

Innovative Ignition Scheme for IFE - Impact Ignition -

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Abstract

An innovative ignition scheme is newly proposed, where the compressed DT main fuel is ignited by impact collision of another fraction of separately imploded DT fuel. The second DT fuel shell is accelerated in the hollow conical target to hyper-velocities in the order of 10^8 cm/sec. The kinetic energy is converted into thermal energy corresponding to temperatures > 5 keV on the collision with the main fuel, and this self-heated portion plays the role of ignitor. The ignitor shell is irradiated typically by nsec-pulses at intensities $> 10^{15}$ W/cm² and laser wavelength of 0.35 μ m to exert ablation pressures > 100 Mbar. A preliminary two-dimensional hydrodynamic simulation shows substantial heating of the compressed core. The impact-shell acceleration and consequent working windows for the beam and target parameters are addressed based on a rocket model. Simple physics, high energy coupling efficiency, low cost, no need for a PW laser, and affordability of investigation in laboratories under rather well established physical understanding and experimental know-how - those are considered to be the notable advantages of the present scheme.

1. Introduction

The fast ignition scheme has attracted attention of a number of researchers in this field since early 90's [1,2]. This is of course not only because it creates quite new research fields relevant to high energy density physics, but also because it is expected to achieve higher energy gain at smaller driver energies and under less compression uniformity than the conventional central spark ignition scheme [3]. As a result, for example, Kodama *et al.* [4,5] at Osaka University (ILE) have demonstrated its feasibility in experiments by using the cone-stuck spherical target. In an orthodox fast ignition scheme, high energetic micro particles such as electrons [6-8], protons [9], and cluster ions are expected to be transported into the core of the compressed DT fuel and to heat it successfully enough beyond the ignition temperature. On one hand, however, this scenario bears still many unknown physics such as the interaction between relativistic electrons and matter and the resultant energy transport.

In contrast with the scheme using micro particles as mentioned above, different ideas for the fast ignition using plasma momentum have been proposed by other authors. Gus'kov [10] has proposed to ignite the fuel by using plasma flow of a thin exploding pusher foil. Another alternative for the fast ignition making use of a plasma jet has been proposed by Velarde *et al.* [11]. The jet is formed by focusing the axi-symmetrical plasma flow emitted from the inner surface of a hollow middle-Z conical target, which is stuck in a spherical fuel pellet with its apex faced outward. In the respect that this scheme utilizes the hydrodynamic momentum of the jet for additional heating, it well contrasts with the above schemes using micro particles, that transport mainly the absorbed energy but not the momentum. In addition, the scheme does not need any additional energy driver for jet production but use the same one as for the main fuel acceleration, i.e., thermal radiation circulating in a hohlraum target. In spite of such an attractive features as the simplicity and tractability, the original jet-driven ignition design,

however, possesses two crucial defects: First, since it uses middle-Z (or even higher) materials for the jet, the turbulent mix, which occurs on collision between the main DT fuel, is expected to significantly degrade the ignition performance. Second, enough amount of thrust moment and thus enough heating cannot be expected with the jet-driven ignition target, which is apparent from the hydrodynamic point of view as follows: Under the almost same acceleration distances and times for both the main fuel and the jet, the specific momentum of the jet, ρv^2 , is at best in the same order of that of the main fuel. Moreover and most important, since the jet is generated as a result of the shock arrival at the rear side of the cone attachment, the total amount of hydrodynamic energy is so small to give substantial heating of the main fuel.

In this paper, we propose a totally new ignition scheme, which also utilizes the hydrodynamic momentum. However, it is expected to fulfill the critical requirements, i.e., strong thrust and high efficiency, so as to enable us to design a high-gain target. Figure 1 shows the initial target structure overlapped with the compressed fuel image at maximum compression. The target is composed of two components: a spherical pellet made of DT shell coated with an ablator and a hollow conical target, which is stuck to the spherical pellet. The conical component for ignition has a fragmental spherical shell also made of DT and an ablator. As will be derived afterward, it is necessary to achieve a high implosion velocity in the order of 10^8 cm/sec to form an igniting hot spot by converting the imploding kinetic energy into its own thermal energy. For this purpose, it seems appropriate to use laser beams for the ignitor-shell acceleration; the irradiation intensity and pulse duration of which can be in the same order as those for the main fuel. Note that an alternative design with the use of heavy ion beams (HIB) is also discussed afterward.

