Fast heating of fuel assembled in a spherical deuterated polystyrene shell target by counter-irradiating tailored laser pulses delivered by a HAMA 1 Hz ICF driver

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Abstract

Fast heating is a method of heating an assembled high-density plasma into a hot state by irradiating it with short-duration (sub-picosecond), high-intensity (>10¹⁸ W cm⁻²) laser pulses before the plasma expands and dissolves hydrodynamically. In this paper, we present detailed experimental results of fast heating fuel assembled in a spherical deuterated polystyrene shell target of 500 µm diameter and 7 µm thickness with counterbeam illumination by using a HAMA 1 Hz, 5.9 J inertial confinement fusion laser driver with pulse tailoring. These tailored pulses contain three pulses in sequence: a ‘foot’ pulse of 2.4 J/25 ns, a ‘spike’ pulse of 0.5 J/300 ps and a ‘heater’ pulse of 0.4 J/110 fs; these pulses are designed to assemble the fuel and heat it. By varying the energy of the foot pulse, we find that fast heating the fuel is achieved only if the fuel is weakly ablated by the foot pulse and then shock-assembled by the spike pulse into the target centre so that the heater pulse can access the fuel with a focal intensity greater than 10¹⁸ W cm⁻². Without a foot pulse, the heater pulse contributes to assembling the fuel. For higher foot-pulse energies, the heater pulse drives a hydrodynamic motion with speeds of the order 10⁷ cm s⁻¹ with intensities of the order 10¹⁷ W cm⁻², resulting in re-assembling and additional heating of the pre-assembled fuel. Once a shock-assembled core is achieved at the target centre, we succeed qualitatively in fast heating the core for shots in sequence with variations of laser energy within 18%. The coupling efficiency
from the heating laser to the core is inferred to be \((10 \pm 2)\%\) in total: \((8 \pm 1.6)\%\) for the ionized bulk electrons and \((2 \pm 0.4)\%\) for the bulk ions. The fusion neutron spectrum detected on the laser axis exhibits peaks at 1.0 MeV, 1.7 MeV and 3.8 MeV. These peaks are attributed to the \(C(d,n)^{13}\)N and \(d(d,n)^{3}\)He reactions induced by counterpropagating fast deuterons accelerated by the photon pressure of the heating pulses.

Keywords: ICF, fast heating, ultra-intense laser, neutron, ICF laser driver, fast ignition

(Some figures may appear in colour only in the online journal)

1. Introduction

Fast heating is a method to heat an imploded high-density plasma before it expands and dissolves hydrodynamically [1, 2]. This method involves irradiating the plasma with a short-duration (less than a few picoseconds), high-intensity \((>10^{18} \text{ W cm}^{-2})\) laser pulse. If the plasma is fusion fuel that is sufficiently hot and dense, fast heating leads to fast ignition. Compared with the conventional inertial confinement fusion (ICF) method of central hot-spot ignition, fast ignition has a possibility to obtain higher gains with lower driver energy and lower susceptibility to the effects of hydrodynamic mixing [3]. The scheme that has been applied in experiments to date [4–8] is as follows. The fuel is assembled under compression from a conventional ICF driver with nanosecond pulse duration. This compressed fuel is then heated by a unidirectional hot electron current produced by a short-pulse (a few picoseconds), high-power (of the order of petawatts) laser. In fast-heating experiments with this particular heating configuration, energy coupling efficiencies of up to 7\% from the laser to the imploded core have been reported [7–10].

In contrast, with our previously proposed bi-directional (counterbeam) irradiating fast-heating scheme [11], we observed a strong photon flash from a core that had been assembled using tailored pulses when we counterirradiated it directly with two 110 fs, 3.5 TW laser heating pulses [12]. The resulting energy coupling efficiency from the laser to the core was greater than 10\%, as inferred from photon emissions. A two-dimensional collisional particle-in-cell simulation revealed that the counter-flowing hot electron currents generate megagauss magnetic filaments as a result of the electromagnetic two-stream instability, also known as the Weibel instability [13]. These strong magnetic fields, which do not occur so much in the unidirectional irradiation case, help in trapping hot electrons in the core, along with their energy [12]. Therefore, the counterbeam irradiating fast-heating scheme has the potential to induce more energy depositions than unidirectional irradiation.

We previously reported that two 110 fs, 3.5 TW heating pulses produced fast electrons that led to the near-simultaneous heating of a shock-assembled core. However, from the experiments we reported here, we also found that the heating pulses were driving hydrodynamic motion, in addition to generating hot electrons and fast ions. The generation of this hydrodynamic motion was dependent on the state of the assembled fuel. In particular, when the pulses heated an expanding fuel, they re-assembled it in addition to heating it.

In this paper, we report detailed experimental results and analysis on fast heating a tailored-pulse-assembled core using the counterbeam configuration. The key technology in these experiments is a tailored-pulse counterbeam configuration delivered by a HAMA laser [14, 15]; a repetitive ICF laser driver can be operated at 1 Hz, which is a scalable repetition rate for future inertial fusion energy (IFE) reactors. In section 2, we discuss the progress in ICF driver development and describe the HAMA laser with its tailored pulses. In section 3, we present detailed results of x-ray photon emission from the assembled core and an estimation of the energy coupling into the fuel. In section 4, we describe the fusion neutron reactions induced by the counterbeam configuration. Finally, in section 5, we summarize the results.

