Experimental Evidence of Impact Ignition: 100-Fold Increase of Neutron Yield by Impactor Collision

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We performed integrated experiments on impact ignition, in which a portion of a deuterated polystyrene (CD) shell was accelerated to about 600 km/s and was collided with precompressed CD fuel. The kinetic energy of the impactor was efficiently converted into thermal energy generating a temperature of about 1.6 keV. We achieved a two-order-of-magnitude increase in the neutron yield by optimizing the timing of the impact collision, demonstrating the high potential of impact ignition for fusion energy production.

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Thermonuclear ignition has been a long-desired goal in laser fusion research. Researchers at the U.S. National Ignition Facility [1] and the French Laser Mégajoule [2] are expected to achieve laboratory ignition soon. In these programs, ignition occurs in a hot spot created near the target center (central ignition). Fast ignition [3] has the potential to achieve thermonuclear ignition using about one-tenth of the laser energy required in these programs. Fast ignition separates fuel compression from ignition, which is attained by injecting an extremely intense and short (so-called petawatt) laser pulse into a precompressed fuel. However, fast ignition still has many intractable physics problems to solve, such as the transport of hot electrons to the dense compressed fuel. Several alternative ignition concepts have been proposed, which eliminate these problems while retaining the compactness of fast ignition. Shock ignition [4] utilizes a converging spherical shock wave that further heats and compresses the hot spot. Jet ignition [5] collides a one-sided jet flow with the precompressed main fuel. Impact ignition [6] extends these concepts; it generates a shock wave by colliding a projectile made of fuel with the main fuel. In this Letter, we report the first experimental evidence of impact ignition, demonstrating a two-order-of-magnitude increase in the neutron yield by precisely timing the impact collision.

In the impact ignition scheme, a portion of the fuel (the impactor) is accelerated to a superhigh velocity, compressed by convergence, and collided with a precompressed main fuel. This collision generates shock waves in both the impactor and the main fuel. Since the density of the impactor is generally much lower than that of the main fuel, the pressure balance ensures that the shock-heated temperature of the impactor is significantly higher than that of the main fuel. Hence, the impactor can reach ignition temperature and thus become an igniter. In the following paragraph, we derive the required velocity and density of the impactor to achieve ignition.

If most of the kinetic energy of the impactor is converted into thermal energy, the impactor velocity $v_{\rm imp}$ needs to be 1100–1500 km/s to achieve the ignition temperature of $T = 5$–10 keV. This is calculated using $m_{\rm DT}v_{\rm imp}^2/2 = 2(3/2)T$, where $m_{\rm DT}$ is the mean ion mass of deuterium and tritium (DT) fuel. The factor of 2 in front of the parenthesis indicates that both electrons and ions are at the same temperature. The actual velocity required is somewhat higher than the estimated value because some of the kinetic energy is not converted into thermal energy. At the same time, the impactor density $\rho_{\rm imp}$ has to be sufficiently high to reduce the impactor energy and thus the required laser energy. The impactor energy is simply given by $E_{\rm imp} = M_{\rm imp}v_{\rm imp}^2/2$, where $M_{\rm imp} = \frac{4\pi}{3}(\rho R)^3/\rho^2$ is the impactor mass (assuming a spherical configuration), ρR is the density-radius product of the impactor, ρ is the impactor density after shock compression and is given by $\rho \approx 4\rho_{\rm imp}$ for the specific heat ratio of 5/3 [7]. For example, if the impactor energy $E_{\rm imp}$ is 10 kJ under typical ignition conditions ($T = 5$–10 keV, $\rho R = 0.4$ g/cm^2), the impactor density before shock compression will be $\rho_{\rm imp} = 31$–44 g/cm^3.

