A new ignition scheme using hybrid indirect-direct drive for inertial confinement fusion

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A new hybrid indirect-direct-drive ignition scheme is proposed for inertial confinement fusion: a cryogenic capsule encased in a hohlraum is first compressed symmetrically by indirect-drive x-rays, and then accelerated and ignited by both direct-drive lasers and x-rays. A steady high-density plateau newly formed between the radiation and electron ablation fronts suppresses the rarefaction at the radiation ablation front and greatly enhances the drive pressure. Meanwhile, multiple shock reflections at the fuel/hot-spot interface are prevented during capsule deceleration. Thus rapid ignition and burn are realized. In comparison with the conventional indirect drive, the hybrid drive implodes the capsule with a higher velocity ($\sim 4.3 \times 10^7$ cm/s) and a much lower convergence ratio ($\sim 25$), and the growth of hydrodynamic instabilities is significantly reduced, especially at the fuel/hot-spot interface.

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In central hot spot ignition scheme of inertial confinement fusion (ICF) [1–3], a spherical capsule which is composed of deuterium-tritium (DT) gas, DT fuel and an ablator, is cryogenically imploded to a high velocity, then the DT fuel is highly compressed and a hot spot is formed at the capsule center due to spherical convergent compression effect. When the alpha-particle heating of the hot spot exceeds the total energy losses, central ignition occurs and a burn wave propagates into the surrounding cold fuel. Two main implosion schemes, direct drive [4] and indirect drive [5], have been proposed for realizing central hot spot ignition. The National Ignition Campaign (NIC) [6] experiments have made great progresses towards ignition using indirect-drive targets. For example, the National Ignition Facility is now capable of delivering 1.9 MJ of 0.35-µm laser light at 500 TW, and the assembled fuel areal density has reached about 1.3 g/cm² which is 80% of the ignition goal [7, 8]. However, the NIC experiments are facing challenges, and the experimental ignition threshold factor which is a metric of the progress towards ignition needs to be increased by an order of magnitude to meet the ignition requirement. Besides laser plasma instabilities (LPI), two major issues in implosion dynamics are: (1) a strong rarefaction wave generated from the expansion of the radiation ablated plasmas seriously decreases the ablation pressure and limits the possibility of increasing implosion velocity; (2) hydrodynamic instabilities are more severe than predicted causing hot spot asymmetry and material mixing, and one of the important reasons for this is multiple shock reflections at the fuel/hot-spot interface during the deceleration phase.

![Diagram](image)

**FIG. 1:** (Color online). (a) Schematic of the hybrid-drive ignition target configuration; (b) capsule cross-section; and (c) indirect-drive radiation temperature (red) and direct-drive laser power (green) vs time.

In this Letter, to overcome the above issues, we propose a new hybrid indirect-direct-drive ignition scheme, whose configuration is shown in Fig. 1(a). A cryogenic ignition capsule encased at the center of a normal cylindrical high-Z hohlraum is first compressed symmetrically on a low adiabat by x-rays converted from indirect-drive laser beams through two laser-entrance holes (LEHs) at opposite ends. Then six clusters of direct laser beams are incident straightly on the capsule through the two LEHs at the ends and four additional symmetrical direct laser channel holes at the waist. The hybrid indirect-direct drive accelerates and finally ignites the capsule. This scheme is different from the previous hybrid-drive concept [9] in which an initial x-ray pulse is used for suppressing initial laser imprints by preheating, but not during the implosion and ignition. As compared with the recently proposed shock ignition scheme in which the compression and ignition steps are separated and both adopt direct-drive lasers [10–14], our hybrid-drive scheme launches direct laser beams simultaneously with the main pulse of the indirect drive, which creates a double-ablation-front (DAF) structure consisting of a radiation ablation front (RAF) and an electron ablation front (EAF). Consequently, the DAF structure results in the formation of a nearly steady high-density plateau, which suppresses the rarefaction at the RAF and greatly enhances the drive pressure. It is found that the enhanced drive pressure pushes the capsule to a higher implosion velocity and quickens the hot spot formation via inward shock/compression waves. Meanwhile, the convergence ratio is kept at a lower level. The hybrid-drive scheme can smooth the imprints and drive asymmetries of direct lasers by keeping the critical surface in the corona at a proper distance away from the capsule, and more beneficially, hydrodynamic instabilities are greatly stabilized even by comparison with the conventional indirect drive as in the point design target (PT) [15] in the NIC mission.
To illustrate our new scheme, we investigate implosion dynamics of a typical ignition capsule with an outer radius of 850 µm, about 4/5 of the PT in the NIC mission. This capsule requires a total drive laser energy of \( \sim 1.35 \) MJ, which is also a representative value for the PT. The cross-section of the capsule is shown in Fig. 1(b). The CH ablator of the capsule has a 117 µm thickness with a density of 1.0 g/cm\(^3\) and a mass of 0.92 mg, while the solid DT fuel layer has a 136 µm thickness with a density of 0.25 g/cm\(^3\) and a mass of 0.19 mg. The density of the DT filling gas is 0.3 mg/cm\(^3\). The total mass of this capsule is about 1.11 mg. Figure 1(c) plots the given radiation drive temperature and direct-drive laser power. The peak radiation temperature is 270 eV, and the estimated indirect laser energy is about 500 kJ by assuming a coupling efficiency of 10% from laser to capsule absorption. The drive pulse of the radiation temperature has four steps at 0.0, 7.2, 9.8 and 10.7 ns. These steps create four successive shocks whose timing follows the Munro criteria. During the rise time of the fourth step (the main pulse), direct-drive laser beams are launched. The 0.35-µm direct laser pulse at 425 TW has only one single step with a duration of 2 ns and a total energy of 850 kJ. The absorbed laser intensity near the critical surface (its radius is \( \sim 1000 \) µm) is about \( 3.4 \times 10^{15} \) W/cm\(^2\).

