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New developments in the theory of ICF targets, and fast ignition with heavy ions

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Abstract
An overview of recent progress in the theory of inertial confinement fusion (ICF) targets is presented. Work on traditional target schemes, based on the hydrodynamic mode of ignition, is reviewed only briefly, while most of the attention is devoted to the fast ignition approach. The general advantages of fast ignition are illustrated with a simple model for characteristic assembled fuel configurations. Special attention is paid to a newly proposed concept of a cylindrical reactor-size target, compressed and ignited (in the fast ignition mode) by two separate beams of very energetic ($E_i \gtrsim 0.5\,\mathrm{GeV\,u^{-1}}$) heavy ions.

1. Introduction

Inertial confinement fusion (ICF) is based on microexplosions of thermonuclear targets. A major challenge has always been to come up with a reliable target design that would be appropriate for energy production, i.e. would generate a sufficiently high thermonuclear energy gain, $G \simeq 50$–200, for a limited ($Y \lesssim 1$ GJ) total yield in a single microexplosion. Presently, efficient targets are designed to perform in either a hydrodynamic ignition mode or in a fast ignition mode. Hydrodynamic ignition is achieved by means of a hot spot (thermonuclear spark) with parameters $\langle\rho R\rangle_s \gtrsim 0.2$–$0.3\,\mathrm{g\,cm^{-2}}$, $T_s \gtrsim 6$–7 keV, naturally formed at the centre of the imploded spherical deuterium–tritium (DT) mass. This ignition mode has become a traditional ICF scheme: it is the main-line approach for the National Ignition Facility (NIF, USA) and Laser Mégajoule (LMJ, France) projects [1].

The idea of fast ignition has always been around in ICF research. In particular, it had underlain implicitly the isochoric ignition mode of Kidder [2] and Meyer-ter-Vehn [3]. This idea has emerged, however, in a fully new light [4] after the invention of the chirped pulse amplification (CPA) of laser pulses, which allowed the power of laser beams to be raised by three or more orders of magnitude. Fast ignition is achieved not by means of implosion, whose task now is simply to compress a few milligrams of DT to the required $\langle\rho R\rangle_{DT} \simeq 2$–$3\,\mathrm{g\,cm^{-2}}$, but by a separate and very fast (within 10–50 ps) injection of energy (10–100 kJ) into a small ($\langle\rho R\rangle_s \simeq 0.5$–$0.6\,\mathrm{g\,cm^{-2}}$) portion of the compressed DT to heat it up to $T = T_s \simeq 10\,\mathrm{keV}$.

In recent years, the fast ignition approach (for a brief review, see [5]) has been at the frontier of theoretical research on ICF targets. At the same time, work has continued on elaborating target designs with more traditional hydrodynamic ignition. In this paper, a brief general review of the recent theoretical work on ICF targets is given, with special emphasis on the possibility of fast ignition with beams of heavy ions.

2. ICF targets with hydrodynamic ignition

In its gross features, the scheme and parameters of the indirect drive laser target for NIF and LMJ remain as they were formulated about a decade ago [1, 6]. Work continues on further optimization and refinement of this design [7], in particular, by initiating three-dimensional simulations of the target performance [8].

The baseline design of the direct drive NIF target has been worked out years later [9], and work still continues on gaining confidence in its performance [10]. Compared with indirect drive, additional constraints on direct drive laser targets are imposed by (i) more severe drive asymmetries due to variations in power among the many irradiating laser beams and by (ii) the Rayleigh–Taylor instability seeded via imprinting of the short-scale non-uniformities of the laser light within individual focal spots.

In heavy ion fusion, theoretical efforts have been focused on working out reactor-scale target designs with energy gains of $G \gtrsim 50$. Only the indirect drive option has been considered feasible because no effective way to smooth out the non-uniformities of the energy deposition for overlapping ion beams under the conditions of the direct drive has been found. Then, the spherical DT fusion capsule can be similar to that in indirect drive laser targets, and one has only to match the hohlraum design with the capabilities of the heavy ion driver.

