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

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Shock ignition, an alternative concept for igniting thermonuclear fuel, is explored as an approach to high gain, inertial confinement fusion targets for the National Ignition Facility (NIF). Results indicate thermonuclear yields of ~120-250MJ may be possible with laser drive energies of 1-1.6MJ, while gains of ~50 may still be achievable at only ~0.2MJ drive energy. The scaling of NIF energy gain with laser energy is found to be $G \sim 126 E(\mathrm{MJ})^{0.510}$. 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.

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In inertial confinement fusion (ICF), a driver – i.e., a laser, heavy-ion beam or pulse power – delivers an intense pulse of energy 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 $^2H + {}^3H \rightarrow n + {}^4He + 17.6\mathrm{MeV}$ would release a specific energy of $3.38 \times 10^{11}$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 for the target 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 the 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 the laser energy is first converted to x-rays [1] – and with ignition via fast-compression (defined below). Extensive analyses and supporting experiments provide confidence that these conventional targets will achieve the NIF ignition goals [4] but they are predicted to produce only modest gains and yields, viz. gains ~15 and fusion yields ~20MJ at laser drive energies of ~1.3MJ. In particular, because of the inherent low efficiency of laser indirect-drive, it is not clear it will scale directly to fusion power applications [2]. Accordingly, in this paper, we establish the physics performance of a class of advanced NIF targets operating under "shock ignition" – an alternative concept for igniting thermonuclear fuel [5, 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. Thus, 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 cryogenic solid DT fuel in the form of a spherical shell surrounded by an outer ablator region of mass comparable to that of the fuel. Energy is rapidly coupled to the ablator from the driver – 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 "hotspot" at ~10-12keV containing only a few percent of the fuel mass then the overall 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 areal density, $\rho R$ (g/cm$^2$), of the compressed fuel at ignition, where $\rho$ is the mass density and R is the radial thickness, and for DT fuel is approximately $f_{burn}(\rho R) \sim \rho R/(\rho R+6)$ [1]. The energy gain G – i.e., the ratio of fusion yield to laser drive energy – then depends on the fuel burn fraction and capsule peak implosion velocity $V$ as approximately $G \sim f_{burn}(\rho R)/(V^{5/4}I^{1/4})$, 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.

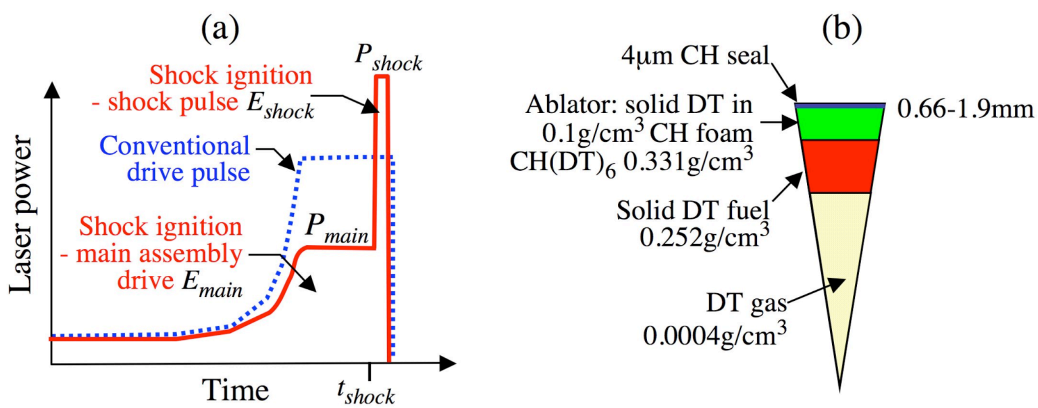


FIG. 1. (a) Schematic laser pulse shape for shock ignition (solid curve) relative to that for conventional indirect or direct drive (dotted curve), (b) spherical radial build of a candidate NIF shock ignition target (COLOR ONLINE)

The principle of shock ignition is shown in Fig. 1(a). Here we illustrate schematically the laser pulse shape required to drive a conventional NIF target under either direct or indirect drive (dotted curve) in comparison with 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 *and* impart a sufficiently high velocity ($V$~3.5-4x10$^7$cm/s) to the imploding shell so that its *PdV* work creates the central ignition hotspot on stagnation [1]; in this regard, conventional hotspot ignition might be referred to as occurring through “fast-compression”.

