Energy and wavelength scaling of shock-ignited inertial fusion targets

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Abstract. In inertial fusion shock ignition, separation of the stages of fuel compression and hot spot creation introduces some degree of design flexibility. A lower implosion velocity can be compensated for by a more intense ignition pulse. Flexibility increases with target (and driver) size and allows for a compromise between energy gain and risk reduction. Having designed a reference ignition target, we have developed an analytical model for (up)-scaling targets as a function of laser energy, while keeping under control parameters related to hydro- and plasma instabilities. Detailed one-dimensional simulations confirm the model and generate gain curves. Options for increasing target robustness are also discussed. The previous results apply to UV laser light (with wavelength $\lambda = 0.35 \mu m$). We also show that our scaling model can be used in the design of targets driven by green laser light ($\lambda = 0.53 \mu m$).
1. Introduction

Shock ignition [1] is a recently proposed approach to laser-driven inertial confinement fusion (ICF), in which an intense laser spike drives a converging shock wave which helps the formation of a central hot spot in an already compressed fuel. Hot spot ignition and substantial fuel compression are indeed essential ingredients of any inertial fusion scheme [2, 3] aiming at the high energy gain (ratio of released fusion energy to driver energy) required for commercial energy production. In the standard laser fusion scheme [2, 3], both fuel compression and creation of the ignition hot spot are achieved by irradiating the fuel-containing capsule with a properly time-shaped laser pulse, driving a high-velocity implosion. Velocities exceeding 300–400 km s$^{-1}$ are required (the actual value depending on the fuel mass and the entropy of the compressed fuel; see also section 3). However, the higher the implosion velocity, the higher the risks associated with the development of the hydrodynamic Rayleigh–Taylor instability (RTI), threatening the integrity of the imploding shell or causing deleterious material mixing. In addition, higher velocity also implies higher driving pressure and hence higher laser intensity, which can result both in degradation of the absorption of laser light and in fuel preheating (making compression less efficient). The detrimental effects of laser plasma instabilities (LPIs), mainly backscattering and generation of hot electrons, may grow with intensity. (In fact, a figure of merit often used to estimate risks related to LPIs is the irradiance $I\lambda^2$, with $I$ the intensity and $\lambda$ the laser wavelength, which enters the gain coefficient of linear LPIs; see e.g. [4].) Fuel
preheat may result from hot electrons, hard x-rays and mistimed shocks, all more likely at higher intensities.

ICF schemes requiring lower implosion velocity are therefore highly desirable [1, 5]. The required compression can still be achieved [6], provided the average entropy of the imploding fuel is kept low. Generation of the igniting hot spot, instead, requires a separate mechanism. In shock ignition [1], a hollow spherical target is first imploded at lower velocity by a standard time-shaped laser pulse, with intensity in the range \((0.3–1) \times 10^{15} \text{ W cm}^{-2}\). Towards the end of the implosion, the target is irradiated by a more powerful, shorter, laser pulse (a spike, see figure 2), with intensity up to ten times larger than that of the compression pulse. (The quoted intensities refer to a laser wavelength of 0.35 \(\mu\)m, the third harmonic of Nd:glass laser.) Absorption of this spike about the critical density generates an ablation pressure of 200–300 Mbar, driving a strong converging shock wave. Collision of this inward-directed shock, intensified by convergence, with the shock bouncing from the centre of the imploded fuel results in compression and heating of the hot spot.

Shock ignition was proposed by Betti et al [1] a few years ago; a first proof-of-principle experiment was performed soon afterwards [7]. Subsequently, several groups designed different targets, studied aspects of their robustness and investigated the physics of shock pressure multiplication [8–15]. Most studies referred to a laser wavelength of 0.35 \(\mu\)m, but also wavelengths of 0.25 and 0.53 \(\mu\)m were considered in [11] and [16], respectively. Gain curves (gain versus driver energy) were also generated by considering families of scaled targets [8, 11, 12]. Different authors scaled targets in somewhat different ways and with different assumptions. We consider a more systematic analysis of target scaling, enlightening the opportunities offered by shock ignition.

In this paper, we derive general relations for scaling targets with size (hence with energy) and laser wavelength and generate gain curves based on different scaling options, and also for different laser wavelengths. We reckon, and show with a few examples, that the above-quoted flexibility can be exploited to increase target robustness to asymmetries and instabilities. The scaling procedure is applied to the so-called HiPER baseline target [17], which was studied in detail in earlier papers on shock ignition [9, 13]. For completeness, the main target and pulse parameters are briefly recalled in section 2.

The main issue for the feasibility of shock ignition concerns the efficient generation of the high-pressure shock, which occurs in a laser–plasma interaction regime not yet studied experimentally. At the relevant intensity (more precisely, the values of the product \(I\lambda^2\) of the intensity and wavelength squared), LPIs might degrade absorption [4]. Also, the generation of a significant amount of hot electrons is expected. We do not study these problems in this paper. However, we study the scaling of \(I\) and \(I\lambda^2\), and show that in any considered option they decrease with target size.

A comment is probably in place concerning reliability of studies based on analytical models and one-dimensional (1D) numerical simulations, in light of the recent results [18, 19] of the National Ignition Campaign (NIC) [20]. NIC experiments so far have shown implosion velocity smaller than predicted (at a given laser power) [18]. Also, inferred hot spot pressures have been found to be smaller than expected (at a given implosion velocity) [19]. The results on the smaller implosion velocity are not necessarily relevant to the direct-drive implosions discussed here, since laser absorption and coupling mechanisms are different in indirect- (where x-ray conversion, x-ray transport and x-ray coupling to the capsule play a key role) and direct-drive laser fusion. The results on the hot spot pressure, instead, should not depend on the
specific drive mechanism. According to the Administrator of the US National Nuclear Security Administration [19] (page 9) ‘the reason for the (pressure) deficit is not clear but is due, most likely, to low-mode fuel asymmetries and to the hot spot experiencing more mixing than expected’. Experiments and improved analyses are required to solve these issues. One may wonder whether and how these effects might alter the conclusions of the present study. If all effects are due to asymmetries and mixing, the model developed here will be unaffected, being 1D, and being designed to scale a given igniting target to larger size. However, the reduction of asymmetries and mixing may turn out to be more difficult than previously assumed. This means that ignition of the reference target to be scaled may require either somewhat higher implosion velocity and/or a more powerful spike than computed here for the baseline target. Provision for these effects can be included in our model by increasing the value of the safety factor $S_m$, introduced in section 2.2.

