Shock Ignition: A New Approach to High Gain Inertial Confinement Fusion on the National Ignition Facility

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(Received 12 March 2009; published 23 July 2009)

Shock ignition, an alternative concept for igniting thermonuclear fuel, is explored as a new approach to high gain, inertial confinement fusion targets for the National Ignition Facility (NIF). Results indicate thermonuclear yields of ~120–250 MJ may be possible with laser drive energies of 1–1.6 MJ, while gains of ~50 may still be achievable at only ~0.2 MJ drive energy. The scaling of NIF energy gain with laser energy is found to be $G \sim 126E$ (MJ)$^{0.510}$. This offers the potential for high-gain targets that may lead to smaller, more economic fusion power reactors and a cheaper fusion energy development path.

DOI: 10.1103/PhysRevLett.103.045004 PACS numbers: 52.57.−z, 28.52.Cx

In inertial confinement fusion (ICF), a driver—i.e., a laser, heavy-ion beam or pulse power—delivers an intense energy pulse to a target containing around a milligram of deuterium-tritium (DT) fusion fuel. The fuel is rapidly compressed to high densities and temperatures sufficient for thermonuclear fusion to commence. The goal of present ICF research is to obtain ignition and fusion energy gain from a DT target [1]. Complete burning of a 50:50 mix of DT fuel through the fusion reaction $^2\mathrm{H} + {}^3\mathrm{H} \rightarrow n + {}^4\mathrm{He} + 17.6$ MeV would release a specific energy of 3.38×10^{11} J/g. The fusion burn of ignited fuel is limited by hydrodynamic expansion but, under appropriate conditions, the fuel mass inertia can provide the confinement necessary to achieve energy gain. The gain of an ICF target is defined as the ratio of the fusion energy produced to the driver energy incident on the target and is a key parameter in determining economic viability of future inertial fusion energy power plants [2].

The National Ignition Facility (NIF) is preparing to demonstrate laser-driven ICF ignition and fusion energy gain in the laboratory for the first time [3]. In the initial phase, this will be performed in indirect drive—where laser energy is first converted to x-rays [1]—and with ignition initiated by fast compression (defined below). Extensive analyses and supporting experiments provide confidence that these conventional targets will achieve NIF ignition goals [4] but they are predicted to produce only modest gains and yields, viz. gains ~15 and fusion yields ~20 MJ at laser drive energies of ~1.3 MJ. In particular, it is not clear they will scale directly to fusion power applications [2]. Accordingly, in this Letter, we establish the physics performance of a class of advanced targets operating under "shock ignition" [5,6]—a new concept for igniting thermonuclear fuel [6]—for possible implementation on the National Ignition Facility following the achievement of conventional indirect-drive ignition. Shock ignition offers the promise for high-gain ICF targets at low laser drive energies that may lead to smaller, more economic fusion power reactors and a cheaper fusion energy development path. The purpose of this Letter is to explore the scaling of fusion yield and energy gain for candidate shock-ignited target designs.

A typical ICF laser target consists of a spherical shell of cryogenic solid DT fuel surrounded by an outer ablator of mass comparable to that of the fuel. Driver energy is rapidly coupled to the ablator—either directly in the form of symmetrical laser beams or indirectly from x rays stimulated by laser interaction in a hohlraum surrounding the capsule—and, as the heated ablator expands outwards, momentum conservation causes the remaining target to be imploded inward. At peak laser drive intensity, the capsule approaches uniform acceleration until spherical convergence effects and gas backpressure cause the fuel to stagnate at high density. Providing this cold dense fuel can be ignited from a central "hot spot" at ~10 keV containing only a few percent of the fuel mass then the fuel burn fraction f_{burn} depends on the balance between the thermonuclear reaction rate and hydrodynamic expansion. It is determined by the tamping effect of the compressed fuel's areal density at ignition, ρR(g/cm^2), where ρ is the mass density and R the radial thickness, and for DT fuel is approximately $f_{\mathrm{burn}}(\rho R) \sim \rho R/(\rho R + 6)$ [1]. The energy gain G—i.e., ratio of fusion yield to laser drive energy—then depends on the fuel burn fraction and capsule peak implosion velocity V as approximately $G \sim f_{\mathrm{burn}}(\rho R)/(V^{5/4} I^{1/4})$, where I is the laser intensity [7]. Note importantly that, providing central ignition occurs, gains increase for lower implosion velocities because a greater fuel mass can be assembled and burned for a given laser drive energy.