Our hydrodynamic simulation shown in Fig. 1 demonstrates that ignition occurs when an impactor with $v_{\rm imp} = 1750$ km/s and $\rho_{\rm imp} = 50$ g/cm^3 collides with the main fuel with a density of 400 g/cm^3. Here, the implosion and

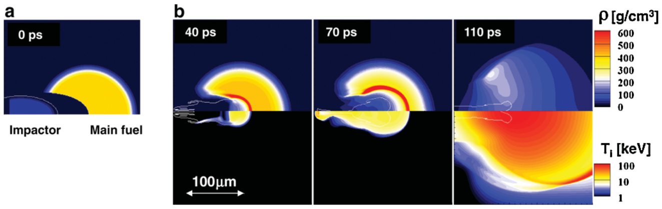

FIG. 1 (color). (a) Initial configuration of the impactor and the main fuel. (b) Snapshots of density and temperature distributions obtained from the simulation. The thin white lines indicate the impactor outer boundary. At a time of 110 ps, ignition and burn can be observed with temperatures >30 keV.

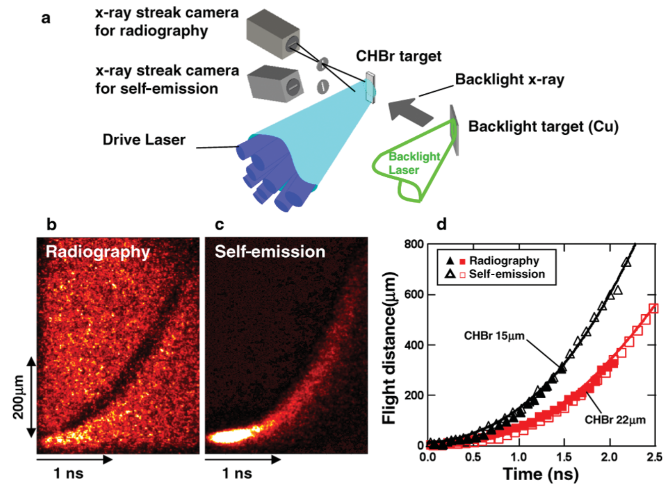

FIG. 2 (color). (a) The setup used for the foil trajectory measurement. The time origin of this experiment is defined as the time of the first half maximum of the laser. (b) Time-resolved x-ray radiography of a brominated polystyrene foil target moving to the target normal. (c) Time-resolved x-ray emission image from the target. (d) Compiled data of the flight distance vs time.

acceleration processes are neglected. The impactor in a bullet shape initially has spatial extensions of 60 and 70 μm in the perpendicular and the parallel directions with respect to the collision axis, respectively. The main fuel has a concave shape to tamp the impactor, as is observed in an implosion with a cone [8]. The impactor energy is only about 10 kJ, whereas the main fuel has a much higher energy than this. However, if the energy of the main fuel is reduced so that it is one to 2 times the impactor energy and if a typical coupling efficiency of 10% from the laser to the internal energy of the fuel assembly is assumed, we estimate that the laser energy for ignition will be 200–300 kJ. This energy is much lower than that required for central hot spot ignition and is comparable to that required for conventional fast ignition [9]. The primary challenges are thus to generate such high velocities while maintaining target integrity and to achieve such high impactor densities. Throughout this study, unless stated otherwise, we define the time origin as the time of maximum compression of the main fuel.

