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Bipolar shock ignition: an option for the HiPER project

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In the general framework of Inertial Confinement Fusion (ICF), the classical process leading to DT ignition is the conversion of the shell kinetic energy into internal energy of a central hot spot, which further acts as an ignition spark. The advent of petawatt class lasers opens the possibility to directly deliver the ignition energy to the compressed fuel at stagnation time. This scheme, known as fast ignition, has first been proposed by Tabak et al. in 1994 [1].

Recently, Betti et al. [2] proposed to ignite the target by means of a strong convergent shock launched in the target at the end of the compression phase and prior to the final focalisation of fuel at target center. Moreover, more recently, this new concept has been experimentally studied at the OMEGA laser facility Theobald et al. [3]. It was demonstrated that a properly timed final shock significantly enhances the neutron yield. This somehow intermediate scheme is highly attractive, because it relaxes the high implosion velocity requirement of the central hot spot ignition approach, and, at the opposite of fast ignition, it does not require any cone-in-a-shell target nor multipetawatt ignition laser [4].

In this work, we study the potential of shock ignition in the context of the HiPER project [5]. CHIC 1D and 2D numerical simulations are used to provide guidelines for physical understanding, optimization, and robustness analysis of the shock ignition process. Further on, we study the possibility of using a bipolar igniting shock, driven by a specific set of laser beams, in order to enhance laser target coupling at the end of the coasting phase of the shell. Fast ignition scheme is studied in the context of the HiPER project [6]. This concept can be divided in two separate stages. In the first phase the DT shell is compressed on a low adiabat ~1, sub-ignition

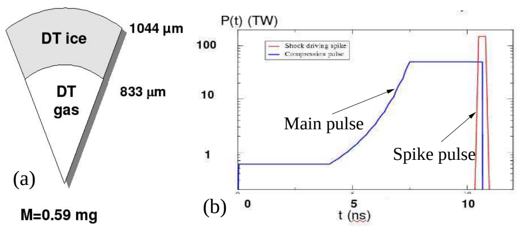

Figure 1: (a) All DT target baseline. (b) Main pulse shape to obtain a low adiabat shell during the compression phase and spike pulse required for shock ignition, about ~80 kJ during ~400 ps (150-200 TW).

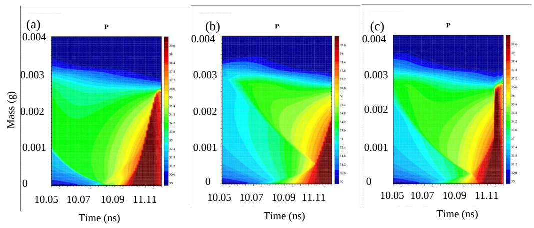

Figure 2: Pressure vs time in mass coordinate around the shell stagnation. (a) the spike is launched too early (b) too late and (c) on time.

velocity $\sim 3 \times 10^7$ cm/s, up to high areal density ~ 1.5 g/cm^2 [6, 7]. The HiPER baseline target characteristics are given in Fig 1a. After the compression phase, the dense core DT is ignited by means of a high power short pulse, typically 80 kJ, 10 ps; this requires a pettawatt-class laser, i.e., a Chirped Pulse Amplification (CPA) technology. In this scheme, the laser energy is transmitted (via a cone) to a beam of fast electrons which ignite the DT core.

The fuel assembly is the same for shock ignition as for PW driven fast ignition. However, for the former scheme, ignition conditions are obtained by the energy dissipation of a converging shock during the shell stagnation phase. The laser required to drive this shock is similar to the compression laser, with about 80 kJ with 200-500 ps laser pulse time duration. The typical pulse shape needed for shock ignition is shown in Fig 1(b). As described in Betti et al work [2], a nonisobaric fuel assembly situation is obtained at stagnation time, as a consequence of the collision of the ignitor shock with the return shock near the inner interface of the cold shell. This effect dramatically increases the central fuel pressure and temperature, which triggers ignition. This situation is described in figure 2. The Fig 2a shows that if the spike launching time is too early: the hot spot mass is not large enough to ignite, (b) too late: the hot spot mass is too large for ignition and (c) on time: the ignition temperature condition is achieved in a thick enough region. A set of monodimensional numerical simulations with various spike power and timing has been carried out in order to study the robustness of the scheme. Figure 3 shows the iso-yield lines, i.e., the lines of constant thermonuclear energy obtained with the spike launching time given on the vertical axis and the laser absorbed power on the horizontal axis. The spike power threshold for ignition is about 50 TW. This figure gives a confidence window about 250 ps for shock launching at 80 TW. However, delivering 80 TW to the target requires 150-200 TW from the laser. The temperature at critical density exceeds 7 keV during the spike and absorption is low, specifically in DT. Moreover, the critical radius is half its initial value at spike launching time. This suggests the use of reduced focal spots with a specific random phase plate (RPP) for the spike beams. A focal spot radius reduction from 600 μm to 400 μm allows to increase