The principle of shock ignition is shown in Fig. 1(a). Here we illustrate the laser pulse shape for a conventional target under either direct or indirect drive (dotted curve) compared to that for a prospective shock ignition target (solid curve). In the conventional target, the standard laser driver pulse is required to assemble the fuel at high density

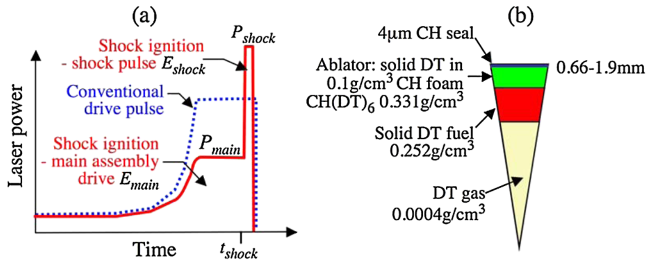

FIG. 1 (color online). (a) Schematic laser pulse shape for shock ignition (solid curve) relative to that for conventional indirect or direct drive (dotted curve), (b) spherical radial build of a candidate NIF shock-ignition target.

and impart a sufficiently high velocity ($V \sim 3.5$–4×10^7 cm/s) to the imploding shell so that its PdV work creates the central ignition hot spot on stagnation [1]; in this regard, conventional hot spot ignition might be referred to as occurring through "fast compression".

By contrast, in shock ignition [6], fuel assembly and ignition phases are decoupled as follows: The cryogenic shell is initially imploded at low velocity on a low adiabat using a laser drive of modest peak power and low total energy. The assembled fuel is then separately ignited from a central hot spot heated by a strong, spherically-convergent shock driven by the high intensity spike at the end of the laser pulse. The launch of the ignition shock is timed to reach the center as the main fuel is stagnating and starting to rebound. The majority of the laser energy is contained in the main portion of the pulse required for fuel compression, while only a modest energy fraction (~20–30%) is required for shock ignition. Crucially, because the implosion velocity is less than that required for conventional fast-compression ignition, considerably more fuel mass can be assembled for the same kinetic energy in the shell, offering significantly higher fusion gains/yields for the same laser energy or, equivalently, retaining acceptable gains at appreciably lower laser drive energies.

High gains and yields may also be attainable with "fast ignition," an alternative method of igniting ICF targets [8–10]. Fast ignition requires two distinct, time-synchronized laser systems whereas shock ignition would be accomplished with a single laser driver. Moreover, timing and spatial focusing requirements for shock ignition should be less demanding, while computer simulations depend only on conventional radiation hydrodynamics at standard laser intensities. However, shock ignition still requires a central, high temperature hot spot and thus conventional hydrodynamic symmetry and stability constraints will apply.

A candidate NIF shock ignition target is shown in Fig. 1(b) and is based on targets studied for conventional direct drive [11,12]. It consists of a spherical shell of frozen DT fuel surrounded by an ablator comprising DT wicked into low density CH foam. Shock-ignited targets could be fielded on NIF under the conventional direct-drive or polar-direct-drive campaigns [11,12]. Our present simulations indicate that it will not be possible to achieve shock ignition on NIF using indirect drive in a hohlraum because, while the laser system can supply the required fast rise of the shock pulse (see below), there is an appreciable time lag in conversion of laser energy to radiation temperature due to the hohlraum heat capacity. Thus the radiation drive rises too slowly to achieve required shock synching relative to the hydro bounce of the stagnating fuel.

