Fusion Energy Output Greater than the Kinetic Energy of an Imploding Shell at the National Ignition Facility

The MIT Faculty has made this article openly available. Please share how this access benefits you. Your story matters.

<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>As Published</td>
<td><a href="http://dx.doi.org/10.1103/PhysRevLett.120.245003">http://dx.doi.org/10.1103/PhysRevLett.120.245003</a></td>
</tr>
<tr>
<td>Publisher</td>
<td>American Physical Society</td>
</tr>
<tr>
<td>Version</td>
<td>Final published version</td>
</tr>
<tr>
<td>Accessed</td>
<td>Fri Mar 29 09:47:59 EDT 2019</td>
</tr>
<tr>
<td>Citable Link</td>
<td><a href="http://hdl.handle.net/1721.1/116411">http://hdl.handle.net/1721.1/116411</a></td>
</tr>
<tr>
<td>Terms of Use</td>
<td>Article is made available in accordance with the publisher’s policy and may be subject to US copyright law. Please refer to the publisher’s site for terms of use.</td>
</tr>
<tr>
<td>Detailed Terms</td>
<td></td>
</tr>
</tbody>
</table>
Fusion Energy Output Greater than the Kinetic Energy of an Imploping Shell at the National Ignition Facility


1Lawrence Livermore National Laboratory, Livermore, California 94550, USA
2General Atomics, San Diego, California 92186, USA
3Laboratory for Laser Energetics, University of Rochester, Rochester, New York 14623, USA
4Plasma Science and Fusion Center, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
5Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA
6Diamond Materials Gmbh, 79108 Freiburg, Germany

(Received 3 November 2017; revised manuscript received 4 May 2018; published 14 June 2018)

A series of cryogenic, layered deuterium-tritium (DT) implosions have produced, for the first time, fusion energy output twice the peak kinetic energy of the imploding shell. These experiments at the National Ignition Facility utilized high density carbon ablators with a three-shock laser pulse (1.5 MJ in 7.5 ns) to irradiate low gas-filled (0.3 mg/cc of helium) bare depleted uranium hohlraums, resulting in a peak hohlraum radiative temperature ~290 eV. The imploding shell, composed of the nonablated high density carbon and the DT cryogenic layer, is, thus, driven to velocity on the order of 380 km/s resulting in a peak kinetic energy of ~21 kJ, which once stagnated produced a total DT neutron yield of 1.9 × 10^{16} (shot N170827) corresponding to an output fusion energy of 54 kJ. Time dependent low mode asymmetries that limited further progress of implosions have now been controlled, leading to an increased compression of the hot spot. It resulted in hot spot areal density (\rho r < 0.3 g/cm^{2}) and stagnation pressure (\sim 360 Gbar) never before achieved in a laboratory experiment.

DOI: 10.1103/PhysRevLett.120.245003

The potential of nuclear fusion as an efficient source of energy was identified decades ago [1]. However, harnessing fusion for energy production has proven to be a difficult task. Throughout the world, billions of dollars are invested in experimental facilities and programs with the goal of demonstrating ignition—the point at which the amount of energy produced via fusion reactions is equal to or greater than the energy supplied to initiate the process [2]. At Lawrence Livermore National Laboratory, the indirect drive approach for inertial confinement fusion (ICF) is pursued at the National Ignition Facility (NIF) [3]. Most ICF work on the NIF is based on the hot spot ignition concept, where the kinetic energy of an imploding shell is converted, upon stagnation, to internal energy in a central hot spot. Fusion is initiated in the hot spot, and a thermonuclear burn front propagates radially outward into the main fuel producing high gain if the main fuel is of sufficiently high areal density. Ignition is only achieved when self-heating of the hot spot occurs: 3.5 MeV \alpha particles produced by the deuterium-tritium (DT) fusion reactions transfer their energy to the central hot spot to compensate for bremsstrahlung, conduction, and any other energy losses. The theoretical fusion yield can be in the megajoule range, exceeding by a factor of 1000 the kinetic energy supplied to the deuterium-tritium fuel by the implosion alone. While megajoule fusion yields are the goal of the ICF program, reaching that stage requires achieving distinct steps in target gain and yield, each representative of the understanding and resolution of key issues.