2. Repetitive ICF laser driver

2.1. Developmental progress

Figure 1 shows the annual progress in output energy from solid-state laser drivers for use in ICF research. Closed squares represent glass lasers with nanosecond pulse durations. In addition, two laser systems not shown in this figure—LMJ (1.3 MJ/3ω, 160 beams) in France and UFL-2M (2.8 MJ/2ω, 192 beams) in Russia—are under either under commissioning or construction. Closed triangles represent glass laser drivers with picosecond pulse duration based on chirped pulse amplification (CPA) [16]. These CPA laser systems enable short-pulse (from femtoseconds to picoseconds), ultra-high-intensity laser beams with a focal intensity greater than \(10^{18} \text{ W cm}^{-2}\). These beams are used to drive relativistic electron motion in the direction of laser propagation with energies upwards of megaelectronvolts.

This laser-driven relativistic motion is used in specific research activities including particle acceleration and ICF. For example, advanced ICF using the avalanche reaction of fusing protons with the boron isotope \(^{11}\)B has been proposed based on advanced CPA laser technology. This would involve either a spherical irradiation geometry [17] or assistance from ultrahigh-magnetic-field trapping [18, 19]. The current status of kilojoule-class petawatt CPA lasers is reviewed in [20].

The lasers represented in figure 1 by closed squares and closed triangles are glass lasers pumped by flash lamps based on single-shot laser technology. When operated at energies beyond a few kilojoules per beam, their repetition rates are limited to one shot every few hours because of the need to cool the glass laser mediums.
The aim of using these single-shot lasers in ICF experiments is to reach the scientific break-even point for ICF: producing greater fusion energy than that of the input laser. The blue arrow in figure 1 represents the progress that has been made towards that point. Following this scientific proof of ignition, engineering development needs to start on IFE that is based on repetitive laser technology. A diode-pumped solid-state laser (DPSSL) is a promising candidate as a reactor driver for IFE because it can be operated at a high repetition rate (>10 Hz) with high efficiency (>10%) [21]. The HAMA laser is a titanium–sapphire (Ti:Al₂O₃) laser pumped by DPSSL designed to demonstrate high-repetition ICF for IFE. The red arrow in figure 1 shows the progress that is required towards an IFE reactor.

2.2. Tailored HAMA laser system

This section gives an overview of the present HAMA laser with tailored pulses and the irradiation system [14, 15]. Figure 2(a) shows a schematic diagram of the tailored HAMA laser and the configuration of target irradiation. The laser comprises a seed laser known as BEAT and a pump laser known as KURE-1. BEAT is a 10 Hz hybrid system via optical parametric chirped pulse amplification (OPCPA) and Ti:Al₂O₃ multi-pass amplifiers [22, 23]. KURE-1 is a second harmonic generation (SHG) 10 J/10 Hz DPSSL system based on a water-cooled Nd:glass zigzag path slab amplification scheme [24]. In KURE-1, a pulse through a nonlinear crystal (CsLiB₆O₁₃) provides two beams: a converted SHG beam and the remaining fundamental beam. A SHG of 10 J is used to pump the HAMA Ti:Al₂O₃ amplifier mounted on the HAMA breadboard shown in figure 2(b). The fundamental beam of 6 J, labelled as the K or ‘foot’ beam, is used as part of the fuel-assembly beam. In HAMA, the output seed pulse of 1 J/300 ps from BEAT is amplified to 3.5 J/300 ps through a four-pass amplifier. This output is divided into two beams by the L–S beam splitter. One beam is an output of 1.5 J/300 ps, labelled L or ‘spike’, that is used as a fuel-assembly beam in combination with K pulses through the K–L beam combiner. The remaining beam of 2 J/300 ps is pulse-compressed to 1.2 J/110 fs; this is labelled as the S or ‘heater’ beam and is used to heat the assembled fuel.

The K, L and S beams are split and combined by a 50:50 beam splitter/combiner in the compression chamber and are then transported to the irradiation chamber as BEAM-1 and BEAM-2. These beams include three pulses in sequence: a foot of 2.4 J/25 ns, a spike of 0.55 J/300 ps and a heater of 0.40 J/110 fs, as shown in figure 2(c). Here, the foot has an irradiation timing of 6 ns in advance to the heater, which is controlled by an electrical synchronization with a jitter of 0.24 ns. The spike has an irradiation timing of 2.4 ns in advance to the heater, with optical synchronization facilitated by tuning the optical pass length. By changing the timing of these three pulses, we can tailor the pulse shape to optimize both the fuel assembly and the heating of the fuel from a spherical shell target. This system has the potential to be operated at repetition rates up to 10 Hz. However, the current capabilities of the target supplier [25–27] and the diagnostic-data accumulation system restrict this repetition rate to 1 Hz.

Figure 1. Progress in solid-state ICF laser drivers. Closed squares are single-shot nanosecond-pulse lasers. Closed triangles are single-shot CPA lasers with picosecond pulse duration. Closed circles are single-shot lasers with subnanosecond-pulse duration. Open circles are single-shot nanosecond-pulse lasers. Open triangles are single-shot CPA lasers with subnanosecond-pulse duration. Open squares are single-shot nanosecond-pulse lasers. Open pentagons are single-shot CPA lasers with picosecond pulse duration. Red dots are single-shot lasers with subpicosecond pulse duration.