By contrast, in shock ignition [5, 6], the 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 hotspot heated by a strong, spherically-convergent shock driven by the high intensity spike at the end of the laser pulse. The launching of the ignition shock is timed to reach the center just 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 the 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.

We note that high gains and yields may also be attainable with "fast ignition", an alternative method of igniting ICF targets [8, 9, 10]. Fast ignition requires two physically 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 also be less demanding, while computer modeling depends only on conventional radiation-hydrodynamics at standard laser intensities so that simulation results should be more tractable. However, shock ignition still requires ignition from a central, high temperature hotspot and thus conventional hydrodynamic symmetry and stability constraints will apply.

A candidate target shock ignition target for NIF is shown in Fig. 1(b) and is based on targets studied for conventional direct drive [11,12]. It consists of a central region of low density DT gas surrounded by a spherical shell of frozen DT fuel and an outer 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 within a hohlraum because, while the NIF laser system can supply the required fast rise of the shock pulse (see below), there is an appreciable time lag in the conversion of laser energy to radiation temperature due to the heat capacity of the hohlraum. Thus the radiation drive rises too slowly to achieve the required shock synching relative to the hydro bounce of the stagnating fuel.

Implosion and thermonuclear burn simulations for NIF shock ignition in this paper were conducted in 1D spherical geometry with the LASNEX radiation-hydrodynamics code [13]. The laser had a fixed focal spot at the target diameter at $t$=0; 3D laser ray-tracing was employed accommodating reflection and refraction so that laser energy transport and inverse Bremsstrahlung absorption was treated correctly in the coronal plasma. The essence of the studies consisted of mating an optimized laser pulse shape to a set of target design subject to maximum power and energy constraints. Figs. 2(a) and (b) show the resulting fusion energy yields and gain curve as a function of the total delivered laser energy (i.e., the sum of the main assembly and shock laser energy) for candidate shock ignition targets ranging from small to large obtained from the 1D LASNEX simulations. For comparison, we show the 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].

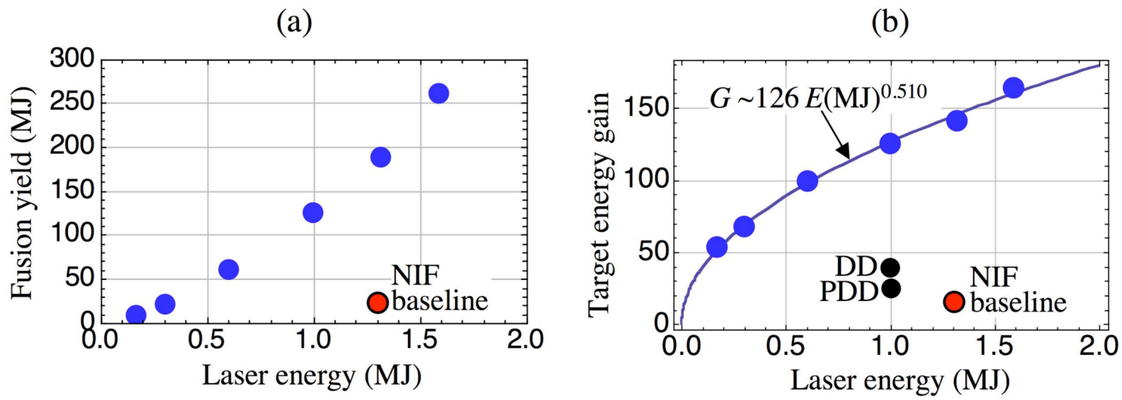


FIG 2. (a) NIF shock ignition fusion yield and (b) target energy gain, as a function of total NIF laser drive energy. Corresponding values for the NIF indirect drive baseline ignition target are shown for comparison, together with gain predictions for NIF targets operating under conventional direct drive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

The 1MJDrive shock ignited case was obtained first by seeking a nominal 100MJ 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 requirement for only modest implosion velocities; such massive thick targets have good hydrodynamic stability characteristics 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.