2. HiPER baseline target

The scaling relations studied in this paper can, in principle, be applied to any target and laser pulse. In this paper, we apply them to design targets up-scaled from the so-called HiPER baseline target.

2.1. Baseline case

This target, a simple cryogenic deuterium-tritium (DT) shell (see figure 1), was originally proposed for fast ignition [17] and later shown to be suitable for shock ignition [9, 13].

The target was designed to satisfy the following constraints:

1. compression intensity at half radius below $5 \times 10^{14}$ W cm$^{-2}$ (with laser wavelength $\lambda = 0.35 \mu$m), to control laser-plasma instabilities;
2. in-flight-aspect-ratio (at 2/3 of the radius, IFAR$_{2/3} < 35$ and growth factor of the fastest mode of the ablation front RTI smaller than seven, to make RTI growth tolerable;
3. in-flight isentrope parameter $\alpha_{df} \leq 1.2$ to reduce compression work. (The isentrope parameter is the ratio of the actual material pressure to the pressure of a cold material, with Fermi degenerate electrons, at the same mass density.)

Target design was based on 1D simulations performed with the DUED code [21, 22], summarily described in appendix A. Target structure and laser power temporal shape are shown in figures 1 and 2, respectively. Also listed are the numerical values of the main quantities defining the baseline laser pulse used in the present study. Timing and power levels depend (weakly) on the material equation-of-state and on the flux limiter coefficient $f$. The laser pulse parameters refer to simulations with flux-limited thermal conduction, with flux limitation factor $f = 0.07$ (sharp cut-off model). The dependence of simulation results on the flux-limiter $f$ is discussed in appendix A.

In the baseline design, the target is irradiated by 48 beams [13, 23, 24], generating a nearly perfectly symmetric irradiation pattern. Each compression beam has a Gaussian profile $I \propto \exp \left(-r/w\right)^2$ with width $w = w_c = 640 \mu$m for the compression pulse and $w = w_s = 400 \mu$m for the final ignition spike.

Without the final spike, the shell implodes at velocity $u_{imp} = 291$ km s$^{-1}$ and achieves a confinement parameter $\langle \rho R \rangle = 1.58$ g cm$^{-2}$, but does not ignite. Ignition and gain $G = 50–70$
Figure 1. HiPER baseline target. All targets considered in this paper are scaled from this target as discussed in the main text.

Figure 2. Temporal shape of the laser power for shock ignition of the targets considered in this paper. The parameters listed on the right-hand side refer to the HiPER baseline target shown in figure 1. The baseline laser light wavelength is 0.351 µm. The final spike adds to the compression spike.

are achieved with the addition of a spike with power \( P_s \geq 100 \text{ TW} \). In the reference case, \( P_s = 240 \text{ TW} \) and \( G = 65 \). Other performance parameters will be listed later in table 3, column H.

2.2. Performance versus implosion velocity and spike power

In shock ignition, the implosion velocity is below the ignition threshold. The igniting hot spot is created with the help of the additional powerful spike. The smaller the implosion velocity, the higher the laser power required for ignition. This is clearly shown by figure 3, showing gain contours in the plane of implosion velocity and additional spike power for the HiPER baseline target. The thick red curve marks the spike power threshold for gain \( G > 50 \). The figure is the result of parametric numerical simulations. The implosion velocity has been varied by varying the compression power. The duration of the compression plateau and the launch time of the...
Figure 3. Gain contours in the plane of implosion velocity and spike power for the HiPER baseline target, obtained from 1D numerical simulations. The red curve indicates the spike power required to achieve high gain ($G = 50$) versus implosion velocity; this line is very close to the gain threshold. The point labelled H indicates the HiPER baseline operating point, chosen with a rather large safety margin.

Figure 4. For the HiPER baseline target, (a) energy gain versus implosion velocity for a conventional implosion, without the final spike; (b) energy gain versus laser spike power, at implosion velocity $u_{\text{imp}} = 290$ km s$^{-1}$.

spike have been optimized to maximize the gain. The spike duration has been kept constant. In all cases, $\alpha_{\text{if}} = 1.2$.

Analysis of two cuts of the gain contours of figure 3 shows interesting features. Figure 4(a) shows gain versus implosion velocity for $P_s = 0$, i.e. conventional implosions, without a spike. We see that ignition occurs for $u_{\text{imp}} > u_{\text{igs}} = 332$ km s$^{-1}$, while peak gain is achieved at $u_{\text{imp}} = u_{\text{pg}} \simeq 370$ km s$^{-1}$. For $u_{\text{imp}} < u_{\text{igs}}$ ignition (or for $u_{\text{igs}} < u_{\text{imp}} < u_{\text{pg}}$ efficient burn) requires the spike. The HiPER target operates at $u_{\text{imp}} = 291$ km s$^{-1}$. As shown by figure 4(b), a spike of
100 TW is already sufficient for large gain. However, we have chosen a baseline spike of 240 TW so as to have some safety margin. As a measure of this margin, we take the ratio \( S_m = \frac{p_h}{p_{ig}} \) of the pressure of the hot spot (computed in a run with alpha-particle heating switched off) to the minimum pressure required for substantial gain (\( G = 50 \)). For the baseline case, \( S_m \simeq 1.25 \). The decrease of the gain as spike power exceeds some optimal value (clearly shown by both figure 3 and 4(b)) is easily explained. At some point excess shock pulse energy is not compensated by an increase of the fusion yield (but it increases ignition safety).

