High-gain shock ignition of direct-drive ICF targets for the Laser Mégajoule

B Canaud\textsuperscript{1,3} and M Temporal\textsuperscript{2}
\textsuperscript{1} CEA, DAM, DIF, F-91297 Arpajon, France
\textsuperscript{2} ETSIA, Universidad Politécnica de Madrid, Spain
E-mail: benoit.canaud@cea.fr

\textit{New Journal of Physics} 12 (2010) 043037 (9pp)
Received 17 November 2009
Published 20 April 2010
Online at http://www.njp.org/
doi:10.1088/1367-2630/12/4/043037

Abstract. High-gain shock ignition is numerically investigated for specific marginally igniting targets—targets producing thermonuclear gain less than one—extracted from two distinct target families. Homothetic transformations keeping constant the implosion velocity, the adiabat, and the in-flight aspect ratio are used to draw target families. Conventional and fast ignition (FI) directly driven targets are considered for the Laser Mégajoule. It is shown that high gain can be achieved with shock ignition for designs, which do not ignite only from the laser compression. Shock ignition is achieved for different targets of the FI family, which are driven by an absorbed energy between 100 and 500 kJ and deliver thermonuclear energies between 10 and 130 MJ.

Direct-drive (DD) inertial confinement fusion (ICF) has been studied for the Laser Mégajoule (LMJ) for a decade [1–10], leading to the definition of a DD baseline design in 2004 [3, 4]. This approach is an alternative to the indirect drive to reach high thermonuclear energy yield and gain. In the DD, laser beams overlap on the external side of a spherical target. The latter usually consists in an ablator layer where part of the laser light is absorbed. The absorber encloses a deuterium–tritium (DT) ice shell, and, in the central part, some DT gas. Laser heats the ablator and the plasma blow-off accelerates the target, which implodes to achieve the conditions of density and the temperatures required to ignite and burn the fuel (DT).

In 2007, we showed [9] that it was possible to assemble a standard DD target on LMJ with the beam layout of the indirect drive. We have also shown [10] that the conventional polar direct drive (PDD) [11] is less interesting for LMJ since we have the possibility to do DD without using the repointing technique. However, only a part of the whole energy of the LMJ is accessible for DD. A new design was then proposed for a specific target design with the optical zooming [5].

\textsuperscript{3} Author to whom any correspondence should be addressed.
Without zooming, the target was marginally igniting with gain less than one. Therefore, it could be interesting to find other solutions to ignite the target.

Recent works at the University of Rochester [12] proposed a non-isobaric ignition of the fuel, called shock ignition, which consists in separating the fuel assembly (at low adiabat and low implosion velocity) from the ignition produced by a separate laser-driven strong shock. This very promising solution was recently proposed [13] to ignite the fast ignition (FI) capsule [14] envisioned for HiPER [15].

The specificity of this new approach lies in the modification of the ignition threshold of the target. Usually, the latter depends on three distinct parameters: the implosion velocity \( v_{\text{imp}} \), the adiabat \( \alpha \) defined as the ratio of the fuel pressure to the Fermi pressure, and the ablation pressure, \( P_a \), at the maximum of the laser drive.

In order to observe the transition between non(or marginally)-igniting targets and high-gain targets, a target family is built from a seed—for instance, the HiPER target—by scaling up or down the size and mass of the target, the laser energy and power, and the laser pulse duration. Thus, for a given set of parameters \((\alpha_{\text{if}}, v_{\text{imp}}, P_a)\), the target family is designed using a homothetic transformation, which keeps constant \((\alpha_{\text{if}}, v_{\text{imp}}, P_a)\). For a specific kinetic energy of the shell, called the ignition threshold, a transition appears between the situation where only the hot spot is burning and the case where an efficient thermonuclear burn wave propagates through the fuel. This kinetic energy, usually, scales as [16–21]

\[
E_{\text{thr}}(\text{kJ}) = (55 \pm 5)\alpha_{\text{if}}^{2.1 \pm 0.3} \left( \frac{3 \times 10^5}{v_{\text{imp}}(\text{m s}^{-1})} \right)^{5.5 \pm 0.5} \left( \frac{10}{P_a(TP_a)} \right)^{0.55 \pm 0.15},
\]

where \( \alpha_{\text{if}} \) is the in-flight (if) adiabat.

