Target design for shock ignition

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Abstract. The conventional approach of laser driven inertial fusion involves the implosion of cryogenic shells of deuterium-tritium ice. At sufficiently high implosion velocities, the fuel ignites by itself from a central hot spot. In order to reduce the risks of hydrodynamic instabilities inherent to large implosion velocities, it was proposed to compress the fuel at low velocity, and ignite the compressed fuel by means of a convergent shock wave driven by an intense spike at the end of the laser pulse. This scheme, known as shock ignition, reduces the risks of shell break-up during the acceleration phase, but it may be impeded by a low coupling efficiency of the laser pulse with plasma at high intensities. This work provides a relationship between the implosion velocity and the laser intensity required to ignite the target by a shock. The operating domain of shock ignition at different energies is described.

1. Introduction
Inertial Confinement Fusion (ICF) is a process to obtain the thermonuclear fusion of small amounts (1 mg or less) of hydrogen isotopes compressed up to several thousands times and heated to the temperature ~ 10 keV. Compression is achieved by means of implosion of a cryogenic solid DT shell, driven by lasers. The central hot spot initiates a thermonuclear combustion wave in the cold, dense fuel around it. A hot spot is obtained at the centre of the target at the end of implosion by conversion of the shell kinetic energy into the internal energy of the innermost parts of the shell. This central ignition scheme demands implosion velocities close to 400 km/s, which present a danger of shell break up during the acceleration stage. Slower implosions, though safer, need an additional source of heating. The principle of shock ignition is to boost up a sub ignition central hot spot by means of a convergent shock wave launched in the target at the end of the compression phase [1, 2]. This shock is formed by a high intensity spike in the laser temporal pulse shape, which may present a risk of excitation of various plasma instabilities. A safe target design for shock ignition results from a trade off between the risks of hydrodynamic and parametric instabilities. The determination of a relation between the spike intensity and the implosion velocity is the goal of this paper.

2. Hot spot pressure
Conditions for hot spot ignition are given by the Rosen-Lindl model for an isobaric fuel assembly [3] and considered in the non-isobaric case in Ref. [4]. The key ignition parameter is the product $\rho R T$ of the hot spot areal mass $\rho R$ by the ion temperature $T$. A substitute for the product $\rho T$ is the hot spot pressure $P_h$ [2]. The hot spot self heating rate per unit volume is written as:

$$E_h \propto \rho_h^2 \langle \sigma v \rangle ,$$

(1)
where $E_h$ and $\rho_h$ are the hot spot energy and mass densities, $<\sigma_v>$ is the Maxwell-average nuclear cross section. The ignition temperatures are in the range of 6 – 12 keV. In this domain, $<\sigma_v>$ scales as $T^p$, with $2 < p < 3$. So the volumic heating rate and characteristic heating time $\tau_h$ scale approximately as:

$$E_h = 3 P_h/2 \propto P_h^2, \quad \tau_h = P_s / P_h \propto P_h^{-1}$$  \hspace{1cm} (2)

The hot spot pressure depends on the implosion velocity $V_i$ as $P \propto V_i^a$, the power $a$ depending on the implosion process. An adiabatic compression corresponds to $a = 5$, whereas in ICF conditions, the Mach scaling $a = 3$ [5] applies at a given in-flight pressure and entropy parameter. The minimum hot spot pressure $P_{ign}$ required for ignition is related to a minimum implosion velocity $V_{ign}$. In order to increase the pressure of shells imploded at sub ignition velocities, it was suggested to launch a convergent shock in the target prior to the time of shell stagnation [1, 2]. Such a converging shock encounters several amplification events related to two different hydrodynamic phenomena.

Following the analysis of Guderley [5], the shock pressure is first amplified from convergence by a factor $C_0.9$ where $C$ is the shock convergence ratio. The second amplification stage results from the collision with another shock that is reflected from the center. Figure 1 shows the pressure variation in function of the shock location obtained from a numerical simulation with the code CHIC. The pressure first grows as predicted by the model [5], until the radius of 70 µm, where it collides with the rebound shock. The pressure is amplified 5 times in the collision and then the shock resumes its convergence.

