Cryogenic thermonuclear fuel implosions on the National Ignition Facility

S. H. Glenzer,1,b) D. A. Callahan,1 A. J. MacKinnon,1 J. L. Kline,1 G. Grim,2 E. T. Alger,1 R. L. Berger,1 L. A. Bernstein,1 R. Betti,1 D. L. Bleuel,1 T. R. Boehly,3 D. K. Bradley,1 S. C. Burkhart,1 R. Burr,1 J. A. Caggiano,1 C. Castro,1 D. T. Casey,4 C. Choate,1 D. S. Clark,1 P. Celliers,1 C. J. Cerjan,1 G. W. Collins,1 E. L. Dewald,1 P. DiNicola,1 J. M. DiNicola,1 L. Divol,1 S. Dixit,1 T. Döppner,1 R. Dylla-Spears,1 E. Dzenitis,1 M. Eckart,1 G. Erbert,1 D. Farley,1 J. Fair,1 D. Fittinghoff,2 M. Frank,1 L. J. A. Frenje,4 S. Friedrich,1 D. T. Casey,4 M. Gatu Johnson,4 C. Gibson,1 E. Giraldez,1 V. Glebov,3 S. Glenn,1 N. Guler,2 S. W. Haan,1 B. J. Haid,1 B. A. Hammel,1 A. V. Hamza,1 C. A. Haynam,1 G. M. Heestand,1 M. Hermann,1 H. W. Hermann,1 D. G. Hicks,1 D. E. Hinkel,1 J. P. Holder,1 D. M. Holunda,1 J. B. Horner,1 W. W. Hsing,1 H. Huang,1 N. Izumi,1 M. Jackson,1 O. S. Jones,1 D. H. Kalantar,1 R. Kauffman,1 J. D. Kilkenney,1 R. K. Kirkwood,1 J. Klingmann,2 T. Kohut,1 J. P. Knauer,3 J. A. Koch,1 B. Kozioziemki,1 G. A. Kyrala,2 A. L. Kritcher,1 J. Kroll,1 K. La Fortune,1 L. Lagan,1 O. L. Landen,1 D. W. Larson,2 D. LaTray,1 R. J. Leeper,6 S. Le Pape,1 J. D. Lindl,1 R. Lowe-Webb,1 T. Ma,1 J. McNaney,1 A. G. MacPhee,1 T. N. Malsbury,1 E. Mapoles,1 C. D. Marshall,1 N. B. Meezan,1 F. Merrill,2 P. Michel,1 J. D. Moody,1 A. S. Moore,7 M. Moran,1 K. A. Moreno,1 D. H. Munro,1 B. R. Nathan,1 A. Nikroo,5 R. E. Olson,6 C. D. Orth,1 A. E. Pak,1 P. K. Patel,1 T. Parham,1 R. Petrasco,4 J. E. Ralph,1 H. Rinderknecht,4 S. P. Regan,3 H. F. Robey,1 J. S. Ross,1 M. D. Rosen,1 R. Sacks,1 J. D. Salmonson,1 R. Saunders,1 J. Sater,1 C. Sangster,3 M. B. Schneider,1 F. H. Seguin,4 M. J. Shaw,1 B. K. Spears,3 P. T. Springer,1 W. Stoeffli,1 L. J. Suter,1 C. A. Thomas,1 R. Tommasini,1 R. P. J. Town,1 C. Walters,1 S. V. Weber,1 P. J. Wegner,1 P. K. Whitman,1 K. Widmayer,1 C. C. Widmayer,1 C. H. Wilde,2 D. C. Wilson,2 B. Van Wonterghem,1 B. J. MacGowan,1 L. J. Atherton,1 M. J. Edwards,1 and E. I. Moses1

1Lawrence Livermore National Laboratory, Livermore, California 94550, USA
2Los Alamos National Laboratory, Los Alamos, New Mexico 87545, 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
5General Atomics, San Diego, California 92121, USA
6Sanda National Laboratory, Sandia, New Mexico 87185, USA
7Atomic Weapons Establishment, Aldermaston RG7, United Kingdom

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The first inertial confinement fusion implosion experiments with equimolar deuterium-tritium thermonuclear fuel have been performed on the National Ignition Facility. These experiments use 0.17 mg of fuel with the potential for ignition and significant fusion yield conditions. The thermonuclear fuel has been fielded as a cryogenic layer on the inside of a spherical plastic capsule that is mounted in the center of a cylindrical gold hohlraum. Heating the hohlraum with 192 laser beams for a total laser energy of 1.6 MJ produces a soft x-ray field with 300 eV temperature. The ablation pressure produced by the radiation field compresses the initially 2.2-mm diameter capsule to a spherical dense fuel shell that surrounds a central hot-spot plasma of 50 μm diameter. While an extensive set of x-ray and neutron diagnostics has been applied to characterize hot spot formation from the x-ray emission and 14.1 MeV deuterium-tritium primary fusion neutrons, thermonuclear fuel assembly is studied by measuring the down-scattered neutrons with energies in the range of 10 to 12 MeV. X-ray and neutron imaging of the compressed core and fuel indicate a fuel thickness of (14 ± 3) μm, which combined with magnetic recoil spectrometer measurements of the fuel areal density of (1 ± 0.09) g cm−2 result in fuel densities approaching 0.09 g cm−2. The fuel surrounds a hot-spot plasma with average ion temperatures of (3.5 ± 0.1) keV that is measured with neutron time of flight spectra. The hot-spot plasma produces a total fusion neutron yield of 1015 that is measured with the magnetic recoil spectrometer and nuclear activation diagnostics that indicate a 14.1 MeV yield of (7.5 ± 0.1) × 1014 which is 70% to 75% of the total fusion yield due to the high areal density. Gamma ray measurements provide the duration of nuclear activity of (170 ± 30) ps. These indirect-drive implosions result in the highest areal densities and neutron yields achieved on laser facilities to date. This achievement is the result of the first hohlraum and capsule tuning experiments where the stagnation pressures have been...
systematically increased by more than a factor of 10 by fielding low-entropy implosions through the control of radiation symmetry, small hot electron production, and proper shock timing. The stagnation pressure is above 100 Gbars resulting in high Lawson-type confinement parameters of $Pr \approx 10$ atm s. Comparisons with radiation-hydrodynamic simulations indicate that the pressure is within a factor of three required for reaching ignition and high yield. This will be the focus of future higher-velocity implosions that will employ additional optimizations of hohlraum, capsule and laser pulse shape conditions. © 2012 American Institute of Physics.

