g. the target for NIF discussed in Ref. [13]).

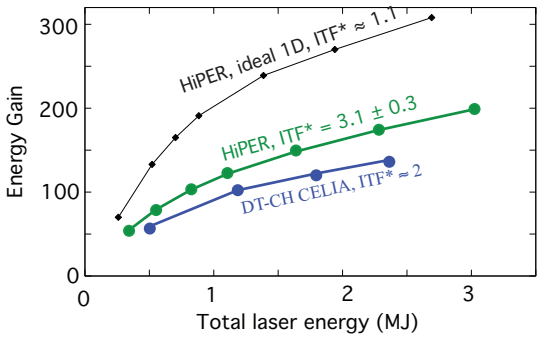

Figure 4: *Gain curves for targets upscaled from the reference targets.*

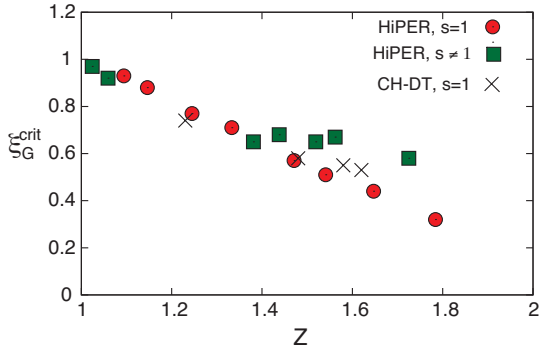

Figure 5: *Critical value of reactivity multiplier allowing for high gain,* $\xi_G^{crit} = (ITF^*)^{-2/3}$ *vs the ratio* $Z = p_{hs}^{no-\alpha}/p_{self-ig}^{no-\alpha}$.

3. Robustness to large scale-length asymmetries vs *ITF**

We have performed 2D simulations to study the sensitivity of the HiPER shock-ignited target to long-scale asymmetries caused by the irradiation by a finite number of beams and by target mispositioning. We have used a 3D ray-tracing package [14] and simulated the 48-beam reference HiPER irradiation scheme.The results confirm those assuming radial rays with angular dependent intensity. Targets with larger *ITF** tolerate larger asymmetries. E.g., at scale $s = 1.53$, the HiPER H-target, with *ITF**=1.57 cannot tolerate a 24 μm offset, while the HiPER R-target, with *ITF**=3, ignites even when displaced by 32 μm.

4. ITF^* and hot spot parameters

The inertial fusion ignition condition is essentially a condition on the product of hot spot pressure and radius (e.g., [2, 7]). It has then been conjectured [15] that the ignition margin is related to the ratio $Z = p_{\rm hs}^{no-\alpha}/p_{\rm self-ig}^{no-\alpha}$, where $p_{\rm hs}^{no-\alpha}$ is the peak hot spot averaged pressure computed in a shock-ignition simulation (with α heating turned off), to the minimum hot spot pressure required to self-ignite the same target, $p_{\rm self-ig}^{no-\alpha}$. A preliminary analysis indeed shows a clear relation between $\xi_{\rm G}^{\rm crit}$ and Z, at least for the same target (see Fig. 5).

5. Conclusions and outlook

We have presented preliminary results of recent SI target studies. In the near future we will perform sensitivity studies on pulse shaping, model studies on hot electron preheat, as well as 2D model studies of short-wavelength RTI growth both at the ablation front and at the hot spot surface. In any case, we remark that our study, based on fluid models, could not address the issues related to laser-plasma instabilities, and should therefore be complemented by studies using kinetic or hybrid models.

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