3. Shock collision

Let us assume that the final hot spot pressure is proportional to the pressure arising from the shock collision $P_s$. Then this post shock pressure must match the criterion for the hot spot self ignition. If $P_s$ is the pressure of the rebound shock and $P_c$ the pressure of the converging shock before the collision, the pressure $P_s$ follows from the Rankine-Hugoniot conditions. The shock amplification factor, $P_s/\max(P_s,P_c)$, is shown in Fig. 2 in function of the ratio $P/P_s$. The maximum of the pressure amplification for a mono-atomic ideal gas is 6 for $P_s = P_c$, and decreases to 3 for $P_s = 5P_c$ or $P_c = P/5$. This curve can be approximated by a simple analytical expression:

$$P_s \propto (P_s^2 + P_c^2 + 10P_sP_c)/(P_s + P_c)$$  \hspace{1cm} (3)

It is 20% accurate in the domain studied in Fig. 3. Assuming that $P_s$ scales as $V_{ign}^a$, and demanding that $P_s$ attains the ignition value $P_{ign}$, we solve Eq. (3) for the shock pressure in function of the dimensionless implosion velocity $u = V/V_{ign}$.

$$P_s = 0.5P_{ign} \left[1 - 10a + 96u^a - 16u^a + 1 \right]^{1/2}$$  \hspace{1cm} (4)

This relation is plotted on Fig. 3 for $a = 3$. The optimal matching condition $P_s = P_c$ corresponds to $P_s = P_{ign}/6$. It is obtained for $u = 0.54$ ($u = 0.65$ for $a = 4$). Above this critical velocity, the shock pressure decreases almost linearly. At $u = 0.4$, the rebound pressure $P_s$ is only 6.4% of the ignition pressure and the required shock pressure is $P_{ign}/2$. For $u = 0.7$, the predicted shock pressure ratio is 0.1. The
corresponding pressure ratio $P_s/P_r$ is close to 0.3 and our approximation (3) is reasonably accurate. Our model can only be applied for velocities between 0.5 and 0.75 of the self ignition velocity.

Figure 2. Pressure $P_s$ after shock collision versus the ratio between the shock pressures $P_r$ and $P_s$. Dashed line presents a simplified relation (3).

Figure 3. Shock pressure $P_s/P_{ign}$ in function of the implosion velocity $u = V/\bar{V}_{ign}$ for $a = 3$. A perfect matching condition is achieved at $u = 0.55$.

4. Laser power for ignition

The shock pressure $P_s$ is proportional to the ablation pressure $P_a$ produced by a intense spike in the laser pulse. The ratio $P_s/P_a$ is given, according [5], by the ratio between the radius of the ablation front and the hot spot radius. The ablation pressure scales with the laser intensity $I$, as $I \propto P_a^{3/2}$. We considered a shock ignition of the HiPER target [7], imploded at different velocities. The numerical constants of the model are compared with simulations using the CHIC hydrodynamic code in Fig. 4, where the absorbed laser spike power at the ignition threshold is plotted as a function of the implosion velocity. Above 320 km/s, the target is close to self ignition, and the required additional power is comparable to the power for compression. Below 200 km/s, the spike power increases sharply, in excess of 300 TW, which may be unacceptable in terms of laser plasma instabilities. We also considered Euler scaled targets, by multiplying time and dimensions by a factor $h$, energies by $h^3$ and power by $h^2$. Then, the hot spot pressure required to satisfy the ignition criterion $(PR)_{ign}$ is reduced by $h$, the spike intensity varies as $h^{-3/2}$, and the ignition power grows as $h^{1/2}$. This was not observed in simulations (not shown), where the power for marginal ignition depends very little on the target scale, for velocities in the 200 – 260 km/s range. Since the area of the critical surface varies as $h^2$, the intensity in the spike decreases as $h^{-3/2}$, according to the model, and $h^2$, according to simulations.