3. Photon emissions from assembled core

3.1. Irradiation layout and experimental setup

Figure 3(a) shows the irradiation chamber where the three sequential pulses shown in figure 2(c) are focused onto a spherical-shell target by a pair of off-axial parabolic mirrors, each with a focal length of 16.5 cm. Irradiation intensities of three pulses on to the target are controlled by their focusing position by changing their beam divergence. In relation to a position of the target center, the foot beam is 290 μm in focus, and ‘spike’ and ‘heater’ are centre focused. The resulting spot sizes are 230 μm and 90 μm, respectively, on the target surface. Table 1 lists the target intensity of each beam. The beam energy balance between BEAM-1 and BEAM-2 is within 7%. The heater intensity is evaluated at the centre of a spot diameter of 11 μm at the 1/e² intensity point. The shell target contains deuterated polystyrene (C₆H₅D₄ or simply CD) with 500 ± 1.2 μm diameter and 7 ± 0.5 μm thickness. This target has two apertures of 400 μm diameter that are perpendicular to the laser axis, as shown in figure 3(a), for detecting photon emission from the plasma core by using the x-ray streak camera or the pinhole camera shown in figure 3(b).

3.2. Fuel assembly and heating by counterbeam

Figure 4(a) shows a pulse train of the counterbeam configuration in the experiments. Figure 4(b) shows a radius versus time (RT) diagram of the fuel-assembly dynamics simulated using a one-dimensional (1D) radiation hydrodynamic code (STAR-1D) [28]. Figures 4(c) and (d) show x-ray streak images for a normal assembly (no heater) and an assembly with fast heating (with heater), respectively. In figures 4(c) and (d), the grey regions are those that were masked by the shell. For the CD with the thickness of 7 μm, a transmission...
intensity for a photon energy of 1.2 keV goes down to $1/e^2$. As can be deduced from figures 4(a)–(d), the foot causes the shell to implode ablatively. In sequence, the spike at 34.6 ns drives a shock with a peak pressure approaching 1 Tpa. This assembles the target inwardly, resulting in stagnation at 36.1 ns with a core diameter of 70 \(\mu m\). From the STAR-1D results, we estimate that the core density was 0.3 g/cc, the core temperature was 20 eV and the average discharge state \(\langle Z \rangle\) was 1.5. By irradiating the heating pulses, we observed an x-ray flash from the core, as shown in figure 4(d). The expanded boxes in figures 4(c) and (d) show the x-ray emission profiles in the core region covering 1 ns in time and 200 \(\mu m\) in space. The two spots in the box in figure 4(d) indicate that the heating laser pulses did access the edge of the core, creating spike emissions where the laser light was actually absorbed. The x-ray streak camera can detect photons with energies in excess of 40 eV. In relation to the sensitivity at 100 eV, the sensitivity for energies of 50–400 eV is in the range 0.5–2.

The distribution of photon emissions depends on the energy of the assembling foot pulse. Figure 5 shows photon emission profiles for foot pulse energies of zero (no foot), 2.6 J/beam and 3.0 J/beam. The left-hand panels in figure 5 show x-ray streak images. In the right-hand panels, photon emission profiles at the target surface \((x = 250 \mu m)\) are shown in the upper part and those at the target centre \((x = 0 \mu m)\) are shown.

Figure 2. (a) Diagram of HAMA and counter irradiation system. (b) Photograph of the current HAMA system. (c) Pulse trace of three pulses in sequence taken by a biplanar phototube.

Figure 3. (a) Irradiation chamber. (b) diagnostics setup.
in the lower part. These profiles are spatially averaged over a distance of 82 μm.

As shown in figure 5(a), in the absence of a foot pulse, there were no emissions from the target centre regions around \( x = 0 \) μm at the timing of the spike pulse irradiation (\( t = 10 \) ns). By irradiating with the heater at \( t = 12.6 \) ns, emissions are observed at \( x = \pm 130 \) μm, which are the locations of the assembling fuel. This indicates that the fuel had not yet reached the target centre. Considering the initial position of the target surface (±250 μm), the speed of fuel assembly driven by the spike pulse is evaluated as \( (4.6 \pm 0.6) \times 10^6 \) cm s\(^{-1}\).

After irradiation by the heater pulse, these emissions move inwards in time, resulting in emissions from the target centre at \( t = 15 \) ns. For the emission diameter, the full width at half maximum (FWHM) was 120 μm. The time delay \( \Delta t \) between the heater irradiation and the emission from the target centre was 2.4 ns. The speed of assembly driven by the heater pulse was \( (8.6 \pm 1) \times 10^6 \) cm s\(^{-1}\). This emission from the centre corresponds to stagnation of the fuel.

In contrast, as shown in figure 5(b), by introducing a foot pulse with an energy of 2.6 J/beam, the fuel assembly begins to move inwards at the timing of the spike pulse, resulting in stagnation at \( t = 11.2 \) ns. The speed of fuel assembly driven by the spike pulse is evaluated as \( (1.0 \pm 0.1) \times 10^7 \) cm s\(^{-1}\). By irradiating with the heater pulse at \( t = 11.8 \) ns, emissions from the core were enhanced instantaneously with a time delay \( \Delta t \) of less than 0.1 ns. This time delay is limited by the streak timing resolution of 0.06 ns for the 30 ns streak range. The FWHM of emission duration was 1 ns and that of the emission diameter was 107 μm. Here, we evaluate the characteristic speed required to enhance the core emission in the target centre driven by the heater pulse by assuming that such pulses are absorbed at the edge of the core emission diameter, resulting in heating of the core centre within a time delay of \( \Delta t \). The estimated speed is \( 8.3 \times 10^7 \) cm s\(^{-1}\). Note that this value is under estimation because the \( \Delta t \) is limited by streak timing resolution.