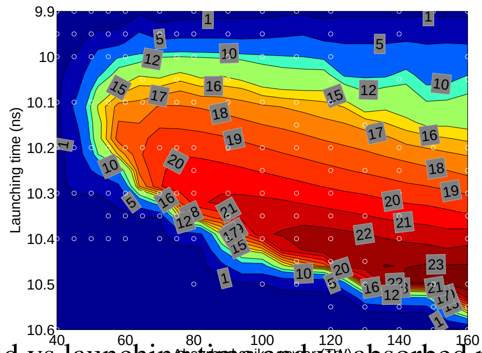

Figure 3: Iso-yield vs launching time and vs absorbed power spike.

the absorption efficiency from 30% up to 45%. Fig.4b gives the specific absorbed laser power and the pressure during the rise time of the spike laser pulse. The distance between the critical surface and the ablation front is large, about 200 μm. This produces a highly efficient thermal smoothing during this phase.

We propose to use a first set of symmetrically aimed beams to compress the DT shell and a reduced number of tightly focused to launch the shock, which may result in a non-symmetric, even bipolar, illumination. In Fig.4a the spike beams are disposed along a cone of half angle θ. Bi-dimensional axisymmetric numerical simulations are performed to study this situation. For $\theta = 0$ the laser irradiation is bipolar, Fig4c shows that the spike pressure is nonisotropic, the shock penetrates the fuel assembly on the polar axis before the equator. For $\theta = 33.2^\circ$ and $\theta = 54.7^\circ$ the pressure becomes more and more isotropic (Fig.4d-e). However, the figure 4f shows the pressure 130 ps later: for all incidences, the pressure becomes isotropizes fastly, and the yield is the same for the three angles, i.e., 18 MJ. This implies that the yield is not much sensitive to the ignitor beam irradiation symmetry. Moreover, several plasma physics effects may show up. The first important issue come from parametric instabilities in the laser plasma coupling. A first estimation for Raman and Brillouin stimulated back scattering gain shows that for an intensity of about 2.5×10^{15} W/cm^2 (200 TW and 12 spike beams with focal spot radii about 400 μm), the gain for Raman scattering is below 2 and below 8 for Brillouin scattering. Hence, the scattering losses are negligible. Finally, some estimation of the hot electron energy deposition can be addressed. The time evolution of the fuel areal density ρR during the spike shows that it varies between 0.03 and 0.09 g/cm^2 whereas the stopping power of DT for 80 keV hot electron remains below 0.01 g/cm^2. This implies that hot electrons, if any, would slow down on the shell's outer surface and contribute to the shock formation.

To conclude, the shock ignition scheme is an attractive solution for HiPER high repetition

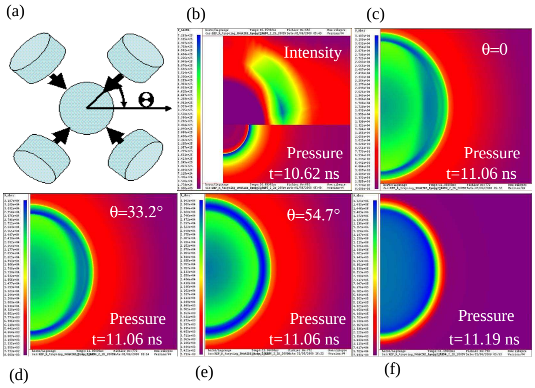

Figure 4: (a) set-up of the ignitor beams with incident angle θ. (b) Laser absorbed power and pressure during the spike irradiation for $\theta = 0$. (c) 440 ps latter: pressure during the shock-ignitor propagation inside the hot spot (c) for $\theta = 0$, (d) for $\theta = 33.2°$ (e) for $\theta = 54.7°$. (f) Pressure becomes isotropic for the three angles 130 ps latter.

rate operation. Most of our results are in agreement with previous results from LLE. Moreover, this concept could be experimented on the laser Megajoule (LMJ). On the LMJ facility, the beam entrance ports for indirect drive implosions are located at the polar angles 33.2 °, 49°, 59.5°. Direct drive implosions at moderate velocities can be successfully achieved using the 49° and 59.5° cones. The two 33.2 ° cones, up to now idle, may be used to deliver the 150 TW required to shock-ignite the target.

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