Research at the Lawrence Livermore National Laboratory (USA) has been focused on various modifications of a heavy ion target with a cylindrical hohlraum and two-sided irradiation scheme [11]. The interior of the hohlraum has a rather complex structure, and this target requires heavy ions (Pb) with two different ion energies, $E_i \approx 3$ and $4\,\mathrm{GeV}$, for the foot and main part of the pulse. Two-dimensional LASNEX simulations have demonstrated energy gains in the range of $G = 50$–130 [11, 12]. If the reactor chamber could accept a quasi-spherical distribution of $\gtrsim 20$ ion beams (as in the direct-drive laser option), a much simpler and, probably, more robust target design with a spherical hohlraum, driven by ions with a single energy of $E_i \approx 5\,\mathrm{GeV}$ and producing an energy gain of $G \approx 70$, might be proposed [13].

In addition to lasers and heavy ion accelerators, wire-array Z-pinches have emerged recently as a potential ICF driver, after they had been discovered as powerful x-ray sources [14]. Several indirect-drive target options, based on the same principles as the indirect-drive NIF target and differing mainly in the hohlraum design, have been proposed recently for ignition with a $\simeq 60\,\mathrm{MA}$ multi-wire Z-pinch of the next generation [15].

3. General advantages of fast ignition

The general advantages of fast ignition over hydrodynamic ignition can be illustrated with the following simple model. Consider two equal spherical masses of the DT fuel in the assembled state, one prepared for hydrodynamic ignition (figure 1(*a*)), and the other prepared for fast ignition (figure 1(*b*)). The hydrodynamically igniting configuration has a central hot spot in

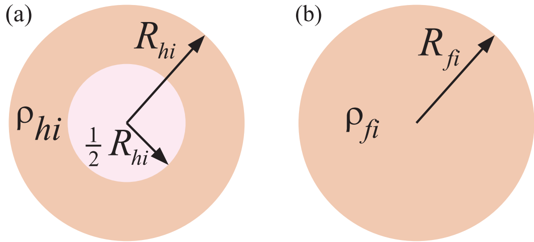

Figure 1. Assembled DT fuel configurations in the case of hydrodynamic ignition (*a*), and in the case of fast ignition (*b*).

pressure equilibrium with the bulk of the fuel; the density of the hot spot is much lower than the density, $\rho_{\rm hi}$, of the surrounding cold fuel. In optimized cases the radius of the hot spot is typically about one half of the outer fuel radius, $R_{\rm hi}$ [1]. The fuel prepared for fast ignition is a uniform sphere of radius $R_{\rm fi}$ and density $\rho_{\rm fi}$. Then, ignoring the mass of the hot spot in the hydrodynamic mode, we write down the condition for the two masses being equal:

$$\tfrac{7}{8}\rho_{\rm hi}R_{\rm hi}^3 = \rho_{\rm fi}R_{\rm fi}^3. \tag{1}$$

As a second condition, we want our two fuel configurations to generate equal thermonuclear yields, i.e. to have equal thermonuclear burn fractions. To a first approximation, the burn fraction is determined by the total $\langle\rho R\rangle = \int \rho\,{\rm d}r$ parameter of the compressed fuel [1]. Then, in addition to equation (1), we have the condition

$$\tfrac{1}{2}\rho_{\rm hi}R_{\rm hi} = \rho_{\rm fi}R_{\rm fi}. \tag{2}$$

From equations (1) and (2) we calculate that for hydrodynamic ignition we need a

$$\frac{\rho_{\rm hi}}{\rho_{\rm fi}} = 7^{1/2} \approx 2.6 \tag{3}$$

times higher fuel compression than for fast ignition. Assuming that in both ignition modes the DT fuel is compressed along the same isentrope, we readily evaluate the ratio

$$\frac{E_{\rm hi}}{E_{\rm fi}} = \frac{P_{\rm hi}R_{\rm hi}^3}{P_{\rm fi}R_{\rm fi}^3} = \frac{\rho_{\rm hi}^{5/3}R_{\rm hi}^3}{\rho_{\rm fi}^{5/3}R_{\rm fi}^3} = \frac{8}{7^{2/3}} \approx 2.2 \tag{4}$$