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I. INTRODUCTION

Inertial confinement fusion (ICF) experiments compress a shell capsule containing a deuterium-tritium ice layer in a high-velocity, low-entropy implosion to form a central hot spot plasma that is surrounded by the high-density nuclear fuel. When the hot spot reaches sufficiently high densities and temperatures from a combination of PdV work and alpha particle deposition, a nuclear burn wave is launched igniting the surrounding dense fuel, sustained by alpha deposition and electron conduction without an external energy source.1–4 This threshold behavior for ignition and burn is predicted in simulations5 when reaching stagnation pressures above 300 Gbars.

Current indirectly driven fusion capsule implosions are performed on the National Ignition Facility (NIF) to approach the required high-pressure conditions for ignition.6–8 In these experiments, the thermonuclear fuel is initially prepared cryogenically into a solid ice layer of hydrogen isotopes on the inside of a low-Z (plastic) ablator and fielded in the center of a radiation cavity called hohlraum. The implosion is driven by a spherical soft x-ray drive from a 300 eV hohlraum that is heated with up to 1.6 MJ of laser energy at peak laser power of 430 TW. The radiation field generates ablation pressures in excess of 100 Mbars resulting in a rocket-like acceleration and burn rate of order 100 ps and set the upper time limit on which most of the burn must occur. Burning approximately 1/3 of deuterium-tritium (DT) fuel will result in 6.5 × 10¹⁸ fusion neutrons with a total neutron yield of 15 MJ and a gain value of about 10.

Near peak compression when the implosion fuel has converted most of the kinetic energy to internal energy, temperatures of about 4 keV must be reached in the hot spot and the fuel must reach high areal densities of >1 g cm⁻². In these conditions, x-particle heating is expected to launch a self propagating burn wave that will heat the plasma to temperatures above 10 keV and overwhelm cooling by expansion, radiation, and electron conduction. The loss and expansion rates are of order 100 ps and set the upper time limit on which most of the burn must occur. Burning approximately 1/3 of deuterium-tritium (DT) fuel will result in 6.5 × 10¹⁸ fusion neutrons with a total neutron yield of 15 MJ and a gain value of about 10.

Several forms of a generalized Lawson-type criterion10–13 have been developed to assess progress towards ignition. For ICF, hot spot formation and thermonuclear fuel assembly can be characterized by the neutron yield from primary deuterium-tritium reactions in the central hot plasma, $D + T \rightarrow {}^{4}\text{He} (3.5 \text{ MeV}) + n(14.1 \text{ MeV})$, and the ratio of down scattered to primary neutrons, $dsr = N(10 - 12 \text{ MeV})/N(13 - 15 \text{ MeV})$, quantifying neutrons that have lost energy by scattering processes in the dense fuel plasma that surrounds the central hot plasma. These measured quantities are combined into an experimental ignition threshold factor ($I\text{TFx}$) for implosions without alpha particle heating.5,9,14 The simulations show that no self-heating implosions with a DT equivalent 14.1 MeV yield of $Y_{DT} = 3.2 \times 10^{15}$ and a down scattered ratio of 7% provide $I\text{TFx}$ values of 1 with a 50% probability for ignition when fielding the experiment with equimolar DT fuel.

The first layered implosion experiments with thermonuclear fuel15,16 have followed commissioning of the NIF (Refs. 17 and 18) and the demonstration of hohlraum symmetry19–21 with adequate soft x-ray drive.6,22 In addition, a suite of tuning experiments have been commissioned23–30 to measure and control31,32 four key capsule performance parameters: drive symmetry during the foot and the peak of the laser pulse, shock timing, peak implosion velocity, and hydrodynamic mix. Layered implosions have since then been routinely fielded to measure performance and to indicate progress towards our goal to field a fusion experiment with high probability for achieving ignition and burn.

The layered implosion experiments use equimolar mixtures of DT or diluted fuel with tritium, hydrogen, and deuterium (THD).9 The fuel is layered in 2.26 mm-diameter CH capsules in a (68 ± 1) μm thick layer; currently, more than 40% of the layered experiments have been performed with fuel ice layer characteristics that meet the specifications for ignition.33 Fielding these layers with adequate laser power balance, laser wavelengths, and laser pulse shaping18 have resulted in near symmetric compression to a sphere with a central hot-spot diameter of 50 μm and a fuel shell of about 80 μm. These indirect-drive implosions demonstrate the highest 14.1 MeV neutron yields of $Y_{DT} = (7.5 \pm 0.1) \times 10^{18}$ and areal densities of $pR = (1 \pm 0.09) \text{ g cm}^{-2}$ achieved to date in laser experiments.

The paper is organized as follows. Section II describes the hohlraum and capsule targets together with fuel layer capabilities on NIF. An example of a groove analysis for a cryogenic fuel layer used for shot selection is also provided. Section III describes the laser drive and soft x-ray production in the hohlraum that resulted in implosion velocities of 95% of the ignition value. Section IV presents the resulting capsule implosion symmetry and core shape that approximately meet ignition requirements. Improvements in areal density and entropy due to implementation of adequate shock timing are described in Sec. V. These values are within 30% of
the ignition-required value. Section VI describes nuclear performance data from cryogenic layered implosion experiments indicating accurate measurements of the experimental ignition threshold factor. This analysis shows that layered implosions approach the ignition regime after each set of successive tuning experiments. Section VII provides estimates of the averaged stagnation pressure from hot spot formation and nuclear fuel assembly data. A generalized Lawson-type confinement parameter is utilized indicating that a factor of three increase in pressure is needed to reach the ignition regime. Section VIII presents the conclusions and an outlook to future experiments that outline future improvements with the goal to reach the ignition regime.