The target designs were scaled up and down from this 1MJ-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 $\rho_{DT}(0)$=0.252gm/cm$^3$ is the initial uncompressed density of frozen DT at 18K. 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 $\alpha$ is the in-flight adiabat of the fuel (i.e., ratio of in-flight fuel pressure to the irreducible Fermi-degenerate pressure), then initial estimates of the main drive powers $P_{main}$ scale approximately as $\sim s^1$ to maintain desired peak areal densities around $\sim 2.5$g/cm$^2$ for the desired fuel burn fraction of ~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, the time of attainment of the main drive power $P_{main}$ and the laser flat-top time for which this power is maintained was then tuned in each LASNEX simulation to obtain the desired areal density of 2.5g/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 rise of the shock pulse – to maximize target gain, subject to the NIF laser performance constraints. Accordingly, for each fixed target design, several hundred LASNEX 1D implosion/burn simulations were performed to optimize the laser drive pulse shape.

NIF, an intrinsic 4MJ infrared (1.053μm) laser, is capable of maximum delivered energies/powers of ~1.8MJ/500TW, when frequency tripled to 0.35μm (UV). From Fig.2, potential thermonuclear yields on NIF under shock ignition range from 9.1MJ for the smallest target driven at a total laser energy (main drive plus shock drive) of 0.17MJ, to 261MJ for the largest target driven at 1.59MJ. The corresponding target gains (ratio of fusion yield relative to laser drive energy) range from 53 to 164, respectively. Fitting to the gain curve in Fig. 2(b) provides a gain scaling for NIF shock ignition of the form $G \sim 126E^{0.510}$ where $E$ is the total laser drive energy in megajoules. The upper design point at 261MJ 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, 10Hz and could then yield a steady-state fusion power of around ~2500MW(th) thermal or ~1000MW(e) electrical.

Thus, shock-ignition offers potential target gains in Fig. 2(b) around five to ten times higher than those predicted for the 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 paper. However, three characteristic parameters for the imploding shell can be extracted from the 1D simulations and used as initial guidance to gauge prospective multidimensional behavior. These are: the peak implosion velocity *V*, the in-flight aspect ratio IFAR (maximum value of the ratio of the mean shell radius to shell thickness during compression) and the convergence ratio CR (ratio of the initial outer radius of the capsule to the final compressed radius of the hotspot 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 ~35 and 30-40, respectively [1].

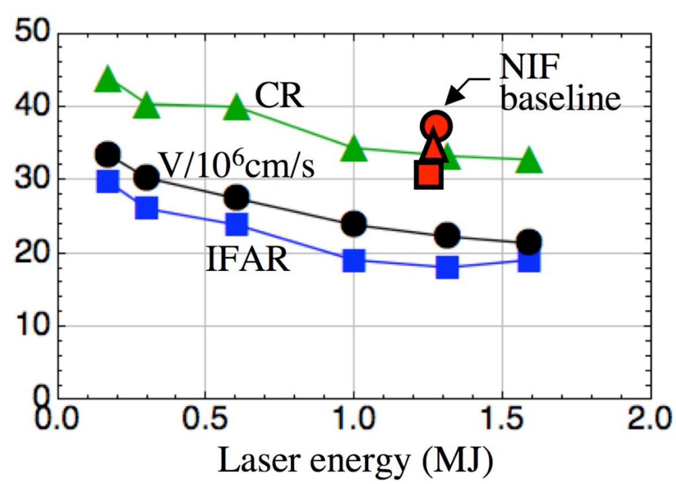


FIG 3. Characteristic implosion parameters for NIF shock ignited targets: In-flight aspect ratio (IFAR), convergence ratio (CR) and peak implosion velocity (V). Corresponding values for the NIF indirect-drive baseline ignition target are shown for comparison. (COLOR ONLINE)