The high foot design, in reducing the implosion vulnerability to hydrodynamic instabilities plaguing low adiabat implosions, achieved a net fuel gain (as defined in Ref. [4]) in a hot spot dominated by alpha heating [5]. Nevertheless, the high foot implosions plateaued near 26 kJ of fusion yield, hot spot areal density < 0.2 g/cm^{2} and 250 Gbar of stagnation pressure. Detailed analyses have shown that symmetry swings were, in part, responsible for the implosion degradation [6] and the high apparent ion temperature measured [7,5].

The high density carbon (HDC) experiments we report on, by controlling low mode asymmetry through the laser history, achieved, for the first time, a fusion yield (54 kJ)
twice the kinetic energy of the imploding shell \( E_K \sim 21 \text{ kJ} \pm 5 \text{ kJ} \)

\[
E_K = \frac{1}{2} (M_{\text{HDC}} + M_{\text{DT}}) V_{\text{imp}}^2.
\]  

(1)

Where the mass of the DT cryogenic layer \( M_{\text{DT}} \) is 0.13 mg, the mass of the nonablated HDC \( M_{\text{HDC}} \) is 0.13 mg \pm 0.03, and the maximum implosion velocity \( V_{\text{imp}} \) is 380 km/cm \pm 30.

At a similar adiabat to the high foot campaign, the HDC approach of minimizing low mode asymmetry of the x-ray drive throughout the implosion history [8,9] led to a hot spot \( \rho r \sim 0.3 \text{ g/cm}^2 \), high enough to stop most \((\sim 85\%)\) of the \( \alpha \) particles. The hot spot areal density is now high enough (see Fig. 4) to sustain self heating once the confinement time is increased. The energy deposited by the \( \alpha \) particle in the hot spot is now \( \sim 10 \text{ kJ} \), more than twice the \( \alpha \) deposited energy of any previous experiment [5]. Furthermore, the stagnation pressure of the hot spot \( (\sim 360 \text{ Gbar}) \) is now higher than the pressure of the solar core [10].

Consequently, the conditions achieved in the hot spot now enable access to a range of nuclear and astrophysical regimes. The density, temperature, and pressure of the hot spot are the closest on earth to conditions in the sun [11,12], and the neutron density \((> 10^{23} \text{ neutron/cc})\) is now relevant for nucleosynthesis studies (such as the \( s \) process), which have traditionally been in need of an intense, laboratory-based neutron source [13,14].

To reach these hot spot conditions, the shell has to implode nearly spherically at all times [15]. The HDC shell sits at the center of a high-Z cylinder (“hohlraum”) irradiated by the 192 NIF laser beams, the symmetry of the x-ray radiation bath resulting from the interaction of the laser beams with the hohlraum walls dictates the symmetry of the imploding shell. The use of HDC ablators [16–18] has enabled us to lower x-ray drive asymmetries. Thin (70 \( \mu \text{m} \)) HDC ablators permit the usage of shorter laser pulses (< 9 ns), facilitating symmetry control as the hohlraum fills over time with expanding high-Z plasma from the hohlraum wall (bare depleted uranium in this Letter).

The implosion symmetry is controlled throughout the laser drive history by adjusting the relative power balance between the inner and outer laser cones. Following the methodology described in [8] using a 5.75 m diameter hohlraum and a 844 \( \mu \text{m} \) inner radius (scale 5.75) HDC shell, the implosion symmetry was measured and optimized at the larger 6.2 scale (Fig. 1). Figure 2 provides an overall quantitative view of symmetry measurements obtained at different times and convergences using multiple experimental platforms [two axis keyhole [19], 2D radiograph of the in-flight compressed shell [20], low convergence gas-filled capsule (“Symcap”) [21], and high convergence cryogenic DT layer [22]]. At all times along the shell trajectory, symmetry is controlled to better than \( \pm 10 \mu \text{m} \); the hot spot at bang time is within 6 \( \mu \text{m} \) of round.