II. INERTIAL CONFINEMENT FUSION TARGETS

Figure 1 shows a schematic of the hohlraum, capsule, and nuclear fuel ice layer employed in these experiments. The thermonuclear fuel is prepared cryogenically in a layer inside a 2.26 mm diameter plastic capsule, which is doped with Si or Ge. The dopant absorbs high energy x-rays from the laser-driven gold hohlraum and is used to tailor the density gradient at the ablator-ice interface. During the cryogenic layering process, the target is fully enclosed by a shroud to protect it from chamber thermal radiation as well as from gaseous impurities that condense on cold surfaces. Additional protection from ice condensates during layering and during the final exposure to the target chamber atmosphere is further provided by the laser entrance hole (LEH) thermally isolated secondary windows.

A smooth solid fuel layer is produced with the technique known as beta layering. With frozen fuel in the fill tube and liquid at the bottom of the fusion capsule, a small drop of the capsule temperature by 45 mK provides a seed for growing the capsule ice layer with the correct orientation. The seed is initially in an unstable fcc ice phase which converts to hcp crystals. Layering is started at a temperature of 100 mK below the triple point, for example $T_{\text{triple}} \approx 19.6$ K for DT, and slowly cooled to about 400 mK below the triple point over a period of 14 to 18 h during which the radioactive self heating from beta decay in the condensed fuel enables redistribution of the solid along the isothersms in the capsule.

The target is shot with a nominal temperature of $\Delta T = -1.5$ K or $\Delta T = -0.8$ K below the triple point. This temperature is reached a few seconds before the system shot by lowering the target temperature from the temperature at the end of the layering process over a period of a 30 s-long quench. The shroud opens close to the end of the quench and 8 s before the laser beams are fired; a small increase in temperature due to exposure to thermal radiation of about 400 mK is compensated for so that the final temperature is reached about 5 s before the shot.

At the cryogenic shot temperature, the scale-575 gold hohlraums are 9.43 mm long with a diameter of 5.75 mm and filled with helium gas at a pressure of 260 $\pm$ 2.5 Torr resulting in densities of 0.96 mg cm$^{-3}$. Earlier hohlraums for Ge-doped capsule implosions had slightly different dimensions with a smaller diameter of 5.44 mm and length of 10.01 mm. In addition, hohlraums with two different LEH diameters of 3.1 mm and 3.375 mm have been fielded. These modifications have been performed to study and improve implosion symmetry at high drive laser energy.

Figure 2 shows an ignition hohlraum target mounted on the cryogenic target positioner before being enclosed by a shroud. Also shown is the fuel distribution inside the capsule measured with 9 keV x-ray point projection radiography using a tungsten L-emission source. Characterization is routinely performed along three lines of sight with an axial view through the laser entrance holes and two orthogonal views, cf. Fig. 2(b). The latter are obtained in the equatorial plane through the starburst cut outs in the hohlraum cylinder walls that can be identified in Fig. 2(a). In addition, low magnification images are taken that provide an estimate of the total groove area by phase contrast enhanced imaging of groove defects. This powerful technique has been shown to detect small but deep grooves in the part of the layer that is not diagnosed with images at standard magnification, see comparison between Figs. 2(b) and 2(c).

For the DT layer shown in Fig. 2(c) only a small groove, i.e., ice defect, can be identified with a length of 86.0 $\mu$m, width of 15.0 $\mu$m, and depth of 2.4 $\mu$m. Estimates of the total effect of grooves on hot spot non-uniformities takes into account the sum over all defects of area $A$ and length $L$,

$$K = \sqrt{\frac{1}{V_{\text{hot}}} \sum_{i=1}^{n} A_i^2 L_i},$$

where we require $A \leq 250 \mu$m$^2$ to avoid a groove from breaking through the layer during the implosion. This analysis indicates that the layer used on shot N110914 is of ignition quality with a total groove area of $A = 114 \mu$m$^2$ and $K = 0.388 \mu$m.
From a total of 17 layered implosion experiments, seven shots were taken with ignition grade layers with $K < 0.7 \mu m$ and 10 layers for tuning experiments, $0.7 \mu m < K < 1.5 \mu m$. Table I provides a summary of the experimental conditions and results of the layered implosion shots. The effect of non-perfect layers on the neutron yield has been estimated with radiation-hydrodynamic simulations that provide an expectation on the reduction of the neutron yield. This yield factor, $Y_F$, includes the characterization data, i.e., the $K$ values and power spectral density value for the ice sphericity. The analysis shows for the seven ignition grade layers $Y_F \geq 0.95$ and $0.6 < Y_F < 0.95$ for the remaining experiments.

### III. LASER AND HOHLRAUM DRIVE

The layered capsule implosions are driven by gold hohlraums heated with 192 frequency-tripled ($3\omega$) laser beams on the NIF. The beams are arranged in four cones entering the hohlraum through the top and bottom LEHs; the inner two cones being at angles of $23.5^\circ$ and $30^\circ$ and the outer two cones being at $44.5^\circ$ and $50^\circ$ to the vertical axis.

Figure 3(a) shows examples of the total $3\omega$ laser powers used to drive cryogenic thermonuclear fuel implosions. These pulse shapes indicate the full range of power and energy variations in this study. The peak power varies from 300 TW to 430 TW and the total energy increases from $(1.05 \pm 0.02)$ MJ to $(1.6 \pm 0.03)$ MJ, respectively. Also shown in Fig. 3(b) are the power cone fraction for two experiments. We employ smoothed beams with polarization rotation, smoothing by spectral dispersion with a laser bandwidth of 45 or 60 GHz and a 17 GHz frequency oscillator. In addition, continuous phase plates are employed that give elliptical vacuum spot sizes providing peak quad vacuum intensities of $I_{23.5} = 5.16 \times 10^{14}$ W cm$^{-2}$, $I_{30} = 5.9 \times 10^{14}$ W cm$^{-2}$, $I_{44.5} = 1.3 \times 10^{15}$ W cm$^{-2}$, and $I_{50} = 1.4 \times 10^{15}$ W cm$^{-2}$ for the 430 TW laser drive.