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 the implosion. Note, in particular, that the smallest target in Fig. 3 has a velocity and IFAR of only $3.3 \times 10^7$ cm/s and 29, respectively, values that are 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 in excess of 40 for the smallest variants. This is a consequence of the converging shock driving the hotspot to smaller radii that is out of pressure equilibrium with the main cold compressed fuel. High convergence ratios are a potential concern as small hotspots will typically be more susceptible to RT growth of perturbations on the inner fuel surface during the late time deceleration phase with potential mix of cold fuel into the hotspot, thus delaying or even preventing the onset of ignition. Future 2D and 3D studies must assess these issues.

Fig. 4 shows the required peak UV (0.35μm) laser powers in the assembly pulse and the shock pulse resulting from the implosion scans together with the peak laser intensity at the time of application of the shock pulse. Laser absorption efficiencies for the assembly pulse/shock pulse ranged from 83.7%/66.8% for the largest target down to 83.4%/55.6% for the smallest target. We have performed an initial validation of these pulse shapes with the NIF Laser Performance Operations Model [15]. Results indicate that the temporal contrasts should be achievable in the main amplifiers and that the proposed pulses do not pose any equipment protection issues. 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, the permissible spread of $t_{shock}$ – ranges from ~0.5ns for the larger targets to ~0.3ns for the smaller targets. Thus, shock synching requirements indicate that required rise-times for the NIF laser shock pulse should be around ~0.1ns. Given present rise-time capabilities are ≥0.25ns, such specifications will necessitate modification to the NIF front-end pulse shape generators – fortunately, a low cost item.

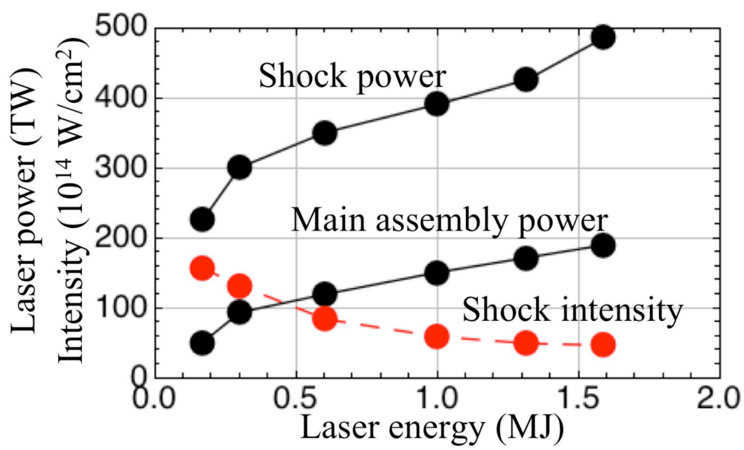


Fig 4. Peak laser powers for the main assembly drive and the shock ignition pulse (solid lines) together with peak laser intensity for the shock pulse (dashed line) (COLOR ONLINE)

Because of the high laser intensities during shock launch (Fig 4.), a potential concern for NIF shock ignition is the onset of parametric instabilities through laser-plasma interactions (LPI) including stimulated Brillouin scattering (SBS), stimulated Raman scattering (SRS) and two-plasmon decay (TPD) [16]. SRS and TPD can result in the 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 the 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. Moreover, the generation of such hot electrons should enhance shock drive performance due to enhanced ablation pressures, strong ablative stabilization of R-T instabilities and symmeterization of the converging shock pressure front. Formal investigation of LPI source terms is beyond the scope of this exploratory paper but we have performed an initial parametric study for the 0.3MJ, gain-68 target above in which a fraction of the shock laser energy was taken as being converted to isotropic SRS electrons at a given 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 50keV electrons, or up to 45% conversion into 100keV 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 – the National Ignition 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 in this field will require full 2D and 3D validation of target implosion symmetry and stability together with detailed attention to the impact of laser plasma interactions.

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