By increasing the energy of the foot pulse to 3.0 J/beam, as shown in figure 5(c), there are weak emissions from the target centre at \( t = 8.5 \) ns. This indicates that the fuel was stagnated only ‘foot’ pulses. At the timing of the spike pulse (\( t = 10 \) ns), we observed emission enhancement with a FWHM diameter of 240 μm. This emission diameter expands beyond 370 μm at the timing of the heater pulse (\( t = 12.8 \) ns). By irradiating with the heater pulse, the emission enhanced again with a time delay of \( \Delta t = 1.5 \) ns, with a FWHM diameter of 210 μm. This indicates that the heater pulse helps in re-assembling the expanding fuel via heating. The re-assembling speed is evaluated as \( (1.0 \pm 0.1) \times 10^7 \) cm s\(^{-1}\).

### Table 1. Beam-assembling and heating beams

| Beam          | Fuel-assembling beam | Heating beam |
|---------------|----------------------|--------------|
| Wavelength (μm) |                      |              |
| Pulse width   | 25.2 ns              |              |
| Energy per beam (J) | 2.4          |              |
| Intensity (W cm\(^{-2}\)) | \( 3.0 \times 10^{14} \) | \( 2.1 \times 10^{13} \) | \( 6.7 \times 10^{18} \) |

Figure 6(a) shows the enhancement of photon emissions \( \Delta I \) from the core (closed circles) due to the irradiating heating pulses, as well as the time delay \( \Delta t \) between heating-pulse irradiation and emission from the target centre (closed triangles) as a function of energy of foot pulse. Figure 6(b) shows the enhancement of photon emissions from the core as a function of the time delay \( \Delta t \). From figure 6(b), we see that enhancement of emission from the core deceases with increasing \( \Delta t \). Therefore, a shorter time delay \( \Delta t \) is required if the heating pulses are to enhance the core emission count.

Figure 7(a) shows the emission diameter as a function of energy of foot pulse. Closed circles represent the emission FWHM diameter at the timing of heater irradiation, whereas closed triangles do so at the emission peak. For energies of foot pulses of zero (no foot pulse) and 3 J/beam, if the assembling core was not localized into the target centre, heater irradiation helped squeeze the core size. In contrast, for energy of 2.6 J/beam, the size of assembling core was close at the timing of heater irradiation and at the emission peak. We consider that fast heating occurred in this configuration, where the assembling core was being squeezed into the target centre by the foot and spike pulses so that the heater pulse could interact with the core at relativistic focal intensities. Here, we suppose the heating process to be a combination of hot electrons and a hydrodynamic mode. Indeed, by setting plastic scintillators (ND1, ND2 and ND3) around the target chamber as shown in figure 3(b), we observed γ-ray signals driven by hot electrons under these conditions. Figure 7(b) shows γ-ray signals detected on the ND3 (laser on-axis) in relation to energy of foot pulse. The strong γ-ray signal was observed when the core was localized into the target center for the suitable energy of the foot pulse. Figure 7(c) shows γ-ray signals in relation to the emission FWHM radius evaluated from figure 7(a) (closed circles) at the timing of heating-pulse irradiation. From figure 7(c),
we see that the γ-ray signals decreases with increasing the emission core size. These data support the heating scenario mentioned above.

The interaction of the heater pulses with the assembled fuel is explained by the pulses’ focal intensities. In figure 8, closed squares represent the measured spot size of the heater pulses in relation to a propagating position. The solid curve is a fit of the Gaussian beam profile $2w_0(1 + (x/z_0)^2)^{0.5}$, where $2w_0 = 11 \mu m$ is the spot diameter at the $1/e^2$ intensity point and $z_0 = 28 \mu m$ is the Rayleigh length. The dashed curve is the focal intensity profile estimated from the fit. The focal intensities range over two orders of magnitude ($10^{16} – 10^{18}$ W cm$^{-2}$) in relation to the laser propagating position from the initial spherical shell surface ($x = 250 \mu m$) to the target centre ($x = 0 \mu m$). Assuming that the heater pulse interacts with the assembled core at the position represented by the emission size shown in figure 7(a) (closed circles), we can evaluate the focal intensity of a heater pulse from figure 8. For example, an emission size of $107 \mu m$ (a foot-pulse energy of 2.6 J/beam) leads to an interaction position of $\pm 53 \mu m$ ($1.8z_0$), providing a focal intensity of $2 \times 10^{18}$ W cm$^{-2}$, which is sufficient to drive relativistic motion of electrons with energies corresponding to megaelectronvolts. In contrast, for an emission core size of $370 \mu m$ (a foot-pulse energy of 3 J/beam), the interaction position extends to $\pm 185 \mu m$ ($6.6z_0$), resulting in a focal intensity of $1 \times 10^{17}$ W cm$^{-2}$, which is too low to
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drive electrons at relativistic energies. Therefore, interactions with intensities of the order of $10^{17}$ W cm$^{-2}$ would drive hydrodynamic motion; re-assembly and heating observed in figure 5(c). Note that the intensity of the order of $10^{17}$ W cm$^{-2}$ is one order of magnitude higher than the corresponding value in shock ignition, where an intensity of $6 \times 10^{15}$ W cm$^{-2}$ is designed to drive an ignitor shock spike to ignite the assembled fuel with a spherically convergent ignitor shock and the associated return shock [29]. Therefore, this result might indicate some relation of this method with the method of shock ignition.