It should be noted that some other authors have used the similar terminology to the present paper such as “impact fusion”. For example, the scheme proposed by Winterberg [12] utilizes the momentum of an accelerated solid projectile to compress the thermonuclear fuel held in an anvil. Or, as another example, Yabe *et al.* [13] and also Winterberg [14] proposed x-ray driven schemes, in which the x-ray source is produced by an impact collision. In all these schemes, the effect of impact is intended to compress the main fuel itself in a direct or indirect manner. Therefore they are essentially different from the present scheme in which the effect of the impact collision is designed to produce an ignitor.

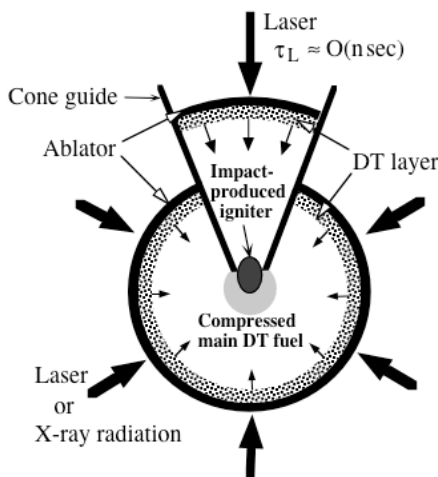


Fig. 1 Initial target structure of the impact ignition target overlapped with the compressed fuel image at maximum compression.

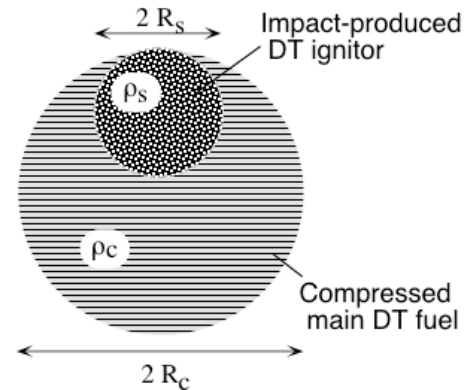


Fig. 2 schematic picture for the fuel configuration at around the maximum compression of the main DT fuel.

The structure of this article is as follows. In Sec. 2, we describe an expected performance on the energy gain in terms of a few basic parameters. In Sec. 3, a preliminary result of 2-D hydodynamic simulation is demonstrated. A summary is given in Sec. 4.

2. Gain Model

Figure 2 shows a schematic picture for the fuel composition at around the maximum compression of the main DT fuel (denoted with the subscript “c” in the following), which is synchronized with the formation of the hot spot ignitor produced by the impact collision of the cone shell (denoted with the subscript “s”). At this time, they are supposed to be approximately in a stationary phase. For simplicity, we assume that each of the two spheres has a uniform spatial profile. A simple gain model discussed below is based on the analytical model of Ref. [15].

For the igniting hot spot, as is well known, the key parameters are the temperature, $T_s \approx 5 \text{ keV}$, and its areal mass density, $H_s \equiv \rho_s R_s \approx 0.4 \text{ g/cm}^2$, where ρ_s and R_s are the mass density and the radius, respectively. On the impact collision, the kinetic energy of the DT ions corresponding to its implosion velocity, v_i , are assumed to be finally converted into the thermal energy to the igniting temperature: $(1/2)m_i v_i^2 = 2(3/2)T_s$, where $m_i = (5/2)m_p$ is the averaged DT ion mass with the proton mass, m_p , and the temperature is measured in cgs units. The required implosion velocity is then uniquely obtained:

$$v_i = (12T_s / 5m_p)^{1/2} = 1.1 \times 10^8 (\text{cm/sec}). \quad (1)$$

The total mass for the ignitor is expressed as a function of only the mass density ρ_s by

$$M_s = \frac{4\pi H_s^3}{3\rho_s^2} = 27 \mu\text{g} \cdot \left(\frac{\rho_s}{100 \text{ g/cm}^3} \right)^{-2} \quad (2)$$

The energy balance is given by $\eta_s E_{Ls} = 3T_s M_s / m_i$, where E_{Ls} and η_s are respectively the invested laser energy for the cone shell and its coupling efficiency to the final thermal energy. The required laser energy is then given as a function of ρ_s in the form,

$$E_{Ls} = \frac{8\pi H_s^3 T_s}{5m_p \eta_s \rho_s^2} = 15 \text{ kJ} \cdot \eta_s^{-1} \left(\frac{\rho_s}{100 \text{ g/cm}^3} \right)^{-2} \quad (3)$$

Thus, the energy required to form the igniting hot spot turns out to be sensitive to ρ_s as is often the case in the orthodox inertial fusion scenario. It is also informative to rewrite Eq. (3) to give the required mass density of the hot spot as a function of E_{Ls} :

$$\rho_s = 120 \text{ g/cm}^3 \cdot \left(\frac{\eta_s E_{Ls}}{10 \text{ kJ}} \right)^{-1/2}. \quad (4)$$