We investigated the feasibility of achieving the above criteria for impact ignition by performing two sets of experiments. First, we conducted experiments on planar foil targets accelerated to velocities approaching 1000 km/s. In conventional targets, Rayleigh-Taylor instability may limit the maximum impactor velocity to being less than the required velocity. However, several techniques have been demonstrated that can reduce the instability growth rate [10–14]. We have employed a double ablation technique [10], in which mid-Z atoms are doped in a plastic foil to generate x-ray-driven ablation in addition to electron-driven ablation. In brief, the targets were made from polystyrene doped with 0.4-atomic% bromine (CHBr) and were 15 or 22 μm thick. They were irradiated by a 0.35-μm-wavelength laser pulse with an energy of 1.5 kJ. The laser pulse had a nearly flat top profile with a 2-ns pulse width [full width at half maximum (FWHM)] at an intensity of 400 TW/cm^2. The trajectory of the target was observed by both x-ray radiography using a 1.3-keV x-ray source and self-emission from the lateral direction of the target, as shown in Fig. 2. Both measurements used a spatially resolved x-ray streak camera. The imaging slit (13-μm width and 50-μm height) was located 6.5 cm away from the target and 143 cm from the streak cathode (magnification of 22). The width direction of the imaging slit was aligned parallel to the target motion to give spatial resolution along the direction of motion [see Fig. 2(a)]. The streak slit was set just in front of the cathode to give temporal resolution. The direction of the streak slit length was parallel to the target motion to record the full length of the motion. In the radiography measurements, self-emission from the target was largely attenuated by a 5-μm-thick Mg filter and a 10-μm-thick Al filter. From the slopes of the images, the terminal velocities were estimated to be 510 km/s (22-μm-thick CHBr) and 700 km/s (15-μm-thick CHBr). The latter velocity is the highest velocity ever achieved with the target staying intact. The target density in flight was determined to be ≈ 0.2 g/cm^3, when terminal velocity was attained, from the target column mass divided by the target thickness; the measured target density was in good agreement with that predicted by the simulation code ILESTA-1D [15,16]. This agreement suggests that Rayleigh-Taylor instability was substantially suppressed, ensuring that the target did not break up.

We further demonstrated the density increase with spherical convergence by colliding the impactor with a precompressed fuel. This was the first integrated experiment of impact ignition. Figure 3(a) shows the target used in the experiment. Both the main fuel and the impactor were irradiated by a Gaussian-shaped laser beam with a wavelength of 0.53 μm and a pulse width of 1.3 ns (FWHM). The main fuel was a deuterated polystyrene (CD) shell that served as a fusion fuel surrogate (500-μm diameter, 7-μm thickness). A gold cone with an apex angle of 90° was inserted into the shell of the main fuel. The cone had an open apex with a diameter of 50 μm to allow the impactor to transmit freely through the

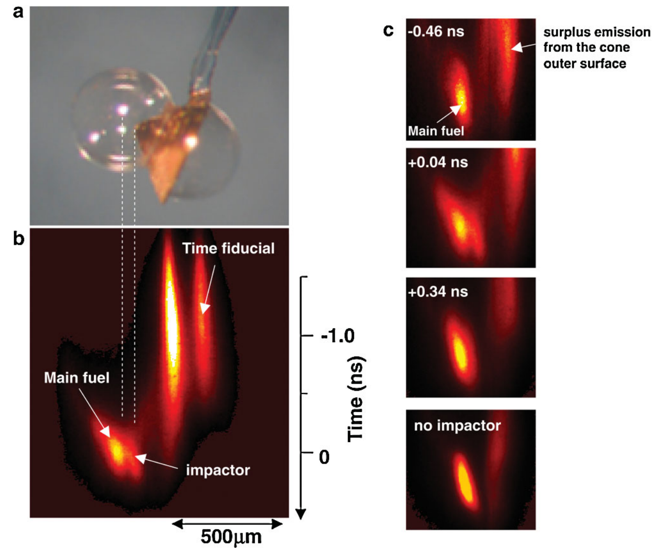

FIG. 3 (color). (a) Integrated target used for the impact ignition experiment. (b) Streaked x-ray image showing the collision of the impactor with the precompressed main fuel. (c) X-ray images at the center for four different times of the impactor collision with respect to the maximum compression.

apex. The impactor was a CD hemispherical shell (500-μm diameter, 10-μm thickness) attached to the entrance of the cone. Nine out of the 12 beams of the GEKKO XII laser (implosion laser) were used to irradiate the main fuel at an energy of 3 kJ. The density and temperature of the precompressed main fuel were inferred to be 50–70 g/cm^3 and 0.3–0.4 keV, respectively, from experiments conducted under nearly identical laser and target conditions [17]. Only a small portion of the impactor's shell (0.25 μg) was irradiated by the three remaining beams (implosion laser) with an energy of 0.41 kJ at a laser intensity of 700 TW/cm^2. The residual mass fraction was estimated to be 19% of the initial mass from both an experimental database of the mass ablation rate and a simulation. The terminal velocity was separately determined to be 580 km/s by a self-emission measurement. These values reveal that the kinetic energy of the impactor was about 8 J, which is equivalent to 2% of the incident laser energy.