between the compression energies required for the two ignition modes. Note that this simple estimate agrees very well with the results of detailed two-dimensional simulations by Atzeni [16] for fully optimized values of the fuel energy gain—when comparison is made for a given thermonuclear yield (and not the driver energy) around 0.5–1 GJ, suitable for energy applications. In reality, the energetic advantage of fast ignition may be even less than a factor 2 due, for example, to lower than expected energy coupling between the igniting laser pulse and the DT hot spot or because the imploded DT mass always tends to have a lower density near the centre [17].

An important characteristic of any implosion is the radial convergence ratio, C_r, for which there always exists an upper bound due to drive asymmetries. For hydrodynamic ignition, C_r is defined as the ratio of the initial capsule radius to the radius of the hot spot $R_{\rm s} = \frac{1}{2}R_{\rm hi}$. For fast ignition, the latter is replaced by the cold fuel radius, $R_{\rm fi}$. Assuming the same initial capsule radii, we find that

$$\frac{C_{r,\rm hi}}{C_{r,\rm fi}} = \frac{2R_{\rm fi}}{R_{\rm hi}} = 7^{1/2} \approx 2.6. \tag{5}$$

The latter means that implosions of the fast-ignition capsules may proceed under significantly relaxed constraints on the drive symmetry. Also, the peak implosion velocity, v_{im}, is reduced by the factor

$$\frac{v_{im,hi}}{v_{im,fi}} = \left(\frac{\rho_{hi}}{\rho_{fi}}\right)^{1/3} = 7^{1/6} \approx 1.4. \tag{6}$$

4. Fast ignition with a petawatt laser

The minimum ignitor energy [16],

$$E_{ig} = 140 \left(\frac{\rho_{fi}}{100\,\mathrm{g\,cm^{-3}}}\right)^{-1.85} \mathrm{kJ}, \tag{7}$$

required for fast ignition is relatively small and, to a first approximation, can be ignored in the overall target energy balance. It is the power and intensity thresholds [16],

$$W_{ig} = 2.6 \times 10^{15} \left(\frac{\rho_{fi}}{100\,\mathrm{g\,cm^{-3}}}\right)^{-1} \mathrm{W}, \tag{8}$$

$$I_{ig} = 2.4 \times 10^{19} \left(\frac{\rho_{fi}}{100\,\mathrm{g\,cm^{-3}}}\right)^{0.95} \mathrm{W\,cm^{-2}}, \tag{9}$$

which pose a major challenge. The only proven way to generate such irradiation powers and intensities is by using CPA lasers.

Laser light itself cannot penetrate as deep as the compressed fuel core with density $\rho_{fi} \gtrsim 100\,\mathrm{g\,cm^{-3}}$: its energy is converted into multi-MeV electrons at a much lower density near the critical surface. How (and whether) the ignition energy can be transported into the dense fuel core by means of a huge (of the order of 100 MA) electron current remains an open question and an area of vigorous research.

Originally, as formulated by Tabak *et al* [4], it was proposed to use two laser pulses for fast ignition: the first longer one, to bore a low-density channel towards the compressed fuel core, and the second shorter one, to deliver the ignition energy into the fuel core. Later, however, the ability of the 'hole-boring' pulse to prepare an adequate channel in the ablated plasma has been seriously questioned. As a more reliable alternative, a not fully spherical cone-guided implosion of the fusion capsule was proposed [18, 19]. This relatively new and still not sufficiently studied approach in ICF target design is schematically illustrated in figure 2.