5. Design issues

The design constraints for shock ignition are three fold. First, the hydrodynamic robustness calls for low implosion velocities, and this is one of the main motivations for shock ignition and fast ignition. Second, one would like to minimize the energy invested in the target. The fuel assembly resulting from the shock collision is non-isobaric and it requires less energy to ignite [2]. According to Fig. 3, an optimal shock configuration is obtained when the target is driven at 55% of its self ignition velocity. Finally, low implosion velocities necessitate high laser powers in the spike, which not only stresses the laser technology, but also presents a risk of low laser plasma coupling efficiency. So the design has to trade off between the dangers of unstable fast implosions, and low laser coupling.

Assuming that the ignitor intensity decreases with the target scale as $h^{-3/2}$, whereas the self ignition velocity decreases as $h^{1/3}$, it is clear that the trade off will be different according to the target scale. Figure 5 shows the laser spike intensity as a function of the implosion velocity, for different values of the compression energy. The laser intensity is given under the assumption of a 50% absorption efficiency and we accounted for the fact that lowering the velocity at constant energy allows to increase the fuel mass. All targets considered in Fig. 5 are scaled, but not hydrodynamically equivalent. We fixed safety limit at $10^{16}$ W/cm$^2$ for the intensity and at 350 km/s for the implosion velocity. There is no sensible shock ignition design using less than 100 kJ of compression energy. At
200 kJ, one can plan implosions in the 230 – 280 km/s range, but with a little margin. The 500 kJ curve offers a much wider range for design, with a working point at 250 km/s, $4\times10^{15}$ W/cm$^2$. This curve is representative of what can be achieved on the NIF, accounting for a strong reduction of hydrodynamic efficiency due to the polar direct drive irradiation scheme envisioned for this facility.

![Figure 4. Minimum ignition laser power (TW) as a function of the implosion velocity (km/s). The solid line, Eq. (4), is compared with numerical simulations (stars).](image)

![Figure 5. Intensity of the ignition spike (PW/cm$^2$) as a function of the implosion velocity (km/s) for the compression energies 100, 200, 500 kJ and 1 and 2 MJ.](image)

6. Conclusion
A shock may ignite ICF targets imploded at sub-ignition velocities due to two successive mechanisms of pressure amplification: shock convergence and shock collision. The latter effect offers the pressure amplification factor of 6. Such a shock may be launched from an ablation pressure of several hundreds of Mbar, which necessitates laser intensities larger than $5\times10^{15}$ W/cm$^2$. However, in this high intensity regime, parametric instabilities may decrease the laser coupling efficiency. Using a simple hydrodynamic model, we derived a relationship between the implosion velocity and the intensity of the ignition laser pulse. Numerical simulations were used to expand the operating domain in the implosion velocity and laser intensity space. The HiPER project envisions the gains close to 80 from a target imploded with 200 – 250 kJ of the laser energy. Our results demonstrate that the implosion velocity should then range between 240 and 280 km/s, with intensities for the shock ignition between $6\times10^{15}$ and $10^{16}$ W/cm$^2$. The operating domain at 500 kJ is much wider, allowing implosion velocities as low as 190 km/s. This domain is representative of anticipated polar direct drive shock ignition experiments on the NIF at 750 kJ, with less efficient but more robust targets.

**Acknowledgment.** This work is partly supported by the Aquitaine Region Council and performed in the framework of the HiPER project (EC FP7 project number 211737).

[1] Ribeyre X et al. 2009 Plasma Phys. Control Fusion 51 015013
[2] Betti R 2007 Phys. Rev. Lett. 98 155001
[3] Rosen M D and Lindl J D 1984 UCRL-50021-83 LLNL pp 3.5-3.9
[4] Ribeyre X et al. 2009 accepted in Plasma Phys. Control Fusion
[5] Kemp A. et al. 2001 Phys. Rev. Lett. 86 3336
[6] Von Guderley G. 1942 Luftfart-Forsch. 9 302
[7] Atzeni S et al. 2009 Nucl. Fusion 49 055008
[8] Zhou C D and Betti R 2008 Physics Plasmas 15 102707
[9] Perkins L J et al. 2009 Phys. Rev. Lett. 103 045004