At these energies and powers, the hohlraum absorbs 80%–90% of the incident energy with the dominating loss mechanism being due to stimulated Raman scattering (SRS) (Refs. 48 and 49) on the inner cones of beams. At our conditions, the SRS instability is saturated as measured with...
TABLE I. Experiments on the National Ignition Facility with layered thermonuclear fuel. Error bars are discussed in the text. Fast fourth rise pulse shapes where the laser rises from the third shock level to peak power in about 1 ns are indicated with “**”; the nominal rise for the other shots is approximately 2 ns.

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<th>Peak power (TW)</th>
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<th>LEH dia. (mm)</th>
<th>Capsule dopant</th>
<th>Fuel (D) %</th>
<th>$T_{\text{r}}$ (keV)</th>
<th>$\rho R$ (g cm$^{-2}$)</th>
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<th>$T_{\text{i}}$</th>
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full aperture backscatter diagnostics and near backscatter imagers resulting in a total loss of (200 ± 40) kJ.30 Scattering losses on the outer beams are below threshold for significant scattering,41,42 a total of (210 ± 40) J of stimulated Brillouin scattering has been measured on a 50° quad of beams. While the SRS power loss is compensated for by crossed beam power transfer as described in Sec. IV, potential capsule fuel preheat from hot electrons51,52 has been shown to be small. Direct hard x-ray imaging of the capsule high-energy bremsstrahlung emission25 has measured 500 J of electrons with energies >170 keV that have the potential to generate fuel pre-heat; this value is about a factor of 2 below current estimated upper limits acceptable for ignition.1

The hohlraum radiation temperature produced in these experiments is inferred from measurements of the x-ray power, $P$, in the energy range of 0 < $E_{\text{x-ray}}$ < 20 keV out of the LEH with the absolutely calibrated broadband x-ray spectrometer Dante.6,28,53,54 The measured radiant intensity provides the temperature via $dP/d\Omega = A_{\text{LEH}}(t)\phi(t) \cos \theta/\sigma T_{\text{RAD}}^4/\pi$. Here, $\sigma$ is the Stefan-Boltzmann constant and $\theta$ is the view angle of Dante towards the hohlraum axis. The dynamically varying source area, $A_{\text{LEH}}(t)$, is estimated from 3–5 keV x-ray images55 of the LEH measured with the Static X-ray Imager. These measurements show a reduction of the LEH diameter to 83% of the initial value. $\phi$ is the view factor that relates the Dante measured drive with the radiation temperature seen by the capsule.

Recent implementation of a time-integrating soft x-ray imager of the LEH at 900 eV has provided new measurements of the LEH aperture, indicating that about 10% of the Dante measured radiant intensity is due to emission from the ablated Au plasma that reduces the LEH clear aperture.56 Assuming 90% of the measured signal is from emission of the hohlraum interior, applying the measured LEH aperture, and adding a small view-factor correction results in a 10 eV corrections for these experiments.

The internal hohlraum radiation temperatures are modeled by balancing the absorbed laser power with the x-ray power radiated into the wall, $P_{\text{wall}}$, absorbed by the capsule, $P_{\text{CAP}}$, and the power that escapes through the LEH, $P_{\text{LEH}}$.

$$\eta_{\text{CE}}(P_{\text{L}} - P_{\text{Backscatter}}) = P_{\text{W}} + P_{\text{LEH}} + P_{\text{CAP}} = \sigma T_{\text{RAD}}^4[(1 - \zeta_{\text{wall}})A_{\text{W}} + A_{\text{LEH}} + (1 - \zeta_{\text{CAP}})A_{\text{CAP}}].$$ (1)

With $\eta_{\text{CE}}$ being the x-ray conversion efficiency from laser power to soft x-rays57–61; $\zeta_{\text{wall}}$ and $\zeta_{\text{CAP}}$ are the x-ray albedo of the hohlraum wall and the capsule, respectively. The albedo is defined as the ratio of re-emitted to incident x-rays. The hohlraum wall area, laser entrance hole area, and capsule surface area are denoted by $A_{\text{W}}, A_{\text{LEH}},$ and $A_{\text{CAP}}$, respectively. Assuming a conversion efficiency of $\eta_{\text{CE}} = 0.9$ at peak laser power, Eq. (1) indicates peak radiation temperatures of 260 eV < $T_{\text{RAD}}$ < 305 eV in good agreement with the results inferred from Dante measurements.15

The solution of the rocket equation shows that achieving high radiation temperatures and low remaining mass1 are important tuning parameters for obtaining high capsule implosion velocities and for approaching ignition conditions.

$$V_{\text{imp}}(km/s) = 10^2(T_{\text{RAD}})^{1/2}ln m_0/m,$$ (2)

with $T_{\text{RAD}}$ in hundreds of eV or keV. Specifically, for the remaining mass we aim at $m/m_0 = 0.08$ with the expectation that this value results in tolerable ablator mix. Since the ignition threshold factor (ITF) that provides a quantitative estimate for the probability of ignition scales like $V_{\text{imp}}^{\text{imp}}$ ((Ref. 8)) increasing
the implosion velocity to a point where additional margin can be achieved is an important ongoing area of effort.