3. Ignition requirements

3.1. Implosion velocity for self-ignition

The previous discussion highlights the crucial role played by implosion velocity in both conventional central ignition and shock ignition. For conventional central ignition, Herrmann et al [25] studied the relation between shell energy for ignition and implosion velocity \( u_{imp} \). They performed systematic parametric simulations and found that the minimum shell kinetic energy for ignition is fitted by the expression

\[
E_{k-ig} \propto u_{imp}^{-5.89 \pm 0.12} \alpha_{if}^{1.88 \pm 0.05} p_{a}^{-0.77 \pm 0.12},
\]

where \( p_{a} \) is the pressure driving the implosion of the shell. Assuming (to a good approximation) that \( p_{a} \propto u_{imp}^2 \) and writing the kinetic energy as \( E_k = (1/2)m_{imp}u_{imp}^2 \), we find that the minimum implosion velocity \( u_{ig} \) for ignition of a mass \( m_{imp} \) of fuel scales as

\[
u_{ig} \propto m_{imp}^{-0.106 \pm 0.2} \alpha_{if}^{0.2},
\]

where we have omitted the error bars in the exponents. Herrmann et al [25] also found that the kinetic energy required to achieve peak gain with a given fuel mass is instead fitted by

\[
E_{k-pg} \propto u_{imp}^{-3.3 \pm 0.4} \alpha_{if}^{1.60 \pm 0.2} p_{a}^{-0.9 \pm 0.1},
\]

from which we obtain the implosion velocity for peak gain as

\[
u_{pg} \propto m_{imp}^{-0.141 \pm 0.225} \alpha_{if}^{0.225}.
\]

As shown in figure 5, the above dependences of the ignition and peak gain velocities on the mass are nicely reproduced by a series of simulations of ours referring to targets scaled from the HiPER baseline targets. All targets have the same payload aspect ratio \( A_p \approx 10 \) and isentrope \( \alpha_{if} \) in the range 1.2–2.3. (Here the payload is the imploded mass \( m_{imp} \), initially contained in a layer of thickness \( \Delta R_{p} \), and we define the payload aspect ratio as the ratio \( A_p = (R_1 + \Delta R_{p})/\Delta R_{p} \) of its initial outer radius to its initial thickness.) The imploded mass, instead, varies over the large range 0.28–5.1 mg. Figure 5 clearly shows that velocities required for threshold ignition and peak gain get closer to each other as target size increases. This is further illustrated by figure 6, showing target gain as a function of implosion velocity for targets with imploded masses of 0.28 and 1.54 mg, respectively.

3.2. Hot spot pressure for ignition

Both in conventional ICF and in shock ignition, ignition occurs in a central hot spot, surrounded by denser fuel, and approximately at rest. In both cases, ignition occurs when the hot spot parameters satisfy a certain ignition condition, which is essentially a condition on the hot
spot pressure. For simplicity, we assume that the compressed stagnating fuel is a DT spherical assembly, initially at rest, consisting of a spherical hot spot with radius $R_h$, temperature $T_h$ and density $\rho_h$, surrounded by cold fuel at density $\rho_c$. The relevant, approximate ignition criterion is [2, 26]

$$\rho_h R_h T_h > 5\sqrt{\rho_h/\rho_c} \text{ g keV cm}^{-2},$$

which, considering the hot spot as an ideal gas, can also be written as

$$p_h > p_{ig} = 470 \left( \frac{R_0}{1 \text{ mm}} \right)^{-1} C_r \sqrt{\frac{6}{\rho_c/\rho_h}} \text{ Gbar},$$

where $R_0$ is the initial shell outer radius and $C_r = R_0/R_h$ is the hot spot convergence ratio.
3.3. Hot spot stagnation pressure

In conventional inertial fusion, the hot spot is generated at the centre of the fuel at the end of the implosion, when the kinetic energy of the fuel shell is converted into internal energy. The hot spot pressure at stagnation is a strong function of the implosion velocity $u_{ig}$. According to a self-similar model $[27, 28],$

$$p_{stagn} \propto u_{imp}^{3} a_{if}^{-9/10} p_a^{2/5},$$

(7)

where pressure $p_a$ is the pressure applied to the shell surface and $a_{if}$ is the in-flight isentrope parameter of the shell. Fuel self-ignition (conventional ignition) occurs when the above stagnation pressure exceeds the ignition threshold illustrated in the previous subsection. In shock ignition, where the hot spot stagnation pressure is insufficient for ignition, the pressure deficit is compensated for by the strong shock driven by the laser spike, as previously discussed in section 2.2.

It is interesting to show that using the simple ignition condition (6) and the self-similar result for stagnation pressure, we find an expression for the scaling of the (self-)ignition implosion velocity with fuel mass and adiabat analogous to equation (2). Assuming $p_a \propto u^2$ and, as appropriate for a thin shell, $m_{imp} \approx 4\pi R_0^3 A_p^{-1}$, we obtain

$$u_{ig} \propto m_{imp}^{-0.09} \alpha^{-0.24} \left[ C_t^{-0.26} \left( \frac{\rho_n}{\rho_c} \right)^{0.13} A_p^{-0.09} \right].$$

(8)

4. Target scaling

In this section, we describe the scaling of a given target (and related laser pulse) to different size and laser wavelength. Before deriving the scaling model, we discuss general aspects of scaling strategies for shock-ignited targets.