3.3. Shot variation

We conducted a total of 88 shots. In particular, we intentionally conducted seven shots in sequence without changing any irradiation conditions or detector sensitivities, where the sigma variation of the core emission intensity was 8%. When the core was assembled by the foot and spike pulses impinging on the target centre, irradiating with the heater pulse led to an x-ray flash from the core for three shots in sequence, as shown in figure 9 (#62, #63 (figure 5(b)) and #65). Shot #64 is a case of unidirectional irradiation to act as a reference for the counterbeam configuration. Although the laser energies were changed slightly for the three shots (variations of 7% for the foot pulse and 18% for the spike and heater pulses), x-ray flashes were still detected from the core. Hence, once an imploded core existed at the target centre because of the foot and spike pulses, as far as an x-ray flash from the core was concerned, the shot success probability was close to 100%.

3.4. Timing dependence of heating pulse irradiation

Figure 10(a) shows x-ray streak images of core emission for different irradiation timings of the heating pulses. We irradiated using a heating pulse at the timings before stagnation, at stagnation and after stagnation (expanding). Dashed lines represent the fuel assembling trace. Figure 10(b) shows the emission enhancement and radius of the fuel assembling trace as a function of the timing of laser irradiation heating. As can be seen in figure 10(b), a bright and compressed spot was found only when the timing was at stagnation, which corresponds to a relative time of $\Delta t = 1.7$ ns. Accumulated core-emission enhancements were dependent on the timing of heating irradiation pulses in relation to the fuel-assembly dynamics, during which the maximum accumulated emission-count enhancement was found for the minimum emission size of the imploded core (corresponding to stagnation). This result indicates that for efficient energy deposition via fast heating, the assembled fuel should be squeezed to occupy the least possible amount of space.

3.5. Coupling efficiency by counterbeam irradiation

From the enhanced photon emissions captured by the 2 ns streak image shown in figure 10(a) at stagnation ($\Delta t = 1.7$ ns), we can estimate the energy coupling between the heating laser and the core. Figure 11(a) shows spatial photon emission profiles recorded before heating-pulse irradiation (at 1.6 ns; blue curve) and at the timing of heating-pulse irradiation (at 1.7 ns; red curve). The grey regions are those that

![Figure 7](image1.png)

**Figure 7.** (a) Emission FWHM diameter FWHM as a function of energy of foot pulse. (b) $\gamma$-ray signals in relation to energy of foot pulse. (c) $\gamma$-ray signals in relation to the emission radius evaluated from figure 7 (a) (closed circles).

![Figure 8](image2.png)

**Figure 8.** Measured spot size of heater pulses (closed squares) and its fit to the Gaussian profile $2w_0(1 + (x/z_0)^2)^{0.5}$ (solid curve), with $2w_0 = 11 \mu$m and $z_0 = 28 \mu$m, in relation to the laser propagating position. Evaluated focal intensities (dashed curve) in vacuum from the fitting in relation to the laser propagating position.
were masked by the shell. The average photon emission counts in the core region of $\pm 25 \mu m$ are represented by the closed circle (at heating) and the closed square (before heating). At stagnation (blue curve), the emission FWHM core size was $72 \mu m$. By irradiating using the heating pulses, the FWHM core size narrowed to $55 \mu m$ with an accumulated emission count enhancement of $(6 \pm 0.8)$ times. The spatial profile of photon emission (red curve) also indicates that the heating laser deposited its energy into the centre of the assembled core rather than into its surroundings. This photon emission lasted for 200 ps, as shown in figure 11(b) (red curve).

The heating process that is driven by the counter-illumination heating pulses was simulated using a collisional two-dimensional particle-in-cell (PIC) code, PICLS2D, that includes the ionization processes in the plasma [30]. Figure 12(a) shows the initial ion-density profile in the simulation-geometry box. The plasma parameters were based on a STAR-1D simulation of the assembled core at stagnation ($t = 36.1$ ns), as shown in figure 4(b). The assembled plasma comprised carbon and deuteron ions with an initial ionization state of 1.0. The initial plasma temperature was $15 eV$, and the initial peak ion density for each species was 12 times the cut-off density $n_c$. The ion cut-off density regions were located at $x = 35 \mu m$ and $x = 85 \mu m$. The counter-illumination heating pulses had a focal intensity of $5 \times 10^{18}$ W cm$^{-2}$, a FWHM time duration of 100 fs and a focal spot size of $10 \mu m$. The peak of the heating-pulse trace reached the edges of the plasma $(x = 35 \mu m$ and $85 \mu m)$ at $t = 250$ fs. Following application of the heating pulses, the electron temperature of the interaction region increased, resulting in additional ionization. Figure 12(b) shows the profile of bulk electron energy density at $t = 726$ fs. The core plasma in a laser spot size of $10 \mu m$ ($Y = 35$–$45 \mu m$) reached full ionization ($Z = 3.5$) with an average electron temperature of $1.3keV$ within 1 ps, as shown in figure 12(c). This average electron temperature is consistent if $28\%$ of the laser heating energy was absorbed by the plasma core.