In its initial state, a conical sector is cut out of the usual spherical DT capsule and replaced by a concentric hollow cone of gold (figure 2(*a*)). The implosion of the not fully spherical

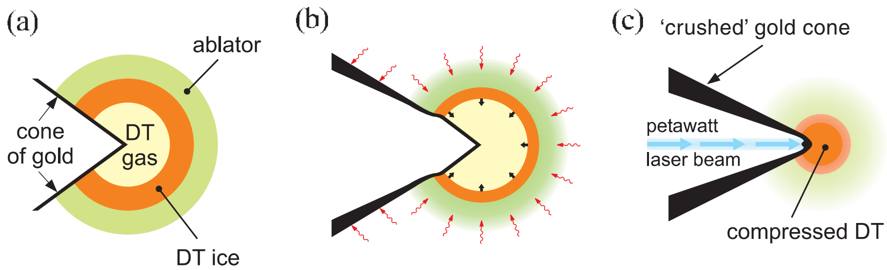

Figure 2. Cone-guided implosion of a not fully spherical fusion capsule: (*a*) initial state, (*b*) intermediate stage of implosion, (*c*) assembled fuel state at stagnation.

capsule is driven in the usual way, with the DT shell sliding along the gold cone towards the centre. Perturbations from the interaction with the cone wall are expected to be moderate [19], so that a good-quality compressed DT state is reached by the end of implosion near the tip of the gold cone (figure 2(*c*)). Because the cone wall is more sluggish than the ablator-fuel shell, the partially 'crushed' gold cone still remains open by the time of fuel stagnation and allows the igniting laser pulse to be delivered in the immediate vicinity of the fuel core.

5. Fast ignition with heavy ions

Being much more massive than electrons and having well defined Coulomb ranges in matter, heavy ions would be a far better candidate than lasers for a fast ignitor, as has been discussed in several previous publications [20,21]. A very difficult problem, however, is the compression of ion beams in time and space required for reaching the needed power (8) and irradiation intensity (9). Recently, a bold new proposal has been formulated by Koshkarev [22] from ITEP (Moscow). He argues that, under the following conditions, (i) the ion energy is increased from the conventional 5–10 to $\simeq$100 GeV per ion, (ii) the method of non-Liouvillian compression of beams of simultaneously accelerated ions with four different masses and opposite electric charges is employed, and (iii) the neutralization of the electric charge density is achieved by combining the beams of opposite charges at the last stage of beam compression, a 400 kJ pulse of heavy ions could be focused on a spot of 50 μm in radius within 200 ps. Such a pulse would produce an irradiation intensity of 2.5×10^{19} W cm^{-2} and might be suitable for fast ignition.

In this scenario, because of the relatively long ranges (5–10 g cm^{-2}) of 100 GeV heavy ions, one is compelled to use a cylindrical rather than spherical target geometry, as shown in figure 3. Implosion to the compressed state could be driven by a separate low-power and high-energy beam of heavy ions with the same $\simeq$100 GeV per ion. Relative inefficiency of cylindrical geometry can be compensated for (at least partially) by using the direct drive approach. A high degree of azimuthal uniformity of ion energy deposition, needed for direct drive in cylindrical geometry, can be ensured by fast rotation of the compression beam around the target axis (see figure 3(*a*)). A recent two-dimensional study [23] has shown that eight to ten beam revolutions over the duration of the main part of the compression pulse should be sufficient to reach the needed radial convergence.

The performance of such a heavy ion fast-ignited cylindrical target has been analysed in [24–26]. The parameters of the assembled DT fibre, $\rho_{\rm DT} = 100$ g cm^{-3}, $R_{\rm DT} = 50\,\mu$m, surrounded by a layer of compressed lead at equal pressure, have been chosen such that the fuel $\langle \rho R\rangle_{\rm DT} = 0.5$ g cm^{-2} is slightly above the threshold value 0.3–0.4 g cm^{-2} for a steady burn wave along a DT cylinder inside a metallic liner [27]. The range of 100 GeV ions in the compressed DT is about 6 g cm^{-2}, which exceeds with a wide margin the required