Figure 2(a) shows the implosion and ignition processes calculated by one-dimensional (1D) simulations, using 2000 meshes with a minimum grid size of 0.05 µm. The first three shocks of indirect drive merge at the inner surface of the DT fuel layer at time \( t = 11.4 \) ns, and the fourth shock chases them, as shown in the subpanel of Fig. 2(a). Direct lasers launched at \( t = 10.9 \) ns deposit energy in the vicinity of the critical surface which is kept about 300 µm away from the capsule. The electron temperature in this region rapidly rises to a maximum of about 7 keV, and an EAF generated by electron thermal conduction propagates towards the RAF with a supersonic speed of \( \sim 8.4 \times 10^7 \) cm/s. When approaching the RAF at about \( t = 11.5 \) ns, the EAF slows down to a subsonic speed and drives an electron thermal shock which travels into the capsule and forms a merged shock (MS) with the previous four shocks.
After $t = 11.5$ ns, the EAF and RAF separate from each other due to their different mass ablation rates, and hence a DAF structure is formed. The EAF compresses the ablated rarefaction plasmas behind the RAF like a piston, which controls the rarefaction effect from the conventional indirect drive and results in a nearly steady high-density plateau with a width of tens of microns, indicated by the gray regions in Fig. 2(b). The density is enhanced from $\sim 0.2$ g/cm$^3$ at $t = 11.2$ ns to $1.5\sim 2.0$ g/cm$^3$ at $t = 12.3$ ns, and correspondingly the pressure at the RAF is significantly increased from $\sim 60$ MBar to $\sim 230$ MBar, as shown in Fig. 2(b). During the implosion process, the drive pressure is further increased as the capsule converges, with an average value of $450$ MBar from $t = 11.5$ to $13.2$ ns, leading to a maximum implosion velocity of $4.25 \times 10^7$ cm/s. Comparing with the PT in the NIC mission, at equivalent total drive energy of $\sim 1.35$ MJ, the (maximum) implosion velocity of our hybrid-drive capsule is about $15\%$ higher. Meanwhile, the increasing drive pressure produces a series of compression waves forming an enhancement shock (ES) at about $t = 12.3$ ns. The ES collides with the rebounded MS near the fuel/hot-spot interface generating an inward shock and an outward one. At about $t = 13.2$ ns, the inward shock arrives at the capsule center, quickly raises the hot spot temperature and pressure, and leads to a lower convergence ratio of $25$. The hot spot rapidly achieves the ignition condition soon after the first shock reflection ($\sim 13.3$ ns) at the fuel/hot-spot interface. If the ES does not exist as in the conventional indirect drive, there would have multiple shock reflections at the fuel/hot-spot interface followed by severe Rayleigh-Taylor instability (RTI) growth. Figure 2(c) shows the stagnation density and temperature profiles at about $t = 13.4$ ns. The corresponding peak fuel density, hot spot areal density and hot spot average ion temperature are $1560$ g/cm$^3$, $0.59$ g/cm$^2$ and $8.8$ keV, respectively. Finally, the DT fuel burns, achieving an energy yield of $17.4$ MJ and an energy gain of $13$.