Following this series of symmetry experiments, two cryogenic DT layered experiments (shots N170601 and N170827) were carried out to test fusion performance at high convergence. The hohlraum was driven to \( \sim 290 \text{ eV} \) radiation temperature by 1.5 and 1.7 MJ of laser energy at 450 TW peak power [Fig. 1(c)]. Figure 3 shows equatorial and polar images of the measured primary neutron emission.
(12–15 MeV) as well as the reconstructed neutron production volume at bang time [23] for N170601 (N170827 has a similar hot spot shape and volume). The neutron volume is slightly ellipsoidal, with a measured $P_2$ of $-6 \pm 2 \, \mu m$, (as fit with the second Legendre moment, $P_2$).

Table I summarizes the results of these two shots (N170601 and N170827) and, for comparison, one of the best performers of the high foot campaign (shot N140304) [24]. The high foot campaign is a high adiabat campaign based on a Plastic (CH) ablator, that reached the $\alpha$ heating regime by reducing the impact of hydrodynamic instabilities on the hot spot compression [5,25]. Neutron yield, down scatter ratio (DSR) and DT ion temperature shown in Table I are directly measured by neutron time of flight (NTOF) detectors [26]. Quantities such as hot spot $\rho r$, hot spot energy, stagnation pressure and $\alpha$ deposited energy are inferred from experimental observables using a “hot spot” model described in [27].

The total neutron yield is derived from the measured primary neutron yield and DSR using the relation

$$Y = \langle \sigma V \rangle \tau V_{hs} N_D N_T,$$

(2)

where $\langle \sigma V \rangle$ is the equimolar DT reactivity, which is a function of the ion temperature. $V_{hs}$ is the volume of neutron emission, which is calculated using the equatorial and polar neutron images, and $\tau$ is the neutron burn width measured by the gamma reaction history detector [29]. The hot spot stagnation pressure is inferred from the hot spot density and ion temperature measured by the NTOF detectors using the relation $P_{stag} = [(Z + 1)/\bar{A} m_p] \rho T_{ion}$, where $Z = 1$ for DT, $\bar{A} = 2.5$ is the average atomic mass number. This leads to the determination of the hot spot energy using the relation $E_{hs} = 3/2 P_{stag} V_{hs}$.

To infer the energy deposited by $\alpha$ particles, the fraction of $\alpha$ energy deposited $f_\alpha$, assuming a spherical hot spot, is first calculated. It is a function of the hot spot $\rho r$ and ion temperature [30]

$$f_\alpha = 1 - \frac{1}{4((\rho r)_{hs}/\rho \lambda_{t})) + 1/160((\rho r)_{hs}/\rho \lambda_{t})^3},$$

(3)

where the $\alpha$ particle stopping range is

$$\rho \lambda_{t} = \frac{0.025T_e^{5/4}}{1 + 0.0082T_e^{5/4}},$$

(4)

where $T_e$ is the electron temperature, assuming $T_e = T_i$, in base units of centimeters, grams, and kiloelectronvolts.

The energy partition in a DT fusion event is 80% to a 14.1 MeV neutron and 20% to a 3.5 MeV $\alpha$ particle. Therefore, the energy deposited by an $\alpha$ particle in the hot spot can be derived from the fraction of $\alpha$ deposited energy and the total fusion yield.

<table>
<thead>
<tr>
<th></th>
<th>N170601 data</th>
<th>N170827 data</th>
<th>N140304 data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total neutron yield</td>
<td>$1.7e16 \pm 2.4e14$</td>
<td>$1.9e16 \pm 3.1e14$</td>
<td>$9.3e15 \pm 1.7e14$</td>
</tr>
<tr>
<td>Fusion yield (kJ)</td>
<td>48</td>
<td>53</td>
<td>26</td>
</tr>
<tr>
<td>DT Tion (keV)</td>
<td>$4.5 \pm 0.12$</td>
<td>$4.5 \pm 0.15$</td>
<td>$5.5 \pm 0.12$</td>
</tr>
<tr>
<td>DSR (%)</td>
<td>3.27 $\pm 0.2$</td>
<td>3.24 $\pm 0.2$</td>
<td>3.4 $\pm 0.2$</td>
</tr>
<tr>
<td>Velocity (km/s)</td>
<td>381</td>
<td>395</td>
<td>380</td>
</tr>
<tr>
<td>Pstag (Gbar)</td>
<td>320 $\pm 40$</td>
<td>360 $\pm 45$</td>
<td>222 $\pm 15$</td>
</tr>
<tr>
<td>Nuclear burn width (ps)</td>
<td>160 $\pm 30$</td>
<td>154 $\pm 30$</td>
<td>163 $\pm 30$</td>
</tr>
<tr>
<td>Hot spot $\rho r$ (g/cm$^2$)</td>
<td>0.26 $\pm 0.032$</td>
<td>0.30 $\pm 0.034$</td>
<td>0.13 $\pm 0.021$</td>
</tr>
<tr>
<td>$\alpha$ deposited fraction $f_\alpha$</td>
<td>0.81</td>
<td>0.87</td>
<td>0.58</td>
</tr>
<tr>
<td>Hot spot energy (kJ)</td>
<td>4.3 $\pm 1.17$</td>
<td>4.7 $\pm 1.7$</td>
<td>3.6 $\pm 1.03$</td>
</tr>
<tr>
<td>Shell max kinetic energy (kJ)</td>
<td>22 $\pm 5$</td>
<td>21 $\pm 5$</td>
<td>25 $\pm 7$</td>
</tr>
<tr>
<td>Alpha deposited energy (kJ)</td>
<td>8 $\pm 1.36$</td>
<td>9.3 $\pm 1.6$</td>
<td>3.3 $\pm 0.58$</td>
</tr>
</tbody>
</table>