Implosion and thermonuclear burn simulations for shock ignition in this Letter were conducted in 1D spherical geometry with the LASNEX radiation-hydrodynamics code [13]. The laser had a fixed focal spot at the initial target diameter; 3D laser ray tracing was employed accommodating reflection and refraction so that laser energy transport and absorption were treated correctly in the coronal plasma. The essence of the studies consisted of mating optimized laser pulse shapes to a set of target designs subject to maximum laser power and energy constraints. Figures 2(a) and 2(b) show resulting fusion energy yields and gain curve versus the total delivered laser energy (i.e., sum of main assembly and shock laser energy) for candidate shock ignition targets ranging from small to large obtained from the LASNEX simulations. For comparison, we show predicted performance of the NIF ignition baseline target (indirect drive) together with gain predictions of NIF targets operating under conventional direct drive (DD) and polar direct drive (PDD) [11,12].

The 1 MJ-drive shock-ignited case was obtained first by seeking a nominal 100 MJ fusion yield at a burn fraction of ~30%, an ablator mass set equal to the resulting fuel mass, and an initial capsule aspect ratio (defined as the ratio of the mean shell radius to the shell thickness) of 2.5. This is a markedly low initial aspect ratio for an ICF target, made possible by the need for only modest implosion velocities; such massive thick targets have good hydrodynamic stability during the implosion acceleration phase (see below). Specification of these three constraints then define the target radial build, i.e., the outer radii of the gas volume, the DT fuel and the ablator.

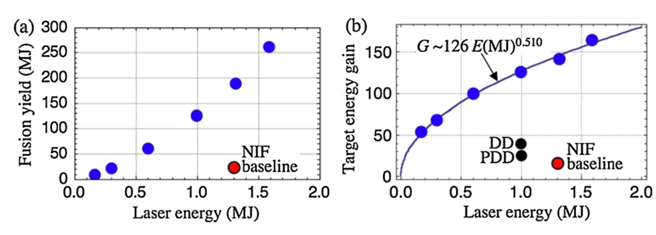

FIG. 2 (color online). (a) NIF shock-ignition fusion yield and (b) target energy gain, versus total NIF laser drive energy. Corresponding values for the NIF indirect-drive baseline ignition target are shown for comparison, together with gain predictions for NIF targets operating under conventional direct drive (DD) and polar direct drive (PDD).

The target designs were scaled up and down from this 1 MJ-drive case by setting the DT fuel mass, $m_{DT} \sim 4\pi r_{DT}^2 \Delta r_{DT} \rho_{DT}(0) \sim s^3$, to provide a desired nominal fusion yield $\sim m_{DT} f_{burn} \sim m_{DT} \rho R/(\rho R + 6)$, where s is the scale factor on capsule linear dimensions and $\rho_{DT}(0) = 0.252\ \mathrm{gm/cm^3}$ is the initial uncompressed density of frozen DT at 18 K. For fixed capsule dimensions, peak areal densities scale as $\rho R \sim E_{main}^{0.33}/\alpha^{0.55}$ [7], where E_{main} is the laser driver energy in the main assembly portion of the pulse and α is the fuel in-flight adiabat (i.e., ratio of in-flight fuel pressure to the irreducible Fermi-degenerate pressure), then initial estimates of main drive powers P_{main} scale approximately as $\sim s^1$ to maintain desired peak areal densities around $\sim 2.5\ \mathrm{g/cm^2}$ for desired fuel burn fraction of $\sim 30\%$. Further, given implosion times go approximately as $t_{main} \sim s^1$, the laser drive energy for the assembly phase could be initially estimated to scale as $E_{main} \sim P_{main} t_{main} \sim s^2$.

With these preliminary powers and energies, attainment time of the main drive power P_{main} and laser flat-top time for which this power is maintained was then tuned in each LASNEX simulation to obtain the desired areal density of $2.5\ \mathrm{g/cm^2}$ for the compressed fuel before application of a shock pulse. Finally, for each scaled target, a further set of 1D simulations was performed by scanning the three shock datum parameters—shock power P_{shock}, shock pulse energy E_{shock}, and start time t_{shock} of the shock pulse rise—to maximize target gain, subject to NIF laser performance constraints. Accordingly, for each fixed target design, several hundred LASNEX 1D implosion/burn simulations were necessary to optimize the laser pulse shape.