For the main DT fuel, the isentrope parameter, $\alpha_c \equiv p / p_{\text{deg}}$ (p and p_{deg} are the fuel pressure and the electron degenerate pressure, respectively), is expected to be as low as possible. In this case, the mass and the total internal energy are respectively given by

$$M_c = 4\pi H_c^3 / 3\rho_c \quad (5)$$

$$\eta_c E_{Lc} = 3.3 \times 10^{12} \alpha_c \rho_c^{2/3} M_c \quad (6)$$

where $H_c \equiv \rho_c R_c$ is the areal mass density of the main DT sphere, and η_c and E_{Lc} have the same definitions as for the igniting hot spot. The total drive energy is given by

$$E_d = E_{Lc} + E_{Ls}. \quad (7)$$

Once the hot spot is successfully ignited, a burn wave is expected to propagates through the

main fuel, and the burn fraction can be roughly estimated by

$$\Phi = H_c / (H_c + H_0) \quad (8)$$

with $H_c = (3\rho_c^2 M_c / 4\pi)^{1/3}$ and the constant, $H_0 = 7 \text{ g/cm}^2$. The energy gain is finally evaluated to be

$$G = \Phi M_c \epsilon_0 / E_d \quad (9)$$

where $\epsilon_0 = 3.4 \times 10^{18} \text{ (erg/g)}$ is a constant, and the small fraction of the thermonuclear energy released from the hot spot is ignored for simplicity.

Figure 3 shows the energy gain thus obtained from Eqs. (1) - (9) as a function of E_d for different values of ρ_c and ρ_s , where $\alpha_c = 3$, $\eta_c = 0.1$, and $\eta_s = 0.1$ are specified as an example. At the igniting points, where the gain curves begin to rise steeply, the total driver energies are attributed almost only to E_{Ls} . The minimum igniting energy strongly depends on ρ_s [see Eq. (3)]. On the other hand, it can be seen that the energy gain is a weak function of ρ_c . Moreover, as can be seen in Fig. 3, it is crucial for high gain to achieve ρ_s in the order of 100 g/cm^3 at a few 100 kJ of the total laser energy. The density compression of $100 - 200 \text{ g/cm}^3$ or $500 - 1000$ times the solid densities do not seem to be too optimistic, because the density level of the order of 1000 times the solid density has been experimentally established [16] though it has been obtained under pure spherical experiments with D_2 -doped plastic shell targets.

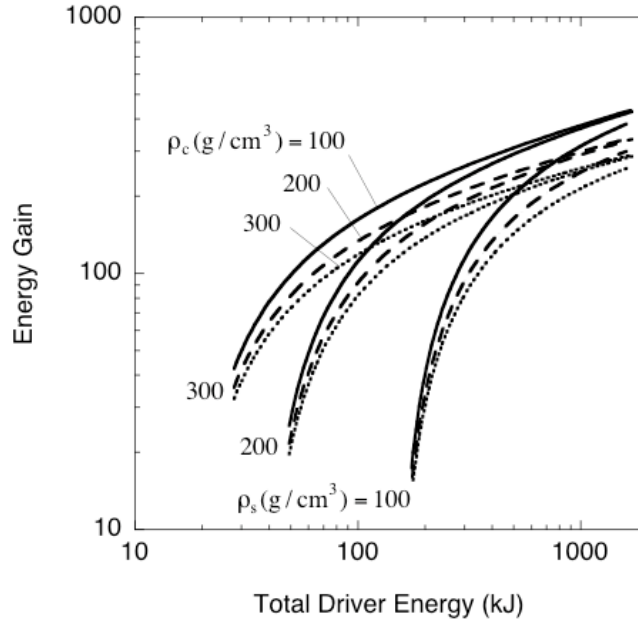


Fig.3 Gain curves of Impact Ignition scheme. Specified parameters are $\alpha_c = 3$, $\eta_c = 0.1$, and $\eta_s = 0.1$.