4.1. Scaling strategies and risk reduction

As we have seen in section 2.2, two parameters, namely the implosion velocity and the spike pulse power, can be adjusted to achieve ignition. This allows some flexibility in target scaling. Such a flexibility increases with target size, and, in principle, allows for significant risk reductions, as illustrated in figure 7 for targets scaled from the HiPER baseline target. The figure shows curves of the spike intensity required to ignite a shell versus the implosion velocity for different values of the energy $E_{Lc}$ of the compression laser pulse. In order to reduce risks associated with laser–plasma instabilities and with RTI, spike intensity and implosion velocity should be kept below some threshold values, e.g. $10^{16}$ W cm$^{-2}$ and 300 km s$^{-1}$, respectively, which constrains the safe operating space. We see that at low $E_{Lc}$, e.g. 200 kJ, both the intensity and the velocity are not far from the instability boundaries. However, at larger energies, the window enlarges considerably, and different scaling options are available. For instance, targets can be scaled at constant implosion velocity, option (a) in the figure. In this case the required spike intensity decreases with energy and LPI risks are greatly reduced. Another option, (b) in the figure, consists in scaling targets by keeping constant the ratio $u_{imp}/u_{ig}$ of the implosion velocity to the self-ignition velocity. In this case both the implosion velocity and the spike intensity decrease with increasing target size, leading to reduced risks for both LPIs and hydrodynamic instabilities. The curves shown in figure 7 refer to targets imploded at the same
Figure 7. Ignition spike intensity versus implosion velocity for different values of the laser compression incident energy. The labelled filled points represent cases discussed in section 5. Laser spike intensity should be limited to reduce laser–plasma instabilities (LPI), while the implosion velocity should be limited to reduce hydrodynamic instabilities (in particular, RTI). The HiPER baseline target operating point \( (\mu_{\text{imp}} = 291 \text{ km s}^{-1}; E_{\text{Le}} = 180 \text{ kJ}) \) is indicated by the red circle. On increasing the target size (and then compression energy), risks can be reduced. The arrows in the figure indicate two scaling strategies considered in this paper: (a) scaling at constant implosion velocity; (b) scaling at a fixed value of the ratio of the implosion velocity to the self-ignition energy.

\( \alpha_{\text{sf}} = 1.2 \). The curves are estimated, while the filled points have been obtained by the detailed 1D simulations illustrated in section 5.

4.2. Characteristic scales: dimensional scaling

In this paper, we refer to the simple target shown in figure 1. We scale the target inner radius by a factor \( s \) and keep fixed the densities \( \rho_{\text{DT}} \) of the cryogenic fuel and \( \rho_v \) of the DT vapour, as well as the payload aspect ratio \( A_p \). Therefore, the imploding mass \( m_{\text{imp}} \), equal to the mass of the effective fuel, scales as \( s^3 \). In addition to the length scale \( s \), we introduce the dimensionless implosion velocity \( w \), time \( \tau \), compression laser energy \( \varepsilon \), compression laser power \( \Pi \), laser wavelength \( \Lambda \) and laser irradiance \( \beta \). This last quantity is the dimensionless value of the product \( I\lambda^2 \), and can be written as \( \beta = (\Pi/s^2)\Lambda^2 \). Of course, \( \tau = s/w \) and \( \Pi = \varepsilon/\tau \) (see table 1). For the reference target, e.g. the HiPER H target, \( s = w = \tau = \varepsilon = \Pi = \beta = 1 \). The imploding mass is a fraction \( y \) of the total mass \( m_t \).

4.2.1. Compression pulse. On dimensional grounds compression pulse energy \( E \), intensity \( I \), target radius \( R \) and pulse time \( t \) are related by \( E \approx IR^2t \). On the other hand, the kinetic energy of the imploding fuel is a fraction \( \eta_h \) of the absorbed laser energy \( \eta_{\text{ac}}E \):

\[
E\eta_{\text{ac}}\eta_h = \frac{1}{2}m_{\text{imp}}u_{\text{imp}}^2,
\]
Table 1. Dimensionless variables characterizing target and laser compression pulse.

| Quantity               | Scaling variable | Our model           |
|------------------------|------------------|---------------------|
| Laser wavelength       | $\Lambda$        |                     |
| Length                 | $s$              |                     |
| Implosion velocity     | $w$              | $w = \beta^{1/3} \Lambda^{-8/9}$ |
| Time                   | $\tau = s/w$    |                     |
| Compression laser energy| $\varepsilon$   | $\varepsilon = s^3 w^{5/4} \beta^{1/4}$ |
| Compression laser power| $\Pi = \varepsilon/\tau$ | $\Pi = \varepsilon/\tau$ |
| Compression laser irradiance ($I^2/\lambda$) | $\beta = \Pi \Lambda^2 / s^2$ | $\beta = \Pi \Lambda^2 / s^2$ |
| Payload mass           | $s^3$            |                     |
| Ablator mass           | $\beta^{0.27} \Lambda^{-0.71} s^{2.78}$ | $\beta^{0.27} \Lambda^{-0.71} s^{2.78}$ |

where $\eta_{ac}$ is the absorption efficiency of the compression laser pulse. Our simulations (see e.g. table 3) show that the absorption efficiency $\eta_{ac}$ is nearly independent of target size and laser wavelength for the considered targets. We therefore neglect $\eta_{ac}$ in the scaling procedure.

For the hydrodynamic efficiency $\eta_h$, we use

$$\eta_h \propto u^{3/4}_{imp} (I_a \lambda^2)^{-1/4}$$  \hspace{1cm} (10)

which was proposed by Betti and Zhou [6] as a fit to detailed numerical simulations. Here $I_a$ is the absorbed light intensity and $\lambda$ the laser wavelength. In fact, our simulations are better reproduced by $\eta_h \propto u^{3/4}_{imp} (I_a \lambda^2)^{-0.2} R^{-0.08}$. However, as we show in appendix B, the scaling relations are nearly insensitive to the differences between these two expressions for $\eta_h$.

Introducing the above dimensionless variables and using equation (10) for the hydrodynamic efficiency, we obtain

$$w = \beta^{1/3} \Lambda^{-8/9}$$  \hspace{1cm} (11)

and the expression of $\varepsilon$ reported in the right-hand-side column of table 1. According to the model, all power levels of the compression laser pulse (e.g. $P_p$, $P_f$, $P_c$; see figure 2) are scaled by a factor $\Pi$, and all times by $\tau$; simulations show that minor adjustments are required to picket duration and foot onset only.