Figure 3(b) shows the collision of the impactor with the precompressed main fuel measured from the temporal evolution of the streaked x-ray images at energies of 1–3 keV. To provide a time fiducial for the streak camera, we irradiated the edge of the gold cone with a portion of the impactor laser. Two straight emission lines on the streak image provide the time fiducial. (Since the left straight emission line contains surplus emission from the outer surface of the cone, we used only the right emission line as the fiducial.) When the timing between the implosion laser and the impactor laser is optimized, the impactor is expected to collide with the main fuel near the initial center of the main fuel. In Fig. 3(b), two x-ray emissions are observable near the time origin. The larger feature in the image is apparently from the main fuel, as confirmed by comparing it with the last frame in Fig. 3(c). The other emission feature disappeared when the timing of the impactor laser pulse relative to the implosion laser pulse was changed so that it became 300 ps or longer [Fig. 3(c)]. These observations clearly indicate that the second emission can be attributed to the collision of the impactor with the main fuel, since it became hot and emitted x rays.

We observed the yield and isotropy of the neutron emission with five neutron detectors, four of which were operated in current mode. These detectors consisted of fast plastic scintillators (Bicron BC422 with a 1% benzophenone quencher) with either 18 cm (diameter) $\times$ 2.5 cm (thickness) or 10 cm (diameter) $\times$ 5 cm (thickness) coupled with fast photomultiplier tubes (Hamamatsu R2083). A 10-cm lead shield was placed in front of each detector. Two detectors were located in the nearly forward and backward directions with respect to the acceleration direction of the impactor, while the other two detectors were positioned in nearly orthogonal directions. The fifth detector was a 421-channel count-mode spectrometer [18] that records the time-of-flights (TOF) of individual neutrons at a distance of 13.4 m from the target. We measured the ion temperature of the impactor from the Doppler broadening of the neutron spectrum. All the detectors were calibrated with respect to DD protons from a deuterium-filled glass shell imploded using a symmetrical irradiation configuration.

Figure 4(a) shows the TOF signals of the four neutron detectors. The first peak in each signal corresponds to x rays from the target. The strong anisotropy of the x-ray signal is presumably due to the different lead shield housings used. Distinct peaks corresponding to 2.45-MeV neutrons are visible. The absolute neutron yields were consistent with each other to within about $\pm 10\%$, which is the statistical uncertainty of the calibration. The isotropy and the lack of an energy shift in the neutron emissions thus obtained indicate that the neutrons were generated by thermonuclear fusion. Moreover, as the timing of the impactor laser pulse relative to the implosion laser pulse was varied, the neutron yield increased sharply by 2 orders of magnitude at the time of the impact collision with the main fuel, as shown in Fig. 4(b). The horizontal dashed line represents the neutron yield obtained when the impactor was not irradiated by laser radiation. The solid curve represents the x-ray emission pulse from the main fuel observed in Fig. 3(b). The collision timing for the peak neutron yield was determined by comparing x-ray pulses from the impactor with those from the main fuel. Those for the other data were obtained from the timing between the implosion laser pulse and the impactor laser pulse. These observations demonstrate that the neutrons were indeed generated by the impact collision. The maximum neutron yield in this experiment was 2×10^6 with an observed ion temperature of $1.59^{+0.29}_{-0.20}$ keV. This temperature is in good agreement with the calculated tempera-