In experiments that employ a 300 to 305 eV hohlraum radiation drive, we find that Si is a more efficient ablator than Ge indicating implosion velocities up to $V_{\text{imp}} = (350 \pm 20)$ km/s from radiography measurements. Here, the Si K-shell absorption edge at 2 keV provides the required M-band radiation pre-heat shielding of the fuel, but leads to a reduced dopant absorption of the thermal 300 eV hohlraum spectrum and to a reduced capsule albedo compared to experiments with a 1.3 keV L-edge of Ge, thus resulting in higher implosion velocities. Present velocities with the 430 TW, 1.6 MJ drive approach 95% of the ignition requirement of 370 km/s.

IV. IMPLOSION SYMMETRY

In this study, symmetry tuning has been performed throughout the whole duration of the laser pulse. In particular, SRS scattering losses on the inner beams have been compensated for and a symmetric radiation drive on the capsule has been achieved by taking advantage of crossed beam power transfer by laser scattering on self-generated plasma optics gratings in the LEH area. Specifically, the laser wavelengths of the 23.5° cones of beams and the 30° cones of beams have been tuned independently from the wavelength of the two outer cones of beams at 44.5° and 50°. The wavelength shift results in power transfer from the outer cones of laser beams to the two inner cones of beams and among the inner cones of beams. Power transfer increases the inner beam power by factors of 1.5 – 2 while allowing all beams to be operated with maximum laser power and producing the required symmetric soft x-ray drive on the capsule.

The crossed beam power transfer tuning mechanism takes advantage of the multiple laser beam interactions with the plasma in the LEH area where all the beams cross. The crossing lasers in the LEH produce spatial intensity modulations. These intensity modulations further drive plasma electron density modulations due to the ponderomotive force. If these modulations move with the plasma sound speed $C_S$ (in the frame of the plasma), then modulations and laser scattering will grow to large levels and efficient energy transfer between beams will occur. In the rest frame, the power transfer rate, $Q$, is determined by

$$Q \sim \left[ (\omega_1 - \omega_2) - k_\lambda (C_S - V_p) + i\nu \right]^2.$$  

In Eq. (3), $V_p$ is the plasma flow velocity and $\nu$ is the Landau damping rate for acoustic fluctuations. The frequency detuning between pairs of beams is denoted as $\omega_1 - \omega_2$. This factor allows us to control the energy transfer between cones of beams in integrated hohlraum experiments, and the frequency difference can be set to transfer power in or out of the different cones of beams on NIF.

Symmetric DT implosions have been achieved by applying results from three different tuning platforms, the so-called symcap, reemit, and mirrored keyhole experiments. These three platforms set the laser cone fraction for various parts of the laser drive as indicated in Fig. 3(b).

First, symcap implosions have been used to tune the total laser wavelengths differences to optimize power transfer and symmetry during peak laser power where simple geometry considerations lead to a cone fraction close to 1/3 to operate all beams at maximum power. For examples of tuning results, see Refs. 15, 19, 21, 22, 29, 30, 62, and 63.

Second, reemit experiments are applied using bismuth capsules that have a high albedo for 100 eV foot hohlraum radiation and whose 760 eV x-ray reemission during the first 2-ns of the laser pulse, known as the picket, measures the radiation symmetry up to about $t = 2.5$ ns. Even during the early part of the laser pulse, there is significant power transfer leading to a required cone fraction of 1/10, cf. Fig. 3(b).

Finally, while early experiments used calculations to determine the cone fraction during the remaining parts of the laser pulse, recently we have begun measuring the symmetry throughout the pulse using velocity interferometer measurements on the shock waves at two orthogonal angles.
Adjustments indicated in Fig. 3(b) during 12 ns < t < 17 ns have been motivated by the results of this tuning platform.

Measurements of the implosion symmetry have been performed with equatorial and axial high-resolution (10 µm) pinhole imaging of the 9 keV x-ray emission from the central hot spot plasma. Both temporally resolved (40 ps) data\textsuperscript{6,19,22,30} from gated microchannelplate detectors\textsuperscript{66} and absolutely calibrated time-integrated image plate data in four broad band x-ray energy channels have been measured. The equatorial brated time-integrated image plate data in four broad band
duce an early azimuthal asymmetry before the holes close during addition, the starburst observation holes that are cut in the azimuthal modes, hohlraum radiation environment.

The orthogo-

FIG. 4. Comparison of the x-ray emission images at 9-keV energy from the DT implosion shot N110914. Both, the (a) equatorial and (b) axial views are shown indicating symmetric conditions with M\(_n\) close to zero and a residual M\(_2\) mode. Also shown (c) is the primary (13–17 MeV) neutron image and (d) the down scattered (10–12 MeV) image, both have been measured from the equatorial view. The analysis of the 17% contours shows good symmetry and compression of 30 in radius with a final hot spot plasma of 50 µm diameter close to the results from the x-ray emission measurements. The hohlraum cylindrical axis of symmetry is vertical.

FIG. 5. DT fusion yield is shown as function of M\(_4\)/M\(_0\) together with examples of polar x-ray images at peak emission time. Red and blue data points are for shots at 1.4 MJ, each set with the same laser pulse shape and cone fraction. The images correspond to the blue data. The black open symbol along with a polar x-ray image represent the 1.6 MJ drive with laser pulse shape and cone fraction consistent with the blue data points. Also shown are the wavelength separation \(\lambda_2\) between the 30° cone and the outer cones of beams, and \(\lambda_3\) between the 23.5° cone and the outer cones of beams. Larger separation results in larger power transfer.