The drive asymmetries of the hybrid-drive ignition scheme originate from both direct laser drive and the x-ray drive. The high-mode direct-drive asymmetries can be smoothed by the inward supersonic propagation of electron thermal conduction, from which the critical surface is kept hundreds of microns away from the capsule. In this Letter, we focus on the intrinsic low-mode direct-drive asymmetries caused by the six limited incident directions. A three-dimensional (3D) ray-tracing package is used to calculate the energy deposition and evaluate the asymmetries, supposing that the laser intensity ($\sim 3.4 \times 10^{15}$ W/cm$^2$) of each cluster is uniform. Figure 3(a) shows the distribution of absorbed laser intensities along the polar angle $\theta$ and the azimuthal angle $\phi$ obtained at a typical time $t = 12.0$ ns using about one million laser rays, and the peak-to-valley ratio is 1.27. Spherical harmonics expansion indicates that the main modes are $Y_{4, \pm 4}$ and $Y_{4, 0}$ with amplitudes of $Y_{4, \pm 4}/Y_{0, 0} = -2.6\%$ and $Y_{4, 0}/Y_{0, 0} = -4.2\%$, respectively. Strictly speaking, accurate evaluation of the intrinsic low-mode drive asymmetries needs 3D simulations which are computationally expensive. Instead, we perform two-dimensional (2D) implosion dynamics simulations with the $Y_{6,0}$ mode to approximate the 3D behavior, and the equivalent amplitude matching the peak-to-valley ratio of 1.27 is $Y_{6,0}/Y_{0,0} \approx -4.5\%$. Figure 3(b) plots the corresponding 2D density contour at stagnation. The capsule seems spherical, and the peak-to-valley amplitude at the fuel/hot-spot interface is $0.9 \mu$m, only $2.6\%$ of the hot spot radius. The average hot spot areal density and ion temperature are close to the 1D results, and the yield over clean (the ratio of the 2D neutron yield to the 1D yield) is almost 1.0. This means that the deformation of the hot spot has limited effects on the ignition. Therefore, the primary investigation indicates that the asymmetry of the direct drive in the hybrid-drive scheme is tolerable. In addition, an x-ray drive asymmetry caused by the four additional direct laser channel holes is expected to be similar to the conventional indirect drive [22].

**FIG. 3:** (Color online) 2D drive asymmetry of direct drive in the hybrid-drive target. (a) Distribution of the absorbed laser intensity normalized to the intensity of direct-drive laser, where $\theta$ is the polar angle and $\phi$ is the azimuthal angle; (b) density contour at stagnation time for direct-drive asymmetry with $Y_{6,0}/Y_{0,0} = -4.5\%$, where the black curve is the ablator/fuel interface.
The hybrid-drive ignition features lower growth of hydrodynamic instabilities. To demonstrate this, we compare the hybrid-drive ignition target with an indirect-drive PT similar to that presented in Ref. [5]. The PT target has an outer radius of $1110 \mu m$ with a $160 \mu m$ CH ablator and $80 \mu m$ solid DT fuel. The profile of radiation temperature for the PT is similar to that of the hybrid-drive target, with the levels of the first three steps equal to those of the hybrid-drive target and the peak temperature of 300 eV. The laser energy requirement is about 1.35 MJ, equivalent to that of our hybrid-drive target. 1D simulations indicate that the implosion velocity of the PT is about $3.8 \times 10^7$ cm/s, and the thermonuclear energy yield is 16 MJ. Then we perform a series of 2D single-mode simulations with the mode number $L$ ranging from 4 to 40. In order to save computation time, the simulations are done on wedges with angles $\theta \in [\pi/2 - \pi/L, \pi/2 + \pi/L]$, and 50 meshes are used in the angular direction.

First, perturbation growth to the ablator/fuel interface is reduced in the hybrid-drive target as compared with that in the PT, as shown in Fig. 4(a). During the acceleration stage of the capsule implosion, i.e. $t \in [11.5, 13.2]$ ns, the DAF structure reduces the Atwood number at the RAF to an average of 0.63. The reduced Atwood number decreases the perturbation growth, since the RTI growth is approximated by the modified Lindl formula $\gamma = \sqrt{A_t kg/(1 + A_t k L_m) - \beta k V_a}$, where $A_t$, $k$, $g$, $L_m$, $V_a$ and $\beta$ are the Atwood number, wave number, acceleration, minimum density gradient scale length, ablation velocity and a constant, respectively.