4.2.2. Ablator mass. Since the fuel aspect ratio is kept fixed, the imploded mass scales as $s^3$; a different law instead applies to the ablator mass, which can be estimated as

$$m_a \simeq 4\pi \mu R^2 t_p,$$  \hspace{1cm} (12)

with $\mu$ the mass ablation rate (ablated mass per unit time and unit surface) and $t_p$ a characteristic pulse duration, proportional to $\tau$. According to simulations of ours, referring to targets analogous to those considered in this paper, the mass ablation rate can be written as

$$\dot{\mu} \propto I_a^{0.6} \lambda^{-0.4} R^{-0.22} \propto (I_a \lambda^2)^{0.6} \lambda^{-1.6} R^{-0.22} ,$$  \hspace{1cm} (13)

where $R$ is the radius of the spherical target. Note that this agrees with the expressions obtained by early theoretical models [29, 30]. Inserting equation (13) into (12), we obtain

$$m_a \propto \beta^{0.6} \Lambda^{-1.6} s^{-0.22} \tau = \beta^{0.27} \Lambda^{-0.71} s^{2.78},$$  \hspace{1cm} (14)

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where the relation \( \tau = s/w = sR^{1/3} \Lambda^{8/9} \) has been used. The mass of the scaled target will then be obtained from that of the HiPER baseline target according to

\[
m_{t} = m_{0} s^{3} [y_{0} + (1 - y_{0}) \beta^{0.27} \Lambda^{-0.71} s^{-0.22}],
\]

where \( m_{0} = 0.576 \, \text{mg} \) and \( y_{0} = 0.48 \) are, respectively, the total mass and the payload fraction of the target with \( s = \beta = \Lambda = 1 \).

### 4.3. Shock ignition spike

Accurate determination of the power of the shock ignition laser spike relies on numerical simulations. However, approximate scaling expressions can be obtained in the two important cases discussed in section 4.1, namely, (a) targets scaled at constant implosion velocity and (b) targets scaled at constant ratio \( u_{\text{imp}}/u_{\text{ig}} \).

#### 4.3.1. Spike power. Targets scaled at constant implosion velocity

We first consider targets scaled in size, but imploding at the same velocity and driven by light with the same wavelength. We proceed as follows [31].

(i) We require hot spot pressure \( p_{h} = S_{m} \rho_{ig} \) or, for equation (6), \( p_{h} \propto S_{m} C_{t}/R_{0} \), where we have neglected the dependence on the density ratio.

(ii) We assume that, for scaled targets, the final pressure \( p_{h} \) is proportional to the product of the ablation pressure and the convergence ratio [12]: \( p_{h} \propto C_{t} p_{a} \), and then using the result of item (i) above we also have \( p_{a} \propto S_{m}/R_{0} \).

(iii) The ablation pressure, in turn, is related to the absorbed intensity, and then to the absorbed laser power \( P_{a} \) by \( p_{a} \propto I_{a}^{2/3} \propto (P_{a} R_{a}^{-2})^{2/3} \propto (P_{a} R_{0}^{-2})^{2/3} \). From this last equation and the previous expression for \( p_{h} \), we obtain \( P_{a} \propto s^{3/2} R_{0}^{1/2} \) and \( P_{a} = k S_{m}^{3/2} s^{1/2} \), where \( k \) is a constant to be determined as shown below.

(iv) The absorbed laser power is related to the incident power of the spike pulse and compression pulse by \( P_{a} = P_{s} \eta_{as} + P_{c} \eta_{ac} \), where \( \eta_{as} \) and \( \eta_{ac} \) are the absorption efficiencies for the spike and compression pulses, respectively. At constant implosion velocity, \( P_{c} \propto R^{2} \) (see table 1), or \( P_{c} = P_{c0} s^{2} \), where \( P_{c0} = P_{c}(s = 1) \) is the power of the laser compression pulse at scale \( s = 1 \), and then

\[
P_{a} = P_{s} \eta_{as} + P_{c0} \eta_{ac} s^{2} = k S_{m}^{3/2} s^{1/2}.
\]

The constant \( k \) is then found by imposing \( P_{s}(s = 1, S_{m}) = P_{c0} \), i.e. the power of the laser spike at scale \( s = 1 \) and safety margin \( S_{m} \). The dimensionless spike power \( \pi_{\text{spike}} = P_{s}/P_{c0} \) then scales with target size as

\[
\pi_{\text{spike}} = \left( 1 + \frac{P_{c0}}{P_{c0}} \frac{\eta_{ac}}{\eta_{as}} \right) s^{1/2} - \frac{P_{c0}}{P_{c0}} \frac{\eta_{ac}}{\eta_{as}} s^{2}.
\]

In the above derivation, we have assumed absorption efficiencies independent of target scale.

#### 4.3.2. Spike power. Targets scaled at constant ratio \( u_{\text{imp}}/u_{\text{ig}} \)

Next, we consider targets scaled in size (and wavelength, too), but imploded at constant ratio \( u_{\text{imp}}/u_{\text{ig}} \), and assume that the
power of the compression laser pulse is much smaller than the spike power. We estimate the spike power scaling as follows.

1. Given the constant value of the velocity ratio $u_{imp}/u_{igs}$ (and then of the stagnation pressure to the minimum ignition pressure), the shock has to multiply the stagnation pressure by approximately the same factor $F_h$.

2. We assume, as in the previous subsection, that the shock pressure is proportional to the product of the spike ablation pressure $p_{as}$ and the convergence ratio (constant for scaled targets, as confirmed by the simulations discussed in section 5). This also means that the shock pressure at the ablation front is proportional to the pressure driving the implosion and therefore, for energy conservation, $p_{as} \propto u_{imp}^2$ for targets with the same aspect ratio.

3. The implosion velocity, in turn, scales with target size as $u_{imp} \propto R^{-0.32}$, since $u_{imp} \propto u_{igs}$ and, for equation (2), $u_{igs} \propto m_{imp}^{-0.106}$.

4. In the relevant high intensity regime, to a good approximation, $p_{as} \propto (I_{as}/\lambda)^{2/3}$, and then $p_{as} \propto (P_{as}/R_{as}^2\lambda)^{2/3}$, where $I_{as}$ and $P_{as}$ are the absorbed laser power and intensity, respectively.