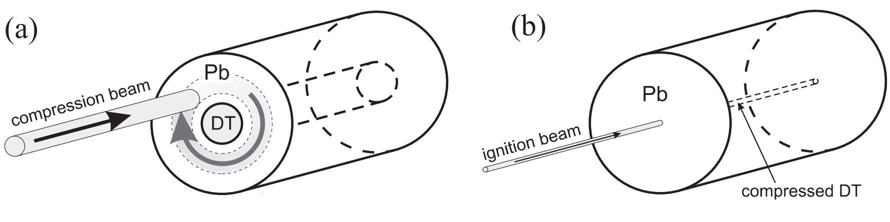

Figure 3. Schematic view of a cylindrical fast-ignition target for heavy ion fusion: (*a*) target implosion is driven directly by a low-intensity compression beam, rapidly rotating around the target axis; (*b*) at maximum compression of the DT fuel, its fast ignition is initiated by a second short and ultra-intense beam of heavy ions.

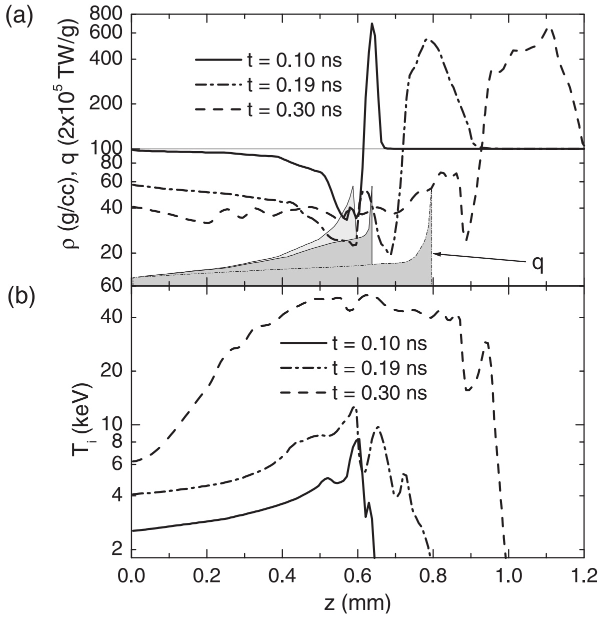

Figure 4. Axial profiles of (*a*) the density ρ (curves) and the specific (per unit mass) beam deposition power, q (shaded areas), and of (*b*) the ion temperature, $T_{\rm i}$, in the target centre at three characteristic times after the igniting beam was turned on. The density and temperature are plotted for $t = 0.10$, 0.19, and 0.30 ns and the deposition power for $t = 0$, 0.10, and 0.19 ns.

minimum value of $\simeq 0.6\,{\rm g\,cm^{-2}}$ [16]. Two-dimensional simulations performed independently with the Eulerian three-temperature (3T) code MDMT [28] at ITEP, and with the MIMOZA-ND code [25] at VNIIEF, have shown that ignition and burn propagation are achieved with the beam energy $E_{\rm fi} = 400\,{\rm kJ}$ delivered in a $t_{\rm fi} = 0.2\,{\rm ns}$ long pulse within the focal radius of $50\,\mu{\rm m}$. The evolution of the density and temperature profiles along the axis of the DT cylinder, as calculated with the MDMT code, is shown in figure 4. In simulations it was taken into account that the beam energy deposition peaks towards the end of the ion range (the Bragg peak) and that the Bragg peak advances along the mass coordinate in the axial direction as the DT density drops (see figure 4(*a*)) due to the radial expansion of the DT channel.

Optimization of the implosion stage was conducted in a separate series of one-dimensional simulations with the 3T code DEIRA [29]. Here, when the implosion is driven by the direct energy deposition of an axially propagating ion beam, the implosion strategy is dictated by the necessity to cope with the effect of 'clearance' of the annular absorber layer: as the density, $\rho_{\rm a}$, of the heated absorber drops in the course of its radial expansion, its mass thickness, $\rho_{\rm a}\Delta z$, in the axial direction (i.e. along the ion trajectories) decreases in the same proportion. As a result, the fraction of the ion energy left in the working target section becomes smaller and smaller (we assume that the ion energy is kept fixed during the pulse). Evidently, beam energy losses due to this effect may become prohibitively excessive for thin-shell absorbers. Hence, the principal aim was to minimize the total beam energy needed to reach the prescribed assembled DT state.