NIF, an intrinsic 4 MJ infrared (1.053 μm) laser, is capable of maximum delivered energies/powers of $\sim$1.8 MJ/500 TW, when frequency is tripled to 0.35 μm (UV) [14]. From Fig. 2, potential thermonuclear yields on NIF under shock-ignition range from 9.1 MJ for the smallest target driven at a total laser energy (main drive plus shock drive) of 0.17 MJ, to 261 MJ for the largest target driven at 1.59 MJ. The corresponding target gains (ratio of fusion yield to laser drive energy) range from 53 to 164, respectively. Fitting the gain curve in Fig. 2(b) provides a gain scaling for NIF shock ignition of the form $G \sim 126E^{0.510}$ where E (MJ) is the total laser drive energy. The upper design point at 261 MJ fusion yield is a fully fusion-energy-relevant target with potential application to an inertial fusion power plant. If qualified on NIF on a single-shot basis, such a target could be fielded on a future facility at, say, 10 Hz rep-rate and could then provide a steady-state fusion power of around $\sim$2500 MW ($\sim$1000 MW electrical).

Thus, shock ignition offers potential target gains in Fig. 2(b) around 5 to 10 times higher than predicted for conventionally driven targets. Of course, these findings must be validated with future detailed 2D and 3D studies of symmetry and stability, tasks beyond the scope of this initial Letter. However, three characteristic 1D parameters for the imploding shell can provide initial guidance to gauge prospective multidimensional behavior, namely: peak implosion velocity V, in-flight aspect ratio IFAR (maximum value of the ratio of mean shell radius to shell thickness during compression) and convergence ratio CR (ratio of initial outer radius of the capsule to final compressed radius of the hot spot at ignition). These are plotted in Fig. 3, together with corresponding values for the NIF indirect-drive baseline target. Hydrodynamic instabilities impose typical upper limits to the IFAR and CR of the order $\sim$35 and 30–40, respectively [1].

The low initial aspect ratios of 2.5, corresponding thick shells and low implosion velocities of these targets result in the high gains above because more mass has been assembled for a given laser drive energy; consequently, they are characterized by beneficially low peak velocities and IFARs. These targets should then exhibit good hydrodynamic stability during the acceleration phase such that Rayleigh-Taylor (RT) growth of outer surface perturbations is unlikely to penetrate the shell during implosion. Note, in particular, that the smallest target in Fig. 3 has a velocity and IFAR of only 3.3×10^7 cm/s and 29, respectively—markedly low for cryogenic ignition targets of such small size and drive energy.

The convergence ratios appear acceptable for the larger targets, but are approaching relatively high values greater than 40 for the smallest variants—a consequence of the shock driving the hot spot to a smaller radius that is out of pressure equilibrium with the main compressed fuel. High convergence ratios are a potential concern as small hot spots will be more susceptible to RT growth of perturbations on the inner fuel surface during late time deceleration; the attendant mix of cold fuel into the hot spot may thus delay or even prevent the onset of ignition. Future 2D and 3D studies must assess these issues.

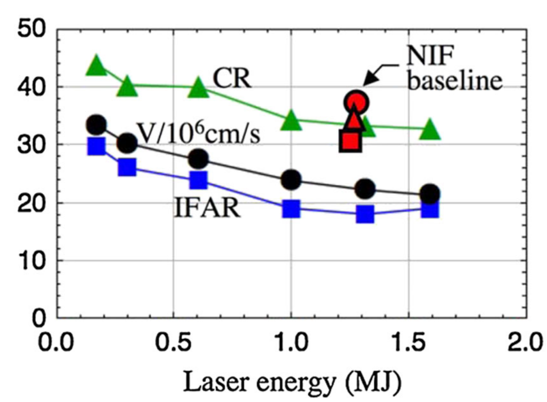

FIG. 3 (color online). Characteristic implosion parameters for NIF shock-ignited targets: In-flight aspect ratio (IFAR), convergence ratio (CR) and peak implosion velocity (V). Corresponding values for the NIF indirect-drive baseline ignition target are shown for comparison.