We find that the x-ray emission measurements of hot spot shape approximately agree with the results from neutron imaging. This system observes the neutron signal from a scintillator with two gated CCD cameras that are timed to measure primary neutrons at 13–17 MeV or down scattered neutrons at 10–12 MeV. The image with energies of 13–17 MeV shows \(P_0 = 27 \mu m\) and \(P_2/P_0 = -0.014\). Two 17% contour lines are shown, the red curve is from the raw data and the blue curve from the best fit. The primary neutron image may be slightly larger than the x-ray emission image because it contains a small contribution from 13 MeV to 14.1 MeV from down scattered neutrons that are scattered in the dense fuel shell at larger radii. Here, the x-ray emission image is integrated over the x-ray emission time while the neutron image integrates over the nuclear burn duration. The x-ray framing camera measurements provide the x-ray emission duration of 120 ± 20 ps, which is close to simulations. Nuclear measurements with \(\gamma\)-ray detectors\textsuperscript{70} show a longer nuclear activity of 170 ± 30 ps. Also shown in Fig. 4 is the image of the down scattered neutrons that indicates a fairly symmetric implosion from the equatorial view providing a fuel shell with M\(_0\) = 23.2 µm, M\(_2\)/M\(_0\) = 0.19, and M\(_4\)/M\(_0\) = 0.037. Figure 4(b) and the inset in Figure 5 compare time-integrated polar images with the gated data at bangtime for shot N110914.

x-ray images. For example, the gated data at x-ray bangtime at t = 22.1 ± 0.05 ns show M\(_0\) = 23.2 µm, M\(_2\)/M\(_0\) = 0.19, and M\(_4\)/M\(_0\) = 0.037. Figure 4(b) and the inset in Figure 5 compare time-integrated polar images with the gated data at bangtime for shot N110914.
shown are examples of polar x-ray images observed along the vertical axis of the hohlraum. The implosion with $M_a/M_b = 0.13$ shows significant four-fold lobes at the location where the $30^\circ$ cones of beams irradiate the hohlraum wall.

Calculations indicate that strong coupling of the $30^\circ$ beams would produce an early compression of the capsule surface area that faces this part of the hohlraum wall (indicated as red arrows in the images of Fig. 5) leaving the remaining capsule surface that faces the $23.5^\circ$ beams behind. Subsequently, being at larger radius the latter is absorbing more radiation and is consequently compressing to smaller radii. This phase reversal is indeed consistent with the experimental observations. By shifting the wavelength of the $23.5^\circ$ cones of beams further to the red by an additional 1 to 2 Å at 1σ, more power has been transferred to the $23.5^\circ$ beams. In this case, we observe that a stronger drive from the $23.5^\circ$ beams (indicated as green arrows in Fig. 5) results in stronger compression of the capsule surface area that faces the $30^\circ$ beams.

By tuning the wavelength differences among the various cones, we achieved $M_a/M_b$ values as small as 4%, and a simultaneous increase in DT fusion yield by a factor of three. The most recent implosions, where symmetry tuning with all three tuning platforms have been implemented have achieved symmetry values close to the ignition requirements of 10% for all modes and have resulted in the highest fusion yield, i.e., shot N111215. Nevertheless, the polar x-ray images indicate that future work is needed to achieve a fully symmetric implosion.

For cryogenic solid DT fuel has determined the adjustments to the pulse shape of order 10%–20%. This technique has been successfully established at the Omega laser at the University of Rochester, where experiments have led to the highest observed values of $\rho R = (0.295 \pm 0.044$ g cm$^{-2}$) for directly driven implosion experiments.

In the present experiments, the spatially averaged down scattered ratio (dsr) has been obtained using the magnetic recoil spectrometer (MRS) (Ref. 74) and three high-dynamic range neutron time of flight (NTOF) detectors, giving four different viewing angles to the impled capsule. The MRS employs a CD foil (275 µm thick, 13 cm$^2$ area) at a distance of 26 cm from target chamber center. The DT neutrons from the implosion collide with the deuterons in the foil; the forward scattered deuterons are spectrally analyzed by a magnet at a distance of 570 cm from the foil. The DT neutrons transfer most of their momentum to the deuterons with $n(14.1$ MeV) + $d \rightarrow n'(1.6$ MeV) + $d(12.5$ MeV). After passing the magnet, the recoil deuterons are measured with a series of CR-39 solid state nuclear track detectors and from their position allows inferring their energy spectrum and hence the neutron energy spectrum.

The NTOF array of photoconductive detectors and scintillator/photonmultiplier systems at distances of 4.5 to 27.3 m measures the arrival time of the neutrons generated during the implosion. On NIF, six NTOF detectors measure the neutron spectrum as a function of neutron energy, integrated over the hot spot, which contains a distribution of temperature and burn rates. The thermal distribution results in a dispersion of the neutron arrival times at distant detectors and allows extracting the relative ratio of down-scattered neutrons to the primary neutron signal.

The absolute neutron yield has also been measured with nuclear activation diagnostics (NAD), where zirconium and copper undergo neutron reactions with energy thresholds just below the DT (Zr and Cu) neutron production energy region of interest. The radioactive decay of the reaction product provides the incident primary neutron fluence above the energy threshold. We find that the DT yield determined by these diagnostics are in excellent agreement with each other. The error bar for the absolute diagnostics, NAD and MRS are 7% and 4%, respectively. When comparing the results from all detectors, we find for these experiments that the 14.1 MeV DT yield reaches 7.5 $\times$ 10$^{14}$ with a standard variation of 2%.

Figure 6 shows examples of MRS spectra for shots before and after shock timing adjustments. The diagnostic setup was identical for the two shots, allowing a direct comparison of the deuteron spectra. The pre-tuning example, shot N110212 provided $dsr = 0.027$. The post-tuning example, shot N110608 shows an increase by about a factor of 1.6 achieving a $dsr = 0.043$. The primary non-scattered neutrons produce the broad peak in the deuteron spectrum centered at 11.5 MeV, while the down-scattered neutrons are responsible for the deuteron signal between 7 and 10 MeV. The plots have been normalized by their 13–15 MeV neutron yields to show the increase in $dsr$. The increase of the $dsr$ is also measured with the NTOF diagnostics albeit absolute values still differ by about 10%–20% likely reflecting spatial variations in areal density.

\[ \Phi = \frac{\rho R}{\rho R + 6(\text{g cm}^{-2})}. \]
Table I summarizes the results for the areal densities as derived from the $dsr$ measurements utilizing radiation hydrodynamic simulations, $pR[g cm^{-2}] = 21 \times dsr$. Areal densities have exceeded 1 g cm$^{-2}$ when increasing the duration of the fourth pulse by 200 ps as delivered in a 1.6 MJ laser pulse to the hohlraum. The prolonged drive appears to assure that high areal densities prevail up to stagnation time; current values fulfill the requirement for burn fraction larger than 14%, which is a pre-requisite for $\geq 5$ MJ yield. Future experiments are planned to further improve shock timing to approach the predicted results for tuned CH implosions, i.e., $dsr = 0.07$ and areal densities of 1.5 g cm$^{-2}$.