In conclusion, we find $P_{as} \propto R^{1.04}\lambda$ or, in dimensionless form,

$$\pi_{spike} = s^{1.04}\Lambda.$$  \hspace{1cm} (17)

To test the above scaling, we have performed parametric simulations of scaled targets irradiated with spikes of different power $P_s$. We have considered the baseline HiPER target (scale $s = 1$) and two larger targets, with scales $s = 1.75$ and 2.43, respectively. (Details on the scaling are given in the following sections.) Figure 8 shows target energy gain as a function of the spike power for each of the three targets. Points of marginal ignition ($G = 1$), high gain threshold (80% of peak gain) and peak gain are evidenced. Figure 8(b) shows that the spike power for marginal ignition scales approximately proportionally to $s$, just as predicted by equation (17). The spike power for high gain, instead, scales approximately proportionally to $\sqrt{s}$. Based on these simulation results, we have chosen to scale spike power according to

$$\pi_{spike} = \sqrt{s}\Lambda.$$  \hspace{1cm} (18)

In future studies, we plan to evaluate how different choices of the spike power scaling affect ignition margins.

5. Scaled targets—fixed laser wavelength

The general scaling relations derived in the previous section and summarized in table 1 can be used to up- or down-scale a specific target (as discussed in the present section) or design targets driven by laser light of different wavelength (as shown in section 6).

Here we consider the two specific scaling strategies discussed above, namely (a) scaling at constant implosion velocity and (b) scaling at constant ratio $u_{imp}/u_{igs}$. The expressions for the dimensionless target and laser parameters for the two cases are listed, respectively, in columns (a) and (b) of table 2. We now consider the two cases separately. In both cases, we also perform parametric simulations to verify the scaling laws and compute target gain.
Figure 8. (a) Gain versus spike power for three scaled targets, driven at the same value of the ratio $u_{imp}/u_{ig}^*$ (1D numerical simulations). The labels H, b1 and b2 refer, respectively, to the HiPER baseline case, and to the scaled targets b1 and b2 discussed in section 5. (b) Spike power for marginal ignition and for high gain versus target linear scale $s$.

Table 2. Scaling relations—fixed wavelength.

| Fixed  | $u_{imp}; \lambda$ | $u_{imp}/u_{ig}^*; \lambda$ |
|--------|--------------------|-------------------------------|
| $w$    | 1                  | $s^{-0.32}$                   |
| $\beta$| 1                  | $s^{-0.96}$                   |
| $\tau$ | $s$                | $s^{1.32}$                    |
| $\varepsilon$ | $s^3$         | $s^{2.36}$                    |
| $\Pi$  | $s^2$              | $s^{1.04}$                    |
| Payload mass | $s^3$            | $s^3$                        |
| Ablator mass  | $s^{2.78}$ | $s^{2.52}$                    |
| $\pi_{spike}$ | Equation (16) | $\sqrt{s^n}$                 |
| $\varepsilon_{spike}$ | $\pi_{spike} \tau$ | $s^{1.82}$                   |
| $\beta_{spike}$ | $\pi_{spike} s^{-2}$ | $s^{-3/2}$                   |

* See the discussion in section 4.3.2.

5.1. (a) Scaling at fixed implosion velocity

Scaling at fixed laser wavelength and implosion velocity is achieved by setting $w = \beta = \Lambda = 1$. The relevant scaling relations for the other dimensionless quantities concerning target size and compression pulse are immediately obtained using the relations in table 1 and are listed in column (a) of table 2. The spike pulse power scales according to equation (16).

The variation of laser power versus target scale is illustrated in figure 9 for targets (up-)scaled from the HiPER baseline target. For the spike power the figure shows curves for $S_m = 1$ and 1.25, i.e. for targets scaled from the baseline target and laser pulses with spikes of 100 and 240 TW, respectively. We see that the spike power decreases with target scale and no
spike is necessary for scale $s > s^*(S_m)$. The total power has a shallow minimum at $s = s^*$, while the total laser energy increases monotonically with $s$.

Detailed 1D simulations verify the accuracy of the scaling laws. Scaled targets driven by scaled pulses attain nearly exactly the same velocity. No adjustment was required for target parameters, pulse power levels, timing of the main pulse and of the ignition spike. Only the duration $t_p$ of the initial picket and the onset of the foot (time $t_1$) required adjustments (usually obtained with no more than two iterations). Scaled targets have nearly the same in-flight-aspect ratio; the hot spot convergence ratio decreases slightly with target size.

Figure 10 shows the gain curve (gain versus total laser energy) for targets scaled from the HiPER target H, with margin $S_m = 1.25$ (red squares). The figure also shows the results of
Figure 10. Gain curves for shock-ignited targets upscaled from the HiPER target H (from 1D numerical simulations). Red curve and squares: targets scaled at constant implosion velocity (according to scaling (a) of table 2); blue curve and circles: targets scaled at constant $u_{imp}/u_{ig*}$ (scaling (b) of table 2); brown triangles: targets scaled from H at constant implosion velocity, without the ignition spike. Labels H, a1, b1 and b2 refer to cases with parameters listed in table 3.

Simulations of the same targets driven by pulses without the final spike (brown triangles). In agreement with the model, a large gain ($G = 120$) is attained at a laser energy of about 800 kJ, or target scale $s = 1.71$, in agreement with the model for $S_m = 1$. The addition of the spike, however, introduces a safety margin that eventually might compensate for possible material mixing or implosion asymmetries.

A possible further bonus provided by the use of the spike is shown in figure 11. The figure compares the implosion flowcharts for two identical targets (with scale $s = 1.71$), driven by pulses without a spike (a), and with a 164 TW spike (b). The two cases achieve nearly the same energy gain, but in the case with the spike ignition is faster, and the distance $\Delta R_h$ travelled by the unstable hot spot surface is shorter. In case (a), the hot spot boundary starts decelerating when its radius is 190 μm; it shrinks to a minimum radius of 60 μm and burn propagates when the radius is about 90 μm, and then the total travelled distance is $\Delta R_h = 160 \mu m$. In case (b), the corresponding radii are 130, 35, and 45 μm, respectively, and $\Delta R_h = 105 \mu m$. The reduction of $\Delta R_h$ is expected to have a beneficial effect on the growth of RTI at stagnation. For a rough estimate, we use linear growth and neglect any stabilizing mechanism. Perturbations with wavenumber $k$ then grow by a factor $\exp(\sqrt{2k \Delta R_h})$ (see e.g. [2], p 242).