In the case of shock ignition, Betti [12] showed that a non-isobaric ignition of the target reduces the ignition threshold by the cube of the pressure ratio \( \phi = P_{\text{noniso}}/P_{\text{iso}} \), where \( P_{\text{noniso}} \) and \( P_{\text{iso}} \) are, respectively, the hot-spot pressure in the non-isobaric and the isobaric ignition conditions. Thus, the new approach allows us to tune the desired ignition energy by adjusting the pressure in the hot spot. This pressure can be achieved, as proposed by Betti, using a spike in the pulse power sent at the right time in order to generate a strong Gbar shock wave that collides with the returning shock (the first shock coming from the fuel assembly after the focalization at the target center). The pressure due to the shock wave is related to the power of the spike. Increasing the spike power increases the hot-spot pressure. To ignite any target from the target family defined by \((\alpha_{\text{if}}, v_{\text{imp}}, P_a)\), it is only necessary to adjust the laser spike parameters in order to significantly decrease the ignition threshold. Therefore, the kinetic energy of the shell can be slightly modified for sufficiently strong ignitor shock while the in-flight adiabat is kept roughly constant. Indeed, when the ignitor shock travels through the shell, the post-shock medium velocity is increased and thus, even if the shell mass is unaffected, the shell kinetic energy is modified. This modification is not sufficient to reduce significantly the ignition threshold, the increase of velocity being, here, less than 10% over the chosen interval of laser power variations, but this effect contributes, in a moderate way, to this reduction. The thermonuclear gain decreases when the velocity increases, thus it must be close to but lower than the target family gain (the gain produced by the target family without an ignitor spike when the kinetic energy is above the ignition threshold).

This paper addresses the opportunity for shock ignition of conventional and FI, marginally igniting, ICF targets dedicated to large-scale facilities such as the LMJ. By conventional, we mean targets designed to ignite with a central hot spot, whatever the driver is (i.e. direct...
Figure 1. Marginally igniting target of the DD LMJ target family (a) and the FI HiPER target, (b) with laser pulses and spikes.

This conventional design concerns the classical DD [9] targets with the implosion parameters: \((\alpha_{id} = 3.5, v_{imp} = 400\,\text{km}\,\text{s}^{-1})\). The second target is the HiPER target [14] with the parameters \((\alpha_{id} = 1, v_{imp} = 280\,\text{km}\,\text{s}^{-1})\). They have low peak in-flight aspect ratios (IFAR: defined as the maximum ratio of shell radius to its thickness during the implosion) of 26 and 30 for the conventional DD and FI families, respectively. The shock ignition of the HiPER target has been studied previously [13] and we will focus on the possibility offered for the LMJ facility to use targets from this family.

Calculations are performed using the one-dimensional (1D) version of the Lagrangian radiation-hydrodynamics FCI2 [22] usually used for ICF design studies at CEA, DIF. It includes tabulated equations of state (e.g. SESAME), flux-limited Spitzer heat transport (here the flux limiter is set at 6%), multigroup radiative transfer, 1D normal-incidence ray-tracing with refraction, multigroup alpha-particle transport and neutron transport. Degeneracy of the fuel during the deceleration is taken into account in the thermal conductivity using a harmonic average between Spitzer and the Hubbard [23] model that is validated by quantum molecular dynamics calculations [24].

Figure 1 shows both target designs, the FI-target being widely studied in [14]. The DD-target is extracted from the target family described in [9]. These two designs are below their ignition threshold. The laser pulses are shaped to achieve a quasi-isentropic implosion. A first-foot pulse launches a shock, that places the fuel on the right adiabat. Then the laser power grows up to the drive part. This second part of the pulse gives the desired implosion velocity of the fuel.

The DD-target uses an ablator made of plastic (CH) foam wetted by frozen DT in order to increase absorption without sacrificing the ablative stabilization of DT [25]. It requires 220 kJ of incident energy (corresponding to 170 kJ absorbed) to assemble the fuel at an areal density of 10 kg m\(^{-2}\) with a peak density of \(500 \times 10^3\,\text{kg}\,\text{m}^{-3}\). The foot power is at 2.3 TW, while the drive is 100 TW.