VI. IGNITION THRESHOLD FACTOR

To estimate performance and the scaling of layered implosion experiments to the ignition regime, we analyze neutron yield and $dsr$ from x-ray and nuclear diagnostics, see Refs. 5 and 15 for a comprehensive description and analysis of diagnostics results. The DT equivalent yield, $Y_n$, and the $dsr$ are combined in the ignition threshold factor; the $ITFx$-value is defined as

$$ITFx = \left( \frac{Y_{DT}}{3.2 \times 10^{15}} \right) \left( \frac{dsr}{0.07} \right)^{2.3}.$$  (5)

This formalism allows the direct use of accurately measured quantities for estimating the progress towards the ignition regime. A series of about 1000 two-dimensional simulations indicate that implosions without alpha particle heating and values of $ITFx = 1$ show a 50% probability for ignition when using DT fuel.

To compare experiments with different deuterium fraction, we estimate the DT equivalent yield. Generally, the observed 14.1 MeV neutron yield data follow a simple scaling that is derived from calculations of the total DT yield

$$Y_{DT} \approx f_{DT} n^2 \langle \sigma_{DT} v \rangle \times V \times \tau.$$  (6)

Here, $\langle \sigma_{DT} v \rangle$ is the DT fusion cross section averaged over the Maxwell Boltzmann velocity distribution function, $f_D, f_T$, and $n$ are the fraction of deuterium and tritium in the plasma and the total atom number density, respectively. $V$ is the hot spot volume and $\tau$ is the burn duration. The data show a scaling (Table I and Ref. 15) that is primarily a consequence of the cross section scaling with temperature. To compare experiments with different fraction of deuterium and to obtain the DT equivalent yield, we scale the measured $Y_n$ according to Eq. (6). For example, for a THD experiment with $f_D = 0.06$ and $f_T = 0.72$, the DT equivalent yield is obtained by multiplying the measured yield with $(0.5^2)/(0.06 \times 0.72) \approx 5.8$. Consequently, the use of small deuterium fractions in THD fuel allows experiments that approach $ITFx$ values of $\geq 1$ without significant $x$-heating.

Figure 7 shows the DT equivalent yield versus the $dsr$ from four campaigns; layered commissioning experiments are shown in black; post-shock timing shots with germanium doped CH ablator are shown in blue; high velocity implosions with silicon doped CH ablator are shown in red, and implosions with spherical shape tuning are shown in brown. Implosions with shock tuned pulses and with sufficient laser energy to avoid coasting produce the most improved $dsr$, the highest areal densities, and $ITFx = 0.08$. In addition, implosions with higher velocity as obtained with a 3.1 mm diameter LEH and with a fast laser rise in the fourth pulse have produced high yields at lower laser energy. In future experiments, these parameters will be optimized simultaneously to further improve implosion performance.

The implosion experiments were modeled using the HYDRA 2D radiation-hydrodynamic code. The x-ray source drive in the simulations was varied until it matched the shock velocity history observed for the first 19 ns up to peak power and then matched the implosion trajectory.
measured via x-ray radiography. The implosion symmetry was also matched using the plasma cross-beam transfer saturation parameter that determines the relative balance of inner and outer laser beam power. 21

Realistic levels of capsule ablator and ice surface roughness were included for modes up to 60, since these are predicted by the point design to have the highest Rayleigh–Taylor (RT) instability growth rate. 8 When capsule and ice roughness has been applied to all the surfaces and interfaces in the calculation, significant RT growth was seen at the ice–gas interface compared to 2D calculations with smooth surfaces. The growth results in cooling of the hotspot lowering neutron yield and areal density. These simulations include corrections to the drive caused by deviations from requested to actual laser pulse shapes, variations in target dimensions, and yield factors due to ice grooves.

The results of the simulations without deposition of α particles, i.e., no α heating, are also listed in Table I. Generally, the dsr from the mode 60 simulations for the shock-induced implosions are within 25% of the measurements while the simulated adiabat inferred is 1.5 < αIF < 1.73. In addition, with one exception the simulations match the observed ion temperature to within 15%.

Significant discrepancies are observed in the measured DT yields, which are of order 10% of the calculated values. This observed discrepancy in DT yield can also be seen in DT yields, which are of order 10% of the calculated values.

ion temperature to within 15%.

VII. PRESSURE

It has been shown in Refs. 5 and 13 that the volume-averaged pressures and confinement time of ICF plasmas can be tied to a generalized Lawson-type criterion that indicate the proximity of a fusion experiment to an ignition physics regime. By fitting x-ray images, burn width, neutron time-of-flight ion temperature, yield, and fuel ρR, a nearly unique set of constraints on conditions can be obtained to model hot spot and fuel conditions that are entirely consistent with the observables. This model has been used to determine hot spot density, pressure, areal density, and total energy, not available from any single diagnostic. Since the pressure in ICF targets at stagnation is designed to be approximately isobaric, uncertainties in these quantities may be estimated by comparing results derived from conditions in the hot spot with those in the fuel.