TABLE I. Summary of experimental data from cryogenic DT layer implosions at 6.20 scale (N170601, N170827) and for a high performance high foot experiment (N140304).
A key achievement of the high foot campaign in 2014 was to achieve a fuel gain of unity: more fusion energy was produced in the hot spot than energy was delivered to the DT fuel. This demonstration required a detailed estimate of the energy balance during stagnation. Here, we have improved the implosion enough to report a net gain of two between the fusion energy produced and the maximum kinetic energy of the imploding shell, including both the DT fuel and the remaining ablator, at peak implosion velocity when the hohlraum does not accelerate the capsule anymore. This can be thought of as the fusion gain of an isolated system (the free-falling imploding shell) and reporting the gain does not have to rely on internal mechanics. The shell velocity is measured using the 2DconA platform (N170419 shot), the position of the shell is recorded as a function of time on an x-ray gated imager. The fraction of nonablated carbon at peak velocity is calculated by HYDRA and consistent with in-flight x-ray radiography. For N170827, the fusion energy (54 kJ) is more than twice the maximum kinetic energy of the imploding shell (21 kJ, see before for details), while for one of the high performing implosions, N140304, the output energy is about equal to the maximum kinetic energy of the imploding shell (see Table I).

As a result of reducing the symmetry swing in the x-ray drive, the improved compression increased the hot spot \( \rho r \) by more than 50% and stagnation pressure by more than 60%. In addition to twice the fusion yield, the energy deposited by the alpha particle in the hot spot increased from \( \sim 3.4 \text{ kJ} \) to \( \sim 9.7 \text{ kJ} \). For N170827, with a hot spot \( \rho r \) of 0.3 g/cm\(^2\) and a \( T_{\text{ion}} \) of 4.7 keV, \( f_a \sim 0.87 \) which implies that the bulk of the alpha particles are stopped in the hot spot.

A static, isobaric hot spot model [4] can be used to estimate the energy balance in the hot spot at peak compression. The self heating condition for an isobaric hot spot can be written

\[
\langle \alpha v \rangle f_a - A_{\alpha 0} T^{1/2}_{\text{ion}} (\rho r)^2 - \frac{3 c_e A_e T_{\text{ion}}^{1/2} \ln \Lambda}{\ln \Lambda} > 0,
\]

where \( \langle \alpha v \rangle \) is the DT reactivity, \( f_a \) is the fraction of alpha energy deposited, \( A_{\alpha 0} = 8.1 \times 10^{40} \text{ erg}/\text{g}^2 \), \( A_e = 3.5 \times 10^{23} \text{ erg g}^{-2} \text{ cm}^3 \text{ s}^{-1} \), \( T \) is the ion temperature, \( \rho r \) is the areal density in g/cm\(^2\), \( \ln \Lambda \) is equal to 3.7 in our hot spot conditions, \( c_e = 1 \), \( A_e = 9.5 \times 10^{19} \text{ erg keV}^{-1/2} \text{ cm}^{-2} \text{ s}^{-1} \). The first term in equation (5) is the deposited fusion power; the second term is the bremsstrahlung emission power density, and the thermal conduction power density is the third term.