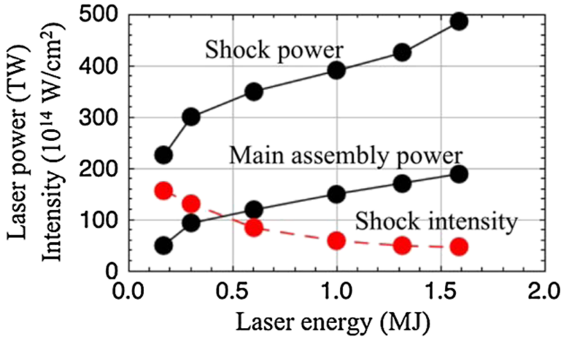

FIG. 4 (color online). Peak laser powers for the main assembly drive and the shock-ignition pulse (solid lines) together with peak laser intensity for the shock pulse (dashed line).

Figure 4 shows required peak UV (0.35 μm) laser powers in the assembly pulse and the shock pulse together with peak laser intensity at the time of application of the shock pulse. Laser absorption efficiencies for the assembly pulse and shock pulse ranged from 83.7% and 66.8%, respectively, for the largest target down to 83.4% and 55.6%, respectively, for the smallest target. We have performed initial validations of these pulse shapes with the NIF Laser Performance Operations Model [15] and results indicate that temporal contrasts should be achievable in the main amplifiers. The shock launch time parameter t_{shock} above determines the arrival of the shock-ignition pulse relative to the hydro bounce of the stagnating fuel. The ignition-shock launching window—that is, permissible spread of t_{shock}—ranges from ~0.5 ns for the larger targets to ~0.3 ns for the smaller targets. Thus, shock synching requirements indicate that required rise times for the NIF laser shock pulse should be around ~0.1 ns. Given present rise-time capabilities are ≥0.25 ns, such specifications will necessitate modification to NIF front-end pulse shape generators—fortunately, a low cost item.

Because of high laser intensities during shock launch (Fig. 4.), a potential concern for NIF shock ignition is the onset of laser-plasma instabilities (LPI) including stimulated Brillouin scattering (SBS), stimulated Raman scattering (SRS) and two-plasmon decay (TPD) [16]. SRS and TPD can result in generation of suprathermal electrons which, for conventional NIF direct and indirect targets, can be a serious source of preheat in the precompressed fuel as soon as the laser approaches its main drive power. However, for shock ignition it is important to note that high laser intensity is not applied until late time where the fuel is approaching stagnation. Thus, the now dense imploding shell is capable of absorbing SRS or TPD-generated hot electrons up to high energies, shielding the inner DT fuel from preheat [5,6]. Moreover, generation of such hot electrons may enhance shock drive performance due to enhanced ablation pressures, strong ablative stabilization of RT instabilities and symmetrization of the converging shock pressure front. Formal investigation of LPI sources is beyond the scope of this exploratory Letter but we have performed an initial parametric study for the 0.3 MJ, gain-68 target above where a fraction of the shock laser energy was taken as being converted to isotropic SRS electrons at a specified kinetic energy. Subsequent transport of this hot electron population with the LASNEX suprathermal electron package showed no appreciable degradation of target gain for up to 100% conversion into 50 keV electrons, or up to 45% conversion into 100 keV electrons.

In conclusion, we have established the preliminary physics basis and energy scaling of shock ignition for inertial confinement fusion on a practical laser facility. We have demonstrated the potential for up to an order-of-magnitude increase in attainable fusion yields and energy gains over those obtainable for conventionally driven targets that may lead to smaller, more economic fusion power reactors and a cheaper fusion energy development path. Further work will require full 2D and 3D validation of target implosion symmetry and stability together with detailed attention to the impact of laser-plasma interactions.

We are pleased to acknowledge informative discussions with J. Nuckolls. This work performed under auspices of U.S. DOE by Lawrence Livermore National Laboratory under Contract No. DE-AC52-07NA27344 and supported by LDRD-08-ERD-050.

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