The FI design is an all-DT target and needs less energy (100 kJ absorbed) to obtain an areal density of 13 kg m\(^{-2}\) and a peak density of \(600 \times 10^3\,\text{kg}\,\text{m}^{-3}\). As the desired adiabat and implosion velocity are lower than in the DD design, foot and drive parts deliver smaller powers of, respectively, 0.2 and 26 TW.

Shock ignition of both targets is tested by adding a spike at the end of the main laser pulse without modifying the latter, contrary to [12]. Shock ignition of both targets is achieved by varying the spike power and the start time of the shock pulse rises. Figure 2 shows the
variation of the thermonuclear gain defined as the ratio of the thermonuclear energy over the absorbed energy, versus the spike power, for different start times. High thermonuclear gains can be obtained for sufficiently high-power spikes arriving at the end of the compression laser pulse. The spike laser pulse is a 300-ps-long plateau with 200 ps rise and fall times. The rise time is fixed at 200 ps. It is a compromise between the requirement to be sufficiently short in order to generate the strong Gbar shock wave and to be compatible with the LMJ specifications. We have not seen any effect of spike duration as far as it is sufficiently long for the decompression wave (due to the end of the spike) not to catch up with the ignitor shock. Shock timing for ignition depends on fuel assembly time and must be adjusted within a 100-ps-wide temporal window. This introduces a relationship between the start time and the spike power. Indeed, the higher the spike power, the faster the shock, the later the start time. We observe that the full temporal width at 80% of the maximum gain is roughly 200 ps for the start time and for both designs.

These results confirm the prediction by Betti that a non-isobaric ignition is possible for ICF targets below their ignition threshold and that the spike power can be tuned as desired. In addition, they also confirm Ribeyre’s results [13] that it is possible to ignite FI targets by a strong converging shock. As shown in figure 2, the FI targets are designed to produce higher thermonuclear gains than conventional DD ones and we will focus on FI designs in the context of LMJ in the following part of the paper.

The LMJ will be a 240 beamlet frequency-trippled (3ω−0.35 µm) Nd-glass laser facility with a maximum energy and power of 1.8 MJ and 600 TW, respectively. Beams are grouped by four in 60 quads (bundles) distributed around the target chamber, in three rings per hemisphere at polar angles of 33°2, 49° and 59°5. Ten quads are distributed equally in each ring. Between each ring, the quads’ azimuthal angles are shifted by π/20 and both hemispheres are also shifted one to the other with the same angle.

In previous works [9], we showed that the fuel assembly of a conventional DD-target could be done with only two rings per hemisphere, at 49° and 59°5, with a power balance of 45%/55% and without repointing the beams (no conventional PDD [11, 10]). This configuration satisfies the Schmitt criteria [26], which consists in placing the beams on both sides of a polar angle: θ ∼ 54°7. The ring-to-ring power balance leads to a total available energy of about 1 MJ and a
Table 1. Detailed information about some designs extracted from the homothetic family. \( R_{\text{int}} \) and \( R_{\text{ext}} \) are expressed in \( \mu \text{m} \), \( E_{\text{ass}} \) and \( E_{\text{sp}} \) in kJ, \( t_{\text{sp}} \) in ns, \( P_{\text{sp}} \) in TW and \( E_{\text{Th}}^{1D} \) in MJ.

| \( \xi \) | Ref | \( R_{\text{int}} \) | \( R_{\text{ext}} \) | \( E_{\text{ass}} \) | \( E_{\text{sp}} \) | \( t_{\text{sp}} \) | \( P_{\text{sp}} \) | \( E_{\text{Th}}^{1D} \) | \( G_{\text{max}}^{1D} \) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | a | 830 | 1040 | 100 | 100 | 10.5 | 200 | 17 | 84 |
| 2 | b | 1050 | 1315 | 180 | 80 | 12.8 | 160 | 38 | 162 |
| 2.7 | c | 1155 | 1450 | 290 | 70 | 14.5 | 140 | 67 | 200 |
| 3.3 | d | 1244 | 1560 | 360 | 65 | 15.7 | 130 | 87 | 213 |
| 4 | e | 1322 | 1657 | 430 | 50 | 16.7 | 100 | 112 | 234 |
| 4.7 | f | 1392 | 1745 | 500 | 45 | 17.4 | 90 | 127 | 235 |