In this plasma state, the thermal diffusion time based on the classical binary collision model [31] was evaluated to be 2 ps. This time is two orders of magnitude shorter than the 200 ps duration of the core emission observed in figure 11(b) and one order of magnitude shorter than the 14 ps time resolution of x-ray streaks for the 2 ns streak range. Hence, we assume that the profiles of emission from the core after laser heating irradiation, shown in figure 11, include a thermal diffusion process. In such a process, for a plasma core heated by a $10 \mu m$-diameter laser spot at a temperature over 1 keV, the thermal energy diffuses isotropically into the peripheral plasmas with a larger diameter with the temperature dropping to a few tens electronvolts. The emission diameter from figure 11(a) (red curve) of $55 \mu m$ is supposed to be this condition. On the basis of the parameters obtained from the STAR-1D simulations, before the heating pulses are applied, the energy of the assembled core (at a density of $0.3g/cc$, a temperature of $20 eV$ and with $(Z) = 1.5$) in this spherical volume was evaluated as $25 mJ$. This energy corresponds to $3\%$ of the laser heating energy of $800 mJ$ in the experiments. A spherical-volume energy of $800 mJ$ corresponds to a core with a temperature of $360 eV$ and with $(Z) = 3.4$.

Next, to establish the photon emission process from the thermally diffused core, we consider a radiation intensity $I(hu)$ as a function of the photon energy $hu$ from the CD bulk plasma (0.3 g/cc). We also consider an electron temperature in the range 20–100 eV for a partially ionized plasma with thickness $\Delta x = 55 \mu m$ realized via a subroutine of the STAR-1D simulation code. Our model includes radiation from the free–free, bound-free and bound–bound processes by considering an emissivity $\eta(hu)$ and an absorption coefficient $\chi(hu)$ in the plasma, which are evaluated from a screened hydrogenic model. Here, the average ionization state $(Z)$ was evaluated from the collisional-radiative equilibrium (CRE) model [32].
Figure 10. (a) X-ray streak images of core emission profiles for different irradiation timing of the heating pulse. (b) Emission enhancement and fuel-assembly trace as a function of timing of heating pulse irradiation.

Figure 11. (a) Spatial photon-emission profiles before heating-pulse irradiation (at 1.6 ns; blue curve) and at the time of heating-pulse irradiation (at 1.7 ns; red curve). (b) Temporal photon-emission profiles at the core centre (red curve) and at the target surface (blue curve). The raw image is shown in figure 10(a) at stagnation ($\Delta t = 1.7$ ns).
Figure 12. (a) Simulation configuration on PICLS2D. (b) Profile of bulk electron energy density at $t = 726$ fs. (c) Distribution of bulk electron energy in the core region enclosed by the dotted rectangle in (b).

Figure 13. (a) Emissivity, (b) absorption coefficient, (c) source function and (d) emission intensity for CD plasma: $\Delta x = 50 \mu m$, density = 0.3 g/cc, temperature = 50 eV.

Figure 13 shows (a) the emissivity $\eta$, (b) the absorption coefficient $\chi$, (c) the source function $\eta/\chi$ and (d) the photon emission intensity $I(h\nu) = \eta/\chi[1 - \exp(-\chi\Delta x)]$ of the CD plasma with 0.3 g/cc, $T_e = 50$ eV and $\langle Z \rangle = 2.3$. From figure 13(a), the emissivity $\eta$ shows that the free-bound process is dominant for photon energies over 50 eV. However, by considering the absorption shown in figure 13(b), the source function $\eta/\chi$ (figure 13(c)) indicates that if free-bound or bound–bound
transition effects are cancelled out, then the spectrum becomes that of the free–free case. The resulting emission intensity shown in figure 13(d) indicates that free–free emission might represent the total spectrum profile. For ‘free–free only’, in relation to ‘all’, the peak spectrum ratio is 0.76 and the integrated spectrum intensity ratio is 0.55. Therefore, as a first step, to estimate the order of the energy coupling from the photon emissions, we consider the bremsstrahlung (free–free) emission from the thermally diffused core. This analysis is based on a simplification of the model. For further analyses, we would need to detect the photon emission spectrum.

The bremsstrahlung photon emission power is proportional to $Z^n_e n_i T_e^{1/2}$, where $Z$ is the ionization state, $n_e$ is the bulk electron density, $n_i$ is the bulk ion density and $T_e$ is the bulk electron temperature [33]. In the thermally diffused core, a rise in bulk temperature induces additional ionization and an increased electron density. The ratio of bremsstrahlung power between the assembled core before heating and the thermally diffused core after heating, represented by $I^* = (\langle Z \rangle n_e n_i T_e^{1/2})/(\langle Z^* \rangle n_e n_i T_e^{1/2})$, gives the increase in photon emission observed in the experiments. Here, ‘s’ denotes values at stagnation and ‘h’ denotes the dose after heating, and $(Z)$ is evaluated from the CRE model. Figure 14(a) shows the values of $I^*$ and $(Z)$ as functions of $T_e$. From figure 14(a), the six-fold increase in photon emission after heating observed in the experiments is explained by radiation from the bulk plasma of 56 eV with an average Z value of 2.3. Figure 14(b) shows the values of the additional ionization energy, the energies of the bulk electrons and bulk ions and the total energy induced into the core as functions of the bulk temperature $T_e$ by accumulation in a spherical volume of 55 $\mu$m diameter. Here, during the thermal diffusion process, the energy of the bulk electrons also relaxes into the bulk ions. Actually, for the CD plasma parameters with which we are concerned (density of 0.3 g/cc; $\langle Z \rangle = 2.3$ and $T_e = 50$ eV), the electron–ion relaxation time is evaluated as 1.1 ps [34]. This time scale is much shorter than the 200 ps core emission time. So, for the duration of the thermally diffused core, we supposed $T_e = T_e^* \approx T_i$. From figure 14(b), for $T_e = 56$ eV, the resulting core energy is 106 mJ in total (closed squares): 65 mJ for electrons (closed circles), 28 mJ for ions (closed triangles) and 13 mJ for the additional ionization (closed diamonds). By considering the assembled core energy of 25 mJ, the energy gain is 81 mJ in total. Thus, the coupling efficiency from the 800 mJ heating laser to the core is inferred to be $(10 \pm 2)$% in total: $(8 \pm 1.6)$% for the bulk electrons including ionization and $(2 \pm 0.4)$% for the bulk ions. Figure 14(c) shows the coupling efficiency, $\eta$, as a function of the increase in photon emissions $I^*$. The error bar is determined from the deviation evaluated by integrating in time for the duration of the bright core spot that appears in the experiments: $I^* = 6 \pm 0.8$. Note that the coupling efficiency is obtained here based on a simplified model. For a more precise estimation, one possibility is to dope the shell with copper and analyse the K-shell radiation spectrum [10].