The initial target configuration was chosen under the constraint that the absorber and the pusher parts of the lead liner have equal initial densities, which should minimize the impact of the Rayleigh–Taylor instability near the absorber–pusher interface. Accordingly, it was assumed that the target consisted of a uniform lead tube at $R_{\rm DT,0} < r < R_0$, filled with the

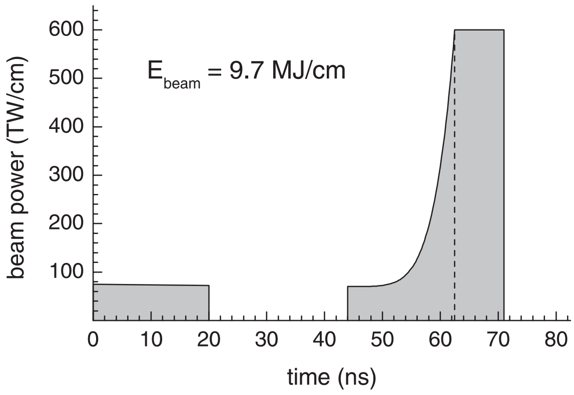

Figure 5. Optimized pulse shape of the compression beam.

DT fuel. The best results were obtained when the entire central region, $0 < r < R_{DT,0}$, was filled with the DT ice. In simulations, the values of $R_{DT,0} = 1.12$ mm and $R_0 = 4$ mm were used. Then, for the DT ice density of 0.225 g cm^{-3}, the DT mass was 8.9 mg cm^{-1} (which is some 10% larger than used in two-dimensional ignition simulations), and the total target mass was 5.2 g cm^{-1}.

In the process of optimization, it was found that the compression beam must deliver an energy of at least 9.7 MJ cm^{-1} in order to reach the required assembled fuel state at stagnation. Out of this, only 6.3 MJ cm^{-1} is actually deposited in the working target section, and the rest is lost due to the clearance of the expanding absorber. The optimal temporal profile of the beam power is shown in figure 5. To minimize the clearance losses, different radii of the beam focal spot, r_f, and of the beam rotation orbit, r_b, were used for the prepulse and the main pulse, namely, $r_f = 1.33$ mm, $r_b = 2.55$ mm for the prepulse and $r_f = 0.65$ mm, $r_b = 1.89$ mm for the main pulse.

Since no two-dimensional integrated simulations of this type of target have been performed so far, only a rough estimate of its energy gain can be made. One-dimensional results indicate that the DT burn fraction should lie in the range $f_b \approx 0.3$–0.6. Then, one can count on target energy gains in the range $G = 90$–180. The total target length, which remained undetermined in the above described one- and two-dimensional simulations, is supposed to be around 1 cm: this would correspond to the total thermonuclear yield of about 1 GJ compatible with conventional reactor chamber concepts.

6. Conclusion

In recent years, theoretical research on ICF targets has been devoted to elaborating the existing target designs, based on the hydrodynamic ignition mode (for laser, heavy ion, and wire-array Z-pinch drivers), as well as to exploring new target concepts. New conceptual developments have been centred mainly around the fast ignition approach. Fast ignition allows separating the ignition process from the stage of compression, which brings in new options for potential target schemes. The main advantage of fast ignition may be not so much in the enhancement of the target energy gain (which, under realistic conditions, appears to be below a factor of two) as in the relaxed demands on the symmetry of implosion and the peak power required for fuel compression. In the context of heavy ion-driven fusion, fast ignition opens a possibility to seriously consider reactor-size cylindrical targets, where implosion is driven by direct energy deposition of very energetic ($E_{\rm i} \gtrsim 0.5\,\mathrm{GeV\,u^{-1}}$) heavy ions propagating along the target axis. The latest innovative ideas concerning the beam compression and final focusing could make fast ignition with heavy ions—in addition to CPA lasers—a viable and competitive option.

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