Peak laser power of less than 360 TW in the drive part of the pulse. In this irradiation geometry, the laser-coupling efficiency was estimated from 2D calculations [9] at roughly 0.6 for the fuel assembly. In this condition, the third cone, at 33°2, could be used to deliver the spike, with a maximum incident power of 200 TW. The original Betti concept of shock ignition [12] requires an incoming spherical convergent shock. However, recent works by Ribeyre [13] have shown, by means of 2D hydrodynamics calculations, that bipolar (with a zero-polar angle) ignitor beams can provide adequate conditions for shock ignition due to thermal smoothing coming from long plasma-density scale length. Thus, this is also valid for polar angles at 33°.

In this context, we sample the HiPER target family curve seeded by the target given in figure 1(b). Each target is a scale up of the seed that is the HiPER FI-target with an homothetic factor \( \xi \). For the fuel assembly, laser pulse times are multiplied by \( \xi \) and power by \( \xi^2 \), and thus energies and masses scale as \( \xi^3 \). The variation of the kinetic energy is achieved by varying the fuel mass, keeping the implosion velocity constant. Table 1 summarizes the details of each target considered here and the corresponding laser conditions for ignition and maximum gain. The variation of the spike parameters concerns the spike power and its start time. We keep the spike duration constant. Thus, the energy involved in the spike can vary. The thermonuclear gain is defined as the ratio of the thermonuclear energy to the total absorbed laser energy containing the energy absorbed for fuel assembly and absorbed from the spike. \( R_{\text{int}} \) and \( R_{\text{ext}} \) are, respectively, the internal and external radius of each target. \( G_{\text{max}}^{1D} \) is the maximum gain achieved with our 1D calculations. In this table, we have separated the energy contributions due to the fuel assembly (absorbed energy \( E_{\text{ass}} \)) and to the ignitor spike (incident energy \( E_{\text{sp}} \), start time \( t_{\text{sp}} \) and laser power \( P_{\text{sp}} \)) producing the maximum gain (\( G_{\text{max}}^{1D} \)).

It can be seen that the required spike power and, thus, energy decrease when the target approaches the ignition threshold. In the original HiPER target (design a), the energy in the spike needed to obtain the maximum thermonuclear gain is almost the same as the one absorbed for fuel assembly. Moreover, the gain is less than the gain of the target family. This is due to the fact that the HiPER target is far from the ignition threshold. In this case, the spike energy is strong enough to significantly modify the implosion velocity and thus the kinetic energy and the gain. Conversely, the gain tends to its asymptotic value given by [27, 28]:

\[
G_{\text{th}}^{1D} \sim 36.5 \left( \frac{3 \times 10^5}{v_{\text{imp}}} \right)^{1.25} \theta(\rho r),
\]
where $\theta = 1/(1 + 70/\rho r)$. The implosion velocity $v_{imp}$ is in m s$^{-1}$, $I_{19}$ is in units of $10^{19}$ W m$^{-2}$ and $\rho r$ is in kg m$^{-2}$.

In addition, the ratio of the start time for $G_{\text{max}}^{1D}$ over the stagnation time stays constant during the homothetic transformation leading to a scaling of this start time as $\xi$.

The thermonuclear energy $E_{\text{Th}}^{1D}$ is taken at the maximum of the thermonuclear gain. It is possible to increase the thermonuclear energy by increasing the spike power but with a lower gain due to a more significant increase of the implosion velocity when the ignitor power grows. In order to focus only on shock ignition (without modifying the ignition threshold due to a modification of implosion velocity), it would be necessary to reduce the fuel assembly energy as performed in [12].