4. Fusion neutron reaction induced by counterbeams

When the assembled core was irradiated by heating pulses, we observed $\gamma$-ray signals for every shot and neutron signals for several shots on the plastic scintillators that were set on the laser axis (ND1, ND3, ND4, ND5 and g-ND2) and perpendicular to the laser axis (ND2 and g-ND1) as shown in figure 3(b). Here, ‘g’ denotes a gated scintillator used to eliminate $\gamma$-ray signals. The rise time of the gated scintillators after $\gamma$-ray arrival and the gate duration time were 50 ns and 200 ns, respectively. Lead shields with a thickness of from 5 to 10 cm were placed in front of these scintillators. The geometrical detection limit of the g-ND2 detector was 250 n/sr. Details of the scintillators are given in [11, 35].

Figure 15 shows x-ray streak images and the plastic-scintillator signals for (a) a fuel assembly without heating and (b) a fuel assembly with fast heating. For no heating as shown in figure 15(a), there were no $\gamma$-ray or neutron signals. In contrast, with heating as shown in figure 15(b), we observed $\gamma$-ray signals at the on-axis plastic scintillators (ND4 and ND5) and neutron signals at the on-axis gated scintillator (g-ND2) at a timing 66 ns later than the timing of $\gamma$-ray arrival. This gated scintillator was 126 cm from the target centre. From a time of flight (TOF) measurement, the neutron speed was $1.8 \times 10^9$ cm s$^{-1}$, which corresponds to an energy of 1.7 MeV. The peak energy of 1.7 MeV is consistent with that of beam-fusion neutrons driven by fast deuterons with an energy of 0.8 MeV and scattered forwards. This deuteron energy is comparable to that obtained in the PIC simulation, where an average of 0.5 MeV was found at the laser-plasma interaction surface.
Figure 15. X-ray streak images and the plastic-scintillator signals for (a) a fuel assembly without heating and (b) a fuel assembly with fast heating.

Figure 16. (a) Layout of the gated scintillators g-ND1 (90°) and g-ND2 (on-axis) in relation to the counterbeam irradiation geometry. (b) Time-of-flight spectra of neutron signals obtained using the gated scintillators g-ND1 (90°) and g-ND2 (on-axis). Reprinted figure with permission from [12], Copyright 2016 by the American Physical Society.

Figure 16(a) shows the layout of the two gated scintillators, g-ND1 (90°) and g-ND2 (on-axis), in relation to the counterbeam irradiation geometry. Figure 16(b) shows the TOF spectra of the neutron signals. These spectra were obtained by accumulating the peak-signal energies of nine shots in series. Note that repetitive operation can obtain TOF spectra in shot series. In contrast, for the single-shot experiments, the spectra are obtained by signal accumulation in space using TOF detector arrays [36].

In figure 16(b), the on-axis neutron spectrum exhibits peaks at both 1.7 MeV and 3.8 MeV. The FWHM values fitted to Gaussian curves are consistent with beam-fusion neutron reactions induced by fast deuterons with energies in the range 0.2–1.5 MeV [6, 37]. Following [38], we evaluate the neutron energy induced by incident fast deuterons as a function of scattering angle and incident deuteron energy. Figure 17(a) shows an interaction geometry in which a fast deuteron interacts with a cold target nucleus at rest. Equation (1) gives the energy $E_n$ of an emitted neutron with a scattering angle of $\theta$ driven by an energetic incident fast deuteron with energy $E_d$:

$$
E_n = \frac{m_d m_n}{(m_d + m_n)^2} \times \left(\cos \theta \pm \sqrt{\cos^2 \theta + \frac{(m_n + m_r)}{m_d m_n} \left(1 + \frac{Q}{E_d} - m_n\right)}\right)^2 E_d,
$$

where $m_d$, $m_n$, and $m_r$ are the masses of the incident deuteron, the emitted neutron and the residual nucleus, respectively, and $Q$ is the $Q$-value of the fusion reaction. Here, we consider two fusion reactions related to the CD target as listed in table 2, namely $d(d, n)^3$He and $C(d, n)^{13}$N. Figure 17(b) shows a neutron spectrum produced by fast deuterons interacting with a cold nucleus.