3. Two-Dimensional Hydrodynamic Simulation

To observe the basic implosion performance, we have conducted preliminary two-dimensional hydrodynamic simulations [16]. Due to limitation of CPU time, radiation transport is switched off. Moreover, the shell material is composed of only plastic (CH) for simplicity. The radial and azimuthal coordinates are respectively assigned with 300 meshes. The outer radius / shell thickness of the cone CH and the main CH are respectively chosen to be $750 \mu\text{m} / 30 \mu\text{m}$ and $660 \mu\text{m} / 21 \mu\text{m}$. Simple Gaussian laser pulses at $\lambda_L = 0.35 \mu\text{m}$ and $\tau_L = 2.5 \text{ nsec}$, which normally illuminate the both shells, are one-dimensionally ray-traced. Applied laser intensities (energies) are $3 \times 10^{15} \text{ W/cm}^2$ (100 kJ) on the ignitor shell and $9 \times 10^{14} \text{ W/cm}^2$ (100 kJ) on the

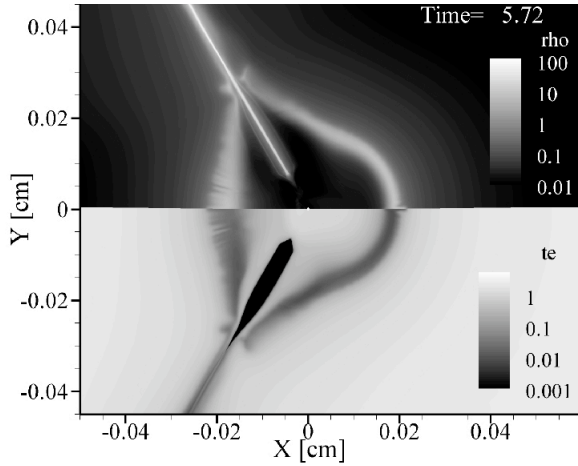


Fig. 4 (a) Isocontour map at a time shortly before the impact.

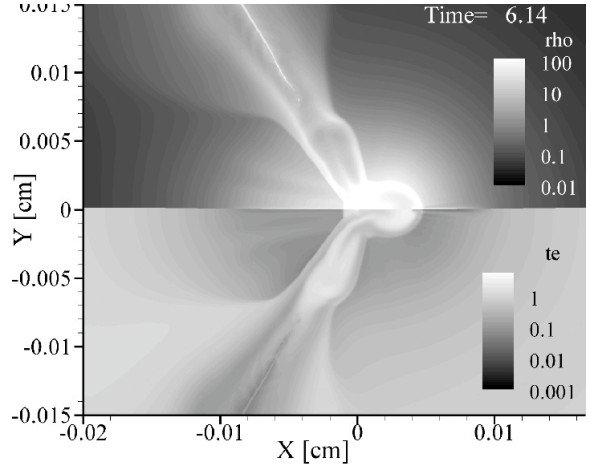


Fig.4 (b) Isocontour map at peak compression shortly after the impact

main shell. The cone guide is made of solid gold with thickness of 10 μm with cone angle of 130 degree, and with diameter for the open hole at its apex of 150 μm .

Figures 4(a) and 4(b) show isocontours maps of the density and the temperature at peak velocity and at maximum compression, respectively. The peak implosion velocities are 6×10^7 cm/sec (cone shell) and 3×10^7 cm/sec (main shell) at around the Gaussian peak. Correspondingly, the ablation pressure of 110 Mbar and the density of 7 g/cm³ are observed for the cone shell in Fig. 4 (a). In Fig. 4 (b), it is observed that the most of kinetic energies of the both shells are transformed into internal energies. The compressed cone shell is found to have such mass-averaged plasma parameters as $T = 3.0$ keV and $\rho = 250$ g/cm³. In the central region of the cone shell, $T > 5\text{keV}$ and $\rho > 400$ g/cm³ are observed. Although those attained plasma parameters are still enough less than expected, it should be stressed that two separately imploded shells are synchronously collided at the center and generated a dense hot core. Thus, in spite of all the deficiency that indwells in this preliminary hydrodynamic simulation, the results shown in Fig. 4 indicate high potential of the impact ignition.

4. Summary

A new ignition scheme utilizing the hydrodynamic impact is proposed. A simple gain model indicates that a high gain of the order of 100 can be possible to achieve at the total driver energy less than a few 100 kJ. A crucial milestone for the Impact Ignition is to demonstrate impact-compressed densities ~ 100 g/cm³ in addition to high implosion velocities $\sim 10^8$ cm/s. It is then required to stably accelerate the ignitor-shell at relatively low Rayleigh-Taylor (R-T) growths. Such highly stable acceleration is now strongly expected to be realistic enough by developing a newly found physical effect for R-T suppression [17] (though we have not discussed the detail in this paper).

A preliminary two-dimensional hydrodynamic simulations show the generation of a dense hot core and thus the potential of the present scheme. Simple physics, relatively high energy coupling efficiency, no need for a PW laser, resultantly low cost, and affordability of investigation in laboratories under rather well established physical understanding and experimental know-how - those are considered to be notable advantages of the present scheme.

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