The ignition threshold corresponds to very large values of absorbed laser energy (at 1 MJ), as seen in figure 3. The plain line represents the homothetic target family curve. The ignition threshold corresponds to a laser energy close to 1 MJ. Above it, the curve converges to the theoretical value given in [27]. In the same plot, we show, for each target of table 1, the thermonuclear gain produced by the variation of the ignitor peak power (each curve corresponds to a set of ignitor powers). The laser energy for fuel assembly is kept constant while the incident energy in the spike is varied. Each curve is obtained by varying the spike power and its start time. It can be seen that all the targets can be ignited by the shock ignitor, even the HiPER target that is far from the threshold (left dotted line). Except the last, all other targets achieve thermonuclear gains close to the corresponding theoretical values.

An implicit relation exists between the power and the start time of the spike to optimize the thermonuclear gain. Indeed, for each power, it is possible to find a start time, which maximizes the gain. The resulting curve, in the $(P_{\text{spike}}, \text{Max}(G_{\text{Th}}^{1D}))$ space, is the external envelope of the curves plotted in figure 2, for instance plotted for each design in figure 4. The curves refer to the targets detailed in table 1. As also shown in table 1, targets closer to the isobaric ignition threshold require lower peak ignitor power. In addition, each curve presents a plateau centered}

\[Figure 3. \text{Thermonuclear gain versus the laser energy for the homothetic target family (plain line) without shock ignition, and with shock ignition for different scalings (dotted lines). The shock timing is optimized to produce the maximum gain for each spike power value. The theoretical gain is also plotted (green dashed line).}\]
Figure 4. Shock ignition thermonuclear gain of capsules versus the spike power for different scalings. The start time is adjusted to produce the maximum gain. 

on the peak power. Figure 4 also shows that each design has an ignitor power threshold above which the gain passes a maximum and decreases after. Below it, the target does not ignite. This power threshold, that is defined as the power corresponding to the maximum gradient of each gain curve of figure 4, decreases when the target approaches the isobaric ignition threshold. Uncertainties exist on its position. It might be displaced toward higher powers due to assumptions made in the description of physics in hydrodynamics codes (α-particles transport, equations of state, heat conduction in degenerate plasmas, ...). The displacement can also be due to geometrical effects (2D or 3D versus 1D) or hydrodynamic instabilities such as Rayleigh–Taylor instability (RTI), for high modes, or low-mode irradiation asymmetries leading to a significant distortion of the areal density at stagnation.

For the LMJ, it appears possible to obtain high thermonuclear gain as soon as the FI-HiPER target is considered. For instance, if we consider the HiPER target and an incident spike power $P_{\text{spike}}$ at 200 TW, we can expect a thermonuclear gain of $\sim 80$ with a fuel assembly energy (absorbed) $E_{\text{ass}} \sim 100$ kJ and a spike energy (incident) $E_{\text{sp}} \sim 100$ kJ. In this case, the total input energy is $\sim 200$ kJ for a thermonuclear energy of $\sim 17$ MJ. With such a spike power, the spike intensity exceeds $5 \times 10^{19}$ W m$^{-2}$, which would result in a high level of parametric instabilities (PI) and hot electron generation. The last would be deleterious for the target in the sense that the hot electrons would preheat the shell during the acceleration phase (before the peak velocity), increasing its adiabat, and would result in a reduction of the peak areal density and compression. In order to define a safer baseline design for shock ignition, the energy dedicated to fuel assembly can be increased, thereby reducing the spike power required at the threshold and increasing the margin for the power of maximum gain. A reasonable solution would be to use design (d), in an intermediate configuration of 600 kJ incident laser, and design (f) for the whole LMJ case. The first would deliver a thermonuclear energy of approximatively 90 MJ with a spike power less than 100 TW for the maximum gain and a spike power threshold below 50 TW. Accounting for the laser–target coupling efficiency, the 3D thermonuclear gain would be 130. The second design would produce an energy of roughly 130 MJ with a spike power around 80 TW for the maximum gain and a spike power threshold below 30 TW. The resulting 3D gain would be 140.
Unknowns have to be addressed in the future. The first one concerns the 2D calculations with full 3D ray-tracing dealing with the full geometry of irradiation of the LMJ. The second one concerns the hydrodynamic stability of the chosen design. A good confidence can be kept due to previous estimations of RTI growth rates obtained with previous DD designs [3] during the acceleration phase. In addition, the previous studies of hydrodynamic stability of the deceleration phase [13] have shown a good stability of shock-ignited target in comparison with the non-shocked one. Other points are the PI and fast electrons created during the spike–plasma interaction in the corona. These points will be addressed by specific calculations. If major difficulties were encountered with these designs, one possibility would consist in using a $4\omega$-laser spike, increasing in this way the PI threshold by a factor of 2. In addition, this solution would also increase the spike absorption rate.