At the conditions achieved on N170827, bremsstrahlung and electron conduction losses are still dominating the alpha deposited energy. We can estimate from N170827 conditions (at constant \( \rho r \) and adiabat) what it would take to reach equilibrium and the onset of the burning plasma regime. At constant \( \rho r \), the alpha deposited energy scales like \( \langle \alpha v \rangle \), which roughly scales like \( T_{\text{ion}}^4 \) [4], thus, the equilibrium is reached for an ion temperature of 4.8 keV, corresponding to a neutron yield of \( 2.4 \times 10^{16} \). The two solid lines shown in Fig. 4 are the yield extrapolation at constant \( \rho r \) for the best high foot and HDC shots based on the DT cross section dependence with temperature. The black diamond shows the point on the yield/ion temperature curve where the alpha deposited energy equals bremsstrahlung and conduction losses. Solid curves are a yield extrapolation with temperature using a constant \( \rho r \) and adiabat.

Figure 4 shows most of the cryogenic DT layered implosions carried out on the NIF since the beginning of the National Ignition Campaign [31]. The performance of HDC implosions was improved, first, by increasing the implosion velocity and, second, by increasing the target scale and shortening the time between the end of the laser pulse and the time of peak neutron emission. At scale 5.75, increasing the implosion velocity resulted in higher ion temperature and, thus, implosion performance with a velocity scaling consistent with scaling of previous high foot experiments [32]. At scale 5.75, 20 kJ of fusion yield was achieved using “only” 1.1 MJ of laser light (versus 1.7 MJ of laser light for a similar high foot implosion). To increase the performance of the HDC design further, the target size was scaled up by 8% from 5.75 to 6.20.
In addition to the power and pulse duration increase, the capsule drive was modified to reduce the time between the end of the laser and the peak neutron emission (“coast time”) [Fig. 1(c)]. A reduced coast time was demonstrated to increase stagnation pressure and yield for high foot implosions [33]. These modifications led to record fusion yields and hot spots $pr$ shown in Fig. 4 (red dots).

Experimental yield data are 30%–50% of axisymmetric (2D) HYDRA [34] radiation hydrodynamic simulations including $\alpha$ deposition. The main source of yield degradation for these implosions is believed to be induced by the fill tube. The fill tube can inject, mix, and create local $pr$ distortion of the shell. To bring simulations in closer agreement with experimental data, mix (i.e., carbon with 0.33% atomic fraction of tungsten) can be uniformly injected in a capsule-only calculation. Typically, 50–100 ng of injected material is needed to reproduce the measured implosion performances.

The HDC campaign has produced, for the first time, a fusion energy (54 kJ) twice the peak kinetic energy of the imploding shell (21 kJ). The implosion performance was improved from previous campaigns on the NIF by lowering $x$-ray drive asymmetry on the imploding shell. A hot spot areal density of 0.3 g/cm$^2$ was achieved, high enough to stop $\sim$85% of the $\alpha$ particles. The conditions in the hot spot with stagnation pressures of $\sim$360 Gbar, greater than the solar core pressure, is attracting a new community of scientists studying nucleosynthesis on the NIF. Future shots in the campaign will aim at increasing the hot spot ion temperature by increasing the implosion velocity and further improving the shell areal density to improve the hot spot confinement.

We thank J. Edwards, N. Abbas, W. Hsing, O.L. Landen, and J. Kilkenney for enabling this research and fruitful discussions. This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract No. DE-AC52-07NA27344. Work was also supported by the Laboratory Directed Research and Development Grant No. 11-ERD-050 and the National Laboratory User Facility and by General Atomics under Contract No. DE-NA0001808.

[14] The neutron fluxes reported in the Letter would allow the measurement of neutron capture by unstable nucleides. Tm-171, due to its importance as a branching point nucleus in the slow process ($s$ process), has been proposed for an experiment on the NIF. Its relatively short half-life renders measurements at accelerator-based neutron irradiation facilities (such as LANSCE) extremely challenging. Adding 10 ng of TM-171 in the HDC ablator would produce $\sim 10^{12}$ atoms of Tm172 that could be captured by the NIF Solid Radiochemistry Diagnostics.