5.2. (b) Scaling at fixed ratio $u_{imp}/u_{ig*}$

For targets scaled at fixed values of the ratio of the implosion velocity to the ignition velocity $u_{imp}/u_{ig*} < 1$, the spike is always needed. The relevant scaling relations listed in column (b) of table 2 are obtained from the general relations by observing that $u_{imp}/u_{ig*} \propto u_{imp}/m_{imp}^{-0.106} \propto ws^{0.32}$, and then

$$w = s^{-0.32}.$$ 

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The spike power is computed using equation (18). Notice that spike energy and power increase with size, but the intensity decreases rapidly ($I \propto s^{-3/2}$).

The main advantage of this option is in the higher achievable gain. Indeed, the simulations show that the 1D gain exceeds 200 for laser energy $E_L \geq 1.5$ MJ.

The main target parameters and simulation results for the reference case (HiPER baseline, case H, scale $s = 1$), and several scaled targets are listed in table 3. The laser parameters include the intensity at peak power and radius reduced to one half of the initial radius, $I_0^*$, and the laser irradiance $I_{\text{p15}}$, with the intensity measured in units of $10^{15}$ W cm$^{-2}$ and the laser wavelength in units of µm. The quantities IFAR$_{2/3}$ and IFAR$_{1/2}$ are the in-flight-aspect-ratio when the radius of the shell is $2/3$ and $1/2$, respectively, of the initial inner radius. (Here the in-flight-aspect-ratio is defined as the ratio of the shell radius to the thickness of the portion of the shell with density exceeding a fraction $1/e$ of the instantaneous peak density.)

### 6. Wavelength scaling

An important feature of the scaling model is the capability of scaling targets with laser light wavelength. To be specific, we consider scaling of the HiPER baseline target from wavelength $\lambda_0 = 0.351$ µm to $\lambda = 0.527$ µm (i.e. green light). We scale the target by keeping the ratio $u_{\text{imp}}/u_{\text{fg}}$ fixed, and setting $\Lambda = \lambda/\lambda_0 = 1.5$. (Alternatively, we could have scaled the target at fixed $u_{\text{imp}}/u_{\text{fg}}$; this would have led to a bigger target, requiring larger laser energy, with a larger
Table 3. Selected targets: parameters and simulation results.

| Case | H | a1 | b1 | b2 | 2oS | 2oL |
|------|---|----|----|----|-----|-----|
| Scaling procedure | – | a | b | b | H-S(+) a (+) |
| Scale s | 1 | 1.71 | 1.75 | 2.43 | 1.96 | 2.67 |
| $\lambda (\mu m)$ | 0.351 | 0.351 | 0.351 | 0.351 | 0.527 | 0.527 |
| $m_1$ (mg) | 0.574 | 2.76 | 2.76 | 6.89 | 3.50 | 8.60 |
| $E_{Ls}$ (kJ) | 180 | 890 | 670 | 1450 | 970 | 2440 |
| $E_{Lc}$ (kJ) | 118 | 137 | 327 | 590 | 630 | 430 |
| $P_c$ (TW) | 298 | 1027 | 997 | 2040 | 1600 | 2870 |
| $P_s$ (TW) | 46 | 175 | 82 | 116 | 94 | 174 |
| $P_p$ (TW) | 240 | 164 | 317 | 374 | 490 | 260 |
| $I_{spike}^{\pi}$ (PW cm$^{-2}$) | 9.0.5 | 3.45 | 0.49 | 0.32 | 0.32 | 0.53 |
| $u_{asc}$ | 74% | 75% | 77% | 78% | 73% | 75% |
| $u_{as}$ | 38% | 35% | 45% | 51% | 56% | 50% |
| $u_{imp}/u_{pg}$ | 291 | 292 | 240 | 213 | 215 | 216 |
| Gain $G$ | 65 | 140 | 152 | 217 | 118 | 205 |
| IFAR$_{2/3}$ | 32.6 | 31.2 | 27.4 | 27.0 | 26.9 | 24.0 |
| IFAR$_{1/2}$ | 16.7 | 17.3 | 16.0 | 16.4 | 13.7 | 13.8 |
| $C_t = R_0/R_h$ | 38.7 | 29.0 | 38.9 | 39.0 | 32.1 | 32.4 |

(+) To scale target 2oS from the HiPER baseline target H; see table 4.
(*) To generate the gain curve for $\lambda = 0.527 \mu m$ using 2oS as a reference, and with spike power optimized to maximize gain.

Table 4. Scaling relations—wavelength scaling at constant ratio $u_{imp}/u_{pg}$.

| Fixed | $u_{imp}/u_{pg}$ | $\Lambda = 1.5, \beta = 1.2$ |
|-------|----------------|-----------------------------|
| Free  | $\Lambda; \beta$ | $\Lambda = 1.98 \beta^{-0.74}$ 1.95 |
| $s$   | $s^{-0.45} = \Lambda^{-8/9} \beta^{1/3}$ 0.74 |
| $w$   | $\Lambda^{-8/9} \beta^{1/3}$ 0.74 |
| $\beta$ | $\Lambda^{2.87} \beta^{-1.07}$ 2.63 |
| $\tau$ | $\Lambda^{4.83} \beta^{-1.53}$ 5.36 |
| $\epsilon$ | $\Lambda^{1.96} \beta^{-0.46}$ 2.04 |
| $\Pi$ | $\Lambda^{5.94} \beta^{-2.22}$ 7.42 |
| Payload mass | $\Lambda^{4.79} \beta^{-1.78}$ 5.04 |
| Ablator mass | $\pi_{spike}^{\pi}$ $s/\Lambda = \Lambda^{1.99} \beta^{-0.37}$ 2.09 |
| $\pi_{spike}^{\pi}$ | $\pi_{spike}^{\pi} = \Lambda^{4.86} \beta^{-1.44}$ 5.52 |
| $\beta_{spike}^{\pi}$ | $\pi_{spike}^{\pi} = \Lambda^{1.97} \beta^{1.11}$ 0.55 |

(+) Approximate values; they apply at constant $u_{imp}/u_{pg}$. 
scaling the HiPER baseline target to laser wavelength $\lambda = 0.527 \mu m$ and gain curve for scaled targets driven by laser light with $\lambda = 0.527 \mu m$. From 1D numerical simulations.

safety margin.) The relevant scaling relations are listed in column (a) of table 4. Numerical values for a specific case ($\Lambda = 1.5, \beta = 1.2$), leading to the design of target $2\omega S$, are listed in column (b). It is apparent that such a 50% increase in wavelength implies an increase of the laser energy by a factor about 5.5.