Second, perturbation growth to the fuel/hot-spot interface is significantly reduced in the hybrid-drive target as compared with that in the PT, as shown in Fig. 4(b). During the deceleration stage of the PT, a merged shock reflects twice (or even more) off the fuel/hot-spot interface leading to an early reverse of the pressure gradient (i.e. $\nabla p \cdot \nabla \rho < 0$) and causing severe growth of RTI. However, in the hybrid-drive target, the collision of the ES with the rebounded MS delays the reverse of the pressure gradient, and a higher hot spot temperature also enhances the stabilization of deceleration phase RTI. By comparison, the growth of the $L = 16$ mode which has maximum growth, is reduced by an order of magnitude in the hybrid-drive target. Figures 4(c) and 4(d) compare the density contours at stagnation times between the hybrid-drive target and the PT, for the $L = 16$ mode with an initial roughness of 350 Å. One can see that the bubble and spike structures at the fuel/hot-spot interface are much smaller in the hybrid-drive target than those in the PT. The lower level growth of hydrodynamic instabilities means that the hybrid-drive target is more robust than the indirect-drive PT, and this is essential for realizing ignition in ICF.
In summary, we have proposed a new hybrid-drive ignition scheme coupling both indirect drive and direct drive. Higher drive pressure (∼450 Mbar) and implosion velocity (∼4.3 × 10^7 cm/s) are obtained due to a high-density plateau between the RAF and EAF. The ignition process is quickened and the convergence ratio is much lower (∼25). It is found that 2D simulation results with intrinsic low-mode asymmetry of direct drive are close to the 1D results. More importantly, the hybrid drive scheme features lower growth of hydrodynamic instability, especially at the fuel/hot-spot interface where the perturbation is reduced almost by an order of magnitude when compared with the conventional indirect drive.

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[1] J. Nuckolls et al., Nature (London) 239, 139 (1972).
[2] J. D. Lindl, Inertial Confinement Fusion (Springer, New York, 1998).
[3] S. Atzeni and J. Meyer-ter-Vehn, The Physics of Inertial Fusion (Clarendon Press, Oxford, 2004).
[4] S. E. Bodner et al., Phys. Plasmas 5, 1901 (1998).
[5] J. D. Lindl et al., Phys. Plasmas 11, 339 (2004).
[6] E. Moses and C. R. Wuest, Fusion Sci. Technol. 47, 314 (2005).
[7] A. J. Mackinnon et al., Phys. Rev. Lett. 108, 215005 (2012).
[8] O. L. Landen et al., Plasma Phys. Control. Fusion 54, 124026 (2012).
[9] H. Nishimura et al., Nucl. Fusion 40, 547 (2000).
[10] R. Betti et al., Phys. Rev. Lett. 98, 155001 (2007).
[11] L. J. Perkins et al., Phys. Rev. Lett. 103, 045004 (2009).
[12] X. Ribeyre et al., Plasma Phys. Control. Fusion 51, 015013 (2009).
[13] A. J. Schmitt et al., Phys. Plasmas 17, 042701 (2010).
[14] S. Atzeni et al., Phys. Plasmas 19, 090702 (2012).
[15] S. W. Haan et al., Phys. Plasmas 18, 051001 (2011).
[16] D. H. Munro et al., Phys. Plasmas 8, 2245 (2001).
[17] W. B. Pei et al., Commun. Comput. Phys. 2, 255 (2007).
[18] R. M. More et al., Phys. Fluids 31, 3059 (1988).
[19] S. Depierreux et al., Plasma Phys. Control. Fusion 53, 124034 (2011).
[20] D. H. Froula et al., Plasma Phys. Control. Fusion 54, 124016 (2012).
[21] M. R. Terry, L. J. Perkins, and S. M. Sepke, Phys. Plasmas 19, 112705 (2012).
[22] When the 0.35-µm lasers irradiate on the hohlraum wall, the velocity of the critical surface is ∼15 µm/ns. Hence, if we insert the bottoms of the direct laser channel holes into the hohlraum with a depth of ∼150-200 µm, the overdense plasmas ablated from the hohlraum wall would have little impact on the four direct laser channels. This depth is only ∼5% of the hohlraum radius, thus the laser beam uniformity could be easily tuned similar to the conventional indirect drive. Furthermore, the indirect-drive asymmetry could be tuned by slightly adjusting the hohlraum and/or balanced by artificial direct-drive asymmetry. In detailed target designs, both 3D simulations and experiments are needed to tune the indirect-drive asymmetry.
[23] W. H. Ye, W. Y. Zhang, and X. T. He, Phys. Rev. E 65, 057401 (2002).