For the hot spot plasma, temperature and density measurements have been performed with high energy x-ray emission data. For this purpose, absolutely measured high-energy x-ray images have been analyzed using calculations of time-integrated bremsstrahlung power, $P_B$. The images consist of a 11–20 keV channel from a Ross pair with 7 μm Mo + 1525 μm Kapton paired with 24 μm Ge coated on 200 μm graphite + 1525 μm Kapton, and a higher energy channel at $>$20 keV from a set with a 2525 μm Kapton filter paired with 7 μm Mo + 1525 μm Kapton. At such high x-ray energies, calculations indicate that the signal is not significantly affected by absorption in the shell and the bremsstrahlung analysis provides $n_e = 8 \times 10^{24}$ cm$^{-3}$ for shot N110914. Here, we utilized $T_e = 3.6$ keV from NTOF and assumed $T_e = T_i$ at these high densities. This results in an estimated stagnation pressure of $P = 92$ Gbars, which represents a significant increase from the first layered experiment that showed pressures of 9 Gbars at 1.05 MJ.

The hot spot pressure values are compared with the estimates of the fuel pressure. Using $\rho R = 1$ g cm$^{-2}$, inferred from MRS data and using an upper estimate for the shell thickness of $\Delta r = 17 \mu$m provides a shell density of $\rho \approx 600$ g cm$^{-3}$ and electron density of $n_e = \rho/(2.5m_p) = 1.4 \times 10^{26}$ cm$^{-3}$. Assuming close to Fermi degenerate conditions and estimating the Fermi degenerate pressure $P_F = 2.17 \times 10^{12}[(\text{erg/g})/(\text{g/cm}^{-3})]^{2/3} \rho^{4/3}$ and using $P = \alpha_IPF$, we arrive at $P_F = 90$ Gbars and $P = 135$ Gbars.

These values must be compared with the model pressure from the best fit of all experimental observables

$$P = 116 \text{ Gbar}$$

and using burn time $\tau = 100$ ps as a lower burn width as estimated from x-ray measurements

$$P\tau = 11.6 \text{ atm s.}$$

This comparison indicates that the error bar of $P\tau$ can be estimated as $\pm 30\%$. In this estimate, the error in the burn width measurements $\tau$ partly cancels; using for example larger values for $\tau$ will result in reduced inferred values for $P$.

Figure 8 shows the pressure-time product versus the measured ion temperature for NIF implosion shots, cf. Table I. The data show an increase in performance reaching values within a factor of three required for ignition. The highest data points with $P\tau > 10$ atm s are from shots N110914 and N112125. Also shown are the results of radiation-hydrodynamic HYDRA modeling indicating that ignition conditions will be reached at $P\tau \approx 30$ and no self-heating temperatures of $T \approx 4$ keV. This temperature is obtained from radiation-hydrodynamic simulations and is close, but slightly below the so-called ideal ignition temperature of 4.3 keV when alpha heating power is exceeding, bremsstrahlung losses in an optically thin plasma. The former is obtained by equating bremsstrahlung losses with Eq. (6) that is multiplied by the alpha particle energy. The slightly lower temperatures needed in simulations indicates that radiation losses are reduced due to high shell opacities. The simulations with and without alpha particle self-heating (i.e., comparing simulations with highly diluted THD and DT fuel) show the threshold for ignition and fusion burn where the fusion yield rapidly increases from 100 kJ to $>1$ MJ for sufficiently high pressures and temperatures.

In ICF implosions, the required $P\tau$ values for achieving the ignition regime are the no self-heating numbers, which
define a threshold for an explosive growth of yield. Thus, postignition pressures and temperatures are very different from pre-ignition values. Larger ICF capsules that are designed for high-gain fusion experiments\(^79,80\) use about an order of magnitude more fuel, but overall the \(P_t\) conditions will not be very different.

The NIF values are compared to data from previous fusion experiments\(^13\) including Omega\(^72,73\) and magnetic confinement fusion plasmas that are of order 1 atm s in both cases. For JET, the core ion temperature reached 28 keV at a confinement time of 0.4 s.\(^83,84\) Fusion gain values from TFTR (Ref.\(^85\)) are 0.28, approximately factor of three lower. DIII-D reached a core performance of temperatures of 18.1 keV and densities of 8.5 \(10^{13}\) cm\(^{-3}\) for ions in the central region. Quoted central pressure (total across all species) is about 0.35 MPa with averaged data points approximately factor of three lower. Confinement time was 0.4 s.\(^83,84\) Fusion gain values from TFTR (Ref.\(^85\)) are 0.28, and a gain of 0.65 is inferred from JET data.\(^81\) For JET, the gain is \(P_{\text{Fusion}}/P_{\text{absorbed}}\) and \(P_{\text{absorbed}}\) is the absorbed neutral beam injected power.\(^86\)

The total neutron yield from the present DT implosions are consistent with pressures of up to 100 Gbars. For example, for DT implosion shot N11215 the total laser energy input was 1.4 MJ, the total DT mass was 156 \(\mu\)g and the implosion velocity was approximately 300 km/s, thus resulting in a total energy into the DT plasma of 7 kJ. The total neutron yield summing the 14.1 MeV and downscattered neutrons is \(10^{15}\), which provides a total energy of 2.8 kJ.

VIII. CONCLUSIONS AND OUTLOOK

Present indirect drive inertial confinement fusion experiments on the National Ignition Facility show implosions with the highest areal densities and neutron yields achieved on laser facilities to date. This achievement is the result of the first hohlraum and capsule tuning experiments where the stagnation pressures have been systematically increased by more than a factor of 10 by fielding low-entropy implosions through the control of radiation symmetry, small hot electron production, and shock timing. The stagnation pressure is above 100 Gbars resulting in high Lawson-type confinement parameters of \(P_t\approx10\) atm s. Comparisons with radiation-hydrodynamic simulations indicate that the pressure is within a factor of three required for reaching ignition and high yield.

We expect that the 1-D performance of our implosions will soon meet or exceed the ignition implosion velocity providing margin for future optimization in areas of mix and pressure. Future experiments will use depleted uranium hohlraums,\(^31\) which in recent experiments have been observed to provide reduced hohlraum wall losses due to improved opacity at low heat capacity. These improvements along with optimized hohlraum geometry and laser power will be fielded for future tuning experiments with the goal to reach values of 30 atm s, which are predicted for the ignition regime.

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