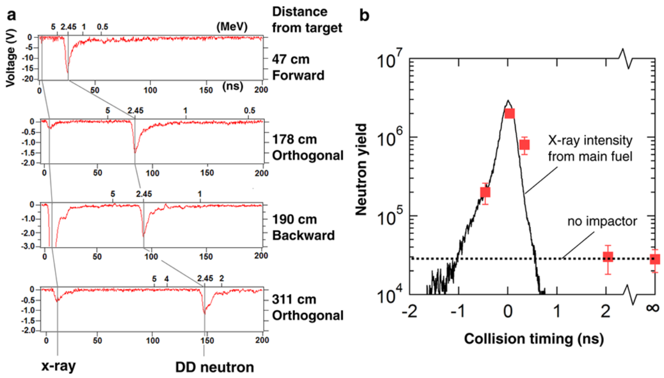

FIG. 4 (color online). (a) Time-of-flight signals of neutron emission. Neutrons were detected at different flight distances and orientations with respect to the acceleration direction of the impactor. (b) Neutron yield as a function of collision timing.

ture of 1.75 keV from the observed impactor velocity (580 km/s) [via $m_{\rm CD}v_{\rm imp}^2/2 = (1 + Z_{\rm CD})(3/2)T$, where $m_{\rm CD}$ ($=7$ atomic mass units) and $Z_{\rm CD}$ ($=3.5$) are the average ion mass and atomic number of the CD target, respectively]. This indicates that the kinetic energy is efficiently converted into thermal energy of the impactor.

We now consider the impactor density at collision from the above neutron data. In the following, we initially assume that neutrons are generated in the impactor only; this assumption is justified later. The neutron yield Y_n is estimated from the ion temperature T_i, the density-radius product ρR of the impactor at the collision time, and the impactor mass $M_{\rm CD}$: $Y_n = \iint (n_D^2/2)\langle\sigma v\rangle_{{\rm DD}n} dV dt \approx (\langle\sigma v\rangle_{{\rm DD}n}/32c_s)M_{\rm CD}\rho R/m_{\rm CD}^2$, where n_D is the deuteron density, $\langle\sigma v\rangle_{{\rm DD}n}$ is the velocity-averaged DD fusion cross section in the neutron branch, V is the volume of the impactor, and t is the reaction time. The above integral is evaluated by assuming that the volume of the shock-compressed impactor (as a sphere) is progressively reduced by the expansion wave propagating toward the center at the speed of sound c_s. Thus, $\iint dV dt \approx V_0 R_0/4c_s$ [19], where the subscript "0" indicates the beginning of the expansion; we also used the relation, $\rho = 2n_D m_{\rm CD}$. Since $\langle\sigma v\rangle_{{\rm DD}n}$ and c_s are both explicit functions of only the temperature, we can obtain a value for ρR and thus a corresponding density of $3.7^{+5.3}_{-2.4}$ g/cm^3 via mass conservation with the help of the observed data for the neutron yield, ion temperature, and residual impactor mass (0.25 μg $\times$ 19%). These densities are considerably higher than the in-flight densities (0.2 g/cm^3) in the planar target experiments. This indicates that the impactor underwent high compression due to the geometrical convergence and shock compression.

From the deduced impactor density (3.7 g/cm^3) and the temperature (1.6 keV), the pressure of the impactor is calculated to be lower than that of the main fuel calculated from the main fuel density (50–70 g/cm^3) and temperature (0.3–0.4 keV). Therefore, the increases in the density and the temperature of the main fuel on collision turn out to be insignificant, and hence the neutron yield from the main fuel should be unchanged. The enhancement in the neutron yield in the impactor itself demonstrates the high potential of the impactor as an igniter, which answers the original strategy of impact ignition.

In conclusion, by increasing the impactor velocity from 700 km/s to over 1500 km/s, increasing the energy efficiency from 2% to 10%, and taking the convergence effect into account, we estimate the laser energy necessary to create a hot spot to ignite DT fusion fuel to be 200–300 kJ, which is much lower than that required for central ignition. Of course, we are still uncertain how the above improvements can be practically implemented. Presumably, these improvements will require a laser with an appreciably shorter wavelength than that of the laser used in this study (e.g., a KrF excimer laser or the fourth harmonic of a Nd:glass laser). Scaling up of the present experiments will demonstrate that full-scale impact ignition could be attained within a practical range.

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