Next, we have generated a gain curve for targets driven by green light, by scaling the $2\omega S$ target at constant implosion velocity (see figure 12). We see that a large gain (about 200) is achieved with a laser energy of about 3 MJ and peak power below 500 TW. The main parameters of two targets driven by green light are listed in table 3: see columns labelled $2\omega S$ and $2\omega L$. We note, in particular, that the $2\omega L$ target appears quite robust: IFAR, $C_r$ and irradiance $I\lambda^2$ take smaller values than those characterizing the HiPER baseline target. More details can be found in [16].

7. Conclusions

In this paper, we have studied the scaling of shock-ignited targets with energy and wavelength. We have derived simple general scaling laws, and shown that shock-assisted ignition offers some degree of freedom in the choice of the scaling strategy. This may allow one to either increase the gain or ignition margins, and/or to decrease the risks associated with plasma instabilities and/or with hydrodynamic instabilities. In particular, we have proposed scaling laws for targets imploded at fixed implosion velocity and at a fixed ratio of the implosion velocity to the self-ignition velocity $u_{ig}$, respectively. In the first case, the power of the shock driving spike decreases with increasing target scale. For sufficiently large targets no spike is necessary. However, addition of the spike increases ignition robustness. The second option leads to larger gain and reduces the risks associated with hydrodynamic instabilities, at the expense of increasing spike power with target size.

The relation between spike power and ignition margins has been briefly discussed. However, a detailed study is necessary for a quantitative analysis. It will be the objective of a future paper. Of course, multidimensional studies will be necessary for an appraisal of symmetry and stability issues.

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Finally, as already stated in the introduction, we remark that a proper assessment of shock ignition requires in-depth investigation of laser-plasma instabilities in the interaction of the laser spike with the plasma corona. These processes have been neglected so far in shock-ignition target simulation. Recent studies [34], however, suggest that their detrimental effects may be limited to acceptable values.

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Appendix A. DUED code model

Simulations were performed with the 1D version of the code DUED [21, 22]. DUED is a two-dimensional, quadrilateral-zone, Lagrangian hydrocode. It includes a standard two-temperature hydrodynamic model, with classical transport coefficients and flux-limited Spitzer thermal conductivity, the real-matter equation of state, (flux-limited) multi-group radiation diffusion, fusion reactions and fuel burn-up. Charged fusion products (in this case the DT fusion 3.5 MeV alpha particles) deposit their energy according to a (flux-limited) multigroup diffusion model. The code neutron transport model is not used; neutron energy is assumed to be completely lost. Laser–target interaction is modelled using a three-dimensional laser ray-tracing [32], taking into account plasma refractivity and inverse bremsstrahlung absorption.

In all the simulations reported in this paper, we have used coefficient $f = 0.07$ and sharp cut-off flux limitation, i.e. the absolute value of the electron thermal flux is the minimum between the classical flux with Spitzer conductivity and a fraction $f$ of the free streaming flux. Parametric simulations show that absorption efficiency and hydrodynamic efficiency decrease with decreasing $f$. The same target performance and yield as for $f = 0.07$ are recovered by increasing the power of the compression pulse and reducing the size of the focal spot of the ignition spike. For example, for the HiPER baseline target and $f = 0.06$, we had to increase the compression pulse power (and energy) by 10% and reduce the focal spot of the spike by 15%. The gain turned out to be reduced by 12%.

Appendix B. Scaling relations from the rocket model

To obtain ablation parameters for laser irradiation conditions relevant to the compression stage of shock ignition targets, we performed 1D parametric simulations of hollow shell targets with the same structure and aspect ratio as the HiPER baseline targets. According to the simulations, ablation pressure, areal mass ablation rate and hydrodynamic efficiency scale as

\[ P_a \propto I_a^{0.75} \lambda^{-0.4}, \]

\[ \dot{\mu} \propto I_a^{0.6} \lambda^{-0.4} R^{-0.22}, \]

\[ \eta_h \propto a_{\text{imp}}^{3/4} (I_a \lambda^2)^{-0.2} R^{-0.08}, \]

respectively. The scaling of the ablation pressure with intensity agrees with earlier models [29, 30] and with a few recent experiments [33]. The mass ablation rate agrees with the
predictions of [29, 30]. Equation (B.3) for the hydrodynamic efficiency differs somewhat from equation (10), used in this paper. Notice, however, that this difference only marginally affects the scaling law for the implosion velocity. Indeed, using (B.3) in our scaling model, we would have obtained
\[ w = \beta^{0.356} \Lambda^{-0.023} \lambda^{0.04}, \]
very close to equation (11).

It is also interesting to compare the above two expressions for the hydrodynamic efficiency with the one obtained from the rocket model, using the above fits for the ablation pressure and the mass ablation rate. From the rocket model, with the assumptions detailed in [17], one obtains
\[ \eta_h = \frac{1}{2} \mu \frac{u_{ex}^2}{I_A} \left( \frac{u_{imp}}{u_{ex}} \right)^{3/4}, \]
(B.4)
with \( u_{ex} = p_A/\mu \). Substituting equations (B.1) and (B.2),
\[ \eta_h \propto u_{imp}^{3/4} (I_A \lambda)^{-0.21} \lambda^{-0.025} R^{0.06}. \]
(B.5)
This last expression shows practically the same dependences on velocity, intensity and wavelength as equation (B.3), and a somewhat different dependence on the radius.

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