In figure 17(b), for the $d(d, n)^3$He reaction (shaded grey), when the energies of the incident deuterons increase, the energies of the neutrons produced by the beam fusion reaction become greater than 2.45 MeV for forward emission (0°) and less than 2.45 MeV for backwards emission (180°). For the perpendicular case (90°), the energy exhibits a small shift from 2.45 MeV. For incident deuterons with energies of 0.2–1.5 MeV, the neutrons emitted forward range from 3–4.7 MeV and those emitted backwards range from 2–1.7 MeV. When fast deuterons moving from two sides collide with cold deuterons in the bulk plasma, as shown in figure 16(a), the on-axis
focal intensities in excess of are accelerated by the self-focusing of heating pulses with possible that fast deuterons with energies in excess of 1 MeV 

According to the photon pressure acceleration [41], a 1 MeV gives in excess of 1 MeV , as shown in Figure 17(a).

Table 2. Neutron production reactions for an energetic deuteron incident on a CD target [38]. Reprinted table with permission from [12], Copyright 2016 by the American Physical Society.

| Reaction         | Q (MeV) | $E_d$         | Cross section (mb) |
|------------------|---------|---------------|---------------------|
| $d(d,n)^3\text{He}$ | 3.269   | $\sim 100$ keV | $\sim 40$           |
| $C(d,n)^{13}\text{N}$ | $-0.281$ | $\sim 1$ MeV  | $\sim 200$          |

detector captures neutrons scattered at angles of both $0^\circ$ (with energies greater than 2.45 MeV) and $180^\circ$ (with energies less than 2.45 MeV). Thus, the obtained two-peak profile shown in Figure 16(b) is similar to the expected curve. This result indicates that laser-induced fast ions can collide with the assembled core, thereby increasing the promise of experimental evidence towards fast heating by fast ions [37, 39, 40] if a sufficient number of fast ions are produced in relation to the energy of the assembled core. For unidirectional irradiation, when we irradiated the CD target with the heating pulses of BEAM-1 only, the on-axis plastic scintillator aligned with BEAM-1 detected backward-scattered neutrons with energies less than 2.45 MeV, and no double peaks were observed [35].

In addition, from Figure 16(b), the on-axis detector also detected a neutron signal of around 1 MeV. This signal is explained by the $C(d,n)^{13}\text{N}$ reaction driven by deuteron energies in excess of 1 MeV, as shown in Figure 17(b) (blue region). According to the photon pressure acceleration [41], a 1 MeV deuteron can be accelerated by a laser intensity of $1 \times 10^{19}$ W cm$^{-2}$ at the cut-off density where most of the laser energy is absorbed. This intensity is slightly higher than that of our laser parameter of $7 \times 10^{18}$ W cm$^{-2}$. However, the laser power of 3.6 TW exceeds the self-focusing power limit of 17.4 GW at the cut-off density [42]. Therefore, in the experiments, it is possible that fast deuterons with energies in excess of 1 MeV are accelerated by the self-focusing of heating pulses with focal intensities in excess of $1 \times 10^{19}$ W cm$^{-2}$, resulting in neutron production through the $C(d,n)^{13}\text{N}$ reaction. Actually, from Table 2, this cross section of this reaction is five times higher than that of the $d(d,n)^3\text{He}$ reaction.

For the on-axis signals, the presence of a peak at approximately 2.45 MeV indicates the possibility of a thermal neutron reaction. For the incident deuteron energy for emitted angles $\theta = 0^\circ$–$180^\circ$.

Figure 17. (a) Diagram showing beam fusion. (b) Neutron energy spectrum as a function of incident deuteron energy for emitted angles $\theta = 0^\circ$–$180^\circ$.

5. Summary and conclusions

We have reported detailed experimental results and an analysis on fast heating of a tailored-pulse-assembled core under a counterbeam configuration by using a HAMA 1 Hz, 5.9 J ICF laser driver. By changing the energy balance and the timing of the foot, spike and heater pulses in sequence, we tailored the pulse shape to optimize both the fuel assembly of a spherical shell target with a 500 \( \mu \text{m} \) diameter and a 7 \( \mu \text{m} \) thickness and the heating of the assembled core. During this optimization, we found that the heating pulses drove either fast particles (hot electrons and fast ions) or hydrodynamic motion to heat the assembled fuel. Generation of this hydrodynamic motion was dependent on the state of the assembled fuel, which was associated with the focal intensity of the heating pulses. In particular, when the heating pulses were irradiated into an expanding fuel, they contributed to re-assembling and heating the fuel with a focal intensity of $10^{17}$ W cm$^{-2}$. This result might indicate some relation of this method with the method of shock ignition.

Once the core had been assembled, we succeeded qualitatively in fast heating the core for shots in sequence with variations of laser energy within 18%. For efficient energy deposition by fast heating, the assembled fuel should be squeezed to occupy the least possible space so that the heating pulses can interact with the fuel having focal intensities in excess of $10^{18}$ W cm$^{-2}$. The coupling efficiency from the heating laser to the core was inferred from the enhancement of photon emission. This was $(10 \pm 2)\%$ in total: $(8 \pm 1.6)\%$ for the bulk electrons including ionization and $(2 \pm 0.4)\%$ for the bulk ions. The fusion neutron spectrum detected on the laser axis exhibited peaks at 1.0 MeV, 1.7 MeV and 3.8 MeV.
Those peaks were explained by the \(C(d, n)^{13}N\) and \(d(d, n)^{3}He\) reactions induced by counterpropagating fast deuterons accelerated by the photon pressure of the heating pulses, thereby offering the promise of experimental evidence towards fast heating via fast ions.

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