The designs outlined in this paper show the advantage of delivering thermonuclear gains above 100. The potential interest of these designs, first shown in [29], has been confirmed for the NIF facility in [30] and should be milestones on the road to inertial fusion energy (IFE).

Acknowledgments

We thank S Laffite, E Lefebvre, B Le Garrec, X Ribeyre, G Schurtz, M Lafon and J L Feugeas for fruitful discussions.

References

[1] Fortin X and Canaud B 1999 Inertial Fusion Science and Applications (Paris: Elsevier) p 245
[2] Canaud B, Fortin X, Dague N and Bocher J 2002 Phys. Plasmas 9 4252
[3] Canaud B, Fortin X, Garaude F, Meyer C, Philippe F, Temporal M, Atzeni S and Schiavi A 2004 Nucl. Fusion 44 1118
[4] Canaud B, Fortin X, Garaude F, Meyer C and Philippe F 2004 Laser Part. Beams 22 109
[5] Canaud B and Garaude F 2005 Nucl. Fusion 45 L43
[6] Sanz J, Garnier J, Cherfils-Clerouin C, Canaud B, Masse L and Temporal M 2005 Phys. Plasmas 12 112702
[7] Riz D, Garaude F, Houry M and Canaud B 2006 Nucl. Fusion 46 864
[8] Temporal M, Jaouen S, Masse L and Canaud B 2006 Phys. Plasmas 13 122701
[9] Canaud B, Garaude F, Clique C, Lecler N, Masson A, Quach R and Van der Vliet J 2007 Nucl. Fusion 47 1652
[10] Canaud B et al 2007 Plasma Phys. Control. Fusion 49 B601
[11] Skupsky S et al 2004 Plasma Phys. 11 2763
[12] Betti R, Zhou C, Anderson K, Perkins L, Theobald W and Solodov A 2007 Phys. Rev. Lett. 98 155001
[13] Ribeyre X, Schurtz G, Lafon M, Galera S and Weber S 2009 Plasma Phys. Control. Fusion 51 015013
[14] Atzeni S, Schiavi A and Bellei C 2007 Phys. Plasmas 14 052702
[15] Dunne M 2006 Nat. Phys. 2 2
[16] Meyer-ter-Vehn J 1982 Nucl. Fusion 22 561
[17] Levedhal W and Lindl J 1997 Nucl. Fusion 37 165
[18] Piriz A 1996 Fusion Eng. Des. 32–33 561
[19] Kemp A, Meyer-ter-Vehn J and Atzeni S 2001 Phys. Rev. Lett. 86 3336
[20] Hermann M, Tabak M and Lindl J 2001 Nucl. Fusion 41 99
[21] Betti R, Anderson K, Goncharov V, McCrory R, Meyerhofer D, Skupsky S and Town R 2002 Phys. Plasmas 9 2277
[22] Buresi E, Coutant J and Dautray R 1986 Laser Part. Beams 4 531

New Journal of Physics 12 (2010) 043037 (http://www.njp.org/)
[23] Hubbard W B 1966 Astrophys. J. 146 858
[24] Recoules V, Lambert F, Decoster A, Canaud B and Clerouin J 2009 Phys. Rev. Lett. 102 075002
[25] Skupsky S, Betti R, Collins T, Goncharov V, Harding D, McCrory R and McKenty P 2002 Inertial Fusion Science and Applications 2001 (Paris: Elsevier) p 240
[26] Schmitt A 1984 Appl. Phys. Lett. 44 399
[27] Betti R and Zhou C 2005 Phys. Plasmas 12 110702
[28] Betti R et al 2007 Plasma Phys. Control. Fusion 48 B153
[29] Canaud B 2009 29th Workshop on Physics of High Energy Density (Hirschegg, Austria, 1st–6th February, 2009)
[30] Perkins L J, Betti R, Lafontune K N and Williams W H 2009 Phys. Rev. Lett. 103 045004